

Department of Transportation Research and Special Programs Administration Office of Pipeline Safety

TTO Number 4

## Integrity Management Program Delivery Order DTRS56-02-D-70036

Pipe Wrinkle Integrity Determination

FINAL REPORT

Submitted by: Michael Baker Jr., Inc. May 14, 2003

ChallengeUs.

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#### Executive Summary

The report documents a review focused on the integrity determination of the Piney Point Pipeline. This work consisted of detailed reviews of analytical determinations concluded by other engineering consultants and Mirant Mid-Atlantic, LLC (Mirant), the operators of the Piney Point Pipeline.

The review focused on two general concerns:

- 1) Acceptance determination based on Code-Specified Analyses
  - *Conclusion:* The review of a number of analyses, especially for fabricated and field bends, found that the buried piping analysis appeared to conform to industry practice and demonstrated compliance. Detailed examination of the results from the computer analyses, and specified factors used in the analyses, was beyond the level of detail of this review but was not a matter of concern to the review effort, since the piping geometrical input data required are straightforward to knowledgeable pipeline stress analysts and the experienced operator.

All involved parties should agree on the tie-in temperature and operating temperature limits to be used in the pipeline analyses. The applied temperature differential is based on the difference between the operating temperature and the tie-in temperature. The tie-in temperature used in analyses to date (50°F) appears reasonable but has been a point of discussion. The majority of the pipeline was constructed in summer and, consistent with standard practice, the tie-in temperature is based on the ambient air temperature at tie-in. Baker understands that Mirant has reviewed the ambient air recorded temperatures for the time of tie-in and has concluded that the value is appropriate. However there is at least one section that was excavated and some section of line replaced during winter. Since the rest of the pipeline was tied-in and backfilled, the stresses/strains are "locked-in" by the soil and thus should not be affected by a localized area. Thus, the concern for the reference temperature should be isolated to any such localized segment. Mirant/Dominion should include documentation addressing this issue in their summary report. In conclusion, Mirant/Dominion's approach on this point is consistent with both theory and standard practice, but should be documented in a final report.

The soil restraint values used in the analyses were critically examined. The values were found to be within ranges typically used in piping analysis for non-buoyant conditions. Contrary to the original understanding of the review team, some bends (though none containing wrinkles) are located in a buoyant condition. Such a condition weakens the soil restraint to pipe movement. The review team performed a sensitivity study during the course of the review and found that weaker soils, whether restraining fabricated or field bends, would increase pipe stress. This differs from the conclusion of the operator based on a former sensitivity analysis submitted for review. At buoyant locations, lessened soil resistance values developed through use of the buoyant soil weight is the accepted industry approach and should be identified as the design state for compliance calculations and for future reference.

In conclusion, the review found the analyses demonstrated compliance with the design

basis operating limits for all bends in non-buoyant conditions. For buoyant conditions, the same methods should be employed using soil resistance values estimated with the buoyant soil weight.

- *Recommendation:* The Compliance Demonstration should be re-issued to document the tiein temperature used and to distinguish bends in buoyant states and ensure that stress results remain within specified limits for all bends. Monitoring, recording, and reporting of the actual operational values should be considered to ensure that actual values remain within the limits used in the demonstration analyses.
- 2) Wrinkle Acceptance Criteria

*Conclusion* - There were a number of wrinkles in the pipeline that were analyzed and judged fit for service using a project-specific methodology and criteria. This methodology utilized Finite Element techniques to develop the strain/stress at wrinkles and used the results to enter data curves to estimate cycles to failure. Questions concerning the modeling technique were answered by the operator during the review. Analyses completed by the review team, including examination of stress/strain demands developed at bends under varied soil resistance values, explored some of the modeling considerations and concluded that the modeling was conservative or adequate in most regards. It is noted that, since the FE wrinkle analysis did not explicitly include the demand of soil resistance, any lowered soil resistance effects including buoyancy effects are moot for this issue and, in any case, the operator has stated that no bends with wrinkles are in buoyant conditions. It was agreed with the operator that analyses including internal pressure effects would be completed.

The methodology to determine an acceptable number of cycles to failure, which is a value reduced from the analytical evaluation of the number of cycles to failure using a factor of safety of 20, was explained further in a February 7, 2003 memo received from the operator and is found compatible with analogous fatigue limit determination techniques. Additional information from Mirant received on February 28, 2003 uses the ASME Boiler and Pressure Code methodology exclusively for fatigue determination, switching to elastic-plastic analyses when directed by the code, and shows agreement with the conclusions developed from the methodology described in the February 7, 2003 memo.

An area of concern remaining from the initial review was the input stress-strain curve where it was recommended that an adjusted stress-strain curve be used in the input to the model to ensure confidence at the lower bound of this curve.

Analyses which fulfilled the above initial recommendations were subsequently completed by Mirant/DEI. Moreover, this subsequent submittal included an assessment of prior damage due to a combination of temperature differentials, using the recommended "rain-flow" procedure. Although the data supporting the split of maximum/minimum differential cycles experienced by the pipeline was not submitted, these subsequent analyses demonstrated that the theory and procedure used is aligned with the review team findings.

*Recommendation:* Mirant and its consultants gather individually submitted reports and data and issue a summary analytical FEA report incorporating and summarizing all information gained since the date of the original report, and especially including internal



pressure and specific wrinkle geometries as reported by NDE in the analysis. The documentation concerning the tie-in temperature, as discussed above, should be referenced. Documentation supporting the assumed split of differential temperatures used in the estimate of prior fatigue usage should also be included.

This report details the review efforts starting with a brief introduction in Chapter 1 and some introductory background information of the Piney Point pipeline in Chapter 2. Chapter 3 outlines the scope and work efforts of the review team and notes the two major issues that were the focus of the review team: B31.4 Code Compliance Demonstration and Wrinkle Acceptance Criteria. Chapter 4 details the review efforts with respect to the first issue, the B31.4 Code Compliance Demonstration, with the individual review of documents related to this issue and then the further work of the review team to put the issue and related information into perspective. Chapter 5 follows the same methodology to address the more difficult issue of the Wrinkle Acceptance Criteria. Chapter 6 details review of materials received during the course of the review from the operator and his consultants, often in response to specific concerns or questions raised by the review team. Chapter 7 summarizes the review findings for both of these issues, with Chapter 8 presenting the recommendations of the review team for the completion of these same issues.

### 1. Introduction

This report has been developed in accordance with the Statement of Work and proposal submitted in response to RFP for Technical Task Order Number 4 (TTO 4) entitled "Pipe Wrinkle Integrity Determination."

This scope included subtasks that required detailed reviews of analytical determinations concluded by other engineering consultants and Mirant Mid-Atlantic, LLC (Mirant), the operators of the Piney Point Pipeline. Mirant completed these analyses to demonstrate that the Piney Point pipeline is fit for purpose following extensive field work, engineering analysis, and NDT evaluation. The central task was to understand the cause of the failure of the Piney Point pipeline at the Swanson Creek crossing and to take appropriate steps to ensure that analogous areas in the Piney Point pipeline, namely those pipe segments exhibiting wrinkles, would safely operate under the designated operational limits. In addition, to ensure line-wide compliance, analyses were completed to demonstrate regulatory compliance using industry accepted techniques, i.e. analytical sequences that do not specifically address existing wrinkles. Having completed both accepted industry compliant procedures for demonstrating compliance, as well as detailed and site-specific examination of existing wrinkles in the pipeline, Mirant is satisfied that the pipeline can be safely returned to service within their designated operational limits and requires regulatory agreement.

This report presents brief introductory background information of the Piney Point pipeline in Chapter 2. Chapter 3 outlines the scope and work efforts of the review team and notes the two major issues that were the focus of the review team: B31.4 Code Compliance Demonstration and Wrinkle Acceptance Criteria. Chapter 4 details the review efforts with respect to the first issue, the B31.4 Code Compliance Demonstration, with the individual review of documents related to this issue and then the further work of the review team to put the issue and related information into perspective. Chapter 5 follows the same methodology to address the more difficult issue of the Wrinkle Acceptance Criteria. Chapter 6 details review of materials received during the course of the review from the operator and his consultants, often in response to specific concerns or questions raised by the review team. Chapter 7 summarizes the review findings for both of these issues, with Chapter 8 presenting the recommendations of the review team for the completion of these same issues.

### 2. Background

#### 2.1. Piney Point Pipeline Overview

The Piney Point Oil Pipeline was constructed for the Steuart Petroleum Company in 1971 and 1972 and put in service in 1973. Potomac Electric Power Company (PEPCO) purchased the pipeline in 1976. In 1995, Support Terminal Services, Inc. (ST Services) purchased the Piney Point Terminal facility from Steuart Petroleum, and ST Services operated the pipeline for PEPCO with former Steuart Petroleum personnel. Fuel oil was delivered to the Piney Point Terminal by marine vessels and then transported from the terminal by the Piney Point Oil Pipeline. The 51.5-mile-long pipeline system was composed of 12-inch and 16-inch-diameter pipeline segments that were used to transport heated fuel oil from the Piney Point Terminal, via the intermediate Ryceville Station, to generating stations at Chalk Point and Morgantown. The pipeline segment from Ryceville to Chalk Point was approximately 11 miles long. The oil was heated to make it flow more easily, and the system operated up to approximately 160° F. A locator map of the Piney Point Oil Pipeline is given in Figure 2.1, and a schematic of the pipeline is depicted in Figure 2.2.



Figure 2.1 Locator Map of the Piney Point Oil

This pipeline is operated intermittently based on Mirant's business needs. Typically this pipeline is laid in No. 2 fuel oil until a batch of No. 6 fuel oil is scheduled. Number 6 fuel oil is received by barge at ST Services tank farm at Piney Point and sequestered until requested by Mirant. The No. 6



fuel oil is heated to a temperature of about 140°F and pumped into the 16-inch nominal diameter pipeline at Piney Point. The 16-inch pipeline extends for about 30 miles from the Piney Point terminal to the Ryceville junction at which point it bifurcates and separates into two 12-inch nominal diameter pipelines. One leg supplies fuel to Mirant's Morgantown power plant and the other supplies fuel to the Chalk Point power plant.



Figure 2.2 Schematic of Piney Point Pipeline

The No. 2 fuel oil is displaced by the No. 6 fuel oil and stored in a tank at the Chalk Point or Morgantown power plants until the batch is complete. Immediately after the delivery of No. 6 fuel oil is complete, the No. 2 fuel oil is used to displace the No. 6 fuel oil where it is sequestered in the Piney Point terminal.

The pipeline was operated manually for startup and shutdown. The Ryceville Station was normally left unattended after initial system startup when no pump was operating at Ryceville. Pipeline operating data were not periodically transmitted to the Piney Point Terminal. The pipeline monitoring system transmitted pipeline pressure, temperature, and flow rate alarms to Piney Point. The pipeline alarms were displayed on the computer screen at the Piney Point Terminal, and audible alarms alerted the ST Services operator on duty to pipeline operating conditions that were outside predetermined limits. Using his computer terminal, the ST Services shift supervisors operating practice while serving as the pipeline controller was to verify the system alarm status, as well as

pressure, temperature, and flow rate information, once each 8-hour shift. The alarm data were stored at each station for 30 days and could be printed locally at each station if a data review was desired. The pipeline computer monitoring system provided the operations data it was designed to gather during No. 6 fuel oil transfers.

PEPCO's Piney Point Oil Pipeline Manual required that during a No. 6 fuel oil transfer, the ST Services pipeline controller had to conduct a daily recording of meter readings and to communicate daily with PEPCO operations personnel to ascertain the delivered quantity, flow rate, available tank capacity, and estimated time of operation completion. The PEPCO manual further required that the ST Services pipeline controller record the pipeline pressure, temperature, and flow rate at Piney Point at 4-hour intervals during a No. 6 fuel oil transfer. The ST Services pipeline controller did not continuously monitor pipeline operating conditions. The ST Services pipeline controller could receive a call from the system that a pipeline operating parameter was out of allowable tolerance, and he could then access the monitoring system to determine the nature of the alarm. Pipeline flushing was performed at the end of each No. 6 fuel oil transfer. Piping alignments for pigging operations were set up similarly to a flushing operation, although there were obvious differences in routing the product through the pig traps. The product did not flow through the meter at the Chalk Point Station during a flushing operation or during the pigging operation on the day of the accident. In addition, the meters and pressure-sensing points at the Chalk Point Station were not in the oil flow path, and the temperature-sensing equipment was not in the direct oil flow path to the Ryceville Station. The pipeline monitoring system was not capable of monitoring pipeline operating conditions because of the meter location and the locations of the sensing points. Pipeline shift supervisors and operators had no predetermined line balance limits to follow to assess pumped and delivered product volumes during flushing or pigging operations. PEPCO's Piney Point Oil Pipeline Manual did not require any pipeline operations personnel to perform periodic line balance calculations during a flushing or pigging operation, nor did they do so.

#### 2.2. Piney Point Pipeline Incident

On the morning of April 7, 2000, the Piney Point Oil Pipeline system, which was owned by PEPCO, experienced a pipe failure at the Chalk Point Generating Station in southeastern Prince George's County, Maryland. The release was not discovered and addressed by the contract operating company, ST Services, until late afternoon.

The 12-inch nominal diameter heated oil pipeline failed and released about 140,000 gallons of a combination of No. 2 and No. 6 fuel oil into the surrounding marsh, Swanson Creek, and subsequently, the Patuxent River, as a result of the accident. The pipeline failed while the operator was preparing it for an ultrasonic internal inspection tool. The investigation revealed that the failure occurred in a buckle (Figure 2.3)

No injuries were caused by the accident, which cost approximately \$71 million for environmental response and clean-up operations.



**Figure 2.3 Buckle in Piney Point Pipeline** 

The Office of Pipeline Safety (OPS) immediately shut down the pipeline and issued PEPCO a Corrective Action Order (Order) with numerous terms. Mirant acquired the pipeline from PEPCO in January 2001.

#### 2.3. Conclusions of the Incident Investigation

The National Transportation Safety Board (NTSB) held a Public Meeting on July 23,2002 to report its findings on the Pipeline Accident of the Rupture of Piney Point Oil Pipeline and Release of Fuel Oil near Chalk Point, Maryland on April 7, 2000. Their summary findings are published in NTSB/PAR-02/01. Their conclusions were:

- "1. Because Pipetronix incorrectly interpreted the results of its ultrasonic tool data for the pipeline feature at odometer station 53526.55, PEPCO was not alerted to the need for additional evaluation of the pipe at the location where it subsequently ruptured.
- 2. Because pipeline operators have no nationally recognized criteria with which to evaluate pipe wrinkles, they may not be effectively determining whether pipe containing wrinkles should be allowed to remain in service.
- 3. The absence of effective pipeline monitoring procedures and practices, including periodic line balancing, delayed the discovery of the fuel oil shortage on April 7, 2000, which delayed the pipeline shutdown and allowed more oil to leak from the pipeline.
- 4. Because pipeline owners and operators sometimes do not update their initial reports to the National Response Center, the notifications provided to emergency responders may not always contain the complete and accurate information needed to develop an effective incident response.
- 5. Because it did not initially put a fully implemented Incident Command System in place, the Unified Command was for several days unable to mobilize and control an effective response to the loss of oil containment that took place on the evening of April 8, 2000."



They also concluded that the probable cause of the April 7, 2000, Piney Point Oil Pipeline accident at the PEPCO's Chalk Point, Maryland, generating station was a fracture in a buckle in the pipe that was undiscovered because the data from an in-line inspection tool was interpreted inaccurately as representing a T – piece (also see #1 above). Contributing to the magnitude of the fuel oil release were inadequate operating procedures and practices for monitoring the flow of fuel oil through the pipeline to ensure timely leak detection.

As a result of its investigation of this accident, the Safety Board adopted safety recommendations to the Research and Special Programs Administration (RSPA) and the Environmental Protection Agency. The recommendation to the Research and Special Programs Administration is germane to this study, namely, to "establish quantitative criteria, based on engineering evaluations, for determining whether a wrinkle may be allowed to remain in a pipeline."

#### 2.4. Operator Response Actions to Compliance Order

After the accident, RSPA required Mirant (which became the pipeline's owner some months after the accident) to prepare an integrity study of the Piney Point Oil Pipeline before it would allow the pipeline to be returned to service. The most prominent conditions for compliance included:

- analyze the pig logs to identify buckles, wrinkles, and ripples on the pipeline;
- analyze the remaining geometric deformity features indicated on the tool logs and develop quantitative criteria to confirm those that can continue operating without remediation;
- perform a thermal analysis on the pipeline to establish the maximum operating temperature of the pipeline; and
- reinspect the pipeline with a high-resolution ultrasonic tool and a geometric tool to ensure that the buckles have not grown since the previous internal inspection performed in 1997.

Data from the 1997 in-line inspection of the pipeline were compared to the actual geometry of various wrinkles in pipeline bends, obtained after excavating the most severe wrinkles and determining the geometry by field measurements. After correlation between the in-line inspection data and the field measurements was completed, the 1997 in-line inspection data were used as the basis for the evaluation of wrinkles that had not been excavated and inspected. An analysis was performed to determine if identified wrinkles needed to be removed. As a result of this work, Mirant developed quantitative acceptance criteria for pipe wrinkles remaining in the pipeline. RSPA accepted the analysis that indicated that some wrinkles could remain in the pipeline, and RSPA allowed the pipeline to return to service.

Field bends containing wrinkles ("wrinkle bends") were installed in pipelines before the hazardous liquid pipeline safety regulations went into effect in 1970. Since then, pipeline regulations have prohibited the installation of pipe containing wrinkle bends during pipeline construction. However, pipe wrinkles that were not discovered during the construction inspection process or that formed sometime after construction are still periodically found in pipelines. According to RSPA's pipeline integrity management rule, when an in-line inspection tool is selected by a pipeline operator to assess the condition of the pipeline, it must be capable of detecting corrosion and deformation anomalies including dents, gouges, and grooves in high-consequence areas. The regulation states that the operator must evaluate all anomalies and repair those anomalies that could reduce a

pipeline's integrity. Although the language in this regulation does not specifically designate wrinkles as a category of deformation anomaly, when questioned by Safety Board staff, RSPA officials indicated that the regulation also applies to wrinkles. Wrinkles can sometimes be identified through the use of in-line inspection tools. However, operators do not have nationally recognized quantitative criteria with which to assess the effect of a specific wrinkle characteristic on a pipe or to determine whether a pipeline can be safely operated while it contains some wrinkles. Therefore, the Safety Board concluded that because pipeline operators have no nationally recognized criteria with which to evaluate pipe wrinkles, they may not be effectively determining whether pipe containing wrinkles should be allowed to remain in service. The Safety Board recommended that RSPA should establish quantitative criteria, based on engineering evaluations, for determining whether a wrinkle may be allowed to remain in a pipeline.

Besides the above, PEPCO hydrostatically tested the pipeline, performed numerous field investigations, repaired and replaced pipeline segments with wrinkles, and nondestructively inspected wrinkles that were removed from service and some that were allowed to remain in service. None of the wrinkles exhibited cracks at the detection limits. Furthermore, none of the wrinkles that were removed or allowed to remain in service approached the dimension of the failed buckle. The relevant dimensions in this case were the aspect ratio of the buckle and its circumferential length.

PEPCO commissioned Kiefner and Associates, Inc. (Kiefner) and Dominion Engineering, Inc. (Dominion) to perform studies on wrinkles to develop quantitative criteria for those that could continue to remain in service. On June 5, 2001, OPS approved the pipeline's return to service.

On October 1, 2001, the pipeline came under the regulatory authority of the Maryland Public Service Commission (PSC). A review by the Commission of the engineering studies Mirant conducted to support continued operation of their pipeline, despite the presence of wrinkled bends, resulted in a letter being sent to Mirant on December 9, 2002, requesting that Mirant discontinue pumping hot oil. Mirant did not agree with the Commission's position and continues to pump hot oil. A typical fuel oil transfer lasts for about four weeks and depends on the inventory of No. 6 fuel oil in Mirant's system and the business need to burn No. 6 fuel oil at the Chalk Point power plant instead of coal. The Order is still open pending final resolution of the wrinkle issue.

#### 3. Review

#### 3.1. Scope of Review

#### 3.1.1. Initial Scope

The OPS commissioned Michael Baker Jr. Inc. (Baker) to review reports concerning pipe wrinkle integrity determination for the Piney Point Pipeline. In addition, Baker was commissioned to determine if additional confirmatory analyses were required and to complete these analyses as part of the review effort. The review work began on January 8, 2003 and was to be completed by February 14, 2003. The specifics of the initial review work tasks are reproduced below:

#### Subtask 01 – Mirant Piney Point Pipeline Review

"Baker will evaluate the series of analytical studies performed by Kiefner, Dominion, and the PSC, and submit a report to OPS on the merits of the arguments proposed by these three parties. The series of studies to be evaluated are listed below:

- Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline (Kiefner and Associates, Inc.)
- Evaluation of Failure Risks Associated with Wrinkles in Buried Pipelines (Dominion Engineering, Inc.)
- B31.4 Code Stress Compliance of the Buried Portion of the Piney Point Oil Pipeline (Dominion Engineering, Inc.)
- Acceptance Criteria for As-Inspected Wrinkles in Piney Point Oil Pipeline (Dominion Engineering, Inc.)
- Industry Acceptance Standards for Wrinkles in Pipelines (CC Technologies Services, Inc. and Kiefner and Associates, Inc.)
- B31.4 Code Stress Compliance of the Buried Hot Bends in the Piney Point Oil Pipeline (Dominion Engineering, Inc.)
- Buried Piping Flexibility Analysis of the Piney Point Oil Pipeline (Dominion Engineering, Inc.)
- Influence of Operating Temperature and Pressure on the Piney Point Pipeline System (Dominion Engineering, Inc.)
- Mirant Piney Point Pipeline: Wrinkles and Bends (Maryland Public Service Commission)

#### Subtask 02 – Analytical Verification for Mirant Piney Point Pipeline

Mirant has completed hydrostatic testing of their pipeline and has performed nondestructive testing of numerous wrinkles. These assessments provide assurance that no wrinkles had associated cracks at the detectable limits. Two other engineering consultants have addressed the effect of the test pressure and duration on the life of wrinkles with and without cracks for this pipeline. These studies have utilized the results of manual calculations and finite element analyses as input into separate



fatigue/crack-growth analysis. Cumulative damage rules with an assessment of stress levels and number of cycles were further utilized to develop applicable scenarios for an assessment of hazard resistance. These studies will be critically reviewed for this pipeline and, as applicable, confirmation analyses completed."

#### 3.2. Scope Extension

Near the completion of this initial review effort, the OPS received additional pertinent information. The OPS requested that Baker extend the review effort to also include these documents:

- 1. Response to DOT Baker Telecon comments by Mirant 2/7/03
- 2. Piney Point Pipeline Basis for Elastic-Plastic Wrinkle Model, Acceptance Criteria, and Factors of Safety
- 3. Dominion Engineering Inc. 2/7/03
- 4. MD PSC Soil Sensitivity Study
- 5. Answers to questions posed by Baker concerning the elastic-plastic analysis of the Piney Point Pipeline By John F. Kiefner February 3, 2003
- 6. Stress-strain curve for Piney Point Pipeline
- 7. Bending Moment for Piney Point Pipeline Wrinkle Models Narrative Explanation

A draft report was submitted to the OPS on the review deadline of February 19, 2003. Subsequent to the submittal, a review meeting was conducted at Mirant's headquarters. Many of the recommendations made in the initial review were accepted and Baker's scope was extended to further review the subsequent submittals.

#### 3.3. Task Initiation

Baker received approval of the review effort on January 8, 2003 and began organizing the various report materials received from the OPS that day.

There were numerous reports delivered and a clear documentation trail was not evident. Thus, it became apparent that a first task was to develop an overall framework for the integrity determination and this review.

The first task was to focus on the identified failure mechanism - pipeline wrinkles. Reports were submitted in late 2000 and early 2001 focusing on the evaluation of pipeline wrinkles. These reports were prepared by either Kiefner and Associates, Inc (Kiefner) or Dominion Engineering Inc. (Dominion), the two engineering consultants for Mirant Pipeline. They included:

• "Industry Acceptance Standards for Wrinkles in Pipelines", E.B.Clark of CC Technologies and J.F. Kiefner of Kiefner and Associates, Inc., This could be characterized as a survey paper of established regulations and research relevant to pipeline wrinkles. This paper had no detailed analysis and attempted no correlation or application to the specifics of the Piney Point Pipeline.



- "Evaluation of Failure Risks Associated with Wrinkles in Buried Pipelines", A.P.L. Turner, PhD, PE, January 2001. An overview paper with no associated detailed analysis, although correlation with the specifics of the Piney Point Pipeline is very evident.
- "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline", J.F. Kiefner et al, Kiefner and Associates, Inc., January 15, 2001. This is a central paper, focusing directly on the characteristics of the Piney Point Pipeline and making a direct recommendation for acceptance criteria of wrinkles for this pipeline.
- "Acceptance Criteria for As Inspected Wrinkles in the Piney Point Oil Pipeline", J.E. Broussard et al, Dominion Engineering Inc. Similar to Kiefner's paper, this report focuses directly on the characteristics of the Piney Point Pipeline and making a direct recommendation for acceptance criteria of wrinkles for this pipeline.

The last two submittals above summarize detailed analyses performed on the pipeline, using the characteristics and observed geometry of the pipeline. The reports appear to have been performed independently, and follow similar overall techniques with different emphasis and different analytical tools and formulations.

The remaining reports submitted by the operator's engineering consultants focus on more or less "standard" techniques for analyses of bends for buried piping. These include:

- "B31.4 Code Stress Compliance of the Buried Portion of the Piney Point Oil Pipeline", Dominion Engineering Inc., Jan. 15, 2001
- "Influence of Operating Temperature and Pressures on the Piney Point Pipeline System", Dominion Engineering Inc., Jan. 24, 2001
- "B31.4 Code Stress Compliance of the Buried Hot Bends of the Piney Point Oil Pipeline", Dominion Engineering Inc, April 25, 2001
- "Buried Piping Flexibility Analysis of the Piney Point Pipeline", Dominion Engineering Inc., December 26, 2001

It appears that these latter four reports form a single analytical task to develop the stress states of the pipeline at bends, both hot and field bends, in the Piney Point Pipeline. We viewed these as a series of update reports, with results being refined as additional field data was developed, culminating in the December 26, 2001 report.

The final report to be reviewed was itself a former review of the operator's submittals performed by the Maryland Public Service Engineering Department (MPSCED). The pipeline came under the authority of the Maryland Public Service in October 2001 and this paper detailed areas of disagreement of the MPSCED with the operator's submittals.

• "Mirant Piney Point Pipeline: Wrinkles and Bends", Maryland Public Service Committee, Eng. Dept.

#### 3.4. Review Approach

Based on the examination of the documents to be reviewed for the OPS, there were two nearly separate issues to be examined more closely:



- 1. Demonstration of compliance of the Piney Point pipeline to code requirements for the specified operational limits of temperature and pressure assuming nominal pipeline geometry, i.e. specified SMYS, nominal thickness and diameter. This involves industry standard procedures for calculating stresses in the pipe and comparing these resultant stresses to code specified stress limits to ensure operational values will not exceed regulatory limits.
- 2. Development of a criterion for the acceptance of existing wrinkles in the Piney Point pipeline. This effort utilizes more advanced analytical techniques for judging the acceptability of the measured geometry of existing wrinkles in the pipeline.

The MPSCED review also focuses alternately on these two issues.

#### 3.5. Structure of this Report

As per the review approach, Chapter 4 of this report focuses on the "Code Compliance" demonstration efforts for the Piney Point pipeline, while Chapter 5 focuses on the Wrinkle Acceptance criteria. Chapter 6 details review of materials received during the course of the review from the operator and his consultants, often in response to specific concerns or questions raised by the review team. Chapter 7 summarizes the findings of the review effort and Chapter 8 presents the recommendations.

### 4. ASME B31.4 Code Compliance Demonstration

This section focuses on the demonstration of code compliance of the Piney Point pipeline, without regard to the issue of the existing wrinkles in the pipeline. That is, assuming the wrinkles are demonstrated to be acceptable by other studies, there remains the need to demonstrate that the pipeline meets regulatory requirements under its proposed operating basis for pressure and temperature differentials.

To demonstrate compliance, the pipe stress analyst has a number of possible tools at his disposal. Manual techniques usually assume complete fixity of the buried pipeline due to soil resistance, and are used to "anchor" code requirements. A number of more sophisticated computer techniques are available which model the soil resistance directly and thus allow limited movement of the pipeline based on the input soil properties. In long, straight runs of buried piping, the system will closely approach full restraint conditions and, thus, computer techniques offer no advantage over manual analysis. The two conditions that usually are addressed by computer programs thus become piping segments where restraint varies due to piping geometry or change in soil restraint, i.e.: 1) bends and 2) buried to aboveground transitions.

Commercial pipe stress computer programs typically have built-in techniques for checking code compliance based on the analytical results. They are used extensively throughout the industry, and it is assumed in this review that the results from such a program are computed correctly by the program. Nevertheless, the user of a commercial program must address the operational limits of the pipeline system in question, correctly specify the piping geometry, and select appropriate soil restraint properties which are consistent with the field conditions of the line.

Section 4.1 contains reviews of the reports submitted by the operator and his chief consultant in this area, Dominion. These reports were seen by the reviewers as a series of interim reports culminating in the final report: "Buried Piping Flexibility Analysis of the Piney Point Oil Pipeline". It was confirmed by the operator in a teleconference on January 29, 2003 that this latter report was their final demonstration package and the values used were consistent with the operators final decision on the pipelines operational limits. Section 4.2 presents discussions from a teleconference with Mirant and its engineering consultants. Section 4.3 summarizes initial findings of the review with the next two sections detailing the main issues. The final section presents the overall assessment of the code compliance analysis for the Piney Point Pipeline.

#### 4.1. Review of Relevant Reports

#### 4.1.1. "B31.4 Code Stress Compliance of the Buried Portion of the Piney Point Oil Pipeline" (Dominion)

This document, Dominion Calculation C-7129-00-1, presents results of a simplified thermal expansion and flexibility analysis of the Piney Point Pipeline System. These calculations assume a temperature differential of 75°F and an internal pressure of 550 psi. The analysis only considered straight pipe and field bends with a minimum bend radius of 18 times the nominal pipe diameter (18D). The calculations are summarized below:

Pipe stress calculations per ASME B31.4 §419.6.4 are included and show that for straight, fully restrained pipe the maximum computed equivalent tensile stress is less than the code allowable limit (90% SMYS).

Pipe stress analyses of portions of the buried pipeline that are not fully restrained, i.e. bends, were conducted using the CAESAR II<sup>TM</sup> piping analysis program. A series of models were analyzed for bend angles from 10 to 90 degrees. Each model consisted of two 1,000-foot sections of straight pipe connected by an 18D bend. Anchors were modeled at the opposite end of the straight sections. Models for the 16-inch and 12-inch diameter pipe were analyzed.

A series of curves were then generated presenting: 1) Equivalent tensile stress versus bend angle, and 2) Expansion stress versus bend angle.

#### 4.1.1.1. Key Assumptions and Findings

Pipeline Properties and Operating Parameters for analysis:

- 16-inch diameter by 0.219 inch wall thickness pipe and 12-inch diameter by 0.203 inch wall thickness pipe.
- Maximum operating temperature is 125°F.
- Minimum operating temperature of pipeline is 50°F.
- Maximum minus minimum temperature differential is 75°F
- Maximum operating pressure is 550 psi.
- Pipeline is constructed from API 5L X42 Electric Resistance Welded (ERW) pipe with a Specified Minimum Yield Strength (SMYS) of 42,000 psi and a joint efficiency factor of 1.0.
- Coefficient of friction between the pipe and soil is 0.3.
- Linearized pipe-soil properties. Lateral stiffness of soil is 1,000 pounds of force per inch of pipe per inch of deflection.
- Pipe bends have a bend radius of 18 times nominal pipe diameter (18D).
- Stress Intensification Factor (SIF) and Flexibility Factor is equal to 1.0 (this was assumed by reviewers)
- Location of water table is below the pipe.

The calculations conclude that the equivalent tensile and expansion stresses for all cases analyzed are below the allowable code limits.

#### 4.1.1.2. Key References

• ASME B31.4-1998

#### 4.1.1.3. Conclusions of Review

This report addresses compliance of Piney Point pipeline field bends without wrinkles to ASME B31.4 requirements. Calculations presented are based on a maximum operating temperature which is given as 125°F versus 160°F presented in other documents reviewed.

#### 4.1.1.4. Further Work

The hoop stress in this report, and in other works, is calculated using nominal wall thickness. Although the process for the use of a nominal wall thickness and the requirements for the reduction of this thickness based on NDE is not an issue of process, it was considered prudent to ask the operator if consideration was given to a corrosion allowance for this pipeline.

# *4.1.2. "B31.4 Code Stress Compliance of the Buried Hot Bends in the Piney Point Oil Pipeline" (Dominion)*

This document, Dominion Calculation C-7129-00-3, presents results of a thermal expansion and flexibility analysis of "hot bends" (i.e., forged long-radius elbow fittings) installed along the Piney Point Pipeline. Analytical models were created in CAESAR II for the majority of elbow groupings based on geometry information collected by a UT in-line inspection tool. These models generally consisted of a 1,000-foot section of straight pipe connected to each side of the elbow grouping or, if a field bend was located within 1,000 feet of the grouping, field bend. An anchor was then placed at the other end of the straight pipe section. For elbow groupings that are located near mode transitions (buried to aboveground), the aboveground portion was not modeled explicitly, but was approximated by a short section of piping and anchorage.

#### 4.1.2.1. Key Assumptions and Findings

Pipeline Properties and Operating Parameters for analysis:

- 16-inch diameter by 0.219 inch wall thickness pipe and 12-inch diameter by 0.203 inch wall thickness pipe.
- Hot bends for both diameters are forged elbows with a wall thickness of 0.375 inches.
- Pipe bends have a bend radius of 1.5 times nominal pipe diameter (1.5D).
- Maximum operating temperature is 125°F.
- Minimum operating temperature of pipeline is 50°F.
- Installation temperature of pipeline was 50°F minimum.
- Maximum operating pressure is 550 psi.
- Pipeline is constructed from API 5L X42 Electric Resistance Welded (ERW) pipe with a Specified Minimum Yield Strength (SMYS) of 42,000 psi and a joint efficiency factor of 1.0.
- Ultimate axial strength at the soil/pipe covering interface is 1.45 psi at a deflection of 0.25 inches.



- Ultimate lateral strength of the soil is 300 pounds per inch of pipe length at a deflection of 0.75 inches.
- Heat loss for the operating pipeline is 1°F per mile.

Restraint of the pipeline within cased road crossings was not modeled explicitly, but was approximated by applying soil restraints.

Aboveground piping is modeled as a 20-foot length of straight pipe and a five-foot wide by 10-foot high expansion loop.

Of the 38 buried elbows, the resultant stresses for 37 were reported below the code allowable limits. The final elbow was determined acceptable if the reheat temperature at Ryceville during normal pumping operation was reduced to 120°F.

#### 4.1.2.2. Key References

- ASME B31.4-1998
- Dominion calculation C-7129-00-1, Revision 0, dated January 15, 2001

#### 4.1.2.3. Conclusions of Review

This report is very similar to that reviewed in Section 4.1.1 and addresses compliance of Piney Point pipeline elbows without wrinkles to ASME B31.4 requirements. Calculations presented are based on a maximum operating temperature which is given as 125°F versus 160°F presented in other documents reviewed. Though it was not explicitly stated, we assume that the default B31.4 Stress Intensification Factors (SIF) and flexibility factors were used for these analyses.

#### 4.1.2.4. Further Work

None

# 4.1.3. "Influence of Operating Temperature and Pressure on the Piney Point Pipeline System" (Dominion)

This document, Dominion calculation D-7129-00-2, evaluates the effects of temperature and pressure reductions on stresses in the Piney Point Pipeline system. The axial forces due to thermal growth and internal pressure are computed with the ratios to the total force used to develop a simplified formula which determines the affects of changes in temperature and pressure from the design condition of 550 psi internal pressure and 160°F operating temperature. A graph presenting the percentage of design stress to percentage of design temperature or pressure for two scenarios, constant pressure with varying temperature and constant temperature with varying pressure, is developed. In summary, the temperature effects are more than twice that of pressure.

#### 4.1.3.1. Key Assumptions and Findings

Reference or "tie-in" temperature of the pipeline is 50°F.



#### 4.1.3.2. Key References

None

#### 4.1.3.3. Conclusions of Review

The calculation considers the force due to full restraint of thermal expansion and the "cap force", i.e., the force due to the internal pressure over the fluid column, but does not consider Poisson force, i.e., the longitudinal force due to hoop stress. Thus the vertical axis label in Figure 5-1, "Percentage of Wrinkle Stress at 550 psi, 160°F" is inaccurate. However, the general conclusion that temperature change has more effect than pressure change is still valid. The horizontal axis in Figure 5-1 should be "Temperature Differential" not just "Temperature".

#### 4.1.3.4. Further Work

None

#### 4.1.4. "Buried Piping Flexibility Analysis of the Piney Point Oil Pipeline" (Dominion)

This report by Dominion evaluates the hot bends and field bends identified on the buried portions of the Piney Point pipeline. The purpose of these evaluations was to establish the maximum pumping temperature at Piney Point, Chalk Point and Morgantown, and re-heating temperature at Ryceville.

#### Flexibility Analysis of Hot Bends

A series of elastic finite element analyses of the 42 hot bends located on the Piney Point pipeline were completed using pipe geometry information determined from Geopig data. These analyses were performed for a range of temperature differentials to determine the maximum allowable local pipe temperature for each hot bend based on a tie-in temperature of 50°F.

Using the maximum allowable local pipe temperature for each hot bend, the maximum pump source temperature was determined based on a 1°F per mile heat loss between the pump and the given hot bend.

#### Parametric Flexibility Analysis of Field Bends

Previous Piney Point pipeline studies indicate that stresses in field bends are a function of the bend radius and bend angle (i.e., higher stresses in smaller bend radii and a parabolic relationship between bend angle and stresses). Parametric analyses were performed for various bend radii and a series of curves generated showing the relationship of bend angle and operating temperature. These curves were used to evaluate each field bend based on bend radius and bend angle information determined from Geopig data, and the maximum allowable local pipe temperature was determined.

A case-specific analysis of the most limiting field bend was conducted "in order to reduce the conservatism inherent in the parametric analyses".

As with the hot bends, the maximum pumping source temperature for each field bend was determined based on a 1°F per mile heat loss between the pump and the given hot bend and the maximum allowable local pipe temperature calculated.



#### 4.1.4.1. Key Assumptions and Findings

The key findings from this report are summarized in three parts under Section II. Part 1 discusses the flexibility analysis of hot bends, Part 2 discusses the parametric flexibility analysis of field bends, and Part 3 presents the maximum pumping/re-heating temperatures for each pumping/re-heating station. These temperatures are:

- Piney Point 150°F
- Chalk Point 149°F
- Morgantown 146°F
- Ryceville 149°F

Key assumptions include:

- Heat loss of 1°F per mile
- Installation temperature of 50°F
- Ultimate strength of the axial shear interface is 1.45 psi at a deflection of 0.25 inches
- Ultimate strength of lateral restraint is 300 lb/in at a deflection of 0.75 inches
- Soil ultimate load in the upward direction is 100 lb/in at a deflection of 0.75 inches
- Nominal wall thickness of hot bends is 0.375 inches
- Internal pressure is 550 psi

#### 4.1.4.2. Key References

- Geopig Caliper/Geometry Survey of Mirant Mid-Atlantic, LLC Oil Lines Geopig Runs: May 17-23, 2001 – Ref. J0427," BJ Pipeline Inspection Services Final Report
- "Chalk Point Wrinkle Axial Pipe Resistance Field Tests Prepared for Murray & Cheng Associates Ltd.," R. W. I. Brachman, Ph.D., February 2001
- "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline," Kiefner, January 2001

#### 4.1.4.3. Conclusions of Review

This report discusses Piney Point pipeline compliance with ASME B31.4 requirements and is considered to supercede the two earlier documents covering compliance of field bends and elbows. This report is apparently based on more accurate information.

#### 4.1.4.4. Further Work

Based on the review, questions and comments were formulated for Mirant and its engineering contractor, Dominion, concerning this report. The questions and comments are listed below and were asked in a teleconference on January 29, 2003 with Mirant and its engineering contractors:



- The report states that the bend radius and angle change from each bend may be tabulated. What curvature gage length was used to calculate the bend radius?
- The report discusses CAESAR's capabilities for modeling buried piping by using industry standard methods to automatically generate the appropriate soil/pipe interface boundary conditions. Can Dominion provide a brief description of the pipe-soil modeling capability in CAESAR and the industry standard methods used?
- According to the report, a series of push and pull tests on spools of 12-inch pipe were conducted and described in Reference 2. Provide a description of the tests and test conditions, e.g., method of pulling/pushing, spool length, depth of cover, soil information, etc. or provide a copy of Reference 2. Provide a description of the insulation strength properties.
- Only a single set of soil properties for use in the analyses is presented. Were any sensitivity studies on soil strength performed? Was the transverse soil resistance computed based on the insulated or un-insulated pipe diameter?
- Pipe material properties used in the analysis are briefly discussed in the report (Section III, Item 4). What were the SIFs (*i* factors) and flexibility factors (*k* factors) used for the elbow fittings? Were the *i* factors and *k* factors modified to account for pressure stiffening?
- The restraint condition specified at the remote boundary of the model should not have any influence on the analysis results at/near the bends of interest. The models should be checked to insure that the boundary length extends beyond the virtual anchor point.
- A tie-in temperature of 50°F is assumed in the analysis. Is there agreement that this value is appropriate?
- The report indicates that CAESAR performs two stress checks (an "operating" stress check that limits the Tresca stress to 90% SMYS and an expansion stress check that limits the expansion stress to 72% SMYS). Which stress check governs the bend response?
- Appendix A states that field bends are included in the analyses of hot bend groupings where appropriate (i.e., field bend within 100 feet of the hot bend groupings). How are the field bends modeled (e.g., as a sweep of constant radius)? Why was the geometry and support conditions of the aboveground piping not modeled explicitly?
- Appendix A briefly discusses the analysis of restrained hot bends. How were the anchor blocks modeled in CAESAR (e.g., discrete linear stops, elastic-plastic springs)?
- We assume that no attempt was made to model any ripples or wrinkles in the field bends analyzed in Appendix B. Confirm if the SIFs (*i* factors) and flexibility factors (*k* factors) were assumed to be 1.0 for this evaluation.
- For the curves presented in Figures B-1 and B-2, which stress check governs the bend response?

#### 4.2. Teleconference Discussion

On January 29, 2003, a teleconference was conducted to discuss questions and comments generated by Baker's report reviews presented above. Representatives of the OPS, MDPSCED, Mirant, Kiefner, Dominion and Baker participated in this discussion. Notes of the teleconference as captured



by the MDPSCED are presented in Appendix A. Relevant to the review of the Code Compliance demonstration analyses the following summarizes the responses:

# **"B31.4** Code Stress Compliance of the Buried Portion of the Piney Point Oil Pipeline" (Dominion)

• The review noted that hoop stress is calculated using nominal wall thickness and that nominal pipe geometrical values are used for developing the pipe section properties. The reviewers asked if consideration was given to a corrosion allowance for this pipeline:

Teleconference information: Whether original design incorporated a corrosion allowance is unknown. Based on inspection data corrosion is limited to localized pitting, therefore no corrosion allowance was incorporated into current analyses.

• The maximum operating temperature is given as 125°F versus 160°F presented in other documentation. The "design" temperature change(s) must be definitively stated before any review can be completed. Has this been done?

Teleconference information: 125 °F proposed to provide an additional factor of safety until more detailed analyses were completed. This temperature was used in some of the initial analyses supporting the return to service of the pipeline. An operating temperature of 160 °F was given in the Piney Point operating manual. This value was used in several other analyses.

Final report for B31.4 compliance ("Buried Piping Flexibility Analysis of the Piney Point Pipeline") determined maximum temperature allowed at each bend and extrapolated this temperature back to the pumping/reheating station based on a 1 °F per mile heat loss. The final values were:

150°F at Piney Point 149°F at Chalk Point 146°F at Morgantown 149°F at Ryceville

The development of a comprehensive statement regarding temperature was mentioned. This should address not just max T, but  $\Delta T$  and maximum/minimum steel temperatures as well.

The additional critical questions were answered satisfactorily, although detailed answers to some of the more technical questions were not received but were subsequently found by the review team to be not critical to conclusion of the review. Several questions were answered by reference to the detailed analytical output provided in the review material. It was noted that a sensitivity analysis of the soil geomechanical values was previously completed and a summary of the results was later forwarded by Mirant, through the OPS, to the reviewers (see Chapter 6 for "Additional Review Material").

#### 4.3. Code Compliance Review

Following the document review, it was determined that the analytical tools and procedures used to demonstrate Code Compliance were suitable and consistent with accepted industry practice. The



most important remaining issues for clarification for the purposes of this review for the belowground piping analysis were determined to be:

- 1. A clearly defined Design Basis, stating the operational limits of the pipeline
- 2. Understanding of the soil restraint values and the implications of their relative uncertainty in the analytical models

#### 4.4. Design Basis

Table 4-1 presents design basis information for the Piney Point Pipeline as determined from the final report referenced above. This table forms the basis for review acceptance of the compliance demonstration, as well as the basis for the wrinkle integrity analyses presented in Chapter 5.

| Table | 4-1 | Piney | Point | Pipeline | Design | Basis |
|-------|-----|-------|-------|----------|--------|-------|
|       |     |       |       |          |        |       |

| Pipe Dimensions:               |                       |  |  |  |
|--------------------------------|-----------------------|--|--|--|
| Outside diameter               | 12.75 or 16 inches    |  |  |  |
| Wall thickness                 | 0.203 or 0.219 inches |  |  |  |
| Dina Matarial                  | API 5L X42            |  |  |  |
| Pipe Material                  | (42000 psi SMYS)      |  |  |  |
| Corrosion Allowance            | None                  |  |  |  |
| Maximum Operating Pressure     | 550 psi               |  |  |  |
| Tie-in Temperature             | 50°F                  |  |  |  |
| Maximum Operating Temperature: |                       |  |  |  |
| Piney Point Station            | 150°F                 |  |  |  |
| Chalk Point Station            | 149°F                 |  |  |  |
| Morgantown Station             | 146°F                 |  |  |  |
| Ryceville Station              | 149°F                 |  |  |  |

#### 4.5. Soil Properties

Restraint of the pipe provided by the soil in the vertical, axial and lateral directions is accounted for in the analyses by providing numerical spring constants. The soil is typically modeled as "elastic-plastic" as shown schematically in Figure 4.1



Displacement

Figure 4.1 Generalized Soil Force-Deflection Curve

The two soil constants are:

- the soil modulus for the soil force-deflection relation from the unloaded state to soil yield point. This value has units of pounds per linear inch of pipe per inch of displacement, and
- the yield strength value or ultimate load of the soil, expressed in terms of pounds per linear inch of pipe.

Generally, for analysis of buried pipelines subjected to extreme loads, the most important parameter is the soil yield strength.

#### 4.5.1. Axial Restraint

The axial yield strength is discussed in the Kiefner report: "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline". Values used in the analysis (presented on Page 9 of this report) are:

- 260.9 lb/ft (21.75 lb/in) for the 12.75-inch line
- 332.6 lb/ft (27.72 lb/in) for the 16-inch line

A formula for the maximum axial soil force per unit length of pipe is provided by the American Lifelines Alliance "Guidelines for the Design of Buried Steel Pipe", July 2001. This report shows the formula as:

$$T_u = \pi D\alpha c + \pi DH/2\gamma (1+K_0) \tan \delta$$

Where:

D = outside pipe diameter

c = soil cohesion representative of the soil backfill

H = depth to pipe centerline

 $\gamma$  = effective unit weight of the soil

 $K_0$  = coefficient of pressure at rest



- $\alpha$  = adhesion factor
- $\delta$  =interface angle of friction for pipe and soil =  $f\phi$
- $\phi$  = internal friction angle of the soil
- f = coating dependent factor relating the internal friction angle of the soil to the friction angle at the soil-pipe interface

Examination of the formula reveals that the first term is zero for a cohesionless soil. The pipe-soil spring properties presented in Table 4-3 were developed assuming a 3 foot depth of cohesionless soil cover with a bulk density of 125 pcf and a friction angle between 28° and 34°. The external pipe coating was taken as polyethylene with a 0.6 friction factor (f). The lower bound values are based on the buoyant soil density and the smaller friction angle while the upper bound values are based on the soil bulk density and the larger friction angle. The values bound Kiefner's values.

However, the soil properties used in the final analyses contained in "Buried Piping Flexibility Analysis of the Piney Point Pipeline", Dominion Engineering, Inc., December 26, 2001 were higher than these values based on field tests performed on the Pinev Point pipe. In a meeting at Mirant's headquarters on March 6, 203 it was verbally confirmed that the cover depth of the tests agreed with the nominal cover depth assumption of 3 feet. The analyses used a value of axial restraint of 1.45 psi at a deflection of 0.25 inches. The axial ultimate load for each pipeline is computed by multiplying the 1.45 psi value by the outside circumference of the pipe (including insulation and jacketing). This is then divided by the 0.25-inch deflection to obtain the axial elastic spring constant for each pipeline. The resulting values are shown in Table 4.2. The values are considerably higher that the estimates given above but are not unreasonable for a soil that has some cohesion. The yield point of 0.25 inches is halfway between the recommended value of 0.2 inches for loose sand and 0.3 inches for stiff clay given by the American Lifelines Alliance guidebook. Thus, the values are acceptable for the analysis, especially in view of a parametric analysis performed by Dominion in which resistance values were varied. Note that the soil resistance value under buoyant conditions is about half that under non-buoyant conditions (the value of  $\gamma$ , the effective weight, is reduced by 62.4 lb/ft<sup>3</sup> from its non-buoyant weight assumed to be about 125 lb/ft<sup>3</sup>).

#### 4.5.2. Lateral Restraint

The lateral yield strength is also discussed in the Kiefner report "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline". Values used in the analysis (presented in Table 3 of this report) are:

- 3,094 lb/ft (257.8 lb/in) for the 12.75-inch line
- 3,521 lb/ft (293.4 lb/in) for the 16-inch line

In later reports by Dominion a lateral yield strength of 300 lb/in is used with a deflection of 0.75 inches. The resulting values are presented in Table 4-2.

A formula for the maximum lateral soil force per unit length of pipe is provided by the American Lifelines Alliance "Guidelines for the Design of Buried Steel Pipe", July 2001. This report shows the formula as:

 $P_u = N_{ch} c D + N_{qh} \gamma HD$ 

where:

D = outside pipe diameter

c = soil cohesion representative of the soil backfill

H = depth to pipe centerline

 $\gamma$  = effective unit weight of the soil

 $N_{ch}$  = horizontal bearing capacity factor for clay (0 for c = 0)

 $N_{qh}$  = horizontal bearing capacity factor (0 for  $\phi = 0$ )

Examination of the formula reveals that the first term is zero for a cohesionless soil. The computed upper and lower bound values are presented in Table 4-3. The ultimate load values bound Kiefner's and Dominion's values.

On the other hand, the values for the lateral elastic spring constant used in the analyses are somewhat higher than those calculated from the American Lifelines Alliance guidelines. This difference is due to the assumed value of deflection when yielding occurs. Procedures for computing the yield strength are well established, while the value of the displacement required to mobilize the strength is based essentially on a simple rule of thumb. Once yield occurs, as is predicted, the effect of initial spring constant becomes fairly insignificant.

The American Lifelines Alliance computes the yield displacement by the formula:

 $\Delta_p = 0.04 (H + D/2) \le 0.10D$  to 0.15D

where:

D = outside pipe diameter

H = depth to pipe centerline

The American Society of Civil Engineers publication "Guidelines for the Seismic Design of Oil and Gas Pipeline Systems" presents virtually the same formula, however the factor at the beginning ranges from 0.02 for dense sand to 0.10 for loose sand. Based on this, the values used in the analyses are considered acceptable.

| Table 4-2 They Tollit Tipeline Son Troperties | Table 4-2 | <b>Piney Point Pipeline Soil Properties</b> |
|---|-----------|---|
|---|-----------|---|

| Nominal Pipe Diameter<br>(in) | Axial Ultimate<br>Load<br>(lb/in) | Axial Spring<br>Constant (lb/in/in) | Lateral Ultimate<br>Load<br>(lb/in) | Lateral Spring<br>Constant (lb/in/in) |
|-------------------------------|-----------------------------------|-------------------------------------|-------------------------------------|---------------------------------------|
| 12                            | 68.3                              | 273.3                               | 300                                 | 400                                   |
| 16                            | 92.2                              | 369.0                               | 300                                 | 400                                   |

| $(\text{Cover Depth-5 rect}, \gamma = 125 \text{ per}, \gamma = 02.0 \text{ per}, \psi_{\text{low}} = 20^{\circ}, \psi_{\text{high}} = 54^{\circ}$ |                       |   |                |                      |                                     |                |                                       |                |
|--|-----------------------|---|----------------|----------------------|-------------------------------------|----------------|---------------------------------------|----------------|
| Nominal Pipe Diameter  | Axial U<br>Lo<br>(lb, | ial Ultimate<br>Load<br>(lb/in)<br>Axial Spring<br>Constant (lb/in/in |                | Spring<br>(lb/in/in) | Lateral Ultimate<br>Load<br>(lb/in) |                | Lateral Spring<br>Constant (lb/in/in) |                |
| (III)  | Lower<br>bound        | Upper<br>Bound  | Lower<br>bound | Upper<br>Bound       | Lower<br>bound                      | Upper<br>Bound | Lower<br>bound                        | Upper<br>Bound |
| 12   | 17.2                  | 39.7  | 85.8           | 198.6                | 138.3                               | 425.6          | 76.8                                  | 236.4          |
| 16   | 24.6                  | 56.9  | 122.8          | 284.3                | 187.5                               | 572.6          | 93.3                                  | 284.9          |

Table 4-3Soil Properties Based on American Lifelines Alliance<br/>(Cover Depth=3 feet,  $\gamma=125$  pcf,  $\gamma'=62.6$  pcf,  $\phi_{low}=28^{\circ}$ ,  $\phi_{high}=34^{\circ}$ )

#### 4.6. Code Compliance Analysis Assessment

The code compliance analysis reported by Mirant through its engineering contractor Dominion Engineering Inc. follows standard and accepted industry techniques for buried piping analysis. The software used, CAESAR, is a well known and respected commercially available program for piping analysis. Through detailed modeling the analysis can determine pipe stress resultants more accurately than closed form methods which rely on fully restrained or unrestrained assumptions. The program has built-in code compliance checking which combines pipe stress resultants and highlights analyses which exceed specified code allowables. Although detailed checking of the program output and formulation of resultants is beyond the scope of this review, we can accept the results of such a widely used analytical piping program with a great deal of confidence.

The analyses reported by Dominion focus on changes in direction, i.e. at both manufactured and field bends. Again this follows standard and accepted analytical approaches for design of buried piping since stresses and movement can be difficult to accurately assess at these locations and such locations are potential problem areas.

The geometrical and mechanical input values to this pipeline analytical program are relatively straightforward. The SMYS, modulus of elasticity and pipe diameters are not questioned. There was a question during the review as to whether the pipe wall thickness used was the nominal wall thickness or whether it was reduced to account for corrosion, i.e. a "corrosion allowance." During the teleconference reported elsewhere, the operator stated that he had reviewed his NDT results and that the detected corrosion did not warrant wall reduction. The technique for determination of allowable wall thickness from NDT corrosion results is a well documented and accepted industry practice and we note no technical areas of concern given the operator's assurance.

The restraint values for the buried piping analyses consist of the soil geotechnical properties. Soil geotechnical properties always have some variability and there is no code required technique for their formulation. Upon review of the values developed by Mirant's consultants we find that the restraint values are within ranges typically used in buried piping analysis for non-buoyant conditions.

Our review noted the possibility of variation of these values especially due to a high water table which would lead to lowered soil resistance. Mirant has stated that while the pipeline does cross under several streams or creeks and other areas where the soils are wet, no wrinkle bends other than the Swanson Creek failure are subjected to tidal wetlands (i.e., areas where the water table elevation

is equal to or higher the elevation of the pipeline) or are in a buoyant state. Nevertheless, there are other bends which are in a buoyant condition. During the teleconference reported elsewhere, the operator and his consultant stated that they had previously performed a sensitivity study of these soil values wherein the values used were both halved and doubled. The results were forwarded to the OPS as noted in Chapter 6 ("Additional Review Material") and the summary of these results is contained in Appendix B.

The review team performed a series of analyses to further explore the effects of lowered soil resistance values. Summaries of the review team findings are contained in Sections 5.4.1 and 5.4.2. Based on these findings, the review team notes the consistent trend that lowered soil resistance values lead to higher stress results for both hot bends and field bends. Thus those bends in buoyant conditions should be identified as such in the summary compliance demonstration report for the Piney Point Pipeline, with notes as to the effect of the higher movement and stresses that would be estimated through analysis at these bends.

The SIF and flexibility factors used for the elbows were not explicitly listed. We assume that the default values from B31.4 Figure 419.6.4(c) were used and this was verbally confirmed at the March 6 meeting. The final input values for the analysis are the operating conditions, i.e. the operating pressure and temperature difference. The analyses demonstrate compliance at 550 psi and we note that this limit should be expected to be reflected in operating limits and alarms of the pipeline but other than that we see no technical area of concern regarding pressure.

The use of a variable temperature difference based on pipeline temperature losses within the system was used in the analyses which is an atypical but not unique approach. The applied temperature differential is based on the difference between the operating temperature and the tie-in temperature. The tie-in temperature used in analyses to date (50°F) has been a point of discussion. The majority of the pipeline was constructed in summer and, consistent with standard practice, the tie-in temperature is based on the ambient air temperature at tie-in. Baker understands that Mirant has reviewed the ambient air recorded temperatures for the time of tie-in and that the value used is appropriate for most of the line. However there is at least one section that was excavated and some section of line replaced during winter. Since the rest of the pipeline was tied-in and backfilled, the stresses/strains are "locked-in" by the soil and thus should not be affected by a localized area. Thus, the concern for the reference temperature should be isolated to any such localized segment. Mirant/Dominion should include documentation addressing this issue in their summary report. In conclusion, Mirant/Dominion's approach on this point is consistent with both theory and standard practice, but should be documented in a final report. The allowable temperatures at each location is defined in the analyses and related to inlet and discharge temperatures at the physical stations of the system. Again, the analyses must demonstrate compliance at these limits and should be expected to be reflected in operating limits, procedures and alarms of the pipeline system to ensure that these limits are not exceeded. With this caveat, we note no further technical areas of concern.

## 5. Wrinkle Acceptance Criteria

This section focuses on the development of an acceptance criteria for existing wrinkles of the Piney Point pipeline. The Swanson Creek spill was determined to be caused by a fracture at an existing wrinkle in the pipeline which was not interpreted correctly after an inspection pig run. There are a number of existing wrinkles in the Piney Point pipeline which were tabulated after inspection runs. Since there is no US regulatory standard that addresses the integrity of pipelines in service which exhibits wrinkles, this is the more challenging issue for the determination of the fitness of the Piney Point pipeline to be returned to service.

To develop a criteria, the operator and his consultants utilized Finite Element techniques to closely model the near-field stress/strain state of wrinkles. It was understood by the review team that the initial study did not have complete information about the geometry of the in-situ wrinkles and so performed a parametric analysis to develop guidelines for excavation, inspection, and replacement where required of wrinkles in the pipeline. Since that initial study the in-situ information has become available and the operator and his consultant were utilizing this information in more detailed and specific studies of the more prominent wrinkles remaining after the completion of field replacement and remediation activities that were based on the aforementioned parametric study.

Detailed Finite Element modeling of the localized effects of loading on the pipe wall is an atypical, though not unknown, activity for the pipeline industry and each model must be carefully scrutinized to ensure that it adequately represents pipe response behavior. Thus, the first item for the review team was to carefully review the modeling assumptions and separately address their adequacy to the extent possible in the limited review.

Unlike specialized pipe stress programs, general commercial stress computer programs typically do not have built-in techniques for checking adequacy for fatigue based on the analytical results and rely on the user to develop guidelines for adequacy using the results. In any case, as mentioned above, there is no established regulatory standard for wrinkle acceptance that could be programmed into a commercial program. Thus, the second major focus of the review effort was to assess the methodology by which the Finite Element results were to be used to develop the estimate of the remaining life of the wrinkles and to further ensure that a clear methodology was established for acceptance that had an appropriate factor of safety on this estimate of remaining life.

Section 5.1 contains reviews of the reports submitted by the operator and his chief consultants in this area, Kiefner and Dominion. The first two reports reviewed in Section 5.1, a discussion of the availability of criteria for wrinkles and a more "high-level" discussion of the propensity for wrinkle development in the pipeline, were generally seen as precursor reports to more detailed analysis. The third and fourth reports reviewed in Section 5.1 were viewed as nearly independent studies completed by the two engineering consultants, Kiefner and Dominion. These studies were "indepth" studies to evaluate the specifics of the Piney Point pipeline and specific criteria for wrinkle acceptance for this pipeline. Section 5.2 presents discussions from a teleconference with Mirant and its engineering consultants. Section 5.3 summarizes initial findings of the review with the remaining sections detailing the main issues. The final section presents the overall assessment of the wrinkle acceptance criteria development for the Piney Point Pipeline.



#### 5.1. Review of Relevant Reports

#### 5.1.1. "Industry Acceptance Standards for Wrinkles in Pipelines" (CC Technologies Services, Inc., and Kiefner)

This document by CC Technologies Services, Inc. and Kiefner presents a review of Codes or Industry Standards to identify criteria by which the anomalies reported on the Piney Point Pipeline may quickly be evaluated to determine whether further action is required.

A brief discussion of American Code provisions (Code of Federal Regulations (CFR) Title 49 Parts 192 and 195, American Society of Mechanical Engineers (ASME) Piping Code B31.4 and B31.8) related to pipe bends and wrinkles is given. This is followed by information on wrinkle acceptance criteria in Australian Standard AS 2885-1987 and-1997 and Canadian Standards Association CSA Z662-1999.

Finally, a discussion of industry research related to structural integrity aspects of wrinkles or buckles in pipelines, including work done for the Trans Alaska Pipeline System, the Australian Pipeline Industry Association and the Line Pipe research Supervisory Committee of Pipeline Research Council International (PRCI) is presented.

Several references related to pipeline wrinkling and buckling research, many of which form the basis for AS 2885.1-1997, are presented. A wrinkle (or ripple) acceptance criteria based on PRCI research, that was proposed as an alternative to the current provisions of 49 CFR 192, is given.

#### 5.1.1.1. Key Assumptions and Findings

• US Codes

Relevant United States pipeline codes and standards contain no criteria that allow acceptance of bends that do not have smooth contours during pipeline construction. Neither do these codes present such criteria in the operation and maintenance sections.

#### <u>49 CFR 195:</u>

§195.212 Bending of pipe.

- "(a) Pipe must not have a wrinkle bend.
  - (b) Each field bend must comply with the following:
  - (1) A bend must not impair the serviceability of the pipe.
  - (2) Each bend must have a smooth contour and be free from buckling, cracks, or any other mechanical damage..."

#### ASME B31.4:

§434.7.1 Bends Made From Pipe.

"(b) Bends shall be made in such a manner as to preserve the cross-sectional shape of the pipe, and shall be free from buckling, cracks and mechanical damage..."

• Foreign codes.

AS 2885.1-99:

Defines a buckle as "an unacceptable irregularity in the surface of a pipe caused by a compressive stress".

Differentiates between "ripples or buckles" formed during cold field bending and those that may be formed as a result of other causes. For bends other than cold field bends, the buckle height cannot be greater than 50% of the wall thickness, must blend smoothly with the adjacent pipe, and cannot reduce the internal diameter to less than the approved minimum value.

§6.6.3 Acceptance limits for field bends

"Unless approved by the operating authority on the basis of a specific test program, acceptance limits defined in the cold field bending procedure shall be as follows:

- (a) The height of any buckle shall not exceed 5% of the peak-to-peak length dimension in Figures 6.6.3(A) and 6.6.3(B).
- (b) Ovality shall not exceed that specified in Clause 6.4.2.
- (c) Surface strain shall not exceed the lessor of the strain tolerance of the coating being used or 10%."

Clause 6.4.2 gives the acceptable ovality as 95%, i.e., the minimum internal diameter shall be 95% of the nominal value of the pipe being examined.

CSA Z662-99:

Section 4.3.1.1

"The designer shall be responsible for determining supplemental local stress design criteria for structural discontinuities, high-temperature thermoelasticity, fatigue evaluations, and structural limits for denting, wrinkling, secondary tensile loading, bending stresses in buried pipelines, and structural stability."

• Industry Research

PRCI Proposed wrinkle (or ripple) acceptance criteria:

No evidence of cracking, creases, or sharp features in the ripple.

Independent of specified strength, ripple heights up to 1.5 times the wall thickness are acceptable provided the wave length/height ratio exceeds 12.

On a case-by-case basis ripples can have a wave length/height ratio of less than 12.

#### 5.1.1.2. Key References

- Australian Standard AS 2885.1-97
- Canadian Standards Association CSA Z662-99
- Olson, R., Clark, T., Odom, T., "Evaluation of the Structural Integrity of Cold Field Bent Line Pipe", Paper 33, Proceedings of the Ninth Symposium on Line Pipe Research, September 1996.

#### 5.1.1.3. Conclusions of Review

No conclusions or recommendations for possible application to the Piney Point Pipeline are presented. Since no connection was made to the specifics of the Piney Point pipeline, there is no objection to this report.

#### 5.1.1.4. Further Work

The single failing in this report is the lack of application of the available quantitative criteria, namely the Australian code, to the Piney Point pipeline. This could be viewed as a "screening exercise" to note which wrinkles could be acceptable, without further detailed work and site specific data, based on this code even though it is understood to be applicable for new construction and its applicability and use for pipelines in service is not known. A worksheet developed by Baker that compares the results of the Australian code criteria with other criteria, including the Piney Point project specific criteria, is presented in Table 5-1 of this report.

#### 5.1.2. "Evaluation of Failure Risks Associated with Wrinkles in Buried Pipelines" (Dominion)

This report by Dominion presents generalized information regarding formation of wrinkles and risks of wrinkles in service. The report is summarized as follows:

- 1. First, a discussion of various pipeline failure mechanisms is presented and concludes that "only progressive failure mechanisms are of structural concern for the Piney Point pipeline return to service." It further states "the progressive failure mechanism that is of primary concern is fatigue cracking at high stress locations, notably wrinkle bends."
- 2. The report next discusses the effects of temperature changes on buried pipelines, and the concept of soil restraint to prevent buckling of straight pipe and excessive bending at changes in direction.
- 3. Characteristics of wrinkle bends (small changes in direction of the pipe containing through wall bending distortions) on the Piney Point pipeline and how these bends might occur are reviewed.
- 4. Next, the report postulates that any accentuation or formation of wrinkles in the Piney Point pipeline likely occurred during the first few heat/pressurize cycles and how the results of finite element analyses indicate localized plasticity is expected on the first heat cycle. The report states "This deformation stabilizes the wrinkle geometry" through redistribution of stresses in the bend and wrinkle, and strain hardening of the pipe material.
- 5. The conditions where additional inelastic deformation on subsequent heat/pressurize cycles might be expected are given as:



- Strain ratcheting a strain range of a magnitude to cause reverse plasticity on each loading/unloading cycle.
- Increased loads on subsequent cycles.
- Degradation of soil support conditions.
- 6. Finally, the Swanson Creek failure is discussed. This discussion focuses on the argument that the Swanson Creek wrinkle was an outlier compared to the other wrinkle bends that have been examined.

#### 5.1.2.1. Key Assumptions and Findings

"No potential failure mechanisms that could lead to pipe wall ruptures in the short term have been identified for the Piney Point pipeline."

#### 5.1.2.2. Key References

None

#### 5.1.2.3. Conclusions of Review

The report states "*The (Swanson Creek) failure location was also in poor soil conditions that probably resulted in inadequate support for the pipe at a direction change.*" The question that arise from this statement are reflected in the questions asked concerning geotechnical conditions and properties during the January 29, 2003 teleconference.

This report presents a fair background and overview of the problem but is mostly qualitative in nature. The calculations of buckling force presented only account for temperature differential and do not include pressure forces (calculated as the internal pressure multiplied by the cross-sectional flow area of the pipe). Buckling and anchoring checks must include both temperature and pressure effects as is mentioned later in the review of "Acceptance Criteria for As-Inspected Wrinkles in Piney Point Oil Pipeline" (Dominion). In summary, this report is seen as subservient to the more definitive report: "Acceptance Criteria for As-Inspected Wrinkles in Piney Point."

#### 5.1.2.4. Further Work

The sole question regarding the soil properties and evidence of better conditions at other changes in direction than at the failure point has already been covered adequately by the discussion regarding soil conditions in for use in the Code Compliance Demonstration in Chapter 4.

#### 5.1.3. "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline" (Kiefner)

This report by Kiefner presents analyses based on classical engineering mechanics principles of the design and wrinkling potential of the Piney Point Hot Oil Pipeline and was seen to represent a parallel effort to a similar evaluation undertaken by Dominion. The stated purpose of both analyses is to "determine the extent of the risk, if any, that other existing wrinkles in the pipeline could cause a failure in the future" as an aid to help decide "when and under what circumstances the pipeline can be returned to service". The overall flow of the calculations is reduced to bullet form as follows:
Michael Baker Jr., Inc.

- The analysis begins with an evaluation of the longitudinal stresses in a straight section of fully restrained pipe per ASME B31.4 §419.6.4(b) and calculation of the corresponding maximum shear (Tresca) stress for a temperature differential of 110°F and an internal pressure of 400 psi for the subject 12-inch and 16-inch pipes. The calculated Tresca stresses are below 90% of the Specified Minimum Yield Strength (SMYS) for both pipes. The temperature differential corresponding to a Tresca stress equal to 90% SMYS for the 12-inch and 16-inch pipes are computed as 148.8°F and 141.4°F, respectively.
- 2. The next calculation provides the thrust force on a fully restrained pipe for a temperature differential of 110°F and an internal pressure of 400 psi for the subject 12-inch and 16-inch pipes. The corresponding calculated forces are 194.8 kips and 268.3 kips, respectively.
- 3. The report then provides a narrative on issues related to soil friction based on References 4 through 16. The main items discussed are the thrust force, the active length (i.e., length to virtual anchor), the axial deflection of the free end, the friction force, the soil uplift resistance, lateral resistance and the coefficient of sub-grade reaction. Formulas from selected references are provided for each of these quantities. Calculated values of these parameters are presented in Tables 2 and 3 of the Kiefner report.
- 4. The analysis then proceeds with calculation of the buckling load for straight pipe based on beam on elastic foundation principles (using a linear coefficient of subgrade reaction). The calculations show that the buckling loads are approximately 14 times larger than the fully restrained thrust loads.
- 5. The next analysis considers an Euler buckling formulation for upheaval (upward) buckling (again, using a linear coefficient of subgrade reaction). These calculations show that the Euler buckling loads are approximately 6 to 8 times larger than the fully restrained thrust loads.
- 6. The next analysis considers upward buckling of a beam with an initial sinusoidal deformation pattern. These calculations suggest that "even with the maximum possible elastically curved overbend, the axial load due to temperature change will not cause upward buckling of the pipeline since the tendency to buckle upward will be offset by the downward deflection from the weight of the soil overburden, pipe and contents".
- 7. The calculations then proceed to evaluate the distributed soil force reaction associated with the computed thrust force for a cold bend with the ASME B31.4 minimum radius. The distributed forces for the 12-inch and 16-inch pipelines are about 10.2 kips per lineal foot (klf) and 11.2 klf, respectively. These values are over 3 times larger than the computed passive lateral resistance for the 12-inch and 16-inch pipelines, respectively. This leads to the conclusion that movement can be expected at bends even under relatively modest temperature differentials.
- 8. The report then moves forward with calculation of the forces and moments in a pipe bend based on: (a) hand calculations for bends made from a single miter joint and (b) CAEPIPE<sup>TM</sup> calculations for a buried pipe bend. No clear connection is made between the hand calculations and the CAEPIPE results. However, the forces and moments computed from CAEPIPE are utilized in subsequent fatigue calculations.
- 9. Using the "worst case" forces and moments computed by CAEPIPE, the report proceeds to compute an "intensified" stress quantity assuming a wrinkle amplitude of 1.5 times the wall





thickness. The formula used for the wrinkle stress intensification factor is based on a publication by Arav on bends with local corrugations (Reference 19). The computed stress intensification factors are 4.2 for the 12-inch pipe and 3.8 for the 16-inch pipe. The intensified stress ranges are about 175 ksi for the 12-inch pipe and 153 ksi for the 16-inch pipe.

10. The intensified stress ranges are then used directly with the ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 Figure 5-110.1 (Design Fatigue Curve) to compute an allowable number of cycles. The allowable number of cycles for the 12-inch and 16-inch pipes are 855 and 1240, respectively.

## 5.1.3.1. Key Assumptions and Findings

The report concludes that:

- "there is no reason to expect the formation of new wrinkles in straight segments of the Piney Point Pipeline in locations where the soil is stable".
- "an overly conservative analysis of the field bends suggests that even those that contain wrinkles having crest-to-trough heights less than or equal to 1.5 times the wall thickness have a substantial amount of serviceability in terms of fatigue life".
- "the assumption of a relatively weak soil" lead to prediction of 855 and 1240 allowable cycles for the 12-inch and 16-inch pipes, respectively subjected to a temperature differential of 110°F.
- "the elastic stresses in some of the larger bends would slightly exceed the ASME B31.4 design limit."
- "the near-term risk of failure from any unrepaired anomalies meeting the acceptance criterion is negligibly small".

## 5.1.3.2. Key References

This report cites several references related to buried pipe analysis (References 4 through 16). One of our main observations is that most of these references are dated pre-1981. Two additional references on the subject of geotechnical properties for buried piping analysis were not cited but are used by the reviewers, namely;

- ASCE, "Guidelines for the Seismic Design of Oil and Gas Pipeline Systems", Committee on Gas and Liquid Fuel Lifelines, 1984.
- American Lifelines Alliance (ALA) "Guidelines for the Design of Buried Steel Pipe", Published by the ASCE American Lifelines Alliance, July 2001.

The calculations contained in the above two references, and especially the second reference above, represent the state-of-the-art with respect to calculation of longitudinal, transverse, horizontal, uplift and bearing pipe-soil spring properties as a function of soil density, friction angle, cohesion, cover depth, etc. Soil properties used by Kiefner are compared to these values in Chapter 4.

Other key references are:

• Arav, F., "Evaluation of Pipe Bends Having Local Corrugations", Third International Conference on Pressure Vessel Technology, Part 1, Analysis, Design and Inspection (1977)

• ASME Boiler and Pressure Vessel Code, Section VIII, Division 2.

## 5.1.3.3. Conclusions of Review

All of the analyses presented in this report appear to be based on the assumption of linear elastic pipe-soil spring response. This linearization of the soil behavior is cited as a necessary simplifying assumption for the conceptual analyses contained herein, which permits the development of bounding estimates of the behavior of the pipeline. While a linearization of the soil is required for the hand calculations, most pipe stress analysis computer programs permit the use of nonlinear, elastic-plastic pipe-soil springs. The use of nonlinear, elastic-plastic pipe-soil springs is within the state of the practice and would provide an increased confidence in the pipe-soil evaluation.

The report states that the term "U" in Equation (12) is defined in Equation (11) but there is no "U" in Equation (11). Presumably, it was intended to use  $R_p$  instead of "U".

Many of the formulas presented for calculation of soil resistance are based on the soil density defined as  $\gamma$ . A density of 125 pcf appears to have been used throughout. For locations where the pipe is buried below the water table, the density of the soil below the water table should be taken as the buoyant density commonly referred to as  $\gamma'$  where  $\gamma' = \gamma - \gamma_w$  (where  $\gamma_w$  is the density of water = 62.4 pcf). For this soil, the submerged (buoyant) density would be  $\gamma'=125-62.4=62.6$  pcf (roughly 50% of the assumed density). Hence, all of the soil resistance terms that depend on the density would be substantially reduced in the presence of a high water table (e.g., water table elevation at or above the ground surface elevation). The soil strength reduction due to buoyancy effects is most pronounced in cohesionless soils. A reduction of the soil strength would lead to a further increase in the propensity for the movement at buried bends. If the pipe is located below the ground water table, an additional upward buoyant force (equal to the weight of the water displaced by the pipe) should also be included in the analysis.

The hand calculations for buckling load presented in this report are a reasonable starting point to eliminate elastic column buckling of the pipe as a potential initiator/driver of excessive pipe deformations (e.g., wrinkles), although it is noted that numerical simulation of buckling of buried pipes is also within the state-of-the-practice (e.g., using computer programs such as UPBUCK<sup>™</sup> or PIPLIN<sup>™</sup>). Numerical analyses of this sort (somewhat similar to the CAEPIPE analyses presented in this Kiefner report) can be used to rapidly compute buckling loads and displacement patterns for straight pipe sections as well as for more general bend or "hump" geometries. These programs also allow for the consideration of pipe yielding and the use of nonlinear, elastic-plastic pipe-soil springs (i.e., inelastic beam on inelastic foundation). Analytical tools of this sort allow for rapid assessment of buckling for a wide range of soil parameters (e.g., lower/upper bound strengths). Nevertheless, the hand calculations suffice in this instance.

A clear connection was not evident between the hand calculations developed for miter bends and the CAEPIPE analyses and it does not appear that the results from the hand calculations were utilized. It appears that these hand calculations could have been excluded without significantly impacting the flow or conclusions reached in the report.

Regarding the computer analyses, CAEPIPE is presumably based on finite element analysis for elastic pipe material with a small-displacements formulation. As previously stated, most pipe stress analysis programs allow for nonlinear soil (and support) behavior. The report did not clearly state



how the pipe-soil springs were modeled although some of the notes written in the CAEPIPE results appear to indicate that the pipe-soil springs were assumed to be linear.

Examination of the deflected shapes provided in the CAEPIPE outputs appears to indicate that the deflected shapes are not symmetrical about the apex of the bend as would be expected.

In the absence of detailed information regarding the wrinkle geometry, the use of Arav's stress intensification factors for wrinkle heights of 1.5 times the wall thickness seems like a reasonable starting point for screening purposes. The use of the intensified stresses with the Section VIII, Division 2 *design* fatigue curve also seems like a reasonable starting point.

Thus, the review found that the only significant deficiency in this report was field data or observations that support the underlying assumption of the soil restraint values. In this regard, it is important to note Kiefner's conclusion listed under the first bullet in Section 5.1.3.1 of this report that no wrinkles are expected to form in straight segments of the pipeline "in locations where the soil is stable" and the conclusions listed under the second and third bullets in Section 5.1.3.1 regarding an "overly conservative analysis" and "the assumption of relatively weak soil".

## 5.1.3.4. Further Work

Based on the review, questions were formulated for Mirant and its engineering contractor, Kiefner, concerning this report. The questions are listed below, and it is noted that most of the questions relate to the soil restraint values which were previously explored in the review for the Code Compliance Demonstration:

- Are any segments of the pipeline located in unstable soil?
- Why are the deflected shapes of the bends not symmetrical?
- To what extent would these conclusions change for bends in high water table locations with the pipe-with soil spring properties computed using buoyant soil densities?
- What is/was the elevation of the water table relative to the ground surface elevation at the failed wrinkle location?
- What are the soil conditions in the vicinity of the failed wrinkle location?
- Are there bends in the pipeline that are buried in locations with a high water table?
- What pipe-soil spring properties were used in the CAEPIPE models?

#### 5.1.4. "Acceptance Criteria for As-Inspected Wrinkles in Piney Point Oil Pipeline" (Dominion)

This report by Dominion provides a discussion on a series of elastic and elastic-plastic finite element analyses (FEA) and fatigue damage calculations that were used in the development and assessment of the wrinkle acceptance criteria for the Piney Point Pipeline.

#### FEA of Wrinkle Bends

A series of elastic and elastic-plastic finite element analyses was undertaken using ANSYS<sup>TM</sup> to develop a basis for determining the acceptability of local wrinkle deformations. The wrinkle geometry parameters that were varied are listed as follows:

- 1. The aspect ratio (i.e., the ratio of the longitudinal wrinkle wave length to the peak-to-trough height of the wrinkle). Aspect ratios of 12, 9 and 6 were considered with selected additional cases considering aspect ratios of 7.5 and 3.
- 2. The maximum peak-to-trough height of the wrinkle. Wrinkle heights of 150%, 300%, 400%, 500% and 600% of the wall thickness were considered.
- 3. The circumferential extent of the wrinkle. Circumferential extents of 90, 180 and 270 degrees (centered on the intrados) were considered for the elastic analysis cases while circumferential extents of 120, 150 and 180 degrees were considered for the elastic-plastic analysis cases.

A model of the wrinkle that failed at Swanson Creek was also evaluated. The key response quantities include the peak stresses from the elastic models and the reversing plastic strain from the elastic-plastic models.

#### Fatigue Life Assessments

Two methods were used to assess the cumulative fatigue damage and remaining life for the various wrinkle geometries investigated.

The first fatigue assessment method is based on experimental data showing reversals to failure versus reversing plastic strain for steels "similar to the pipeline's API 5L Grade X42 steel". This assessment method showed that all wrinkles with aspect ratios of 7.5 or greater and circumferential extents of 180 degrees or less have computed reversing plastic strain values that would result in failure after approximately 2500 cycles or more. Additionally, the geometry of the wrinkle that failed at Swanson Creek was calculated to have a reversing plastic strain that would result in failure after approximately 200 cycles. These results lead to the conclusion that "the wrinkles that meet the acceptance criteria have large margins on their remaining fatigue lives".

The second fatigue assessment method is based on the ASME Boiler and Pressure Vessel Code Section III Class 1 fatigue design rules. (This S-N relationship is identical to the ASME Section VIII, Division 2 fatigue relationship used in "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline" by Kiefner). The alternating stress intensity computed from elastic analysis is used directly with the ASME *design* fatigue relationship to compute design fatigue lives for the different wrinkle geometries. This assessment method showed that all wrinkles with aspect ratios of 7.5 or greater and circumferential extents of 180 degrees or less have design fatigue lives greater than the 150 cycles experienced to date. The geometry of the wrinkle that failed at Swanson Creek was calculated to have a design fatigue life 40% lower than the 150 cycles experienced to date.

## 5.1.4.1. Key Assumptions and Findings

The key findings from this report are summarized in two parts under Section II. Part 1 discusses the FEA of wrinkle bends and Part 2 discusses fatigue life based wrinkle acceptance criteria.

#### FEA of Wrinkle Bends

The analysis results show that:

- Elastic peak stresses and reversing plastic strain increase with decreasing wrinkle aspect ratio and increasing circumferential extent.
- For a given aspect ratio, elastic peak stress and reversing plastic strain decrease with increasing wrinkle height *[for aspect ratios of 9 and 12]*.
- The elastic peak stress and reversing plastic strain for the wrinkle that failed at Swanson Creek are significantly higher than other wrinkle geometries measured during investigative digs.
- The wrinkle acceptance criteria developed by Dominion was selected such that plasticity should be limited to a small enough region to preclude ratcheting effects. A wrinkle geometry was considered acceptable only when the reverse plastic strain that occurs on unloading is limited to a small region on only one surface of the pipe (i.e., on the ID or on the OD, but not both).

#### Fatigue Life Based Wrinkle Acceptance Criteria.

The overall conclusions made in this report are as follows:

- Wrinkles with aspect ratios of 7.5 or greater and circumferential extents of 180 degrees or less are acceptable for immediate return to service.
- Wrinkles with an aspect ratio of 7.5 and a circumferential extent of 180 degrees have expected fatigue lives ten times greater than the Swanson Creek wrinkle geometry, based on experimental data.

#### 5.1.4.2. Key References

- ASME Boiler and Pressure Vessel Code, Section III, Nuclear Vessels, 1998 Edition with Addenda through Summer 2000.
- ANSYS Engineering Analysis System, Revision 5.6, ANSYS, Inc.
- Boyer, H., "Atlas of Fatigue Curves," American Society for Metals, 1986.

#### 5.1.4.3. Conclusions of Review

This is the key document for the wrinkle acceptance criteria. Kiefner defers to the details of this report in their companion document. As such, it received a great deal of scrutiny and forms the focus for the review effort for wrinkle criteria.

Overall, the review team agrees that the analyses presented in this report are of high quality and that the report provides a useful framework for developing wrinkle acceptance criteria. In our opinion, the primary shortcomings of this work are related to the unknown level of conservatism provided by neglecting soil effects in the finite element analysis combined with the exclusion of internal pressure load as part of the typical operating cycle.



Nevertheless, because of the importance of this report, a number of detailed questions evolved during the review – many of them to ensure the reviewers understanding of the analytical procedure. Accordingly, many questions asked during the teleconference with the operator and his consultants relate to the details of the finite element model, the assumed loading, and the FEA results.

#### 5.1.4.4. Further Work

Based on the review, questions and comments were formulated for Mirant and its engineering contractor, Dominion, concerning this report. The questions and comments are listed below, and it is noted that most of the questions relate to the FEA. A summary of the responses are listed in Section 5.2 of this report:

- 1. Can Dominion provide a brief description or reference document on the 20-node SOLID95 finite element and the elastic-plastic material model used in elastic-plastic analyses (e.g. yield criterion, hardening rule, etc.)?
- 2. The stress-strain coordinates shown in Figure III-4 are presumably true-stress, true-strain values. What are the stress-strain coordinate values? Are these stress-strain coordinates based on representative test data for X-42 pipe? Were any sensitivity studies performed on the shape of the stress-strain curve?
- 3. The finite element mesh appears to consider a single bend angle of 5-degrees. Is there a reason why a single bend angle was considered?
- 4. We believe that providing the wrinkle geometry as input is a reasonable and practicable approach for considering a wide range of wrinkle profile geometries.
- 5. Regarding the FEA meshes, what were the minimum longitudinal and circumferential element dimensions?
- 6. Why were different circumferential extents considered for the elastic and elastic-plastic analyses?
- 7. For the elastic-plastic analyses, did the profile and circumferential extent of the wrinkles change appreciably? How much ovalling occurred in the bend?
- 8. The FEA results were tuned to provide target levels of elbow displacement under a constant axial load (equal to the fully restrained thermal force) by varying the leg lengths. What was the basis of "tuning" the FEA results to provide bend center deflections of 1, 1.5 and 3 inches? What sort of leg lengths are required to reach these deflections?
- 9. Why was the internal pressure load not considered in the FEA models? We believe that the presence of internal pressure would have at least three potentially important influences:
  - a. The inclusion of a "cap force" (the longitudinal force acting on the fluid column contained in the pipe is equal to the product of the internal pressure and the bore area). As the pipe turns through a bend, the cap forces from each leg combine to provide a net outward resultant disturbing force on the pipe. This force would tend to increase the outward displacement of the bend.



- b. The addition of "pressure stiffening" of the pipe cross section which would tend to resist ovalling and additional distortion in the vicinity of the wrinkle.
- c. The addition of hoop tension which would tend to create a more bi-axial stress condition in the pipe wall which in turn could increase yielding (plastic flow) at/near the wrinkle on the compressive side of the pipe in the elastic-plastic model.
- 10. The elastic analysis results would be easier to spot check if the nominal axial force and bending moment quantities were also tabulated so that a "Stress Concentration Factor" or SCF could be computed for a given wrinkle geometry (the SCF is typically taken as the ratio of the peak stress to the nominal stress). Are any sample moment diagrams available?
- 11. The presence of soil around the pipe at a bend subject to pressure and temperature differential loads would result in the engagement of a profile of transverse soil bearing forces (e.g., on the outside of the bend) as well as a profile of longitudinal pipe-soil engagement. It is also possible that a gap could form between the pipe and the soil along the inside of the bend as the bend moves outward (depending on the soil conditions). It is also physically reasonable to expect that the presence of soil could act to restrain ovalling of the pipe section as well as local flexing at/near a wrinkle. Although it is possible to capture many of these pipe-soil interaction effects in a "pipe (beam) on inelastic foundation" model of the bend, it is particularly difficult to include soil effects in a "local" shell or solid mesh of the bend.
- 12. We understand that the FEA model was developed without soil in an attempt to provide a conservative basis for evaluation of wrinkle stresses and strains. No attempts were made to assess the degree of conservatism that results from neglecting the soil in the FEA. Perhaps overlay comparisons of the global moment diagrams from pipe-soil interaction analyses of a similar 5 degree bend configuration including soil (e.g., similar to the CAEPIPE and CAESAR analyses presented in other reports) would provide a starting point for assessing the degree of conservatism provided by neglecting the soil in the FEA. [This is further addressed in Section 5.3]. A review of the pipe bending moment diagrams obtained from pipe-soil interaction analyses of a side bend in a 16-inch diameter by 0.219-inch thick buried pipe model indicates that the shape of the moment diagram used by Dominion provides a fairly reasonable approximation to the shape of the moment diagram computed considering pipe-soil interaction.
- 13. It is our experience that the growth of a wrinkle under displacement controlled loading is somewhat analogous to the formation of a "bending hinge" allowing for a concentration of curvature at the wrinkle with an associated redistribution (unloading) of moment and straightening in the adjacent pipe sections on either side of the wrinkle. The report indicates that changing the material properties from elastic to elastic-plastic "tends to spread out the strain in regions of high stress, such as the wrinkle center". We would have expected the converse of this statement to be true i.e., allowing the material to yield would tend to spread out (redistribute) the stress in regions of high deformation (strain). Perhaps this is a result of the temperature differential being applied under force control instead of displacement control?
- 14. The elastic-plastic analysis results were processed to provide the stress/strain response at the "wrinkle center" and the "wrinkle edge". We observe that the wrinkle edges shown in Figure III-3 appear to contain a relatively sharp corner. As an aside, we observe that the photograph shown in Figure 2.3 (of this report) appears to show the presence of small side lobes on either side of

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the main wrinkle lobe. We believe that consideration of wrinkles with a single inward or outward lobe with relatively sharp corners is a reasonable approximation. However, our experience with ripples measured on the intrados of cold bends often indicates the presence of multiple adjacent ripple lobes with both inward/outward components.

- 15. For the elastic-plastic analyses, the loading simulates the application of a single thermal load cycle from ambient to maximum temperature and back to ambient. Were any of the analyses extended to consider additional thermal load cycles to check if the model shakes down to elastic behavior?
- 16. Using the maximum computed reversing plastic strain from a wrinkle model with an aspect ratio of 7.5 and from a model of the wrinkle that failed at Swanson Creek, a fatigue evaluation was performed using the lower curve of the "band for undeformed specimens" on the total strain amplitude versus reversals to failure plots shown in Figures III-14 through III-18. For the wrinkle with an aspect ratio of 7.5, approximately 2500 cycles to failure were predicted. For the wrinkle that failed at Swanson Creek, approximately 200 cycles to failure were predicted. We observe that the lines shown as the "band for undeformed specimens" appear to envelope most of the experimental data points and that a curve drawn through the middle of this "band" would be nominally centered on the mean path of the data points. Hence, the lower curve of the band provides some margin of safety relative to the mean path of the data points.
- 17. Additional fatigue calculations were performed using the maximum alternating stress intensity from elastic analysis with the ASME design fatigue curve. The results from this evaluation are presented in Table III-4. Based on this assessment, Dominion concludes that "any configuration that has a design fatigue life greater than the estimated 150 operation cycles the pipeline has experienced to date is acceptable to returned to service without modification". [Subsequent correspondence from Dominion indicates that the ASME design fatigue curve can not be used when the elastic stress intensity exceeds 60 ksi. Apparently this limitation was not considered in the development of Table III-4 since most of the tabulated stress intensity values exceed 60 ksi].
- 18. An "apples-to-apples" overlay of the fatigue data presented in Figures III-14 through III-19 with the ASME design S-N values (as well as other well established S-N relationships) might provide a useful indication of the margins of safety associated with these fatigue calculations.

## 5.1.5. "Mirant Piney Point Pipeline: Wrinkles and Bends" (PSC)

This report was prepared by Elizabeth Skalnek of the Maryland Public Service Commission. The report provides a critique of the MPP pipeline engineering analyses performed by DEI, Keifner and CC Technologies on behalf of Mirant.

#### 5.1.5.1. Key Assumptions and Findings

This report makes the following conclusions:

1. §195.402(d)(2) defines exceeding design limits as an "abnormal operation" – it could be argued that "normal" operating conditions must not exceed design limits. Section 402 of Part 195 is retroactive and the design limits therefore become retroactive. If this argument stands, wrinkles must comply with §195.110.



- Wrinkles in the MPP pipeline violate §195.110 design requirements (must meet ASME B31.4 section 419) at their stated "normal" pipeline operating conditions.
- Wrinkles in the MPP pipeline violate ASME B31.4 section 419 requirements at MPP pipeline normal operating limits.
  - Thermal cycling between 1972 and 2000 exceeded the design limits of the pipeline at wrinkles.
  - = Thermal cycling at current operating conditions will fatigue wrinkles, possibly leading to rupture.
- Bends (Hot & Cold) and wrinkles must meet the design limits set by §195.110 which references ASME B31.4 section 419.
  - = ASME B31.4 design limits are exceeded for some bends at the current operating conditions.
  - Thermal cycling between 1972 and 2000 exceeded the design limits of the pipeline at some bends.
- Pipeline installation temperature determines the stress-free reference temperature for ASME B31.4 section 419 analysis. Maximum and minimum operating temperatures must not stress the pipeline beyond 90% of SMYS for restrained pipelines.
  - *Pipeline installation temperatures for the Morgantown and Chalk Point segments of the MPP pipeline may have been as low as 32 F.*
- 2. Operating temperatures, maximum– minimum, determine the thermal cycling delta T for purposes of fatigue analysis.
  - *Minimum operating temperatures would be close to ambient temperatures for #2 flushing oil.* 
    - Number 2 flushing oil was pumped from Piney Point to Morgantown when ambient temperatures were between 15 F and 42 F in February 2002.
    - = Number 2 flushing oil was pumped from Morgantown to Ryceville in February 2002.
    - = Number 2 flushing oil was pumped routinely from Chalk Point to Ryceville during pumping operations.
  - Some wrinkles may continue to fatigue as the result of ambient temperature variations (even without pumping hot oil to induce thermal cycling), especially near river crossings and in areas of less than 3' burial depth.
- 3. Fatigue experienced by pipeline to-date has not been adequately characterized. Operating temperatures between 1972 and 2002 are not known.
  - No cracking has been observed to-date in any excavated feature other than the ruptured wrinkle at Swanson's Creek.
  - Localized hardening at high stress locations on wrinkles removed from the MPP pipeline



confirm that metallurgical changes have occurred as the result of the thermal cycling in the wrinkles.

4. Internal Inspection techniques do not have the capability to monitor the geometry of wrinkles.

This report also makes the following recommendations:

- 1. Reject Mirant's position that the MPP hot oil pipeline may continue to operate with wrinkles with an aspect ratio greater than 7.5 which exceeds ASME B31.4 section 419 under their current operating conditions.
- 2. Limit the maximum operating temperature range for the MPP pipeline to meet the requirements of ASME B31.4 section 419 at all locations, especially at bends and wrinkles.
- 3. Identify bends that have experienced excessive fatigue (based on ASME Boiler Pressure Vessel Codes) due to thermal cycling between 1972 and 2002. Require repairs as needed.
- 4. Compel Mirant to monitor the temperature at all sensitive locations to insure that the maximum operating temperature range has not been exceeded.

Appendix I of this report contains the following list of unresolved questions:

- 1. Determine the wrinkle acceptance criteria that will meet ASME B31.4 section 419 at the MPP pipeline's current operating conditions.
- 2. Identify bends that have experienced excessive (more than 10% of life) fatigue based on ASME Boiler Pressure Vessel Codes due to thermal cycling between 1972 and 2002.
- 3. Document Thermal cycling limits
  - Pipeline Operating Temperatures 1972 2002
  - Installation temperatures 1971Morgantown -1972 Chalk Point
    - *Mirant must verify that oil has never been reheated at Ryceville for delivery to Piney Point.*
- 4. Calculate B31.4 Section 419 Maximum Allowable temperature at wrinkles left in service.
- 5. Tabulate size of features in 1997 vs. size of features in 2001 to substantiate claim that "no growth" has occurred in features.
- 6. Obtain Fatigue curves for X42 pipeline steel.
- 7. Mirant must justify their claim that fatigue data included in their study is not relevant.
- 8. Was Hoop Stress considered for maximum alternating stress intensity in table III-4 of "Acceptance Criteria for As Inspected Wrinkles in the Piney Point Oil Pipeline"?
- 9. Correlation of burial depth less than 3' with "features of interest"
- 10. Mirant must evaluate bends that have experienced stresses that exceed 90% SMYS since the pipeline was last inspected for cracks.
  - The minimum temperature at the time of installation could not be demonstrated to be above 50 F at Chalk Point and Morgantown. Recent pumping operation consisted of pumping



~40 F #2 fuel oil from Piney Point to Morgantown.

## 5.1.5.2. Key References

A total of 26 different references are provided in Appendix V. The key reference appears to be:

• Dominion Engineering, Inc., "Acceptance Criteria for As Inspected Wrinkles in the Piney Point Oil Pipeline – DEI 656 – Revision 0", January 2001.

## 5.1.5.3. Conclusions of Review

All involved parties should agree on the tie-in temperature and operating temperature limits to be used in the pipeline analyses. The applied temperature differential is based on the difference between the operating temperature and the tie-in temperature. The tie-in temperature used in analyses to date (50°F) has been a point of discussion. The majority of the pipeline was constructed in summer and, consistent with standard practice, the tie-in temperature is based on the ambient air temperature at tie-in. Baker understands that Mirant has reviewed the ambient air recorded temperatures for the time of tie-in and that the value used is appropriate. However there is at least one section that was excavated and some section of line replaced during winter. Since the rest of the pipeline was tied-in and backfilled, the stresses/strains are "locked-in" by the soil and thus should not be affected by a localized area. Thus, the concern for the reference temperature should be isolated to any such localized segment. Mirant/Dominion should include documentation addressing this issue in their summary report. In conclusion, Mirant/Dominion's approach on this point is consistent with both theory and standard practice, but should be documented in a final report.

On pages 2 and 3, MDPSCED indicates concern over the ability of the smart pigs to evaluate wrinkle geometry. While no information is presented as to the applicability of UT data as a means of evaluating wrinkle geometry, some of the information we have reviewed appears to indicate that UT pig data signatures were well correlated with physical measurements taken at excavated wrinkles. We are familiar with caliper data gathered by the Geopig and believe that the Geopig can do a good job of characterizing wrinkle geometry (therefore, we disagree with Conclusion 4 from this report as it relates to the Geopig). It would be useful to examine how well the 2001 Geopig caliper data correlated with the UT based and physically measured wrinkle geometries. It would also be useful to review the feature sizes from 1997 data as compared to the feature sizes from 2001 data (as mentioned under unresolved question 5) to confirm that no growth has occurred.

On page 5, this reference cites ASME B31.4 section 419(c) with respect to a term " $S_{max}$ " as the maximum allowable stress on a pipeline being limited to 90% SMYS. The actual stress limits set forth under B31.4 Section 419.6.4 with respect to section (b) *Restrained Lines* and section (c) *Unrestrained Lines* are described as follows:

For fully restrained pipe, the code defines a net longitudinal compressive stress due to the effects of temperature rise and fluid pressure as:

 $S_L = E\alpha(T_2 - T_1) - \nu S_h$ 

where:

 $S_L$ = longitudinal compressive stress;

 $S_h$  = hoop stress due to fluid pressure;

 $T_1$ = temperature at the time of installation;

T<sub>2</sub>= maximum or minimum operating temperature;

E = modulus of elasticity of steel;

 $\alpha$ = linear coefficient of thermal expansion ;

v = Poisson's ratio (0.3 for steel);

This (compressive) longitudinal stress is added to the hoop tension stress to compute an equivalent tensile stress based on the maximum shear stress (Tresca) theory. As specified under paragraph 402.3.2(c), this equivalent tensile stress shall not be allowed to exceed 90% SMYS. For the purposes of this review, we use the variable  $S_{TRESCA}$  to define the equivalent tensile stress quantity:

$$S_{\text{TRESCA}} = S_{\text{L}} + S_{\text{h}} \le 0.9 \text{ SMYS}$$

For unrestrained pipe, the code defines the following expansion stress term:

$$S_E = (S_b^2 + 4 S_t^2)^{1/2}$$

where:

 $S_E$  = expansion stress range;

 $S_b$  = resultant bending stress, including stress intensification effects, given by:

$$S_{b} = \frac{\sqrt{(i_{i} \cdot M_{i})^{2} + (i_{o} \cdot M_{o})^{2}}}{Z}$$

 $S_t = torsional stress = M_t/2Z;$ 

Z = pipe section modulus;

 $M_t$  = torsional moment;

 $M_i$  = in-plane bending moment;

 $i_i$  = in-plane bending stress intensification factor;

 $M_o = out-of-plane bending moment;$ 

 $i_o =$  out-of-plane bending stress intensification factor.

The expansion stress  $S_E$  is limited to 72% of SMYS:

 $S_E \leq 0.72 \text{ SMYS}$ 

Although the above equation does represent a fatigue check, this simple rule does not explicitly consider the number of expansion cycles "N". As a point of reference, the B31.1 and B31.3 code rules provide a means of including the number of expansion cycles in the allowable expansion stress via the stress range reduction factor "f" (note that the value of "f" is provided by tables or by the expression  $f=6(N)^{-0.2}$ .) Effectively, this normalizes the allowable stress to Markl's S-N fatigue curve developed for pipe with a girth weld (*i*=1). The value of "f" was established as 1.0 for 7,000 or fewer cycles in order to avoid making fatigue computations for facilities that do not experience a large number of cycles; 7,000 corresponds approximately to one cycle/day over 20 years of operation.

By referring to a stress limit of "90% SMYS" on page 5, MDPSCED appears to be considering the pipe as if it were fully restrained. MDPSCED then uses the elastically computed maximum alternating stress intensity for a temperature differential of 110°F (from column 6 of Table III-4 of the DEI report "*Acceptance Criteria for As Inspected Wrinkles in the Piney Point Oil Pipeline*") to compute a new quantity called the "*PSC calculated B31.4 Maximum Allowable Delta T*" which is shown in column 7 of the table on pages 4 and 5. This temperature differential corresponds to an elastically computed maximum alternating stress intensity equal to 90% SMYS.

The primary observation regarding this stress check is that the elastically computed maximum alternating stress intensity used in these calculations is computed from an FEA model that is not fully restrained. It appears inconsistent to impose a pipe stress check based on fully restrained conditions to pipe stress demand measures that are computed based on "less than fully restrained" conditions. It would be more consistent to consider a check that limits some measure of expansion stress (i.e., a fatigue check). In the context of the B31.4 code, this check would be provided by limiting the expansion stress to  $S_E \le 0.72$  SMYS or in the context of the B31.1 or B31.3 codes, by limiting  $S_E$  to an "N" dependent allowable stress. Note that the B31 fatigue rules are rooted in the use of fatigue test based stress intensification factors (*i* factors) which are not directly available for the subject wrinkles. As stated in B31.4 Section 400 (e), "… the specific requirements of the code usually revolve around a simplified engineering approach to a subject. It is intended that a designer capable of applying more complete and rigorous analysis to special or unusual problems shall have latitude in the development of such designs and the evaluation of complex or combined stresses. In such cases, the designer is responsible for demonstrating the validity of the approach...".

In order to account for the effects of localized stresses and the number of load cycles, Dominion elected to undertake fatigue assessments using reversing plastic strain computed from elastic-plastic FEA with experimental data showing reversals to failure versus reversing plastic strain for steels "similar to the pipeline's API 5L Grade X42 steel". As a check, Dominion used the elastically computed stress intensities from the FEA directly with the ASME Boiler & Pressure Vessel "design" fatigue relationship to estimate allowable numbers of operation cycles for a range of wrinkle geometries.

On the bottom of page 5, MDPSCED states that "*there is no indication that Dominion considered hoop stress when performing these calculations*". In the review of the subject Dominion report, the review team also raised the point that pressure effects were not included in the FEA.

On page 7, this report mentions "*areas of less than 3' burial depth*". If there are locations on the pipeline with less than 3 feet of soil cover these should be described further. Again, the reviewers

ChallengeUs.

agree with this comment and asked the operator and his consultants to ensure the review on this point.

On page 8, item 2: The review team did not understand the basis for selecting "10% of life" as the threshold of "excessive fatigue".

On page 8, item 6: The report states: *Obtain fatigue curves for X-42 pipeline steel*. The review team agrees that it would be desirable to have this information.

On page 8, item 7, the review team did not understand the statement that "Mirant must justify their claim that fatigue data included in their study is not relevant". The review team assumed that this item had reference to ongoing discussion between MDPSCED and Mirant.

This report appears to dismiss the conclusions and recommendations made in the subject reports based mainly on the computed quantity labeled "*PSC calculated B31.4 Maximum Allowable Delta T*" which is shown in column 7 of the table on pages 4 and 5. This temperature differential corresponds to the elastically computed maximum alternating stress intensity being equal to 90% SMYS. The review team does not believe that it is appropriate to dismiss the conclusions and recommendations made in the Mirant reports based on this calculation. This is because MDPSCED is comparing the results from a model that is less than fully restrained to an allowable stress measure that considers the pipe to be fully restrained. We do not believe that the calculations that limit the elastically computed maximum alternating stress intensity to 90% of SMYS can be used to support recommendations 1 and 2 of this report.

Although we may not agree with all of the details of the approach used by Dominion to calculate the local stress demands based on FEA, it is unlikely that the bends behave as though they are fully restrained. It follows that fully restrained pipe stress checks are not appropriate for bends that are less than fully restrained, and that the bends that are not fully restrained should be checked for fatigue damage under operational cycling. In the absence of wrinkle-specific *i* factors and specific guidelines for including the number of cycles per the B31.4 expansion stress check, Dominion elected to use the elastically computed stress intensities from FEA together with the ASME Boiler & Pressure Vessel "design" fatigue relationship to estimate allowable numbers of operation cycles for a range of wrinkle geometries.

5.1.5.4. Further Work

None

## 5.2. Teleconference Discussion

On January 29, 2003, a teleconference was conducted to discuss questions and comments generated by Baker's report reviews presented above. Representatives of the OPS, MDPSCED, Mirant, Kiefner, Dominion and Baker participated in this discussion. Notes of the teleconference as captured by the MDPSCED are presented in Appendix A. Relevant to the review of the Wrinkle Acceptance Criteria, the following summarizes the responses:

# "Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline" (Kiefner)



Many of the formulas presented for calculation of soil resistance are based on the soil density defined as γ. A density of 125 pcf appears to have been used throughout. It should be pointed out that for locations where the pipe is buried below the water table, the density of the soil below the water table should be taken as the buoyant density commonly referred to as γ' where γ'= γ- γ<sub>w</sub> (where γ<sub>w</sub> is the density of water = 62.4 pcf). For this soil, the submerged (buoyant) density would be γ'=125-62.4=62.6 pcf (roughly 50% of the assumed density). Hence, all of the soil resistance terms that depend on the density would be substantially reduced in the presence of a high water table (e.g., water table elevation at or above the ground surface elevation). The soil strength reduction due to buoyancy effects is most pronounced in cohesionless soils. A reduction of the soil strength would lead to a further increase in the propensity for the movement at buried bends noted in this report.

Question: What bends are located in potentially buoyant soil conditions?

Question: What are the soil conditions in the vicinity of the failed wrinkle location? What is/was the elevation of the water table relative to the ground surface elevation at the failed wrinkle location?

Teleconference information: A sensitivity analysis was done using soil restraint values equal to one-half and twice the nominal values used in the analyses. The summary report (Dominion) is to be transmitted to the OPS [a summary was received which contained cases where the nominal values for lateral soil resistance were halved and doubled and a case where the nominal values for axial restraint were changed (elastic constant increased and the load limit decreased). This information is contained in Appendix B].

• The report did not clearly state how the pipe-soil springs were modeled although some of the notes written in the CAEPIPE results appear to indicate that the pipe-soil springs were assumed to be linear.

Question: What pipe-soil spring properties were used in the CAEPIPE models?

Teleconference information: CAEPIPE models considered only elastic soil springs.

Subsequent analyses utilizing CAESAR considered bi-linear springs.

• Examination of the deflected shapes provided in the CAEPIPE outputs appears to indicate that the deflected shapes are not symmetrical about the apex of the bend as would be expected.

Question: Why are the deflected shapes of the bends not symmetrical?

Teleconference information: Cursory review of this situation was conducted, however, since forces and moments calculated at each end of the bend were of similar magnitude further investigation was not pursued.

## "Acceptance Criteria for As-Inspected Wrinkles in Piney Point Oil Pipeline" (Dominion)

Most of the review observations relate to the finite element model, the assumed loading, and the FEA results. The main observations and questions are summarized as follows:

• Are these stress-strain coordinates shown in Figure III-4 based on representative test data for X-42 pipe? Were any sensitivity studies performed on the shape of the stress-strain curve?



Teleconference information: It was reported that stress-strain data was based on a tensile test of a specimen from the Piney Point pipeline, thus no sensitivity analysis was conducted.

• The finite element mesh appears to consider a single bend angle of 5-degrees. Is there a reason why a single bend angle was considered?

Teleconference information: This bend angle was based on geometry of the Swanson Creek failure. Data indicated that no other bends had angles greater than this value. It was reported that FEA results showed less stress for smaller bend angles.

• Why were different circumferential extents considered for the elastic and elastic-plastic analyses?

*Teleconference information: Elastic analyses were completed first. Elastic-plastic analyses were refined based on the results of the initial elastic analyses.* 

• For the elastic-plastic analyses, did the profile and circumferential extent of the wrinkles change appreciably?

Teleconference information: Elastic-plastic analyses were based on small displacement theory; no appreciable changes in wrinkle geometry were noted.

• The FEA results were tuned to provide target levels of elbow displacement under a constant axial load (equal to the fully restrained thermal force) by varying the leg lengths. What was the basis of "tuning" the FEA results to provide bend center deflections of 1, 1.5 and 3 inches? What sort of leg lengths are required to reach these deflections?

Teleconference information: The 3-inch value was used in the majority of the analyses and was conservatively based on the reported observation of a cavity (~1-inch) at the Swanson Creek failure location. Cavity was located on extrados when pipe was in cold condition.

Leg lengths were on the order of 9-10D, 12-13D and 20D for the 1-, 1.5- and 3-inch deflections, respectively.

- Why was the internal pressure load not considered in the FEA models? We believe that the presence of internal pressure would have at least three potentially important influences:
  - The inclusion of a "cap force" (the longitudinal force acting on the fluid column contained in the pipe is equal to the product of the internal pressure and the bore area). As the pipe turns through a bend, the cap forces from each leg combine to provide a net outward resultant disturbing force on the pipe. This force would tend to increase the outward displacement of the bend.
  - 2. The addition of "pressure stiffening" of the pipe cross section which would tend to resist additional distortion in the vicinity of the wrinkle.
  - 3. The addition of hoop tension which would tend to create a more bi-axial stress condition in the pipe wall which in turn could increase yielding (plastic flow) at/near the wrinkle on the compressive side of the pipe in the elastic-plastic model.



Teleconference information: Pressure was initially neglected to simplify the analyses. Additional analyses including pressure for wrinkles near pumps (Piney Point) are to be completed.

• We understand that the FEA model was developed without soil in an attempt to provide a conservative basis for evaluation of wrinkle stresses and strains. No attempts were made to assess the degree of conservatism that results from neglecting the soil in the FEA. Perhaps overlay comparisons of the global moment diagrams from pipe-soil interaction analyses of a similar 5-degree bend configuration including soil (e.g., similar to the CAEPIPE and CAESAR analyses presented in other reports) would provide a starting point for assessing the degree of conservatism provided by neglecting the soil in the FEA. Comments?

Teleconference information: The statement was made that the moment at the apex is essentially the applied force times the apex offset distance and mentioned a value of 3 million inch-lbs (3000 kip-inch) for the 16-inch line. The boundary conditions are fixed against rotation (this means that some moment can develop at the ends of each leg).

• For the elastic-plastic analyses, the loading simulates the application of a single thermal load cycle from ambient to maximum temperature and back to ambient. Were any of the analyses extended to consider additional thermal load cycles to check if the model shakes down to elastic behavior?

Teleconference information: Additional thermal cycles were reported to have been completed but not documented. The use of isotropic work hardening was mentioned, but kinematic hardening was also mentioned. It was stated that stable hysteresis loops (if not shake down) were expected.

- Using the maximum computed reversing plastic strain from a wrinkle model with an aspect ratio of 7.5 and from a model of the wrinkle that failed at Swanson Creek, a fatigue evaluation was performed using the lower curve of the "band for undeformed specimens" on the total strain amplitude versus reversals to failure plots shown in Figures III-14 through III-18. For the wrinkle with an aspect ratio of 7.5, approximately 2500 cycles to failure were predicted. For the wrinkle that failed at Swanson Creek, approximately 200 cycles to failure were predicted. We observe that the lines shown as the "band for undeformed specimens" appear to envelope most of the experimental data points and that a curve drawn through the middle of this "band" would be nominally centered on the mean path of the data points. Hence, the lower curve of the band provides some margin of safety relative to the mean path of the data points. Comment? Our present position favors the use of fatigue damage calculations based on elastic analysis. Problems or uncertainties associated with fatigue damage calculations based elastic-plastic analyses include:
  - 1. Unknown "virgin" material stress-strain properties for subject pipe (this includes intrajoint, joint-to-joint and heat-to-heat variations).
  - 2. Unknown material stress-strain properties (and residual stresses) after cold bending. These will vary around the pipe circumference.
  - 3. Unknown sensitivity of the key response parameters to details of the shape of the stressstrain curve.





- 4. Elastic-plastic results are not scalable to consider other temperature differentials.
- 5. Lack of familiarity with fatigue data presented in Figures III-14 through III-18 and its applicability to X-42 pipe. Unknown factor of safety of lower band curve with respect to mean of the data points.
- 6. We do not necessarily believe that the results from a fatigue analysis based on elasticplastic analysis are any more accurate than the results from a fatigue analysis based on elastic analysis (e.g., consider the B31 fatigue design procedures based on the "Markl" fatigue tests).
- Additional fatigue calculations were performed using the maximum alternating stress intensity from elastic analysis directly with the ASME *design* fatigue curve. The results from this evaluation are presented in Table III-4. Based on this assessment, Dominion concludes that "any configuration that has a design fatigue life greater than the estimated 150 operation cycles the pipeline has experienced to date is acceptable to returned to service without modification". It appears that the ASME curve/procedure is becoming the standard used by MDPSCED as the benchmark criteria. Is this Mirant's view as well?

Teleconference information: The possible use of strain-based criteria has not been ruled out.

There are currently no defined acceptance criteria based on elastic-plastic (strain-based) methods, while the ASME code (elastic method) is recognized and has well documented factors of safety.

With respect to the plastic fatigue data, Mirant is of the opinion that a factor of safety of 2 on cycles would provide a safety factor of at least 2 standard deviations on failure. A method to document the expected safety factor associated with the acceptance criteria was requested.

Mirant stated an additional comfort with the results since the demand model is conservative.

Dominion supports the plastic fatigue approach due to a concern over ASME extrapolation in to low cycle fatigue regime. It also shows a bigger difference between the Swanson Creek wrinkle and the other wrinkles as compared to elastic. Mirant believes plastic fatigue is more appropriate over entire range of stress/strain.

#### 5.3. Wrinkle Acceptance Criteria Review

Following the document review, it was determined that the two areas of concern that required additional study for completion of the review were:

- A better understanding of the effects of the modeling procedures and geometry used in the ANSYS analysis.
- A better understanding of the methodology to use the FE results to judge wrinkle acceptability.

Section 5.4 discusses the approach of the review team to explore the ANSYS model and especially to understand the ramifications of a demand model that does not incorporate soil restraint explicitly, but through modeling restraint conditions attempts to simulate its effects on a buried pipeline.

Section 5.5 states the review basis for the fatigue assessment. As a prelude to a more detailed discussion of the wrinkle criteria for this pipeline, Section 5.6 compares wrinkle criteria developed for this pipeline to other criteria, including the previously reviewed Australian code criteria. It is specifically noted that other criteria was intended for design/construction situations and not necessarily in-service pipeline, but nevertheless gave the review team useful perspective on the Piney Point pipeline wrinkle condition. Section 5.7 states the review team's approach to wrinkle acceptability determination and compares this to the Mirant approach.

#### 5.4. Discussion of Finite Element Analysis of Fatigue Demand at Wrinkles

Dominion undertook an extensive series of elastic and inelastic analyses of finite element models of a selected range of wrinkle geometries. The stress and strain "demand" results from these analyses were utilized by Dominion as a key element of the development of their wrinkle acceptance criteria. The primary comments and observations regarding the demand analyses are summarized as follows:

The Dominion demand models neglect the presence of soil around the pipe. In general, this is a conservative assumption since temperature differential and pressure loads acting on real bends buried in competent soil will result in some level of pipe-soil interaction. In simple terms, the soil in contact with the pipe can act to restrain the pipe movement – this includes global "beam on foundation" movements as well as local distortions of the pipe wall (e.g., flexing near wrinkles, ovalling, etc.). This soil restraining effect would be reduced in situations where a gap exists between the pipe and the soil (e.g., on the inside/outside of pipe bends under hot/cold conditions). Figure 5.1 provides example spatial plots of the pipe bending moment, axial force, transverse and longitudinal pipe-soil spring forces from a pipe-soil interaction analysis of a 30-degree buried side bend in a 16-inch diameter by 0.219-inch thick pipe. The model is subjected to a 550 psi internal pressure followed by a temperature differential of  $110^{\circ}$ F. The upper and lower bound soil spring properties developed in Chapter 4 (Table 4-3) were used for these analyses (note that the lower bound properties are based on the buoyant soil density).

The Dominion demand models treat the axial force due to restrained thermal expansion as a force controlled (primary) load when in reality, thermal expansion is a displacement controlled (secondary) load. This is also a conservative assumption since even modest levels of longitudinal and transverse pipe movements at a bend can reduce the pipe axial force to well below the fully restrained value in between the adjacent virtual anchor points. A drop-off in the pipe compression force in the vicinity of the buried 30-degree side bend model described above is clearly illustrated in Figure 5.1(c). Note that the axial force drop off is most significant for the lower bound soil case. It should also be noted that the magnitude of the axial compression force drop off will depend on the bend angle. For example, separate sensitivity studies on side bends with angles of 30, 15, and 5 degrees buried in the lower bound soil indicate that the compression force in the pipe steel dropped from 164.2 kips to 43.1, 102.8 and 152.4 kips, respectively (i.e., 26%, 63% and 93% of the fully restrained compression force).

No attempt was made to make a connection between the local stress/strain demands computed by the local FEA models and the global demands (e.g., axial force and bending moment) that would be computed using a global pipe-soil interaction analysis model (e.g., as in Dominion's December 2001 Report "*Buried Piping Flexibility Analysis of the Piney Point Pipeline*"). In the absence of this

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information, it is not possible to directly assess the degree of conservatism associated with the items above.

The analyses reviewed in the above reports neglect the effects of internal pressure. Neglecting internal pressure has both conservative and unconservative aspects. Since pressure stiffening acts to restrain localized distortion of the pipe wall, analyses that calculate the local stress/strain demands at/near wrinkles neglecting pressure stiffening would tend to be conservative. On the other hand, neglecting the hoop stress and the outward cap force resultant at bends due to internal pressure is unconservative. Dominion indicated that final analyses will include internal pressure effects. Comparison of the results from analyses with and without internal pressure provide indication of whether or not the analyses that neglect internal pressure are, overall, conservative.

The inelastic FEA considered a single stress-strain curve. It is important to point out that the stressstrain relationship assumed by Dominion provides a stress of approximately 49.4 ksi at a strain of 0.5% (about 18% larger than the material SMYS). There are situations where we feel that using a pipe material yield strength that exceeds the material SMYS is appropriate (e.g., for a failure analysis investigation with known material properties or in situations where a statistically significant number of material stress-strain curve samples are available to establish representative lower bound yield and ultimate strengths). However, in this situation, we believe that using a material strength well in excess of the specified minimum yield strength based on a single material test result is overly optimistic. It was recommended that a further analysis be conducted to consider how a modified stress-strain relationship that passes through the material SMYS at 0.5% strain influences the computed reversing plastic strain or whether reversing plastic strain occurs on only one surface of the pipe (i.e., on the ID or the OD, but not both). The shape of a pipe material stress-strain relationship can vary from pipe joint to pipe joint and within a given pipe joint. The shape of the stress-strain relationships in the longitudinal and circumferential directions can also be significantly different. Moreover, the stress-strain relationships around the circumference of a section of cold bent pipe (e.g., at the intrados vs. the extrados) can also be different due to work hardening effects. It would be informative to consider how the shape of the stress-strain curve influences the key results from the inelastic FEA (i.e., the reversing plastic strain).



Figure 5.1(a) Bending Moment versus Distance from Bend Apex



Figure 5.1(b) Transverse Force versus Distance from Bend Apex





Figure 5.1(d) Longitudinal Force versus Distance from Bend Apex

## 5.4.1. Buried Pipe Side Bend Sensitivity Studies Based on Cold Bends

A series of analyses was undertaken on buried side bends in a 16-inch diameter (0.219 inch wall thickness) X42 pipeline using the upper and lower bound elastic-plastic pipe-soil springs from Table 4.13. The side bends were fabricated using cold bends with a radius of curvature of 24 feet (based on the minimum R=18D specified in ASME B31.4 Code) and a wall thickness of 0.219 inches. Residual stresses and strains due to cold bending were neglected. A number of side bend angles ranging from 5 degrees to 90 degrees (i.e.,  $5^{\circ}$ ,  $15^{\circ}$ ,  $30^{\circ}$ ,  $45^{\circ}$ ,  $60^{\circ}$ , and  $90^{\circ}$ ) were considered in the analyses. Leg lengths of at least 1,000 feet were modeled on each side of the side bend. In all cases the leg lengths were checked to make sure that they extended beyond the virtual anchor point on each side of the bend.

PIPLIN [5-1] was used to analyze the series of cold bend configurations described above. The loading on the buried side bend models consisted of an internal pressure of 550 psi plus a temperature differential of 110 degrees F. Key results from the PIPLIN analyses are presented in Figures 5.2 and 5.3. Figures 5.2 (a) through 5.2 (d) present the axial force, bending moment, extrados axial stress and intrados axial stress at the apex of the bend as a function of the side bend angle. Figures 5.3 (a) through 5.3 (c) present the transverse pipe displacement, curvature and pipe centerline axial strain at the apex of the bend as a function of the side bend angle.





Figure 5.2(b) Bending Moment at Bend Apex



















Figure 5.3(c) Centerline Axial Strain at Bend Apex

An additional "side study" was conducted for a set of 30-degree side bend configurations. In this side study, the strength of the pipe-soil springs was varied from the values shown in Table 4.13. On one extreme, the upper bound strength was increased by a factor of 10 and on the other extreme, the lower bound strength was reduced by a factor of 4. For both extreme cases, the pipe-soil spring displacement required to mobilize the strength was held constant. PIPLIN analyses were conducted as described above. Key results from this side study are presented in Figures 5.4 and 5.5. Figures 5.4(a) through 5.4 (d) present the axial force, bending moment, extrados axial stress and intrados axial stress at the apex of the bend as a function of the transverse horizontal soil strength. Figures 5.5 (a) through 5.5 (c) present the transverse pipe displacement, curvature and pipe centerline axial strain at the apex of the bend as a function of the transverse horizontal soil strength.







Figure 5.4(b) Bending Moment at Bend Apex















Figure 5.5(b) Curvature at Bend Apex





Based on the operating load simulations of the PIPLIN cold bend configurations, it is observed that for all bend angles considered, the moment and stress demands at the apex of the bends are largest for the lower bound pipe-soil spring cases, and in terms of maximum moment and stress demand, the most critical side bend angle is 30 degrees.

## 5.4.2. Buried Pipe Side Bend Sensitivity Studies Based on Long Radius Piping Elbows

A series of analyses was undertaken on side bends in a 16-inch diameter (0.219 inch wall thickness) X42 pipeline using the upper and lower bound elastic-plastic pipe-soil springs from Table 4.13. For this series the side bends were fabricated using long radius piping elbows with a radius of 1.5D (i.e., 24 inches) and a wall thickness of 0.375 inches. These elbows have a flexibility factor of 11.2 and an in-plane stress intensification factor of 3.22. A number of side bend angles ranging from 5 degrees to 90 degrees (i.e.,  $5^{\circ}$ ,  $15^{\circ}$ ,  $30^{\circ}$ ,  $45^{\circ}$ ,  $60^{\circ}$ , and  $90^{\circ}$ ) were considered in the analyses. Leg lengths of at least 1,000 feet were modeled on each side of the side bend. In all cases the leg lengths were checked to make sure that they extended beyond the virtual anchor point on each side of the bend.

AutoPIPE [5-2] was used to analyze the series of elbow configurations described above. The loading on the buried side bend models consisted of an internal pressure of 550 psi plus a temperature differential of 110 degrees F. Key results from the AutoPIPE analyses are presented in Figures 5.6 and 5.7. Figures 5.6 (a) through 5.6 (d) present the axial force, bending moment, and maximum and minimum intensified longitudinal stress measures (i.e.,  $F/A\pm iM/Z$ ) at the apex of the bend as a function of the side bend angle. Figures 5.7 (a) and 5.7 (b) present the transverse pipe displacement and the Tresca equivalent tensile stress (B31.4) at the apex of the bend as a function of the side bend angle.

























An additional "side study" was conducted for a set of 30-degree side bend configurations. In this side study, the same pipe-soil spring strength variations considered by Dominion were evaluated (see Base Case, Case 1, Case 2 and Case 3 from the Dominion follow up report (dated 2/7/03) table developed for elbows 14450 and 14480). AutoPIPE analyses were conducted using long radius piping elbows as described above. Key results from this side study are presented in Figures 5.8 and

5.9. Figures 5.8 (a) through 5.8 (d) present the axial force, bending moment, expansion stress and the Tresca equivalent tensile stress at the apex of the bend as a function of the transverse horizontal pipe-soil spring strength (i.e., comparing the Base Case to Cases 3 and 4). Figures 5.9 (a) through 5.9 (d) present the axial force, bending moment, expansion stress and the Tresca equivalent tensile stress at the apex of the bend as a function of the longitudinal pipe-soil spring strength (i.e., comparing the Base Case to Case 2).





Figure 5.8(b) Bending Moment at Bend Apex versus Transverse Horizontal Soil Strength



Figure 5.8(c) Expansion Stress at Bend Apex versus Transverse Horizontal Soil Strength











Figure 5.9(b) Bending Moment at Bend Apex versus Longitudinal Soil Strength

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Figure 5.9(d) Tresca Equivalent Stress at Bend Apex versus Longitudinal Soil Strength

Based on the operating load simulations of the AutoPIPE elbow configurations, it is observed that for all bend angles, the moment and stress demands at the apex of the bends are largest for the lower bound pipe-soil spring cases and in terms of maximum moment and stress demand, the most critical side bend angle is 30 degrees.

Using the Dominion pipe-soil spring sensitivity cases in a series of "generic" side bend models leads to the conclusion that lower transverse pipe-soil spring strengths lead to higher pipe stress demands (see Figure 5.8). However, using the Case 2 axial spring strength (reduced to 86% of the Base Case strength) resulted in a modest (< 3%) increase in the pipe stress demands (i.e., the response curves shown in Figure 5.9 are essentially flat over this range of axial pipe-soil spring strengths).

# 5.5. Discussion of Fatigue Capacity Used to Evaluate Wrinkles

Dominion undertook fatigue damage calculations using stress/strain demands computed from elastic/inelastic finite element analyses of a range of wrinkle geometries based on two different types of fatigue capacity relationships. The first fatigue evaluation method used the reversing plastic strain computed from inelastic FEA to compute a total strain demand which is used with total strain amplitude versus reversals to failure fatigue capacity plots. This is compared to a second evaluation method which used the maximum alternating stress intensity computed from elastic analysis as the

demand measure with the ASME Boiler and Pressure Vessel *design* fatigue capacity curve. These inelastic and elastic fatigue capacity relationships (i.e.,  $\varepsilon$ -N or S-N curves) were used to find the number of cycles to failure (i.e., on the horizontal "N" axis) associated with the strain or stress demand value (i.e., on the vertical  $\varepsilon$  or S axis) corresponding to a given operating cycle. Hence, the assumed fatigue capacity relationships are a key component of the wrinkle evaluations undertaken by Dominion.

The calculation of fatigue damage is an inexact science and there is always a significant scatter in experimental fatigue data. For the purposes of new design, it is usual to make conservative assumptions in order to ensure that if the design satisfies the design criteria, then the probability of fatigue failure is extremely small. This is done by using *design* S-N curves that ensure a very low probability that fatigue failure will occur. This is typically accomplished by selecting a design S-N curve that provides a near lower bound envelope to the experimental (S-N) data points. Some fatigue design codes (e.g., BS 7608 [5-3]) provide S-N relationships in terms of the mean and standard deviations of their basis data. A design S-N curve is typically selected based on the mean minus two standard deviations. Assuming a normal distribution, the calculation of a usage factor (i.e., cumulative damage ratio) of 1.0 using a design S-N relationship based on the mean minus two standard deviations corresponds to a 2.3% nominal probability of failure. On the other hand, calculation of a usage factor of 1.0 using the mean S-N relationship corresponds to a 50% nominal probability of failure (i.e., half of the S-N data points would lie above the mean S-N relationship and half of the S-N data points would lie below the mean S-N relationship). This means that analyses attempting to predict an actual fatigue failure should utilize the mean S-N relationship. This illustrates how using the statistics of the fatigue data can provide a framework for quantifying the factor of safety associated with a given fatigue assessment.

The concern for assessing the state of the Piney Point pipeline wrinkles is whether there is a *significant* probability of fatigue failure, not whether there is a *minute* probability. Hence, it could be argued that a *decision* S-N curve somewhere between the mean and the design curves would be most appropriate for guiding decisions to ensure the integrity of the pipeline.

We are not aware of any direct pipeline industry experience using the total strain amplitude vs. reversals to failure fatigue data presented by Dominion. However, it seems reasonable to expect that the use of a  $\epsilon$ -N relationship instead of a S-N relationship can be used to capture the fatigue behavior in the low cycle fatigue (LCF) regime (say N < 50,000). The lines shown as the "band for undeformed specimens" on the data curve used by Dominion appear to envelope most of the experimental data points and that a curve drawn through the middle of this band would be nominally centered on the mean path of the data points. Hence, the lower curve of the band provides some margin of safety relative to the mean path of the data points.

There is substantial pipeline and piping industry experience with the use and application of the ASME Boiler and Pressure Vessel *design* fatigue curve. As described in [5-4] this is a "*design*" fatigue curve which has a significant factor of safety with respect to the mean of its basis data. Figure 5.10 presents a comparison of the "best fit" curve with the basis data for carbon steels. The best fit curve is based on the following S-N relationship:

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$$S = \frac{E}{4\sqrt{N}}\ln\frac{100}{100 - A} + B$$

where the best fit values of A and B are shown in Figure 5.10.



Figure 5.10 Best Fit Curve vs. Fatigue Test Data for Carbon Steels (from [5-4])

Figure 5.11 provides a comparison of the best fit S-N relationship from Figure 5.10 (shown as the blue curve in Figure 5.11) and the S-N values from Table 5-110.1 and Figure 5-110.1 of ASME Section VIII, Division 2 (the triangle symbols). Also shown in Figure 5.11 are the curves corresponding to the best fit S values divided by 2 (i.e., S/2) and the best fit N values divided by 20 (i.e., N/20). This comparison provides an indication that the margin of safety for the *design* curve is a factor of 2 on stress or 20 on life relative to the basis data points, whichever is more conservative at each point [5-4]. Note that the "N/20" curve governs in the low-cycle fatigue region where the stress coordinates of the "N/20" curve correspond to a factor of safety of approximately 4.0 to 4.5 relative to the stresses for the "best fit" curve in the range of  $10 \le N \le 100$ .


Figure 5.11 ASME S versus N Relationships

By performing two separate fatigue damage calculations; one based on the lower "band" of the experimental data presented in Dominion Figures III-14 through III-19 and another based on ASME design S-N values, this evaluation approach appears to be somewhat aligned with the framework of a "design" and "decision" level fatigue assessment (e.g., see Reference [5-5]). The idea is that a "design" fatigue curve has a significant factor of safety with respect to the mean of its basis data. The results from a wrinkle fatigue assessment based on a design curve provide an indication whether the wrinkle would satisfy criteria used for new pipeline design. A "decision" curve, on the other hand, is selected to provide less of a factor of safety with respect to the mean of the basis data. The use of a decision curve is better suited for deciding on actions to be taken in the short term (e.g., whether or not a wrinkle should be repaired).

# 5.6. Comparison of Piney Point Pipeline Data With Published Wrinkle Acceptance Criteria

In order to provide a reference basis for the Mirant wrinkle acceptance criteria, a range of published wrinkle/ripple acceptance criteria have been compared in Table 5.1. The data were gathered from



reports for the Piney Point pipeline, although the heritage of the data is neither clear nor required for this comparison exercise. The criteria used to develop Table 5.1 are described as follows:

- Australian Standard AS 2885.1 1997: Height ≤ 5% of Peak-to-Peak Length. See discussion in Section 3.1.
- PRCI Criteria: Height  $\leq 1.5$  WT and Aspect Ratio > 12. See discussion in Section 3.1.
- International Pipeline Conference (IPC) 2002 for Liquid Pipelines: Shallow ripples having crest-to-trough dimensions up to 0.5% of the pipe OD for hazardous liquid pipelines operating at (hoop) stress levels in excess of 47 ksi, increasing to 2% of the pipe OD for hazardous liquid pipelines operating at (hoop) stress levels at less than 20 ksi.
- DEI Criteria: Aspect Ratio ≥ 7.5 and Circumferential Extents ≤ 180 degrees. See discussion in Section 3.5.
- UT Data-Based Wrinkle Excavation Criteria: Circumferential Extents > 135 degrees. See discussion in: Piney Point Pipeline Summary Report: Field Inspection and UT Feature Correlation Results, SEPP, January 16, 2001.

It should be noted that the wrinkle acceptance criteria from the first 3 bullets above each make a statement to the effect that more severe wrinkle or ripple geometries can be accepted based on testing and/or more detailed analysis. For example, Reference [5-6] states that *"larger ripples than the suggested limits may be permissible based on detailed analysis. Also, more restrictive size limits may apply to pipelines subjected to intensely cyclical operation, large temperature differentials, inadequate soil support or high axial loadings"*. This reference also states that other reasons may exist to limit ripple magnitude. These reasons might include the long-term integrity of the pipe coating, unusual or severe loadings on the pipeline, extremely soft soil conditions, future changes in the mode of pipeline operation and the need for conservative workmanship standards to achieve quality construction in the field. Therefore, it is clear that these criteria should be considered as a simple basis for screening wrinkles. Finally, it is noted that the Australian code, PRCI and IPC criteria are all assumed to have been developed for assessing design/construction conditions and their applicability to operating/decision conditions has not been investigated to the knowledge of the review team.

With the above caveats understood, it is nevertheless instructive to examine Table 5.1 and note the general trends of the criteria when applied to the Piney Point pipeline wrinkles. An examination of the data in Table 5.1 indicates reasonable agreement among the various criteria. Generally the worst combinations of aspect ratio and feature height (i.e., smallest aspect ratio and largest feature height) are rejected by all criteria. As the aspect ratio gets larger and the feature height less, the level of acceptance among the criteria increases. In the area between rejection by all criteria and acceptance by all criteria (17 locations), the Dominion criteria is less conservative than the stated screening criteria. It should be expected that a criteria developed for a specific pipeline with given operating conditions can be less conservative than general screening criteria, so this is not a matter of immediate concern. Rather, it gives reviewers some perspective on the condition of the line when viewed by a variety of techniques and the area of focus - namely those intermediate wrinkles which are passed using a project specific criteria but fail using general screening criteria.



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|---------------------|--------------|-----------------|-----------------|-------------------|--------------------------------|--------------------------|------------------------|------------------|------|-----------------|------------------------|
| Nominal<br>Diameter | Type<br>(UT) | Ranking<br>(UT) | Aspect<br>Ratio | Feature<br>Height | Pipetronix<br>odometer<br>(UT) | Total<br>Degrees<br>(UT) | Australian<br>Standard | PRCI<br>Criteria | IPC  | DEI<br>Criteria | Excavation<br>Criteria |
| 12                  | U            | 0               | 4.740           | 0.940             | 44075.3                        | 231                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 12                  | А            | 1               | 5.920           | 0.848             | 9936.5                         | 219                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 12                  | Α            | 1               | 11.870          | 0.482             | 9131.9                         | 183                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 12                  | U            | 0               | 3.000           | 1.000             | 53526.6                        | 276                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 16                  | U            | 0               | 5.630           | 0.718             | 118575.0                       | 167                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 16                  | В            | 0               | 5.240           | 0.845             | 88582.1                        | 200                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 16                  | В            | 0               | 6.740           | 0.585             | 142000.3                       | 160                      | Fail                   | Fail             | Fail | Fail            | Fail                   |
| 16                  | В            | 1               | 10.980          | 0.355             | 88576.1                        | 142                      | Fail                   | Fail             | Fail | Pass            | Fail                   |
| 12                  | Α            | 1               | 14.780          | 0.466             | 35689.1                        | 111                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 12                  | Α            | 1               | 10.270          | 0.474             | 38284.9                        | 108                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | Α            | 1               | 10.180          | 0.568             | 69480.7                        | 125                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | Α            | 1               | 10.810          | 0.433             | 69485.7                        | 125                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | Α            | 1               | 12.660          | 0.614             | 69477.1                        | 120                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | Α            | 2               | 15.890          | 0.362             | 134360.4                       | 115                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | Α            | 2               | 8.940           | 0.443             | 134411.1                       | 102                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | В            | 1               | 9.200           | 0.380             | 22913.7                        | 110                      | Fail                   | Fail             | Fail | Pass            | Pass                   |
| 12                  | Α            | 2               | 12.730          | 0.302             | 2663.3                         | 114                      | Fail                   | Pass             | Fail | Pass            | Pass                   |
| 12                  | Α            | 2               | 17.480          | 0.305             | 43607.6                        | 102                      | Fail                   | Pass             | Fail | Pass            | Pass                   |
| 16                  | В            | 1               | 16.210          | 0.301             | 134408.2                       | 142                      | Fail                   | Pass             | Pass | Pass            | Fail                   |
| 16                  | Α            | 1               | 20.930          | 0.363             | 36297.8                        | 108                      | Pass                   | Fail             | Fail | Pass            | Pass                   |
| 16                  | В            | 1               | 14.300          | 0.290             | 24300.3                        | 120                      | Fail                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | В            | 1               | 13.320          | 0.303             | 134182.8                       | 120                      | Fail                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | С            | 1               | 14.850          | 0.307             | 4511.5                         | 99                       | Fail                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | D            | 1               | 14.280          | 0.277             | 13770.8                        | 92                       | Fail                   | Pass             | Pass | Pass            | Pass                   |
| 12                  | D            | 3               | 23.720          | 0.187             | 33117.0                        | 102                      | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 12                  | Α            | 2               | 22.240          | 0.160             | 11012.0                        | 103                      | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 12                  | В            | 2               | 24.690          | 0.156             | 11010.5                        | 100                      | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | Α            | 1               | 26.700          | 0.234             | 36310.0                        | 88                       | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | Α            | 2               | 26.700          | 0.234             | 36305.3                        | 78                       | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | Α            | 2               | 27.100          | 0.295             | 36254.4                        | 73                       | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | В            | 1               | 28.200          | 0.275             | 36258.1                        | 98                       | Pass                   | Pass             | Pass | Pass            | Pass                   |
| 16                  | В            | 2               | 32.500          | 0.200             | 36269.9                        | 67                       | Pass                   | Pass             | Pass | Pass            | Pass                   |

 Table 5-1
 Acceptance Criteria Comparison

### 5.7. Recommended Framework for Evaluating Serviceability of Wrinkles in Cold Bends

As noted in many of the subject reports and in the pipeline industry literature on this subject, there are currently no universally accepted guidelines or specific criteria that can be used to limit the geometry of wrinkles or ripples in pipeline cold bends. However, it is the review team's understanding that the B31.8 Code Committee is presently considering an agenda item allowing for ripples with peak-to-trough heights of up to 1% of the pipe diameter based on work presented in [5-

6] and [5-7]. It is also our understanding that the B31.4 Code Committee is also presently considering an agenda item related to the acceptance of mild ripples.

It is intuitively reasonable to expect that very mild ripples along the intrados of a field bend will not impair the structural integrity of a pipeline (i.e., small ripples are benign). When it comes to evaluating the serviceability of bends containing ripples and wrinkles, the fundamental question is *"how big is too big"*? The answer to this question will depend on many variables including the soil conditions, the pipeline operating history, the magnitude of operating cycles, etc.

The development of a consistent analysis framework for accessing wrinkle serviceability would provide a very important step forward for the pipeline industry on this subject. Based on the team's experience with piping and pipeline analysis, a ripple analysis framework is presented in this chapter. The level of complexity of the serviceability analysis depends on numerous issues including how much is known about the wrinkle/ripple geometry, the geometry of the cold bends, the pipeline operating history, the pipe material properties, the soil conditions and other variables.

- 1. Develop Models of Buried Pipeline Bends. Develop "global" pipe-soil interaction models of the buried pipe field bend configurations of interest. The bend model geometry can be developed based on as-built pipeline drawings or (preferably) geometry pig (e.g., Geopig) survey data. A field bend is typically modeled as a series of short, straight pipe elements that turn through a specified angle at a specified radius (with flexibility and stress intensification factors of 1). Wrinkles along the intrados of the bend are not explicitly considered in this model. The state of practice for modeling buried pipe-soil interaction is through the use of a "beam on foundation model" where the centerline of the pipe (beam) is supported by a nonlinear Winkler foundation. Well established procedures are available for computing the pipe-soil spring properties in the longitudinal, transverse horizontal, uplift and bearing directions (e.g., see Reference [5-8] and [5-9]) based on the cover depth, soil density, friction angle and cohesion. The pipe-soil springs are typically assumed to be elastic-perfectly plastic. The yield strength is the key calculated pipe-soil spring parameter while the displacement required to mobilize the full strength is usually based on a simple rule of thumb. Due to the variability of soil properties, they are often specified as a range (e.g., the friction angle is between 30 to 35 degrees). It is common practice to develop both a "softweak" spring based on lower range strength and largest yield displacement as well as a "stiffstrong" spring based on upper range strength and smallest yield displacement. Analyses are performed for both the "soft-weak" and "stiff-strong" soil spring assumptions in order to bound the expected pipe-soil interaction behavior. Sophisticated soil support models are available to capture the formation of a full or partial gap on either side of the pipe due to cyclic loading. Although pipeline analysis tools are capable of including inelastic pipe material behavior in the pipe-soil interaction analysis model, elastic pipe material represents the most appropriate starting point for this framework.
- 2. Analyze the Buried Pipeline Bends for Global Demand Measures. The developed buried bend models are analyzed for pressure and temperature differential loadings based on a predefined pipeline design basis that specify the design pressure and temperature differential. Depending on how much is known about the pipeline operating hydraulics and heat transfer, it may be possible to develop estimates of location specific maximum pressures and temperature differentials. The results from these analysis include the displacements at the



pipe nodes, the forces and deformations in the pipe-soil springs, as well as the "global" axial force (F) and bending moment (M) "demands" in the pipe elements. Example results from pipe-soil interaction analyses are shown in Figure 5.1. The pipe-soil interaction analysis is advantageous since it provides estimates of the longitudinal and transverse pipe movements that can occur at bends and it can capture the pipe axial force variation between fully restrained sections (e.g., long straight runs) and partially restrained sections (e.g., bends) of the pipeline.

3. Analyze Representative Wrinkle Geometries for Local Demand Measures. The purpose of this step is to develop estimates of the degree of local stress concentration associated with a given wrinkle geometry. Although it may be possible to use closed-form solutions or regressions for this purpose (e.g., Reference [5-10]), the most general approach is to develop detailed shell or solid finite element models of pipe stubs containing an appropriate range of wrinkle geometries. The fundamental wrinkle geometry parameters are the wrinkle height, the wrinkle wavelength and the circumferential extent of the wrinkle. Additional wrinkle geometry parameters that are worthy of consideration include the number of ripple or wrinkle "lobes" and whether the wrinkle profile is predominantly inward or outward. It is also possible to include the bend radius and bend angle in the finite element models, although this introduces two additional geometric parameters and complicates the loading. A relatively short (e.g., 6D) straight finite element mesh of a stub of pipe with the wrinkle geometry will usually suffice. It should be possible to use a one-quarter model mesh of the wrinkled stub assuming that the wrinkle has two planes of symmetry. Although it is possible to include the effects of soil restraint in the "local" analyses, it is most practicable to neglect soil restraint. It is also possible to consider inelastic pipe material behavior in the local analyses, however elastic pipe material represent the most appropriate starting point. The main advantages of using linear elastic pipe material are that the material stiffness is defined essentially by a single quantity (the elastic modulus, E) and that the results from a given load case are scalable. The main advantages of considering inelastic pipe material properties are that it can provide a better representation of "damage" due to pipe yielding and the associated redistribution of load. These advantages tend to be offset by the lack of scalability and the unknowns associated with the shape of a pipe material stress-strain relationship (which can vary in the longitudinal and circumferential directions, from joint to joint, and around the circumference of a cold bend). For the most part, the stress localization can be adequately represented by performing linear elastic, small displacements analysis of the FEA stub model for three load cases; namely a unit axial force (e.g., F=1000 kips), a unit internal pressure (e.g., P=1000 psi) and a unit applied bending moment (e.g., M=1000 kip-inches). For each load case and wrinkle geometry, evaluate the stress concentration factor (SCF) defined as the maximum computed local stress (or stress intensity) in/near the wrinkle to the corresponding nominal stress (e.g., F/A for axial force, PD/2t for internal pressure and M/Z for bending).

- 4. **Combine the Global and Local Demand Measures.** For each bend and wrinkle model of interest, scale the global pressure, axial force and bending moment demands computed from the pipe-soil interaction models by the SCFs computed from the local finite element analyses of the wrinkled stub models to compute the overall intensified stress demand measures that are associated with an operating cycle at/near the wrinkles of interest.
- 5. **Perform Fatigue Damage Calculations.** Use the overall intensified stress demand measures at/near the wrinkles from Step (4) with appropriate fatigue "capacity" curves (i.e., S-N curves) to compute the number of operating cycles to failure for each wrinkle. It may be appropriate to consider both *design* and *decision* level S-N curves in this step. We would suggest the ASME procedure, e.g. Section VIII, Division 2 *design* curve or an appropriately adjusted version of Markl's S-N relationship [5-11] as a starting point. Operating cycles that may not produce the full design pressure or temperature differential can be included using an appropriate cycle counting algorithm (e.g., rainflow) and a cumulative damage rule (e.g., Miner's rule [5-12]). Ideally, the selected fatigue capacity relationship should provide close correlation with available wrinkle fatigue test data. As appropriate, if the demand models exceed the limitations of the elastic based methodologies described in ASME code provisions, elastic-plastic methodology should be employed. For the most part, it is expected that initial "screening" curves can be based on elastic procedures, with elastic-plastic procedures and methodologies described but specific application left for the end-user.

The analysis framework described above is attractive because it is a relatively simple approach that includes (a) the "global" effects of pipe-soil interaction, (b) the "local" effects of (unrestrained) stress concentration at wrinkles and (c) a basis for estimating the fatigue damage at wrinkles for a given operating cycle. This framework is also reasonably consistent with the analysis procedures presently used to evaluate piping and pipeline designs per the ASME B31 Codes (e.g., elastic pipe, inelastic supports, evaluation of operating load cases, fatigue check, etc.). The procedure can be used to determine appropriate limits on wrinkle geometry. The wrinkle acceptance criteria presented in Reference [5-6] and [5-7] is based essentially on the application of this approach to a set of generic pipeline configurations.

# 5.8. Overall Assessment of Mirant's Wrinkle Acceptance Criteria

At this point, it is useful to summarize how the wrinkle acceptance criteria developed by DEI fits in to the analysis framework described in the previous section. Although some of the reports developed by Dominion considered pipe-soil interaction analysis of bends (e.g., see Dominion's December 2001 "*Buried Piping Flexibility Analysis of the Piney Point Pipeline*"), none of the analysis work presented in support of the wrinkle acceptance criteria directly incorporated the effects of soil restraint. No attempt was made in the initial reviewed documents to make a connection between the "global" pipe-soil interaction analysis of bends and the "local" stress/strain results obtained from FEA. In effect, the overall local demands due to an operation cycle were computed in a single step (i.e., in the FEA). Neglecting the effects of pipe-soil interaction in the demand analysis is a conservative approach and in this sense the demand results are acceptable. However it is our opinion that the demands computed using this approach are unlikely to be realistic for application to general buried pipe bends and, thus, the direct correlation attempted with the Swanson Creek failure is suspect. The conservatism in the demand calculation in the original report is offset to an unknown



degree by neglecting the effects of internal pressure (in the analyses reviewed to date) and thus it was helpful that Mirant agreed to complete analyses that incorporate pressure.

The fatigue capacity relationships utilized by Dominion were reasonable and acceptable, and additional confidence is gained by a recent Dominion comparison with results derived directly using ASME procedures. Correspondence from Dominion indicates that they intend to provide a factor of safety of 20 on cycles relative to the elastic-plastic fatigue basis data they used, and this is also acceptable.

It is noted that the simplified wrinkle evaluation presented in Kiefner's *"Review of Design and Propensity for Wrinkling of the Piney Point Hot Oil Pipeline"* is reasonably well aligned with analysis framework described above. Global demands computed from a buried pipe bend analysis model (using elastic soil) were combined with a SCF (from Reference [5-10]) associated with a given wrinkle geometry to obtain a measure of the overall intensified stress demand. The intensified stress demand measure was then used with the Section VIII, Division 2 *design* S-N curve to estimate cycles to failure.

## 5.9. References

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[5-2] AutoPIPE *Pipe Stress Analysis and Design Program*, Version 6.2, Bentley Systems, Inc., Walnut Creek, CA., 2002.

[5-3] Code of Practice for Fatigue Design and Assessment of Steel Structures, British Standard, BS 7608: 1993.

[5-4] Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2.

[5-5] "Fatigue Damage Curves for Damage Calculations for a Dented and Ovalled Section of the Trans-Alaska Pipeline System" by Stevick, Hart and Flanders, Proceedings of the International Pipeline Conference (IPC), 1998

[5-6] Rosenfeld, M. J., Hart, J. D., Zulfiqar, N., Gailing, R., "Development of Acceptance Criteria for Mild Ripples in Pipeline Field Bends", IPC02-27124, ASME International Pipeline Conference, Calgary, Alberta, Canada, September 29-October3, 2002.

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[5-8] American Lifelines Alliance (ALA) "Guidelines for the Design of Buried Steel Pipe", Published by the ASCE American Lifelines Alliance, www.americanlifelinesalliance.org, July, 2001.

[5-9] ASCE, "Guidelines for the Seismic Design of Oil and Gas Pipeline Systems", Committee on Gas and Liquid Fuel Lifelines, 1984.

[5-10] Arav, F., "Evaluation of Pipe Bends Having Local Corrugations", Third International Conference on Pressure Vessel Technology, Part 1, Analysis, Design and Inspection (1977)

[5-11] Markl, A. R. C., "Fatigue Tests of Piping Components", Paper 51-PET-21, *Trans. ASME*, 17 pages (1952).]

[5-12] Miner, M. A., "Cumulative Damage in Fatigue", Journal of Applied Mechanics, ASME Vol. 12, 1945.

# 6. Additional Review Material

As mentioned previously, a teleconference was held during the course of this review during which several questions posed by the reviewers were discussed with Mirant and its team of engineering consultants. On February 10<sup>th</sup> the OPS received from Mirant a number of supplementary documents that directly relate to the items discussed during the teleconference. These items are contained in Appendix B. Section 6.1 discusses the major topics presented in the supplementary information.

On March 6, 2003 a meeting was held at the Mirant Service Center in Upper Marlboro, Maryland. This meeting was attended by representatives from the OPS, MDPSCED, Mirant, Dominion, and Baker. The purpose of the meeting was to discuss the results of reviews by Baker and to determine remaining actions required to finalize the analyses and reviews to the satisfaction of the regulatory agencies. Meeting minutes as recorded by MDPSCED are attached as Appendix C.

As a result of this meeting, Mirant agreed to additional analyses to be conducted by Dominion and on March 24, 2003 information pertaining to these analyses was forwarded to Baker for review by the OPS. This information is presented as Appendix D. Section 6.2 discusses the major topics contained in this information.

# 6.1. Teleconference Follow-up Document Review

# 6.1.1. Pipe-Soil Interaction

A cursory sensitivity study was conducted by Dominion to determine the effects of soil resistance on pipe stress. The results of this study, along with a force versus deflection graph developed as part of the field push-pull tests, were transmitted for review. In a meeting at Mirant's headquarters on March 6, 2003, it was verbally confirmed that the cover depth of these field tests agreed with the nominal cover depth assumption of 3 feet.

The sensitivity analysis consisted of three soil resistance variations from the base case scenario applied to two bend models. One case examined the effects of changing the values for axial restraint to a lower yield strength with a higher spring constant, while the other two varied the lateral soil resistance from the base case by factors of  $\frac{1}{2}$  and 2 (i.e., 50% and 200% of base case resistance values).

In the axial spring sensitivity study, stresses decreased slightly when compared with the base case. In the lateral spring sensitivity study reducing the values of yield strength and spring constants reduced stresses (3% to 36%), while increasing the values increased stresses (0.3% to 9.7%).

Pipe-soil interaction analyses performed as part of this review indicate that the bending moment and curvature change at the apex of the bend and the associated "displacement stress" (i.e., a key component of the fatigue demand) tends to increase with decreasing soil strength. This is intuitively reasonable since decreased soil resistance results in increased transverse bend displacements, which in turn increases the displacement (expansion) stress range. However, the follow-up information provided by Dominion indicates that "...when the soil resistance goes down (which is essentially what would happen in buoyant soil conditions), stresses also go down due to the reduction in constrained motion at the elbows...". This statement appears to be inconsistent with Dominion's previous statement that "....The (Swanson Creek) failure location was also in poor soil conditions)



*that probably resulted in inadequate support for the pipe at a direction change...* "which seems to indicate that the poor (weak) soil conditions at Swanson Creek made things worse for this wrinkle, not better. Our pipe-soil interaction analyses of a series of side bend configurations did show a drop-off in the compressive axial force profile across the bend with the amount of the drop-off being more significant for weaker soil conditions. It follows that the stresses due to axial force alone (i.e., F/A) decrease for weaker soil conditions. However, the axial stress due to bending associated with the transverse displacement of the bend apex clearly increases with increasing bend displacement (and reduced soil strength) which overrides the axial stress drop-off due to the reduced axial force. Therefore, Dominion's statement is inconsistent with our results and our expectations.

## 6.1.2. Thermally Induced Bending Moment

A short paper was transmitted to correct the value of bending moment reported during the teleconference. This paper briefly explains calculations performed to quantify the bending moment induced by thermal expansion at a 5-degree bend in the pipe. These calculations showed a value of 1.5 million foot-pounds as opposed to the 3 million foot-pounds stated during the teleconference. The moment diagram on each leg of the model consists of an equal and opposite moment applied to each end with a linear variation in moment between ends (i.e., zero moment at the mid length of each leg). Note that the sketch (a marked up version of Figure III-5) provided by Dominion showing the sense of the bending moments acting on each leg of the model appears to indicate a constant moment diagram along each leg (+M<sub>o</sub> over the leg length) as opposed to the linearly varying moment diagram (from  $-M_0$  to  $+M_0$  over the leg length) described in the text. The linearly varying moment diagram provides a reversal of curvature (i.e., the moment passes through zero) in the middle of each leg. A moment diagram of this sort is reasonably consistent with the shape of the moment diagrams established from pipe-soil interaction analyses, which show a reversal of curvature within a short distance (e.g., about  $\pm 6$  to  $\pm 10$  feet) from the maximum positive moment location at the apex of the bend. However, the magnitude of the negative moment "lobes" from the pipe-soil interaction analyses is less than 50% of the positive moment value compared to 100% for the Dominion moment diagram. Without performing a case-specific pipe-soil interaction analysis, it is not possible to check the magnitude of the moment at the apex of the bend.

# 6.1.3. Stress-Strain Curve for Elastic-Plastic Analysis

The true stress-true strain curve used in the elastic-plastic finite element analysis of wrinkles was transmitted for review. This curve was derived from a stress-strain curve for X-52 steel since it closely matched the measured yield strength, tensile strength and elongation of a sample taken from the Piney Point pipeline. The original curve was modified to reduce the proportional limit to 45 ksi and then the tensile strength of approximately 65 ksi was derived from the true stress-true strain curve. Both these values are somewhat lower than the corresponding values from the test sample.

While this approach might be appropriate to gain a accurate understanding of the point on the pipeline where the sample was taken, there are not sufficient test results presented to make it appropriate for application to the remainder of the line. Fairly large variations in material properties from pipe lot to pipe lot or even pipe joint to pipe joint are well documented and therefore this approach is not necessarily conservative. Finally, the stress-strain curve values submitted for review exceeds SMYS by about 18%, rather than being at or near SMYS as expected. For all these reasons,



the review team recommended that analysis be completed using a modified stress-strain curve having a stress value of 42 ksi corresponding with a strain value of 0.5%.

## 6.1.4. Temperature Differential and Internal Pressure for Fatigue Analysis

To date all wrinkle analyses used a temperature differential of 110°F. Mirant collected and analyzed temperature data during a recent cold weather pumping cycle. Mirant indicates that this data supports the temperature used in the analyses as an upper bound pipe wall metal temperatures for the entire pipeline.

The elastic-plastic analyses conducted by Dominion did not include pressure loading and thus did not account for a number of effects related to pressure loading.

### 6.1.5. Fatigue Data

The fatigue evaluation conducted by Dominion used a fatigue curve for HSLA steel since, based on a single tensile test result from the Piney Point pipeline steel, it was felt that this curve was appropriate for the evaluation. However, this curve was not the most conservative of those presented, therefore Mirant elected to use the low cycle fatigue properties of the more conservative curve (AISI 1006 material) to calculate fatigue lives of the remaining wrinkles when using this evaluation technique.

### 6.1.6. Factors of Safety

The fatigue evaluation conducted by Dominion indicated a factor of safety of approximately 10 on cycles (relative to the accumulated cycles). However, the fatigue design curve in the ASME Boiler and Pressure Vessel Code, Section VIII, incorporates a safety factor of 20 on cycles. DEI indicates that a factor of safety of 20 on cycles corresponds to a factor of safety of the square-root of 20 (4.47) on plastic strain amplitude. (Note: this factor of safety appears to be qualitatively reasonable based on the governing N/20 curve shown in Figure 5.11 which provides a factor of safety on stress of approximately 4.0 to 4.5 in the range of  $10 \le N \le 100$ ). Thus Mirant elected to apply a safety factor of 20 on cycles for fatigue evaluation of the remaining wrinkles in the Piney Point pipeline when using this technique.

### 6.2. Review Meeting Follow-up Information Review

# 6.2.1. Elastic-Plastic Analysis

As stated on the original report, DEI-656, Dominion selected elastic-plastic finite element analysis as the primary basis for evaluation of wrinkles in the Piney Point Pipeline. Dominion provided additional justification for the use of elastic-plastic analysis in the follow up document "*Piney Point Pipeline Basis for Elastic-Plastic Wrinkle Model, Acceptance Criteria and Factors of Safety*" dated 2/7/03.

The primary benefits provided by elastic-plastic analysis are that it can be readily applied to the evaluation of small wrinkles where the material behavior is essentially linear elastic as well as to the evaluation of large wrinkles that experience significant levels of plasticity. We would also agree that



formal elastic-plastic analysis methods would be superior and more generally applicable then the "simplified elastic-plastic analyses" allowed by the ASME code (wherein elastically computed stress measures are multiplied by a generic  $K_e$  factor).

The same modeling strategy and analysis methodology used by Dominion in their original analyses has been applied in their follow up analyses. Hence, all of the review comments previously developed in this report with regards to these items are still applicable.

## 6.2.2. Acceptance Criteria

The Dominion reports indicate that the first part of their acceptance criteria was that plasticity should be limited to a small enough region of the wrinkle to preclude ratcheting effects. A wrinkle geometry was considered acceptable only when the reverse plastic strain that occurs on unloading was limited to a small region on only one surface of the pipe (i.e., on the ID or on the OD, but not both). Dominion has indicated that all modeled wrinkle geometries that did not satisfy this "anti-ratcheting" criterion (including the Swanson Creek wrinkle) have been removed from service. Dominion believes that ratcheting and associated accentuation of the wrinkle geometry at Swanson Creek did occur, which is one reason for its short fatigue life.

The original Dominion report, DEI-656, undertook fatigue life calculations using published strain cycling fatigue data (i.e.,  $\varepsilon$ -N relationships) for "steels similar to X-42 steel" as well as using the ASME Section VIII, Division 2 fatigue design (S-N) relationships (i.e., Table/Figure 5-110.1) for carbon steel. As stated in our original review, it is reasonable to expect that the use of a  $\varepsilon$ -N relationship instead of a S-N relationship is the most direct way to capture the fatigue behavior in the low cycle fatigue regime. However, the lack of a well documented "factor of safety" associated with the published strain based fatigue data lead the review team to favor the use of the ASME fatigue design relationships, which has a well documented factor of safety with respect to its basis data (i.e., a factor of 20 on cycles in the low cycle fatigue regime).

As part of the 2/28/03 follow up documentation entitled "Application of ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Appendix 5 for Calculation of Fatigue Lives of Wrinkles in the Piney Point Pipeline", Dominion generated a table (Table 1) that summarized fatigue cycles for a range of wrinkle geometries based on the strain cycling data and on the ASME S-N relationships (converting in-elastically computed strains to equivalent elastic stresses). This table was the subject of extensive discussions at the 3/6/03 review meeting. Based on these discussions, and with the approval of MPSCED and Baker, Dominion agreed to use the ASME fatigue evaluation procedure for all subsequent fatigue calculations and fatigue life acceptance.

# 6.2.3. Modified Stress-Strain Curve

Based on our initial review of the Dominion finite element analyses, it was observed that on the assumed stress-strain relationship, the yield stress value at 0.5% strain (once converted to engineering stress-strain coordinates) was approximately 49.4 ksi and the corresponding ultimate stress was about 66.8 ksi. These yield and ultimate stress values are about 18% and 11% larger, respectively, than the minimum yield and ultimate stress values (42 ksi and 60 ksi) specified by API 5L. Based on this observation, it was recommended that additional analyses be performed by Dominion using a stress-strain curve that was adjusted to match the API 5L minimum values.

Dominion provided a revised stress-strain curve in Figure 1 of the submittal dated 3/21/03. This figure presents a revised true stress-strain curve used for subsequent finite element analyses. The true stress-strain coordinates from this curve were manually scaled and converted to engineering stress-strain coordinates. Using this approach, it was determined that the yield stress (defined at 0.5% strain) was approximately 42 ksi and the ultimate stress was approximately 60 ksi and hence the revised stress-strain curve is aligned with the API 5L specified minimum yield and ultimate stress values. The original and revised true and engineering stress-strain relationships are shown in Figures 6.1 and 6.2, respectively.



Figure 6.1 True Stress-Strain Curves used in Wrinkle Analysis



### Figure 6.2 Engineering Stress-Strain Curves Developed from True Stress-Strain Curves

# 6.2.4. Additional Geometric Information

Dominion's 3/21/03 follow up document indicates that additional data to characterize the wrinkle geometry has become available since the time that the original report, DEI-656, was completed. The additional geometry data includes Geopig measured bend angles at individual wrinkles (a 5 degree bend was used for all wrinkles in the original wrinkle parametric analyses). The actual bend angles at the remaining wrinkles shown in Table 1 of the 3/21/03 follow up document are all less than 5 degrees. Previous information provided by Dominion indicated reduced wrinkle stresses for reduced bend angles. Table 1 also provides wrinkle specific circumferential extents ranging from 120 to 150 degrees. These circumferential extents are on the low end of the circumferential extents considered in the original DEI-656 parametric studies. Previous information provided by Dominion indicated wrinkle stresses for increased circumferential extents. In summary, the additional geometric information on both bend angle and circumferential extent has lead to a reduction in the calculated wrinkle stresses.

### 6.2.5. Temperature Loading

The original analyses presented in DEI-656 assumed that a temperature differential of 110°F was bounding for all locations along the Piney Point Pipeline. Detailed calculations performed by MPSCED have indicated that 110°F may not be bounding for all locations for all of the past operating cycles but that 110°F would be an appropriate upper bound temperature differential for future operating cycles. The maximum temperature differential computed by MPSCED was 137°F. At the 3/6/03 meeting, it was agreed that additional calculations would be performed using the

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location specific temperature differentials computed by MPSCED. It was also agreed that it would be appropriate to consider some combination of high and low end temperature differentials for past cycles (e.g., some cycles occurred in cold weather while some cycles occurred in warmer weather) using a "rain-flow" type cycle counting procedure.

The cover letter and Table 1 from the 3/21/03 follow up document indicate that 10% of the past operating cycles were based on the MSPCED maximum temperature differential curves while 90% of the of the past operating cycles were based on the MSPCED minimum temperature differential curves. The basis for selecting the "10%-90%" past cycles combination is not clearly stated. The second to last column of Table 1 presents the cumulative damage (fatigue usage) for the estimated 150 past operating cycles. However, fatigue damage (usage) is only provided for the "10%-90%" past cycles combination, not for the separate maximum and minimum temperature differential components so it is not possible to extract results for alternative "rain flow" combinations (e.g., 100% maximum temperature differential with 0% minimum temperature differential).

The last column of Table 1 presents the remaining cycles based on the location specific temperature differential profile for forward looking operating cycles. Based on the results presented in Table 1 for the "10%-90%" past cycles combination, all of the remaining wrinkles have at least 1,622 remaining design fatigue cycles. Note that the tabulated remaining design cycles include a factor of safety of 20 relative the ASME fatigue basis data.

## 6.2.6. Pressure Loading

In the initial review of DEI-656, it was observed that internal pressure loading was not considered in the finite element evaluations and recommended that the wrinkle evaluations should be extended to include internal pressure effects.

In both the 2/28/03 follow up document entitled "Application of ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Appendix 5 for Calculation of Fatigue Lives of Wrinkles in the Piney Point Pipeline", and in the more recent "Evaluation of Plastic Strain Amplitudes and Fatigue Usage for Wrinkles in the Mirant Piney Point Pipeline" document dated 3/21/03, Dominion included pressure effects in the finite element analyses.

# 7. Conclusions of this Review

The documents included in the original scope were reviewed in detail. Basically, the documents were seen as addressing one of two issues:

- 1. ASME B31.4 code provisions at bends
- 2. Acceptance Criteria for wrinkles evident in the Piney Point pipeline

## 7.1. Code Compliance Analyses

For the first item, ASME B31.4 code provisions, Mirant and its consultants performed a series of analyses, using commercially available and qualified software, and checked the stress results against code allowables. The pipe material and geometric properties required as input for these analyses were reviewed and the only potential denigrating influence, that of a lesser wall thickness, was questioned with Mirant and its consultants stating that they had reviewed this and there was no reason to lessen this value. Since there is no technical question as to how this is done, the assertion by Mirant and its consultants statisfied this potential influence.

Secondly, there was a concern that the design basis, namely the operating pressure and temperatures used in the analyses, were variably cited in the various reports. Mirant and its consultants stated that the definitive values were the basis of its final report. Mirant further investigated the tie-in temperature using ambient air data during construction – though this was not received by the review team it is agreed that this is the accepted method to document tie-in temperatures and the review team recommends this documentation be included in any final report. Given that these values are stated and documented in this final report, and that the corresponding code checks were found acceptable based on these values, there are no further technical areas of concern in this area of the code evaluation process. There remains the issue that the startup stipulations and operating manual of the Piney Point pipeline reflect and/or enforce these limits and that they are adhered to throughout operations but these details are outside the scope of this review.

Finally, there was a concern that the soil values used in the analyses reflect field conditions, especially in view of the comment that the previous failure condition was exacerbated by poor soil conditions. This was quantitatively evaluated in this review and the results compared to values used by Mirant and its consultants. Again, the values are variably cited in the various reports, but we noted that a field test was performed to further detail the axial yield value so the change was understandable. The values used were found to be within limits that are typically used for buried piping evaluation in non-buoyant oil conditions. Typically, it is prudent to consider variations of these values and explicitly consider any pipeline soil segments that are in buoyant conditions. Bends in buoyant conditions should be identified in the summary report and appropriate values used in the demonstration.

In summary, with the assertions and studies performed by Mirant and its consultants outside the scope of this review, we are satisfied that Mirant has followed accepted practice and prudent procedures to demonstrate this issue of code compliance at bends in non-buoyant conditions given the design basis operating conditions. For those bends in buoyant soils, they should be identified and values appropriate to those conditions substituted for the soil restraint values.



We recommend that the summary report be based on the design basis operating conditions and that the actual operating conditions be monitored, recorded and reported to ensure that the actual conditions remain within the limits that are the basis of the demonstration analyses.

### 7.2. Wrinkle Acceptance Criteria

The various reports addressing this subject were reviewed with attention focused on the Dominion report "Acceptance Criteria for As-Inspected Wrinkles in Piney Point Oil Pipeline". Questions concerning the details of the finite element analysis were posed by the review team early in the review process. Most of these questions were answered in teleconference with the operator and its consultants and/or in later submittals made by the operator. These submittals and a number of more simplified studies completed by the review team confirmed the conservatism or adequacy of the model in its geometric and boundary condition modeling.

At a meeting at Mirant's headquarters on March 6, 2003, the buried pipe side bend analyses performed by the review team were briefly reviewed. The analyses showed that reduced soil strengths lead to increased "expansion" stress due to thermal cycles. The review team analyses subsequent to the meeting confirmed the same trend for hot bends. The review team's findings thus disagree with Dominion's conclusions on this particular issue. However, this inconsistency has no quantitative impact on the Dominion wrinkle finite element models since, in effect, the effect of soil restraint is neglected in these models. As stated in Section 5.4 of the initial report, submitted before the March 6 meeting, and repeated at the meeting, we believe that the Dominion FEA models are conservative since they are applying the fully restrained axial compression force to an unrestrained pipe model in order to generate moments at the wrinkle. As illustrated in Figure 5.1(c), the axial compression force computed at the apex of the bend in a buried pipe model (for both upper and lower bound soils) is significantly less than the fully restrained axial compression force realized in the fully restrained sections of the model (e.g., past the virtual anchor). This is because the bend moves in/near the apex and hence the pipe is not fully restrained in the vicinity of the apex. It was also stated that the leg lengths (and the shape of the associated moment diagram) used by Dominion appear to be reasonable based on comparison with the shape of the moment diagrams from our buried pipe models.

A serious deficit of the initial modeling was seen to be its lack of pressure loading which was noted in the review team initial report and discussed at the March 6th meeting. During the meeting, it was agreed that further analyses performed by Mirant/Dominion would include pressure loading effects.

A final area of modeling concern was the stress-strain curve used as input to the initial FEA models. The basis for the initial curve used was submitted by the operator. However, the curve showed significant differences from a nominal X-42 curve that is anchored based on code and material acceptance criteria, e.g. anchoring the SMYS value to 0.5% strain. Moreover, it was reported that no material tracking for the original construction was available and, apparently, only one tensile test was performed. In view of experience with testing variability and possible differences in base heats for the pipe material, it was recommended that the possibility of material variation be addressed by using a stress-strain curve consistent with the minimum yield and ultimate strength specified for Grade X42 steel in API 5L.



Subsequently, Mirant submitted a revised true stress-strain curve used in their final analyses, which included pressure effects. Upon conversion from true stress-strain to engineering stress-strain coordinates by the review team it was determined that the submitted curve aligned with the API 5L minimum values. For clarity in the future, it is suggested that both the true stress-strain curve and the corresponding engineering stress-strain curves be included in any final report (e.g., see Figures 6.1 and 6.2).

Finally, the initial FE results were compared to experimental data to find the estimated number of cycles to failure. In this review, we initially found that this methodology was not sufficiently detailed to demonstrate the level of confidence and acceptable factor of safety for a final acceptance. The clarification of procedure, given in the February 7, 2003 memo, including the designation of the data curve for the estimated cycles to failure given the analytical results, and the designation of an acceptable factor of safety to finally determine the acceptable number of cycles for acceptance review was found to be both reasonable and acceptable.

In response to these concerns and additional discussions, Mirant agreed to utilize the final FE results together with the ASME design fatigue curve to estimate the number of cycles to failure. Results of this comparison (see Appendix D) provided information for the past 150 cycles based on a fixed combination of 10% of the cycles at maximum temperature differential and 90% of the cycles at the temperature differential used in the original analysis. The approach used to estimate damage from two different loading scenarios is consistent with accepted practice. The origin/basis of the 10%-90% combination selected by Mirant/Dominion is not provided in the transmitted document although the reviewers have no contradictory evidence. Further, the number of cycles developed through the procedure used are higher than required for an integrity demonstration assuming the operational estimates of Mirant/Dominion which provides additional confidence in the results. In a telephone conversation with Mirant/Dominion on April 3, Mirant stated that they were separately researching and documenting ambient temperatures and such data could be used to further justify the 10%-90% split estimate. Because the cumulative damage due to past cycles is only provided for the assumed 10%-90% combination, the review team was not able to manipulate the results to provide fatigue damage bounds for alternative "rain flow" cycle combinations. This is considered as a documentation recommendation only, since the theoretical and procedural techniques have been agreed upon and are acceptable.

# 8. Recommended Actions

With regard to the two distinct areas of concern cited previously:

### 8.1. Code Compliance Analyses

We recommend that:

- OPS ensure the capture of all ancillary studies by Mirant and its consultants, e.g. bend analyses in buoyant conditions, documentation of differential temperatures, NDE results that verify no corrosion allowance is required. Note that there should be no technical items of concern here since the procedures and processes are dictated by standard practice and have been further reviewed in this report.
- The operating conditions used in the analyses be reflected both in any stipulations for startup as well as the pipeline operating procedures. Based on the results and the need to closely define the values used in the analyses to demonstrate acceptance, Mirant should consider hardware (e.g., alarms, procedures, and/or facilities) that prevent exceedence of these operational limits.

## 8.2. Wrinkle Acceptance Criteria

We recommend that:

• Mirant and its consultants gather individually submitted reports and data and issue a summary analytical FEA report incorporating information gained since the date of the original report, especially including internal pressure and specific wrinkle geometries as reported by NDE in the analysis. The documentation concerning the tie-in temperature, as discussed above, should be referenced. Documentation supporting the assumed split of differential temperatures used in the estimate of prior fatigue usage should also be included.