White Paper
Guidelines For Evaluation and Mitigation of Expanded Pipes

Energy Pipeline Industry
Pipe Quality Action Plan
June 9, 2010

The INGAA Foundation
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The work conducted to produce this white paper was initiated and sponsored by the Joint Industry Project on Alternate Design Basis - Life Cycle Management, in cooperation with the INGAA Foundation and participation from members of the energy pipeline industry and the U.S. Department of Transportation, Pipelines and Hazardous Materials Safety Administration, Office of Pipeline Safety. This white paper is the culmination of work to understand line pipe steel stress-strain behavior, the onset of yielding or expansion, and the extent of expansion expected, ultimately, to define a process for the evaluation and mitigation of expanded pipes.

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White Paper - Guidelines For Evaluation and Mitigation of Expanded Pipes
Life Cycle Management - Joint Industry Project –
Pipe Quality Initiative – Work Groups 6 and 7

Background

The INGAA Foundation held a summit on June 11, 2009, referred to as the Pipe Quality Summit, to discuss issues related to high strength, low alloy steel pipe that had been observed on some projects with pipe orders that commenced in 2006. There were 120 participants representing all aspects of the supply chain including:

- Natural gas and hazardous liquid pipeline operators
- Pipe manufacturers
- Coating manufacturers and applicators
- Standards developing organizations, and
- Consultants and third-party inspectors.

The summit included plenary sessions and breakout discussions to define key issues and develop action plan elements to address the issues.

A leadership group within the INGAA Foundation developed a Pipe Quality Action Plan and shared it with members of the energy pipeline industry and the staff of the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS) a week later, on June 18, 2009. The Leadership Team is chaired by Dan Martin, of El Paso Corporation, and includes as its members Jeryl Mohn, Panhandle Energy, Andy Drake, Spectra Energy, Terry Boss, INGAA and Mark Hereth, P-PIC.

There are eight elements of the Pipe Quality Action Plan, each with a work group assigned to execute the elements of the plan. The eight elements and the corresponding work groups are:

Work Group 1 - Identification of Low and Variable Mechanical Properties in High Strength, Low Alloy Steel
Work Group 2 - Line Pipe Quality Management
Work Group 3- Evaluation of Enhancements to Standards, Including API 5L
Work Group 4 - Evaluation of Enhancements to Operator Specifications and Practices
Work Group 5 - Evaluation of Enhancements to Pipe Manufacturer Specifications and Practices
Work Group 6 - Understanding Steel Stress Strain Behavior and Pipe Expansion
Work Group 7- Development of Methods to Understand Implications of Expansions on Stress and Strain and Implications to Each Threat in ASME B31.8S
Work Group 8 - Evaluate Implications of Expansions On Coatings

The objective of the Pipe Quality Action Plan is to develop a comprehensive approach that integrates the outcomes of the individual work group efforts listed above and works to ensure that high quality pipe is placed in the ground. The integration of the work efforts to improve the quality of pipe that is produced is depicted in Figure 1. This work effort is directed at pipe that has been produced and is now in service, as well as production of high quality pipe for future projects.

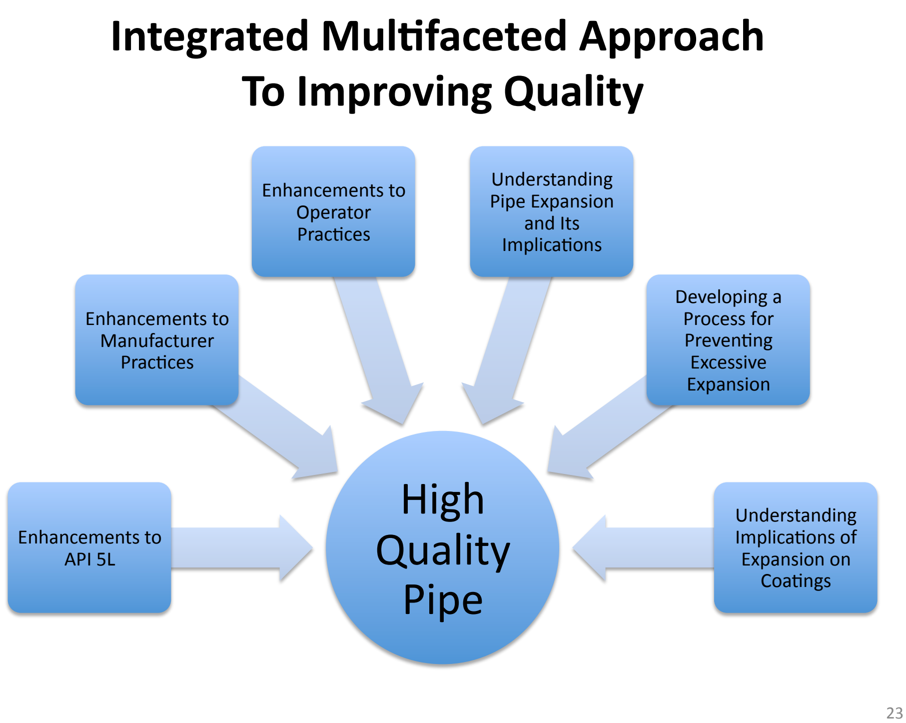


Figure 1 – Integration of Action Plan Work Efforts

Introduction

This document provides an overview of the process to evaluate and mitigate expanded pipes. The objective of the process is to apply the same level of diligence envisioned by the Office of Pipeline Safety (OPS) in their September 10, 2009 Guidance and draw upon work done by Work Groups (WGs) 1, 6 and 7 of the Pipe Quality Initiative.

This white paper presents a process, the product of WGs 6 and 7, (depicted in Figure 2, below) begins where the process to identify expanded pipe ends. Briefly, the finished product of WG 1, the White Paper, "Identification of Pipe With Low and Variable Mechanical Properties in High Strength, Low Alloy Steels", included a process (presented below in Figure 3 and continued in Figure 4) that entails

Figure 2 - Evaluation and Mitigation of Expanded Pipes

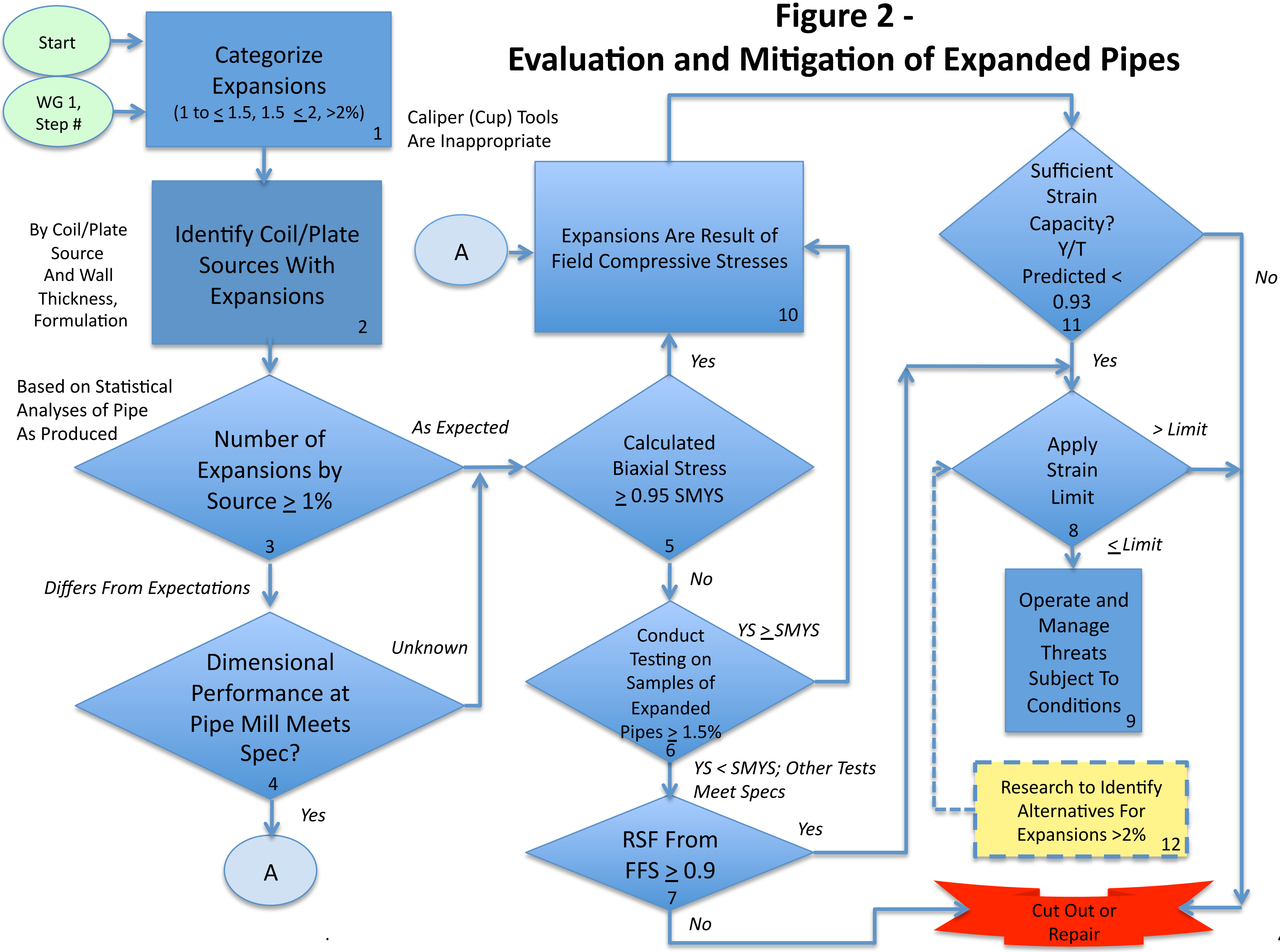
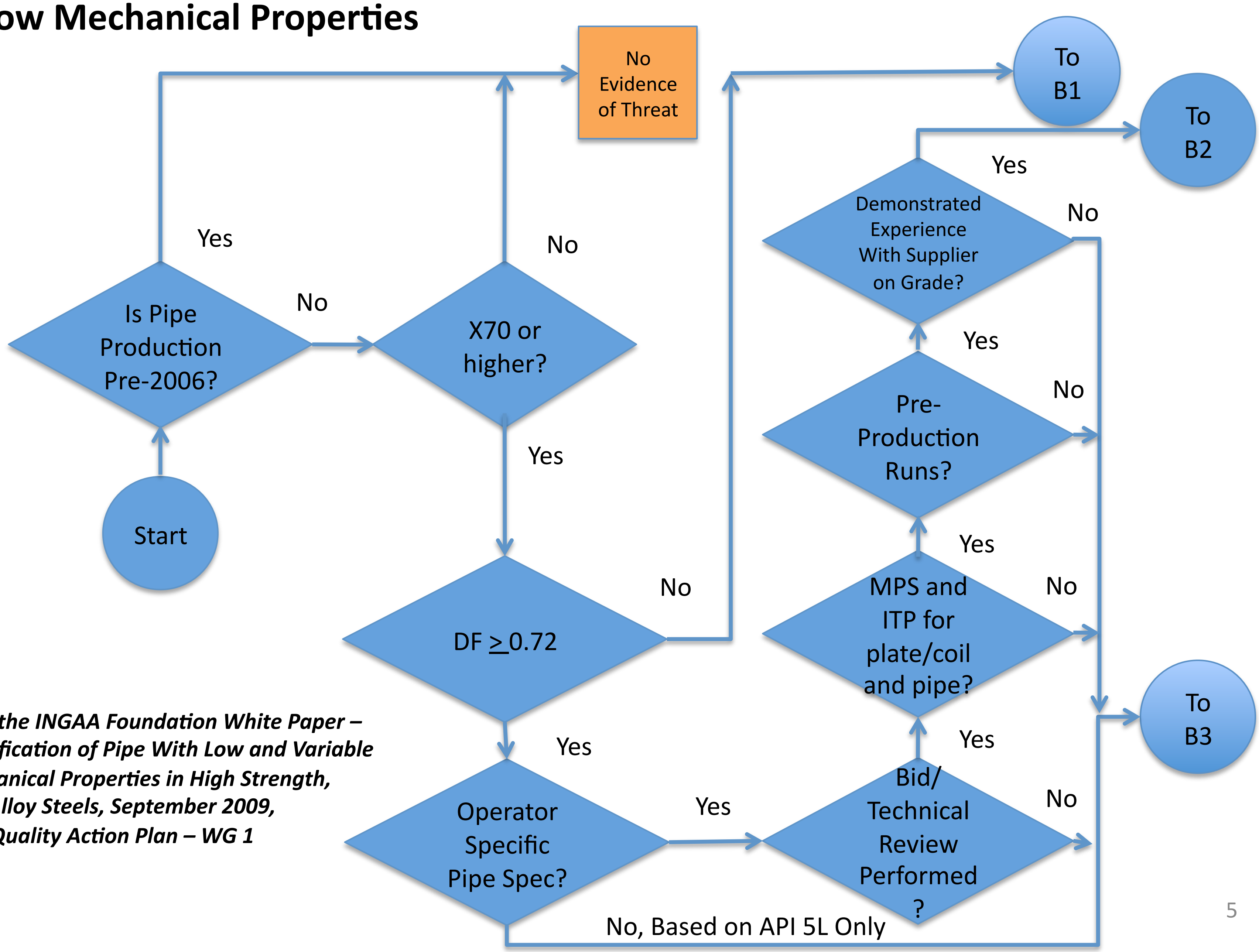


Figure 3 - Identification of Pipes With Low Mechanical Properties



From the INGAA Foundation White Paper – Identification of Pipe With Low and Variable Mechanical Properties in High Strength, Low Alloy Steels, September 2009, Pipe Quality Action Plan – WG 1

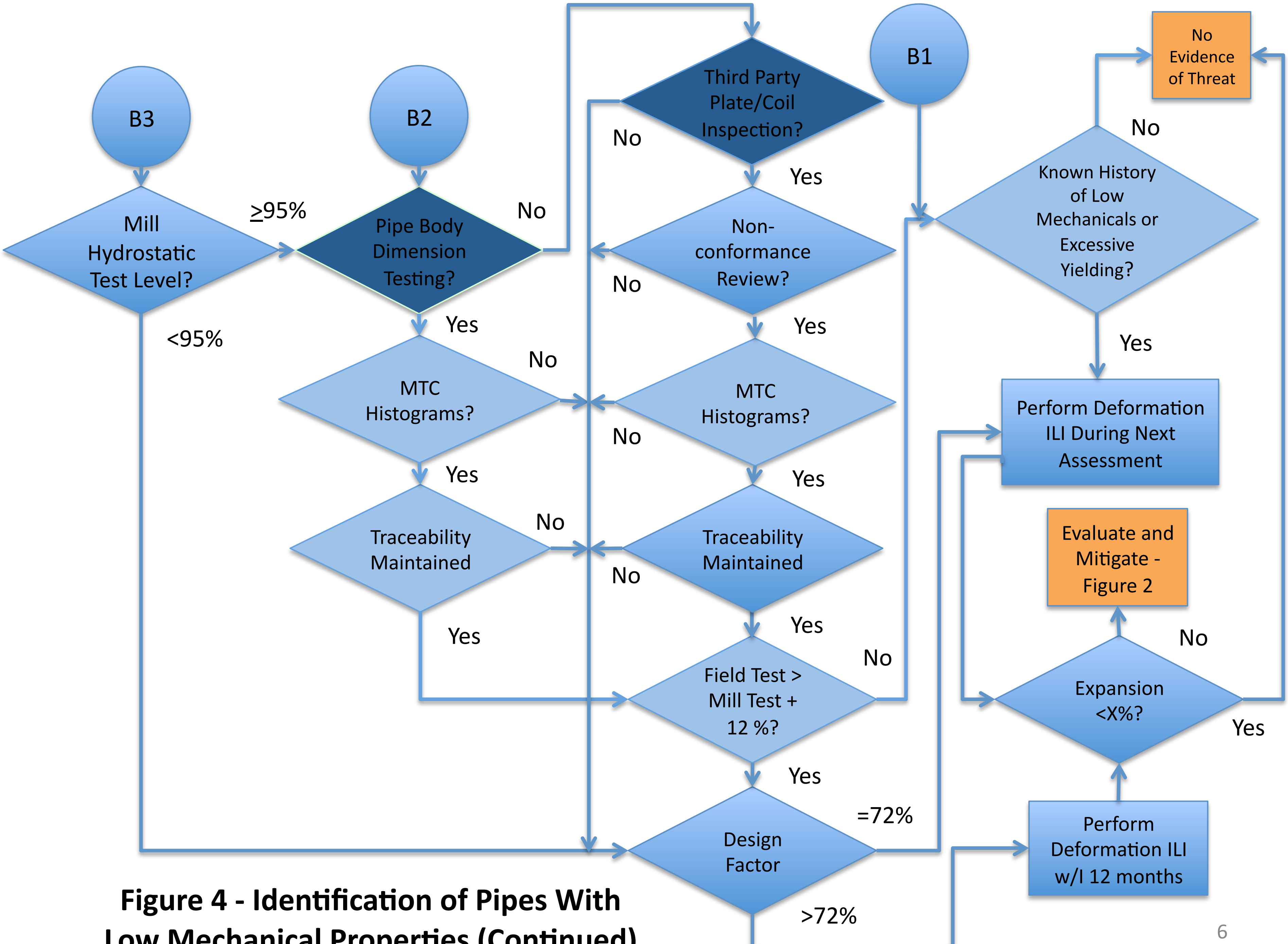


Figure 4 - Identification of Pipes With Low Mechanical Properties (Continued)

examination of information and records from the design, specification and manufacturing of the pipe to evaluate the potential for having expanded pipe. Figures 3 and 4 are provided for convenience so the reader can see how one moves from application of Figures 3 and 4 into the process being described in this white paper (depicted in Figure 2).

As can be seen in Figure 4, there are two outcomes that lead to a requirement to run a deformation ILI tool, one within 12 months and one with the next scheduled assessment for metal loss and dents. While the process addresses running a deformation ILI tool, there have been findings reached since the production of the WG 1 white paper that are important to discuss and document. These are addressed in the subsection that follows.

Selection of the Appropriate ILI Tool

The process, which is the subject of this white paper, begins when an operator reaches the point in Figure 4 where running a high-resolution deformation tool is required. Deformation tool means an in-line inspection tool that uses "fingers" or other sensors to measure deformations or other dimensional changes along multiple paths on the ID circumference of a pipeline. Such changes can include ovality, general or local expansions, indentations or dents. It is necessary for the tool to accurately measure outward deformations up to 3% of the pipe diameter. As most deformation tools are designed to record deformations that tend to reduce the diameter, this performance requirement may necessitate a modification of the conventional usage, including data analyses and interpretation. The performance requirements should be discussed with the ILI service vendor. There have been instances where the data collected for runs conducted with finger-type tools have been reanalyzed to identify expansions.

Operators have tried without success to use data from caliper, cup-type tools and correlate the signals to expansions found in the excavated pipe. The use of this technology has not been adequate to locate, identify and quantify the dimensional changes of interest here.

Proper Analyses of ILI Data

The way in which deformation tool data are analyzed is also critical in identifying the extent of expansion in particular pipes. Experience of the work group members has shown that the maximum internal diameter average (Max ID Avg) is the measure that best reflects the degree to which the pipe has expanded. The Max ID average is the average of multiple internal diameter measurements. It is computed by taking the average of all of the individual sensor pairs (typically 60 to 90 sensors), that is, discrete internal diameter measurements using all of the sensor pairs on the tool. This is effectively the same as measuring the inside diameter using a pie tape. This method allows for accurate measurement of uniform expansions as well as localized expansions that might occur on a portion of the pipe circumference.

Experience has shown that comparing the joint location in question with three joints upstream and downstream will provide a sound basis for determining the amount of expansion. Members of the work group found great value in reviewing scans of the bore from the ILI data. The bore scan provides a vivid visual depiction of diameter changes, indicative of yielding or expansion. The percent expansion is computed by taking the average of the internal diameter measurements from the deformation tool at the location of the maximum expansion. The Max ID Avg must be compared to locations both upstream and downstream pipe from the suspected expanded location to compute the percent expansion. It is not adequate to compare the Max ID Avg to a nominal measurement of the internal diameter. It must be compared to adjacent pipes. The equation below shows how the computation is made:

$$\%\ \text{Expansion} = \frac{\text{Max ID Avg}_{\text{subject joint}} - \text{Max ID Avg}_{\text{adjacent joints}}}{\text{Max ID Avg}_{\text{adjacent joints}}} \times 100$$

It is important to account for the internal pressure at the time expansions are measured, both by the deformation ILI tool and when the pipe is physically measured in the ditch. ILI tools run immediately after completion of construction, prior to being placed in service, are run at ambient or relatively low pressure. ILI tools run can be run with the line in service, under pressure, sometimes reduced pressure, although some tools can run with bypass to enable the line to run at or close to MAOP.

When a line is pressurized below the yield point, the pipe will expand due to this pressure. This is referred to as elastic expansion, as this expansion is proportional to the pressure and will return to zero when the pressure is released. The operator must account for this elastic expansion when evaluating expanded pipe joints. The amount of elastic expansion can be approximated by applying the ratio of the pressure during the ILI run as a fraction of the yield pressure (100% SMYS) to the amount of expansion representative of the yield point, which is established in the ASTM and API methods as 0.5% strain. This is a simple approach and one that the work group members believed could be applied readily by operators in evaluating expansions.

The equation based on this approach for calculating the amount of elastic is provided below:

$$\text{Percent Elastic Expansion} = (P_{ILI} / P_{SMYS}) \times 0.5$$

where,
P_{ILI} is the operating pressure at the time the ILI was run, and
P_{SMYS} is the yield strength calculated by the Barlow formula

An example is provided as follows for 36-inch, X70, 0.375 wall pipe, where the operating pressure of the ILI was conducted at 700 psig.

$$\text{Percent Elastic Expansion} = (700/1{,}458) \times 0.5$$

$$= 0.24\%$$

So in this example if the strain measured by the ILI deformation tool was 1.87%, the plastic strain level is 1.87% - 0.24% or 1.63%.

Run Deformation ILI Tool and Categorize Expansions (Step #1)

The first step in the process is to run the appropriate ILI deformation tool, analyze the data and categorize the expansions into one of three groups:

- 1 to ≤ 1.5%
- 1.5 to ≤ 2%, and
- >2%.

Indications of less than 1% are not considered as expansions warranting evaluation and will not be further considered in this analysis. Most tool service providers state a minimum of 1% as their detection limit. While the experience of the work group members has shown that in fact the tools are capable of achieving detection levels below 1%, in some instances as low as 0.5%, expansions of less than 1% pose no threat to the integrity of the pipe and are below the stated detection limit of the tools. Furthermore, caliper tool service providers also typically specify a tolerance of 1% of diameter as the process capability for reporting ID dimensions. As part of the data analysis process, calibration digs are recommended to verify the ILI data.

Identify Coil/Plate Sources With Expansions (Step #2)

The next step is to categorize the expansions by coil/plate source, wall thickness and chemical formulation. This helps the operator to identify the nature and extent of the expansions and perhaps limit or bound the pipe that may be exhibiting this behavior. Such categorization may be accomplished by a series of questions, such as:

- Did expansions occur on one wall thickness from one pipe mill and one coil source or from many?
- Did they occur with one particular chemistry formulation used by one coil or plate supplier?
- Is there a pattern of heat number, parent slab, coil number, or pipe position in the coil?

Evaluation of Numbers of Pipes Observed Knowing Pipe Distributional Characteristics (Step #3)

Knowing the nature and extent of the expansions, the next step is to evaluate whether the distribution of expansions found is consistent with what would be projected based on the distribution of yield strengths for the pipe as manufactured and the test pressures to which it has been subjected. This entails an evaluation of the yield strength distributions based on mean, standard deviation and shape of the distributions.

It is important to understand that individual joints of pipe in orders meeting the requirements of API 5L can exhibit yield strengths less than the specified minimum yield strength (SMYS) for the particular grade ordered. As a specific example, depending on the characteristics of the distribution of X70 pipe, there can be yield strengths of individual pipes less than 70 ksi. An operator can estimate the fraction of the order below 70 ksi and the minimum value by knowing the mean, standard deviation and shape of the distribution. The shape of the distribution can be defined by applying a goodness of fit test to potential distribution types. The general shape of the distributions of yield strengths is normal. However, some distributions appear lognormal, especially when the mean value is relatively close to the SMYS. Hence there is a need to determine the most descriptive distribution type, i.e., normal, log normal, other, through a goodness-of-fit evaluation.

Several sources of distribution characteristics were identified. These included a compendium of data developed to evaluate tensile property variation in DSAW and ERW line pipe by Malcolm Gray and Bill Fazackerly published in a PRCI Report in July 1999[1] . Within the data for DSAW X70, there were mean values of yield strength from 72.1 to 81.8 ksi; with standard deviations from 1.65 to 3.1 ksi. Malcolm Gray presented additional data at the 12th Joint EPRG/PRCI Technical Meeting in Groningen, Germany in 1999[2]. Within the available data, there were standard deviations from 1.65 to 3.99 ksi; mean values were not reported.

As an example, if the yield strengths of X70 pipe from a particular coil source, wall thickness and chemistry formulation were described by a normal distribution with a mean value of 76 ksi and a standard deviation of 2.3 ksi, one would expect perhaps 1 out of 200 pipes to be found to have a yield strength below 70 ksi, and perhaps 1 out of 1,000 to be below 69 ksi. (For these distribution characteristics, about 0.45% of the population would be below 70 ksi.) Also, following the logic of Figures 3 and 4, there is no reason to expect expanded pipes if the mill test that produces hoop stress of a minimum of 95% SMYS and the field tests were conducted at or below a pressure equivalent to 107% SMYS (gauge).

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[1] Gray, J. Malcolm, Fazackerly, W. and Fazackerly, B., Tensile Property Variation in DSAW and ERW Line Pipe, PRCI Report L51805, July 1999.

[2] Gray, J. Malcolm, Tensile Property Varaition in DSAW and HFERW Line Pipe, 12th Joint EPRG/PRCI Technical Meeting in Groningen, Germany in May 17-21, 1999.

As an example, if the pipe population is described by a normal distribution with a mean value of 74 ksi and a standard deviation of 3.8 ksi, one can expect as many as 1 in 7 individual pipe yield strengths to be below 70 ksi. These values can be used to statistically project the numbers of pipes below 70, 67, 65 and even 60 ksi.

Causes of Expansion

In a practical sense, there are a finite number of possible causes of expanded pipe. The first results from pipe having yield strength significantly below the specified minimum. There are other causes as well which can act upon the pipe to result in expansion. The most significant of these can be compressive stresses, that is, situations where axial compressive stresses are acting on the pipe. These are likely to be unique and location-specific conditions and can include, but are not limited to:

- Compressive residual stress at a tie-in
- Compressive residual stress caused by weight of pipe string in area with sharp elevation change
- Compressive residual stress caused by buoyancy acting on pipe in groundwater,
- Compressive residual stress due to weights (set-on type) acting on pipe
- Bending stresses caused by post-construction settlement or lack of uniform support under the pipe in the ditch
- Compressive stress due to pipe settlement during hydrostatic testing
- Other possible source of residual stress due to installation

The additional axial compressive stress lowers the field test pressure required to cause through thickness yielding. In many applications these axial compressive stresses relieve themselves or "shake out". However, where the residual stresses cannot relieve because of physical constraints, the soil not moving or settling by the time the field hydrostatic test is conducted, the axial compressive stress may act to reduce the hydrostatic pressure required to cause through thickness yielding and can result in pipe expansion greater than anticipated.

There are other factors that can contribute to pipe expanding but alone are not a basis to result in expansion of greater than 1%. The pipe was oversize initially. It was larger than expected when shipped from the manufacturer. This could be due to inadequate dimensional control during manufacture. Under-gauge wall thickness can also contribute to pipe expansion. It is important to recognize that providers of raw materials have precise control of processes today and especially for coil. Gauge control on coil is very precise and there can be instances where the wall thickness for much of the coil in an order is below the nominal wall thickness, yet it remains compliant with API 5L. Experience of work group members has shown that the wall thickness can be as much as 1.5% below nominal; the API 5L tolerance on weight in effect allows for a 1.75% deviation below nominal. This must be considered in evaluating expansions. The thinner wall will result in a greater level of expansion at a given pressure.

Amount of Expansion

If the expansion of the pipe occurs in the mill, the amount of expansion can be computed by application of the von Mises equation accounting for the combined effective stresses in the mill test, i.e., hoop, axial and radial stresses. The way in which the mill and field hydrostatic tests act on a pipe to cause yielding is described in the white paper developed by WG1 of the Pipe Quality Action Plan[3]. To place this in context, a pipe with a D/t of approximately 90 (e.g. – X70, 36" diameter, with 0.402" wall thickness) tested in the mill at 95% SMYS (gauge) that expands by 1% during the mill test had an initial yield strength of approximately 63 ksi.; and one that expands to 1.5% during the mill test had an initial yield strength of approximately 61 ksi. The calculations should be done using the specific grade, diameter and wall thickness of the pipe. So one can see from the example using a D/t of 90 that the yield strength of the pipe must be well below the specified minimum yield strength for expansion greater than 1% to occur.

In the field, soil friction along a length of pipeline prevents the pipe from contracting, which results in a tensile (positive) axial stress. This tensile stress when combined with the hoop stress results in a greater combined stress required to achieve yielding to compensate for the effect of the tensile stress. This has the effect of strengthening the pipe, as shown by the von Mises equation. So a higher gauge pressure is required to achieve the same effective stress level. As described in the WG1 white paper, the field test gauge pressure must typically be 12% higher than the mill test pressure. For example, a pipe with a D/t of approximately 90 (e.g. – X70, 36" diameter, with 0.402" wall thickness) tested in the field to 107% SMYS (gauge) that expanded to 1% during the field test had an initial yield strength of approximately 62 ksi., and one that expanded to 1.5% during the field test, had an initial yield strength of approximately 60 ksi. These are based on a presumption that no axial compressive forces are acting on the pipe. As was the case with the mill test, the pipe must be well below the specified minimum yield strength to result in expansion greater than 1%. Compressive forces described in the previous section can act to lower the effective stress to cause through-thickness yielding, in some instances counteracting the tensile stresses provided by the soil. Members of the work group have observed expansions in excess of 2% resulting from the effect of compressive field stresses.

Evaluation of Outcomes (Step #3)

Once the analyses of the pipe mill test data and the ILI data are complete, they must be evaluated against the expansion behavior that would be expected to occur. There are essentially two potential outcomes – the observed expansions are about as expected based on the statistical analysis or the observed expansions differ

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[3] White Paper, Identification of Pipe With Low and Variable Mechanical Properties in High Strength, Low Alloy Steels, INGAA Foundation, September 2009, Appendix A.

significantly from the expectations based on the statistical analysis. Each of these is discussed further below.

Observed Expansions Are As Expected Based on Statistics
This is the situation in which the prediction of expanded pipes based on the distributional characteristics and the ILI data are consistent with each other in both number of expanded joints and amount of the expansion. This situation can occur where there are many (even hundreds) expanded pipes, or otherwise, just a few. It is not the total number of expanded pipes but how well the number of expansions compares with the ILI results based on the distributional characteristics. In this situation, the next step is **Step #4**, an evaluation of dimensional measurements made in the pipe mill. Generally, if the number and degree of expansions is relatively low, indicative of little to no low yield strength pipe, the next steps will lead relatively directly to **Step #10**.

There can be the situation in which the ILI data indicate either a significantly greater number of expanded pipes or pipes exhibiting significantly greater expansions than predicted by the distributional characteristics are present. This is not necessarily a situation in which the numbers of expanded pipes appears large, but is rather the situation where the anticipated behavior differs significantly from observed behavior. For example, a recent project constructed by a member of the work group was reviewed in which the distributional characteristics indicated that no expansions were expected and yet the ILI data indicated expanded pipes were present. In this case, the number of expansions differs from what is expected and the evaluation leads to **Step #4.**

Observed Expansions Differ From Statistical Expectations
If, on the other hand, the number and degree of expansions in Step 3 differ from expectations based on the distribution of values from the mill tests, the outcome will be through **Step #5** and most likely **Step #6**, where additional sampling and testing may be necessary.

Dimensional Performance at Pipe Mill Meets Specifications? (Step 4)

Projects where the actual numbers of expansions differ from expectations are then evaluated by using available dimensional measurements in the pipe rolling mill following the hydrostatic test. If the pipe mill test was conducted to at least 95% hoop stress, diameter measurements were taken on a statistically representative percentage of pipe after hydrostatic testing in the pipe mill, and the measurements show the pipe met the dimensional tolerances of API 5L, then the process follows a **path at A.** This means that the pipe expansion occurred in the field and was the result of compressive stresses from installation. As described below, the expansion may not be attributed to pipe having less than specified yield strength, as the testing and inspection performed have already confirmed the strength.

In the case where it cannot be confirmed that adequate dimensional measurements were made[4] in the pipe mill and recorded on a sufficient number of pipes as they were produced and tested in the pipe rolling, the process goes to a decision diamond, **Step 5** - the same one as the case where the expansions were as expected. Both of these situations are treated the same because both require additional consideration of mill and field-testing stresses.

Calculated Biaxial Stress Greater Than or Equal to 95% SMYS? (Step #5)

For pipes having exited the decision diamond (**Step 3**) "as expected", or where the outcome of evaluating the dimensional tolerances (**Step 4**) resulted in "unknown", the next step in the process is to evaluate which of the hydrostatic tests appears to be the controlling test and then calculate whether or not the calculated biaxial stress is greater than or equal to 95% SMYS. The evaluation can be made using the von Mises formula for estimating the yield strength that would have resulted from the respective tests. The von Mises formula uses the combined effective stress (sum of hoop, axial and radial stresses) on the pipe to calculate the final yield strength. The test that produces the higher combined stress as a percentage of the yield strength is referred to as the controlling test.

Expanded pipes for which the value of the calculated yield stress is less than the SMYS go to a step where additional diligence is applied through additional testing (**Step #6**). Expanded pipes with calculated biaxial stress levels less than 95% SMYS warrant evaluation and testing because their effective yield strength may be significantly less than SMYS.

Expanded pipes having experienced a biaxial stress level greater than 95% SMYS go to **Step #10** for further evaluation.

The value of 95% SMYS was established in this test recognizing that pipe meeting API 5L and the customer's specification can have yield strengths below SMYS. In addition, there is known to be approximately 1 ksi variability in the measurements attributable to the tensile testing methods of ASTM A370 and variability among laboratories[5]. In addition, the variation within particular pipes as a result of forming and expansion of double submerged arc weld (DSAW) pipe has been observed to be

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[4] This process does not address the scenario of pipes not meeting dimensional tolerances because that situation should not occur. The process defaults to the situation that joints are expanded which is a being safely conservative. WG 1 recognized the possibility that all pipes may not be measured in the body of the pipe at multiple locations if one simply applied API 5L. The WG members have developed a recommendation that the body diameter be measured in multiple equally spaced locations on every pipe. This recommendation has been shared with the API Line Pipe Committee and will be reflected in operation best practices in pipe specification.

[5] Gray, J. Malcolm, R.L. Fazackerly and W.J. Fazackerly, Tensile Property Variation in DSAW and ERW Line Pipe, Pipeline Research Council International, Inc., PR-187-9602, July 1999, P. 10.

as much as 4.7 ksi[6]. The variation in helically formed pipe has been shown to be slightly less than for DSAW[7]. In either case the impact of variability in the method and variability within particular pipes is the basis for the use of 0.95% of SMYS as opposed to a simple application of 100% of SMYS.

An approach has been developed for evaluating pipes that appear to have expanded more than predicted based on the biaxial stress applied during the hydrostatic test. The basis of the approach is to plot paired values of measured percent expansion (based on strain level from ILI and accounting for elastic expansion at line pressure) versus the local or elevation corrected test stress level as a percentage of SMYS. An example is shown in Figure 5 (below). The figure shows a unity line, the point where the elevation corrected test stress level produces an expected amount of expansion. The pipes of interest in this step will appear above the unity line, that is the percent expansion observed will be greater than expected. [Need more explanation of the unity line – where it comes from, is the x-axis hoop stress based on gauge pressure or is it effective or biaxial stress, etc.]

A sample of the pipes undergoing the analysis using Figure 5 should undergo testing described in **Step 6**. A basis for sampling is shown in Table 1 below. It recognizes that for small numbers it is not possible to develop a statistically valid sampling method. Pipes that make it to Step 10 are not subject to this evaluation as their dimensions were confirmed to have met dimensional tolerances after testing in the pipe mill. The expansion may not be attributed to pipe having less than specified yield strength, as the testing and inspection performed have already confirmed the strength.

Table 1 – Sampling Basis for Expanded Pipes That Show Expected Behavior Based on Statistical Analysis of Distribution of Pipe

Number of Expanded Pipes	Number to be Tested
1 to 3	1
4 to 12	2
12 to 20	5
>20	More regimented approach

[6] Ibid, page 12.
[7] Ibid, page 13.

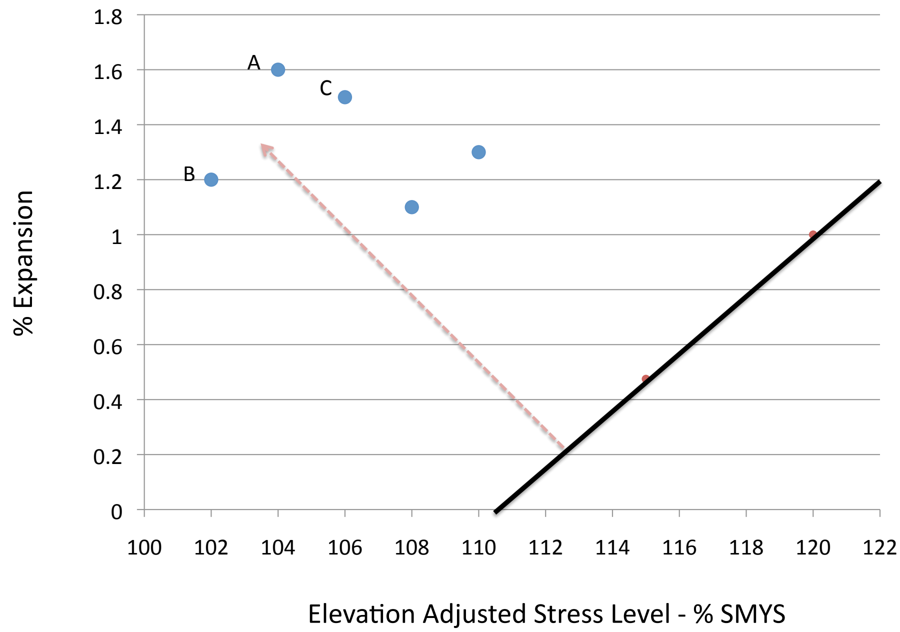

Figure 5 – Example Plot - Identification of Pipes With Expansion Levels Greater Than Predicted

In the example shown in Figure 5, applying the criteria in Table 1, two expanded pipes will be selected for testing. The basis of the approach is to identify pipes whose representation on Figure 5 lie furthest from the unity line; meaning that the degree of expansion observed is greater than would be expected. This is not necessarily going to be the pipes with the largest expansions. In this example, it is the **Pipe A** that was tested to 104% SMYS (elevation adjusted field stress level) with 1.6% expansion, and a second pipe, **Pipe B** tested at 102% SMYS showing 1.2% expansion. **Pipe C** and the two other pipes depicted on Figure 5 were tested to higher levels but it is the degree to which the actual expansion deviates from the expected amount (i.e., the distance from the unity line (black)) that defines the pipes to be selected, and so these pipes were not among those selected.

Applying the approach defined above, these two pipes are to be cut out and tested using the approach defined below in **Step 6**. If the pipes meet chemical, mechanical and toughness specifications, then the remaining pipes can remain in service and no further testing is required. If one or both of the pipes fail to meet specification for any of the criteria, then additional testing must be conducted applying the criteria in Table 1.

Conduct Testing of Expanded Pipes That Are Removed From Service (Step #6)

This step determines whether the pipe meets chemical, mechanical and toughness specifications[8]. The testing required is:

- Chemistry and hardness
- Yield and ultimate tensile strength,
- Charpy V-notch toughness and shear area, and
- Drop weight tear tests (if the Charpy shear areas do not meet specification).

The analyses are to be conducted using ASTM A370.

This step is to confirm that expanded pipes are not a result of inappropriate or deficient chemistry or out-of-spec rolling processes. In addition, it is critical that the ductility and toughness of the pipe meet specifications even in the presence of an expansion.

Depending on the number of pipes that are to be addressed in this step, it may be appropriate to conduct testing on a representative number of pipes in each expansion category. That means, for example, for expansions >2%, testing representative samples from each plate or coil source and from each wall thickness.

Fitness for Service Evaluation (Step #7)

Pipes meeting the specifications described above are then evaluated for fitness for service. Briefly, the modeling described in this paper has been applied to compare the burst pressure of an expanded pipe to the burst pressure of a nominal pipe. API 579 – 1 /ASME Fitness For Service – 1, 2007[9], defines a generalized fitness for service approach and allows for a remaining strength factor (RSF) of 0.9 for pressure vessels, boilers, and piping. This generally accepted RSF of at least 0.9 has been adopted here as a means of accepting pipes for consideration as long as they also meet the specifications defined in **Step #6**.

Becht Engineering developed a closed form solution to calculate the burst pressure of an expanded pipe given grade, diameter, wall thickness, and the controlling test pressure. The closed form solution is based on modeling using burst tests conducted on expanded pipes, and validated with burst tests on expanded and non-expanded pipes.

When applying the FFS closed form solution, pipes not meeting the RSF of 0.9 must be cut out or repaired using an appropriate repair method. Pipes having a remaining strength factor greater than 0.9, are addressed in the decision diamond in **Step #8**.

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[8] Specification in this context means the limits, both maxima and minima as defined in the pipe rolling mill Quality Assurance Plan or Inspection and Testing Plan.

[9] API 579 initially published in 2002, was issued in 2007 as a combined API/ASME document with the official title, “API 579 – 1 /ASME Fitness For Service – 1, 2007”.

Application of a Strain Limit (Step #8)

Pipes that exceed the RSF minimum of 0.9 are evaluated with respect to a strain limit. The work group members considered available standards addressing strain in pipelines including ASME B31.8 and CSA Z662.

ASME B31.8 at Section 833.5, Design for Stress Greater Than Yield, and specifically in 833.5(b), establishes a maximum plastic strain limit of two percent with due consideration for ductility and strain capacity of the seam weld, girth weld and pipe body materials, avoidance of buckles, swelling or coating damage.

The Canadian standard for managing the integrity of pipelines, CSA Z662, prior to the 2007 version, in the section on Offshore Steel Pipelines, for design and as well for operation, established a maximum permissible strain limit of 2.5%. The requirement stipulated that the combined strain of 2.5% must account for installation and operation. Later versions of the CSA standard provide for a formula based approach.

WG 8 has addressed the levels of expansion that result in coating damage. This work was undertaken to evaluate the possibility that coatings were a limiting factor in considering strain. The Canadian Standards Association requires certification of coatings used on pipelines. One element of the certification is the requirement to pass a bend test of 3 degrees /PD at -30oC for FBE coated pipe.[10] The 3M corporation developed basis for approximating the equivalent level of strain in the pipe body when considering the results of a bend test.[11] A 3 degree/PD bend is equivalent 2.61% strain in the pipe. In addition, in testing conducted by members of WG 8, it was found that FBE coatings began to craze (i.e., show visible evidence of stressing without cracking) at approximately 6% strain and began to crack between 6 and as high as 10% strain at 32^{o}F and thickness of 14 mils.

After consideration of the ASME and CSA codes as well as discussion of ASME 833.5, its development and incorporation into the code with members of the B31.8 Committee, adoption of this limit subject to demonstrating that the pipe is ductile and has sufficient strain capacity in the welds and pipe body and the coating has not been damaged by expansion seemed appropriate in this application. Use of the Canadian Standard and consideration of the strength of coatings could have supported adoption of a maximum limit as high as 2.5% but the work group believed that the more conservative ASME basis was appropriate. In using the 2% strain limit, coatings are not expected to be a limiting factor with respect to residual strain or expanded pipe.

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[10] External Fusion Bond Epoxy Coating for Steel Pipe - External Polyethylene Coating for Pipe, CSA Z245.20-02

[11] Tech Brief, Bend Test, 3M, Pipeline and Construction Markets, Austin, Texas, Publication No. 80-6105-6624-4(119.3)BP, 1989.

In applying the strain limit to pipes with expansions less than 2% operating under the Alternative MAOP regulations or an Alternative MAOP Special Permit must manage the threats to integrity under their Integrity Management Program **(Step #9)** and the applicable regulatory or Special Permit provisions.

The Pipeline Research Committee International (PRCI) has elected to undertake a project to evaluate existing research on strain limits and consider alternative limits if applicable (**Step #12**).

Field Compressive Stresses (Step #10)

It was found in evaluating expansions observed from several projects that the methods described above did not fully account for the amount of expansion observed. The amount of expansion was greater than predicted by calculating the amount that would result from the biaxial stress applied during hydrostatic testing. This can be the case for pipes having "yes" as the response in decision diamond in **Step #4** –the expansions were not expected based on the distributional characteristics of the pipe as produced and yet the pipe met dimensional requirements for the pipe body on every pipe in the mill. This is an indication that the pipes likely expanded in the field under the influence of stresses due to external loadings concurrent with the hydrostatic test pressure.

Simply requiring that all pipes go through **Step #5** leads to unnecessary excavations, examinations and testing if the expansions were caused by stresses other than those considered in the von Mises equation. In the case where there is documentation of the pipe distribution characteristics and dimensional measurements in the pipe body, testing will not provide information pertinent to managing the pipes. The likely causes of a pipe expanding more than projected, based on the von Mises formula, are those situations where axial compressive stresses are acting on the pipe. As stated above, these are likely to be unique and location-specific conditions.

Compressive stress can be relatively uniform axial loading, such as from thermal expansion. It can also be variable, both axially and circumferentially, such as from bending, where part of the cross section is in compression and part of it is in tension. The bending stress varies linearly across the cross section, going through zero at the neutral axis.

Regardless of whether it is uniform or not, the portion that is in compression and at a high hoop stress may exceed the yield boundary during the field hydrostatic test. There is a key difference between the two conditions (axial vs. bending) regarding how much of the cross section yields. With an axial load in compression, the entire circumference may yield, expanding more or less uniformly for some length except where there are locally harder or stronger yield strength zones. With bending, possibly only the portion of the cross section in compression will actually yield, depending on the magnitudes of the bending and hoop stresses. Assuming the bending stress is applied first and then the pipe is brought up to pressure, yielding would be expected to start in a localized manner and extend both along and around the as pressure increases. Expansion would occur but would likely be a bit eccentric as the tensile side of the pipe and the midsection that has low bending stress will remain in the elastic stress regime.

If the bending is due to sag or displacement, there could be an offsetting stretch on the pipe as well due to the pipe subtending a longer path. That just increases the amount of displacement or curvature necessary to cause the yielding.

Residual Strain Capacity (Step #11)

Where it is known (or suspected) that the pipe is in an area where axial compressive stresses may have acted on the pipe, the next step in the process is **Step #11**, a decision diamond. This step entails estimating the residual strain capacity in the pipe given the extent of expansion caused by the combined stress on the pipe, including the contribution from the axial compressive stress. The ratio of yield strength to ultimate tensile strength, also referred to as Y/T, is a measure of the residual strain capacity. API 5L establishes a limit of 0.93 for Y/T, which has adopted here for this analysis. The exact Y/T for the pipe will not be known, but can be approximated using the first principles modeling. Knowing the percent expansion, grade, wall thickness and diameter as well as the test pressure of the controlling test, a yield strength can be calculated. This yield strength is then divided by the minimum specified ultimate tensile strength for the grade of pipe to calculate a Y/T. This is a very conservative measure of the Y/T, as the ultimate tensile strength may be significantly larger than the minimum. To provide some perspective on Y/T values, realistic upper limits for observed pipe mill behavior are 0.90 for helical welded pipe and 0.92 for UOE pipe. If the Y/T is less than 0.93, then the pipe is suitable for service subject to management of threats under the Integrity Management Program.

Pipes with a calculated Y/T greater than 0.93 may have insufficient remaining strain capacity. These are addressed in **Step #8**. In this decision diamond, the amount of expansion is considered. Deformation or plastic strain levels greater than or equal to 2% must be cut out or repaired by an appropriate repair method. Pipes with less than 2% expansion can either be tested to measure the actual residual strain capacity or be cut out or repaired.