INNOVATIVE TECHNOLOGY
Summary Report

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Cryogenic Drilling

Subsurface Contaminants Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

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OST Reference # 155

Subsurface Contaminants
Focus Area

Demonstrated at
Lawrence Berkeley National Laboratory
Berkeley, California

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Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://OST.em.doe.gov under "Publications."

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SECTION I

SUMMARY

Technology Summary

Problem
Environmental drilling is used to conduct site investigations and to install monitoring and remediation wells. Employing conventional drilling techniques to conduct environmental investigations in unconsolidated soils can result in borehole collapse and may also lead to cross-contamination of aquifers and soil formations. For investigations in certain geologic conditions, there are currently no viable conventional drilling techniques available.

How it works
Cryogenic drilling improves upon conventional air rotary drilling by replacing ambient air with cold nitrogen (either liquid or gas) as the circulating medium (see Figure 1). The cold nitrogen gas stream freezes moisture in the ground surrounding the hole. The borehole wall is stabilized by freezing as drilling occurs, using nitrogen gas as cold as -320°F (-196°C). The frozen zone prevents the collapse of the hole and prevents the movement of groundwater or contaminants through and along the hole. In addition, cryogenic drilling enables the drilling of boreholes in ground that has not previously been accessible.

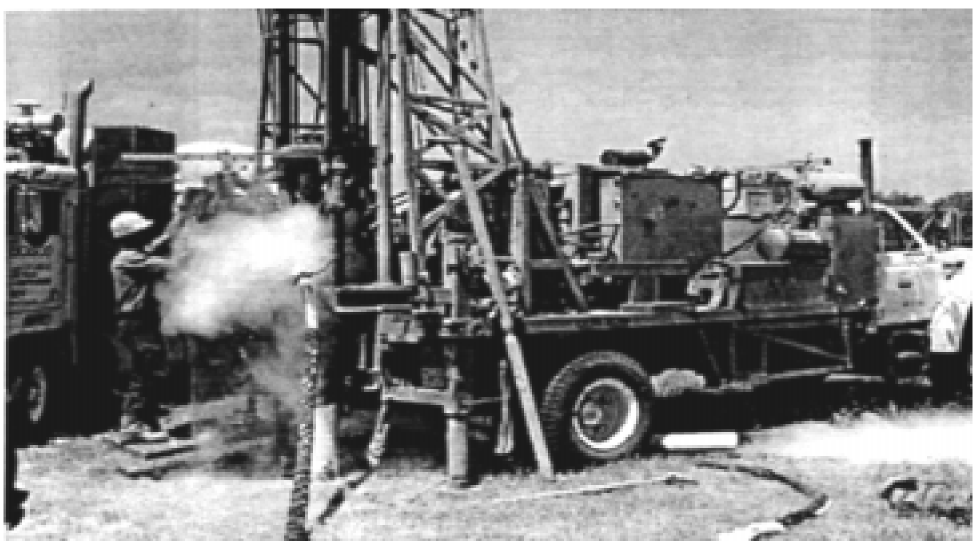

Figure 3. Cryogenic Drilling in Operation

Advantages over baseline
In addition to providing borehole stability and preventing contaminant transport through and along the borehole, the cryogenic drilling method:

- Eliminates the need for installation and removal of a casing to stabilize the borehole;
- Allows the drilling of a smaller diameter borehole since a casing isn't required;
- Minimizes investigation-derived wastes;
- Is environmentally benign—nitrogen gas is inert and nonexplosive;
- Can produce more representative samples;

- Enables the drilling of boreholes in areas and in ground that have not previously been accessible;
- Results in improved cutting and reduces trouble time associated with drilling in difficult materials;
- Allows for open-hole completions—the hole can remain open and frozen as long as is necessary—before a permanent well casing is installed or for logging or other purposes;
- Causes only temporary formation damage—full permeability is restored upon thawing;
- May reduce monitoring well development time; and
- Requires minimal equipment modifications to existing drill rigs.

Development Summary

Low-temperature fluids have been used to freeze soil since the end of the 19th century, but they have been used mainly for either temporary ground support or groundwater control. Cryogenic drilling has been developed as a technique to stabilize the borehole and prevent cross-contamination during drilling.

- Lawrence Berkeley National Laboratory (LBNL), Earth Science Division, and the University of California at Berkeley developed the cryogenic drilling technique by modifying a standard top-drive rotary rig. Using off-the-shelf equipment, the developers designed a method of introducing nitrogen into the drill pipe just below the drive head.
- Field demonstrations of the cryogenic drilling technology were conducted in May 1994, May 1995, May 1996, and September 1996. Demonstrations took place at LBNL in May 1994 (two demonstrations) and in May 1995; at the Aerojet Site in Rancho Cordova, California, in May 1996; and a slant hole was drilled at LBNL in September 1996.
- Cryogenic drilling is not commercially available, but it can be assembled from off-the-shelf components plus a special drill string and swivel. No company currently provides cryogenic drilling as part of its services.
- Cryogenic drilling technology is being developed further to obtain quality core samples. Since the technology freezes the soil particles in place and prevents introduction of foreign material into successive layers of an excavation, it could be used to obtain samples that are truly representative of a formation.

Contacts

Technical

Dr. George Cooper, Principal Investigator, Department of Material Science and Mineral Engineering, 595 Evans Hall, University of California, Berkeley, California 94720, (510) 642-2996, e-mail: gcooper@socrates.Berkeley.edu

Management

Jim Wright, DOE Subsurface Contaminants Focus Area Program Manager, (803) 725-5608

More information on cryogenic drilling can be found on the Internet at http://www.mse.berkeley.edu/faculty/cooper/cryodrilling/cryodrilling.html.

Other

All published Innovative Technology Summary Reports are available online on the DOE Office of Science and Technology (EM-50) web site at http://ost.em.doe.gov/IFD/OSThome.htm. The Technology Management System, also available through the EM-50 web site, provides information about OST programs, technologies, and problems. The Tech ID for Cryogenic Drilling is 155.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process

System configuration

- Cryogenic drilling uses a conventional, top-drive, rotary drill rig modified by the addition of a side-entry swivel to allow introduction of cold nitrogen (gas or liquid) about a foot below the drive head (see Figure 2). Special cold-resistant drill pipe may also be necessary.
- Nitrogen is supplied by a pressurized tank or from a pumper truck capable of delivering nitrogen at a variety of temperatures, flow rates, and pressures. This equipment is commercially available.
- A special diverter carries the exhaust nitrogen and drilled cuttings away from the drilling area.
- Only the nitrogen supply hose, swivel, drill pipe, drill bit, air return diverter, and exhaust hose contact the low-temperature fluid. A special drill string and swivel must be made from stainless steel or other alloy that does not become brittle at low temperatures, and must be fitted to the rig. In addition, the bit crossover sub is fitted with back-cutting teeth for reaming the hole.

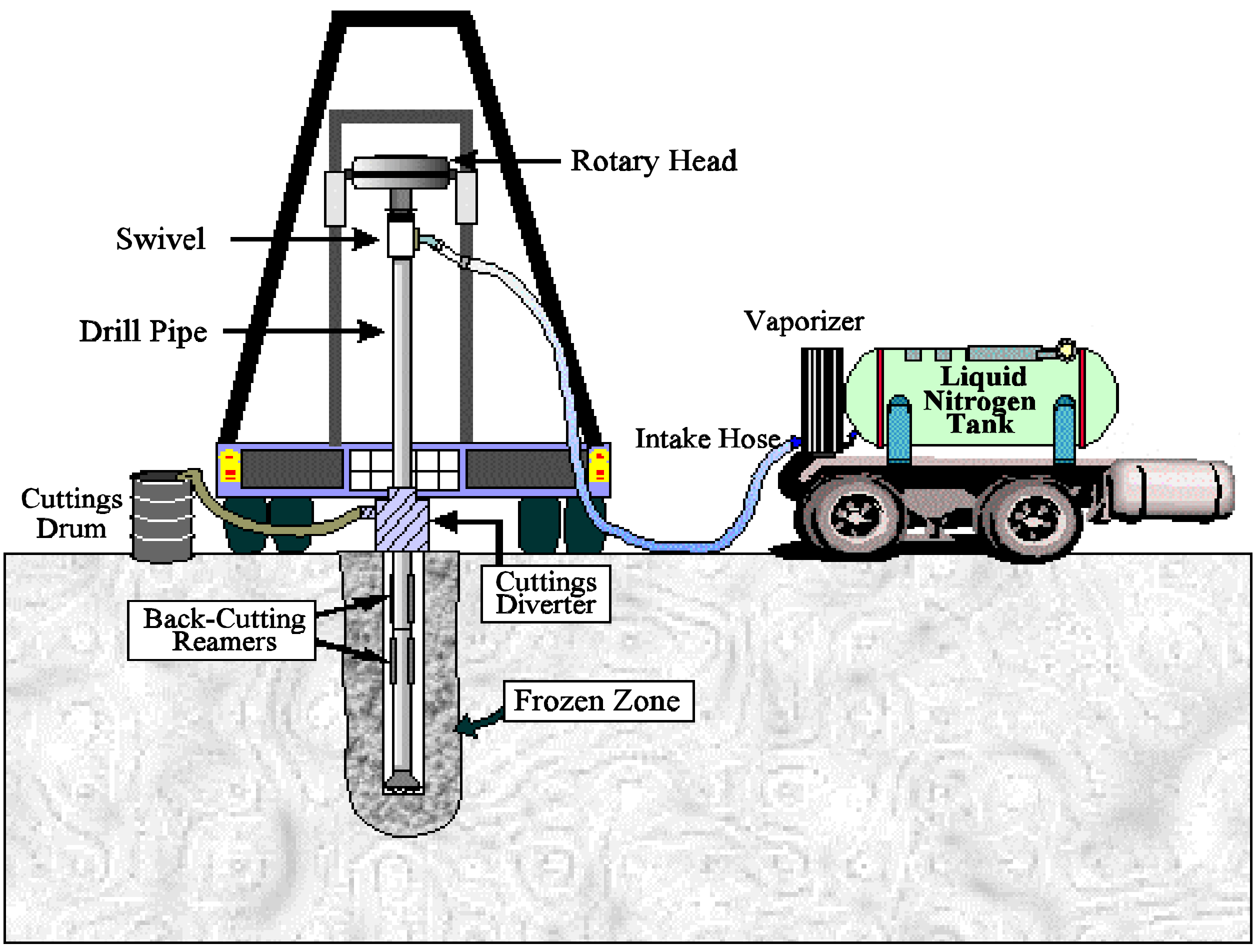

Figure 4. Liquid nitrogen tanker with vaporizer unit attached to the completed drilling assembly.

Process description

- The nitrogen descends the drill pipe and exits the drill bit, typically a conventional roller cone or drag bit, and blows the cuttings to the surface through the borehole annulus in the usual manner of an air drilling operation.

- The cold nitrogen gas stream freezes moisture in the ground surrounding the hole. The borehole wall is stabilized by freezing while drilling, using nitrogen gas as cold as -320°F (-196°C). The frozen zone prevents the collapse of the hole and prevents the movement of groundwater or contaminants along the hole. The solidified ground at the drill bit also results in improved cutting of rubble and other difficult material.

- Nitrogen pressures and flow rates required for cryogenic drilling are determined in the same manner that air pressures and flow rates are determined for air rotary drilling of a similar size borehole. If a pressure less than 200 pounds per square inch (psi) is required, a pressurized nitrogen tank will be adequate. If pressures higher than 200 psi are required, then a pumping unit capable of delivering nitrogen at a variety of temperatures, flow rates, and pressures will be needed.

- Drill string removal is aided by back-cutting teeth for reaming the hole on the bit crossover sub. This is especially helpful when high soil moisture content has caused the frozen borehole to expand.

- When the hole is allowed to warm up, the ground returns to its original condition.

- Thawing time depends on formation type, water content, permeability, and freezing time. In practice, thawing time has averaged 1 to 4 hours.

System Operation

Capabilities and limitations

- The borehole is stabilized during drilling by freezing, and without the need for a casing or a drilling fluid such as mud. The method is particularly useful for drilling in unstable soils and for directional drilling.

- Cryogenic drilling can be used in soils with as low as 2 percent moisture content.

- Cost appears to be the primary limiting factor on a practical maximum depth using cryogenic drilling, as nitrogen costs increase with depth. Technical depth limitations are comparable to those encountered with air rotary drilling.

- The technique can increase effectiveness of cutting and rate of penetration in difficult ground such as rubble or sticky clays.

- Continuous operation may be required with cryogenic drilling, since interruption in the application of nitrogen for an extended period may allow the borehole wall to thaw and collapse. Temporary interruption to the nitrogen flow, for example, when making drill pipe connections, generally causes no problems.

- Cryogenic drilling works well in the vadose zone and in low-flow aquifers. Limitations will occur in high-flow aquifers, such as those found in fractured rock, because of the difficulty in adequately freezing the borehole wall under high-flow conditions.

- Subsurface samples may be more representative than samples collected with other drilling techniques for several reasons: Nitrogen is inert and no other liquids are introduced into the borehole, freezing prevents contaminant migration through and along the borehole, and the cold temperature can help to preserve any volatile contaminants that may be present.

Investigation-derived waste and decontamination issues

- The secondary waste is of a similar amount and composition to that of standard air drilling, given a similar borehole size. Since no casing is required with cryogenic drilling, however, it allows for the use of a smaller borehole, thereby generating less drill cutting waste than with cased methods.
- Storage facilities similar to those for standard air drilling are required for secondary waste.
- Decontamination requirements are similar to those for standard air drilling.

Worker safety

- A 3/8-inch-thick polycarbonate sheet is used as a shield between the driller and the drill string.
- The drillers wear pants, goggles, and long-sleeved clothing to protect their skin from leakage of cold gas or liquid nitrogen.
- Cryogenically-insulated leather work gloves are used for pipe handling.
- The cold temperature of the cuttings can reduce the volatility of some contaminants present.
- Emergency respiratory equipment is not necessary.
- Workers who are responsible for handling or transportation of nitrogen must be knowledgeable of applicable regulations.

SECTION 3

PERFORMANCE

Demonstration Overview

Cryogenic drilling was demonstrated five times between May 2, 1994 and September, 1996 (see Tables 1, 2, 3, 4, and 5). The technology was demonstrated four times at LBNL in Berkeley on May 2 and May 21, 1994; in May 1995; and in September 1996. On May 7–8, 1996, cryogenic drilling was demonstrated at the Aerojet Site in Rancho Cordova, California, near Sacramento.

Equipment

- The field tests were conducted using Mobile Drill B-61 and Mobile Drill B53 HDX auger rigs mounted on Ford truck chassis equipped with the nitrogen supply swivel, a conventional bit, and standard pipe. Figure 3a shows a drill rig in auger configuration before modifications have been made. Figure 3b shows the rig modified for cryogenic drilling.

- Nitrogen gas at -125°C (-190°F) and 80 psi was supplied from a pumper truck. A 2,000-gallon mobile pumping unit capable of delivering nitrogen at a variety of temperatures, flow rates, and pressures was used to deliver 99.99 percent pure nitrogen gas to the drill rig. A stainless steel hose connected the tanker outlet to the swivel inlet.

- Modifications and improvements have been made to the equipment since the first demonstration. Some of these improvements include the addition of a purpose-built diverter for drill cuttings, the use of beryllium copper taper threads and the elimination of pins in the pipe connector, the addition of back-cutting teeth on the bit crossover sub for reaming, and 5-ft. stainless steel drill pipe.

Table 1. Demonstration Results, Lawrence Berkeley National Laboratory, May 2, 1994

Geologic features	Sand, gravel, and clay layers
Borehole size	17-ft deep, 3.5-in diameter
Equipment modifications	N/A
Total drilling time	6 hours, including time for positioning equipment, converting drill rig from auger to cryogenic roller-cone setup, installing safety equipment, drilling, and reconverting to auger configuration.
Average rate of penetration	5 ft/hour
Nitrogen flow rates	100 to 200 ft^3/min
Nitrogen used	30,000 ft^3 (roughly 325 gal in liquid form)
Results	No problems encountered during drilling.

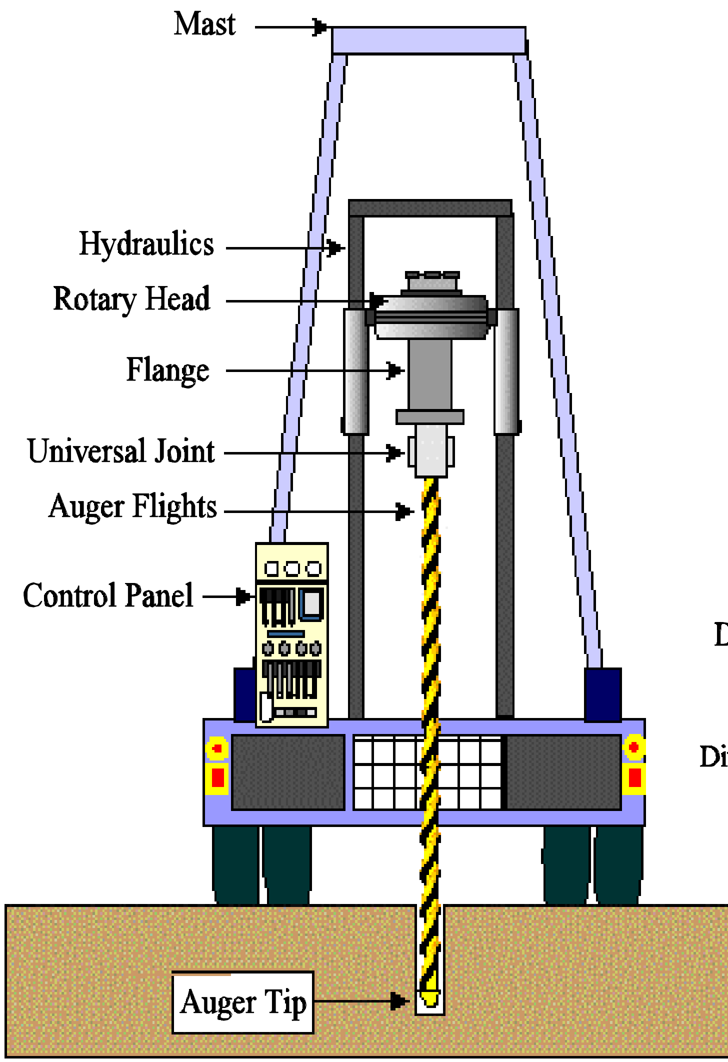

Figure 5a. Drill rig in auger configuration.

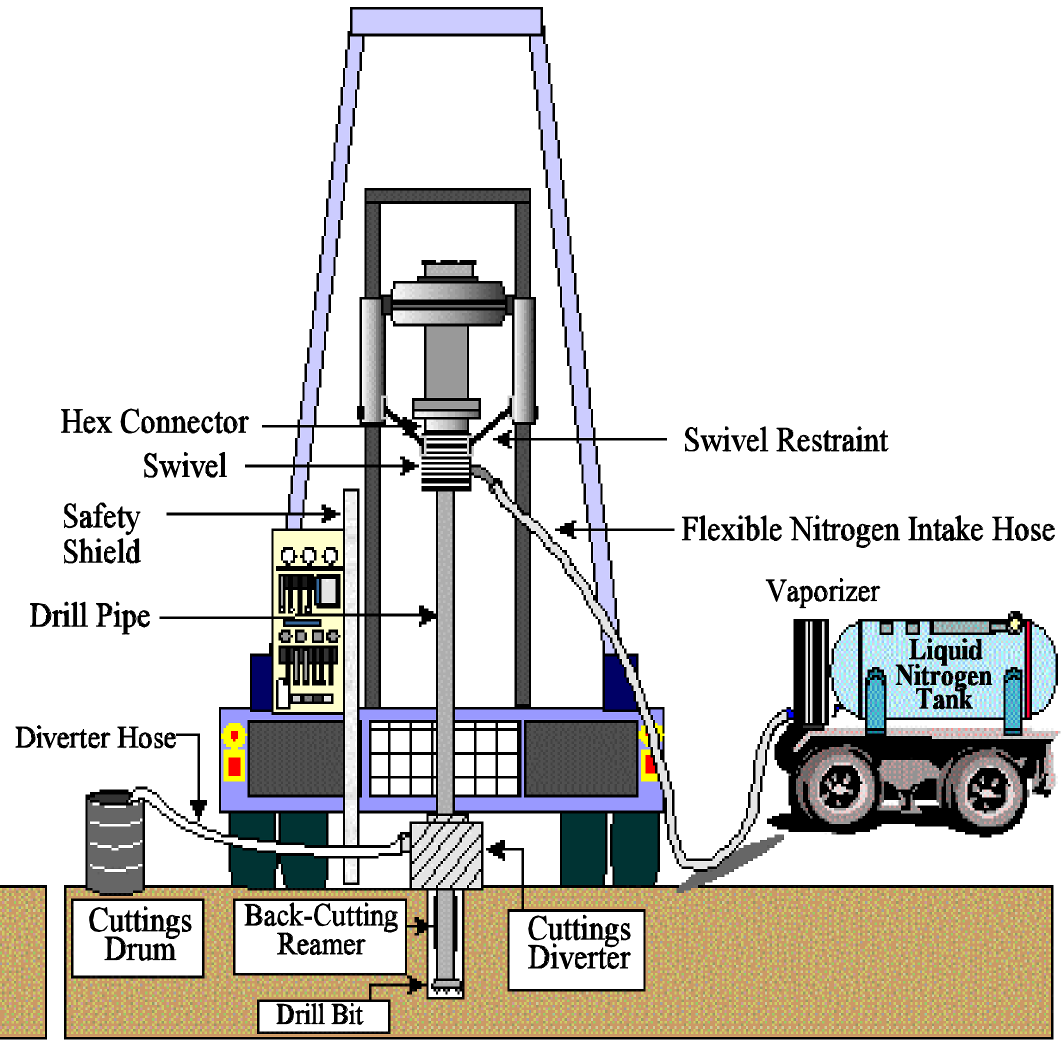

Figure 3b. Drill rig in cryogenic drilling configuration.

Table 2. Demonstration Results, Lawrence Berkeley National Laboratory, May 21, 1994

Geologic features	A series of loosely consolidated volcanic sediments, including some clay layers
Borehole size	8-ft deep, 7⅞-in diameter
Equipment modifications	The same equipment as was used in the first field test, except for a larger drill bit and a new purpose-built diverter. The diverter was designed to carry the exhaust nitrogen and drilled cuttings from the drilling area to reduce further the possibility of worker exposure to cold temperatures.
Total drilling time	1 day
Average rate of penetration	N/A
Nitrogen flow rates	300 to 700 ft^3/min
Nitrogen used	N/A
Results	• Initial drilling operations were successful and occurred as expected. • Drilling was discontinued at a depth of 8 ft because of a failure in the uppermost joint of the drill pipe. The failure was attributed to excessive wear from previous drilling and exposure to extremely cold temperatures. • The diverter and the swivel functioned as expected.

Table 3. Demonstration Results, Lawrence Berkeley National Laboratory, May 1995

Geologic features	The upper section consisted of approximately 12 ft of clay with boulders, underlain by a series of sands and sandy clays. The water table was at approximately 10 ft.
Borehole size	52-ft deep, 4.75-in diameter
Equipment modifications	A 4.75-in diameter roller-cone drill bit was used. Also used stainless steel drill pipe, rectangular threads, and stainless steel and bronze connectors.
Total drilling time	11 hours
Average rate of penetration	20 ft/hour
Nitrogen flow rates	200 to 700 ft^3/min
Nitrogen used	N/A
Results	• The target depth of 52 ft was accomplished; conventional auger equipment had failed in three previous attempts at 5, 7, and 8 ft because the auger had been unable to penetrate the boulders. • Groundwater was encountered at 11 ft, but it did not enter the hole because the nitrogen froze it outside the hole. • Good-quality split spoon samples were recovered every 5 ft from the dry, frozen hole. • After the soil thawed, 30 ft of debris sloughed into the borehole, and the water level rose to 10 ft below the surface. This indicates that the borehole might have been unstable if it had not been frozen while being drilled.

Table 4. Demonstration Results, Aerojet Site, May 7–8, 1996

Geologic features	Semiarid, alluvial, unconsolidated, sedimentary formation. The geology provided new challenges of rough drilling in a sandy soil matrix containing cobbles and boulders, which identified both strengths and weaknesses in the current cryogenic drilling equipment.
Borehole size	80.5-ft deep, 4.75-in diameter
Equipment modifications	New diverter, stainless steel cutting pipe, beryllium copper taper threads (pinned rectangular threads as a retrofit to old pipes), and a single-blade cutting tooth on the bit crossover sub for reaming.
Total drilling time	11 hours over 2 days
Average rate of penetration	10 ft/hour
Nitrogen flow rates	The use of nitrogen gas increased steadily with depth. Increased nitrogen flow rates at 30, 60, and 80 ft were necessary to lift larger cuttings out of the hole.
Nitrogen used	395,000 ft^3 (15,800 liters of liquid nitrogen)
Results	• An 80.5-ft deep, 4.75-in diameter borehole was drilled, falling short of the target depth by 19.5 ft. Drilling was stopped because the hex swivel shaft failed as a result of rough conditions. The attained depth, however, was 28.5 ft deeper than was previously achieved with the cryogenic technique. • Three pin failures occurred in the beryllium copper/stainless steel-pinned, pipe-joint connections. (Redesign eliminated this problem in future tests.) • Swivel nitrogen temperature and pressure variations with depth were noted.

Table 5. Slant Hole Demonstration Results, Lawrence Berkeley National Laboratory September 1996

Geologic features	The boring was drilled into the Orinda Formation, consisting of pebbles, cobbles, and boulders up to 1 ft in diameter.
Borehole size	37-ft deep, 4.75-in diameter, (30 degree slanted)
Equipment modifications	Totally redesigned swivel with a larger drive shaft and hex connection, pins eliminated from pipe connections, taper threads, 5-ft pipes (cut from 10-ft), three back-cutting blades on the bit crossover sub for reaming.
Total drilling time	4 hours during a 10-hour work day
Average rate of penetration	9.25 ft/hour
Nitrogen flow rates	The pressure ranged from 60 to 150 psi while drilling. Flow rates were between 280 and 800 ft^3/min.
Nitrogen used	150,000 ft^3
Results	• The aquifer that was encountered was frozen, stabilized, and penetrated. • Cryogenic drilling equipment was adapted easily to the Mobile Drill B53 rig. • The slant hole was drilled successfully, with only minimal training of the drilling crew. • Sample recoveries (using conventional split-spoon sampler) ranged from good quality to very poor; occasionally no penetration of the sampler in hard formation.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

Cryogenic drilling offers solutions to several problems commonly encountered in environmental investigations. Compared to conventional drilling techniques, cryogenic drilling can produce more representative sampling of subsurface solids and fluids, while minimizing the potential for cross-contamination, avoiding the introduction of drilling fluids such as mud into the borehole, and reducing the amount of investigation-derived waste. Cryogenic drilling may also reduce development time for monitoring wells, since the method leaves the formation surrounding the borehole virtually intact. In many situations, the advantages that cryogenic drilling offers over conventional drilling techniques will make it a superior choice for environmental drilling. Under certain site conditions, cryogenic drilling may even be the only viable drilling method.

Cryogenic drilling works well in sands, clays, gravels, and rock. It is particularly appropriate for sites with difficult drilling conditions such as loose sands, gravels, cobbles, and boulders or alternating layers of clay with unstable soils. Cryogenic drilling can also be very useful in providing borehole stability when directional drilling is required. The method solidifies the ground at the drill bit, not only stabilizing the borehole, but also improving the cutting effectiveness and rate of penetration in sticky clays or other viscous materials, which are rendered brittle by the cold temperature.

The technique has been used successfully in the vadose zone and in low permeability aquifers. Laboratory tests indicate that cryogenic drilling should be possible even in dry, arid sites with soil moisture content as low as 2 percent. This minimum moisture content is required to insure adequate strength of the frozen soil. Cryogenic drilling will have limitations in certain high-flow aquifers, however, due to the difficulty in ability to freeze the larger volume of water.

Cryogenic drilling can produce more representative environmental samples than competing technologies. With cryogenic drilling, no formation-altering liquids are introduced into the borehole. Nitrogen, which is environmentally inert, is used as the circulating medium. Because the method prevents cross-contamination between layers of soil, it can be used to obtain representative core samples, especially microbiological samples. In addition, the cold temperatures used can preserve any volatile contaminants.

Potential markets

Difficult drilling conditions are found at U.S. Department of Energy sites at Sandia National Laboratories near Albuquerque, New Mexico; Hanford near Richland, Washington; and Idaho National Engineering and Environmental Laboratory near Idaho Falls, Idaho, where there are areas with loose sands, gravels, and boulders and where the water tables tend to be relatively deep. If using conventional drilling techniques under such conditions of unstable soils, the increased depth of an open borehole can result in an increased risk of contaminating the deep groundwater. Cryogenic drilling at these sites would stabilize the loose soils during drilling without the injection of a drilling fluid such as mud, thereby minimizing the environmental impact of drilling.

Site conditions

- Cryogenic drilling is most appropriate for sites that contain unconsolidated sands and gravel that are difficult to drill by other methods.
- The technique is useful for drilling through alternating hard and soft layers, such as sandy zones with alternating layers of cobbles and boulders (see Figure 4).
- A 2 percent minimum soil moisture content is required to ensure adequate strength of the frozen soil.

- At sites with deep water tables, where conventional drilling techniques can increase the risk of introducing contamination to the groundwater, cryogenic drilling offers the advantage of building frozen walls that prevent movement of groundwater or contaminants through and along the hole.

- Limitations will occur when drilling below the water table in highly permeable formations because of the excessive water influx and the inability to adequately freeze the soil.

Figure 6. A cryogenic drilling site. Large boulders in the subsurface, visibly exposed in the trench in the foreground, do not present a drilling challenge using this technique.

Competing Technologies

Competing conventional drilling technologies include cable tool, hollow-stem auger, mud rotary, dual-wall percussion hammer, dual-tube reverse circulation, and air rotary casing hammer. Cryogenic drilling will compare favorably to these other techniques when certain site conditions and monitoring program objectives are considered.

Cryogenic drilling has competitive advantages over casing driver rigs, which install casings to stabilize boreholes. The necessity of installing and removing casings contributes to the total time of drilling and, therefore, increases the cost of drilling operations.

Cryogenic drilling may reduce the time for monitoring well development because the method leaves the formation surrounding the borehole virtually intact. For this same reason, it can also produce more representative samples than are obtained with other methods. All competing technologies may allow cross-contamination of the hole, change *in situ* porosity and permeability, and introduce inaccuracies in sampling. Cryogenic drilling appears uniquely able to recover biologically unaltered material.

Some of the other disadvantages of competing technologies include the following:

- Technologies that require the introduction of fluids to the subsurface for borehole stability will risk regulatory and community acceptance due to their potential to alter the formation;

- When used at environmental restoration sites, the volume of investigation-derived waste that is contaminated can be significant with many of the other methods; and

- Difficult site conditions, such as layers of loose sand, negatively impact the cost of using these other technologies.

The only disadvantages specific to cryogenic drilling include the need to provide the nitrogen supply, and the requirement for a special swivel and cold-resistant drill pipe. Some other issues related to specific competing technologies include the following:

- **Cable tool**
  Advantage: Can penetrate almost any formation.
  Disadvantages: Slow; causes local compaction around the hole.
  Difficult to obtain undisturbed sample.

- **Hollow stem auger**
  Advantage: Allows sampling through the auger, which supports the hole.
  Disadvantages: Has difficulty in handling unstable soils, particularly flowing sands.
  Cannot penetrate hard rock or cobbles.

- **Mud rotary**
  Advantage: Can penetrate almost any formation.
  Disadvantages: Equipment is bulky, and mud can be invasive, causing extensive formation alteration. Mud disposal may be expensive, particularly if contaminated.

- **Dual-wall percussion hammer**
  Advantage: May be rapid under favorable conditions.
  Disadvantage: May cause heating and/or compaction of the sample.

- **Dual tube reverse circulation**
  Advantage: Casing supports hole wall.
  Disadvantages: May have problems with recovering temporary casing; expensive.

- **Air Rotary Casing Hammer**
  Advantage: Casing supports hole while drilling.
  Disadvantages: May not penetrate hard rock or cobbles; may cause difficulties in retrieving casing; expensive.

SECTION 5

COST

Introduction

Cryogenic drilling can offer competitive advantages over conventional drilling techniques when certain site conditions and monitoring objectives exist. While cryogenic drilling can offer cost savings compared to conventional techniques, in many cases the cost of cryogenic drilling is higher than it is for other competing technologies. There are situations where cryogenic drilling will be the preferred technique, however, because the other technologies are not able to achieve the same level of success. Cryogenic drilling is most appropriate at sites with severely unconsolidated soils, where conventional drilling is tedious or impossible and hole stabilization is difficult.

Cost Analysis

Costs associated with cryogenic drilling that are not incurred with other drilling methods include capital costs to convert a conventional drill rig and operational costs for the nitrogen supply. Depending on site conditions, some or all of these costs may be offset by savings realized from the advantages of cryogenic drilling. When using cryogenic drilling in unconsolidated soils, for example, some costs can be reduced compared to competing drilling techniques because no casing is needed to stabilize the borehole. Not only are costs associated with driving and removing casing then eliminated, but drill rig costs (including the cost of personnel) and disposal of investigation-derived waste may be reduced because a smaller borehole can be drilled. Cryogenic drilling can also save costs by reducing trouble time that may be encountered with other technologies when drilling in difficult materials. In addition, for monitoring wells, development time may be reduced compared to other methods because the formation surrounding the borehole is unaltered.

Due to the variability of the cost of alternative drilling methods, the following considerations must be evaluated for a true cost comparison to be made:

- Site conditions;
- Monitoring or assessment program objectives;
- Regulatory constraints; and
- Availability of equipment and supplies.

Capital Costs

Capital costs associated with adapting a conventional drilling system for cryogenic drilling result from modifications to the rig for the introduction of nitrogen and special equipment that is needed for drilling at cold temperatures. Modifications to specific drill rigs typically cost under $1,000 and are generally limited to pipe-connecting tools, a swivel mounting system, and a safety shield to protect the drillers from the cold nitrogen gas. Special equipment costs can run between $10,000 and $15,000. These usually include a new swivel, drill pipe, and cuttings diverter, all of which must perform at low temperatures. The costs can be offset by the reduced time that is required to drill the well, principally because of improved cutting rates and the reduction in trouble time associated with borehole collapse.

Operational Costs

Operational costs for the nitrogen supply are associated with mobilization of the nitrogen tank system, tank rental, the amount of nitrogen used, and personnel required to operate the supply system.

- Liquid nitrogen is commercially available in tonnage quantities and can be delivered to most sites by road tanker. See Tables 6, 7, and 8 for actual and estimated costs for mobilization of the nitrogen tank system to the site.

- The liquid nitrogen costs from 30 to 70 cents per 100 standard cubic feet. The quantity of nitrogen required is dependent upon drilling conditions and typically adds from $5 to $20 per foot, in addition to regular drilling costs.

- During the demonstrations, nitrogen use averaged approximately 150,000 ft^3 per well. The volume would be expected to increase with increasing borehole depth.

- The workforce required for cryogenic drilling ranges from two to four people, the same number as for a regular drilling and sampling operation. In many cases, the drillers can operate the nitrogen tanker, so there is no increased cost for personnel. However, if a diesel pumping tanker is required (for delivering nitrogen at pressures greater than 200 psi), then a dedicated nitrogen operator will increase personnel costs, and the cost of the nitrogen supply equipment will also be higher.

Actual and Estimated Costs for Cryogenic Drilling
The cost information presented in Table 6 is based on actual costs incurred during cryogenic drilling of a 52-ft borehole at LBNL during May 1995. The total cost to drill the soil boring was slightly more than $6,000, roughly half of which was for the nitrogen supply. The nitrogen supply costs include the liquid nitrogen as well as mobilization and set-up, delivery, tanker rental, and the nitrogen system operator. The nitrogen supply costs incurred during this demonstration were higher than were required for the site, and it is anticipated that in future practice, actual costs could be reduced.

Table 6. Actual Cryogenic Drilling Cost for 52-foot Soil Boring

Drilling System	Rate	Cost
NITROGEN (200 - 1000 psi)		
Mobilization/demobilization	$500/day (2 days)	$1000
Tanker rental (pumper)	$250/day (2 days)	$500
Personnel (pumper operator)	$50/h (14.5 h)	$725
Nitrogen	$0.40/100 ft^3 (140,000 ft^3)	$560
Trip mileage	$1.90/mile (120 miles)	$228
NITROGEN SUBTOTAL		**$3013**
B-61 DRILL RIG		
Mobilization/demobilization	$1,000	$1000
Rig and crew	$145/h (14 h)	$2030
DRILLING SUBTOTAL		**$3030**
TOTAL COST		**$6043**

Nitrogen pressures and flow rates required for cryogenic drilling are determined in the same manner that air pressures and flow rates are determined for air rotary drilling of a similar size borehole. If a pressure less than 200 psi is required, a pressurized nitrogen tank will be adequate and equipment and personnel costs are less. If pressures higher than 200 psi are required, then a more expensive pumping unit and a dedicated operator are needed.

Although the site did not require the higher pressure and flow rate, during the May 1995 demonstration at LBNL, nitrogen was delivered to the rig with a variable pressure pumping unit, increasing the cost of both equipment and personnel. Crew inexperience also increased the drilling time, which added to the rental cost of the nitrogen supply equipment. It is expected that for a hole requiring less than 200 psi nitrogen, assuming additional crew experience, costs for the nitrogen supply could be reduced significantly. The total costs for cryogenic drilling may then be comparable to competing methods such as mud or air rotary drilling. Depending on site conditions, cryogenic drilling may even be less expensive than other methods when improved drilling rates, costs for disposal of investigation-derived wastes, and monitoring well development time are also considered. Table 7 shows estimated costs for cryogenic drilling of a 50- to 75-foot investigation well requiring LESS than 200 psi drilling fluid pressure. The cost of the nitrogen supply is just over $1000, or a little more than one third of the costs incurred during the demonstration.

Table 7. Estimated Costs for Cryogenic Drilling of an Average 50- to 75-foot Investigation Well Requiring < 200 psi Fluid Pressure

Drilling System	Rate	Cost
NITROGEN (0 - 200 psi)		
Mobilization/demobilization	$295 (1 ea.)	$295
Tanker rental	$125/day (1 day)	$125
Nitrogen	$0.40/100 ft^3 (140,000 ft^3)	$560
Trip mileage	$2.00/mile (est. 100 miles)	$200
NITROGEN SUBTOTAL		**$1180**
AUGER DRILLING RIG		
Mobilization/demobilization	$1,000 (1 ea.)	$1000
Rig and crew	$145/h (8 h)	$1160
Trip mileage	$2.00/mile (est. 100 miles)	$200
Drilling supplies (e.g., bit, grout)	$200	$200
DRILLING SUBTOTAL		**$2560**
TOTAL COST		**$3740**

Increased crew experience is also expected to reduce overall costs when more than 200 psi nitrogen is needed, however, under these conditions, the cost for the nitrogen is still substantial due to higher equipment and personnel costs. An evaluation of site conditions will help determine if these higher nitrogen costs can be offset by faster drilling rates and reduced trouble time, lower drill rig and personnel costs, and lower disposal costs for investigation-derived waste. Even in cases where cryogenic drilling will be more expensive than other methods, however, it may have performance advantages that make it more desirable, such as the capability for more representative sampling.

Table 8 shows estimated costs for cryogenic drilling of a 50- to 75-foot investigation well requiring MORE than 200 psi drilling fluid pressure. These estimates (Tables 7 and 8) assume a typical drilling period of one day. The drilling system requires an auger rotary drilling rig, but does not require any fluid pumps as with conventional water or air drilling systems. The nitrogen delivery system provides the pressure for the drilling fluid. A nitrogen tanker technician (pumper operator) is required for nitrogen delivery when more than 200 psi nitrogen is needed.

Table 8. Estimated Costs for Cryogenic Drilling of an Average 50- to 75-foot Investigation Well Requiring > 200 psi Fluid Pressure

Drilling System	Rate	Cost
NITROGEN (200 - 1000 psi)		
Mobilization/demobilization	$795 (1 ea.)	$795
Tanker rental (pumper)	$65/h (8 h)	$520
Personnel (pumper operator)	$50/h (8 h)	$400
Nitrogen	$0.40/100 ft^3 (150,000 ft^3)	$600
Trip mileage	$2.00/mile (est. 100 miles)	$200
NITROGEN SUBTOTAL		**$2515**
AUGER DRILLING RIG		
Mobilization/demobilization	$1,000 (1 ea.)	$1000
Rig and crew	$145/h (8 h)	$1160
Trip mileage	$2.00/mile (est. 100 miles)	$200
Drilling supplies (e.g., bit, grout)	$200	$200
DRILLING SUBTOTAL		**$2560**
TOTAL COST		**$5075**

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

- The cryogenic drilling technology is similar to standard air rotary drilling. It requires the same permits that are associated with other drilling technologies.

- Investigation-derived wastes, such as drilling fluids, cuttings, and equipment decontamination fluids, must be handled according to Resource Conservation and Recovery Act (RCRA) requirements. Cryogenic drilling minimizes the amount of investigation-derived waste generated.

- Occupational Safety and Health Administration (OSHA) requirements must be reviewed to ensure worker protection against high noise levels. Like all drilling methods, cryogenic drilling may produce noise levels that are considered dangerous to workers not wearing proper protection. Additionally, OSHA requirements for cold exposure should be reviewed to ensure that workers are knowledgeable of, and protected against, the extremely cold temperature and the potential for oxygen deprivation associated with liquid nitrogen.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and safety issues associated with the drill rig operation when performing cryogenic drilling are essentially equivalent to those for conventional drilling technologies. Worker exposure to hazardous and radioactive materials can be expected to be less with cryogenic drilling because no drilling liquids (such as mud) are used and the amount of investigation-derived waste is minimized.

- Frostbite and asphyxiation hazards could be associated with exposure to liquid nitrogen. Large clouds of condensed water vapor caused by the release of cold nitrogen into the atmosphere could be a nuisance and a safety hazard. Training is required to ensure worker protection from these hazards.

Community Safety

- Cryogenic drilling does not produce routine release of contaminants.

- No unusual or significant safety concerns are associated with the transport of equipment, samples, waste, or other materials associated with cryogenic drilling.

Environmental Impacts

- Cryogenic drilling systems require essentially the same amount of space as conventional techniques but will require additional space for the liquid nitrogen tank(s).

- The chemistry and biology of the region within a meter of the borehole may experience a small impact because of the injection of nitrogen and the cold temperature.

- Liquids near the borehole will be frozen, thereby reducing the risk of cross-contamination during drilling.

- Operation of the drill rig will create moderate noise and small amounts of diesel exhaust in the immediate vicinity.

Socioeconomic Impacts and Community Perception

- Cryogenic drilling has a minimal, short-term economic or labor force impact.
- The general public has limited familiarity with cryogenic drilling technology. However, there is greater potential for community acceptance of cryogenic drilling than of competing technologies that require the use of drilling muds.

SECTION 7

LESSONS LEARNED

Implementation Considerations

- The potential exposure of the equipment to liquid nitrogen's extremely cold temperature will impact design decisions as this technology is brought closer to commercialization. The following considerations are applicable:
  — Conventional drilling equipment is made of plain carbon steel, which becomes brittle at low temperatures.
  — The ductility and sealing properties of seals and packings decreases at low temperatures.
  — The lubricants could freeze.
  — Thermal expansion and decreases in ductility of some metals can lead to a decrease in the robustness of joints and welds.

- The following steps could be taken to compensate for such design issues:
  — Using face-centered cubic metal alloys, including most types of brass, bronze, stainless steels, and aluminum for the components of the swivel and drill pipe. These alloys are not adversely affected at liquid nitrogen temperatures;
  — Substituting graphite-filled polytetrafluoroethylene in the form of a chevron or rope packing for seals; and
  — Selecting dry lubricants commonly used in the aerospace industry, which are suited for exposure to extreme cold.

Technology Limitations/Needs for Future Development

- Future work could involve refining the modeling process, drilling slant wells and vadose zone drilling in highly unstable sand and boulder geologies, testing materials for exposure to liquid nitrogen during the drilling process, and determining the effects of the low-temperature drilling on bit wear and rate of penetration.

- Testing the technique in more challenging formations will establish the advantages and capabilities of cryogenic drilling. Work to perfect the cryogenic drilling field equipment, technique, and development of cryogenic sampling and liquid cryogenic drilling is ongoing.

- Further developments in cryogenic drilling may allow for horizontal (utility line or other) drilling without the use of drilling muds.

Future Technology Selection Considerations

Private industry is considering further testing and implementation of cryogenic drilling. Future activities could include the following:

- Using larger, more powerful, more versatile drill rigs;
- Using cutting containment systems compatible with cryogenic drilling;
- Developing a cryogenic coring technique for use with the cryogenic drilling technique to obtain excellent-quality core samples; and
- Investigating the potential for well completion in an open (uncased) borehole in unstable ground.

APPENDIX A

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