Appendix N

Pipeline Design Approach
Appendix N

Pipeline Design Approach
Alaska Stand Alone Gas Pipeline / ASAP

Design Methodology to Address Frost Heave Potential

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EXECUTIVE SUMMARY

The purpose of this report is to introduce the design methodology for addressing potential threats related to frost heave in areas where the ASAP is routed through frost susceptible soils. Specifically, this report introduces the ASAP approach to the structural mechanics issues of the pipeline, particularly the methodology employed to ensure pipeline mechanical structural integrity when subjected to potential displacements associated with earth movement.

The report also addresses questions raised by the Pipeline and Hazardous Materials Safety Administration (PHMSA) to the Alaska Gasline Development Corporation (AGDC) regarding the approach to structural mechanics of the Alaska Stand Alone Gas Pipeline /ASAP (ASAP) relating to potential ditch displacements, such as frost heave, which could affect the longitudinal stress/strain response of the pipeline.

The ASAP project methodology to ensure pipeline integrity from time-dependent threats such as frost heave depends on the evaluation of a limiting curvature of the pipe. The limiting curvature of the pipe is used for design screening of the route terrain units and developing operational monitoring using pipeline in-line inspection (ILI) tools that detect pipeline movement (e.g., high resolution geometry pigs). The limiting curvature criterion is derived from consideration of limiting tensile and compressive strains capacities of the pipe material. This criterion is used to screen pipe route segments which do not exceed the criteria limits, after evaluation of the interaction of the pipe material, its operating characteristics, and the segment route subsurface behavior. Those segments that are determined to potentially exceed the curvature criteria limits are subject to mitigative actions to reduce the pipe response to within acceptable bounds.

Section 1 through Section 4 introduce the ASAP design terminology as it applies to this effort. In particular, these chapters relate the development of the methodology that employs curvature limits to ensure pipeline integrity, especially for those displacement-controlled loadings that induce transverse bending. The introductory material includes background on the determination of the loading, its associated soil and pipe resisting functions, and how these are integrated in a combined pipe-soil interaction analysis. The analytical process measures the effect of the loading and soil resisting functions on pipe response against quantitative structural integrity criteria for the range of route soils to be encountered and a range of operational conditions. This evaluation process for the range of alignment conditions forms the demand evaluation.

Section 5 focuses on the line pipe material and fabrication, and the corresponding development of appropriate design limits using these materials. These limits are used as the capacity evaluation and are used to judge the acceptance or rejection of the demand developed in the previous chapters. Section 5 then addresses the questions:

- How are the curvature limits to be developed?
- What tests will be conducted to verify the limits?
- What material requirements will be imposed?

Section 6 outlines the application of the design methodology to the alignment. This includes an introduction to the alignment conditions where the loading under consideration in this report, frost heave, would not occur. The application methodology is presented as a progressive exclusion sieve, narrowing
down the alignment conditions, and associated alignment geographical segments, where the concern needs more detailed evaluation and potential mitigation. This chapter addresses the questions:

- Where would curvature criteria be used?
- Where would curvature criteria not be used?

Section 7 addresses construction requirements relating to frost heave answering the question:

- What modifications to standard construction techniques will be needed?

Section 8 addresses potential operational mitigation methods if operational monitoring concludes that the established curvature/strain limits may be exceeded and pipeline integrity is at risk. This chapter addresses the questions:

- What monitoring will be required during operations to ensure the limits are not exceeded?
- What mitigation measures will be employed should the limits be approached or exceeded?

As discussed with PHMSA, AGDC has not yet developed the final quantitative criteria, nor has AGDC compiled the ASAP alignment subsurface evaluation, which would allow completion of this design determination and application of the frost heave methodology to final design. Nevertheless, AGDC is confident that the process presented herein addresses the design methodology requirements needed at this front end of preliminary design, and forms a framework for successful evaluation of the route in final design.
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Executive Summary</td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td>Acronyms and Abbreviations</td>
<td>vii</td>
</tr>
<tr>
<td>Section 1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Project Overview</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Project Phasing and Associated Deliverables</td>
<td>4</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Project Phasing</td>
<td>4</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Design Deliverables</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Organization of the Report</td>
<td>7</td>
</tr>
<tr>
<td>Section 2</td>
<td>Structural Mechanics of Buried Pipelines</td>
<td>8</td>
</tr>
<tr>
<td>2.1</td>
<td>Pressure Containment</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Treatment of Longitudinal Loadings</td>
<td>10</td>
</tr>
<tr>
<td>2.3</td>
<td>Effective Stress</td>
<td>11</td>
</tr>
<tr>
<td>2.4</td>
<td>Application of the Methodology</td>
<td>13</td>
</tr>
<tr>
<td>Section 3</td>
<td>Geohazards</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>Geothermal Considerations</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>Design Development</td>
<td>16</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Geotechnical/Geothermal Data</td>
<td>16</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Selection of Geotechnical/Geothermal Parameters for Design</td>
<td>16</td>
</tr>
<tr>
<td>3.3</td>
<td>Application of the Methodology</td>
<td>19</td>
</tr>
<tr>
<td>Section 4</td>
<td>Strain Demand Determination</td>
<td>20</td>
</tr>
<tr>
<td>4.1</td>
<td>Pipe-Soil Interaction Analysis Overview</td>
<td>20</td>
</tr>
<tr>
<td>4.2</td>
<td>Pipe Material Properties</td>
<td>22</td>
</tr>
<tr>
<td>4.3</td>
<td>Geothermal Input</td>
<td>23</td>
</tr>
<tr>
<td>4.4</td>
<td>Soil Resistance Characterization</td>
<td>26</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Uplift resistance</td>
<td>27</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Bearing Resistance</td>
<td>28</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Longitudinal Resistance</td>
<td>28</td>
</tr>
<tr>
<td>4.5</td>
<td>Model geometry</td>
<td>29</td>
</tr>
<tr>
<td>4.6</td>
<td>Imposed Loads</td>
<td>29</td>
</tr>
<tr>
<td>Section 5</td>
<td>Strain Capacity Determination</td>
<td>32</td>
</tr>
<tr>
<td>5.1</td>
<td>Material Requirements</td>
<td>32</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Line Pipe</td>
<td>32</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Coating Effect</td>
<td>35</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Dimensional Control</td>
<td>36</td>
</tr>
<tr>
<td>5.1.4</td>
<td>Girth Welds</td>
<td>36</td>
</tr>
<tr>
<td>5.1.5</td>
<td>Weld Overmatch</td>
<td>36</td>
</tr>
<tr>
<td>5.1.6</td>
<td>Weldment Toughness</td>
<td>36</td>
</tr>
<tr>
<td>5.2</td>
<td>Testing Requirements</td>
<td>37</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Curved Wide Plate Testing</td>
<td>37</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Full-Scale Tension Testing</td>
<td>37</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Compressive Strain Validation</td>
<td>38</td>
</tr>
<tr>
<td>Section 6</td>
<td>Route Application</td>
<td>39</td>
</tr>
<tr>
<td>6.1</td>
<td>Design Approach</td>
<td>39</td>
</tr>
<tr>
<td>6.2</td>
<td>Segment-by-Segment Design</td>
<td>39</td>
</tr>
<tr>
<td>6.3</td>
<td>Potential Design Mitigative measures</td>
<td>41</td>
</tr>
<tr>
<td>Section 7</td>
<td>Construction Related Issues</td>
<td>42</td>
</tr>
</tbody>
</table>
7.1 Welding Procedures ................................................................................................................. 42
7.2 Automated Ultrasonic Testing ..................................................................................................... 42

Section 8. Operations and Maintenance ............................................................................................. 43
8.1 Monitoring Potential Frost Heave ................................................................................................. 43
8.2 Potential Operational Mitigative measures .................................................................................... 44
  8.2.1 Temperature Control ............................................................................................................. 44
  8.2.2 Line Leveling .......................................................................................................................... 45

Section 9. Conclusion ............................................................................................................................. 46

Section 10. References .......................................................................................................................... 47

Appendix A PHMSA Correspondence .................................................................................................. A.1

Appendix B Structural Mechanics of Buried Pipelines ......................................................................... B.1

TABLES
Table 3.1 U.S. Army Corps of Engineers Frost Design Soil Classification System................................. 17
Table 3.2 Geotechnical Tests for Frost Heave Potential ........................................................................... 18
Table 3.3 Additional Geotechnical Tests for Frost Heave Evaluation ....................................................... 18

FIGURES
Figure 1.1 Route Map .......................................................................................................................... 3
Figure 1.2 Project Schedule .................................................................................................................. 4
Figure 1.3 Design Approach Flowchart ................................................................................................. 6
Figure 2.1 Illustration of Tresca and von Mises Yield Functions .............................................................. 12
Figure 3.1 ASAP Permafrost Characteristics .......................................................................................... 15
Figure 4.1 Frost Heave Illustration ........................................................................................................ 21
Figure 4.2 Frost Bulb Schematic ............................................................................................................ 24
Figure 4.3 Illustration of Maximum Curvature Time History ................................................................. 31
Figure 5.1 Normative Properties of a Steel Stress-Strain Relationship .................................................. 33
Figure 5.2 Illustration of Differing Stress-Strain Behavior in the Knee Region ....................................... 34
Figure 6.1 Frost Heave Route Assessment Flow Chart .......................................................................... 40
ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
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<td>ADOT&amp;PF</td>
<td>Alaska Department of Transportation and Public Facilities</td>
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<td>AGDC</td>
<td>Alaska Gasline Development Corporation</td>
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<tr>
<td>API</td>
<td>American Petroleum Institute</td>
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<tr>
<td>APSC</td>
<td>Alyeska Pipeline Service Company</td>
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<tr>
<td>ARRC</td>
<td>Alaska Railroad Corporation</td>
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<td>ASAP</td>
<td>Alaska Stand Alone Gas Pipeline</td>
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<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
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<td>ASTM</td>
<td>American Standard Testing Materials</td>
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<tr>
<td>AUT</td>
<td>Automated ultrasonic testing</td>
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<tr>
<td>BLM</td>
<td>Bureau of Land Management</td>
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<tr>
<td>cf</td>
<td>Cubic feet</td>
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<tr>
<td>CFR</td>
<td>Code of Federal Regulations</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CTOD</td>
<td>Crack tip opening displacement</td>
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<tr>
<td>D/t</td>
<td>Diameter to wall thickness ratio</td>
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<tr>
<td>DGGS</td>
<td>State of Alaska Division of Geological and Geophysical Surveys</td>
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<tr>
<td>FEL</td>
<td>Front end loading</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>HDD</td>
<td>Horizontal directional drill(ing)</td>
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<tr>
<td>HT</td>
<td>Hoop tension</td>
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<tr>
<td>Ili</td>
<td>In-Line Inspection</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
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<tr>
<td>ksi</td>
<td>Kips per square inch</td>
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<tr>
<td>LT</td>
<td>Longitudinal tension</td>
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<tr>
<td>MAOP</td>
<td>Maximum allowable operating pressure</td>
</tr>
<tr>
<td>MMscfd</td>
<td>Million standard cubic feet per day</td>
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<tr>
<td>PHMSA</td>
<td>Pipeline and Hazardous Materials Safety Administration</td>
</tr>
<tr>
<td>psi</td>
<td>Pounds per square inch</td>
</tr>
<tr>
<td>psig</td>
<td>Pounds per square inch gage</td>
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<tr>
<td>ROW</td>
<td>Right-of-way</td>
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<td>SMYS</td>
<td>Specified minimum yield strength</td>
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<td>UAF</td>
<td>University of Alaska Fairbanks</td>
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<td>USGS</td>
<td>U.S. Geological Survey</td>
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SECTION 1. INTRODUCTION

The purpose of this report is to introduce the design methodology for addressing potential threats related to frost heave in areas where the ASAP is routed through frost susceptible soils. Specifically, this report introduces the ASAP approach to the structural mechanics issues of the pipeline, in particular the methodology employed to ensure pipeline mechanical structural integrity when subjected to potential displacements associated with earth movement.

Presentation of the design methodology will help address questions raised by the Pipeline and Hazardous Materials Safety Administration (PHMSA) in correspondence to the Alaska Stand Alone Gas Pipeline/ASAP project (ASAP or the Project) and in meetings between PHMSA and the ASAP technical team. Correspondence with PHMSA is reproduced in Appendix A of this report. The specific item of interest is the section entitled “External loads that exceed design allowable – strain based design” contained in the letter to Dan Fauske from Jeffrey Wiese, received by the Alaska Gasline Development Corporation (AGDC) on May 4, 2011. In the beginning of this section, five code segments of the federal regulations are cited: 49 CFR 192, paragraphs 192.103, 192. 105, 192.111, 192.317, and 192.620. Further discussion of these regulations is presented in Section 2.

Potential threats to the pipeline integrity are generally identified and assessed using ASME B31.8S, Managing System Integrity of Gas Pipelines, which has an overview of a generalized procedure to the approach to earth movement threats contained in Section A-9, “Weather Related and Outside Force Threat (Earth Movement, Heavy Rains or Floods, Cold Weather, Lightning).” The potential pipeline displacement loading from earth movement used to illustrate the approach in this report is frost heave. Note that frost heave is a time-dependent threat, which is different from other familiar earth movement threats, such as seismicity, which are time-independent.

1.1 PROJECT OVERVIEW

The purpose of the Alaska Stand Alone Gas Pipeline/ASAP is to provide the in-state infrastructure for the reliable delivery of natural gas, primarily from the existing gas production facilities on the North Slope of Alaska, to markets in South Central Alaska, Fairbanks, and other communities, as practical. The pipeline routing is generally along the state’s existing highway corridors from the North Slope to tidewater in Southcentral Alaska. A route map is presented in Figure 1.1.

The design basis for ASAP consists of a 24-inch-diameter chilled natural gas pipeline, approximately 737 miles in length, with a flow rate of up to 500 million standard cubic feet per day (MMscfd). The mainline pipeline system will be designed to transport natural gas consisting of either a highly-conditioned natural gas enriched in non-methane hydrocarbons or of conditioned natural gas containing mostly methane. At the 500 MMscfd throughput a single compressor station is required to be located approximately 286 miles south of Prudhoe Bay. A 12-inch lateral pipeline, approximately 35 miles in length, will tie-in to the mainline at approximately ASAP milepost 458 to supply up to 60 MMscfd of utility grade gas to Fairbanks.

The majority of the pipeline will be installed belowground utilizing conventional trenching techniques. The mainline pipeline will be API 5L X70 pipe with a minimum wall thickness of 0.595 inches, for the maximum allowable operating pressure (MAOP) of 2500 psig, which corresponds to
a design factor of 0.72. There is no intention of utilizing the alternative MAOP provisions of the 49 CFR 192 regulations which allow an increase of the design factor to 0.80. Since much of the pipe lies within the state roadway right-of-way (ROW), the design factor for over half the length of the mainline is 0.60 resulting in a wall thickness increase to 0.714 inches. The decrease in the design factor is required so as to conform to the 49 CFR 192.111(b)(2) when the pipeline is in a parallel encroachment. The Fairbanks Lateral will be API 5L X65 pipe with a minimum wall thickness of 0.250 inches (increased from 0.190 inches for constructability) for the MAOP of 1480 psig.
Figure 1.1  Route Map
1.2 PROJECT PHASING AND ASSOCIATED DELIVERABLES

1.2.1 PROJECT PHASING

Research shows that the disciplined application of a stage-gated process is strongly correlated with producing superior project outcomes. The gated approach involves breaking a capital project into discreetly defined phases, where a clear set of deliverables or outcomes is outlined for each phase, which must be completed before the project is approved to move into the next phase. AGDC will be employing a stage-gated approach to project execution and delivery.

The first major phase of the gated project delivery process is FEL (front-end loading). Three stages usually comprise the FEL process (Conceptual Engineering, Preliminary Design, and Detailed Design) prior to project sanction (start of Execution). ASAP is currently in Conceptual Engineering, or early definition stages of project development.

The results of the initial phases provide critical input for making the final authorization decision to move forward with the project. The primary objective of FEL is to achieve an understanding of the project that is sufficiently detailed so that significant and costly changes in engineering, construction, and the startup phases of a project will be minimized.

The Conceptual Engineering project objective is development of the Project Plan due July 1, 2011. This will be the end of Conceptual Engineering. After that time, the Alaska Legislature will decide whether the Project will proceed to Preliminary Design, utilizing State funding, or whether the Project will be shelved or in some way modified at the end of the funding period in July 2011.

As the Project progresses into Preliminary Design and beyond, development of a large integrated project team will be needed comprised of people with a wide range of capabilities that can perform key functional roles in the project team organization. Project skill sets that will be required to move the project forward include operations, maintenance, business, process design, project controls, construction management, procurement and contracting, quality assurance, health and safety, and permitting.

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<td>Order Pipe &amp; Major Equipment</td>
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<td>Construction</td>
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<td>Pipeline Startup &amp; Restoration</td>
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<td>Record of Decision</td>
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<td>Project Sanction</td>
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Figure 1.2 Project Schedule
1.2.2 DESIGN DELIVERABLES

The frost heave design approach is depicted in Figure 1.3 and will be explained further throughout this report. As the design progresses from Preliminary Design though Detailed Design and then Construction, information is being collated and verified to allow the design to progress along this design approach flowchart. In general, Preliminary Design follows the methodology development, scopes the data collection required for the demand and capacity to be further verified, and starts the data development for the route. Tasks scheduled to be finalized in Preliminary Design include:

- Identification of the input parameters required for the project approach that will implement this design methodology, including the analysis of the geothermal conditions and the structural analysis.
- Trial analyses completed and documented.
- The terrain units along the identified alignment are identified and captured in the project GIS – appropriate geotechnical parameters identified as required input for the methodology are assigned to the terrain units based on borehole analysis.
- The alignment route geo-database is implemented within the project GIS, concentrating on the subsurface information available along the routes from past exploratory tasks.
- Gaps in the route geo-database will be identified for required exploration.
- Potential manufacturers of the line pipe are contacted, and joints of the line pipe acquired for small-scale testing to be completed before the end of Preliminary Design.

Detailed Design will include finalizing the capacity and demand-capacity application evaluation process for the route including the following tasks:

- Finalization of the frost heave design approach methodology.
- The line pipe strain capacity is determined using the small-scale test results, and verified with full-scale testing.
- The route geo-database will be queried using the design methodology with route segments displaying potential unallowable heave potential subjected to additional scrutiny and/or mitigative measures.
- The final material and pipe order will incorporate any requirements to implement these measures.

The identified potential line segments subject to additional scrutiny identified in final design may require special mitigative measures that could be the basis of a special construction team. Baseline monitoring will be required within a practicable time after startup, followed with operational monitoring throughout the life of the project.

Design reviews by PHMSA and other agencies will occur throughout the various phases of the project.
Figure 1.3 Design Approach Flowchart
1.3 ORGANIZATION OF THE REPORT

Section 1 through Section 4 introduce the ASAP design terminology as it applies to this effort. In particular, these chapters relate the development of the methodology that employs curvature limits to ensure pipeline structural integrity especially for those displacement-controlled loadings that induce transverse bending. The introductory material includes background on the determination of the loading, its associated soil and pipe resisting functions, and how these are integrated in a combined pipe-soil interaction analysis. The analytical process measures the effect of the loading and soil resisting functions on pipe response against quantitative structural integrity criteria for the range of route soils to be encountered as well as a range of operational conditions. This evaluation process for the range of alignment conditions forms the demand evaluation.

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- Where would curvature criteria not be used?

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- What modifications to standard construction techniques will be needed?

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- What monitoring will be required during operations to ensure the limits are not exceeded?
- What mitigation measures will be employed should the limits be approached or exceeded?
SECTION 2. STRUCTURAL MECHANICS OF BURIED PIPELINES

Although some sections of the ASAP are aboveground, notably at waterway crossings and at the beginning of pipeline route on the North Slope, ASAP is primarily a buried pipeline. Buried pipelines are essentially “restrained,” that is, displacement of the pipe is restricted by the soil around it.

For the problem of frost heave, advanced analytical tools, and input functions needed to characterize the components of the frost heave methodology, are required to integrate the various parts of the loading and resistance functions so as to correctly address the loading demand on the pipeline. This section reviews some of the familiar parts of the demand problem, such as the internal pressure and change in temperature, and then reviews how these are integrated into the time-dependent loading functions for the longitudinal stress components to derive a unified mechanical approach.

The basis of the structural mechanics for pipeline engineering is summarized in Appendix B. For such a straightforward “structure,” a pressurized pipe can actually exhibit fairly complex behavior involving significant stress components in a biaxial stress state.

The resultant mechanical state of the pipeline that arises from the external loads imposed from different sources, causing both hoop and longitudinal pipe stress effects, is referred to as the “demand” on the pipeline. Since the overall resultant is a complex stress state, the demand is best characterized in this combined state – i.e., because the relative magnitudes of the orthogonal components are roughly of the same magnitude, the interaction mechanics must be considered.

Yet, this evaluation of the “demand” is not sufficient for design, since it must be judged where the behavior is acceptable in the design, i.e., whether the “capacity” of the pipe is sufficient to resist the demand. The basis for material regulatory acceptance of the line pipe centers on the yield point for a uniaxial condition. The yield point for pipeline engineering is defined by testing requirements to be the point at which the specified minimum yield strength (SMYS) of the pipe is recorded – 0.5% strain. As noted, this definition of the “yield” does not concisely fit classical “textbook” definitions of yield, which is often defined as the point at which non-recoverable, i.e., “plastic” deformations, initiate. For example, if the ASAP API 5L X70 pipe material was considered to be governed by Hooke’s law ($\sigma = E\varepsilon$, where $\sigma$ is stress, $\varepsilon$ is strain, and $E$ is the modulus of elasticity) to the SMYS of 70 ksi, the associated strain would be only:

$$\varepsilon = 70\text{ksi} / 29,500\text{ksi} / \text{in} / \text{in} = 0.00237\text{in} / \text{in} = 0.237\%$$

Thus, to reach the strain associated with SMYS, an additional 0.263% strain occurs, which cannot be accounted for by an elastic relationship. Alternative yield point characterizations are defined using an “offset” method where a line with the elastic slope is drawn from a specified strain offset point – again confirming the necessary incorporation of non-recoverable (plastic) deformation just to reach the SMYS of the pipe.

In addition, as noted the SMYS value is defined in a uniaxial condition. Again because the orthogonal stress components are roughly comparable in magnitude, the simple uniaxial relations must be extended to consider actual biaxial conditions. Generally, the extensions involve structural
mechanics relationships that allow the combined stress conditions to be related back to uniaxial tests and uniaxial stress conditions or “effective” stresses that characterize the biaxial conditions, often by reference to a skewed reference frame.

2.1 PRESSURE CONTAINMENT

The governing regulatory document for the ASAP pipeline, 49 CFR 192, addresses the “…design pressure for steel pipe…” in 49 CFR 192.105. The design factor used in this formula for the design pressure is addressed in 49 CFR 192.111.

Although there are provisions for alternative approaches to this design factor, with additional associated requirements for utilizing this alternative formulation, AGDC has elected to everywhere avoid this alternative formulation for the design factor. Thus, requirements relating to this alternative formulation, including those cited in 49 CFR 192.620, are not applicable to ASAP and are not further addressed in this report.

The design pressure formula cited in the federal regulations \( P = (2 \frac{S}{D}) \times F \times E \times T \) is recognized as the classical Barlow’s formula derived from basic equilibrium considerations (see Appendix B). The derivation does not depend on the material type (e.g., steel, aluminum, etc.), the mechanical state of the pipe material (elastic, inelastic, plastic…) nor consideration of pipe behavior in the orthogonal longitudinal direction. The robustness of this formulation makes it ideal for the focus of pressure containment guidance, both in regulations and consensual standards.

On the other hand, and somewhat because there are no associated limiting conditions arising from the derivation for the application of this formula, there are no associated explicit requirements for other types of loadings that can be deduced from this design pressure formula. In particular, there are no requirements associated with the design pressure formula that impose any conditions or limitations upon the longitudinal stress/strain behavior of the pipeline. There are more exact formulations for thick-walled pipes (generally defined as having a diameter to wall thickness ratio \( D/t \) of less than 20), but typical transmission lines, including ASAP, are thin-walled pipes.

Thus, the design pressure formula cited in the regulations will be met regardless of the design limitations imposed on the longitudinal effects, i.e., if the pipeline diameter, thickness, and operating pressure meet a 72% specified minimum yield strength (SMYS) requirement at startup, the same combination of these input parameters into the design pressure formula cited in the regulations will produce the same limiting stress of 72% SMYS, and thus identically meet these regulatory requirements indefinitely throughout operations, regardless of the longitudinal behavior. This is a conclusion from the stress mechanics of pipelines, and is not peculiar to any aspect of the ASAP nor to any transmission pipeline.
2.2 TREATMENT OF LONGITUDINAL LOADINGS

In contrast to the explicit requirements for the design pressure formula, the federal regulations contain only general guidance for additional types of loadings, and no explicit limitations. General guidance is contained in 49 CFR 192.103 which states:

Pipe must be designed with sufficient wall thickness, or must be installed with adequate protection, to withstand anticipated external pressures and loads that will be imposed on the pipe after installation.

More specifics about potential hazards to be investigated are contained in 192.317:

(a) The operator must take all practicable steps to protect each transmission line or main from washouts, floods, unstable soil, landslides, or other hazards that may cause the pipeline to move or to sustain abnormal loads...

If additional thickness is found to be required for reasons other than pressure containment, the allowable pressure must not be increased through a re-computation of the design pressure formula to take advantage of this additional thickness as per 49 CFR 192.105.

The requirements of 49 CFR 192 quoted above, though general in nature, are an explicit reminder to all operators that prudent oversight of the potential detrimental effects from external loads requires diligent investigation and cannot be waived. To satisfy this requirement, the pipeline industry has addressed the lack of explicit requirements in the regulatory framework through consensual standards so as to satisfy the general regulatory requirements.

The U.S. gas industry accepted standard for requirements in areas where the regulations give only general guidance is ASME B31.8, Gas Transmission and Distribution Piping Systems. To be clear, where there is a disagreement in ASME B31.8 with the regulations, the regulations are followed.

In particular, ASME B31.8 Section 833 addresses longitudinal loads and is the basis for industry analysis of longitudinal stresses – in compliance with the need for such an analysis of external loads as required by the regulations, and in no way contradictory or contraindicating any specific requirements in the regulations as to the details of such an undertaking. These requirements are incorporated in all commercial pipe stress analysis programs such as CAESAR II and AUTOPIPE. Section 833.3 sets the longitudinal stress requirements for restrained pipe with a limitation of 90% of SMYS, while Section 833.4 sets the combined stress requirements for restrained pipe with a limitation of 90% of SMYS for long term loading and 100% of SMYS for short term loading (ASAP has no temperature derating), while Section 833.5 details the requirements for design to utilize a stress greater than yield.

AGDC follows the procedure as described above, which adheres to regulatory requirements, using explicit industry recommended procedures to satisfy those requirements. AGDC has identified no exceptions to this described procedure.
2.3 EFFECTIVE STRESS

To characterize the combined effects of the operational circumferential load, i.e. the hoop stress due to pressure containment, with the longitudinal effects from frost heave, a method of determining the combined effect is required. Further, this combined effect must be able to be compared to the actual material tests that are typically performed and/or required for material requisition, which are uniaxial.

As noted above, the SMYS value is defined in a uniaxial condition. Again because the orthogonal stress demand components are roughly comparable in magnitude, the simple uniaxial relations must be extended to relate to the actual biaxial conditions. Generally, the extensions involve structural mechanics relationships that allow the combined stress conditions to be related back to uniaxial tests and uniaxial stress conditions or “effective” stresses that characterize the biaxial conditions, often by reference to a skewed reference frame. This section presents the background for the “effective stress” combinatorial techniques, which are used within the frost heave design methodology.

The two most commonly used theories for determining effective stresses in pipelines are the maximum shear stress theory, commonly referred to as the Tresca theory, and the maximum distortion energy theory, commonly referred to as the von Mises’ theory. The effective stresses that result from these theories are both represented in ASME B31.8.

The first approach is the Tresca yield criterion, and as described in more detail in Appendix B, for the biaxial stress conditions that exist in pipelines the yielding criterion is expressed as follows:

\[
\begin{align*}
|\sigma_H| & \leq \sigma_y \\
|\sigma_L| & \leq \sigma_y \\
|\sigma_H - \sigma_L| & \leq \sigma_y 
\end{align*}
\]

where:
- \(\sigma_H\) is the hoop stress;
- \(\sigma_L\) is the longitudinal stress; and
- \(\sigma_y\) is the yield stress of the pipe.

The hexagonal Tresca yield function is illustrated in longitudinal stress vs. hoop stress space in Figure 2.1 for an elastic-plastic material with a yield strength of 70 ksi. Any stress falling within the hexagon indicates that the material behaves elastically while points on the hexagon indicate that the material is yielding. This criterion is implemented under B31.8 Section 833.4 to limit combined stress for restrained pipe as:

\[
|\sigma_H - \sigma_L| \leq k \cdot S \cdot T
\]

where:
- \(k\) is an allowable stress multiplier (for loads of long duration, \(k = 0.90\), and for occasional non-periodic loads of short duration it is 1.0);
- \(S\) is the pipe SMYS; and
\[ T \text{ is the temperature derating factor (T=1.0 for temperatures } \leq 250^\circ\text{F, per B31.8 Section 8.41.116).} \]

The second approach is the von Mises' yield criterion, which defines a different effective stress to compare against the uniaxial "yield point" as:

\[ \sqrt{\sigma_1^2 - \sigma_1 \cdot \sigma_2 + \sigma_2^2} = \sigma_y \]

This is the equation of an ellipse as also shown in Figure 2.1 for an elastic-plastic material with a yield strength of 70 ksi. Any stress falling within the ellipse indicates that the material behaves elastically while points on the ellipse indicate that the material is yielding. This criterion is implemented under B31.8 Section 8.33.4 to limit combined stress for restrained pipe as:

\[ [\sigma_L^2 - \sigma_L \cdot \sigma_H + \sigma_H^2] \leq k \cdot S \cdot T \]

**Figure 2.1 Illustration of Tresca and von Mises Yield Functions**

Note that the Tresca hexagon meets the von Mises ellipsoid at certain points around the periphery of the ellipsoid and is elsewhere contained within the ellipsoid. Since points located within the
yield function boundaries are said to define elastic states while those on the yield function boundaries define a yielded condition, the Tresca criterion can be seen to be slightly more conservative than the von Mises criterion. The differences, however, are small and both approaches are accepted. In general, the von Mises theory is the more widely used in computer applications and advanced inelastic analysis because of its smooth surface and corresponding continuously differentiable function. The Tresca theory, because of its simplicity, is often used in manual/hand calculations.

2.4 APPLICATION OF THE METHODOLOGY

The methodology described above for the combination of the orthogonal stresses in the pipe that arise from the operational load acting concurrently with the imposed frost heave, are effectively combined within the analytical pipe stress program PIPLIN, which will be described in more detail in Section 4 of this report.
SECTION 3. GEOHAZARDS

A geohazard is defined as a naturally occurring or project-induced geological, geotechnical, or hydrological phenomenon that could load the pipeline, causing a pipeline integrity concern, or that could impact the ROW, causing an environmental concern. The principal geohazards of concern for ASAP design are frost heave and thaw settlement.

3.1 GEOTHERMAL CONSIDERATIONS

Geothermal design considers the coupled effect of soil mechanics and heat transfer principles that drive physical processes that can impact the operational reliability and performance of the pipeline. Examples of these processes are:

- Frost bulb formation;
- Frost heave beneath the pipe;
- Thaw bulb formation; and
- Thaw settlement of the soils supporting the pipe.

The preferred mode for the ASAP is buried and it is anticipated the pipeline will encounter thermal states ranging from continuous permafrost in the north, to discontinuous permafrost in the center, and thawed muskeg, alluvial, lacustrine, glacial moraine, and outwash type soils in the central and southern regions (see Figure 3.1). These conditions require designs that allow for pipeline deformations caused by frost heave and thaw settlement.

In general, the pipeline will be operated chilled (≤32°F) in the continuous and discontinuous permafrost regions, but may operate above freezing at least during parts of the year along the southern portion (south of Nenana). As a result, frost heave is likely in unfrozen frost-susceptible soils where the pipeline operating temperature is below freezing, and there is a potential for thaw settlement to occur in frozen, ice-rich soils where the pipeline operating temperature is above freezing.

To reduce potential impacts along the northern portion, the gas will be chilled to 30°F before leaving the North Slope Gas Conditioning Plant. As the gas travels southward, the operating temperature will fluctuate based on several factors including time of year, surrounding ambient ground temperature, and the Joule-Thompson effect.

With chilling of the gas, it is anticipated that the majority of the pipeline will operate below freezing for most or all of the year. As indicated in Figure 3.1, permafrost is typically continuous or discontinuous until the south flank of Alaska Range. For the remainder of the alignment to the pipeline terminus, the permafrost is mapped as sporadic or isolated and the pipeline will be buried in glacially derived landforms that are typically frost susceptible.
Figure 3.1 ASAP Permafrost Characteristics
Frost heave is anticipated where unfrozen frost-susceptible soils exist in combination with other critical conditions such as available water. Frost heave mitigation may involve removing/replacing frost-susceptible soils within the influence zone of the pipeline or providing insulation or heat to prevent the frost-susceptible soils below the pipe from freezing. A heater may be installed near Willow to raise the pipeline operating temperature above freezing and mitigate potential frost bulb development between Willow and the terminus (i.e., eliminate the frost bulb during the summer). However, basic design details such as the size, location, and expected operating schedule will only be determined after extensive geothermal analysis has been completed.

3.2 DESIGN DEVELOPMENT

3.2.1 GEOTECHNICAL/GEOTHERMAL DATA

Geotechnical/geothermal data will be used for general and specific geotechnical analysis for the gas pipeline. The following data have been gathered and available to the project:

- Soils, thermal state, and groundwater data from historical borehole and from test pit logs drilled by the project (Tanana River at Nenana), ADOT&PF, ARRC, the University of Alaska Fairbanks (UAF) Water and Environmental Research Center, and the UAF Geophysical Institute.
- Laboratory data from index property and engineering property tests done on borehole and field samples acquired by the project and ADOT&PF.
- General and specific geological and geotechnical data from published sources including the State of Alaska Division of Geological and Geophysical Surveys (DGGS) and U.S. Geological Survey (USGS).
- Orthoimagery and other aerial or satellite based imagery acquired for the project or available from DGGS 2011 LiDAR survey.
- Topographic data from project field survey work, aerial photography, and published maps.
- Bedrock data from borehole logs, laboratory testing of samples, field reconnaissance, and available public sources such as ADOT&PF, DGGS, and USGS.
- Terrain unit and landform data developed by the project and from published maps and reports.
- General reconnaissance data from field programs.

3.2.2 SELECTION OF GEOTECHNICAL/GEOTHERMAL PARAMETERS FOR DESIGN

Many design parameters are site specific and will be obtained over time as field studies from the various disciplines are completed. Additional guidelines and the basic approach to geotechnical and geothermal analyses are discussed below.

Geotechnical parameters necessary for frost heave analysis and design will initially be estimated based on terrain unit analyses already completed and calibrated against legacy borehole and lab test data recovered for the project. This approach will be augmented by field and laboratory test results from planned geotechnical investigations. Frost susceptibility is primarily a function of soil grain size where non-plastic fines (typically silt) create pore spaces that facilitate capillarity and
freezing point depression. The U.S. Army Corps of Engineers frost design and classification system is a universal standard for addressing frost heave behavior (see Table 3.1). Critical conditions for pipeline frost heave distress occur where the pipeline traverses abrupt contrasts in soil conditions and the soils freeze and thaw repeatedly (seasonally).

Note that the frost classification system is based primarily on soil particle size distribution. Geotechnical tests to properly classify and analyze frost heave potential include the following tests with corresponding standard test methods.

<table>
<thead>
<tr>
<th>Frost Susceptibility&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Frost Group</th>
<th>Note</th>
<th>Kind of soil</th>
<th>Amount finer than 0.02mm (wt%)</th>
<th>Typical soil type under USCS&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible to low</td>
<td>NFS&lt;sup&gt;c&lt;/sup&gt;</td>
<td>a</td>
<td>Gravels</td>
<td>0 to 1.5</td>
<td>GW, GP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>Sands</td>
<td>0 to 3</td>
<td>SW, SP</td>
</tr>
<tr>
<td>Possible</td>
<td>PFS&lt;sup&gt;d&lt;/sup&gt;</td>
<td>a</td>
<td>Gravels</td>
<td>1.5 to 3</td>
<td>GW, GP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b</td>
<td>Sands</td>
<td>3 to 10</td>
<td>SW, SP</td>
</tr>
<tr>
<td>Low to medium</td>
<td>S1</td>
<td>Gravels</td>
<td>3 to 6</td>
<td>GW, GP, GW-GM, GP-GM</td>
<td></td>
</tr>
<tr>
<td>Very low to high</td>
<td>S2</td>
<td>Sands</td>
<td>3 to 6</td>
<td>SW, SP, SW-SM, SP-SM</td>
<td></td>
</tr>
<tr>
<td>Very low to high</td>
<td>F1</td>
<td>Gravels</td>
<td>6 to 10</td>
<td>GM, GW-GM, GP-GM</td>
<td></td>
</tr>
<tr>
<td>Medium to high</td>
<td>F2</td>
<td>a</td>
<td>Gravels</td>
<td>10 to 20</td>
<td>GM, GM-GC, GW-GM, GP-GM</td>
</tr>
<tr>
<td>Very low to very high</td>
<td></td>
<td>b</td>
<td>Sands</td>
<td>6 to 15</td>
<td>SM, SW-SM, SP-SM</td>
</tr>
<tr>
<td>Medium to high</td>
<td>F3</td>
<td>a</td>
<td>Gravels</td>
<td>&gt;20</td>
<td>GM, GC</td>
</tr>
<tr>
<td>Low to high</td>
<td></td>
<td>b</td>
<td>Sands except very fine silty sands</td>
<td>&gt;15</td>
<td>SM, SC</td>
</tr>
<tr>
<td>Very low to very high</td>
<td></td>
<td>c</td>
<td>Clays, I&lt;sub&gt;p&lt;/sub&gt;&gt;12</td>
<td>-</td>
<td>CL, CH</td>
</tr>
<tr>
<td>Low to very high</td>
<td>F4</td>
<td>a</td>
<td>All silts</td>
<td>-</td>
<td>ML, MH</td>
</tr>
<tr>
<td>Very low to high</td>
<td></td>
<td>b</td>
<td>Very fine silty sands</td>
<td>&gt;15</td>
<td>SM</td>
</tr>
<tr>
<td>Low to very high</td>
<td></td>
<td>c</td>
<td>Clays, I&lt;sub&gt;p&lt;/sub&gt;&gt;12</td>
<td>-</td>
<td>CL, CL-ML</td>
</tr>
<tr>
<td>Very low to very high</td>
<td></td>
<td>d</td>
<td>Varved clays and other fine-grained banded sediments</td>
<td>-</td>
<td>CL and ML, CL, ML and SM: CL, CH, and ML: CL, CH, ML, and SM</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on laboratory frost-heave tests
<sup>b</sup> G, gravel; S, sand; M, silt; W, well graded; P, poorly graded; H, high plasticity; L, low plasticity
<sup>c</sup> Non-frost susceptible
<sup>d</sup> Requires laboratory frost-heave test to determine frost susceptibility

Source: Johnson et. al. 1986

(Andersland and Ladanyi 2004)
<table>
<thead>
<tr>
<th>Table 3.2</th>
<th>Geotechnical Tests for Frost Heave Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Standard</td>
</tr>
<tr>
<td>Moisture content</td>
<td>ASTM D2216</td>
</tr>
<tr>
<td>Gradation (sieve analysis)</td>
<td>ASTM C136</td>
</tr>
<tr>
<td>Gradation (sieve with hydrometer)</td>
<td>ASTM D422</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td>ASTM D4318</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.3</th>
<th>Additional Geotechnical Tests for Frost Heave Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Standard</td>
</tr>
<tr>
<td>Moisture-Density Relationship</td>
<td>ASTM D1557</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>ASTM C127</td>
</tr>
<tr>
<td>Unit Weight of Frozen Soil</td>
<td>Gravimetric test of undisturbed frozen soil</td>
</tr>
</tbody>
</table>

Additional geotechnical parameters needed to forecast frost heave include permeability, pressure on the freezing front; frost penetration rate and frost heaving rate; longitudinal, bearing and uplift resistance; soil load/deflection and creep characteristics; soil temperature gradient, and climatic data. Many of these parameters can be empirically correlated with the results of geotechnical tests listed above. A probabilistic approach to assigning soil properties may be adopted if sufficient sample data is acquired by the project. When data gaps are identified, they will be filled as necessary. Climatic data will be updated to include most recent data from stations along the route. Limits of applicability of climatic data will be based on geographic similarities along the line.

The approach to frost heave analysis will be to combine route soils data with climatic data and pipeline thermal predictions and pipe deformation analysis. Thermal conditions of the pipeline and ground will be predicted using a coupled hydraulics/geothermal model. This model will be comprised of a linear hydraulics model of the pipeline with two-dimensional “slices” of soil defined at intervals along the pipeline. The slices are defined principally by the terrain unit analysis, thus geotechnical information will accompany each slice that allows prediction of frost heave. The hydraulics model will predict temperatures along the pipeline for a given throughput, inlet temperature and pressure, initial soil temperatures, and gas properties. The pressure and temperature of the flowing gas depends upon the heat flux through the pipe wall which, in turn, depends on the pipe interaction with the subsurface thermal state (ground temperatures).

Predictions of the ground temperatures surrounding the pipe will be made by the geothermal model. The model will consider a two-dimensional “slice” of the pipe surrounded by soil regions and bounded on the surface by location dependent varying climatic functions. A finite element
approach will be applied to develop a series of “snapshots” along the pipeline of the changing thermal condition of the subsurface over time, which is in turn used to estimate the heat flux along the alignment to the flowing gas. The result is an estimate of the magnitude and timing of freezing of initially thawed ground including the geometry of the evolving frost bulb. The same process is used to predict thawing of initially frozen ground.

The pipe/soil thermal regime and geotechnical properties that define the soil’s frost susceptibility will then be used to predict the amount of heave beneath the pipeline. The frost heave predictions will be calibrated against results of previous frost heave laboratory and field testing performed by the research community and special testing completed by industry for other projects.

### 3.3 APPLICATION OF THE METHODOLOGY

Similar to the data describing the pipe material properties and the associated functional behavioral description, the geotechnical properties are also integrated in the pipe-soil interaction analysis within the program PIPLIN, described in Section 4 of this report. These geotechnical properties describe two parts of the soil interaction analysis: the displacement imposed on the pipe ditch bottom over time (i.e., the restrained heave), and the resistance to the pipe movement by the soils surrounding the buried pipe. As described in Section 4, the pipe strain demand resulting from the predicted frost heave is determined through a series of pipe-soil interaction analyses that consider heave of the soils beneath the pipe as a function of time and take into account pressure feedback from the pipe at the base of the frost bulb, and the resistance of the soil to differential pipe movement.

Problematic areas identified in performing this route-wide analysis will be subject to site-specific analysis. The site-specific analysis will follow the same general approach, but will utilize more refined soil and thermal inputs. If the site-specific analysis results in unacceptable levels of pipe strain demand (i.e., pipe strain demand that exceeds the pipe strain capacity), then mitigative measures would be employed as described in Section 6.3.
SECTION 4. STRAIN DEMAND DETERMINATION

4.1 PIPE-SOIL INTERACTION ANALYSIS OVERVIEW

The mechanism of pipeline frost heave has been investigated in detail for many previous arctic gas pipeline projects. Frost heave occurs when a chilled pipeline freezes water in frost-susceptible soil in which it is buried. As the soil freezes, it expands and forms a frost bulb around the pipe. Upward heave of the pipe is produced by swelling at the bulb face as the bulb grows. Significant pipe stresses and deformations can occur when the buried pipeline runs between a stable soil and a frost-susceptible soil. Because the pipe heaves in the frost-susceptible soil section but remains stationary in the adjacent stable soil section, a differential vertical heave displacement profile is produced across the transition between the stable and frost-susceptible soil sections.

The strain demand analyses for frost heave of ASAP will be carried out using the PIPLIN computer program (SSD 2011). PIPLIN is a special-purpose finite element program developed to perform stress and deformation analysis of two-dimensional pipeline configurations. The analyses will consider several nonlinear aspects of pipeline behavior, including pipe yield, large-displacement effects, and nonlinear frozen soil support.

A heaving section of a pipeline together with a schematic view of the corresponding PIPLIN model is illustrated in Figure 4.1. To reduce the required size of the model, a symmetric boundary condition (i.e., zero rotation and zero longitudinal translation) is normally imposed at the end of the model corresponding to the center of the heave span. The sufficient model length is such that the boundary condition specified at the remote end of the model has no influence on the key analysis results. The pipe is typically assumed to be initially straight with a uniform depth of soil cover.

The pipe is modeled using beam type elements in which the stresses and strains are monitored at a number of fiber points around the pipe cross section at the element ends. PIPLIN achieves additional economy by considering a plane of symmetry through the pipe centerline (e.g., the vertical plane in frost heave model) so that only one-half of the pipe cross section is analyzed. In these analyses, the pipe cross-section is assumed to remain circular and plane sections are assumed to remain plane. The pipe element accounts for large displacement effects (i.e., changes in the equilibrium due to large displacements) by adding geometric stiffness coefficients to the element stiffness matrix. This allows PIPLIN models to accurately capture important column buckling and cable tension effects.
Pipe yield at the fiber points around the pipe cross section is taken into account assuming the von Mises yield criterion so that interaction between hoop and longitudinal stresses is included. The pipe steel material is modeled using the Mroz (Mroz 1967) multi-linear kinematic hardening plasticity model which is able to accurately capture anisotropic pipe steel stress-strain relationships.
(e.g., pipe that has different stress-strain curves in the longitudinal tension/compression vs. hoop tension/compression directions). The pipe material model provides a very reasonable representation of steel behavior under monotonic, unloading and cyclic load conditions.

The soil is modeled as a nonlinear Winkler foundation. This means that the soil support is idealized as a series of discrete, independent, nonlinear springs lumped at the element midpoints. In effect, this assumes that the soil can be regarded as a series of plane “slices”. The basic assumption is that the slices deform independently of each other. The pipe-soil springs are assumed to have uniform properties over any pipe segment.

The frost heave analyses are typically initiated with the application of gravity, internal pressure and temperature differential loads. If desired, a hydrostatic test loading/unloading sequence can be considered prior to applying the operating loads. A multi-year (typically 20 to 30 years) frost heave simulation of the pipe-soil interaction model is then undertaken. The frost heave analyses are nonlinear time-history analyses performed using small steps through time. Within the heave span, the frost bulb geometry and frost heave vary with time. Seasonal variations of the uplift, longitudinal, and bearing creep soil temperatures (and corresponding resistance) are also specified with each heave time step. The heave is imposed progressively at the base of the pipe-soil springs within the heave span. The amount of heave at the ditch bottom is calculated separately for each transverse pipe-soil support in turn accounting for the important pressure feedback from the pipe at the base of the frost bulb. A transition length between the finite length section of heaving soil and the adjacent non-heaving soil section can be specified if desired.

The complete pipe-soil deformation state is established at each increment of the analysis. The program output includes pipe displacements, soil support deformations and reactions; pipe axial forces, bending moments and curvatures; axial, hoop and von Mises stresses and axial and hoop strains in the pipe. The maximum pipe tension and compression strain demands are established at each output state to provide time-history plots of these key response quantities.

4.2 PIPE MATERIAL PROPERTIES

As implemented in PIPLIN, the Mroz plasticity model assumes that the pipe material yields according to the von Mises theory under plane-stress conditions. The bi-axial stress-strain behavior is defined by a set of progressively larger, non-overlapping elliptical yield surfaces in longitudinal stress vs. hoop stress space. The Mroz theory specifies that as the steel yields, the individual ellipses translate without changing size or shape, which is the well-known kinematic hardening assumption. The theory also specifies the direction of movement of each ellipse – essentially, any ellipse moves so that when the stress point reaches the next larger ellipse, the yielding ellipses do not overlap.

One of the key features of the PIPLIN steel model is that the elliptical yield functions can be shifted to initial positions in order to mimic the effects of the pipe expansion phase of the UOE manufacturing process. The shifts are selected such that the analytical uniaxial stress-strain results closely match a set of uniaxial longitudinal tension (LT), hoop tension (HT) target stress-strain curves. For pipe steel fabricated with the UOE process, the ellipses tend to be shifted along the HT axis. The pure HT ellipse shifting pattern tends to result in an elevated proportional limit and
relatively sharp (abrupt) yielding point for the HT curve (due to work hardening and bunching of the ellipses) and a low proportional limit with progressive (well rounded) yielding for the hoop compression (HC) curve (due to Bauschinger effect). The steel model is well suited for capturing key aspects of the anisotropy patterns typically observed in UOE pipe.

As described in “A Material Model for Pipeline Steels” (Hart, et. al 1996), an 8-parameter model can be used to develop input material properties for strain levels below 2%. This portion of the steel stress-strain curve can be divided into 3 regions namely; a linear elastic region, a curved transition or “knee” region, and an essentially linear “fully plastic” region. The term “fully plastic” is not strictly correct since the steel still has a finite hardening modulus. The model requires that the HT and LT curves have the same elastic modulus and the same fully-plastic strain hardening modulus. However, the shape of the HT and LT curves in the yield transition region can be different i.e., the curves can have different proportional limits and different degrees of “sharpness” or “roundedness” through the transition from elastic to fully-plastic conditions. The strength levels of the curves in the fully-plastic strain hardening region need not be the same. A 2-root fitting process can be used to determine the ellipse sizes and initial shifts required to closely match a given “target” LT-HT pair of stress-strain curves (as well as a 3-root fitting process when a “target” LT-HT-LC triple of stress-strain curves is available).

### 4.3 GEOTHERMAL INPUT

Frost heave is associated with growth of a frost bulb around the chilled pipe and it is assumed that heave is produced by swelling at the bulb face as the frost bulb grows wider and deeper (see Figure 4.2). The amount of heave for a given increase in frost bulb depth is influenced by several parameters including the type of soil, the availability of moisture, the speed with which the frost bulb grows, the bearing pressure exerted by the pipe on the ditch bottom and other factors. In addition, the amount of movement at the ditch bottom depends on the depth of the frost bulb, with a given amount of swelling producing less ditch bottom heave as the frost bulb gets progressively deeper. Free heave is the heave that would occur if the pipeline provided no resistance to movement. Restrained heave, which is less than the free heave, is the heave that results accounting for the pipelines resistance to movement which tends to increases the amount of pressure at the base of the frost bulb.
PIPLIN analyzes the effects of restrained frost heave by treating heave movements as equivalent support "settlements," applied at the ditch bottom (i.e., at the base of the bearing springs). Because heave originates at the frost bulb face, a theory is needed to convert swelling of the soil into ditch bottom movements. PIPLIN has several different options for specifying pipeline frost heave effects. The “Revised Formula Method” is the option selected for the ASAP project. In the Revised Formula Method, the program calculates ditch bottom movements using the segregation potential theory (Konrad 1981) given certain information describing the frost bulb properties.

The following time-independent parameters are specified:

1. A reference pressure \( P_o \) to be used in the segregation potential equation.
2. The frost bulb density \( \gamma \) which is used to calculate the soil pressure at the frost bulb base due to bulb self weight.
3. The equivalent burial depth \( D_o \) which is used in the calculation of soil pressure.
4. The initial overburden force correction term \( F_o \) which is used in the calculation of soil pressure.

In addition to the time-independent parameters described above, time-histories of the following frost bulb and soil properties are provided as an input table:

1. Frost bulb depth \( D \) below pipe.
2. Shear force per foot of pipe \( S \). In general, the shear force term can be due to side shear and/or end shear effects. Note that because a time-history of \( S \) is input, seasonal variations can be directly included.
3. Bearing width \( B_o \) at the base of the frost bulb over which the shear force \( S \) is assumed to be distributed. That is, the soil bearing pressure at the frost bulb base due to \( S \) is \( S/B_o \).
At any given time \( t \) and at any given point within the heaving section of the pipe, the values of \( D(t) \), \( S(t) \), \( B_S(t) \), \( B_F(t) \), \( G(t) \), \( a(t) \) and \( S_{Po}(t) \) can be obtained from the input time-history table. Note that for most applications, the values of \( a \) and \( S_{Po} \) are constant with time. One exception to this is for a layered soil profile where \( a \) and \( S_{Po} \) may vary with depth. The variation with depth can be considered indirectly as a variation with the times that the bottom of frost bulb reaches the different soil layers. When a pipe segment has a different heave material at each end (e.g., when considering a heave material transition), the heave material properties at a given transverse support location are obtained by linear interpolation between the properties at end “I” and end “J” of the segment. The values of \( S \), \( D \), \( B_S \) and \( B_F \) and \( G \) are calculated at the middle of the time step, by interpolation in the input time-histories. The pressure to be used in the equation for heave rate is computed as follows:

\[
P = \gamma (D + D_o) + \frac{S}{B_S} + \frac{(F - F_o)}{B_F}
\]

where the parameters \( \gamma \), \( D \), \( D_o \), \( S \), \( B_S \), \( F_o \) and \( B_F \) are defined above. The term “\( F \)” is the feedback force exerted by the pipe on the ditch bottom per unit length of pipe (i.e., \( F \) is equal to the current transverse (T) support reaction). As already noted, the quantities \( \gamma \), \( D_o \) and \( F_o \) are constants and the quantities \( D \), \( S \), \( B_S \) and \( B_F \) vary with time. The bearing force \( F \) is obtained from analysis of the interaction between the pipe and soil, and varies with location along the pipe as well as with time. If overburden (soil plus pipe) loads are specified, the initial pipe bearing force will equal the overburden soil weight plus the pipe weight. The initial value of the pressure for heave calculations will thus include the effect of the soil weight at the ditch bottom level (in the \( \gamma D_o \) pressure term) plus the effect of the overburden soil weight (in the \( (F - F_o)/B_F \) pressure term). If no \( F_o \) correction is made, the overburden soil weight will be included in the pressure calculation twice. The parameters \( D_o \) and \( F_o \) are selected to provide the desired initial pressure for heave calculations. The shear resistance term \( S \) can be used to represent the resistance provided by the unfrozen soil on the sides of the soil “block” above the widest point of the frost bulb and/or the resistance provided by the frozen soil “abutments” at each end of the heaving span.

When the frost bulb depth increases during an analysis time step, the heave rate, \( \dot{H}(t) \), is calculated using the segregation potential equation:

\[
\dot{H}(t) = 1.09 S_{Po}(t) e^{a(t)(P(t) - P_o)} G(t)
\]

and the heave increment is given by:

\[
\Delta H = \dot{H}(t) \Delta t
\]
If the frost bulb depth decreases (“retreats”) during a time step, thaw settlement rather than frost heave occurs. The amount of settlement is set equal to the amount of heave that occurred over that depth interval when the frost bulb depth was increasing. PIPLIN tracks the heave vs. frost bulb depth “path” for each transverse spring within the heaving segments of the model. Once the frost bulb depth starts to increase again after a decreasing interval, the “old” heave vs. frost bulb depth path is overwritten at depth levels larger than the most recent "retreated" depth (i.e., the new heave vs. frost bulb depth path need not follow the original path after retreating). This “settlement upon frost bulb depth retreat” feature can be deactivated if desired.

In any time step, increments of movement at the ditch bottom are assumed to be in the transverse direction only. If the pipe is horizontal, this will be the vertical direction. The effect of the movement is calculated using a step-by-step procedure. The amount of heave is calculated separately for each support in turn. The resulting displacement pattern is treated exactly like a settlement profile, and the response of the pipe is calculated.

During a heave analysis, the program predicts a “trial” heave displacement increment ($\Delta H_{\text{trial}}$) at each transverse spring in the heaving section of the model for each time step based on the current bearing pressure, and applies this displacement increment profile to the model. The program then recalculates the bearing pressure and a corresponding “adjusted” heave displacement increment ($\Delta H_{\text{adjusted}}$) at each transverse spring in the heaving section of the model based on the average pressure over the time step. If $\Delta H_{\text{adjusted}}$ differs from $\Delta H_{\text{trial}}$ by more than user specified tolerances at any transverse spring in the heaving section of the model, a new prediction is made and the time step is repeated. If convergence cannot be obtained within a specified number of iterations, the time step is automatically halved, and the process is repeated. If the time step is subdivided more than a specified number of times, the program stops executing. If convergence is obtained rapidly, and if the time step has been subdivided, the subdivided step is doubled, but is never allowed to exceed the basic time step.

### 4.4 SOIL RESISTANCE CHARACTERIZATION

As previously noted, the soil is modeled in PIPLIN as a nonlinear Winkler foundation, i.e., the soil support is idealized as a series of discrete, independent, nonlinear springs lumped at the pipe element midpoints. The longitudinal pipe-soil springs provide resistance to longitudinal motion and the transverse pipe-soil springs provide resistance to transverse motion where longitudinal and transverse are defined relative to the original, un-deformed, geometry of the pipe axis. The pipe-soil springs are assumed to have uniform properties over any pipe segment.

Longitudinal pipe-soil spring supports are distributed along the pipe axis to represent cohesive resistance of the soil to longitudinal displacement of the pipe. For each pipe element, the longitudinal pipe-soil spring state is determined from the average of the longitudinal displacements of the pipe nodes at each end of the element. The supports are assumed to provide resistance to longitudinal movement up to a specified force per unit length of pipe and then to slip at constant load.

Transverse pipe-soil spring supports are distributed along the pipe to represent the transverse (T) resistance of the soil (e.g., upward or downward). For each pipe element, the transverse pipe-soil
spring state is determined from the average of the transverse displacements of the pipe nodes at each end of the element. In any pipe segment, different properties may be specified for downwards/bearing (+T) and upwards/uplift (−T) loading on the soil. The soil bearing (+T) resistance is the resistance of the trench bottom to downward movement of the pipe. For ASAP, frost heave simulations, the bearing resistance of the soil will be accounted for in the model using elasto-plastic springs. The strength of the bearing spring is typically selected to correspond to the minimum annual pipe temperature. For ASAP, the pipe-soil bearing resistance will also consider temperature and bearing pressure dependent secondary creep. The soil uplift (−T) resistance is the resistance of the soil to upward movement of the pipe. The ASAP frost heave analyses will consider the temperature, displacement rate and displacement dependence of the uplift pipe-soil springs using PIPLIN’s uplift analysis capability.

In Arctic regions, the soil around a buried pipeline may be completely frozen during the winter but significantly thawed during the summer. Also, the temperature of the pipe contents may be intentionally cycled so as to create a thaw annulus around the pipe as a means of mitigating frost heave. Under these conditions, the resistance of the soil can vary significantly. PIPLIN’s uplift, longitudinal pipe-soil spring (L-spring) and creep analysis features allow strength variations of this sort to be taken into account during a frost heave simulation. Duringthe course of a frost heave analysis, a typical year is broken up into several (typically 12) multi-step analysis sequences such that the near sinusoidal pipe and soil temperature variation, and the corresponding soil resistance variations are approximated using a piecewise-linear variation through time. A typical “steady-state” annual cycle is normally assumed to apply for each year of the analysis.

### 4.4.1 UPLIFT RESISTANCE

PIPLIN’s uplift analysis feature allows for the specification of uplift soil spring strengths that depend on the uplift spring displacement, the uplift soil temperature, and the displacement rate of the uplift spring. Uplift force-displacement relationships can be specified based on a piecewise-linear “backbone curve” defined using up to 8 uplift force-displacement coordinates for up to 60 different soil temperatures at up to 10 different uplift deformation rates. The uplift strength will typically, but not necessarily, increase with decreasing soil temperature and increasing uplift deformation rate and will typically, but not necessarily, decrease with increasing uplift displacement after reaching a peak strength value at a relatively small displacement. For uplift soil temperatures, displacements and deformation rates between the specified input values, the strengths are obtained using 2-way linear interpolation between the input backbone relationships for different uplift displacement rates and uplift temperatures. For uplift temperatures and displacement rates outside of the specified input range, the backbone curve corresponding to the nearest specified temperature or displacement rate is used. For displacements greater than the last specified displacement, the last specified strength is assumed. Within a given uplift analysis step, the uplift properties at each spring are modified based on the uplift temperature, the current rate of uplift spring displacement, and the current uplift displacement.

As described above, PIPLIN’s uplift analysis option allows for consideration of the displacement and displacement rate dependence of the pipe-soil uplift springs as well as the temperature dependence as influenced by seasonal ground surface and/or pipe temperature variations. The approach proposed for the ASAP frost heave analyses is to use a single uplift soil temperature (32°F)
corresponding to thawed soil conditions together with two or more uplift soil temperatures to cover the range of frozen soil temperature conditions encountered over a typical year of operation during the frost heave analysis. The uplift temperature values and the time between adjacent temperature values are specified for a typical 1 year analysis cycle. The uplift soil temperature will be taken as equal to the pipe temperature or some measure of the average backfill temperature, both of which have a seasonal variation that resembles a sine wave. The ASAP project proposes to compute the thawed and frozen uplift pipe-soil spring properties based on publically available geotechnical procedures (e.g., see COLTKBR 2003 and COLTKBR 2007).

### 4.4.2 BEARING RESISTANCE

PIPLIN has sophisticated creep support analysis capabilities including pressure and temperature dependent primary and secondary creep. If desired, creep properties can be associated with any transverse segment support, and creep analyses can be carried out. The pressure and temperature dependence is considered by specifying the creep parameters at up to 5 temperatures for up to 20 pressures. For temperatures and pressures within the specified temperature and pressure ranges, the creep parameters are obtained by linear interpolation between input values. For temperatures and pressures that are outside of the specified temperature and pressure ranges, the creep parameters associated with the nearest input temperature or pressure are used.

For the ASAP frost heave analyses, it is proposed to consider secondary creep in the bearing pipe-soil supports. Including secondary creep has the effect of adding a secondary creep dashpot – a viscous support element that provides resistance proportional to the velocity – (with a dashpot coefficient $C_s$) in series with the elastic-perfectly plastic bearing spring associated with each pipe element. The dashpot coefficient $C_s$ is specified to be dependent on both temperature and the bearing pressure between the pipe and soil, typically decreasing with increasing temperature and pressure. The ASAP project proposes to use publically available geotechnical procedures (COLTKBR 2007) to compute the bearing spring and dashpot properties.

### 4.4.3 LONGITUDINAL RESISTANCE

In any segment, the strength of the L-spring can be defined to vary with temperature, by specifying up to 20 temperatures and up to 20 corresponding strengths. For temperatures between the specified values, the strengths are obtained by linear interpolation. For temperatures outside of the specified range, the strength corresponding to the nearest specified temperature is assumed. An initial temperature (the same for all segments) is specified, and this determines the L-spring strength at the beginning of the analysis. The effect is to place an upper limit on the strength of the L-spring. If this strength is exceeded at any location, the stiffness is reduced to zero. The effect, initially, is exactly as if a stiffness ($K$) value of zero had been specified for the support. However, the behavior differs from that with $K=0$, because the strength can subsequently be changed.

In any load sequence, it can be specified that the longitudinal (L-spring) soil temperature changes progressively, so that the cutoff on the strength also changes. If the strength decreases, the resistance developed by the support is progressively reduced, leading to a redistribution of load along the pipeline. If the strength increases, the support force remains unchanged but the stiffness becomes nonzero (the value on the basic force-displacement relationship for the current support
force). In this case there is no redistribution of load. The strength may be cycled in any desired way, for as many seasonal cycles as desired.

As described above, L-spring analysis allows for consideration of the temperature dependence of the pipe-soil longitudinal springs as influenced by seasonal surface and/or pipe temperature variations. The approach proposed for the ASAP frost heave analysis is to specify a single longitudinal soil temperature corresponding to thawed soil conditions together with several additional longitudinal soil temperatures to cover the range of frozen soil temperature conditions encountered over a typical year of operation during the frost heave analysis. The longitudinal temperature values and the time between adjacent temperature values are specified for a typical one year analysis cycle. The longitudinal soil temperature will be taken as equal to the pipe temperature which has a seasonal variation that resembles a sine wave. For ASAP, the thawed longitudinal pipe-soil spring properties will be computed using conventional procedures (e.g., see ASCE 1984, Hart et. al 2001, and Honegger et. al 2004). For frozen soil conditions, the ASAP project proposes to utilize publically available geotechnical procedures (COLTKBR 2007) for estimating the pipe-soil longitudinal spring relationship.

4.5 MODEL GEOMETRY

The typical model geometry consists of a straight, horizontal section of the pipeline with a uniform depth of frozen soil cover. The chilled pipeline is assumed to cross an initially thawed span – this is the location where a frost bulb will grow around the pipe resulting in differential frost heave. A plane of symmetry is assumed at the center of the heaving span so that only one-half of the heaving pipeline configuration is analyzed. A transition length (or ramp) between the finite length section of heaving soil and the adjacent non-heaving soil section can be specified if desired. A multi-span analysis approach is undertaken considering different simulations for on the order of 10 different span lengths ranging from very short spans (e.g., down to say 10 feet) to very long spans (e.g., up to say 150 feet). The variation in span length is an important consideration because shorter spans, which are often associated with relatively high levels of strain per inch of heave tend to be “shut down” due to pressure feedback effects (i.e., high bearing pressures increase the stresses at the base of the frost bulb which tends to shut down frost heave). For very long spans, the imposed heave profile approaches a step-change (e.g., similar to a fault crossing). The end result of the multi-span evaluation approach is that it leads to a “critical span” corresponding to the span with the highest strain demand at a given point in time. The critical span length depends on several parameters including the pipe stiffness, the soil resistance and the pressure sensitivity of the heaving soil.

4.6 IMPOSED LOADS

As previously mentioned, frost heave analyses are typically initiated with the application of gravity, internal pressure and temperature differential loads. If desired, a hydrostatic test loading and unloading sequence can be included prior to applying the operating loads. A multi-year frost heave evaluation of the pipe-soil interaction model is then undertaken holding the gravity and internal pressure loads constant. The applied temperature differential can be varied in a sinusoidal pattern over each year of the simulation based on the difference between the time-varying pipe temperature and the constant tie-in temperature. The frost heave analyses are nonlinear time-
history analyses performed using small steps through time. Within the heave span, the frost bulb geometry and frost heave vary with time. Seasonal variations of the uplift, longitudinal and creep soil temperatures are specified with each heave time step. The heave is imposed progressively at the base of the pipe-soil springs within the heave span. The amount of heave at the ditch bottom is calculated separately for each transverse pipe-soil support in turn accounting for pressure feedback.

For a selected heave span length, the results from a PIPLIN frost heave analysis include a detailed output of the state of the pipe-soil interaction model at each time step. The output state includes the current time, the pipe axial force, bending moment, hoop stress, top and bottom fiber von Mises stress, longitudinal stress, hoop strain and longitudinal strain and the curvature at each node of the pipeline model. The output state also includes the uplift, creep and longitudinal soil control temperatures, the longitudinal and transverse spring forces and displacements, the uplift spring displacement rate and the creep displacements for each element of the pipeline model. At the pipe-soil spring locations within the heaving section of the model, the frost bulb width, depth and shear are available together with the pressure components at the base of the frost bulb due to the frost bulb weight, the transverse pipe-soil spring, and shear as well as the total pressure. The current unrestrained mid-span free heave is also provided. The results described above can be post-processed in a number of different ways. Spatial plots and time history plots of various response quantities usually provide the most useful methods for understanding and interpreting the results. It is also possible to develop animations of various spatial response plots to gain a better understanding of how the overall results vary over the course of the multi-year analysis duration.

The most important results from a frost heave simulation for a given span length are the time histories of the maximum tension and compression strain demands. Detailed processing of the PIPLIN deflected shape at each point in time is used to develop time history plots of “digitally pigged” bending strains or curvatures which provides a basis for relating geometry monitoring data (e.g., smart pig survey data) to the corresponding nodal tension and compression strain demands. A schematic illustration of the maximum pig curvature is presented in Figure 4.3 for a 25-year frost heave simulation. Note that the “wiggles” in the curvature time history plots are due to the seasonal variations in the pipe-soil spring resistance.

Figure 4.3 can be used to illustrate, on a conceptual basis, the pipeline curvature monitoring approach to be utilized for ASAP for a high heave location. The dashed yellow horizontal line corresponds to the intervention curvature criterion while dashed red horizontal line corresponds to the curvature associated with the governing pipe strain limit. Note how the intervention threshold is reached in the 13th year of the simulation while the governing strain limit threshold is reached in the 16th year of the simulation.
Figure 4.3  Illustration of Maximum Curvature Time History
SECTION 5. STRAIN CAPACITY DETERMINATION

5.1 MATERIAL REQUIREMENTS

The ASAP will be constructed of API 5L X70 line pipe with a wall thickness that varies between 0.595 inches and 0.857 inches as appropriate for the Location Class (i.e., design factor of 0.72, 0.60, and 0.50 for Class Locations 1, 2, and 3, respectively).

5.1.1 LINE PIPE

A generic stress-strain relationship where various properties of the stress vs. strain curve are highlighted is presented in Figure 5.1. For the purposes of strain demand calculations, the maximum strain range of interest typically runs out to about 2% strain. The initial elastic slope of the curve, frequently called “Young’s modulus” is denoted in Figure 5.1 as $E_{\text{start}}$. The point at which the tangent slope of the curve first departs from a projection of the elastic slope is called the proportional limit. The tangent slope of the curve at high strains (i.e., the slope to the right of the point labeled “fully plastic”) is denoted as $E_{\text{end}}$. Note that the term “fully plastic” is not strictly correct since the steel still has a finite hardening modulus (slope) at this point whereas fully plastic implies a slope of zero. The section of the curve between the proportional limit and the fully plastic point is often referred to as the “knee” region where the steel transitions from elastic to plastic conditions. The dashed line tangent projections from the curve passing through the proportional limit and the fully plastic point (bounding the knee region) make up what is referred to as the backbone curve. For pipe steels, the yield strength is defined as the stress at a strain of 0.5% per API 5L, shown as the stress coordinate denoted as “Y” in Figure 5.1. Note that for nominal pipe size (NPS) 8 and above, the yield strength is defined based on the hoop tension stress-strain curve.

The shape of the pipe steel stress-strain relationship can have a significant effect on the pipe strain demand and as well as the pipe strain capacity (particularly the compressive strain capacity). An illustration of pipe steel stress-strain relationships with different behaviors across the knee region of the curve is presented in Figure 5.2. In general, pipe steel stress-strain curves with a relatively abrupt or “sharp” elastic-to-plastic transition (purple and red curves) tend to lead to larger strain demands and lower strain capacities than stress-strain curves with a relatively rounded elastic-to-plastic transition (blue curve). Similarly, stress-strain curves with relatively low strain hardening modulus (slope) characteristics (e.g., the red curve in the flat “Lüders plateau” region) tend to lead to larger strain demands and lower strain capacities than stress-strain curves with relatively high strain hardening modulus characteristics. Deformation analyses should consider a range of bounding input steel stress-strain relationships that have been developed to be consistent with exemplar stress-strain test results from the project pipe material.

In addition, the shape of stress-strain curves can be significantly different for pipe steel tests performed in the LT, HT, LC and HC directions, especially for higher grade pipe materials and for UOE pipe. In other words, these materials are anisotropic. Based on experience with UOE pipe test results, it is generally observed that over the strain range from approximately 0.2% to 0.8% strain (i.e., in the so-called “knee” region), the four stress-strain curves tend to have the following relative strength ranking: HT > LC ≥ LT > HC and that the HT curve usually tends to be the “sharpest” of
the four curves. Unlike the specifications under API 5L which are focused on the hoop tension yield and ultimate tensile strengths (in order to satisfy the pressure induced hoop stress design requirements), the following sections are focused on the longitudinal tension stress-strain characteristics.

![Figure 5.1 Normative Properties of a Steel Stress-Strain Relationship](image-url)
Figure 5.2 Illustration of Differing Stress-Strain Behavior in the Knee Region

(1) MINIMUM LONGITUDINAL YIELD STRENGTH

As noted above, the longitudinal tension (LT) stress-strain curves tend to be slightly weaker than the hoop tension (HT) stress-strain curves in the knee region (e.g., in the region where yielding is defined). In many cases, the LT yield stress is actually below the specified minimum yield strength. This is not normally a cause for concern since as previously noted, the pipe SMYS is defined in the hoop tension direction.

(2) LONGITUDINAL TENSILE STRENGTH

Consideration will be given to specifying a minimum longitudinal tensile strength, as well as to specifying a relative low yield to tensile ratio to ensure a sufficient work hardening rate to avoid strain localization.

(3) MINIMUM UNIFORM LONGITUDINAL ELONGATION

Likewise, consideration will be given to specifying a minimum uniform longitudinal elongation to further avoid strain localization.
(4) LONGITUDINAL STRESS-STRAIN CURVE

Basic pipe mill certificates will always provide a direct characterization of the yield and ultimate strengths in order to demonstrate that the material meets the specified minimum strength requirements. For ASAP strain-based design, it is anticipated that representative fully digital stress-strain curves will be obtained from both the LT and HT directions. It may also be desirable to obtain representative LC stress-strain curves.

Given the digital stress-strain data from representative pipe samples, it will be straight-forward to compute various measures of anisotropy such as the ratio of HT/LT yield and ultimate strengths or strengths at several selected strain levels of interest (e.g., at 1.5%, 2%, etc.). It will also be possible to compute various measures of curve shape or sharpness for the different curve directions such as the ratio of strengths at different levels of strain across the knee region and/or the plastic complementary energy at various levels of strain. These parameters can be used to characterize the variability of the project stress-strain relationships.

(5) LUDERS PLATEAU

Localized bands of plastic deformation may occur in certain materials before fracture. These bands are commonly referred to as Lüders bands as they were first reported by Guillaume Piobert and W. Lüders. These localization deformations result in a slight drop in strength below the initial yield strength, which is maintained for a moderate increase in imposed strain. The overall range of formation of the bands may form a flat yield, or Lüders, plateau.

Increasing imposed strain beyond the end of the plateau results in an increase in strength through strain-hardening. Strain-hardening continues to a peak that typically exceeds the yield strength by thirty to sixty percent.

For strain-based design applications, it is advisable to avoid excessive sharpness in the knee region of the stress-strain curves from any direction (e.g., LT or HT) and also to avoid a Lüder’s plateau. These characteristics can significantly increase the pipe strain demand (while at the same time decreasing the pipe strain capacity).

5.1.2 COATING EFFECT

Strain aging of pipe (e.g., due to heating during coating application) can tend to increase the sharpness of the knee region particularly for the HT curve with higher temperatures leading to higher levels of sharpness. Strain aging is also known to increase the pipe yield and ultimate strengths. Because strain aging tends to increase the yield strength more than it increases the ultimate tensile strength, it also tends to reduce the strain hardening modulus (i.e., as characterized by the Y/T ratio and/or the slope parameter E_end) in the region of interest for strain demand. For these reasons, it may be desirable to develop pipe specifications that include review of both as-received and aged stress-strain curves as well as to limit the heat to which the pipe is exposed during coating application if practicable.
5.1.3 **DIMENSIONAL CONTROL**

Dimensional imperfections within a single length of line pipe can act as buckle initiation points and need to be minimized. However, the key concern for strain-based design is variation from pipe to pipe that acts as an imperfection and results in strain concentrations at girth welds. Any aspects of pipe geometry, such as ovality, variations in thickness, or tolerances in pipe diameter, that can result in misalignment across the weld can impact strain capacity. This is particularly true for thicker pipes, where internal or external alignment clamps may not be able to fully ‘round out’ pipe for welding.

5.1.4 **GIRTH WELDS**

Several welding techniques can be employed on girth welds joining lengths of pipe together. All have some impact on strain capacity. For example, GMAW with low CO2 content shielding gases produces the best combinations of strength and toughness but can be prone to generation of long defects if the welding procedure is not adequately optimized prior to field deployment. It is commonly used for mainline girth welding of long, large diameter pipelines. The various torch configurations such as single torch, dual torch, tandem wire, etc., also have implication on strain capacity. Single torch welding tends to give better results due to the lower heat input, but can affect construction efficiency and pipeline cost, especially in the arctic regions where the construction period is limited and logistics are challenging. Again, a well-balanced approach is needed to select the appropriate welding processes for the double jointing, mainline, tie-in, and infield repair procedures. The requirements of selecting welding procedures for these different types of welds to achieve both high strength and toughness may be challenging. The selected welding processes will need to be properly qualified and tested to confirm that the required strain capacity is met reliably.

5.1.5 **WELD OVERMATCH**

The key difference between welding for typical pipelines and those subject to high strain is the need for substantial and reliable strength overmatch of the weld metal relative to the base pipe. Reliable overmatch is critical for ensuring flaw tolerance adequate to allow for cost effective pipeline construction while ensuring safe design. This has been demonstrated in full-scale pressurized testing, where high weld overmatch was able to prevent failure at a large manufactured defect, resulting in fracture in the pipe body instead of the welds at high strain. The level of yield strength overmatch required to ensure a safe design depends on project-specific factors such as pipe grade, pipe geometry, flaw acceptance criteria, and the required strain capacity.

5.1.6 **WELDMENT TOUGHNESS**

Toughness of the weld metal and heat affected zone are critical to strain-based pipeline performance. Upper shelf behavior is required to resist fracture initiation by cleavage. It is also important to ensure adequate upper shelf toughness, which relates to ductile tearing resistance. The Charpy impact test is an excellent tool for assessing toughness and providing a quality check during weld procedure qualifications but is not sufficient for the detailed engineering of strain-
based design pipelines. For these applications, fracture mechanics tests, such as the crack tip opening displacement (CTOD) test, should also be used to ensure adequate resistance to fracture with weld imperfections. Achieving high toughness in small scale testing is necessary but not sufficient to ensure a safe and cost effective strain-based design. The relationship between small scale toughness and full scale performance at high strain has not been adequately established by industry.

### 5.2 TESTING REQUIREMENTS

A number of small-scale and full-scale tests will be conducted to assist in determining the actual strain capacity of the line pipe to be used on the Project.

#### 5.2.1 CURVED WIDE PLATE TESTING

Curved Wide Plate Testing (CWPT) has been used by industry as a proof test for qualifying strain-based design for many years. The test specimen consists of a large dog bone shape samples cut from a pipe containing the specific girth weld to be qualified. A flaw is saw-cut or electrical discharge machined (EDM) into the desired zone of the weld, and the specimen is pulled to failure in tension. Unfortunately, CWPT is not capable of quantifying the effect of biaxial loading due to internal pressure. It is also impractical to use CWPT to evaluate the effect of high-low misalignment on strain capacity. Recent full scale data have shown that these effects on strain capacity can be very significant. However, CWPT is still considered a cost effective and useful test for line pipe and weld procedure qualification and to establish initial estimates of the strain capacity.

#### 5.2.2 FULL-SCALE TENSION TESTING

Although research is underway to develop suitable alternatives, pressurized full-scale tension testing remains the only fully validated method to confirm tensile strain capacity. If a limited number of tests are planned, an effective strategy is to use these tests to examine lower bound behavior. The goal is to confirm that the design meets the strain demand requirement when the key parameters are at the extremes of the acceptable construction envelope. Care should be taken to select test samples representative of the worst expected combination of the key fabrication parameters. On the other hand, selecting overly conservative parameters can result in an undesirable outcome. Another consideration is the availability of test frames to conduct these full scale tests. At this time, 30-inch pipe with a 0.630-inch wall thickness is near the limit of testing capability, which should be adequate for ASAP. Full-scale bend tests with internal pressure have been used, but are less efficient due to the limited weld length reaching the maximum strain. Additionally, modeling of the load/response behavior can be very challenging relative to a tension test.
5.2.3 COMPREHENSIVE STRAIN VALIDATION

Industry has developed and validated empirical equations and finite element modeling methods for estimating the compressive strain capacity of pipelines. The most widely used measure of pipe compressive strain capacity is that associated with the peak moment from an imposed curvature test on a full-scale pipe specimen or finite element analysis of a pipe stub section. Note that this strain limit is a serviceability limit state with a significant post-wrinkling reserve margin before the pipe pressure integrity is compromised (usually due to the development of high local strains within the wrinkle(s)). Empirical equations of this sort will be used to establish preliminary pipeline compressive strain capacity. Finite element analyses (FEA), and possibly pressurized full-scale bend tests, will be conducted to establish the compressive strain capacity. These studies will account for the effects of pipe anisotropy, material work hardening characteristics, girth weld misalignment or high-low, internal pressure fluctuations, axial loading, and thermal aging. The FEA method will be the primary tool to quantify the effect of variability in all major parameters; full-scale bend or buckling tests will only be used to validate the finite element models and provide useful experimental design data, if deemed necessary. A large number of finite element analyses may be required to cover a full range of parametric studies in support of a design reliability assessment. Because the compressive strain is defined over a certain gauge length (typically one to two pipe diameters), the selection of gauge length will accommodate geometric deformation effect and ensure the practical strain detectability by ILI tools. A common gauge length in finite element compressive strain capacity assessment, strain demand assessment, operation ILI monitoring, and any full-scale bend tests will be used.
SECTION 6. ROUTE APPLICATION

6.1 DESIGN APPROACH

A number of approaches can be used when considering a strain-based design, ranging from a relatively simple and straightforward deterministic design approach, where estimates of the strain demand and strain capacity are compared, to more elaborate methods that consider the probability of failure or the reliability of the pipeline.

For the ASAP, a deterministic design approach will be utilized and materials that have strain capacity well in excess of the maximum expected strain demand will be select. All of the parameters used in determining either strain demand or capacity will be conservatively selected. An appropriate safety margin between the conservatively estimated demand and capacity will be applied. The margin will be determined based on the uncertainty level of the key parameters used in ascertaining the design values.

6.2 SEGMENT-BY-SEGMENT DESIGN

Using route geotechnical data in conjunction with the results of the demand and capacity analyses, a segment-by-segment design will be completed to identify the frost heave potential along the alignment. The segment-by-segment design approach is presented in Figure 6.1. The four possible outcomes from application of the flow chart are briefly described below:

- Areas of continuous permafrost, low water table, or where the pipeline operating temperature is greater than 32°F will not be susceptible to frost heave and therefore no rigorous frost heave analysis will be required.
- Areas where the predicted combined pipe stress due to frost heave for the critical span length remain below the allowable combined stress as per ASME B31.8 are classified as having low heave potential and no special mitigative measures will be implemented.
- Areas where the predicted curvature (from digital pigging analysis) due to frost heave for any span length remain below the allowable curvature are classified as being heave susceptible and will require ongoing monitoring. Should the measured curvature reach the intervention curvature limit over time then mitigative measures will be implemented.
- Areas where the predicted curvature (from digital pigging analysis) due to frost heave for any span length exceed the allowable curvature are classified as having high heave potential and mitigative measures will be implemented during design and construction.
Figure 6.1  Frost Heave Route Assessment Flow Chart

1. Start
2. Continuous Permafrost?
   - YES
   - NO
3. Operating Temp >32°F?
   - YES
   - NO
4. Low Water Table?
   - YES
   - NO
5. Frost Heave Critical Span Stress < Allowable?
   - YES
   - NO
6. High Heave
7. Frost Heave Any Span Curvature > Allowable?
   - YES
   - NO
8. Low Heave
9. Heave Susceptible
6.3 POTENTIAL DESIGN MITIGATIVE MEASURES

For those pipeline route segments where the estimated heave potential may exceed the ability of the pipe to withstand the imposed displacement, a number of mitigative options, or combinations of options, could be employed to reduce the potential for deleterious movement including:

- Reroute within the alignment corridor to a non-frost-susceptible terrain unit, if available;
- Investigate the subsurface of the suspect terrain segment more closely so as to reduce the conservatism inherent in the station to station approach;
- Change the operating temperature profile of the segment so as to reduce the freeze potential, e.g., by adding heater stations, cycling the temperature, etc.;
- Insulate the pipe ditch to reduce the heat flux through the frost-susceptible soil;
- Increase the pipe wall thickness to increase the resistance of the pipe to ditch displacements, as well as increasing the ability of the pipe to withstand higher displacements;
- Over-excavate the frost-susceptible soil beneath the buried pipeline and replace with non-frost-susceptible soils;
- Excavate soils with high uplift resistance above the pipe springline and replace with soils with low uplift resistance;
- Elevate the pipeline aboveground placing it in an embankment. Elevating the pipe would reduce or eliminate the heat extracted from the ground;
- Elevate the pipeline aboveground placing it on overhead supports. Elevating the pipe would eliminate the heat extracted from the ground and uncouple the pipe from the soil resistance;
- Heat trace the soil underneath the pipe to counteract frost penetration;
- Emplace stand-alone heat pipes to freeze the soil quickly, reducing the ability of the frost-susceptible soil to cause large soil volume changes; and
- Combine compatible concepts presented above.
SECTION 7. CONSTRUCTION RELATED ISSUES

7.1 WELDING PROCEDURES

To ensure high quality welds, a reasonable amount of flexibility is needed in welding parameters to allow welders the ability to manipulate the process and reduce the likelihood of producing unacceptable weld imperfections. The acceptable ranges of parameter variability that are intended to provide the performance that is similar to the completed qualification test welds will be established.

Weld qualification testing will bound the variability of critical parameters. In particular, heat input is critical because heat input modifies the metallurgical features of the HAZ and weld metal. Weld procedures will be qualified to a full suite of small scale tests and may also include large scale performance testing such as curved wide plates or full-scale tension tests with artificial defects. A test program that confirms the adequacy of the welds to provide resistance to fracture with a weld defect at the extreme of the welding process parameters acceptable during construction will be conducted.

7.2 AUTOMATED ULTRASONIC TESTING

Qualification of inspection equipment is critical to the successful implementation of a strain-based design for the pipeline. Materials qualification for strain-based design is intimately tied to the establishment of defect acceptance criteria with height and length restrictions. Radiographic testing does not give qualitative information about defect height and is therefore not suitable for a strain-based design. In order to determine both defect height and length with confidence, automated ultrasonic testing (AUT) will be required. A qualification program will be required to establish not only the detection capability, but also the sizing accuracy of the AUT system to be used during construction. The AUT system will be capable of detecting the critical defect height with high confidence. The sizing error of the system will be established for the range of defect dimensions at the acceptance limit. This error will be subtracted from the critical defect size to establish the acceptance criteria to be used during pipeline welding.
8.1 MONITORING POTENTIAL FROST HEAVE

During design the frost heave potential along the alignment will be evaluated using the available route alignment data combined with the line pipe capacities and advanced engineering simulation methodology to explore the potential interaction between the soil subsurface and the pipe during its operational life. To address the differential values along the route, soil displacements and resistance values will be estimated using the landform characteristics along the route derived from the project geo-database. Scrutiny will continue throughout the operational life of the pipeline.

A key consideration in any strain-based pipeline design is the “monitor and maintain” component of the design philosophy. Periodic monitoring of the pipeline will identify locations that are of concern with respect to the pipe structural integrity. The monitoring interval is selected such that there will be enough time to plan and undertake intervention prior to the pipe experiencing a loss of structural integrity.

The best way to monitor curvature along ASAP is through periodic ILI surveys. An ILI geometry survey provides the most practicable and reliable way to accurately characterize the geometry of the entire length of the pipeline. Use of a high resolution inertial navigation system (INS) based geometry tool will result in the highest possible level of survey accuracy.

Several ILI vendors offer high resolution INS tools. The instrumentation on these tools includes a strap down, tri-axial fiber optic gyroscope based Inertial Measurement Unit (IMU), a tri-axial accelerometer, an odometer as well as a multi-arm mechanical caliper. The gyroscopes measure the change in orientation of the pig in terms of the pitch, azimuth, and roll angles; the odometer measures the along-the-pipe distance coordinate tie-points; and the calipers measure pipe ovality or dents and also locate the pipeline girth welds. The gyroscope and odometer data can be numerically differentiated to compute the pipeline curvature (which is proportional to the bending strain) or numerically integrated to estimate the pipe position between coordinate tie-points.

Typical accuracies of inertial survey tools are as follows:

- Curvature Detection: ±0.02% Strain
- Bend Angle Detection: ±0.1°
- Dent/Ovality: ±2.5 mm
- Weld-to-Weld Distance: ±12.5 mm
- Mapping Accuracy 1:2000 (depends on distance between coordinate tie-points)

Since the early 1990’s, the pipeline industry has gained experience with these tools and they have become a key component of pipeline systems which incorporate the “monitor and maintain” component of the strain-based design philosophy. While the pipeline (X-Y-Z) position mapping is useful for GIS applications and pipeline location, the most important result from an inertial survey of a pipeline for structural integrity assessments is the curvature/bending strain not associated with intentional bends. The caliper data can also be extremely useful for establishing out-of-roundness and incipient wrinkling deformations of the pipe wall at high curvature/bending strain locations.
Note that the terms curvature ($\Psi$) and bending strain ($\varepsilon_{\text{bending}}$) are used somewhat interchangeably herein (since $\varepsilon_{\text{bending}} = \Psi D/2$).

An important consideration of the ASAP ILI program will be an initial/baseline geometry survey of the pipeline as soon as practicable after construction. This survey will provide a detailed characterization of the as-installed pipeline geometry for comparison with subsequent surveys. Survey-to-survey curvature changes can be used as a basis for estimating the rate of curvature accumulation at any areas of concern. The ASAP curvature monitoring program will establish a curvature limit associated with the governing pipe tension or compression strain limits and an intervention curvature limit will be established as some fraction of the curvature associated with the governing strain limit. The idea is that when high curvature locations are identified, the current curvature and the rate of curvature change can be measured against the intervention curvature limit which will provide a threshold condition at which an intervention can be planned and executed with sufficient time before the curvature reaches that associated with the governing strain limit. This monitoring approach is illustrated conceptually in Figure 4.3.

### 8.2 POTENTIAL OPERATIONAL MITIGATIVE MEASURES

For those pipeline route segments where the evaluation of ILI or other measurement data shows that the effect on the pipe due to the soil frost heave may exceed the ability of the pipe to withstand the imposed displacement, mitigative options, or combinations of options, could be employed to reduce the criteria exceedance potential during operations. Some of these are seen to be the same as for design, although the practical ability to employ them during operations may be limited. The options include:

- Insulate the pipe ditch to reduce the heat flux through the frost-susceptible soil;
- Excavate soils with high uplift resistance above the pipe springline and replace with soils with low uplift resistance;
- Elevate the pipeline aboveground placing it in an embankment. Elevating the pipe would reduce or eliminate the heat extracted from the ground;
- Emplace stand-alone thermosyphons to freeze the soil quickly, reducing the ability of the frost-susceptible soil to cause large soil volume changes; and
- Combine compatible concepts presented above.

#### 8.2.1 TEMPERATURE CONTROL

Another potential operational philosophy that might be considered is temperature control or temperature cycling. In areas of continuous permafrost, the line is not susceptible to frost heave and operating the line below 32°F will ensure the supporting soils do not thaw and possibly be subjected to another geothermal phenomenon – thaw settlement. Conversely, operating the line above 32°F in areas of thawed ground will guard against frost heave.

In areas of discontinuous or sporadic permafrost, temperature cycling, i.e., fluctuating the operating temperature from below 32°F to above during the course of the year, may limit the overall potential for frost heave or thaw settlement over the life of the line.
8.2.2 LINE LEVELING

Line-leveling is one possible form of intervention/mitigation that can be employed should the measured curvature approach or exceed the curvature limits established for the project. This would entail excavating the line in areas experiencing frost heave and re-leveling the line to reduce the curvature.
The design approach to frost heave explained in this report is summarized in Figure 1.3 which shows the flow of the various steps needed to define and begin the assembly of the components of the project approach in preliminary design; finalize the assembly and verification and apply the approach to the alignment in final design; and continue route monitoring and potential mitigation throughout operations. In the current front end loading phase of the project, the design approach is being developed and scoped of initiation during the next phase - preliminary design.

Although only the approach to frost heave is developed in this report, the approach is illustrative of the design approach to other displacement loadings that may cause longitudinal stress in the pipe such as thaw settlement.

AGDC is committed to the complete development and verification of the design approach for application throughout the design life. As the development progresses, AGDC will share the ongoing verification and application studies with PHMSA throughout this process to ensure concurrence and heighten confidence in the safety and integrity of the pipeline.
SECTION 10. REFERENCES


APPENDIX A  PHMSA CORRESPONDENCE

2. State of Alaska, Office of the Governor letter to Mr. Jeffrey Weise, Associate Administrator for Pipeline Safety, US Department of Transportation, dated April 12, 2010
March 3, 2010

Mr. Bob Swenson
Alaska Stand Alone Pipeline
Natural Gas Transportation Project
411 W. 4th Avenue, Suite 2C
Anchorage, AK 99501-2343

Re: Alaska Stand Alone Pipeline Natural Gas Transportation Project

Dear Mr. Swenson:

The Pipeline and Hazardous Materials Safety Administration (PHMSA) is writing to request information about the nature of the proposed Alaska Stand Alone Pipeline Natural Gas Transportation Project (ASAP Project) and plans for the submission of special permit applications for the project pursuant to 49 C.F.R. § 190.341. A special permit is an order by which PHMSA waives compliance with one or more of the Federal Pipeline Safety Regulations under the standards set forth in 49 U.S.C. 60118(c) and 49 C.F.R. § 190.341, subject to conditions and limitations set forth in the order. A special permit may be issued to a pipeline operator (or prospective operator) for specified facilities that, absent waiver, would be subject to the regulation.

PHMSA would appreciate a project briefing to review any need that the ASAP Project may have for a special permit. To avoid project delays, PHMSA requests that the ASAP Project submit any special permit applications as soon as possible. PHMSA advises the ASAP Project to submit its applications before making design-related decisions that could require special permits.

Additionally, to facilitate our review of the project for compliance with the gas pipeline safety regulations at 49 C.F.R. Part 192 and any special permit application(s), please provide the safety and environmental information listed in the informal preliminary information requests enclosed with this letter as Enclosures A and B. Depending on your response, PHMSA may request additional information, including, but not limited to: data, reports, studies, documents, and independent third party analyses. PHMSA expects a detailed safety and environmental review to take a minimum of 12 months or more, depending upon the extent and nature of the request, any requirements for additional information or studies, and the quality of submittal documents.

PHMSA is required to conduct an environmental review in accordance with the National Environmental Policy Act. An overview of the preliminary environmental information needed to support your anticipated special permit applications is provided in Enclosure B. Your timely submission of permit applications and detailed safety and environmental information will enable
PHMSA to properly analyze potential risks to public safety and to the environment that could result from our decision to grant or deny a special permit.

Please contact Dennis Hinnah at 907-271-4937, or Alan Mayberry, Director of Engineering and Emergency Support, at 202-366-5124, if you have any questions.

Sincerely,

[Signature]

Jeffrey D. Wiese
Associate Administrator for Pipeline Safety

Cc: With Enclosures

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Federal Energy Regulatory Commission
888 First Street, NE, Room 1A
Washington, DC 20426
Enclosure A

Information Request for the Proposed ASAP Project

1.0 Introduction

This document outlines preliminary information PHMSA will need to begin both review of project compliance with 49 Code of Federal Regulations (CFR) Part 192 and consideration of anticipated special permit applications. It is not an exhaustive listing of required information, but identifies initial information needs on the types of issues PHMSA believes might require more extensive review.

Gas pipeline operators must comply with 49 CFR Part 192 (the Regulations), and the industry codes and standards incorporated by reference into the Regulations, when designing, constructing, inspecting, testing and operating natural gas pipelines. Compliance with the Regulations, codes, and standards provides a substantial basis for concluding that pipelines have been designed, fabricated, constructed, inspected, and tested in a manner that will protect public safety.

If an operator (or prospective operator) of a pipeline facility wishes to deviate from one or more Regulations, the operator may apply for a special permit to do so. Pursuant to 49 USC 60118(c) PHMSA has the authority to issue orders (special permits) granting a waiver of compliance with the Regulations with respect to such pipeline facility on terms PHMSA considers appropriate if PHMSA determines that the special permit is not inconsistent with pipeline safety. PHMSA often places conditions on special permits designed to address any safety issues that are identified during the special permit review process. The procedures for processing special permits are set out in 49 CFR § 190.341.

PHMSA anticipates that the ASAP Project will propose alternative design methods, most notably the use of a Reliability Based Design approach addressed in Supplement to ASME B31.8R-2008. The use of Reliability Based Design is not recognized under current Regulations. In addition, PHMSA anticipates ASAP Project may apply for special permits to waive other regulations including, but not limited to, requirements regarding post construction pressure tests, depth of cover, and valve spacing.

Use of design, material, construction, operational and integrity management approaches not recognized under current Regulations will have potential effects on many functional areas, including specified design attributes, fabrication, construction, operation, monitoring, and integrity management. This information request outlines our preliminary information needs in each functional area. Within each functional area, the criteria being assessed are identified together with the underlying technical requirement (code, standard, rule, etc.). The required information associated with the criteria statement is then identified. There is also a general set of
required information that enables definition of the scope of anticipated special permit (waiver) requests. This information request is not comprehensive. As design and operating intent matures, it is expected that additional information will be identified in these functional areas:

- General Requirements (Section 2)
- Design Requirements (Section 3)
- Material and Fabrication Requirements (Section 4)
- Construction Requirements (Section 5)
- Corrosion Control Requirements (Section 6)
- Testing Requirements (Section 7)
- Operation and Maintenance (O&M) Requirements (Section 8)
- Integrity Management Requirements (Section 9)
2.0 General Requirements

2.1 Applications for Special Permits (Waivers)

2.1.1 Criterion: In order to understand the impact of anticipated special permits, PHMSA must be provided with sufficient information early in the design phase of the pipeline.


(a) Required Information: A summary of codes, consensus industry standards and special assurance practices (design, operational, maintenance, and integrity management) that ASAP Project will apply to the full life cycle of the Project.

(b) Required Information: An overview summary of the extent to which the design will comply with, go beyond, and/or deviate from, existing regulatory requirements.

(c) Required Information: A listing of all regulations (including consensus industry standards and other material incorporated into the regulations by reference [Re: 49 CFR § 192.7]), by specific section, that will be the subject of a special permit request. For any regulation/requirement not listed, it will be assumed that the ASAP Project intends full compliance in accordance with the pipeline safety regulations contained in 49 CFR Part 192. The nature of the deviation from the requirement must be identified. If you do not submit any applications for a special permit when replying to this request, please note when you will submit special permit requests. For each regulation for which a special permit (waiver) will be sought, the applicable pipeline segments to which these special permits apply must be identified. If the deviation applies to the entire pipeline, identify as “all segments.”

(d) Required Information: It is anticipated that one condition of any special permit would be full-time oversight by federal PHMSA inspectors, both in the ASAP Project’s headquarters design and operations offices and at construction camps. This oversight will require suitable office space and/or accommodations both at headquarters offices and at all construction camps, and unfettered access by federal inspectors to documents, records, and activities subject to federal oversight. The ASAP Project should commit to satisfy these conditions.

(e) Required Information: Identify the pipeline stationing and mile posts for the location or locations of the applicable special permit segment(s).
2.2 Quality Management System

2.2.1 Criterion: The unique challenges associated with the ASAP Project’s proposed project, including the anticipated need for special permits from established pipeline safety regulations, places a greater burden on the ASAP Project’s quality and management systems to assure pipeline integrity, safety, and environmental protection for the life of the pipeline. A robust quality management system is essential to meet these objectives and to provide PHMSA with the confidence in the pipeline design, operational, maintenance, and integrity management plans to approve anticipated special permits.

Basis: 49 CFR § 192.13

(a) Required Information: Provide the prospective Quality Management System plan/program. Please indicate whether you will conform to, and implement, API Specification Q1. Please describe and justify any exceptions taken to API Specification Q1.

2.3 Construction Quality Assurance and Quality Control

2.2.1 Criterion: The unique challenges associated with the ASAP Project’s proposed project, including the anticipated need for special permits from established pipeline safety regulations, places a greater burden on the ASAP Project’s quality of construction to assure pipeline integrity, safety, and environmental protection for the life of the pipeline. A robust construction quality assurance and quality control process is essential to meet these objectives.

Basis: 49 CFR § 192.13

(a) Required Information: Provide the ASAP Project’s construction quality assurance and quality control plans and procedures. Please identify and indicate your commitment to conform to, and implement, applicable construction quality standards.
3.0 **Design Requirements**

3.1 **Reliability Based Design**

3.1.1 **Criterion:** It is implicit in 49 CFR 192 that operators are to apply stress-based design practices for pipeline design. Since many specific regulations assume this approach and are predicated on a stress-based design, the application of other design practices requires a special permit. Use of a Reliability Based Design and Assessment (RBDA) approach requires review of extensive information in order to reach the conclusion that pipeline safety is not compromised.

**Basis:** 49 CFR Part 192, Subpart C.

(a) **Required Information:** Provide pipeline design criteria and identify associated limit states associated with each criterion for applicability to the reliability based model.

(b) **Required Information:** Identify all target reliability values associated with pipeline and component design and provide the basis for their determination, including specific identification of any assumptions used and the basis for validity of each assumption. Also identify where target values have been increased to improve the margin of safety.

(c) **Required Information:** Provide the model used to determine the reliability of the pipeline, including the value of the applicable limit states and the associated limit state functions. Include the basis for any non-conservative inputs, such as wall thickness, when compared to similar values that would be derived from a design determined using methods that comply with 49 CFR 192 requirements. Include the basis for any segmentation of the pipeline for purposes of establishing the reliability target.

(d) **Required Information:** Identify any time-dependent inputs that could affect model results, such as population density determinations. For such time-dependent inputs, provide programs or procedures that will evaluate these inputs and their impact on the model.

(e) **Required Information:** Provide the basis for the use of empirical or test data when developing the reliability model, including documented evidence that the data used is representative for its intended purpose. Justify applicability of the data.
used to new pipeline construction and operation in the service conditions expected.

(f) Required Information: Provide the basis for key assumptions and any simplifications in the model.

(g) Required Information: Provide a listing of the hazards considered by the model, including natural phenomena hazards (e.g., seismic, slope instability, freeze-thaw effects), and the basis for their contribution to the probability of pipeline failure.

(h) Required Information: Provide the basis for uncertainty that exists with the model and identify safety margins applicable to the pipeline.

(i) Required Information: If any risks, such as environmental risks, are not considered by the model, give the basis for elimination of such risks.

3.2 Strain Based Design

3.2.1 Criterion: It is implicit in 49 CFR Part 192 that operators are to apply stress-based design practices for pipeline design. Since many specific regulations assume this approach and are predicated on a stress-based design, the application of other design practices requires a special permit. Use of a Strain Based Design approach requires review of extensive information in order to reach the conclusion that pipeline safety is not compromised.

Basis: 49 CFR Part 192, Subpart C.

(a) Required Information: Identify applicable threats and limit states for which strain based design techniques will be used for each pipeline segment.

(b) Required Information: Because a comprehensive consensus industry standard has not yet been developed for strain based design, it is incumbent upon the ASAP Project to establish, document, and justify the design process/procedure, design criteria, and safety margins. The ASAP Project must submit its formal design process description and design criteria. This material must include the basis for all design criteria, how the criteria were established, data used to determine acceptability of design criteria, justification for design/safety factors incorporated into the design criteria, and means incorporated in the design or operation to verify the consistency of operational conditions with design basis assumptions. This applies to line pipe (including special...
pieces/joints such as induction bends) and pipeline components (such as compressor stations, valves, pressure vessels, etc.)

(c) Required Information: Identify the design basis natural phenomena and/or outside force events/hazards applicable to each pipeline segment, the associated magnitude of these events/hazards, and the bases for any assumed values. This includes seismic events (earthquake zones and fault zones), frost heave, freeze/thaw cycles, landslides, soil creep, soil collapse, severe weather events, volcanic loadings and any other credible outside force scenario. The ASAP Project should submit the design criteria, including design margin/safety factors, to address each event/hazard.

3.3 Additional Design Requirements for Alternative MAOP

3.3.1 Criterion: It is our understanding that the ASAP Project’s strain based design approach and methodology for post-construction verification of pipeline integrity will likely apply for a special permit from MAOP and/or class location requirements of Subparts J and/or L. Even if a special permit is not requested, the ASAP Project may desire to operate at the alternative MAOP allowed in Part 192. In either case, the additional design requirements of 49 CFR §§ 192.112 and 192.620 apply.

Basis: 49 CFR §§ 192.112 and 192.620

(a) Required Information: Provide information that demonstrates compliance with 49 CFR §§ 192.112 and 192.620 for applicable pipeline segments.

(b) Required Information: Provide a detailed pipe fracture control plan that demonstrates compliance with 49 CFR § 192.112(b).

3.4 Depth of Cover

3.4.1 Criterion: Known deviations from depth of cover requirements must be documented and reviewed for acceptability. In these cases, the ASAP Project must apply for a special permit.

Basis: 49 CFR § 192.137(c)

(a) Required Information: Provide a description of the locations where the pipeline will be exposed and buried. Where buried, identify the depth of cover. Identify any design features which provide additional protection to the pipeline due to deviations from required depth of cover. Identify the segments and
locations by milepost to which these additional protective features will be provided.

### 3.5 Valve Spacing

#### 3.5.1 Criterion: Regulations require minimum block valve spacing based on the class location in which the segment is located.

- **Basis:** 49 CFR § 192.179

- **(a) Required Information:** The ASAP Project should identify the criteria and technical basis for establishing block valve spacing and location.

### 3.6 Pipeline Components

#### 3.6.1 Criterion: The unique challenges of the ASAP project could also have significant affect on the design of compressor stations and other components of the pipeline system, besides line pipe.

- **Basis:** 49 CFR Part 192, Subpart D

- **(a) Required Information:** The ASAP Project should identify the criteria, specifications, and technical basis for designing pipeline components other than line pipe, including as a minimum all items listed in Subpart D.
4.0 **Material and Fabrication Requirements**

4.1 **Steel Pipe Manufacturing Specification and Quality**

4.1.1 **Criterion:** The proposed pipeline will operate at pressures well above those typical for US pipeline operation and therefore require very heavy wall pipe. In addition, there have been recent examples of sub-standard steel being installed in new pipelines in the lower 48 states. The steel and pipe must meet all technical and quality standards. In addition, the ASAP Project has indicated its intent to request a special permit from post-construction pressure testing. As a result, additional activities or requirements to assure pipe quality are imperative.


(a) **Required Information:** Provide all specifications that will be used to manufacture the steel and pipe.

(b) **Required Information:** Identify all consensus industry standards which will be used for manufacturing, and testing the properties of, the steel and pipe.

(c) **Required Information:** Provide a description of the ASAP Project’s quality oversight process with respect to the manufacture of steel and pipe. This should include the process used to qualify the selected steel mill(s) and pipe manufacturing facilities and the process by which the ASAP Project will provide quality oversight of steel and pipe manufacturing process.

(d) **Required Information:** Provide a description of testing that will be performed to verify the quality and material properties of the pipe. This should include a listing of all material properties to be tested and acceptance criteria for all properties. A special permit will be requested for post-construction pressure testing, PHMSA would expect that 100% of pipe joints be tested to verify material properties. If a sampling approach is used to verify pipe material properties, the ASAP Project must submit an engineering and technical justification for assuring that all pipe joints meet material specifications. Because of recent problems at other construction projects with pipe steel not meeting specified minimum yield strength (SMYS) specifications, the ASAP Project should explicitly address its processes and procedures for
assuring that all pipe joints meet minimum material property specifications.

(e) Required Information: Provide a process description for analyzing and dispositioning material properties and flaws. If applicable, provide the basis for determining the use of Engineering Critical Assessment methodology to address the acceptability of material flaws.
5.0 **Construction Requirements**

5.1 **Qualification of Welding Procedures**

5.1.1 **Criterion:** Existing PHMSA regulations specify minimum requirements for welding of pipe. Welding of pipe in arctic environment presents challenges.

**Basis:** 49 CFR Part 192, Subpart E

(a) **Required Information:** Provide any special processes, procedures, or additional requirements used to qualify the weld procedure in accordance with API 1104. In particular, if strain based design is used, the destructive testing used to qualify the weld procedure should be both a hoop stress overstress test and a bending/mechanical deformation overstrain test. Include a description of all special processes (e.g., backwelding).

(b) **Required Information:** If API 1104, Appendix A will be used for welding and weld non-destructive testing, the ASAP Project must outline guidance documents for the testing of weld and non-destructive testing (NDT) procedures for various pipe steel suppliers and pipe manufacturers. The guidance must document how pipeline welders and NDT technicians will be qualified. The guidance document must outline how Appendix A will be developed into construction procedures that give guidance to Construction Personnel and Quality Assurance Personnel to properly handle pipe lifting and lower-in operations with out invalidating API 1104, Appendix A.

(c) **Required Information:** Provide a description of how the weld procedures account for very heavy wall pipe, the extreme arctic environment, and any other unique condition not typically encountered in pipeline construction in the lower 48 states. Factors such as pre-weld heat treatment, post-weld heat treatment, maintenance of heat on weld, and maximum time allowed between passes should be explicitly addressed. Demonstrate how the shop qualified weld procedure or procedure qualified in a controlled environment is appropriate for the field environment.

(d) **Required Information:** Provide a description of how the weld procedures account for the potential difficulties encountered with weld site preparation and pipe fit-up for any field-cut factory bends and pipe wall thickness variances. This information should include, but not be limited to, fit-up tolerance for alignment of pipe ends, joint design, accounting for wall thickness variance,
(e) Required Information: Provide a description of how the weld procedures will be qualified and field implemented for conducting backwelding and repair welding to meet API 1104.

5.2 Qualification of Welders

5.2.1 Criterion: Existing PHMSA regulations specify minimum requirements for welder qualification. Welding of pipe in arctic environment presents challenges.

Basis: 49 CFR Part 192, Subpart E

(a) Required Information: Provide a description of the process for qualifying individuals to weld on the pipeline. Explicitly describe any special features of the welder qualification process that address very heavy wall pipe, the extreme arctic environment, and any other unique condition not typically encountered in typical pipeline construction in the lower 48 states.

5.3 Weld Acceptance Testing and Acceptance Criteria

5.3.1 Criterion: Because the ASAP Project has indicated it intends to request a special permit from post-construction pressure testing, weld acceptance testing and acceptance criteria are critical.

Basis: 49 CFR Part 192, Subpart E

(a) Required Information: Provide the specific written weld test program and weld acceptance criteria. Because the ASAP Project has indicated it intends to request a special permit from post-construction pressure testing, PHMSA would expect that 100% of welds would be nondestructively tested. The ASAP Project should describe and justify its weld acceptance criteria, using API 1104 as the basis; in particular, the ASAP Project should describe and justify if it intends to incorporate alternative acceptance criteria from Appendix A of API 1104 and use of any other proposed standards. The ASAP Project should describe the pipe conditions where backwelding will be used including for fittings, heavy wall pipe and transitions.

5.4 General Construction in Arctic Conditions

5.4.1 Criterion: Each transmission line or main must be constructed in accordance with comprehensive written specifications or standards that are consistent with Part 192. If the ASAP Project intends to request a special permit from post-construction pressure testing, additional measures are needed to
assure that the pipeline does not sustain integrity-threatening damage during construction. In addition, extreme arctic conditions pose unique challenges to pipeline construction.

Basis: 49 CFR Part 192, Subpart G

(a) Required Information: The ASAP Project should submit its plans and processes for quality oversight of construction activities, including QC inspection of all construction activities.

(b) Required Information: The ASAP Project should submit its plan regarding how it will address the unique challenges of the arctic environment during pipeline construction (e.g., discontinuous permafrost, stability of disturbed permafrost, pinch points). The ASAP Project should address if and how it will apply API RP 2N to its pipeline construction activities.

(c) Required Information: The ASAP Project should submit its plan to assure pipe coating durability and integrity during pipe lowering, backfilling, and horizontal directional drills. The plan should describe all pipeline installation activities including procedures for handling pipe, lowering pipe into the ditch, type of backfill material to be used, and backfill procedures.

(d) Required Information: PHMSA expects that all construction personnel would be covered under the ASAP Project’s Construction OQ program for the Alternative MAOP Rule, since mistakes during construction could lead to threats to pipeline integrity. The ASAP Project should describe all construction and verification related tasks to be included in its Construction OQ program. Helpful information for compliance with the Alternative MAOP Rule can be found at: http://primis.phmsa.dot.gov/maop/index.htm.

(e) Required Information: The ASAP Project should submit its plan regarding how it will address the unique challenges of the arctic environment during the time period between completion of construction for each segment and operational startup. PHMSA would expect the pipeline to be maintained and monitored sufficiently to prevent damage from outside forces, corrosion, etc. prior to being placed into service. The ASAP Project should address how it will monitor the pipeline for potential damage (including strain conditions) that could occur to the pipeline segments during long periods of disuse prior to placing the pipeline system into service.
5.4.2 Criterion: Regulations require that pipeline and components must have sufficient supports to preclude undue strain, including but not limited to, that caused by temperature-induced contraction/expansion or by high internal pressures.

Basis: 49 CFR § 192.161

(a) Required Information: Provide design and construction requirements for support structures.

5.5 Recent Construction Issues

5.5.1 Criterion: PHMSA has identified problems at recent construction projects in the lower 48 states that could present special challenges during construction in an arctic environment. PHMSA expects the ASAP Project to proactively develop its construction processes and procedures to avoid these problems.

Basis: 49 CFR Part 192, Subpart E

(a) Required Information: Provide a description of plans, processes and procedures to address/prevent the following problems: field cuts of factory or induction bends (sized for segmenting), poor weld fit-up, poor quality welding, poor backfill material, damaged or improperly installed coating, damaged pipe from improper bending in the field, hydrogen assisted cracking, damage or over-strain during lowering in ditch and backfill, and poor quality NDT.

5.6 Additional Construction Requirements for Alternative MAOP

5.6.1 Criterion: It is our understanding that the ASAP Project’s strain based design approach and methodology for post-construction verification of pipeline integrity will necessitate the need to apply for a special permit from MAOP and/or class location requirements of Subparts J and/or L. Even if a special permit is not requested, the ASAP Project may desire to operate at the alternative MAOP allowed in Part 192. In either case, additional construction requirements of 49 CFR §§ 192.384 and 192.620 apply.

Basis: 49 CFR §§ 192.384 and 192.620

(a) Required Information: Provide information that demonstrates compliance with 49 CFR §§ 192.384 and 192.620 for applicable pipeline segments.
6.0 Corrosion Control Requirements

6.1 External Corrosion Control

6.1.1 Criterion: An effective corrosion control program is essential to long term pipeline integrity.

Basis: 49 CFR Part 192, Subpart I

(a) Required Information: Submit plans for managing external corrosion, including coating system, cathodic protection (CP), surveillance, monitoring, and periodic assessment (i.e., ILI assessment). The plans should provide comprehensive details of the CP system design, installation, operation, maintenance, and performance (including minimum performance specifications). PHMSA expects plans to include interference surveys to identify and mitigate all sources of interference (e.g., telluric currents, nearby pipelines, high voltage electric transmission lines, third party structures, etc.) and how they impact CP of the pipeline.

(b) Required Information: Submit plans for managing internal corrosion, including moisture control, inhibitors, coupons, monitoring, and periodic assessment (i.e., ILI assessment).

(c) Required Information: Submit plans for managing atmospheric corrosion on non-buried pipe, including monitoring and periodic assessment (i.e., ILI assessment).

6.2 Internal Corrosion Control

6.2.1 Criterion: An effective corrosion control program is essential to long term pipeline integrity.

Basis: 49 CFR Part 192, Subpart I

(a) Required Information: Describe your program to monitor for and mitigate the presence of, deleterious gas stream constituents, including, as applicable:

i. Provisions for use of filter separators or separators and gas quality monitoring equipment,

ii. Use of gas quality monitoring equipment including moisture analysis, chromatograph, and periodic hydrogen sulfide sampling

iii. Use of cleaning pigs and inhibitors, and sample accumulated liquids

iv. Use of corrosion coupons for internal corrosion monitoring
(b) Required Information: Describe your program to address deleterious gas stream constituents including the following as applicable:
   i. Provisions to limit carbon dioxide and limits
   ii. Provisions to restrict the presence of free water and limits
   iii. Provisions to limit hydrogen sulfide and limits

(c) Required Information: Describe your program for review of the effectiveness of your mitigation and monitoring efforts, including anticipated frequency of formal review
7.0 **Testing Requirements**

7.1 **Post Construction Pressure Test**

**Criterion:** Each pipeline must be pressure tested to substantiate material strength, proposed MAOP, and that it is leak-tight. It is our understanding that the ASAP Project intends to request a special permit from this requirement. This is a critical aspect of pipeline regulations that verifies pipeline integrity prior to being placed into service. Other provisions of the pipeline safety regulations are predicated upon a successful demonstration of pipeline strength by pressure test. Any special permit from conducting a pressure test that fully complies with 49 CFR Part 192, Subpart J would require a substantial justification, including mitigation measures to assure an equal or greater level of pipeline safety.

**Basis:** 49 CFR Part 192, Subpart J

(a) **Required Information:** The ASAP Project should describe its proposed alternative methods to verify the strength and leak-tightness of the pipeline prior to being placed into service. As part of this information, the ASAP Project should describe additional compensatory measures related to pipeline design, construction, inspection, and testing of materials, operational measures and components to assure pipeline integrity. A comprehensive quality assurance and verification program description will ultimately be required of the ASAP Project.

(b) **Required Information:** If the ASAP Project chooses to conduct a pressure test in conformance with Subpart J, describe the test plans and procedures to be used. The procedures should address the specific challenges associated with conducting the pressure test in arctic conditions.
8.0 **Operation and Maintenance (O&M) Requirements**

8.1 **MAOP**

8.1.1 **Criterion:** Existing regulations require that MAOP be established based on test pressure and assuring that the hoop stress does not exceed SMYS (with safety margin) for the class location in which the pipeline segment is located. If the ASAP Project applies for a special permit from the regulations pertaining to the MAOP, and/or class location, PHMSA would expect the applicable provisions of 49 CFR § 192.620 to apply. Even if a special permit is not requested, the ASAP Project may desire to operate the pipeline in accordance with the alternative MAOP allowed by Part 192. In either case, the ASAP Project should describe its program for complying with 49 CFR § 192.620.

**Basis:** 49 CFR Part 192, Subparts J and L; 49 CFR § 192.620

(a) **Required Information:** Describe and justify your alternative process for establishing the MAOP of the pipeline, if applicable.

(b) **Required Information:** Describe and justify your program for complying with the O&M requirements contained in 49 CFR § 192.620(d) for operating at alternative MAOP, if applicable.

8.2 **Strain Monitoring**

8.2.1 **Criterion:** With a traditional stress based design, assuring that the pipe hoop stress is not exceeded is a relatively simple matter of enforcing the MAOP. With a strain based design, long term assurance that design basis strain loading conditions are not exceeded requires the effective use of strain gauges and an effective monitoring program. PHMSA would expect that the ASAP Project’s additional preventive measures would include a formal program for monitoring strain and ROW conditions. PHMSA would expect additional monitoring in earthquake zones and fault zones, hill/mountain side cut areas, discontinuous permafrost and permafrost areas including freeze/thaw areas. Because of the anticipated special permit to use strain based design, and the proximate threat of outside forces, PHMSA expects the ASAP Project to implement a robust strain monitoring program.

**Basis:** 49 CFR Part 192, Subpart L
(a) Required Information: Describe and justify the systems, tools, and plans for continually monitoring and analyzing localized strain on the pipeline, along with procedures for implementing preventive and mitigative measures to proactively address conditions that could cause design basis strain limits to be exceeded. PHMSA would expect such a program to include periodic ILI assessment with tools capable of identifying pipe deformation and other anomalies indicative of pipe movement, deformation, or other strain conditions.

8.3 Reliability Based Assessment

8.3.1 Criterion: It is implicit in 49 CFR Part 192 that operators are to apply stress-based design practices for pipeline design. Since many specific regulations assume this approach and are predicated on a stress-based design, the application of other design practices requires a special permit. Use of a Reliability Based Design and Assessment (RBDA) approach requires review of extensive information in order to reach the conclusion that pipeline safety is not compromised. A key aspect of RBDA is the periodic assessment of pipeline condition and integrity to assure that limit states are not exceeded during the life of the pipeline.

Basis: 49 CFR Part 192, Subparts C, J, L, and O.

(a) Required Information: Provide a description of the program for monitoring pipeline integrity and the material condition of the pipeline, including assessment methodology, acceptance criteria for anomalies/defects, and frequency of assessment. PHMSA would expect such a program to include an ILI assessment program and a comprehensive strain monitoring program.

(b) Required Information: Provide a description of the operational approach that will be used as the dense gas phase transitions between gaseous, liquid and supercritical fluid. PHMSA would expect the approach to include normal and abnormal operations and associated monitoring and mitigation.
9.0 **Integrity Management Requirements**

9.1 **Failure Impact Zone**

9.1.1 **Criterion:** Covered pipeline segments must comply with the integrity management requirements of 49 CFR Part 192, Subpart O. In addition, ASME B31.8S provides guidance for managing pipeline integrity. An important aspect of managing pipeline integrity is understanding the consequences of an explosion and/or fire that could occur following a failure. It is our understanding that the ASAP Project intends to request a special permit from key requirements such as design and pressure testing. As part of granting such a special permit, PHMSA would expect the ASAP Project to develop rigorous and robust failure impact zone analysis for the entire pipeline.

**Basis:**

49 CFR Part 192, Subpart O and ASME B31.8S

**(a) Required Information:** Identify the covered pipeline segments as defined by Subpart O. Identify how the covered segments are identified, including how the potential impact radius (PIR) is determined. This should include justification for derivation of the PIR formula in accordance with ASME B31.8S for the unique operating parameters contemplated, including very large pipe diameter, very high operating pressure, and very rich gas.

**(b) Required Information:** The ASAP Project should identify and justify how it will use the methodology in ASME B31.8S (or other methodology) to identify the leak or failure impact zone of an explosion and/or fire resulting from a leak or failure of the pipeline. The ASAP Project should also analyze and provide a report on the potential consequences arising from injury to any persons in proximity to the pipeline, population density, proximity of population with limited or impaired mobility, damage to property in proximity to the pipeline, damage to the environment, potential for secondary failures, and the impact on public convenience and necessity. The report should include a justification for the threshold heat flux and shock wave used to evaluate each type of damage receptor and consider fire duration. Note that consequences may vary based on the richness of the gas transported and as a result of how the gas decompresses. The richer the gas, the more important defects and material properties are in modeling the characteristics of the failure. Because of the unique circumstances in Alaska, it is important to assure that the impact of an explosion or fire on nearby critical infrastructure is minimized. This includes, but is not limited to, the Trans Alaska Pipeline System (TAPS), bridges, electric power transmission lines, etc. In additional, the ASAP Project should
analyze the effects of un-ignited gas releases and impacts resulting from interruption of service.

9.2 Periodic Integrity Assessments

9.2.1 Criterion: The integrity management rule requires that pipeline integrity be assessed at least every 7 years. It is our understanding that the ASAP Project intends to request a special permit from key requirements such as design and pressure testing. As part of granting such a special permit, PHMSA would expect the ASAP Project to conduct integrity assessments for the entire pipeline more frequently than the minimum required in Subpart O.

Basis: 49 CFR Part 192, Subpart O and ASME B31.8S

(a) Required Information: Describe the planned integrity assessment methods, frequency, and how they address all threats applicable to the entire pipeline.

9.3 Preventive and Mitigative Measures

9.3.1 Criterion: The integrity management rule requires that pipelines in high consequence areas have additional preventive and mitigative measures, beyond those otherwise required by 49 CFR Part 192. It is our understanding that the ASAP Project intends to request a special permit from key requirements such as design and pressure testing. PHMSA would expect the ASAP Project to develop rigorous and robust preventive and mitigative measures for the entire pipeline to assure long term pipeline integrity.

Basis: 49 CFR Part 192, Subpart O and ASME B31.8S

(a) Required Information: Describe the planned preventive and mitigative measures, and how they address all threats applicable to the pipeline.

(b) Required Information: Correlate preventive and mitigative measures to the proposed application of RBDA and its associated catalog of design limits. The information must demonstrate how the ASAP Project, using RBDA, confirms consistency with the integrity management requirements.

9.4 Risk Analysis

9.4.1 Criterion: The integrity management rule requires operators to conduct a risk analysis for pipeline segments in high consequence areas and use the risk analysis results to schedule and prioritize integrity assessments, identify threats, and determine preventive and mitigative measures to manage
those threats. It is our understanding that the ASAP Project intends to request a special permit from key requirements such as design and pressure testing. As part of granting such a special permit, PHMSA would expect the ASAP Project to develop and implement a rigorous and robust risk analysis methodology for the entire pipeline to assure long term pipeline integrity.

**Basis:**
49 CFR Part 192, Subpart O and ASME B31.8S

(a) **Required Information:**
Describe the planned risk analysis methodology, and how it will be used to manage all threats applicable to the entire pipeline and assure pipeline integrity.

(b) **Required Information:**
The ASAP Project should describe the methodology for using risk analysis results to identify the risk drivers for each pipeline segment and how those risk drivers will be used to determine the most effective integrity assessment and/or mitigation option. In doing so, the ASAP Project should analyze the unique circumstances associated with each special permit request as well as the failure impact zone to identify how to manage the threats and prevent or mitigate the consequences of a leak or failure, when the special permit conditions are in place, using the most effective engineering, integrity assessment and operational measures for risk mitigation.

(c) **Required Information:**
The ASAP Project should describe how it will validate its risk analysis methodology to assure that the methods used have produced results that are usable and consistent with the operator’s and industry’s experience. The ASAP Project should describe how it will analyze and monitor operational, maintenance or other activities to identify areas that are inaccurately represented by the risk analysis process, and use that information to modify and continually improve its risk analysis process.
Enclosure B

Guidance for Special Permit Applicants on Providing Environmental Information

The processing of an Alaska gas pipeline special permit (SP) application will involve an environmental analysis in accordance with the National Environmental Policy Act of 1969 (NEPA), the President’s Council on Environmental Quality regulations implementing NEPA (40 CFR 1500-1508), and Department of Transportation (DOT) policy. To the extent PHMSA’s grant or denial of your special permit request may constitute a Federal action under NEPA, in addition to analyzing any potential risks to public safety, PHMSA also analyzes any potential risks to the environment that could result from such grant or denial. PHMSA will evaluate whether the special permit would significantly impact the likelihood of a pipeline spill or failure as compared to the environmental status quo in the absence of the special permit.

PHMSA requests that the applicant submit its special permit applications and environmental information as soon as possible. If PHMSA does not receive special permit applications and all necessary supporting information well in advance the ASAP Project decision making on design, construction and other issues, the project may be delayed.

To facilitate PHMSA’s environmental analysis, the special permit applicant needs to provide certain environmental information. The purpose of this form is to provide guidance to the applicant on what information should be provided. Any information submitted by the applicant is subject to being made public.

I. Purpose and Need

[Describe pipeline and specify county and state where the affected segments located]

[Cite regulation(s) for which special permit (waiver) is sought. Paste relevant portion of regulation(s) here.]

[State the unique circumstances and reasons for your special permit request. Explain how the special permit will benefit you and the public.]

II. Site Description and Affected Environment

Describe the right-of-way and the type of environment in the vicinity of the affected pipeline segments including:

[Provide map if available]

[Describe extent to which landowners, businesses, and residential areas are in the vicinity including parks]
[Describe surface waters in the vicinity including wetlands]

[Describe drinking water aquifers in the vicinity]

[Describe soils and vegetation in the vicinity]

[Describe wildlife habitats including fisheries in the vicinity]

[Describe any geologic hazards]

[Describe any cultural resources that may be affected if a special permit were granted]

[Describe any socioeconomic impacts or special impacts on Native Americans, if any, if a special permit were granted]

[Describe the existing infrastructure that is within the Potential Impact Radius of the pipeline]

III. Mitigation Measures

[Describe the alternative mitigation measures you are offering to implement in lieu of compliance with the regulations for which you are seeking a special permit.]

IV. Analysis and Investigation of Alternatives

[Explain the basis for the particular set of alternative mitigation measures listed in section III above. Explain whether the measures will ensure that a level of safety and environmental protection equivalent to compliance with existing regulations is maintained.]

[Discuss how the special permit would affect the risk or consequences of rupture or failure (positive, negative, or none)]

[Discuss any effects on pipeline longevity and reliability such as life-cycle and periodic maintenance. Discuss any technical innovations as well]

[Discuss how the special permit would impact human safety]

[Discuss whether the special permit would affect land use planning]

[Discuss any pipeline facility, public infrastructure, and environmental impacts associated with implementing the special permit. In particular, discuss how any environmentally sensitive areas could be impacted]

[Evaluate alternatives to the special permit and any beneficial or adverse consequences of such alternatives.]
NOTE: The ASAP Project should include the pipeline stationing and mile posts (MP) for the location or locations of the applicable special permit segment(s).
April 12, 2010

Mr. Jeffrey D. Wiese
Associate Administrator for Pipeline Safety
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

Dear Mr. Wiese,

The Office of the Governor is in receipt of March 3, 2010 request for information about the nature of the proposed Alaska In-State Gas Pipeline Project and plans for the project to submit waivers for compliance with Federal Pipeline Safety Regulations under the federal standards you identified.

Our Office has reviewed Enclosure A included in your letter that requests information concerning special permits. I am enclosing a table with this letter which responds to each criterion you identified. Please note a number of concerns raised in Enclosure A are related to procedures that have been identified, or are under consideration by other proposed arctic natural gas pipeline proponents. The Alaska In-State Gas Pipeline Project (identified in your letter as the Alaska Stand Alone Pipeline) is attempting to maintain a tight timeline in order to provide for the near term energy needs of residents and commercial interests within the state of Alaska. Our team has made specific efforts throughout our planning and initial engineering design to highlight issues that might cause delay, and has worked hard to avoid the need for any request for submission of special permit applications for the project pursuant to 49 C.F.R. Section 190.341. We believe there are no special permit applications required at this time, but will remain diligent in our review of such need.

For example, we are not requesting waivers for the Alaska In-State Gas Pipeline Project (identified in Enclosure A of your March 3, 2010 letter) for the following key permits:

- application of reliability based design and assessment;
- deviation from depth of cover and valve spacing requirements;
- relief from post-construction hydrotest requirements;
- alternative MAOP requirements; or
- deviation from class location requirements.

Enclosure B to your letter contains “Guidance for Special Permit Applicants on Providing Environmental Information.” An Environmental Impact Statement (EIS) in accordance with the National Environmental Policy Act (NEPA) is currently underway with the U.S. Army Corps of Engineers (USACE) as the lead federal agency with several other federal agencies acting as cooperating agencies. The EIS will assess potential risks to the public and the environment that could result from approval of the Alaska In-State Gas Pipeline Project. In the event that the Alaska In-State Gas Pipeline Project needs to deviate from one or more regulations, a special permit waiver
would be filed with Pipeline and Hazardous Materials Safety Administration (PHMSA). Alaska In-State Gas Pipeline Project would coordinate with PHMSA, the USACE, and the cooperating agencies to evaluate the potential environmental effects of any special permit waiver and analyze this request in accordance with NEPA.

The Alaska In-State Gas Pipeline Project team will also stay informed on the progress of other pipeline projects in the state, and will stand ready to adopt any new policies for arctic conditions as they are developed and PHMSA deems them appropriate for our project.

We would appreciate it if you would continue to include us in any deliberations as these matters progress.

Sincerely,

Robert Swenson
Project Manager
Alaska In-State Pipeline

Enclosure

cc: The Honorable Gene Therriault, Office of the Governor
    Serena Sweet, U.S. Army Corps of Engineers
    Ron Denton, Bureau of Land Management
    Mike Thompson, Joint Pipeline Office
    Harold Heinze, Alaska Natural Gas Development Authority
### In-State Gas Pipeline Project [Alaska Stand Alone Pipeline (ASAP)]

**PHMSA March 3, 2010 Information Request - Response Outline**

<table>
<thead>
<tr>
<th>Issue</th>
<th>Criterion Summary</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1</td>
<td>Provide PHMSA with sufficient information early in design process</td>
<td>The detailed design phase of the Alaska Stand Alone Pipeline (ASAP) project is scheduled to start in 2011.</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Quality Management System</td>
<td>A Quality Management System for the ASAP project would be implemented during detailed design.</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Construction Quality Assurance</td>
<td>A construction QA/QC plan would be developed for construction, in conjunction with the selected construction contractors.</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Reliability Based Design and Assessment</td>
<td>A Reliability Based Design and Assessment (RBDA) approach is not proposed for use by the project.</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Strain Based Design</td>
<td>Strain based design for integrity assurance for arctic geohazard potential loadings would be developed, as required, in accord with American Society of Mechanical Engineers (ASME) B31.8, Para833.5: “Design for Stresses Greater than Yield”.</td>
</tr>
</tbody>
</table>
| 3.3.1 | Additional Design Requirements for Alternative Maximum Allowable Operating Pressure (MAOP) | No special permit for the following are being sought:  
- class location requirements, or  
- alternative MAOP |
<p>| 3.4.1 | Depth of Cover | No special permits are being sought for deviations from depth of cover. |
| 3.5.1 | Valve Spacing | No special permits are being sought for deviations from minimum block valve spacing. |
| 3.6.1 | Pipeline Components | No special permits are being sought for pipeline components. |
| 4.1.1 | Steel Pipe Manufacturing Specification and Quality | The specifications for the proposed X70 line-pipe will be ensured to meet all regulatory requirements and PHMSA guidelines. However, detailed pipe specifications and vendor qualifications pipe are not expected to be addressed until the detailed design phase. |
| 5.1.1 | Qualification of Welding Procedures | Welding requirements would be developed during detailed design. |
| 5.2.1 | Qualification of Welders | Welder qualification requirements would be specified in the construction bid. |
| 5.3.1 | Weld Acceptance Testing and Acceptance Criteria | No special permits are being sought for deviations from post-construction pressure testing. |</p>
<table>
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<tr>
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<tr>
<td>5.4.1</td>
<td>General Construction in Arctic Conditions</td>
<td>No special permits are being sought for deviations from post-construction pressure testing. Special construction practices required for arctic conditions would be addressed in the Construction plan and Quality Assurance &amp; Quality Control (QA/QC) manual.</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Recent Construction Issues</td>
<td>Construction practices required to avoid pipe quality issues, and to remediate all identified defects would be addressed in the Construction plan and QA/QC manual.</td>
</tr>
</tbody>
</table>
| 5.6.1      | Additional Construction Requirements       | No special permits for the following are being sought:  
- class location requirements, or  
- alternative MAOP                                                                                                                                 |
| 6.1.1      | External Corrosion Control                 | External corrosion control would be addressed during detailed design                                                                 |
| 6.2.1      | Internal Corrosion Control                 | Internal corrosion control would be addressed during detailed design                                                                 |
| 7.1        | Post Construction Pressure Test            | No special permits are being sought for deviations from hydrotest requirements.                                                          |
| 8.1.1      | MAOP                                       | No special permits for the following are being sought:  
- class location requirements, or  
- alternative MAOP                                                                                                                                 |
| 8.2.1      | Strain monitoring                          | Operational monitoring techniques would be developed in accord with any strain based design measures                                        |
| 8.3.1      | Reliability Based Assessment               | A Reliability Based Design and Assessment (RBDA) approach is not proposed for use by the project.                                          |
| 9.1.1      | Failure Impact Zone                        | No special permits are being sought for deviations from hydrotest requirements.                                                           |
| 9.2.1      | Periodic Integrity Assessments             | No special permits are being sought for deviations from hydrotest requirements.                                                           |
| 9.3.1      | Preventive and Mitigative Measures         | No special permits are being sought for deviations from hydrotest requirements.                                                           |
| 9.4.1      | Risk Analysis                              | No special permits are being sought for deviations from hydrotest requirements.                                                           |
Mr. Daniel Fauske  
President  
Alaska Gasline Development Corporation  
P.O. Box 101020  
411 West Fourth Ave., Suite 1E  
Anchorage, AK 99501

Re: Supplemental to PHMSA letter dated March 3, 2010;  
State of Alaska letter to PHMSA dated April 12, 2010  
ASAP Plan of Development dated March 2011

Dear Mr. Fauske:

On March 3, 2010, the Pipeline and Hazardous Materials Safety Administration (PHMSA) wrote to Mr. Robert Swenson of the Alaska Gasline Development Corporation (AGDC) requesting information concerning the proposed Alaska Stand Alone Gas Pipeline Project (ASAP Project). PHMSA informed AGDC that to the extent the ASAP Project proposal called for design, materials, construction, or operating specifications that would not meet the current Federal Pipeline Safety Regulations, AGDC may need to submit one or more special permit applications for the project pursuant to 49 C.F.R. § 190.341. A special permit is an order by which PHMSA waives or modifies compliance with one or more of the Federal Pipeline Safety Regulations under the standards set forth in 49 U.S.C. § 60118(c) and 49 C.F.R. § 190.341, subject to conditions and limitations set forth in the order. A special permit may be issued to a pipeline operator (or prospective operator) for specified facilities that, absent waiver, would be subject to the regulation.

AGDC’s April 12, 2010, response to our March 3, 2010 letter stated that “We believe there are no special permit applications required at this time, but will remain diligent in our review of such need.” AGDC has briefed PHMSA technical experts several times on certain aspects of the project, but the level of detail has been insufficient for PHMSA to fully understand AGDC’s plans and approach to some of the technical and regulatory issues described in the letter.

Based on the information on the ASAP Project provided in connection with the limited project briefings, we believe that current regulations may not allow the approach to the ASAP Project that AGDC may be proposing in certain geo-hazard areas. More specifically, one or more special permit applications may be required if the following approaches are being used:
**External loads that exceed design allowable – strain based design**

As prescribed in 49 CFR §§ 192.103, 192.105, 192.111, 192.317, and 192.620, natural gas pipelines must be designed to limit stresses below the specified minimum yield strength (SMYS) by a design factor based on class location. AGDC has indicated that it intends to operate under the standard maximum allowable operating pressure (MAOP) provisions of 49 CFR Part 192 and the alternative MAOP provision in section 192.620 allowing 80% SMYS under certain circumstances will not be used. Most of the pipeline is anticipated to be located in a Class 1 location. Accordingly, for those segments located in a Class 1 location, the stress must be limited to 72% SMYS. Lower allowable stresses would apply to Class 2 and 3 locations. The regulations in 49 CFR §§ 192.103 and 192.105 also require additional wall thickness sufficient to handle concurrent external loads, and require that the pipeline be protected from foreseeable hazards and conditions that may cause the pipeline to sustain abnormal loads.

AGDC has indicated that “Strain based design (SBD) for integrity assurance for arctic geo-hazard potential loadings would be developed, as required, in accordance with American Society of Mechanical Engineers (ASME) B31.8, para833.5: “Design for Stresses Greater than Yield”” (see Enclosure A, State of Alaska letter to PHMSA dated April 12, 2010). PHMSA believes this approach may result in the pipeline being subjected to indefinitely sustained loads in excess of 72% SMYS in areas of frost heave, thaw settlement, slope instability, and other areas of expected significant soil movement. To date, PHMSA is not aware that design and operational methods to predict and monitor strain to assure that external loads that exceed the pipe SMYS and approach ultimate tensile strength are detected and mitigated have been proposed for the ASAP Project.

The current Part 192 code is based on hoop strength and internal pressure. Part 192 has no provisions for the material, design, operations and maintenance, or integrity management aspects of SBD; nor do any sections of API 5L, ASME/ANSI B31.8 or B31.8S that have been incorporated by reference into Part 192. Therefore, a special permit application with detailed technical and engineering analysis of materials, design, and operating parameters and a full description of proposed mitigative measures would be required to allow PHMSA to make a determination as to whether the proposed use of SBD to allow the ASAP pipeline to indefinitely sustain external loads in excess of current design strength requirements is consistent with pipeline safety.

**Fracture Control Plan**

Under 49 CFR § 192.112(b), the ASAP Project is not required to have a fracture control plan if the pipeline will be operated at 72% SMYS operating pressures or less. Should the ASAP Project decide to design, construct, and operate the pipeline in accordance with the alternative MAOP Rule as prescribed in 49 CFR § 192.112, however, the pipeline must be designed for fracture initiation and fracture arrest which will require additional pipe toughness or crack arrestors to limit fracture propagation in failure situations.
Pipeline external coating
As prescribed in 49 CFR §192.455(a), a pipeline must have an external protective coating that meets the requirements of §192.461 and it must have a cathodic protection system designed to protect the pipeline in accordance with Subpart I. It is important to note, however, that use of an external coating with a shielding layer would likely prevent full cathodic protection from reaching the pipe. Therefore, all pipeline external coatings would be required to be compatible with cathodic protection as required in §192.461. If the pipeline is operated at an alternative MAOP, external coatings would also be required to meet § 192.112(f).

To avoid project delays, PHMSA suggests that ASAP submit any special permit applications for the above items or other project items that would not meet Part 192 as soon as possible. PHMSA advises ASAP to submit any special permit applications before making design-related decisions that could be adversely impacted by possible special permit conditions and measures that PHMSA may require in lieu of compliance with existing code provisions.

Additionally, to facilitate our review of your special permit application(s), please provide the information listed in Enclosures A and B of PHMSA’s March 3, 2010 letter with any special permit application. Depending on your response, PHMSA may request additional information, including, but not limited to: data, reports, studies, and independent third party analyses.
PHMSA expects a detailed safety and environmental review of a special permit application to take a minimum of 12 months or more, depending upon the extent and nature of the request, any requirements for additional information or studies, and the quality of submittal documents.

While the Army Corps of Engineers (COE) is currently designated as the lead agency for environmental reviews of the overall project, PHMSA is required to conduct an environmental review of any environmental impacts of its decision to grant or deny a particular special permit. An overview of the preliminary environmental information needed to support your special permit applications and facilitate PHMSA’s environmental review is provided in Enclosure B. Enclosure C details information requested for a special permit for allowable external loads over 72% of Specified Minimum Yield Strength (SMYS) of the pipe – Strain Based Design.

Your timely submission of special permit applications and detailed safety and environmental information will enable PHMSA to properly analyze potential risks to public safety and to the environment that could result from our decision to grant or deny a special permit.

Please contact Dennis Hinnah, Deputy Director of Western Region at (907) 271-4937, or Jeffery Gilliam, Director of Engineering and Research Division, at (202) 366-0568, if you have any questions.

Sincerely,

Jeffrey D. Wiese
Associate Administrator for Pipeline Safety

cc: With Enclosures B and C
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Appendix A PHMSA Correspondence

Enclosure B
Guidance for Special Permit Applicants on Providing Environmental Information

The processing of an Alaska gas pipeline special permit (SP) application will involve an environmental analysis in accordance with the National Environmental Policy Act of 1969 (NEPA), the President’s Council on Environmental Quality regulations implementing NEPA (40 CFR 1500-1508), and Department of Transportation (DOT) policy. To the extent PHMSA’s grant or denial of your special permit request may constitute a Federal action under NEPA, in addition to analyzing any potential risks to public safety, PHMSA also analyzes any potential risks to the environment that could result from such grant or denial. PHMSA will evaluate whether the special permit would significantly impact the likelihood of a pipeline spill or failure as compared to the environmental status quo in the absence of the special permit.

PHMSA requests that the applicant submit its special permit applications and environmental information as soon as possible. If PHMSA does not receive special permit applications and all necessary supporting information well in advance the ASAP Project decision making on design, construction and other issues, the project may be delayed.

To facilitate PHMSA’s environmental analysis, the special permit applicant needs to provide certain environmental information. The purpose of this form is to provide guidance to the applicant on what information should be provided. Any information submitted by the applicant is subject to being made public.

I. Purpose and Need
[Describe pipeline and specify county and state where the affected segments located]
[Cite regulation(s) for which special permit (waiver) is sought. Paste relevant portion of regulation(s) here.]
[State the unique circumstances and reasons for your special permit request. Explain how the special permit will benefit you and the public.]

II. Site Description and Affected Environment
Describe the right-of-way and the type of environment in the vicinity of the affected pipeline segments including:
[Provide map if available]
[Describe extent to which landowners, businesses, and residential areas are in the vicinity including parks]
[Describe surface waters in the vicinity including wetlands]
[Describe drinking water aquifers in the vicinity]
[Describe soils and vegetation in the vicinity]
[Describe wildlife habitats including fisheries in the vicinity]
[Describe any geologic hazards]
[Describe any cultural resources that may be affected if a special permit were granted]
[Describe any socioeconomic impacts or special impacts on Native Americans, if any, if a special permit were granted]
[Describe the existing infrastructure that is within the Potential Impact Radius of the pipeline]

III. Mitigation Measures
[Describe the alternative mitigation measures you are offering to implement in lieu of compliance with the regulations for which you are seeking a special permit.]
IV. **Analysis and Investigation of Alternatives**

[Explain the basis for the particular set of alternative mitigation measures listed in section III above. Explain whether the measures will ensure that a level of safety and environmental protection equivalent to compliance with existing regulations is maintained.]

[Discuss how the special permit would affect the risk or consequences of rupture or failure (positive, negative, or none)]

[Discuss any effects on pipeline longevity and reliability such as life-cycle and periodic maintenance. Discuss any technical innovations as well]

[Discuss how the special permit would impact human safety]

[Discuss whether the special permit would affect land use planning]

[Discuss any pipeline facility, public infrastructure, and environmental impacts associated with implementing the special permit. In particular, discuss how any environmentally sensitive areas could be impacted]

[Evaluate alternatives to the special permit and any beneficial or adverse consequences of such alternatives.]

**NOTE:** The ASAP Project should include the pipeline stationing and mile posts (MP) for the location or locations of the applicable *special permit segment(s)*.
Enclosure C

Information Requested for the Anticipated Special Permit for Allowable External Loads over 72% Specified Minimum Yield Strength (SMYS) – Strain Based Design

Information that would be needed in a special permit application includes:

- Arctic Engineering
  - Route data, geothermal, hydraulics, and geo-technical
  - Frost heave & settlement prediction models
  - Pipe to soil structural modeling
    - Frost heave lab tests
    - Frozen soil uplift tests
    - Heave field test comparisons
    - Full scale bend tests
  - Environmental loads – soil properties, hill sides, slide areas, settlement areas outside frost heave locations
  - Strain demand basis

- Materials
  - Pipe grade and wall thickness
  - Internal pressure effects – strain capacity and combined hoop stress on pipe
  - Pipe mechanical and chemistry properties, and steel and pipe rolling practices
  - Pipe weld end and body diameter and ovality requirements to meet on a consistent basis maximum girth weld misalignment assumptions for strain capacity
  - Pipe and steel inspection procedures
  - Pipe girth weld properties and procedures
  - Non-destructive pipe girth weld inspection practices
  - Coating application temperature effects – strength increase/decrease, work hardening (Y/T), and elongation effects
  - Allowable anomalies in pipe, weld and during operations and location of them – welds and pipe such as cracked welds, weld anomalies, pipe dents, and wall loss
    - Maximum girth weld misalignment and affect on strain capacity
    - Maximum girth weld flaws and there affect on strain capacity
      - Crack driving force for which a ductile crack becomes unstable as measured by a crack tip opening displacement (CTOD) test
    - Low strength steel and there affects on strain capacity
    - Wall loss anomalies in both circumferential and longitudinal direction and there affects on strain capacity
    - Pipe dents and there affect on strain capacity

- Pipeline Engineering and Construction
  - Strain demand and strain capacity basis
  - Design –
    - Design safety factors – review of arctic data, material data, and construction specifications
    - Reliability assessment - does it meet safety design factors
- Strain capacity design basis – how are the below properties considered and destructive test results
  - Weld strength overmatch
  - Steel and weld toughness and heat affected zone softening
  - Curved wide plate tests
  - Full scale plate tests
  - Full scale bend tests
  - Finite element simulations
- Design safety factors – any needed adjustments
  - Allowable strain limit versus ultimate strain limit
- Construction
  - Construction specifications
    - Weld procedures – procedure testing, welder testing, and on-going verification tests during construction
    - Geotechnical verification parameters
    - Installation specifications – including verification parameters and any specification deviation parameters
    - Quality Assurance/Quality Control (QA/QC) practices to ensure engineering parameters are meet or exceeded
      - Training procedures
      - Inspection procedures
    - Documentation of construction, QA/QC and in-place installation findings
- Operations and Maintenance (O&M)
  - Pipeline segments
    - Type monitoring required and monitoring interval – normal and strain design locations
    - O&M integrity actions to mitigative findings – when and intervals
    - Training of O&M personnel – type
    - Integrity Management (IM) – how strain capacity design is integrated into IM
      - Strain monitoring – type and intervals
      - Strain intervention criteria
      - Reviews of program to meet special permit, code, specifications, procedures, and keep public, employees, environment, and facilities safe
APPENDIX B  STRUCTURAL MECHANICS OF BURIED PIPELINES

Although some sections of the ASAP are aboveground, notably at waterway crossings and at the beginning of pipeline route on the North Slope, ASAP is primarily a buried pipeline. Buried pipelines are essentially “restrained,” that is, displacement of the pipe is restricted by the soil around it.

Engineering calculations typically address the pipe in a bi-axial stress state called plane stress. The active stresses considered in pipe engineering calculations are shown in Figure B.1 – a hoop stress and strain which act around the circumference of the pipe, and a longitudinal stress and strain which are directed along the long axis of the pipe. In general, there is a third stress, a shear stress, which could be acting on the edges of the above unit section, but this is not normally significant and usually neglected in engineering calculations of transmission pipelines. Pipelines with diameter to wall thickness ratios (D/t) greater than 20, typical of transmission pipelines, are considered “thin-walled” as the distribution of normal stress perpendicular to the surface is essentially uniform throughout the wall thickness.

Figure B.1  Pipe Stresses and Strains

The relation between stress (σ) and strain (ε) for pipeline steel when loaded in one direction (i.e., a uniaxial stress-strain curve) can be generally represented as shown in Figure B.2. Below the proportional limit, the stress is linearly related to the strain, a relation called Hooke’s law, given by:

\[ \sigma = E \varepsilon \]

with the constant “E” known as the Young’s modulus. The yield point for pipeline engineering is defined by testing requirements to be the point at which the specified minimum yield strength (SMYS) of the pipe is recorded – 0.5% strain. Note that this definition of the “yield” does not concisely fit classical “textbook” definitions of yield, which is often defined as the point at which non-recoverable, i.e. “plastic” deformations, initiate. For example, if the pipe material was considered to be governed by Hooke’s law to SMYS of 70 ksi, the associated strain would be only:

\[ \varepsilon = \frac{70 \text{ksi}}{29,500 \text{ksi/in}} = 0.00237 \text{in/in} = 0.237\% \]
Thus, to reach the strain associated with SMYS an additional 0.263% strain occurs, which cannot be accounted for by an elastic relationship. Note that alternative yield point definitions are defined using an "offset" method where a line with the elastic slope is drawn from a specified strain offset point – again confirming the necessary incorporation of non-recoverable (plastic) deformation just to reach SMYS.

**Figure B.2** Typical Pipe Stress-Strain Uniaxial Curve

where:

1. True Elastic limit (first dislocation)
2. Proportionality Limit
3. Elastic Limit
4. Yield point

Below the proportional limit of the pipe stress-strain curve, where the stresses and strains are linearly related the relationship between stress and strain under plane stress conditions can be expressed as:

\[
\begin{pmatrix}
\varepsilon_H \\
\varepsilon_L
\end{pmatrix} = \frac{1}{E} \begin{pmatrix}
1 & -\nu \\
-\nu & 1
\end{pmatrix} \begin{pmatrix}
\sigma_H \\
\sigma_L
\end{pmatrix}
\]

Equation B.2

where:

- \( E \) is the Modulus of Elasticity, sometimes called Young’s modulus. For steel in the temperature range of operations, the value is approximately 29,500 ksi/in/in;
- \( \varepsilon_H \) is the strain in the hoop direction;
- \( \varepsilon_L \) is the strain in the longitudinal direction;
\( \sigma_H \) is the stress in the hoop direction;

\( \sigma_L \) is the stress in the longitudinal direction; and

\( \nu \) is Poisson’s ratio which is defined as the negative of the ratio of strain perpendicular to the load to the strain parallel to the load, and is a constant for stresses below the proportional limit. The value of Poisson’s ratio for steel is 0.3.

### B.1. HOOP STRESS

Hoop stress (\( \sigma_H \)), also known as “circumferential stress” is the normal stress on a longitudinal plane through the pipe centerline (see Figure B.3) resulting from internal forces (Q) resisting the fluid pressure force (P).

![Figure B.3 Hoop Stress Free Body Diagram](image)

To satisfy the equilibrium equation:

\[ \sum F_y = 0 = P - 2Q \]

With \( P = p2rL \) and \( Q = \sigma_H Lt \); then

\[ p2rL - 2\sigma_H Lt \]; or

\[ p2rL = 2\sigma_H Lt \]; or

\[ \frac{p2r}{2t} = \sigma_H \]; setting \( 2r \) to \( d \) gives:

\[ \boxed{\sigma_H = \frac{pd}{2t}} \]

Equation B.3
This formula is commonly known as **Barlow's Formula** and is the base equation used in 49 CFR 192 to determine the design pressure for steel pipe after applying a design factor, a longitudinal joint factor, and a temperature derating factor.

### B.2. LONGITUDINAL STRESS

The typical causes of longitudinal stress in buried pipelines are:

- Changes in steel temperature that, under unrestrained conditions, would cause lengthening or shortening of the pipe;
- Changes in internal pressure that, under unrestrained conditions, would cause lengthening or shortening of the pipe; and
- Transverse bending (flexure) of the pipe as it conforms to outside forces/displacements, such as frost heave or thaw settlement.

In straight pipe, the longitudinal strains due to internal pressure and temperature differential act uniformly across the section of the pipe. Transverse bending causes a linear variation in longitudinal strain across the section of the pipe. These relationships are illustrated in Figure B.4.

![Figure B.4 Uniform, Bending and Total Longitudinal Pipe Strains](image)

#### PRESSURE EFFECT ON LONGITUDINAL STRESS/STRAIN

As noted in Equation B.2, there is a relation between stress and strain for the two stress components of interest, and this relation can be used to derive additional information about the stress state. For example, although the hoop stress is directly related to the containment pressure, there is also an effect of the containment pressure on the longitudinal stress components.

In the elastic range, the associated longitudinal stress due to the pressure effect in the buried line can be found by substituting the known hoop stress for the pressure containment and noting that the longitudinal strain for a fully restrained pipe is zero, and then using this information in Equation B.2:
By the second equation:

\[
0 = -\frac{vpd}{E2t} + \frac{\sigma_{L\text{-pressure}}}{E}; \text{ or:}
\]

\[
\sigma_{L\text{-pressure}} = \frac{vpd}{2t} = 0.3\sigma_H
\]

Equation B.4

For aboveground, i.e., unrestrained sections of the pipe, the longitudinal strain is not zero

**TEMPERATURE**

For a pipeline that is free to expand, the strain caused as a result of temperature differential (change in temperature of the pipe steel from its installation temperature) is defined by:

\[
\varepsilon_{L\text{-temp}} = \alpha(T - T_i)
\]

where:

- \(\varepsilon_{L\text{-temp}}\) is the longitudinal strain due to temperature (in/in) in an unrestrained pipeline;
- \(\alpha\) is the coefficient of thermal expansion (in/in/°F);
- \(T\) is the temperature for the state of interest (°F); and
- \(T_i\) is the installation temperature (°F)

In aboveground segments of the pipeline, the thermal expansion and contraction is partially restrained and so produces longitudinal force and induces secondary longitudinal bending stress especially where the pipe configuration affords this partial restraint to thermal movement, such as near supports and at and near bends, and offsets. The design temperature differential is typically input into a pipe/structural analysis program in combination with other applicable loads to find the effects of these load components on aboveground segments.

A fully restrained pipeline has a net longitudinal strain of zero – i.e., it resists that tendency to expand with an equal and opposite mechanical strain of: \(\varepsilon_{L\text{-temp}} = -\alpha(T - T_i)\), thus producing a total net strain of zero.

In the elastic range, the associated stress due to thermal restraint in the buried line can be found by noting that the associated hoop stress for this load is zero, and then using this information in Equation B.2:
By the second equation:

\[
\varepsilon_{L-temp} = \frac{\sigma_{L-temp}}{E}; \quad \text{or:} \\
\sigma_{L-temp} = E\varepsilon_{L-temp} = -E\alpha(T - T_i) = E\alpha(T_i - T)
\]

Equation B.5

As can be seen from the equation, operating temperatures that are less than the installation temperature would cause a longitudinal tensile component (stress component is positive), while operating temperatures that are greater than the installation temperature would cause a longitudinal compressive component (stress component is negative).

**BENDING**

When an initially straight pipe is bent into a circular arc, longitudinal strains, and stresses, develop through the pipe cross-section in the plane of the bend. Below the proportional limit the longitudinal strain and stress in the extreme fibers of the pipe cross section are defined by:

\[
\varepsilon_{L-bending} = \pm \frac{r}{R} \quad \text{and} \quad \sigma_{L-bending} = \pm \frac{E r}{R}
\]

where:

- \(\varepsilon_{L-bending}\) is maximum longitudinal strain due to bending (in/in);
- \(\sigma_{L-bending}\) is maximum longitudinal stress due to bending (psi);
- \(r\) is the outside radius of the pipe section (in); and
- \(R\) is the longitudinal radius of the arc of bend of the pipe centerline (in).

When subjected to external forces/displacements a pipe resist via beam action. This beam action induces bending moments within the pipe section, which can be converted to stress by:

\[
\sigma_{L-bending} = \pm \frac{M r}{I}
\]

where:

- \(I\) is moment of inertia of the pipe (in\(^4\)); and
- \(M\) is bending moment (in-lbf)
B.3. **COMBINED STRESS**

The general state of stress in a buried pipeline under a combination of loads can be determined by considering the principal stresses within the pipe. For biaxial stress conditions that exist in pipelines, the principal stresses are the hoop stress ($\sigma_H$) and the longitudinal stress ($\sigma_L$). The longitudinal stress is the summation of longitudinal stresses from temperature, pressure, and bending ($\sigma_{L-temp} + \sigma_{L-pressure} + \sigma_{L-bending}$). Longitudinal stresses from other axial forces, if present, are also included.

### YIELD CRITERION

The two most commonly used yield criteria for determining effective stresses in pipelines are the maximum shear stress theory, commonly referred to as the Tresca theory, and the maximum distortion energy theory, commonly referred to as the von Mises' theory.

1. **MAXIMUM SHEARING STRESS THEORY**

As discussed in "Mechanics of Materials" by Popov [Popov 1976], the maximum shearing stress theory is based on the observation that in a ductile material, slipping occurs during yielding along critically oriented planes. This suggests that the maximum shearing stress plays a key role in the yielding behavior. It is assumed that the material yielding depends on the maximum shearing stress so that whenever a critical value $\tau_{critical}$ is reached, yielding commences. The value of $\tau_{critical}$ is set equal to the shearing stress at yielding under uniaxial tension (+$\sigma_y$) or compression (–$\sigma_y$) loading:

$$\tau_{max} \equiv \tau_{critical} = \frac{\pm \sigma_y}{2}$$

Hence, the maximum shearing stress is equal to $\frac{1}{2}$ of the uniaxial yield stress. For biaxial stress conditions that exist in pipelines the corresponding yielding criterion is expressed as follows:

$$|\sigma_H| \leq \sigma_y \quad \text{and} \quad |\sigma_L| \leq \sigma_y \quad \text{and} \quad |\sigma_H - \sigma_L| \leq \sigma_y$$

This is referred to as the Tresca yield criterion. The hexagonal Tresca yield function is illustrated in longitudinal stress vs. hoop stress space in Figure B.5 for an elastic-plastic material with a yield strength of 70 ksi. Any stress falling within the hexagon indicates that the material behaves elastically while points on the hexagon indicate that the material is yielding. This criterion is implemented under B31.8 Section 833.4 to limited combined stress for restrained pipe as:

$$|\sigma_H - \sigma_L| \leq k \cdot S \cdot T$$

where:

- $k$ is an allowable stress multiplier (for loads of long duration, $k$ is 0.90, and for occasional non-periodic loads of short duration it is 1.0);
- $S$ is the pipe SMYS; and
(2) **MAXIMUM DISTORTION ENERGY THEORY**

As discussed by Popov [Popov 1976], a widely accepted criterion for yielding of ductile materials is based on energy concepts wherein the total elastic energy of the material is divided into two parts: one associated with volumetric changes of the material, and the other causing shearing distortions. By equating the shearing distortion energy at yield under uniaxial tension to that under combined stress, the yield criterion for combined stress is established. For plane stress conditions, with principal stresses $\sigma_1$ and $\sigma_2$, the yield condition for an ideal plastic material becomes:

$$\frac{\sigma_1}{\sigma_y} + \frac{\sigma_2}{\sigma_y} = 1$$

or

$$\sqrt{\sigma_1^2 - \sigma_1 \cdot \sigma_2 + \sigma_2^2} = \sigma_y$$

This is the equation of an ellipse as shown in Figure B.5 for an elastic-plastic material with a yield strength of 70 ksi. Any stress falling within the ellipse indicates that the material behaves elastically while points on the ellipse indicate that the material is yielding. This is referred to as the von Mises yield criterion. This criterion is implemented under B31.8 Section 833.4 to limited combined stress for restrained pipe as:

$$[\sigma_L^2 - \sigma_L \cdot \sigma_H + \sigma_H^2] \leq k \cdot S \cdot T$$
Figure B.5 Illustration of Tresca and von Mises Yield Functions