Trenching of Pipelines for Protection in Ice Environments

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Summary
Subsea pipelines located in ice environments need to be protected from potential ice gouging (also known as ice scouring) created when a moving ice keel interacts with the seabed. The integrity and operability of the pipeline can be affected by direct contact between the ice keel and the pipeline, or from loading imposed on the pipeline through soil deformation caused by ice gouging. The typical method considered for protecting against the risk of damage caused by ice gouging is through pipeline burial.

Conventional methods of pipeline burial use equipment such as ploughs, mechanical trenchers, and jetters, the majority of which have been designed to accomplish a maximum of 2 to 3 m of pipeline burial. Dredges can be used, but they have water depth limitations and limited productivity. Land-based equipment has been used for shore crossings, but is limited to shallow depths where temporary construction berms can be used as a working platform.

The capabilities of existing technologies are based on current industry practice developed for pipeline burial in ice-free environments. Pipeline burial requirements have generally been for improved hydrodynamic stability, mechanical protection (e.g., from anchors), controlling pipeline movements (e.g., expansion and buckling) and/or for flow-assurance purposes (reducing heat loss). A 2- to 3-m burial depth has been generally adequate to satisfy these conventional requirements. As developments are proposed for areas that experience relatively deep ice gouging (up to 5 m), burial depth requirements will exceed the capabilities of current pipeline burial technologies. New technologies capable of working in deeper water, achieving greater burial depths, achieving reasonable trenching advance rates, operating in harsh environments, and trenching through variable and difficult seabed soils will be required.

This paper highlights the issues and challenges surrounding pipeline trenching and burial in ice-gouge environments. The current state of practice is discussed along with the technology gaps that need to be addressed to prepare for future offshore developments in ice-covered waters where there is the potential for seabed ice gouging.

Introduction
Ice gouging of the seafloor (sometimes referred to as ice scouring) is a near-shore feature for most of the northern continents. In the Arctic, sea ice is driven by wind and current forces and tends to pile up, creating pressure ridges. This happens primarily during freeze-up and break-up seasons, while the sea ice sheet is highly mobile. These pressure ridges have keels extending below the water surface that move with the ice sheet. In other regions, glacial ice in the form of icebergs can have a keel that extends hundreds of meters below the water surface. Occasionally, these ice keels intrude into water with depths less than the ice keel draft and form a gouge in the seafloor soils **(Fig. 1).** The most common method used for protecting pipelines from ice keel damage in ice-gouge environments is to trench them to a selected depth below the mudline.

Geophysical surveys of the seabed are conducted and high-resolution bathymetry data is taken to measure the depths and widths of individual ice gouges. Side-scan sonar records have been used to help identify the individual gouges and to measure the gouge orientation. Gouges in the seabed are altered by ice-gouge recurrence, sedimentation, and bedload transport by bottom currents. Shallow areas with sandy sediments exposed to vigorous waves and currents during the open water season may have all bathymetric traces of ice gouging destroyed by the end of each summer season.

A primary input to any pipeline design is the design ice-gouge depth. The maximum gouge depth can be calculated for different values of return periods on the basis of the relationship described by Lanan et al. (1986). The methodology is a general approach, not developed for any specific project, and can be applied to any site. As such, it is recommended by API RP 2N (API 1995) to be applicable to any structure that is linear in shape, such as a pipeline. An alternative approach for predicting maximum gouge depth is based on the relative strength of the ice keel compared to the strength required to form a deep gouge in specific soil conditions. This approach has been successfully used on pipeline projects in ice-gouge regions that have limited historical geophysical data. It was found to be helpful for areas with firm seabed soils but would not conservatively limit maximum predicted-gouge depths in areas with soft soils, icebergs or consolidated multiyear ice features. Project site-specific conditions may also lend themselves to the analysis of ice flow driving energy, or force evaluations, vs. the resistance of the seabed soils and strength of the ice keels.

A pipeline on the seafloor may not be able to withstand the ice contact loadings and typically must be buried below the predicted design ice keel gouge depth for protection. As an ice keel comes in contact with any point in the seabed, vertical and lateral stresses are applied to the soil at the keel base. The result is a distribution of vertical and lateral soil displacements with depth beneath the ice keel, typically termed subgouge deformation of the seabed. This deformation can impose forces on the pipe body and result in deformation of the pipeline **(Fig. 2).** The configuration of the pipeline after gouging, and hence the bending strain in the pipeline, depends on the pipeline properties, the soil characteristics, the depth of the design ice gouge, and the depth of the pipeline below the mudline. The pipe must be trenched sufficiently beneath the ice keel to limit the imposed pipeline strains to within acceptable limits. If the pipeline is trenched below the zone of significant soil movement, it will experience increased soil pressure but not high bending strains because of the relatively small soil displacements. If the pipeline is trenched within the zone of significant soil movement, it may experience excessive plastic strains. Therefore, the induced soil displacements at the pipeline depth caused by ice gouging and re-

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sulting bending strains in the pipeline must be calculated and evaluated. The effect of this soil displacement and the loading on the pipeline can be evaluated through methods such as physical model testing, nonlinear finite-element analysis, and coupled Eulerian-Lagrangian analysis.

Trenching Equipment for the Arctic

Pipeline trenching equipment and the associated project execution plan must be compatible with offshore Arctic conditions. The equipment must be able to operate in summer or winter environments (depending on the execution plan) and be able to create a suitable trench profile in the site-specific soil conditions. A viable option in deeper water may not be the best solution in nearshore areas (e.g., a plough may be effective in thawed soils in deeper water but it may not be effective through near-shore permafrost).

The trenching capability must be such that additional excavation/trenching can be carried out if required. The presence of seabed permafrost or massive ice features may require overexcavation, which will in turn require additional reach capability of the trenching equipment. The seabed materials may also require significant overexcavation to achieve a stable trench profile. Inadequate reach capability may result in an inability to excavate the trench to the required pipeline depth of cover (original seabed to top of pipe).

When operating in below-freezing temperatures, ice may form on the support vessel(s), trenching equipment, and any survey equipment used to measure the trench profile. Severe ice accumulation on equipment could result in equipment damage. Trench survey operations could also be affected by cold weather, which may prevent necessary documentation of the trench configuration and measurement of the final pipeline depth of cover. Icing can also lead to increased equipment weights and/or delays for equipment de-icing.

Existing floating trenching equipment is generally not designed specifically for use in Arctic conditions. Floating vessels used in trenching or in support of trenching during open water may be subject to ice incursions. Equipment not designed for such an environment may not be suitable for working in these conditions and may be subject to damage. Ice that does not come in direct contact with floating equipment still could affect construction if the ice were to come in contact with anchor lines. The use of ice-management vessels in support of trenching operations needs to be considered during construction planning.

Fig. 1—Artistic illustration of iceberg gouging.

To operate in Arctic conditions, significant modifications to existing equipment may be required. The vessels would require winterization to allow operation in below-freezing conditions and the hulls may require strengthening to withstand ice loads. If construction cannot be completed in a single season, consideration must be given to mobilization and demobilization or overwintering of equipment.

Summer Trenching

Several trenching techniques could be used during the summer. Some are applicable only to pre-lay (i.e., before the pipeline is

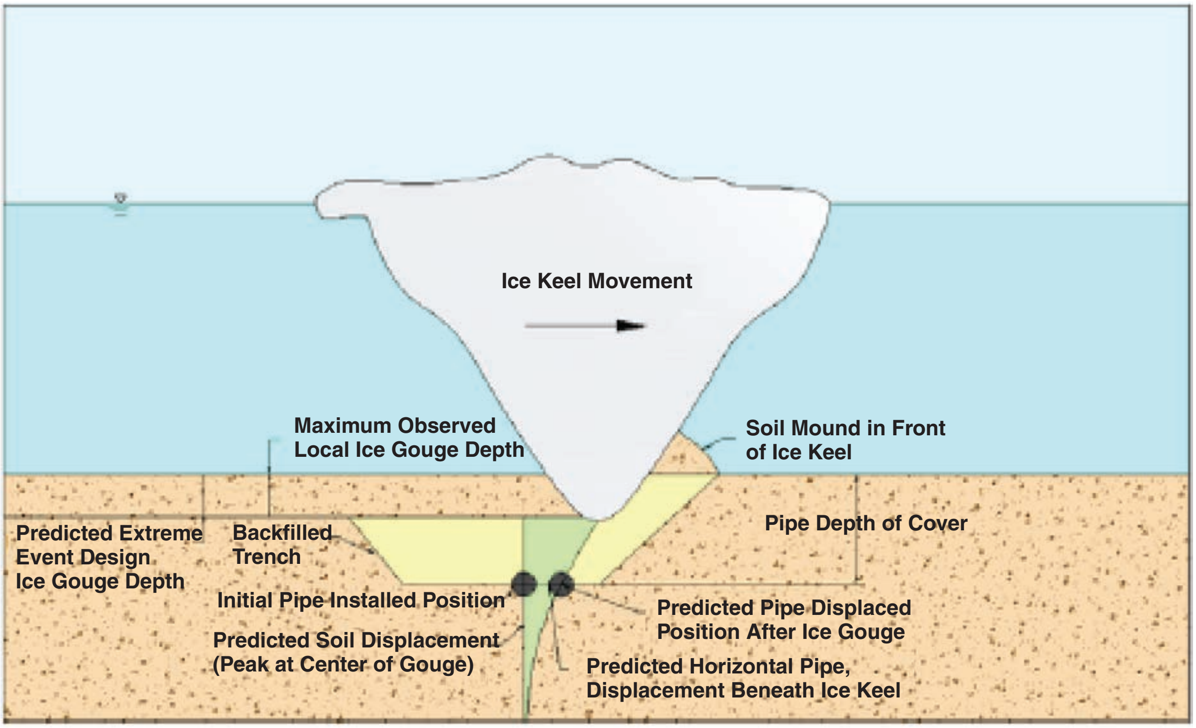

Fig. 2—Schematic of subgouge deformation.

installed), whereas others are best suited to post-lay installation. These methods include, but are not limited to:

- Conventional excavation
- Hydraulic dredging
- Ploughing
- Jetting
- Mechanical trenching

Protection of the installed pipeline could be provided by pre- or post-lay techniques. However, a pre-lay method or post-lay immediately following installation of the pipeline would most likely be required for Arctic conditions (depending on the area) because the pipeline would otherwise rest on the seabed and would be potentially exposed to the action of ice keels moving into the area.

Conventional Excavation. Hydraulic backhoes, clamshell-bucket dredges, or similar methods can be used to excavate a pipeline trench in shallow waters. In summer, the equipment could be operated from a flat-deck barge, which could maneuver by winching itself forwards and using spuds to remain on location while digging. Intruding ice could affect the operation depending on the station-keeping ability of the barge and the ice-management plans. Alternatively, in shore crossing areas, berms could be built in the near-shore area that could be used as platforms from which to dig the trench.

Conventional excavation is a proven but time-consuming method, and productivity would be similar for winter or summer construction. Also, the reach of an extended or long-reach backhoe is limited (practically) to a combined water and trench depth of approximately 15 m. Special consideration may need to be given to areas where ice-bonded permafrost may be encountered. Blasting has been used to assist in trenching pipelines through near-shore permafrost.

Hydraulic Dredging. The most common hydraulic dredges used for the excavation of pipeline trenches are cutter suction dredgers (CSD) and trailing suction hopper dredges (TSHD). The CSD excavates the trench with a rotating cutter head on the end of a ladder extended to the seabed. The cutter head breaks the soil, and pumps transport the soil/water slurry through a pipe up the ladder and through a discharge pipe. The end of the discharge pipe is typically located within a couple hundred meters from the dredge and is moved often to prevent excessive dredged spoil from accumulating in one area. Spoil can also be disposed of by discharging into barges, which can then travel to a disposal area. This would have the advantage of limiting the amount of sediment in the water column. Silt curtains have been used successfully to limit sediment dispersion during soil dumping.

The dredge advances by sweeping the cutter head back and forth while advancing longitudinally using spud piles. Because of the sweeping motion of the vessel, the trench tends to be wide. Smaller cutter-suction equipment components have been developed that can be mounted on a backhoe arm.

TSHDs excavate the trench by lowering a suction head to the seabed and pumping slurry into a hopper in the vessel's hull. When the hopper is full, the suction head is raised and the vessel sails to a designated spoil-dump area to empty the hopper. The slurry can also be side-cast or discharged to smaller vessels for disposal. The dredge then returns to the pipeline route and continues dredging. This cycle is repeated until the trench is complete. Because the suction pipe is not rigid, the position of the suction head cannot be controlled exactly, thus resulting in a wide trench. Because of their operating draft, dredges of this type are often limited to water depths greater than 6 m. The maximum water depth is limited by the length of the drag arm used to reach the seabed; however, at the time of this report, the industry minimum is 155 m.

When some soils are dredged and discharged (such as silts) using hydraulic dredging, more sediment is suspended in the water column than through mechanical excavation methods. This would need to be evaluated from an environmental-impact perspective. Again, special consideration may need to be given to areas where ice-bonded permafrost may be encountered.

Ploughing. Ploughs can also be used to lower a pipeline into a trench. This is usually accomplished post-lay, but they can be used for pre-lay trenching as well. Ploughs are usually preferred when the pipeline route is long because of their relatively quick advance rate. A plough could be used in either summer or winter. The primary determining factors for plough design, and ultimately its size, are the type of soil and the desired trench depth. This, in turn, affects the force required to pull the plough. The plough is advanced over the seabed by pulling with a large tug, a derrick barge, or a winch mounted on a frame traveling on the surface of land-fast sea ice.

Historically, ploughs have achieved a trench bottom depth on the order of 1.5 to 1.8 m with an average ploughing speed on the order of 200m/hr (Brown and Palmer 1985). Some multipass ploughs have been built which should have the capability of achieving a trench depth of 2.5 m if the soils are soft enough to allow ploughing, but should also be strong enough to remain stable until the pipeline touches down in the bottom of the trench. Multipass ploughs capable of excavating a trench 10 m deep have been investigated, but full-scale ploughs with this capability have not been built. Brown and Palmer (1985) have indicated that multipass ploughs for Arctic pipelines capable of trenching 4 to 6 m are feasible, depending on geotechnical conditions. Pipeline-trenching ploughs tend to be quite large, approximately 90 to 270 tons dry weight and 9 to 27 m in length. Several ploughs have been fabricated for previous pipeline projects, and these may be available for use on Arctic projects. The shore approaches would need to be excavated using other means, and special consideration may need to be given to areas where permafrost, hard soils, and bedrock may be encountered.

This activity would require a marine support vessel capable of supplying the large pull loads to move the plough along the pipeline route. Also critical is having a large crane or A-frame capable of deploying and recovering the plough. If used for post-lay trenching, these operations must be carefully controlled to avoid damaging the pipe.

Jetting. This method involves either pulling a jet sled along the top of a pipeline after it has been installed or flying a jetting ROV along the specified route before or after laying the pipe. Jet sleds and ROV-jetting systems are more generically described as jetters. High-pressure water jets liquefy the soil, and air lift or eductor pumps remove it from under the pipeline. In the case of post-lay jetting, the pipeline lowers itself to the bottom of the trench as the jet sled advances. This type of work is normally performed in above-freezing temperatures.

To achieve a trench depth of 3 m in most soil conditions, jetting often uses multipass techniques. Jetting would only work in certain soil types and would be ineffective against large boulders and bedrock. Because of the very large fluidized sediment load created, environmental concerns may also be an issue. As a supplement to other trenching techniques, localized jetting may be carried out to fluidize the trench bottom in order to lower a pipe that is spanning between local trench-floor high points following pipeline installation.

Another issue with jetting is the management of the excavated material. The spoils are in a fluidized form and if they must be returned to the trench to meet design backfill requirements, soil may need to be barged in to backfill the pipeline trench. The shore approaches may need to be excavated using other means, and special consideration may need to be given to areas where permafrost or hard soils may be encountered.

Mechanical Trenching. Mechanical trenching is commonly used for burying cables and umbilicals and has been used on pipeline-trenching projects. Typically, this method is used in openwater conditions and supported by a large marine vessel. There are two main types of mechanical trenchers: barge-mounted chain cutters; and tracked, crawler-style trenchers. Both of these rely on hydraulic power to operate their cutters and tracks (where appropriate).

The barge-mounted mechanical trenchers can be used in water depths of less than 100 m. They often feature high-volume jetting capability for the removal of overburden and a large chain cutter for stiff soils or rock. The crawler-style trenchers are capable of operating in water depths up to approximately 1500 m and often use high-pressure jetting as well as chain cutting. The hydraulic power requirements make these trenchers very large, often requiring large buoyancy tanks to keep the trencher from sinking into the soil and collapsing the trench, and to facilitate handling of the machine. These trenchers are large pieces of equipment and require a large marine vessel which must have a large A-frame to launch and recover the trencher.

Mechanical trenching to achieve a trench depth of 3 to 4 m is considered to be the conventional limit of what present installation equipment can achieve for soft soils.

Winter Trenching

Several trenching techniques could be used during the winter, and some are variations on the summer methods presented previously. Again, protection of the installed pipeline could be provided by pre- or post-lay techniques. However, a pre-lay method or post-lay immediately following pipeline installation would most likely be required for Arctic conditions because the pipeline would otherwise rest on the seabed and be exposed to the action of ice moving through the area.

Ice-based excavation has been performed on several pipeline projects using hydraulic backhoes working from stable land-fast sea ice. The sea ice is artificially thickened to support the trenching and pipe-lay activities. A slot on the order of 3 m wide was cut in the ice using a mechanical trenching machine. The ice is cut into blocks and removed using backhoes. The blocks are then moved by front-end loaders and trucks to locations away from the work site to prevent excessive deflections of floating ice in the working areas.

The trench is then excavated using backhoes. This construction method permits a continuous trenching, pipe-laying, and backfilling program. Excavation could start at more than one location concurrently. The trenching activity is characterized by water depth because this affects backhoe efficiency. The backhoe boom length needs to be increased in deeper water which requires changing out the associated bucket size. Shorter-reach backhoes with larger buckets ($\approx$3 m^3) would be used in shallower water. In deeper water, an extended-reach boom and smaller bucket ($\approx$0.76 m^3) might be used.

The trench depth would be checked as excavation proceeds. A scaled version of a CSD pump attached to a backhoe arm might be used to achieve the desired trench-bottom smoothness immediately before the pipeline is installed.

Most of the excavated trench soil would need to be temporarily stored on the ice before backfilling. The material excavated from floating ice would need to be trucked off and stored temporarily on bottom-fast ice in a designated area. If stored on floating ice, consideration must be given to sinking or creep (deflection) of the ice. Once a section of the pipeline is installed in the trench, backfilling using recently excavated trench spoils would commence.

Recent Project Experience

On the basis of a recent study for a proposed long-distance Arctic pipeline, it appears that the most economic method of preparing a trench before laying a pipeline in the Arctic is to use a multipass pre-lay plough. Normally, a ploughed pipeline is first laid on the seafloor, and then a post-lay plough is used to dig the trench to the desired depth. A post-lay plough straddles the pipeline and is guided along the correct route by the pipeline as it is towed by a pull barge or by the pipe-lay barge. Post-lay trenching would have less applicability in the Arctic because of the danger that ice keels could move into the area of the pipeline and damage the pipeline before it can be placed into the trench. This would need to be assessed on a case-by-case basis.

Tests have demonstrated that a pre-lay plough can be steered sufficiently to provide a suitable trench for subsequent pipe placement. In this particular case, a multipass unit was deemed necessary because of the depth of trench required to protect the pipeline from ice gouging. Attempting to plough a trench in one pass to the depths required for an Arctic pipeline would require extremely high towing forces.

The seabed soil conditions limit the use of a plough. If too sandy, the trench may fill back in, and if too stiff, the towing forces become excessively large. This recent pipeline study suggested that a multipass plough could be used for much of the route along the Alaskan coast and would only require TSHDs in the presence of soft, sandy material. Unfortunately, there is limited soils information upon which to evaluate the effectiveness of using a plough.

TSHDs were determined to be the next best alternative to ploughing for this particular project because they have a higher dredging capacity than CSDs and they can position the material removed from the trench for future use to backfill the trench. Earlier TSHD designs could not control the draghead position sufficiently to dredge a straight pipeline trench. They were also limited to handling relatively soft material. With recent developments in TSHD design, dredging contractors report that draghead position can now be adequately controlled and that by adding cutters to the draghead, the soils found in most of the Beaufort Sea can be excavated.

CSDs can excavate almost any type of seabed soil and thereby improve the potential for achieving the desired trench. The limitations of a standard CSD are maximum water depths and relatively slow linear advance rate because of the way that they move on their spud poles. They either "rainbow" the soil from the trench or discharge it through a floating line. In either case, the material is not readily available for use in backfilling the trench.

As part of this study, a conceptual CSD was designed that works on two sets of two spud poles in moveable carriages to improve the forward movement of the dredge. In addition, the dredge ladder was to be converted to a swinging ladder to eliminate the need for the entire mass of the dredge to be rotated back and forth.

Future Direction

Petroleum Research Newfoundland & Labrador (PRNL) is a member-based organization that identifies opportunities, develops proposals, funds and manages the execution of research and technology development projects on behalf of the Newfoundland and Labrador offshore oil and gas industry. PRNL has initiated Phase 1 of a Joint Industry Project (JIP) for the "Development of a Trenching System for Subsea Pipelines, Flowlines and Umbilicals in Ice Scour Environments."

This JIP is considered groundbreaking because of the deep pipeline-burial requirements for ice gouge protection in areas such as the Grand Banks, Labrador Shelf, Greenland, and the Beaufort Sea, for example. The development of new burial technology will be an enabler of safe and economic hydrocarbon development in these areas and other cold offshore regions.

The JIP will be a phased project. The overall objective of the project is to prove a trenching system that is capable of meeting the requirements outlined here. The goal of Phase 1 is to conduct studies, including participation from potential trenching contractors and technology solution providers, to determine a shortlist of technologies to be further developed/evaluated in Phase 2. The results of this multiphased project will allow future field developments to be planned on the basis of a reliable, predictable trenching solution able to create variable trench depths in a variety of soil conditions and water depths. Phase 1 will fund initial study work and conceptual engineering by selected technology solution providers.

To achieve the JIP goals, a trenching/burial system is required which is capable of:

(a) Trenching to depths greater than current industry norms (burial depths greater than 3 m with potential trench depths as much as 7 m).

(b) Trenching in highly variable soil conditions that may include sand, gravel, clay, glacial till, and bedrock, including the possible presence of boulders.

(c) Trenching in water depths beyond the majority of trenching requirements (water depths from 5 m up to 300 m).

(d) Operating in harsh marine conditions (for example, the Western North Atlantic).

A "trencher" or "trenching system" is considered to be not only the active piece(s) of equipment on the seafloor that creates the trench or provides the burial, but also encompasses everything else that is required for transport, survey (pre- and post-), deployment (power, tracking, monitoring, etc.), operation, backfill (if required), and retrieval.

Conclusions

Pipelines located in ice environments need to be protected from potential ice gouging created when a moving ice keel interacts with the seabed. The integrity and operability of the pipeline can be affected by direct contact between the ice keel and the pipeline, or from loading imposed on the pipeline through soil deformation caused by ice gouging. The conventional method used to protect against ice-gouging damage is through pipeline burial.

Conventional methods of pipeline burial use equipment such as ploughs, mechanical trenchers, and jetters, the majority of which have been designed to accomplish a maximum of 2 to 3 m of pipeline burial. Dredges can be used, but they have water depth limitations and limited linear advance rates. Land-based equipment has been used for shore crossings, but is limited to shallow water depths where temporary construction berms or stable land-fast sea ice can be used as a working platform.

The capabilities of existing technologies are based on current industry practice developed for pipeline burial in ice-free environments. Pipeline-burial requirements have generally been for improved hydrodynamic stability, mechanical protection, controlling pipeline movements, and/or for flow-assurance purposes. A 2- to 3-m burial depth has been generally adequate to satisfy these conventional requirements. As developments are proposed for areas that experience relatively deep ice gouging (up to 5 m), burial-depth requirements will exceed the capabilities of current pipeline-burial technologies. New technologies capable of working in deeper water, achieving greater burial depths, achieving reasonable trenching advance rates, operating in harsh environments, and trenching through variable and difficult seabed soils will be required.

The research and development needed to bridge the gap between what is currently available in trenching technology and what is needed to effectively and economically bury pipelines, flowlines, and cables in an ice-gouge environment is a significant undertaking. A JIP has been initiated to prove a trenching system that can trench pipelines to depths beyond industry norms, in water depths up to 300 m, in highly variable soil conditions and under harsh marine conditions. The Project will consider existing trenching/burial technologies, existing technologies that might be further developed/scaled, and conceptual or prototype systems that might achieve the requirements through further research and development. The Project is engaging qualified companies in regard to the development, manufacture, and potential operation of a trenching/burial system capable of meeting the requirements described in this paper.

These qualified companies have carried out a 3- to 4-month study during JIP Phase 1 to better define and present their technology, and to develop a proposed way forward for Phase 2. From this study/proposal evaluation, companies may be selected to perform more detailed engineering in Phase 2 and future phases of the Project.

The Project is also looking at auxiliary equipment that might be incorporated into an overall trenching/burial "system." This could include, but is not limited to, support vessels, positioning equipment, survey equipment, and boulder-detection technology.

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