RESPONDING TO A NORTHERN PIPELINE CHALLENGE

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ABSTRACT
An 800-mile natural gas pipeline is being considered as part of an Alaskan liquefied natural gas (LNG) project. Concepts to maximize the pipeline's value and minimize its cost are considered. The pipeline's operating pressure has been synchronized with the LNG plant's inlet pressure to achieve system efficiencies. Line pipe steels are optimized to address pressure, fracture and geotechnical issues. An advanced approach to designing and operating a gas pipeline in discontinuous permafrost is evaluated. Construction methods and strategies have been developed in areas such as trenching and winter construction. Finally, future work to further develop these concepts is identified.

INTRODUCTION
The Alaska North Slope Liquefied Natural Gas Project (the Project) will tap more than 25 trillion cubic feet of natural gas reserves located in the vicinity of Prudhoe Bay, where associated gas is currently re-injected at a rate of more than eight billion standard cubic feet per day (Bscfd). Gas will be conditioned on the North Slope and transported by an 800-mile buried pipeline to a liquefaction plant at an ice-free port in southern Alaska, then shipped by tanker to East Asia (Figure 1). Project start-up may be as early as 2008, depending on market conditions. The pipeline required to transport this "stranded gas" across isolated arctic regions, mountainous terrain and discontinuous permafrost makes this project different and more challenging than any other LNG project to date.

Four diverse companies (the Sponsor Group) have come together to study conceptual methods of making this project economically viable. In addition to applying the latest technologies, a different overall approach was required. This approach included a strong focus on the LNG market and an integrated, commercial-technical approach towards defining the Project. Stage one of this conceptual study, with the objective to define the Project and reduce cost, has recently been completed. This paper focuses on the pipeline portion of the Project, and describes some of the concepts considered by the project team to enhance the pipeline's value and minimize its cost.

THE PROJECT TEAM
The Sponsor Group established a small, integrated, project team of commercial and technical personnel in Anchorage, Alaska, comprised of employees of the individual sponsor companies. This organization, as shown in Figure 2, was designed to optimize available sponsor group expertise, assure a cross-functional approach, link commercial and technical work, and progress technical and commercial work in parallel.
The system integration team was responsible for establishing the overall LNG Project system and matching individual facility capacities to projected LNG market demand. The pipeline and plants technical teams determined the major conceptual issues to be addressed and worked closely with contractors to complete the work and estimate project costs.

The project team utilized over 100 technical and business experts from the sponsor companies and approximately 30 different contractors from across the continent in conducting the work. These resources performed their assignments in their normal work locations and traveled to Anchorage only when required. Using this approach, the project team accomplished its Stage One objectives at significantly lower costs than anticipated.

The pipeline contracting strategy involved accessing expertise from Alaska, Canada, and the Lower 48 States—individually and as parts of a team to perform focused studies. The pipeline technical team provided liaison between individual studies, ensuring consistent assumptions, and used the results to develop a pipeline design basis and cost estimate.

**MARKET Viable Project**

The initial LNG production rate was targeted at 7 million tons annually, with the potential for expansion as market conditions warrant. The project must be small enough to secure a toehold in the highly competitive East Asian market and otherwise be competitive with other green field LNG projects around the world. The smaller initial project size also reduces market and capital risk and is specifically designed to defer capital investment.

**ROUTE AND SITE SELECTION**

The project team evaluated 30 alternatives, comprising 18 LNG plant locations, three pipeline routes, and nine alternate concepts for transporting this energy. They reduced these options to five route/site combinations in a series of meetings designed to rate alternatives against a set of criteria. Studies addressing pipeline routing, LNG plant site preparation, geotechnical hazards, permitting and shipping were presented in a series of workshops, where benefits and concerns of each alternative were evaluated against the criteria. This process yielded two viable plant site/pipeline route alternatives: Nikiski, on the Cook Inlet and Anderson Bay near Valdez. Since this is a conceptual study, the project team decided to retain the two alternatives for further consideration.

**THE CHALLENGES**

A long distance, arctic natural gas pipeline adds significant cost to this Project. Comparison with pipeline project costs in Canada and the Lower 48 States show that the isolated location, lack of pipeline construction infrastructure, difficult and sensitive terrain and reduced productivity resulting from the terrain and cold weather result in Alaskan pipeline costs several times greater. The challenge was to optimize the pipeline's value to the LNG Project and explore practical concepts to reduce its cost. Therefore, an innovative approach to integrating the pipeline into the Project and a reduction of pipeline capital and operating costs were needed to contribute to the viability of the Project.

**MEETING THE CHALLENGES: SYSTEM DESIGN**

The Project facility components were designed as one system to achieve efficiency and reduce total cost. More conventional LNG projects consist of an upstream component to establish a gas supply, an LNG plant with a gas treatment plant designed to operate at around 700 psig, as well as storage tanks, port facilities and ships. The gas for this project is part of the eight Bscf/d presently being circulated back into the formations at Prudhoe Bay, eliminating the requirement for new upstream production facilities. The gas is conditioned to near-LNG quality and compressed to the 2800 psig pipeline operating pressure at a new gas conditioning plant at Prudhoe Bay. The LNG plant design takes advantage of the remote treatment plant and high pipeline pressure to achieve efficiencies by operating at an inlet pressure of 2,000 psig, substantially higher than conventional LNG plant design. System facilities are shown in Figure 3.

The concept of a pipeline which links the vast Prudhoe Bay natural gas reserves with other projects has the potential to further increase the pipeline’s value. The project team is pursuing synergies with other projects, including sharing capacity with a potential gas pipeline to the Lower 48 States and providing gas as feedstock to new and existing industries at the southern Alaska port. This concept of an “Energy Highway”, as shown in Figure 4, would reduce the capital cost of the pipeline and increase its value in developing Alaska’s stranded North Slope gas.

The pipeline design selected is a 30 inch diameter, X-80 to Nikiski on the Cook Inlet, or a 28 inch, X-80 pipeline to Anderson Bay in the Port of Valdez. The pipeline diameter to Nikiski is larger in anticipation of in-state gas usage in the Cook Inlet area. Compression along the pipeline is deferred until needed. Further Project expansion is achieved through additional compression rather than pre-investment in larger pipe diameter.

**MERITS OF HIGH-PRESSURE PIPELINE**

The high-pressure pipeline is well suited to northern design and operation requirements. A high-pressure pipeline requires a smaller diameter and a greater wall thickness than a conventional, larger diameter pipeline operating at lower pressure, while transporting the same volume of gas. The high-pressure pipeline costs about the same to construct and operate as the low-pressure system in more southerly locations. However, the stiffer pipe geometry of the high-pressure pipe provides increased capacity to resist frost heave forces typical in discontinuous permafrost. The high-pressure application fits well with high tensile strength X-80 line pipe steel, requiring a 0.613-inch wall
thickness for the Anderson Bay, and a 0.656-inch wall thickness for the Nikiski alternatives in Class 1, Division 1 code locations.

The lower pipe wall thickness and tonnage required by the X-80 pipe over lower steel grades reduces transportation and construction costs. Grade X-80 pipelines have been successfully constructed in Canada using automatic welding to achieve required weld consistency. Canadian, European, and Japanese pipe mills have successfully supplied X-80 pipe to owner specifications.

FRACTURE ISSUES

Preliminary fracture analysis indicates toughness required for pipe body fracture arrest is within current pipe mill capabilities. Current, industry-accepted procedures were used to model gas decompression and calculate pipe body toughness required to arrest longitudinal ductile fractures. Results indicate that smaller pipe diameters operating at higher pressures and lower temperatures may require lower toughness values than more conventional larger diameter pipe operating at lower pressures and higher temperatures. More work is required to determine the suitability of current models for these operating conditions. As well, full-scale burst tests may be required to validate these calculations.

PERMAFROST

Perhaps the most difficult issue associated with a pipeline in northern regions is in dealing with permafrost. The proposed pipeline routes cross Alaska from north to south, crossing areas of continuous, discontinuous and sporadic permafrost, including some ice-rich soils that are not thaw stable and some thawed soils that have a high frost heave potential. The objective is to develop a pipeline design approach that will result in low life cycle costs, and provide for safe pipeline operation by accommodating movements caused by frost heave or thaw settlement.

A team of experts provided an integrated approach to meeting this objective. Pipeline system engineers analyzed hydraulic parameters and temperature control system requirements using ambient soil temperatures, pipe/soil heat flux, soil properties, climatic data, and desired summer and winter operating temperatures along the routes. Frost heave and thaw settlement was calculated using the finite-element geothermal model, TQUEST, and pipe stress was predicted using pipe-soil interaction model, PIPLIN. Laboratory tests of X-80 steel specimens were performed to assist in evaluating the allowable strain limits of the pipe. Designs to accommodate or mitigate frost heave and thaw settlement induced pipe movements were evaluated. Methods to monitor and, if necessary, remediate pipe movements were considered.

Several advances were made during this study that have the potential to result in significantly lower costs for this pipeline compared to natural gas pipelines in previous studies. Operating this pipeline at higher temperatures than pipelines in previous studies will lower mechanical chilling costs and reduce frost heave potential. The pipeline will operate below freezing in the permafrost region of the North Slope. However, the pipe will be allowed to operate above freezing in many discontinuous permafrost areas. While this will cause thaw settlement of some pipeline segments, a solid monitoring program and, if necessary, remediation will maintain pipeline integrity.

Detailed strain and fracture analysis has significantly increased the proposed allowable strain limits for the pipeline. This will allow the pipeline to accommodate higher allowable movements from frost heave and thaw settlement, resulting in significant reduction in the required amount of heavy wall pipe.

Pipe wall thickness was chosen as the primary mitigative measure to accommodate pipe movement resulting from heave and thaw settlement. The 28- and 30-inch diameter X-80 pipe, with sufficient wall thickness to satisfy the high operating pressure requirements, was found sufficient to accommodate all but the most difficult soil conditions. The most difficult cases, which are estimated to be minimal, will be handled by increasing the pipe wall thickness or through special designs such as insulating the pipe or replacing the susceptible soil with non-frost susceptible and thaw stable granular material.

Monitoring the pipeline for movement during its design life is a critical element of safe and economical operation. A well-planned monitoring program can signal impending problems and allow for more focused monitoring and planned remedial measures if necessary. This approach relies heavily on internal inspection tools or “smart pigs”, which have proven successful in measuring pipe movement.

A number of remediation measures to maintain pipeline integrity if excessive differential movement occurs were studied. Among them is the concept of transporting warm gas through pipe segments to thaw the frost bulb in a heaved area.

In order to progress from conceptual engineering towards final design, additional work is required. Although more specific field data is needed, numerical modeling can be used to identify critical route-specific geotechnical data required to more accurately predict pipe movement, thereby facilitating more focused, lower cost field geotechnical investigation and laboratory programs. The steady state model used in this study provided a “snapshot” of pipe hydraulic and thermal profiles. Future work will simulate the pipe and its contents, coupled to the surrounding soil and climatic inputs on a time step basis, providing a better understanding of dynamic effects of the pipe on the surrounding soil and of the soil on the pipe. It will also help in evaluating the concept of cycling gas temperatures from cold to warm to mitigate the effects of frost heave.

PIPELINE CONSTRUCTION

Pipeline construction in Alaska is significantly more complex and expensive than it is in the Canadian provinces and the Lower 48 States. The major reasons are the isolated location and lack of infrastructure, difficult and sensitive terrain, and lower construction productivity resulting from cold weather.

ISOLATED LOCATION/LACK OF INFRASTRUCTURE

Pipeline construction is a production-based, labor and equipment-intensive process. The pipe and much of the heavy construction equipment must be shipped from distant locations by a number of consecutive-transportation modes. This study determined that carefully planned logistics—such as matching supply sources with...
construction location and utilizing innovative transportation methods—will reduce transportation costs. However, these costs remain higher than those of southern projects. One innovative transportation method is the blimp concept for transporting heavy loads where highway and bridge infrastructure limit economies of scale, or traditional forms of transportation are prohibited during road bans or tourist season. Lighter pipe materials, such as steel and glass fiber composite and glass fiber and epoxy, must be considered. Higher strength steels will also reduce transportation and handling costs, if they can be proven fit for cold weather pipeline service.

Much of the labor resource must be transported from distant locations and housed in camps during construction, where in more southerly locations, they are more closely available and easily housed in existing commercial facilities. Camp costs to house construction personnel are high because of lack of existing infrastructure. Opportunities for synergies between the hotel and construction industries must be explored to improve the construction housing issue.

DIFFICULT AND SENSITIVE TERRAIN

The ability to effectively and efficiently trench for a buried pipeline in permafrost and hard rock is a major construction cost driver, since trenching can limit the construction production rate. During this study, trenching production rates were developed and summarized from prior trenching tests in cold permafrost regions, as well as vendor data and vendor interviews. From this work, it was determined that a large majority of both pipeline route can be excavated using either chain or wheel mechanical trenching equipment, at production rates that have never been experienced or anticipated on previous large diameter arctic pipeline installations.

This work also determined that utilizing native and/or processed native material to bed, pad, and backfill the pipe trench reduces the quantities of more costly imported materials. The mechanical trenchers pre-process the trench spoil material to a large extent, making it more acceptable for backfill. Specialty paddling machines can be utilized where required to separate rocks and debris from the trench spoil material and place the remaining fine materials directly into the pipe trench.

A trench and backfill characterization database developed for this study provides a tool for construction planning and cost estimating. This system links surface and subsurface characteristics along the route with trencher production rates and costs to determine the required trenching method, as well as the most appropriate backfill method and material requirements.

The surface and subsurface characteristics for this study were established using information from other projects. Ultimately, a detailed investigation of these characteristics pertaining specifically to the final pipeline routing must be made. New methods of establishing this data at minimum cost must be implemented. In addition to subsurface investigation programs at specific locations, ground-penetrating radar (GPR) has been successfully used in a variety of terrains to determine soil stratigraphy, permafrost ice content, bedrock profile and presence of boulders. GPR could be used along the route to refine the construction plan, reduce uncertainties and minimize the requirement for subsurface investigation.

In order to confirm trenching production rates in various terrain and permafrost soils for this size of construction project, a field program may be required to test the performance of the chain trencher.

In general, pipeline construction is less expensive when performed during the summer months. However, because of environmentally sensitive and swampy terrain, as well as long winters in Alaska, winter construction is both necessary and practical. The pipeline team worked with construction contractors to plan major construction activities to take place in two winter seasons and one summer season. Work pads to provide a solid work surface and protect sensitive areas, such as tundra, are critical to construction production and contribute significantly to the high cost of arctic pipeline construction. Ice and snow work pads have proven successful in replacing gravel work pads in arctic locations and have been specified for most winter work. When construction occurs in winter, the frozen ground provides a stable work surface and the snow or ice work pad protects the surface vegetation from construction equipment. Abnormal changes in weather patterns, in which the ambient temperature is warmer than usual, where there is less snow than usual, or where summer construction must be conducted in sensitive or swampy areas, would require these work pads to be replaced with gravel work pads at many times the cost. More work is required to address the requirement for work pads and performance of snow/ice work pads under less than ideal conditions.

While winter construction is advantageous in Alaskan pipeline construction, it also has major disadvantages. Additional labor and equipment resources are required for lighting the work area and heating construction equipment. Equipment must be prepared for the arctic environment with arctic grade hoses, seals, fluids and insulated cabs, and higher maintenance is required to repair cold-related problems. Labor productivity is lower in cold temperatures and downtime is frequent due to cold weather and storms.

CONCLUSION

Although this work has resulted in a recipe for success, more work is required to transform the Project from concept to reality.

Working in cross-functional teams and including design and construction contractors in conceptual design and project planning can yield innovative ideas, which add value and reduce costs.

New technology has progressed over the last 20 years, which will allow analysis of innovative solutions, and less conservative designs through modeling during the design stages. Development of tools such as dynamic hydraulic/thermal pipeline models can be leveraged to reduce overly conservative field investigation programs, pipeline designs and construction processes and reduce project costs.

Base research, such as alternative methods of protecting sensitive terrain from, and mitigating the effects of construction activities, as well as the effects of less conservative designs on permafrost would assist regulators and project proponents in approving and constructing safe, environmentally sound and economically viable arctic gas pipeline systems.

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