

## Paper #6-6

# ARCTIC SUBSEA PIPELINES AND SUBSEA PRODUCTION FACILITIES

Prepared for the  
Technology & Operations Subgroup

On March 27, 2015, the National Petroleum Council (NPC) in approving its report, *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Technology & Operations Subgroup. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

**These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.**

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 46 such working documents used in the study analyses. Appendix D of the final NPC report provides a complete list of the 46 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website ([www.npc.org](http://www.npc.org)).

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# Topic Paper

(Prepared for the National Petroleum Council Study on Research to Facilitate Prudent Arctic Development)

**6-6**

## **Arctic Subsea Pipelines and Subsea Production Facilities**

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### **SUMMARY**

Offshore pipelines, wellheads and production facilities in the Arctic must be designed to prevent damage due to interaction with deep ice keels. There have been a handful of offshore pipelines installed in sub-Arctic sea ice and Arctic environments starting as early as 1942 in Russia and 1978 in Canada. Operation of modern offshore pipelines in ice environments began in 2001. These include pipelines in shallow waters in the US Beaufort Sea and deeper waters offshore Russia. Subsea wells in evacuated drill centers began successful production to FPSOs offshore Canada in 2005. There have been no instances of damage or product spills associated with any of the pipelines. Notwithstanding the unique ice environmental challenges for each Arctic area, much of technology developed and the experience gained from these projects will directly benefit and be applicable to future US Arctic developments in the Beaufort and Chukchi Seas. Burial is the most common method of pipeline protection where required, and much research has been conducted in the past 20 years to establish design methodology to set pipeline burial depth that will keep the pipeline within safe working limits. The cost of burial, especially if coupled with multi-season installation and the need to construct new-build installation vessels, can make offshore Arctic pipelines many times more expensive than their open water counterparts. While there have been few subsea wellhead installations and no subsea production facilities installed in ice environments, several research and concept studies have been conducted to understand the feasibility and nature of technology for protection of subsea wellheads and production facilities. Additional technology enhancements and ice environmental data will continue to improve reliability and economics of pipeline construction and operation. However, it is expected that further technology enhancements will be largely incremental vs. enabling because the means to design, construct and safely operate such pipelines.

### **I. ARCTIC-SPECIFIC CHALLENGES FOR OFFSHORE PIPELINES AND SUBSEA FACILITIES INSTALLATION AND OPERATION**

Offshore pipelines may be used in conjunction with Arctic offshore production platforms to export the produced fluids to shore. Additionally subsea pipelines may be used for in-field transfer from subsea wellheads to a production platform or to carry fluids from a production platform to a nearby offloading buoy for export by tanker. Additionally, offshore pipelines may be used to export production from subsea wellheads directly to shore, e.g., subsea to shore. Subsea wellheads and production facilities tied back to shore or a fixed platform in shallower water are likely to be used extensively for deeper water Arctic developments in order to minimize or eliminate the need for floating production facilities in ice. Subsea wellheads may also be used to minimize the number of platforms required for drill centers in fields with distributed reserves.

There are a number of unique aspects of pipeline and subsea installation and operations that differentiate the offshore Arctic environment from an open water environment. Key Arctic offshore factors (not present in every circumstance) are listed below and then discussion follows describing the interactions of the Arctic environment with installation and operations.

- Interaction of ice keels with the seafloor and subsea facilities
- presence of a continuous sea ice cover during the winter
- cold ambient temperature
- finite duration of open water season
- strudel scour during thaw season
- presence of near-surface permafrost in the pipeline burial zone

#### A. Interaction of ice keels with the seafloor and subsea facilities

Ice features that can gouge the seafloor in the US Arctic offshore include the keels of first-year and multi-year pressure ridges and ice island fragments. The US Arctic is not affected by drifting icebergs, but ice island fragments have been observed. Figure 1 shows a schematic of the ice gouge process. First-year ridges have rubble keels that extend tens of meters below the ice sheet. The maximum depth depends on the local ice conditions. While first-year keels consists of relatively lightly consolidated blocks of ice and ice rubble, they have been shown through seafloor bathymetry surveys to be capable of gouging several meters into the seafloor depending on the strength of the seafloor sediment (Ref. 1, 2). Multi-year ridge keels and ice islands tend to be less deep than first-year keels, but are more consolidated and stronger ice and can likewise gouge the seafloor to depths of several meters. Due to the mechanics of their formation (pushing of buoyant fragments of broken ice below the ice sheet), the maximum extent to which these first- and multi-year ice keels extend beneath the sea surface is about 35 to 40 meters. There is some evidence that a rare keel may reach deeper, For instance, the Geologic Survey of Canada (Ref. 3) report an extensive, multi-year database for the Canadian Beaufort Sea wherein the deepest water depth for what is classified as a *modern* seafloor gouge is 52 meters (from the 2008 repeat survey). Icebergs, which are not present in the US Arctic, can also produce gouging, and experience from offshore locations with icebergs contributes to the overall design practice.

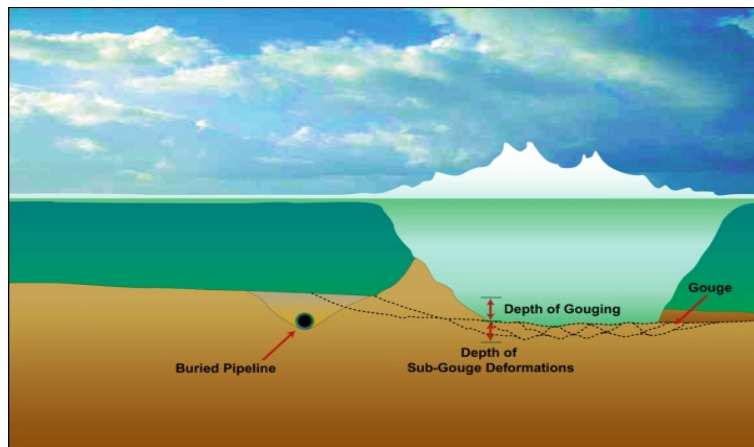


Figure 1. Ice gouging process

The ice environment that would likely produce the deepest gouges would be where relatively strong ice features are driven by the high forces of drifting thick pack ice. This could, for example be an ice island fragment or a ridge keel in a very competent multi-year ice floe that is embedded in the polar pack in the Alaskan Beaufort Sea.

Any subsea facilities located in water depths within the reach of ice keels must be protected from interaction with the ice. For seafloor pipelines, this usually means burial below the depth of gouging ice,

and for subsea wellheads and production templates, this could mean use of an engineered protection structure and/or placement in an excavation or buried caisson that extends below the seafloor.

### **B. Presence of a continuous sea ice cover in the winter**

During the winter months in most Arctic offshore areas, sea ice grows to 1.5-2.2 meters thickness and covers 90+% of the sea surface. Beyond the landfast ice edge (typically beyond the 20 meter water depth contour), this sea ice is mobile and typically highly deformed. The presence of thick, drifting ice presents operational challenges for subsea equipment access and maintenance or other operations that require station-keeping by an intervention vessel and the use of access lines or umbilicals. Ice cover also renders conventional surface based surveillance methods for pipeline leak detection ineffective.

### **C. Cold ambient temperature**

Buried pipelines installed in cold ambient temperatures must be designed to prevent upheaval buckling due to high thermal expansion when the line is later heated by production fluids. All Arctic pipelines could be subject to flow assurance issues (gas hydrate formation or solidification of waxes in crude oil) because of the cold ambient temperatures, but both of these issues are also common to all deepwater pipelines where seawater temperature is just above freezing.

### **D. Finite duration of open water season**

Generally, the open water season in US Arctic offshore areas containing hydrocarbon varies depending on location and year from two to four months. This limits the time available to install facilities, or requires installation operations be conducted in the presence of ice. For a very long pipeline, installation may require multiple seasons due to difficulty of maintaining station and heading of a pipe-lay vessel in drifting sea ice using conventional pipe-lay equipment. No offshore pipeline has been installed from a floating pipe-lay vessel in the presence of thick, drifting sea ice (the Baydaratskaya Bay pipeline, as discussed later, may have been completed in the thin, new ice growth of November). If subsea facility maintenance or workover operations must be conducted during open water conditions, the time available for such operations could be limited to a one to a few months each year.

### **E. Strudel scour during the thaw season**

Strudel scour is a type of hydraulic erosion whereby melt water, from a river during breakup or from large melt ponds on the ice sheet, runs out over the ice, thaws a hole in the ice and then energetically flows down through the hole to erode the shallow seafloor below. Strudel scour is primarily an issue where pipelines are located near river outlets. Strudel scours have been observed to create erosional depressions in the seafloor of tens of meters width and several meters deep out to water depths of about 5-6 meters. Such scours have the potential to remove the soil cover from buried pipelines. According to Palmer and Croasdale (Ref. 4), there is some indication from the monitoring of the Northstar pipeline route that thawing due to the presence of a shallow heated pipe may exacerbate strudel scour along the pipeline.

### **F. Presence of near-surface permafrost in pipeline burial zone**

Subsea permafrost is relatively common in shallow water in the Arctic, although it often lies many meters below the seabed due to gradual heating from the overlying seawater. In some offshore Arctic locations, however, shallow permafrost exists near the seabed. This permafrost would be susceptible to thawing from an uninsulated product line and hence could be difficult to trench through and also be the source of significant potential settlement of the pipe. In areas where the subsea permafrost is discontinuous, high differential settlements can occur as the pipeline settles in thawed permafrost zones and remains stable in non-permafrost zones. These differential settlements can induce significant strains in the pipeline. To the author's knowledge, no offshore pipelines have been installed in permafrost; however, shoreline crossings in Alaska have been insulated to avoid thawing of nearby or underlying permafrost.

## **II. PRUDENT DEVELOPMENT CONTEXT**

The concept of “prudent development” has several facets -- for this study is defined as *“Development, operations, and delivery systems that achieve a broadly acceptable balance of several factors: economic growth, environmental stewardship and sustainability, energy security, and human health and safety. Prudent development necessarily involves tradeoffs among these factors.”* This section seeks to provide perspective on how Arctic subsea pipelines and facilities relate to the multiple facets of prudent development. The most important concern is in providing protection for facilities so that interaction with ice does not lead to a major spill.

#### **A. Personnel Safety**

Personnel safety is a minor aspect of subsea pipelines and facilities because the bulk of these facilities are located away from locations of frequent personnel activities. The primary concern is to safeguard against ice-induced pipeline ruptures, especially lines carrying gas and especially near where pipelines tie in to manned offshore platforms.

#### **B. Environmental Protection**

Environmental considerations for subsea pipeline and facilities include potential impacts associated with installation and operations as well as environmental impacts from escape of hydrocarbons due to loss-of-containment failures.

**1. Installation and operations.** There is potential for ecological impacts due to the excavation of the seafloor for buried pipelines or subsea facilities. These issues are addressed in project environmental impact assessments. For example, consideration is given to disturbance of critical seafloor biota, impacts on marine life that feed on seafloor dwellers, disturbance of migration pathways due to vessel activity, construction activity and associated marine sound. These are temporary disturbances associated with installation and will generally occur in the open water season. These issues are regularly managed in the offshore environment in accordance with region-specific protective regulations. There may also be long-term operations-related considerations such as marine sound emissions from subsea facilities.

**2. Loss-of-containment failures.** The critical environmental concern for subsea facilities in an ice environment is escape of hydrocarbons due to leakage or rupture caused by ice interaction. This issue is addressed by prudent design, monitoring and maintenance.

#### **C. Impacts to Indigenous Peoples**

The interface of offshore pipelines with indigenous people would occur during installation when there could be potential for activities to alter migration paths of mammals important to subsistence hunting. Shoreline crossings, with the potential to initiate or exacerbate shoreline erosion, could also impact indigenous people. These are also issues that would be addressed and mitigated in a project environmental impact assessment study.

There are also positive impacts of a pipeline to shore for indigenous people, because it can represent a source of income from land use taxes on facilities, and a source of short- and long-term local employment for pipeline construction and maintenance.

#### **D. Economic Considerations**

Because Arctic subsea pipelines and facilities in water depths exposed to ice interaction require burial for protection, they are more costly than their non-Arctic counterparts. The cost of installing such pipelines can be significant, and due to short installation season, can take multiple years to complete. In the U.S. Arctic, Jones Act requirements dictate that dredging vessels needed to bury an offshore pipeline be U.S. constructed and crewed. Likewise, vessels that carry

supplies and crew from U.S. ports fall under Jones Act provisions. Since no suitable vessels currently exist, the cost of construction of a Jones Act compliant spread will fall on the first development project, which creates a significant economic hurdle. Unit cost comparison numbers for an installed pipeline provided to this study by Fluor indicate that the cost per kilometer for a buried offshore pipeline in the U.S. Chukchi Sea could be as high as 14 times the cost of a similar pipeline in the Gulf of Mexico. Finally, due to the remoteness of many Arctic locations, there may be no practical onshore destination for an export pipeline. Hence, in some cases, pipelines may not provide an economical alternative for evacuating product.

### **III. HISTORICAL INSTALLATIONS IN ARCTIC OR ARCTIC-LIKE ENVIRONMENTS**

What follows are brief descriptions of installed Arctic subsea pipelines. Extensive descriptions can be found in Palmer and Croasdale along with details of the overall Arctic pipeline technology development. These descriptions illustrate the technology, capabilities, and experience that have been developed in the US and elsewhere that are now available to help meet future challenges in US Arctic offshore hydrocarbon developments.

#### **A. Drake Project (1978)**

The first major subsea hydrocarbon-carrying pipeline to be installed in the West in an ice environment was that by Panarctic Oils in the Drake field in 1978. This was a 1.1 km demonstration pipeline for transport of gas from the Drake 76 well to Melville Island. The pipeline consisted of a pipe-in-pipe bundle of two 6-inch pipes plus other control umbilicals. The pipe-in-pipe concept was used to introduce a refrigerant to keep the soil around the buried pipe frozen. The shore approach was constructed by directional boring and the offshore portion beyond the drilled-in section was buried to a depth of 1.5 meters by trenching.

#### **B. Offshore Alaska Projects: Northstar, Oooguruk and Nikaitchuq (2000-2009)**

These are all shallow water developments in the Beaufort Sea that consist of a gravel drilling island with buried shallow water pipelines to carry produced fluids to shore. They were constructed by essentially the same means – excavation from thickened landfast ice. The Northstar Production Island is located about 10 km offshore in the US Beaufort Sea. The oil export line was installed in the winter of 2000 and comprises a two bundled 10-inch pipes with a leak detection tube. The maximum design burial depths were 1.8 and 2.1 meters depending on location.

Design burial depths were determined based on multiple seasons of surveys of seafloor gouges in the area. The pipe was installed in winter in up to 3 meters of water using long-reach track hoes from atop a thickened landfast ice sheet. A slot was cut in the ice and straddled by the excavators, which removed seafloor soil to form a trench for the pipeline (Fig. 2). The pipe was welded and bundles assembled and then long sections were lifted into the subsea trench per conventional onshore pipe burial operations. The soil was stockpiled on the ice and used to backfill the trench after installation of the pipe. Because of the shallow water depth, no portion of the Northstar pipeline was installed from a floating pipelay vessel; hence, from an installation perspective, the pipelay more closely resembled a conventional onshore operation. The Northstar pipeline bundle includes continuous, hydrocarbon permeable tubing that was included as a test of such a system for pipeline leak monitoring.

The Oooguruk pipeline was installed in 2007 in up to 2.3 meter water depth. It consisted of bundled 12-inch production line, 6-inch gas lift and injection flowline and a heating fuel line, all contained within a 16-inch outer pipe. Due to natural sheltering and very shallow water, gouging is not an issue.



Figure 2. Pipeline construction and installation from ice (Courtesy of: INTECSEA)

The Nikaitchuq pipeline was constructed in 2009 in up to 3m water depth. It is 5.6 km long and consists of a pipeline bundle consists of a 14-inch pipe-in-pipe production flow line in an 18-inch carrier, a 12-inch insulated water injection line, 6-inch spare line and a 2-inch diesel line. Like Oooguruk, there is low risk of ice gouge in the area.

### **C. Sakhalin 1 Project (2005-2013)**

The Sakhalin 1 project installed export pipelines from offshore gravity based platforms to carry produced fluids to onshore treatment facilities and injection water back to the platform. The pipelines of various diameters up to 28 inches were installed during the open water season, which is generally six months offshore Sakhalin Island. Because there were no existing international standards, a strain-based design methodology was used in the Project Specific Design Code developed by the project in conjunction with Russian design institutes and with approval of Russian design authorities (Ref. 5). With the exception of areas where water depth exceeded about 30 meters (roughly maximum design ice keel depth), the pipelines were buried to a depth that exceeded the design extreme ice keel gouge depth. Design burial depths were based on extrapolation of hazard curves developed from seafloor gouge surveys conducted immediately after ice clearance over a period of several years. The designs also accounted for potential seafloor erosion over the life of the pipelines. Shore approaches through the surf erosion zone and through the dynamic shoreline were constructed by deep trenching in a cofferdam-supported section. These pipelines have been in service since 2005 without incident or reported contact with gouging ice. The latest is the pipeline (installed in 2011) connecting the Sakhalin 1 Arkutun Dagi field Berkut platform in 35 meters water depth to the Chayvo onshore production facilities (Figure 3).



Figure 3. Sakhalin 1 Arkutun Dagi pipeline shore approach (Photo: Sakhalin 1)



The Sakhalin 1 project also buried a 28-inch concrete-coated oil export pipeline across the 20 km Tatar Strait to the Dekastri oil export terminal and a 48-inch line from the onshore terminal facility to the offshore loading platform. The strait experiences high currents and some areas of seabed erosion or lithodynamic alteration of the seafloor in areas where there are mobile seafloor sand waves. The Sakhalin 1 pipeline was trenched in place using a mechanical excavator/jetting sled. In addition to the Sakhalin 1 oil export line, Sevmorneftegaz has operated an oil line crossing the Strait since 1942 (it was replaced in 1986), and Gasprom installed two gas lines crossing the Strait in 2009 using a dredge to achieve burial targets.

#### **D. Sakhalin 2 Phase 2 Project (2003-2008)**

Offshore pipelines totaling nearly 270 km in total length connect the platforms in the Piltun-Astokhskoye field and the Lunskeye field with the onshore oil and gas pipeline systems to the Onshore Processing Facility/ LNG plant in the south of Sakhalin.

For Piltun 4 separate 14-inch concrete weight coated pipelines deliver crude oil and dry gas from PA-A and PA-B to an onshore manifold at the Chayvo landfall over a distance of 46 and 71 km respectively, totaling 234 km length. J-Tubes were installed on the PA-A facilities, whereas PA-B Gravity base Structure used flanged preinstalled risers, with ice scour protection structures and buried spools near the platform.

For Lunskeye two 30-inch multi-phase concrete weight coated pipelines run from LUN-A to the Lunskeye landfall over a distance of approximately 15 km and continue onshore to the Onshore Processing Facility (OPF). In addition, two offshore power and communication cables and a 4.5” Mono-Ethylene Glycol (MEG) offshore pipeline originating at the OPF are installed from the Lunskeye landfall to the LUN-A platform. For the flanged connection between the pipeline spool and the GBS riser, a flexible protection structure was designed to protect against ice loads and dropped objects.

The pipeline design took into account high strain capacity requirements and extremes of ambient temperatures to avoid the potential for brittle fracture. The installation method used was double joint S-lay combined with stringent AUT inspection of the offshore welds (see Figure 4). A significant part of the offshore pipeline sections is in water depths shallower than 32 meters and therefore complete burial is required to protect them from ice gouge damage. Also seabed morphology and coastal erosion influenced burial depth design. Shore approaches through the surf erosion zone were constructed with extra deep trenches, using major dredging equipment and cofferdams. For routing the pipelines in the non-buried zones, boulder fields and seabed scars were avoided and/or removed as required. These pipeline systems have been in service since 2009 without incident or reported contact with gouging ice. The pipeline systems are equipped with an Atmos leak detection system and an oil spill blockage system.



Figure 4. *PLV Seamac* laying pipe for Sakhalin 2 (Photo: Shell)

### **E. Kashagan Project (2005-2014)**

Installation of the Kashagan offshore flow lines, fuel lines, and hydrocarbon transfer pipelines in the North Caspian Sea began in 2007 and will ultimately comprise hundreds of kilometers of buried subsea pipelines ranging in diameter from about 8 to 28 inches. Water depths for these pipelines are very shallow, with a maximum of about 7 meters. A mix of conventional trenching in shallow flats, trenching from ice and offshore open water trenching using purpose-built excavating and backfilling equipment, have been used to achieve pipeline burial. As in the previously discussed pipelines, design burial depths are based on multiple years of extensive seafloor gouge surveys and generally are less than two meters.

### **F. Varandey Oil Terminal Project (2008)**

The Varandey offshore oil export terminal consists of a fixed or bottom-founded platform located 18 km from shore in about 21 meters water depth in the Russian Pechora Sea. The facility was installed in 2008. It is connected to onshore crude oil storage facilities via two 20 km 36-inch pipelines that are buried with 1.5 meters cover for protection from potential first-year ice ridge keel gouges. A fleet of icebreaking tankers evacuate oil from the platform year round. The Varandey pipelines were trenched using a trailing suction dredge and backfilled with barged-in sand material.

### **G. Baydaratskaya Bay Pipeline Crossing Project (2008)**

The project consists of installation in the summer of 2008 of two 48-inch concrete coated gas pipelines to carry product from the Bovanenkova and Harasawejskoje gas fields on the Yamal Peninsula, Russia 68 km across the Baydaratskaya Bay in the southern Kara Sea. Water depth for the 40 km dredged portion varied between 9 and 23 meters. The pipeline was buried with a cover depth of 1.5 meters in a dredged trench and backfilled with dredged sandy borrow material from near the Ural coast. Pre-construction gouge surveys indicated deepest gouge depth of 1.0m. The construction extended into November, and based on published photographs, some of the floating operations may have been conducted in very thin newly grown sea ice.

### **H. Terranova and White Rose excavated drill centers (2001 and 2005)**

There are currently two operating floating production, storage, and offloading vessels on the Grand Banks offshore Newfoundland. Terranova was installed in 2001 and White Rose in 2005. The subsea well templates for these FPSO developments are located within excavated pits in the seafloor, commonly known as excavated drill centers (Figure 5). The excavated drill centers were dredged with cutter suction dredging equipment in about 100 meters water depth to produce large pits that would allow the wellheads to remain below the level of the seafloor to protect from seafloor-gouging icebergs. Subsea flowlines for these fields are sacrificial – not buried, but instead designed to be flushed and isolated in the rare event that an iceberg threatens contact with them. The seafloor in the Grand Banks area contains hardpan and boulders, rendering it very challenging to bury pipelines. To the author's knowledge, these are the only functioning subsea facilities exposed to potential ice (albeit iceberg) contact.



Figure 5. Excavated drill center for FPSO operation (Courtesy of: Husky Energy)

#### IV. OFFSHORE ARCTIC PIPELINE DESIGN PRACTICE

Protection from damage due to contact by ice is the primary unique design requirement for Arctic offshore pipelines. Methods used for offshore Arctic pipeline design to date have been well documented by DNV (Ref. 6) and will not be repeated herein. Design of offshore Arctic pipelines is discussed in section A.14.3.5.1 of ISO 19906. Design of pipelines subjected to potential ice interaction is also discussed in DNV OS-F101 and API RP2N (3<sup>rd</sup> edition will adopt ISO 19906). DNV OS F101 does not present an explicit methodology for the assessment of loads imposed on offshore arctic pipelines, but does require ice load effects to be considered in areas with probable occurrence of ice gouging. C-CORE (Ref. 7) prepared a report for the U.S. Minerals Management Service on design options for pipelines in the U.S. Chukchi and Beaufort Seas.

Establishment of pipeline burial depth requirements requires consideration of three components:

1. No ice is allowed to contact the pipeline, i.e., the pipeline must be buried deeply enough to avoid any contact with the pipe by a defined, extreme gouge feature;
2. An additional burial allowance may be required to maintain design pipeline cover in the event of loss of cover due to seafloor erosional processes;
3. A further burial allowance may be required to avoid excessive pipeline strains from being induced by subgouge soil deformation.

With regard to component 1, the extreme gouging feature is commonly based on a design return interval meant to yield a specific target reliability against failure (typically 1000's of year return interval). It is determined primarily from an extrapolation of a gouge depth database collected over multiple seasons. It is determined based on the gouge depth distribution and the frequency of gouges that occur per kilometer of pipeline length per season. Gouge depth surveys are made during the open water season using multi-beam sonar bathymetry measurement, which have accuracy on the order of 0.05m. An example is shown in Fig. 6. In some cases, seafloor gouges can become infilled by sediment, so infill allowances may be in order. In areas like the Beaufort Sea or Grand Banks, where gouges are not obliterated annually by seafloor lithodynamics, it can be very difficult to determine the age of measured gouges. Hence, repeated surveys over a period of years are required to estimate the frequency of gouging occurrence.

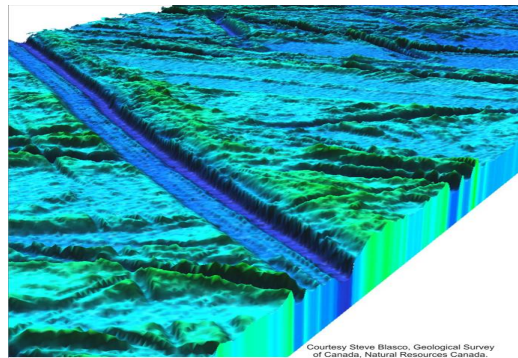


Figure 6. Example multibeam survey of ice-gouged seafloor.

(Courtesy of the Geological Society of Canada)

Long-term seafloor lithodynamic analyses are used to project potential loss of cover due to erosion of the seafloor over the life of the pipeline. This constitutes an allowance added to the extreme burial depth.

A subgouge deformation allowance is established based on an analysis of strain induced in the pipeline by soil deformations that occur for some depth below the gouging ice feature. The subgouge deformation profile below a gouging ice feature is estimated from principles of soil mechanics, and the deformation

field is applied analytically to the pipe using various models from structural spring models to three-dimensional finite element methods.

In all design cases, the objective is to insure that pipeline strains are limited to values that prevent rupture and leakage. Typically a two-tier design criterion is used wherein the strain in the pipe for an intermediate return interval event (say several hundred years) is kept below a value that would lead to damage needing repair, i.e., a serviceability limit. The extreme performance limit is meant to limit pipeline strains from the extreme design ice gouge below a level that could lead to pipe rupture.

#### **IV. PIPELINE INSTALLATION**

##### **A. Trenching and Burial**

The primary challenge for offshore Arctic pipelines is in attaining the required burial depth in an expeditious and economical manner. Based on the design considerations discussed above, required burial depths can be several meters of cover over top of pipe in the U.S.a Beaufort and Chukchi Seas.

There are various technologies available for trenching and burial of offshore pipelines. These include backhoe excavators in very shallow water, standard dredging equipment, pulled plow-type sleds or even seafloor-crawling cutting and jetting excavators. The choice of appropriate equipment depends on the water depth, depth of trench required and the type of seafloor soil conditions. The greatest challenges are associated with deeper water depths and hard or cemented seafloor soils or soils containing large boulders.

##### **B. Shoreline approaches**

Shoreline approaches and crossings in the Arctic can be particularly challenging if the shoreline soils consist of frozen permafrost. Arctic shorelines are susceptible to rapid erosion due to the melting of permafrost. Disturbance of the permafrost by excavation or the presence of a warm pipeline, can lead to accelerated erosion in the shoreline crossing area and potential exposure of the pipe. Shoreline approaches are constructed either by tunneling, horizontal directional drilling or direct excavation and backfill. Excavated shore crossings in permafrost areas have been over-excavated and backfilled with thaw stable material and also included thermal siphons to keep surrounding permafrost frozen. Excavated crossings usually involve the construction of a temporary cofferdam to maintain soil stability until pipe lay and backfilling are completed.

#### **V. PIPELINE TIE-IN AND SUBSEA WELLHEAD/EQUIPMENT PROTECTION FROM ICE INTERACTION**

##### **A. First-year sea ice environment**

As discussed previously, offshore Arctic pipelines are best protected in a sea ice environment by burial so that the seafloor soils shield it from gouging ice keel features. Pipeline tie-ins to bottom founded gravity based structures typically enter the platform above the seafloor. If the water depth is within range of ice interaction with the seafloor (say less than 40 meters), the tie-in spool is vulnerable to interaction by ice and hence requires protection. Protection has commonly been achieved by structural tunnels and/or rock armament. Likewise, subsea wellheads and subsea production equipment requires protection when within range of interaction with sea ice ridge keels. Various subsea protection structures have been proposed which typically involve embedded or partially embedded steel or concrete caissons or steel protection structures that extend above the seafloor. Such structures must be designed with sufficient foundation capacity to resist ice interaction without being displaced into the protected wellhead or subsea template.

##### **B. Multi-year ice or ice island environment**

Protection of subsea facilities from multi-year ice or ice island interaction involves significantly higher loads since the ice interacting with the structure can be much more competent than first-year ridge keels. In the SIRAM JIP, C-CORE developed conceptual designs for wellhead protection structures for a Grand

Banks free-drifting iceberg environment (Ref. 8). More substantial designs may be needed for protection of wellheads or subsea facilities that are susceptible to interaction with ice islands or multi-year ice keels. The U.S. Arctic offshore would fall into the category of having potential interaction with ice islands and multi-year ice keels in water depths ranging from the landfast edge out to about 40 meters.

## **VI. LONG-TERM MONITORING OF SUBSEA PIPELINES AND PRODUCTION FACILITIES IN THE ARCTIC**

### **A. Leak detection**

Routine surveillance of Arctic subsea pipelines can be challenged by the presence of ice cover. Consequently, most Arctic pipelines either constructed or proposed include provisions for some form of enhanced leak detection so they can be shut-in quickly in the event of a breach and thereby minimize spilled product. Leak detection can range from computational differential flow and/or pressure measurements along a pipeline segment, continuous fiber optic lines or hydrocarbon-permeable detection lines buried in the pipeline bundle to regular pipeline route surveys with underwater vehicles equipped with sensitive hydrocarbon detection instruments such as fluorimeters or mass spectrometers (Ref. 9). Emergency isolation valves could be located in strategic points of the pipeline (say at shore crossings) to allow the flow of product to be stopped in the event of a detected leak and to minimize the volume of product that might be released from a ruptured pipeline. The subsea facilities industry has been developing sensitive leak detection instrumentation that could be readily adopted for Arctic subsea applications.

### **B. Seafloor gouge monitoring**

In areas of active ice gouging, the seafloor can be re-surveyed periodically (if warranted) at the end of the ice season to inspect for seafloor erosion and to characterize any seafloor ice gouging that occurred during the winter. Ice gouge monitoring allows confirmation that gouges have not exceeded the design criteria and verification that there has been no potential for pipeline disturbance by ice. Vessel-mounted multi-beam bathymetry surveys are conducted in a swath around the pipeline so that gouge depths can be measured and gouge frequency determined. The gouge survey might trigger a pipe deformation survey if any deep (i.e., design-level) gouges are observed crossing the pipeline.

### **C. Deformation monitoring**

Another potential method to monitor pipeline integrity in the event of an unexpected gouge event is to use deformation monitoring. Deformation monitoring is possible using a “smart” pigging device (e.g., geopig or caliper pig) capable of detecting changes in pipeline geometry and/or changes in pipe deformation or strain. Such surveys would typically be run upon completion of the ice season as discussed above.

## **VII. RECENT AND CURRENT RESEARCH**

### **A. Burial depth requirements**

Most of the recent and ongoing research work on pipeline burial relates to subgouge soil deformation and pipe strain prediction. Large joint industry funded programs have been conducted since the mid-1990’s to study the gouging process and associated soil deformations and induced strains in buried pipelines. These programs included the PRISE and PIRAM JIPs, whose results have been extensively documented. Petroleum Research Newfoundland-Labrador (PRNL) is also progressing work using the NL producer’s research obligation funding in conjunction with Petroleum Research Canada with the intent to ultimately conduct large scale gouge tests in prepared soil beds with embedded instrumented pipes. Scores of finite element modeling studies have been conducted by many academic and industry researchers to advance methods for prediction of pipe strain due to ice gouging. All of these are well documented in the previously referenced DNV study (Ref. 6). This work has advanced significantly over the past 20 years and is reaching a fairly mature state of incremental improvements aimed more at improved economics vs.

enabling technology. For instance, the goal of the most recent work is to reduce pipeline burial depths to reduce the high cost of burial while maintaining target levels of reliability.

### **B. Seafloor gouge surveys**

Seafloor surveys are discussed in more detail in topic papers developed for the chapter on Measurement and Characterization of the Ice Environment. The need for historical datasets to help establish design criteria are site specific. Much work has been done with repeat seafloor gouge surveys in various areas to better understand the frequency of occurrence and depth distribution of ice gouges. The best work (from a perspective of long-term record of repeat surveys) has been performed by the Geologic Survey of Canada. Industry has conducted proprietary gouge surveys in most areas of interest for exploration and production. Since few datasets extend back more than a decade, additional repeat surveys will continue to improve the basis for design criteria and hence overall pipeline reliability.

### **C. Pipeline trenching methods**

Since burial depth requirements in some theaters could be substantial (e.g., ~5 meters in the Beaufort Sea and Grand Banks and potentially 7 meters in the iceberg environment offshore West Greenland), some research has been conducted on improved trenching methods, both for trenches in deeper water iceberg environments and for deeper depth trenches. One of the Newfoundland-Labrador research projects being stewarded by PRNL on behalf of the Grand Banks producers has as its objective to develop an offshore pipeline trencher that can excavate to a depth of 8 meters in seafloor soils containing boulders and in water depths to 300m. This is a proprietary study that for some confidentiality period will belong to the sponsoring companies.

### **D. Subsea wellhead and production facilities protection**

The primary work in this area has been conducted under the SIRAM JIP and focused mainly on protecting seafloor facilities from ice or iceberg contact using fabricated steel structures. This work, conducted by the Newfoundland-based company, C-CORE, is documented in the previously cited Ref. 8.

## **VIII. POTENTIAL TECHNOLOGY ENHANCEMENTS**

An inventory of areas where technology extensions would be useful (albeit probably not enabling) would include the following:

- Uniform design codes and standards;
- Improved ice gouge databases from repeat surveys in areas where data are sparse;
- Understanding of subgouge deformation phenomena with respect to soil conditions and trench configuration;
- Pipeline trenching methods to attain deep burial depths;
- Methods for age dating of seafloor gouges to distinguish between relic and modern gouges;
- Economic ice gouge protection structures;
- Leak detection and quick pipeline shut-in;
- Design for minimizing or avoiding product loss from a damaged pipeline;
- Robust shoreline approaches;
- Installation of buried subsea pipelines in drifting pack ice.

Owing to a large body of work related to recent subsea pipelines installed in ice environments, current opportunities for research are mostly confined to cost saving as opposed to enabling – e.g., shallower burial criteria, improved reliability, better leak monitoring instrumentation, quicker installation methods, and better trenching capability to deeper depths. In this vein, some research is being done (primarily at the Newfoundland-Labrador Center for Arctic Resource Development) on physical limits on gouge depths from FYI keels to reduce burial depth.

Enhancements are needed in the area of buried pipeline leak detection and shut-in technology and similar leak detection and monitoring technology for Arctic subsea installations. Fortunately, Arctic applications can leverage work that is ongoing on leak detection for deep water subsea facilities

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