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INTEGRATING AUTOMATED BALL INDENTATION WITH ASME B31G CODE TO ASSESS INTEGRITY OF CORRODED PIPELINES

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ABSTRACT
In order to provide deterministic structural integrity assessment for safe and efficient operation of corroded pipelines, the following information is required: (a) the actual key mechanical properties (yield and ultimate strength, and fracture toughness) of the pipeline materials, (b) the present thickness and diameter of the pipeline, and (c) the profile of the maximum depth of corrosion pits over the pipeline axial length, and the size of sharp cracks. Both items (b) & (c) can be determined by conventional techniques. A patented *in-situ* Stress-Strain Microprobe (SSM) system was used to provide item (a), the required key mechanical properties (tensile and fracture toughness), in a nondestructive and localized fashion without any interruption of the pipeline transmission using its novel Automated Ball Indentation (ABI) test technique.

The SSM system was used on a short segment of a 356-mm (14-inch) diameter Kerosene pipeline. Although there was no documentation of the pipeline steel grade, the minimum ABI-measured yield strength at four locations was 277 MPa (40.2 ksi) and the minimum ultimate tensile strength was 378 MPa (54.8 ksi) indicating that the steel met the requirements of Grade “A”. Both the Rstreng software and the ASME B31G code were used to calculate the maximum safe operating pressure for the corroded pipeline. The calculations showed that a profile with a few corrosion pits [3-6 mm (0.075-0.236 inch) maximum depth spaced over 483 mm (19 inches) length] reduced the maximum safe pressure significantly from 4.24 MPa (615 psi) to 0.74 MPa (107 psi). The operator of the pipeline limited the maximum operating pressure to 0.69 MPa (100 psi). Furthermore, it was recommended that the ABI measurements be performed on at least 10% of the 7-km Kerosene pipeline and on all patches and welds in order to provide the minimum yield strength values required for determining the remaining strength of the pipeline. This work proves that the integration of the ABI measurements with the corrosion pitting profile allows calculation of the maximum safe operating pressure in order to make the appropriate decision of replacement or repair of certain pipeline sections.

INTRODUCTION
In June 2003, a fire occurred due to a leak from a 356-mm (14-inch) diameter Kerosene pipeline (approximately 7 km long). A part of the pipeline that was damaged by the fire was cut and replaced. Following the repair, a hydrostatic test was conducted, and the resulting few leaks were repaired. A second hydrostatic test was conducted at 13 kg/cm^2 (185 psi) for one hour and no leaks occurred. Currently, the maximum operating pressure is 7 kg/cm^2 (100 psi).

The carbon steel pipeline is more than 20-years old with undocumented grade. For undocumented pipelines, Section 49 of the US Code of Federal Regulations (CFR) Part 192.107 (b) (2) stipulates a yield strength of 165 MPa (24,000 psi) must be used in the equation that determines the design pressure of the pipe section. To overcome this limitation, a pipeline operator must determine the actual yield strength. The innovative ABI test is an ***in-situ,*** nondestructive technique that measures several key mechanical properties of metallic materials. Furthermore, ABI tests provide the actual yield strength values of base metal, welds, and heat-affected-zones which, most of the time, are higher than the conservative CFR value of 165 MPa; thus natural gas or oil pipelines can be operated at maximum efficiency while maintaining safety. Moreover, when cracks and other pipeline flaws are produced due to service conditions (e.g. severe corrosion and/or mechanical damage), the ABI-measured fracture toughness values can be used in the deterministic structural integrity assessment of the pipeline based on fracture mechanics analysis. The ABI test technique is described in detail in many publications [1-9]. Two photographs of the 14-inch diameter Kerosene pipeline tested in Egypt are shown in Fig. 1. An example of ABI data and test results are shown in Figure 2.

According to the United States Department of Transportation (US DOT) rules, the design pressure for steel pipe is determined using the following formula:

$P = (2St/D) \times F \times E \times T$

Where
P = Design pressure in pounds per square inch gauge.
S = Specified minimum yield strength (SMYS), psi or the measured yield strength
t = Nominal wall thickness of the pipe, in.
D = Nominal outside diameter of the pipe, in.
F = Appropriate design factor for steel pipe from Section 192.111 according to the class location of the pipe.
E = Longitudinal joint factor for steel pipe from Section 192.113
T = Temperature derating factor for steel from Section 192.115. For our case here, T = 1.00

For example, for a 14-inch pipe with unknown steel grade (S will be assumed to be 24,000 psi according to CFR), a nominal wall thickness of 0.299 in, F = 0.60, E = 1.00, and T = 1.00, the design pressure for pipe with no corrosion will be:
$P = (2 \times 24000 \times 0.299/14) \times 0.60 \times 1.00 \times 1.00 =$ 615 psi.

However, once a pipeline is placed in service, the maximum allowable operating pressure (MAOP) is lower than the design pressure based on the calculation of the corrosion pitting profile using the ASME B31G Code [10] or the RSTRENG V3.0 PC software [11].

NOMENCLATURE
ABI = Automated Ball Indentation
CFR = Code of Federal Regulation
SSM = Stress-Strain Microprobe
SMYS = Specified minimum yield strength

PURPOSE
1. To inspect a 14-inch diameter Kerosene pipeline in order to assess the structural integrity and fitness-for-service of the pipeline and to recommend the appropriate actions (repair or replacement, and maintenance).
2. To verify the grade of the pipeline by performing in-situ, nondestructive ABI tests using the SSM system in order to measure the yield strength and other tensile properties at several locations.
3. To determine the remaining strength of the corroded pipeline and its maximum safe operating pressure using the SSM-measured yield strength data and the corrosion data of pit depth and axial spacing in the calculations of the ASME B31G Code and the RSTRENG V3.0 PC software code.

SAMPLE IDENTIFICATION
Four locations were tested in August 2003. The first location is near Tie Number 2, the second location is 120 m west of Tie Number 2. The third location is 120 m west of location 2 and across railroad metal marker 10/200. The SSM/ABI tests were conducted on the upper side (12 o'clock position) of the pipeline at these three locations. The fourth location was at the same axial distance as the third location except that the ABI tests were conducted on the bottom side (6 o'clock position) of the pipeline.

The SSM System and Its Nondestructive ABI Technique
The laboratory version of the patented [1] Stress-Strain Microprobe (SSM) system has been in commercial use since 1991 and the portable SSM version received a 1996 R&D 100 Award. In 1999, the miniature SSM system was introduced to

provide even greater portability and easier field applicability. Equipped with a small, portable battery pack and magnetic mounts, this system has proven to be a valuable test instrument for the pipeline industry. The accuracy, reliability, and easy field applicability of the SSM system to test pipeline materials with unknown properties have been demonstrated on samples and on pipeline sections from several major natural gas pipeline operators [6]. Fig. 2 shows examples of the ABI test data and stress-strain curve results.

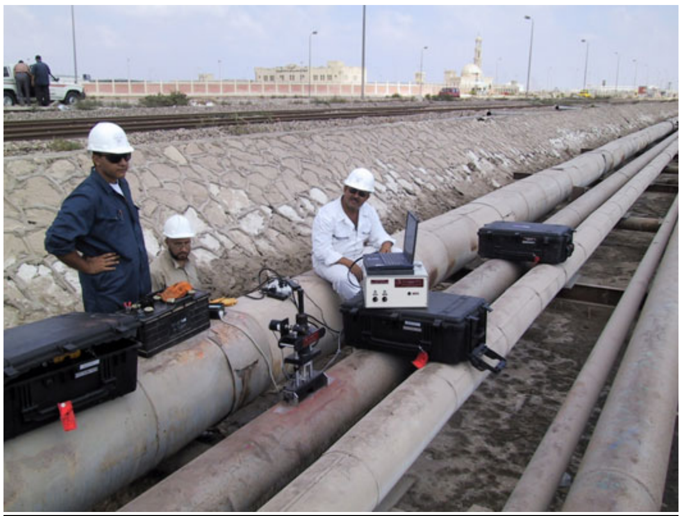

Fig. 1 Photographs of the 14-inch diameter Kerosene pipeline in Alexandria, Egypt.

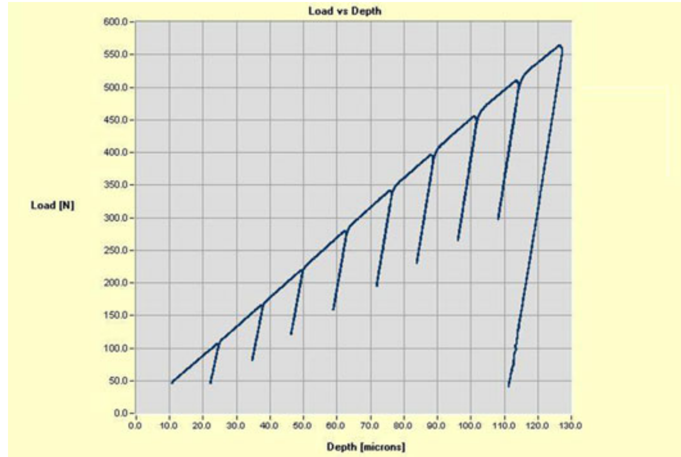

Fig. 2(a) Load versus depth data from an ABI test on X52 pipeline steel using a 0.76-mm (0.030-in) diameter tungsten carbide indenter.

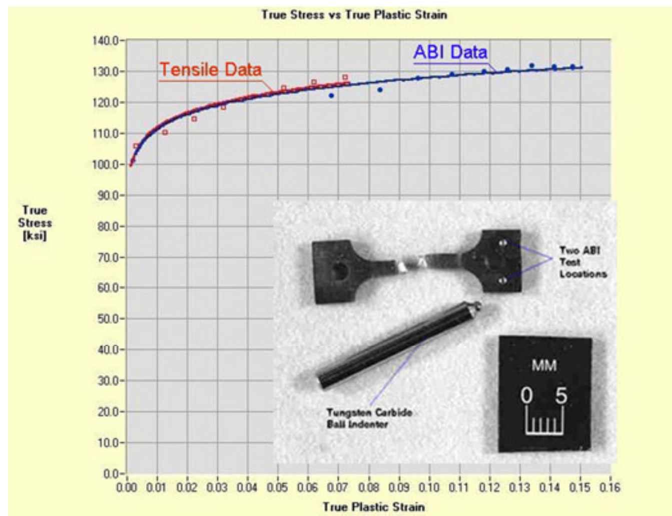

Fig. 2(b) Comparison of true-stress versus true-plastic-strain curves from ABI and tensile tests of high strength steel. (1 ksi = 6.895 MPa). The inset photo shows a tensile specimen and 1.57-mm (0.062-in) diameter tungsten carbide indenter.

Figure 3 shows comparisons of yield and ultimate strength values from the nondestructive ABI tests and from destructive tension tests on various grades of pipeline steels (Grades "B" to X65) manufactured in 1931 through 1978 [6]. A $600k research grant from the US DOE enabled a comparison of the results of numerous ABI-measured fracture toughness tests on several pressure vessel steel materials and welds with the results from destructive tests. The final report [7], as well as reference [6], is available for downloading from the website: www.atc-ssm.com. At the request of numerous industry and government users, a draft ASTM Standard for the "ABI Test Methods" is currently in the balloting process under Committee E28 of ASTM International.

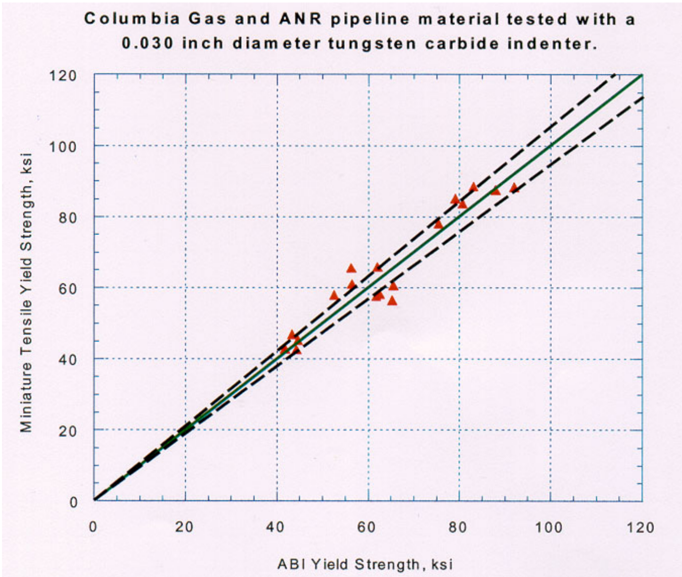

Fig. 3a Comparison of yield strength values from ABI [using a 0.76-mm (0.030 inch) diameter indenter] and tensile tests of seven pipeline steels. 1 ksi = 6.895 MPa. The dashed lines are the ± 5% variation from perfect agreement.

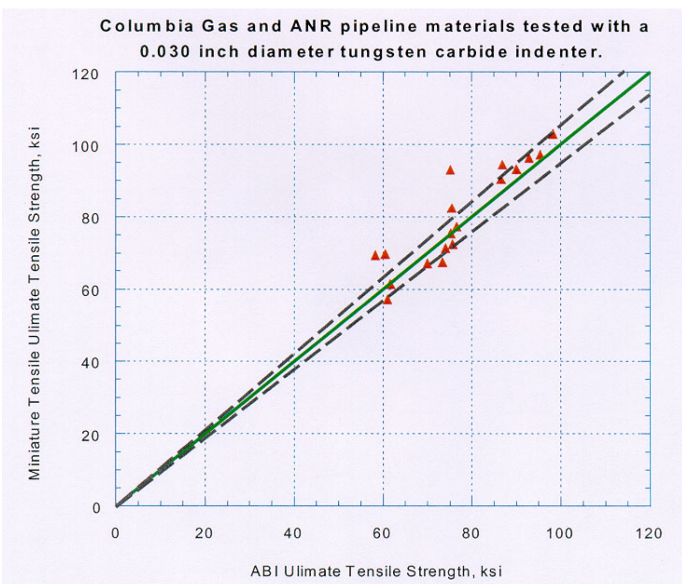

Fig. 3b Comparison between the ultimate strength from ABI [using a 0.76-mm (0.030 inch) diameter indenter] and tensile tests. The dashed lines are the ±5% variation from the perfect agreement.

The ABI test is based on progressive indentation with intermediate partial unloadings until the desired maximum depth (maximum strain) is reached, and then the indenter is fully unloaded. The indentation load-depth data are collected continuously during the test using a 16-bit data acquisition system. The nonlinear, spherical geometry of the tungsten carbide indenter allows increasing strain as the indentation penetration depth is increased. Hence, the incremental values of load and plastic depth (associated with each partial unloading cycle) are converted to incremental values of true-stress and true-plastic-strain according to elasticity and plasticity theories [2,3]. The ABI test is fully automated (using a notebook computer, a data acquisition system, and a servo motor), and a single test is completed in less than two minutes. Furthermore, in addition to the ABI stress-strain curve measurements, the nondestructive and localized ABI technique of the SSM system provides fracture toughness properties that cannot be obtained from the destructive (and costly for operating pipelines) tensile test. The determination of fracture properties from ABI tests is described in detail elsewhere [7-9]. The initiation fracture toughness is calculated from the integration of the tri-axial deformation energy up to a critical indentation depth (i.e., when the maximum pressure underneath the ball indenter equals the critical fracture stress of the steel material or at the critical fracture strain value, depending on the flow properties of the steel at the ABI test temperature).

RESULTS AND DISCUSSION

Three ABI tests were conducted at locations 1 and 2 while five and four ABI tests were performed at locations 3 and 4, respectively. A minimum of three ABI tests is recommended for each location in order to have a reasonable statistical sampling of the key mechanical properties. The additional tests at locations 3 and 4 proved that the steel material of the 0.2 km section is reasonably homogenous as shown by the overlay of the load versus depth data and the true-stress/true-plastic-strain curves (see example in Figs. 4 and 5). Table 1 includes the brief summary of the ABI-measured tensile properties from 15 ABI tests conducted at the four pipeline locations. The ABI-determined fracture toughness values are shown in Figure 6.

CALCULATION OF MAXIMUM SAFE PRESSURE

The Rstreng software and the ASME B31G Code results of the pipeline short section, without corrosion using the ABI-measured minimum yield strength of 40, 200 psi, indicate that the maximum safe pressure is 1030 psi. However, the existance of a few corrosion pits over a 483-mm (19 inch) axial pipeline length reduces the maximum safe pressure to 143 psi as shown in Figure 7. If the minimum yield strength was not determined from destructive tension tests or from the nondestructive ABI tests; the maximum safe pressure would only be 86 psi (Fig. 8) because of the CFR mandatory use of the 24,000 psi value of the yield strength for undocumented steel pipelines. The minumum ABI-determined ultimate strength of 54,800 psi meets Grade “A”. Hence, the use of the SMYS value of 30,000 psi for Grade “A” resulted in maximum safe operating pressure of 107 psi according to ASME B31G as shown in Figure 9. This pressure is slightly higher than the current opeating pressure of 100 psi, indicating that the corroded section must be repaired for safe operation.

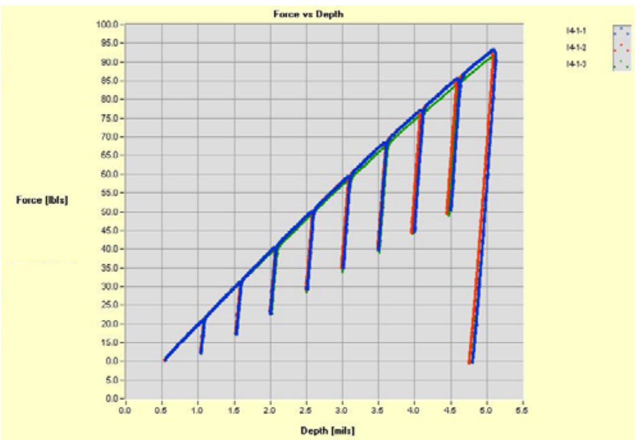

Fig. 4 Overlay of the ABI load versus depth data from three ABI tests conducted on the 14-inch Kerosene pipeline at location Number 1 (near Tie No. 2).

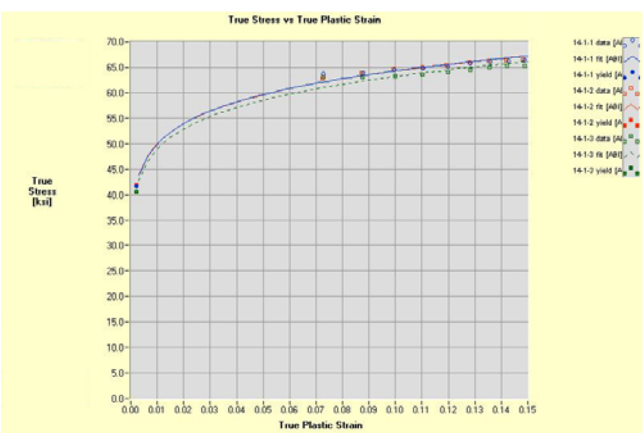

Fig. 5 Overlay of the ABI-measured true-stress/true-plastic-strain curves from three ABI tests conducted on the 14-inch Kerosene pipeline at location Number 1 (near Tie No. 2).

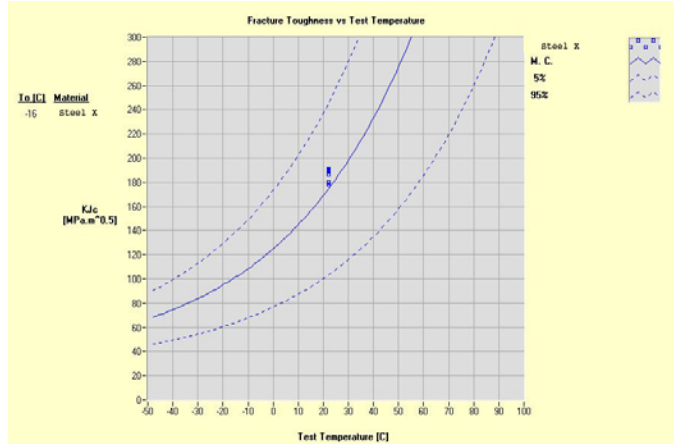

Fig. 6 The ABI-determined fracture toughness values, median curve, and the 95% and 5% confidence limit curves.

Table 1 Brief summary of ABI-measured tensile properties from 15 ABI tests at 4 locations.

Test Name	Yield Strength [ksi]	Estimated Engineering UTS [ksi]	Strength Coefficient (K) [ksi]	Strain Hardening Exponent (n)	Calculated Uniform Ductility [%]
14-1-1	41.7	58.1	82.6	0.109	11.7
14-1-2	41.9	58.2	82.6	0.109	11.7
14-1-3	40.6	57.2	81.6	0.111	11.8
14-2-1	43.3	59.0	82.9	0.105	11.5
14-2-2	41.8	59.4	85.1	0.113	11.9
14-2-3	42.3	58.5	82.8	0.108	11.7
14-3-1	43.9	59.7	83.9	0.105	11.5
14-3-2	43.5	59.3	83.3	0.105	11.5
14-3-3	43.6	59.3	83.4	0.105	11.5
14-3-4	43.1	59.2	83.5	0.106	11.6
14-3-5	42.7	57.8	81.0	0.103	11.4
14-3D-1	40.2	56.8	81.6	0.114	11.8
14-3D-2	40.7	54.8	77.1	0.105	11.4
14-3D-3	41.7	59.5	85.4	0.115	11.8
14-3D-4	41.0	57.9	83.0	0.113	11.8

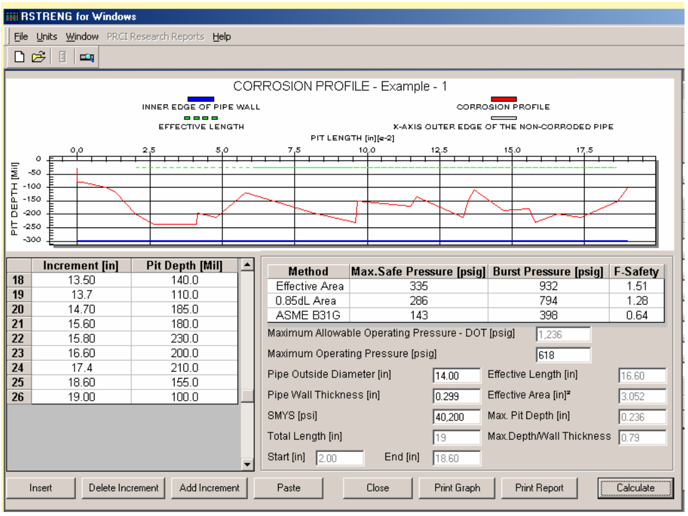

Fig. 7 Few corrosion pits over a 19-inch long section reduced the maximum safe operating pressure from 615 psi (when no corrosion pitting exists and with unknown yield strength) to 143 psi.

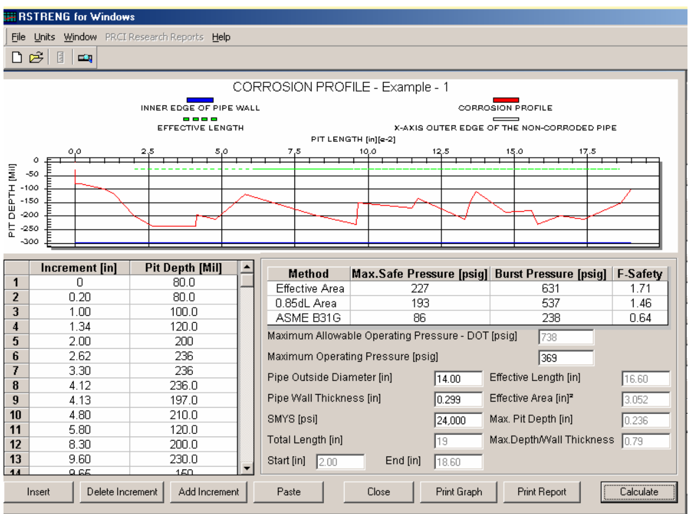

Fig. 8 If the minimum yield strength was not determined from the destructive tension tests or from the nondestructive ABI tests; the maximum safe pressure would only be 86 psi (because of the CFR conservative value of 24,000 psi for the yield strength for undocumented pipeline instead of the minimum ABI-measured value of 40,200 psi) which is below the current operating pressure of 100 psi (7 kg/mm^2) instead of the 143 psi of Fig. 7.

Fig. 9 The ABI-determined minimum ultimate strength was 54,800 psi, which meets Grade "A". Hence, the SMYS value of 30,000 psi for Grade "A" was used here to calculate a maximum safe operating pressure of 107 psi. Again, this is very close to the current operating pipeline pressure of 100 psi.

CONCLUSIONS

The use of the SSM system to test aged and new construction pipelines and their welds in the field will improve their structural integrity evaluation as well as their operational efficiency. For an accurate and complete fitness-for-service assessment, the following should be noted: (1) the use of the SMYS or the minimum ABI-measured yield strength to calculate the maximum pipeline operating pressure is appropriate only when there are no cracks, and (2) when cracks exist (due to severe corrosion and/or mechanical damage), the ABI-measured fracture toughness values of the base metal and welds should be used to calculate the critical crack size. Calculating the critical crack size for a given pipeline geometry and pressure, based on deterministic fracture mechanics analysis, allows accurate decisions to be made regarding the repair or replacement and the frequency of crack/flaw inspections.

The SSM System provides the key mechanical properties (tensile and fracture toughness) in a nondestructive and localized fashion without any interruption to the transmission. The SSM system was used on a 14-inch pipeline. The minimum SSM-measured yield strength from testing at 4 locations was 40,200 psi and the minimum ultimate tensile strength was 54,800 psi indicating that the steel meets the requirements of Grade "A" steel. The corrosion pitting profile was used together with the minimum SSM-measured yield strength in the Rstreng software in order to calculate the maximum safe operating pressure. Both the Rstreng software and the ASME B31G code were used to calculate the maximum safe operating pressure for the 14-inch Kerosene pipeline. Results of the calculations showed that a profile with a few deep pits [3-6 mm (0.075-0.236 inch) maximum depth spaced over 19 inches length] reduces the maximum safe pressure significantly from 615 psi to only 107 psi.

The SSM measurements should be performed on at least 10% of the total pipeline sections and on all steel patches and weld repairs in order to provide the minimum yield strength values required for determining the remaining strength of corroded pipelines according to the ASME B31G Code. Other conventional nondestructive inspections such as visual inspection and the profile of the maximum depth of corrosion pits as a function of their axial pipeline locations at worst corrosive places (including those under soil or water and at the bottom or the sides of the pipeline) must be performed on the entire line. The integration of the SSM measurement with the corrosion pitting profile measurements (using appropriate ultrasound equipment or others) will allow making the appropriate decision of calculating the maximum safe operating pressure, and the determination of replacement or repair of certain pipeline sections. The life of this old pipeline or any new pipeline could be improved significantly by applying proper coating and cathodic protection and by raising the pipeline above the ground and water level.

The results of this paper serve as an example to be followed for this pipeline as well as others in order to provide deterministic structural integrity assessment for safe and efficient operation.

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