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ANALYSIS OF PIPE EXPANSION ASSOCIATED WITH FIELD HYDROSTATIC TESTING

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ABSTRACT

Pipeline construction projects built in the United States to the recent requirements for operation at 80% SMYS are subjected to high stress pre-service hydrostatic tests. At very high stress levels, pipe diameter expansion, as measured by an ILI caliper tool, should not be a surprising result. In some cases, however, excessive pipe expansion has occurred and been reported by PHMSA in an industry advisory bulletin regarding potentially low yield strength results for X-70 and X-80 grade pipes.

In response to this advisory notice, a detailed review was made of pipe expansion conditions for the 270 mile Southeast Supply Header (SESH) pipeline which was built in 2008. This review included a statistical analysis of the pipe yield strength and dimensional characteristics prior to installation, a review of hydrostatic test levels during the pre-service field hydrotest, and the corresponding diameter results measured by the multi-channel in-line inspection caliper tool. The results demonstrate that the pipe yield strength property distribution was well within good X-70 and X-80 process capability.

The purpose of this paper is to demonstrate that explanations other than low yield strength pipe may be responsible for pipe expansion.

INTRODUCTION

Pipeline construction projects built in the United States to the recent requirements for operation at 80% SMYS are subjected to high stress pre-service hydrostatic tests. At very high stress levels, pipe diameter expansion, as measured by an ILI caliper tool, should not be a surprising result. In some cases, however, excessive pipe expansion has occurred and been reported by PHMSA in an industry advisory bulletin regarding potentially low yield strength results for X-70 and X-80 grade pipes.

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The incremental expansion that did occur in several pipe joints (of 23,000) was therefore attributed to the pre-service field hydrostatic test. A detailed review was made of the available pipe mill data and field test data to develop an explanation for the expansion results of the pipeline. Results are presented that demonstrate that the pipe expansion is not due to low yield strength pipes, or under gauge wall thickness. Rather, as the field hydrostatic test itself approaches the material yield strength limit, incremental construction stresses that act as a residual compressive stress may enable expansion. Such incremental residual stresses due to a number of normal field construction conditions (residual bending stress, thermal stresses due to ambient temperatures, tie-in weld stresses, others) act to increase the effective hoop stress during the field hydrostatic test and facilitate expansion.

Some consideration is being given to the removal of several pipe joints from service to validate the yield strength results. The removal of these pipes is not considered urgent, as pipe with incremental expansion have been in service for many decades with no fitness concerns. The purpose of this paper is to demonstrate that explanations other than low yield strength pipe may be responsible for pipe expansion.

QC/QA ACTIVITIES WITH RESPECT TO COIL SUPPLY

Due to the size of the project and the challenging delivery requirements for 36” and 42” SAWH (helical submerged arc weld) pipes, X-70 and X-80 grade coil supply was split among three sources in order to assure continuous and uninterrupted flow of raw material. Each of the three coil suppliers developed chemistry and material properties as per the project needs and internal Corinth Pipeworks S.A (CPW) specification requirements. Special attention was made by CPW to assure that the proposed steel:

1. was in accordance with applicable specifications and suitable for the intended design,
2. was allowing the steel suppliers reasonable “safety zone” away from marginal conditions,
3. was reasonably uniform among the three suppliers in order to assure homogenous welding properties, minimize field welding qualification cost, and produce uniform dimensional quality.

The steel suppliers’ proposals were documented through a Manufacturing Procedure Specification (MPS) and Inspection & Test Plan (ITP). The MPS described in detail the specific manufacturing route to be used and addressed all the critical process points to be monitored (e.g. detailed chemistry, casting speed, rolling parameters, etc.) including operating limits as well as aimed values.

The proposals were thoroughly examined by CPW and were presented to SESH for comments and approval at the very early stages of the project. Final details were tuned during Pre-Production Meeting (PPM) held at each supplier’s designated manufacturing location at the presence of CPW and SESH delegation.

STATISTICAL ANALYSIS OF PRODUCED PIPE

A statistical distribution of pipe body outside diameter measurements of 36” x 0.386” X-70 is presented in Figure 1. This figure represents pipe body diameter measurements made in the pipe mill after a mill hydrostatic test of 95% SMYS with the application of end load compensation. The distribution curve is very narrow and the average value of the diameter is 914.8 mm with a standard deviation (σ) of 0.37 mm. Note that the blue box in the central region of the distribution curve represent the range of dimensional results for those individual pipes that later experienced expansion during the field hydrostatic test. The purpose of this exercise is to demonstrate that no pipe yielding occurred as a consequence of the mill hydrostatic test.

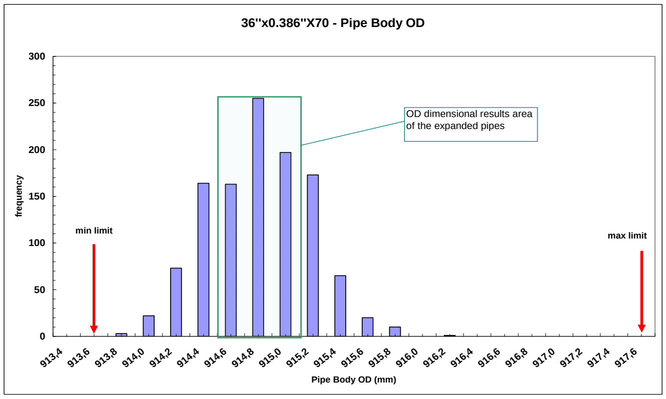

Figure 1 – Distribution of Pipe Body Diameter Results after Mill Hydrostatic Test

The distribution histogram of pipe yield strength ($Rt_{0.5}$) using flattened strap specimens is shown in Figure 2. The blue box in the central region of the distribution curve represents the range of yield strength results for the expanded pipe heats. The expanded pipe joints were all sourced from a single supplier. The mean and standard deviations were 75.0 ksi and 2.41 ksi, respectively.

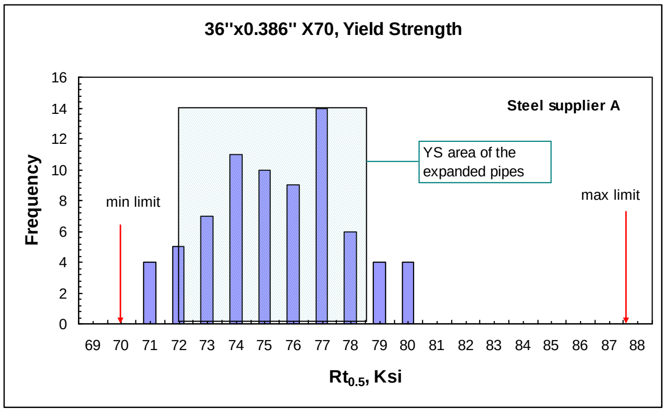

Figure 2 – Distribution of Pipe Yield Strength as tested in the pipe mill laboratory

SUMMARY OF ILI EXPANSION FINDINGS

In-line-inspection multi-channel caliper tools were used for post-construction detection of mechanical damage such as dents and pipe ovality. At the request of PHMSA, the caliper tool data was later used to evaluate the pipeline for evidence of expansion and to report any instances of expanded pipe greater than 1% of diameter in the SESH line. Of particular interest was evidence of expansion greater than 1.5%; six such locations were identified, and these locations serve as the basis for this analysis.

Details of the expansion results from the caliper tool and subsequent verification excavations are given in Table 1. The three largest expansions from the caliper data analysis were chosen for excavation and assessment in accordance with Spectra Energy's field inspection procedure. For each expansion location, the entire joint was excavated (from girth weld to girth weld) with approximately 6-inches of clearance underneath the pipe. The pipe surface was cleaned of any heavy dirt and debris to assure accurate diameter measurements. Once excavated, location was confirmed by verifying the measured joint length with as-built data. Beginning at one end of each pipe, a diameter measurement was made every 12 inches using a Pi tape.

The ILI caliper tool inspection was run at virtually ambient pressure prior to line commissioning; the field verification measurements were made under in-service conditions at line pressure. Therefore, the elastic response of the pipe due to operating pressure was accounted for in calculating the pipe expansion results. Also, the coating thickness was taken into account during field measurements. The field measurement results reported in Table 1 include both corrections (elastic pipe response and coating thickness).

The correlation between the ILI data and field verification measurements were well within the ILI service provider tolerance capability and no further field excavations became necessary. Because no pipe expansion exceeded 2% of diameter (which was established as an internal acceptance criteria), none of the expanded joints were considered to be an integrity threat. As a result, none of the joints were removed from service. Additional guidance was later proposed by PHMSA and some consideration is still being given to the removal of several expanded pipes for further metallurgical testing.

Coil Number Reference	Pipe Sequence from Coil	Percent Expansion by ILI Caliper [%OD]	Percent Expansion - Field Measurement and Corrections [%OD]
B	7th pipe	2.03	1.85
E	9th pipe	1.69	1.56
D	9th pipe	1.63	1.66
D	8th pipe	1.58	N/A
A	7th pipe	1.57	N/A
C	9th pipe	1.55	N/A

Table 1 - ILI Expansion Analysis and Field Measurement Results

ANALYSIS OF FIELD HYDROSTATIC TESTS AND ITS IMPLICATIONS

As a specified condition of gas pipeline operations at 80% SMYS, the field hydrostatic test must be conducted to a minimum pressure of 100% SMYS for the Class I locations. A summary is given in Table 2 that displays the ILI expansion results for each of the six individual pipes above 1.5% expansion along with the expansion results of other SAWH pipes produced from the same coil.

	Pipe Sequence from Coil	Field Hydrotest Stress Level (SMYS, actual gauge pressure at elevation) [%SMYS]	Percent Expansion-Caliper Tool Estimate [%OD]
A	1st pipe	103.31	< 1
	2nd pipe	105.36	< 1
	3rd pipe	105.10	< 1
	4th pipe	105.50	< 1
	5th pipe	103.35	< 1
	6th pipe	104.66	< 1
	7th pipe	104.44	1.57
	8th pipe	104.98	1.11
	9th pipe	102.49	< 1
	10th pipe	102.10	< 1
B	1st pipe	103.92	< 1
	2nd pipe	102.39	< 1
	3rd pipe	103.62	< 1
	4th pipe	106.71	< 1
	5th pipe	104.46	< 1
	6th pipe	106.29	< 1
	7th pipe	106.57	2.03
	8th pipe	103.94	< 1
	9th pipe	106.74	< 1
	10th pipe	106.63	< 1
C	1st pipe	102.66	< 1
	2nd pipe	102.75	< 1
	3rd pipe	105.04	< 1
	4th pipe	104.44	< 1
	5th pipe	102.72	< 1
	6th pipe	102.7	< 1
	7th pipe	105.12	< 1
	8th pipe	102.49	< 1
	9th pipe*	105.41	< 1
	9th pipe*	106.39	1.55
	10th pipe	105.38	< 1
D	1st pipe	104.75	< 1
	2nd pipe	101.82	< 1
	3rd pipe	104.58	< 1
	4th pipe	101.88	< 1
	5th pipe	102.76	< 1
	6th pipe	surplus pipe, not used	< 1
	7th pipe	105.88	< 1
	8th pipe	104.71	1.58
	9th pipe	102.98	1.63
	10th pipe	104.59	< 1
E	1st pipe	102.04	< 1

	2nd pipe	108.48	< 1
	3rd pipe	106.52	< 1
	4th pipe	106.78	< 1
	5th pipe	106.72	< 1
	6th pipe	103.62	< 1
	7th pipe	104.84	< 1
	8th pipe	104.83	< 1
	9th pipe	106.72	1.69
	10th pipe	105.84	< 1
* note that this pipe was field cut for tie-ins, one half experienced expansion, the other did not			

Table 2 - Pipe Field Hydrotest and Expansion Results

From these results above, the following observations are made:

1. Pipe from each of the subject coils contained pipes that were tested to similar field test stress levels.
2. The process control data of these individual coils from which the pipes under investigation were examined. The examination revealed that:
    a. Heat analysis was well in accordance with the specification and very similar among the coils.
    b. Rolling parameters for all coils were within the optimum process envelope.
    c. Coils were produced with very stable and uniform conditions. No evidence was available to suggest that coils were different or could exhibit inferior properties whatsoever along their length.
3. Figure 1 previously demonstrated that no expansion occurred in the pipe mill as a consequence of the mill hydrotest. A discussion follows later in this paper that explains the nature of biaxial stress conditions for field hydrotest and that the hoop stress of the mill test represents a higher hoop stress than the field test at field test pressures lower than about 107% SMYS. And herein lays the conflict. The mill hydrotest produced a higher hoop stress than the field test, and yet the pipe clearly expanded during the field test. A conclusion from this is that the pipe expansion resulted from hoop stress levels that are not predicted by simple biaxial conditions of a field test. An extension of this conclusion is that the pipe expansion was likely the result of high hoop stress conditions during the field test rather than due to low/variable pipe yield strength results.

ANALYSIS OF HYDROSTATIC TEST STRESSES

The wall of a pressurized pipeline experiences a 3-dimensional state of stress with reference to circumferential, longitudinal, and radial orientations. For many practical situations the radial stress component has only a small effect so the stress state is reduced to biaxial plane stress. The magnitude of the biaxial stress is expressed by an effective stress calculated as $\sigma_{eff} = [\sigma_H^2 - \sigma_H\sigma_L + \sigma_L^2]^{0.5}$ where σ_H is the hoop or circumferential stress component and σ_L is the longitudinal stress component. [Ref. 1] The pipe wall is presumed to yield when σ_{eff} exceeds the "yield strength" of the material (however that property is defined, recognizing that the threshold for inelastic behavior may be indistinct and may actually be above or below specified minimum values measured by a particular convention). The yield threshold is then described by a "yield ellipse" on a plot of σ_H versus σ_L. The portion of the yield ellipse applicable to hoop stress in tension is shown in Figure 4.

If internal pressure is the only significant load acting on the buried pipeline, $\sigma_H = PD/2t$ and $\sigma_L = 0.3\sigma_H$. (This relationship is based on the conventional assumption for a long buried pipeline that soil friction prevents axial straining of the pipe. Note that if the pipe is "short" and capped, $\sigma_L = 0.5\sigma_H$.) Thus the effective biaxial stress for a buried pipeline is $\sigma_{eff} = [\sigma_H^2 - (\sigma_H)(0.3\sigma_H) + (0.3\sigma_H)^2]^{0.5} = 0.889\sigma_H$. The table below gives the effective biaxial stress level corresponding to various hoop stress levels, where internal pressure is the only significant loading:

Hoop Stress [%YS]	Eff. Stress [%YS]
72	64.0
80	71.1
90	80.0
95	84.4
100	88.9
101.2	90.0
105	93.3
106.9	95.0
110	97.8
112.5	100.0

Table 3 – Hoop & Effective Stress for Pipe in a State of Biaxial Stress

The table above is interpreted to mean that when, for example, a pipeline operates at a hoop stress of 80% of SMYS, its biaxial stress state is only a little over 70% of SMYS. Or when a pipeline is tested to a hoop stress level of 105% of SMYS, it is only 93% of the way toward yielding.

The biaxial stress state for a buried pipeline with only internal pressure loading is shown with respect to the yield ellipse in Figure 3. Yielding occurs where the line having a slope of 1/0.3 intersects the yield ellipse, indicated at Point "A" in Figure 3. This leads to the recognition that a buried pipeline under hydrostatic test would not be expected to "yield" until the hoop stress due to internal pressure exceeds 112.5% of the "yield strength". Thus, a hydrostatic pressure test to a hoop stress below that level would not be expected to result in yielding in the pipe if internal pressure is the only significant loading and the pipe has actual yield strength in excess of SMYS.

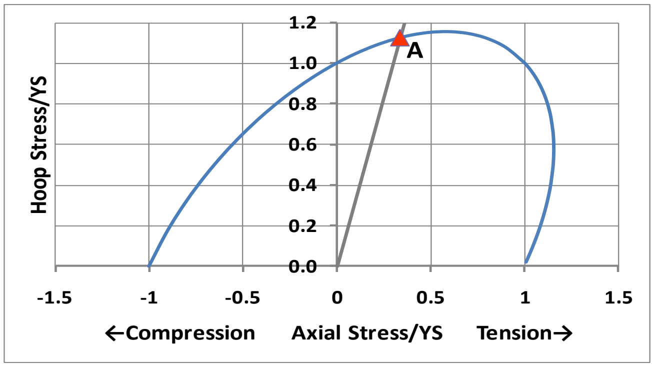

Figure 3 - Yield Ellipse for a Buried Pipeline

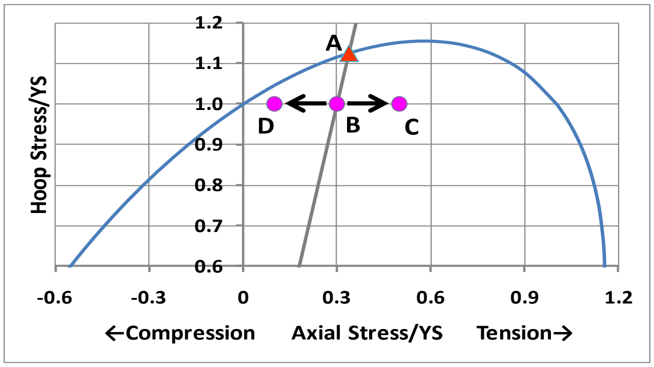

Figure 4 - Detail of Yield Ellipse with Hydrotest Condition and Externally Applied Longitudinal Stress

The manner in which the external stresses affect the tendency to yield during a hydrostatic test can be understood from the yield ellipse diagram. Figure 4 shows a detail of the upper part of Figure 3. Consider a pipeline under test at a pressure where yielding would not be expected, for example a hoop stress due to internal pressure equal to 100% of SMYS, indicated at Point "B" in Figure 4. Where externally applied longitudinal stresses are positive tensile, the biaxial state of stress moves farther away from the yield boundary, shown at Point "C" in Figure 4. Where externally applied longitudinal stresses are in compression, the biaxial state of stress moves toward the yield boundary as shown at Point "D". If the externally applied compressive stress is large enough, the biaxial state of stress will cause Point "D" to cross the yield boundary, resulting in yielding even though the stress state associated with the hydrostatic test pressure is well inside the yield boundary. Hence, where yielding does occur at hydrotest hoop stress levels well below 112.5% SMYS, and such causes as thin wall, oversize diameter as-manufactured, or low yield strength are ruled out as statistically unlikely, then external loading must be considered as a possible contributor to the overall state of stress.

An analysis was performed to estimate how low the actual yield strength would need to be in order to explain the largest instances of expanded pipe in the SESH project. The analysis considered the effective biaxial strain at the expanded diameter (D_x) to be $\varepsilon_{eff}=(2/\sqrt{3})\ln(D_x/D_o)$, [Ref. 2] along with wall thinning as the pipe diameter expands, and a Ramberg-Osgood stress-strain curve, leading to an expression relating the expanded diameter to the stress-strain relationship as follows:

where $\eta=(1-\nu+\nu^2)^{0.5}$, ν is Poisson's ratio, t_o is the initial wall thickness, D_o is the initial diameter, n is the strain hardening exponent, and s_o and ε_o are stress and strain values at the limits of elastic behavior. In order for the largest amounts of expansion to have occurred only due to the internal pressure during the hydrostatic testing, the pipe yield strengths at 0.5% extension under load (EUL) would need to be around 61 to 64 ksi, with elastic limits as low as 57 to 62 ksi, as shown in Figure 5 below.

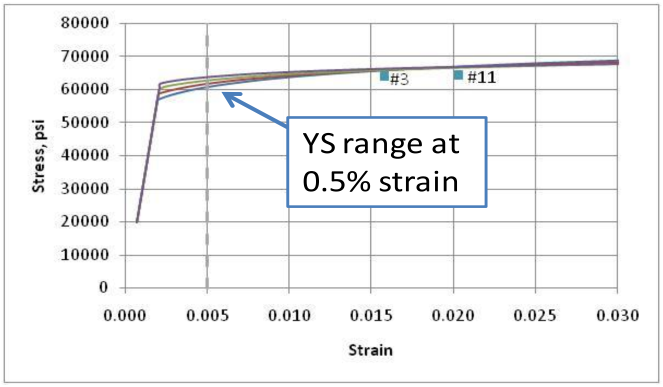

Figure 5 - Yield Strengths Necessary to Explain Pipe Expansion Due to Hydrotest Pressure Only

The statistical likelihood of pipe having such low yield strength was calculated considering the distribution of strength values from the pipe mill test reports presented in Figure 2. The SMYS was 2.08 standard deviations below the mean yield strength, so the probability of any pipe having actual yield strength below the SMYS of 70 ksi was 1 in 54. However, the probability of pipe having a yield strength sufficiently low to expand more than 1.5% at the test pressure (that is, 64 ksi or less according to the above calculations) was only 1 in 437,000. Since there were only 23,000 pipe joints in the project, low yield strength does not appear to be the most likely explanation for the observed expansion of several pipe joints. Therefore, some other factor must have influenced the behavior of the pipe during the test. The most likely cause was thought to be external loadings acting on the pipe, as will be discussed below.

EFFECT OF EXTERNAL LOADINGS DURING A HYDROSTATIC TEST

Many conditions commonly encountered in the field and associated with pipeline construction can impose loadings on the pipe that produce longitudinal stresses in the pipe. In a buried pipeline, such longitudinal stresses are "secondary" in nature, being the result of displacement-controlled conditions or self-constraint. Both test and theory have demonstrated that the presence of such stresses do not lower the burst pressure of the pipe. [Ref. 3] However, they can induce through-wall yielding at pipe section outer fibers, resulting in a redistribution of stress. The pipe section subject to only a bending moment (without concurrent internal pressure) will tend to ovalize, reducing the cross section diameter and moment of inertia normal to the axis of bending. When internal pressure is present concurrently, the pressure counteracts the ovality, increasing stiffness, altering the moment-curvature relationship, and altering the critical buckling threshold. In an isotropic material, the direction of strains is perpendicular to the yield surface. Thus where Point D (or Point C for that matter) in Figure 4 intercepts the yield ellipse, a plastic strain vector normal to the yield ellipse would be comprised of components in the direction of the applied load (compressive at Point D or tensile at Point C) and tensile circumferentially. Bending loading in the plastic range in the presence of internal pressure therefore results in an increase in pipe circumference and, therefore, diameter. [Ref. 3]

The external loads that could affect a buried pipe include but are not limited to the following:

- difficult alignment at tie-ins
- post-construction settlement
- uneven fit between ditch and pipe, or lack of uniform support under pipe
- weight of pipe string uphill
- installation in soft, unconsolidated, or swampy soils
- thermal expansion

Many of these conditions can occur locally in almost any pipeline construction project. The question is, how severe do such conditions have to be in order to cause yielding during a sub-yield hydrostatic pressure test? The answer may be "not very".

Consider a 36-inch OD pipeline constructed from X70 line pipe undergoing a hydrostatic pressure test to a hoop stress of 100% of SMYS. The longitudinal stress due to the test pressure is 30% of that, or 21 ksi. From Figure 4, an applied longitudinal stress of 21 ksi in compression would fully offset this stress (at Point D) to bring the pipe to the point of incipient yielding if the pipe material yield strength actually is only 70 ksi. If the pipe yield strength is in excess of SMYS, a larger applied compressive stress would be necessary to bring the pipe to the point of yielding. For example, if the actual pipe yield strength is 75 ksi (as it was on average for the affected SESH pipe heats), a hoop stress equal to 100% of SMYS or 70 ksi during the test is 93.3% of actual yield, and the effective biaxial stress is only 82.9% of actual yield. The biaxial stress equation indicates that a compressive stress of 12.3% of the 75-ksi yield strength, or 9.2 ksi, would be required to cause the pipe to yield. At the test condition, an external load that introduces a compressive stress of 21.0 ksi + 9.2 ksi = 30.2 ksi would bring the pipe to the point of yielding during the test. In this case, a 7% greater yield strength increases the capacity for external load during the test by almost 44%.

Consider this same pipeline locally sagging into a zone of post-construction settlement over a limited length of a few pipe joints, a condition which might occur for any number of reasons. How much local settlement, h, distributed over a length, L, might induce yielding during the hydrotest? This is a complex problem, but it can be solved using a variety of approaches. The stress introduced by the sag can be estimated as the sum of a bending stress, $\sigma_B=\pm C_1EDh/L^2$, and an elongating stress, $\sigma_X=C_2E(h/L)^2$. [Ref. 4] The coefficients $C_1=16.0$ and $C_2=2.479$ for a uniformly loaded beam with moment-fixed ends; or they are $C_1=9.87$ and $C_2=3.050$ for a cosine function displacement profile. Other profile shapes could develop but these might be representative.

If the pipe yield strength is only equal to the SMYS of 70 ksi, the amount of sag that induces this stress is shown as the lower range of values in Figure 6. The range is bounded by the uniformly loaded beam profile and the cosine displacement profile. Note that this only brings an outer fiber of the pipe along the inside of an induced curvature to the point of yielding. Gross yielding of the pipe cross section would not be expected at this load. However, gross yielding probably would occur when the pipe approaches its maximum moment capacity. The moment capacity during the hydrostatic test, can be estimated using limit state concepts [Ref. 5] to be approximately 1.27 (and up to 1.4) times the initial yield moment for a pipe with a D/t between 68 and 77 (which would be the case for an X70 pipeline designed to operate with Class 600 components and at hoop stress levels between 72% and 80% of SMYS). Assuming that the moment-curvature relationship is approximately linear up to this point, the amount of sag that would induce the maximum moment capacity is shown in the upper shaded range of Figure 6. The results indicate that only a few inches of sag over 2 to 4 pipe joints can potentially cause yielding during a hydrotest, if the yield strength of the pipe only equals the SMYS.

The yield strength of line pipe on average is greater than the SMYS. Stronger pipe would better tolerate external loadings during a hydrostatic test. The amount of sag that could cause yielding during testing of an X70 pipe with actual yield strength of 75 ksi, similar to the average strength of the pipe of interest, is shown in Figure 7. Figures 6 and 7 are plotted on the same scales for comparison. Although the stronger-than-SMYS pipe has better tolerance for external loading, it still may take relatively small amounts of sag or misalignment to cause a threat of gross yielding during a hydrostatic test. The yielding would only occur over the length of pipe experiencing the highest bending stresses, perhaps as little as a pipe diameter.

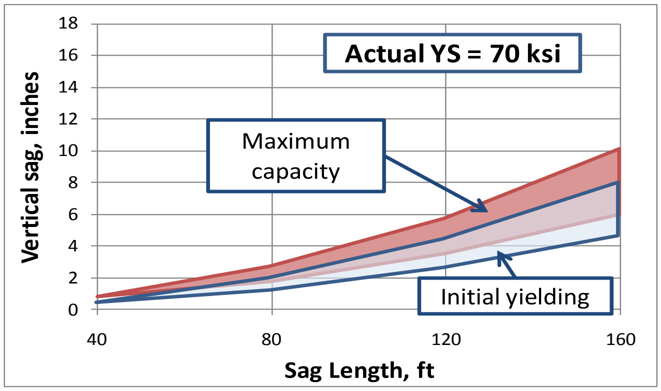

Figure 6 - Vertical Sag to Cause Yielding During a Hydrotest, with YS = 70 ksi

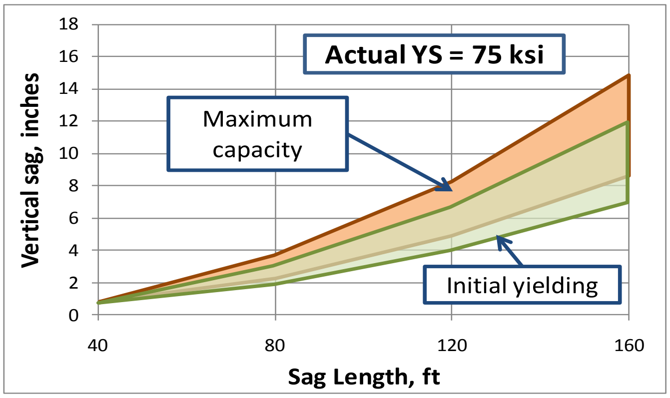

Figure 7 - Vertical Sag to Cause Yielding During a Hydrotest, with YS = 75 ksi

The results presented here illustrate how, even with pipe that exceeds all specifications, hydrostatic testing of a pipeline to a high proportion of the pipe yield strength leaves little room for large loadings other than internal pressure during the test, even where such loadings are not a concern at normal operating stress levels.

In SESH's case, swamp weights were installed at 6 of the 9 locations where pipe was discovered to have expanded beyond threshold levels. In fact, swamp weights were present along only 5% of the project length, yet were present in the immediate vicinity of 2/3 of the expanded pipe occurrences. It is not difficult to recognize that the combination of variable weight loading, buoyancy, and soft soils could have produced variances in vertical alignment as-built that introduced loadings similar to those discussed above.

CONCLUSIONS

An analysis was completed of the SESH pipeline to evaluate the conditions which contributed to the presence of expanded pipes on the SESH pipeline. These conclusions are specific to the SESH pipeline, as they are based upon SESH data with respect to material supply, pipe mill dimensional data, and field hydrostatic testing results.

1. No pipe yielding occurred at the pipe mill for pipe supplied to the SESH project.
2. The pipe mill hydrostatic test at 95% SMYS produced a higher hoop stress level than the field test after consideration of biaxial loading condition in the field test.
3. Six pipes experienced expansion greater than 1.5% of diameter as a consequence of the field test.
4. The expansion of these pipes is likely due to incremental compressive stresses attributed to everyday construction practices rather than as a consequence of low yield strength pipes.

Work done through industry organizations is on-going to define fitness-for-service criteria for pipe with diameter expansion greater than 1.5% of diameter and presented in other papers of this conference. In the case of SESH, pipes with measured expansion less than 2% of diameter remain in-service, as has been the case for many past projects including vintage pipelines.

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