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Innovative SSM Technology Determines Structural Integrity of Metallic Structures: Example Applications for Pressure Vessels and oil and Gas Pipelines

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Abstract

Structural integrity and operational efficiency of metallic structures such as oil and gas pipelines, pressure vessels, ship structures, and bridges degrade with aging and service conditions. Continued safe operation of these structures requires periodic examination of their current physical condition (with respect to the existence of flaws/cracks) and their actual mechanical properties. Until late 1980s, advances in physics and materials science focused on non-destructive testing (NDT) techniques to detect and size flaws, cracks, corrosion pitting, stress corrosion cracking, and reduction in thickness, while there were no NDT methods or instruments to determine the key mechanical properties (namely, tensile and fracture toughness) of in-service structures. Old techniques involved the extraction of boat samples or hot-tapping to machine destructive specimens. These undesirable/unaccepted techniques result in expensive loss of service and require some repair actions. The new Portable/In-Situ Stress-Strain Microprobe® (SSM) system was invented in 1989 to fill this gap for numerous industries by providing non-destructive and *in-situ*/field capability to measure the required mechanical properties. Applications of the innovative SSM system, that utilizes nondestructive Automated Ball Indentation (ABI) test techniques to determine tensile and fracture toughness of in-service steel pipelines, are described in this paper.

Introduction

Advanced Technology Corporation (ATC) developed the scientific concepts of its US Patent into a state-of-the-art SSM systems (bench-top and in-situ/field versions), and commercial equipment existed since 1991. The SSM systems are being used in most of the US national laboratories, defense laboratories, NASA, pipeline inspection companies, and few international organizations in Europe and Asia. The author, inventor, and founder of ATC is a graduate of Alexandria University. Hence, in appreciation to Haggag's birth country, ATC is now in the process of transferring its innovative SSM technology to the developing Arab countries, and an SSM system became available in Alexandria, Egypt, in April 2005.

Applications of the SSM system in the nuclear industry included assessment of the integrity of nuclear pressure vessels, the effects of neutron irradiation on the embrittlement of the base metal and welds, and the effects of thermal annealing on the recovery of ductility and fracture toughness of the vessel steels. The SSM system is now being used as enabling technology for material solutions to transport hydrogen in pipelines and in the use of high strength steels (X80 and higher grades) in the construction of new pipelines utilizing strain-based design and demanding stringent weld quality control requirements.

The SSM technology received numerous awards, including the "Advanced Technology Award" of the Inventors Hall of Fame, Inventors Club of America, 1992, and the coveted "R&D 100 award in 1996" as one of the 100 most technologically significant products of the year. Furthermore, the US Office of Pipeline Safety and the recommendation letter signed by the US Secretary of Transportation in 1999 also evaluated the SSM technology. More than 25 publications describing various SSM applications are available for downloading from ATC's website: www.atc-ssm.com.

Applications of the innovative SSM system, that utilizes an ***in-situ*** nondestructive Automated Ball Indentation (ABI) test technique to determine tensile and fracture toughness of in-service steel pipelines, are described in this paper. The ABI test provides the actual/current values of tensile and fracture toughness properties for base metal, welds, and heat-affected-zones (HAZs). The ABI-measured key mechanical properties are used with other nondestructive measurements, such as crack/defect sizes (determined from in-line smart pigs or from on-line ultrasound instruments), to determine the safe operating pressure of the pipeline or to necessitate certain rehabilitation actions. The ABI test is based on progressive indentation with intermediate partial unloadings until the desired/required maximum depth (maximum strain) is reached, and then the indenter is fully unloaded. The ABI test is fully automated (using a laptop computer, 16-bit data acquisition system, and a servo motor), and a single test is completed in less than two minutes. This paper describes two recent field investigations, and a demo SSM/ABI test on a pipeline section will be performed during the presentation at the conference.

The first investigation assessed a catastrophic failure that occurred in a natural gas plant on a cold winter night shortly following the leak of liquid natural gas into a natural gas pipeline. The combination of cold temperature and high strain rate near a crack resulted in the destruction of approximately a 12-meter section of a 508-mm (20-inch) diameter pipeline into several hundred small pieces. Since the remaining pieces from the exploded pipeline section were not sufficient to machine destructive tensile and fracture toughness specimens, the SSM system was used to measure the tensile and fracture toughness properties from multiple ABI tests on several pipeline pieces. The ABI-measured tensile and fracture toughness results provided the basis for the fitness-for-service assessment of the remaining pipeline sections of the natural gas plant.

The second application involved a fire that occurred due to a leak from a 356-mm (14-inch) diameter Kerosene pipeline. The fire-damaged section of the pipeline was cut out and replaced. As part of the effort to prevent future accidents, the entire 7-km pipeline needed a structural integrity assessment. Field/In-Situ ABI tests were conducted to measure the tensile and fracture toughness properties, from each ABI test at four locations, for the fitness-for-service assessment since the carbon steel pipeline had undocumented grade.

Thousands of kilometers of oil and gas pipelines are becoming older and new inspection regulations and practices are now more stringent to insure safe and efficient operation. This situation brings concerns over pipeline rehabilitation as well as in meeting the current and future energy demands through increasing the transmission throughput safely. When cracks and other pipeline flaws are produced due to service conditions (e.g. corrosion, stress-corrosion cracking, and/or mechanical damage), fracture toughness values, not provided by the steel grade certification, are required for the deterministic integrity assessment based on a fracture mechanics analysis.

The latest advances include the use of ABI-measured fracture toughness values in the deterministic structural integrity assessment. The nondestructive ABI test technique is described in detail in many publications [1-9]. Photographs of the SSM system used in testing oil and gas pipelines are shown in Fig. (1). Examples of ABI data and test results are shown in Fig. (2).

Nomenclature

ABI = Automated Ball Indentation
CFR = Code of Federal Regulations
SSM = Stress-Strain Microprobe
SMYS = Specified minimum yield strength
T_0 = the reference temperature when fracture toughness $K_{Jc} = 100$ MPa√m

Fracture Toughness

The current challenge for numerous industrial applications is to obtain fracture toughness of Ferritic steel structures without cutting boat samples or hot tapping to machine miniature fracture toughness specimens. Miniature specimens produce invalid fracture toughness values most of the time because of the violation of the geometry requirements for plane strain. However, ABI tests will produce valid fracture toughness values all of the time (because of the ability to select the appropriate indenter diameter for the steel test material), and the current ASTM destructive fracture toughness test methods may never produce valid test results.

Figure 1: Photographs of the SSM system used in testing 14-inch diameter pipelines: a Kerosene pipeline in Alexandria, Egypt (Left Photo) and a demo in Tennessee (Right Photo).

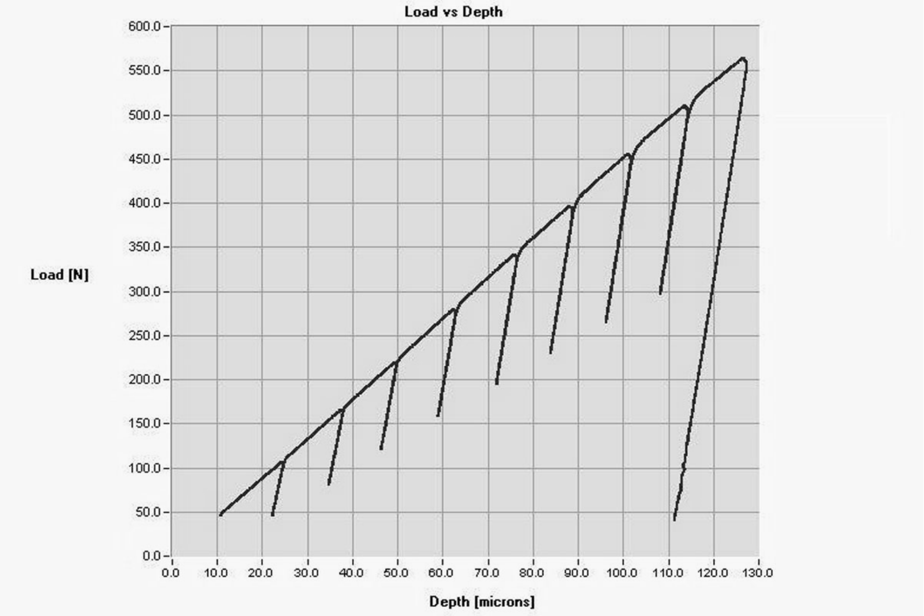


Figure 2a: Load versus depth data from an ABI test conducted on X52 pipeline steel using a 0.76-mm (0.030-in) diameter tungsten carbide indenter.

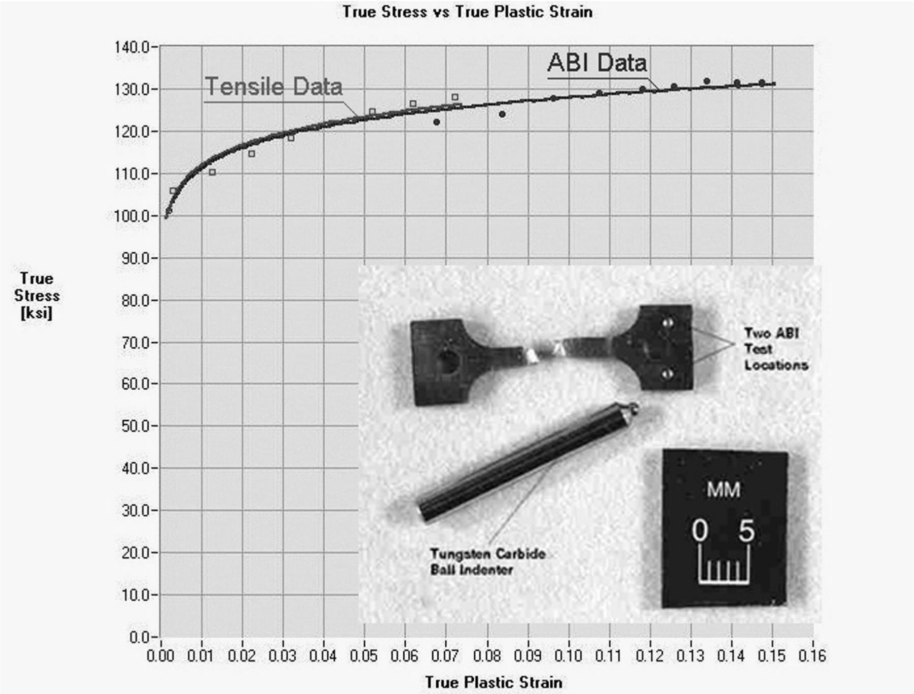
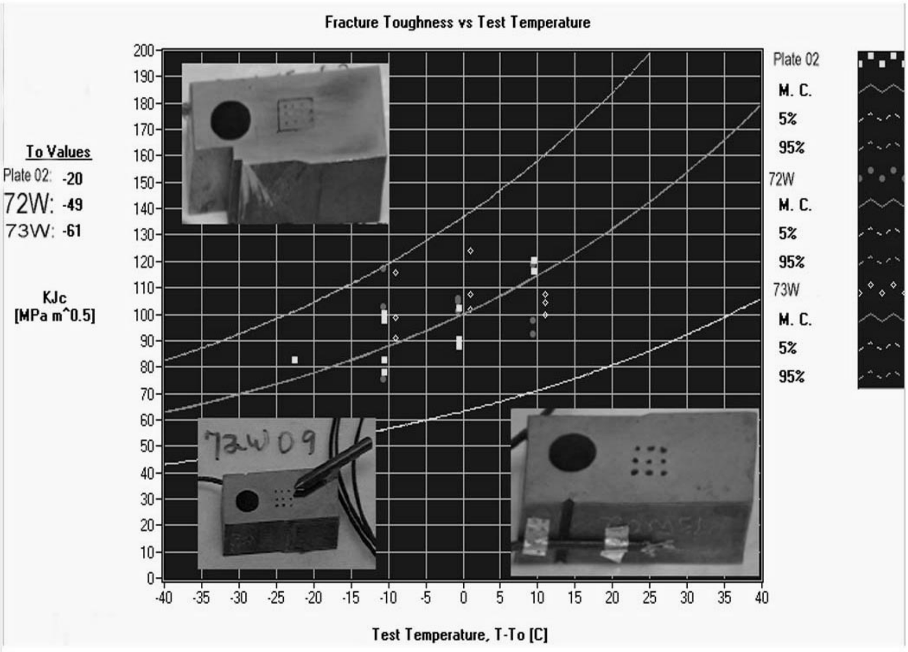
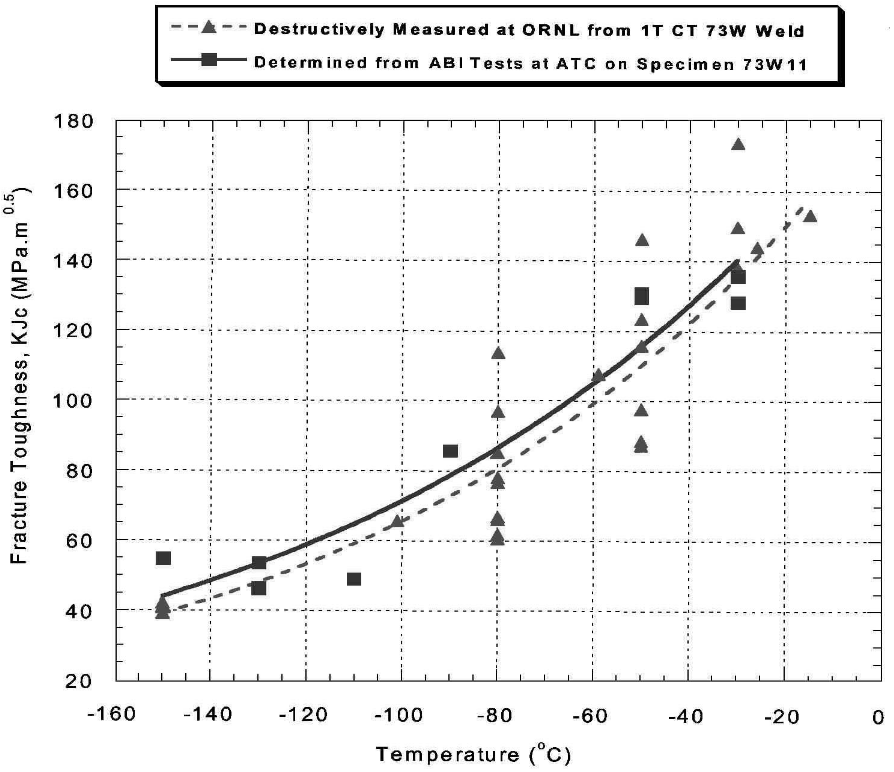


Figure 2b: Comparison of true-stress versus true-plastic-strain curves from ABI and tensile tests of high strength steel. (1 ksi = 6.895 MPa). The inset photo shows a tensile specimen and 1.57-mm (0.062-in) diameter tungsten carbide indenter.


Fracture Toughness vs Test Temperature
To Values
Plate 02: -20
72W: -49
73W: -61
KJc
[MPa m^0.5]
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
Test Temperature, T-To [C]
Plate 02
M. C.
5%
95%
72W
M. C.
5%
95%
73W
M. C.
5%
95%
72W09

(c)


Destructively Measured at ORNL from 1T CT 73W Weld
Determined from ABI Tests at ATC on Specimen 73W11
Fracture Toughness, KJc (MPa.m^0.5)
180
160
140
120
100
80
60
40
20
-160
-140
-120
-100
-80
-60
-40
-20
0
Temperature (°C)

(d)

Fig. 2(c) Fracture toughness Master Curve obtained from ABI tests on three pedigreed Ferritic steels. A 0.51-mm (0.020-inch) diameter tungsten carbide indenter was used to perform 11 ABI tests on Plate 02 (the specimen on the top left of the figure), and 9 ABI tests each on the 72W and 73W weld samples (shown on the left and right lower part of the figure, respectively). The ABI-determined reference temperatures of the three materials were within 5ºC of the values from the pedigreed destructive fracture toughness tests [Refs. 7, 10]. Fig. 2(d) Comparison between nondestructively ABI-measured $(K_{Jc})^{ABI}$ values from tests performed at ATC (using a 1.57-mm indenter) and destructive 1T CT fracture toughness test results of 73W weld of ORNL.

Also, most or all steel pipelines are not manufactured in the large thickness required to obtain valid fracture toughness test results, and often the owner/operator will not allow hot tapping or cutting of a pipeline section. Another great advantage of the ABI technique is its applicability to nondestructively test small welds and heat-affected-zones (HAZs) where the current ASTM destructive test techniques might not be feasible or are economically prohibitive.

How Can Fracture Toughness of Ferritic Steels Be Determined From the Abi Test?

An ABI test does not produce fracture in a metallic test sample due to the plastic constraint and the ductility of the test material, and there is no fatigue crack requirement for the ABI test (which makes it nondestructively/economically desirable). However, the success of this technique to determine fracture toughness of Ferritic steels in the transition region is based on (1) the attainment of a high degree of stress-triaxiality (stress concentration similar to that ahead of a crack-tip) because of the plastic constraint provided by the test material surrounding the spherical indentation, (2) the increase of the value of maximum stress (110% of the mean pressure in the material beneath the ball indenter) with increasing indentation depth until reaching or exceeding (at some low test temperatures) the critical fracture stress of the material, (3) the fracture of Ferritic steels at low temperatures in the transition region is controlled by the critical fracture stress of the material, and (4) the ductile fracture of Ferritic steels at high temperatures is controlled by the critical fracture strain of the test material.

Indentation with a small ball indenter generates concentrated stress (and strain) fields near and ahead of the contact of the indenter and the test surface, similar to concentrated stress fields ahead of a crack, albeit the indentation stress fields are mostly compressive. The high value of the stress under the ball indenter is an example of plastic constraint where the rigid material surrounding the indentation volume does the constraining. Hence, at a certain critical ball indentation depth, there is a high state of transverse and lateral stresses similar to those in front of a sharp crack/notch in an elastic material. Although the conditions for crack initiation might be attained, the high degree of plastic constraint is the reason that cracks do not develop during ball indentation of ductile metallic materials. The initiation fracture toughness is calculated from the integration of indentation deformation energy up to the critical depth (when the maximum pressure underneath the ball indenter equals the critical fracture stress of the steel material at the test temperature or reaches a critical strain value of 0.12, whichever occurs first).

Although ball indentation does not produce cracks in ductile metals, researchers at Advanced Technology Corporation (ATC) have produced cracks in two perpendicular directions in a single sodium chloride crystal using a 1.57-mm diameter ball indenter (work performed by ATC for the US Navy, see Fig. 3) which proved that the maximum stress underneath the ball indenter reached the fracture stress of the single crystal. Moreover, in the non-standardized bulge test (sometimes called small punch test), a very thin sheet of metal is clamped in a die and a punch with a large spherical end is pushed against one surface of the thin sheet until the sheet is fractured on the opposite/tensile side. In the bulge test, fracture occurs even though the specimen does not contain any fatigue crack prior to the test. However, fracture toughness cannot be calculated from the plane stress sample of the bulge test.

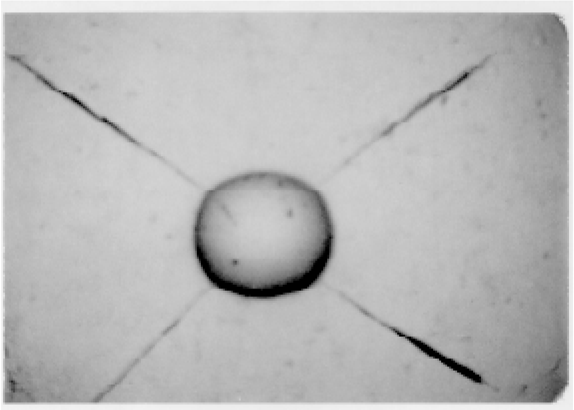


Figure 3: Cracks produced with a 1.57-mm diameter ball indenter in a sodium chloride single crystal.

In an ABI test, the maximum stress underneath the indenter increases with depth, but fracture does not occur because of the plastic constraint of the material surrounding indentation (the specimen or the structure thickness must be ten times the maximum indentation depth to avoid back surface dimpling effects and to obtain valid ABI test results). Furthermore, in a destructive J_{Ic} fracture toughness test, although we propagate/extend the fatigue crack, we extrapolate the power-law-fit of the J-integral versus crack extension curve to intersect a line parallel to the blunting line (0.2 mm offset line) where the intersection point determines the J_{Ic} initiation fracture toughness. This empirical procedure is required since it is very difficult to stop loading the sample at the deformation energy level associated with the onset of crack extension from the pre-existing fatigue crack of the destructive fracture toughness specimen. The true initiation fracture toughness value from the destructive test is actually the deformation energy up to the point of initial crack extension. Hence, the capability to determine fracture toughness from the ABI test without having to machine and fatigue crack a specimen is a truly innovative method, and it is the only method for in-situ/field nondestructive direct measurement.

Recent developments allow ABI testing at ambient temperature and determining the fracture toughness at other temperatures using the fracture toughness master curve concept and the appropriate critical fracture stress or strain model depending on the actual test temperature. Furthermore, dynamic fracture toughness values can be estimated from the measured static fracture toughness and yield strength test results [9].

This new ABI-measured fracture toughness capability is, in practical terms, material thickness independent since indenters with different diameters can be used for all pipelines with thin or thick wall. Furthermore, its localized nature allows testing welds and heat-affected-zones (HAZs) that cannot be tested destructively because of their irregular shape and small volumes.

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 pipeline sections and on samples from several major natural gas pipeline operators [6]. A $600k research grant from the US DOE enabled a comparison of the results of numerous ABI-measured fracture toughness tests on several pedigreed pressure vessel steel materials and welds with the results from destructive tests. The ATC's DOE final report [7] 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.

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 laptop 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 indentation deformation energy up to a critical indentation depth (e.g., 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

Case 1: A catastrophic failure occurred in a natural gas plant on a cold winter night shortly following the leak of liquid natural gas into a natural gas pipeline. The combination of cold temperature and high strain rate near an existing, but previously undetected crack resulted in the destruction of approximately 12-meter section of a 508-mm (20-inch) diameter pipeline into several hundred small pieces. The plant operator was concerned that the pipeline steel might not have the appropriate flow and fracture toughness properties since the fracture surfaces of many small pieces indicated brittle fracture. Although the pipeline piece containing the crack was not found at the time of the report, the ABI tests on several small pieces confirmed that the pipeline steel material met the mechanical properties specified for the seamless, carbon steel pipe at the time of construction. Multiple ABI tests were conducted on a block machined from a small steel piece at several low temperatures. All ABI tests were conducted using a 0.51-mm (0.020-inch) diameter tungsten carbide indenter at a speed of 0.01-mm/s (0.0004 in/s), or a strain rate of 0.014/s, to a maximum indentation depth of 0.076-mm (0.003-inch). Stress-strain curves and fracture toughness values were measured from each individual ABI test. In addition, the fracture toughness median curve as well as its 95% and 5% confidence limit curves were determined from the ABI tests. The reference temperature, T_o, defined in the ASTM Standard E1921-97 [Ref. 10], as the test temperature corresponding to a median fracture toughness level of 100 MPa√m (90.9 ksi√in), was determined from the 17 ABI tests conducted at several low test temperatures. The ABI tests determined a T_o value of -24ºC for the base metal of the pipe (Fig. 4).

The ABI-determined T_o value demonstrates that the pipeline material has good static fracture toughness of 100 MPa√m at a low temperature of -24ºC that is lower than the normal pipeline operating temperature in winter of the gas plant. However, these ABI-measured static fracture toughness values do not prevent brittle failure that might result from the existence of a small crack (developed during pipeline service) and due to the combination of very low temperature and a dynamic loading at a high strain rate (it should be noted that all carbon steels have a lower/brittle fracture toughness shelf with a median value of 30 MPa√m regardless of their various values of much higher fracture toughness at higher operating temperatures). The ABI-measured tensile and fracture toughness values assured the officials in the gas plant that the remaining pipeline sections, procured earlier with the same grade and heat, were fit for continued service.

Case 2: 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 fire-damaged section of the pipeline was cut out and replaced. To avoid future accidents, the entire 7-km pipeline needed a structural integrity assessment. 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 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. Since the carbon steel pipeline had undocumented grade, 15 ABI tests were conducted at four pipeline locations in order to measure the tensile and fracture toughness properties for the fitness-for-service assessment. The ABI-determined tensile and fracture toughness values are shown in Table 1 and **Fig. (5)**. 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 **Fig. (6)**. Results of the ABI tests indicate the pipeline steel is within specifications.Further investigation indicates coating failure as the source of corrosion and subsequent failure.

Table 1: Summary of ABI-determined tensile and fracture toughness values (the latter is calculated from the indentation deformation energy up to a critical strain value of 12%). The15 in-situ/field ABI tests were conducted on the in-service 14-inch diameter kerosene pipeline at four locations.

Test Number	**Yield Strength (MPa)**	**Estimated Engineering UTS (MPa)**	**Strength Coefficient (K) (MPa)**	**Strain-Hardening-Exponent (n)**	**Uniform Ductility (%)**	**Fracture Toughness (MPa√m)**
14-1-1	287	401	570	0.109	11.7	190
14-1-2	289	401	570	0.109	11.7	189
14-1-3	280	394	563	0.111	11.8	187
14-2-1	299	407	572	0.105	11.5	191
14-2-2	289	410	587	0.113	11.9	191
14-2-3	291	403	571	0.108	11.7	189
14-3-1	303	412	579	0.105	11.5	191
14-3-2	300	409	574	0.105	11.5	191
14-3-3	301	409	575	0.105	11.5	190
14-3-4	297	408	576	0.106	11.6	190
14-3-5	295	399	559	0.103	11.4	189
14-3D-1	277	392	563	0.114	11.8	180
14-3D-2	280	378	532	0.105	11.4	178
14-3D-2	288	410	589	0.115	11.8	190
14-3D-4	283	399	572	0.113	11.8	187

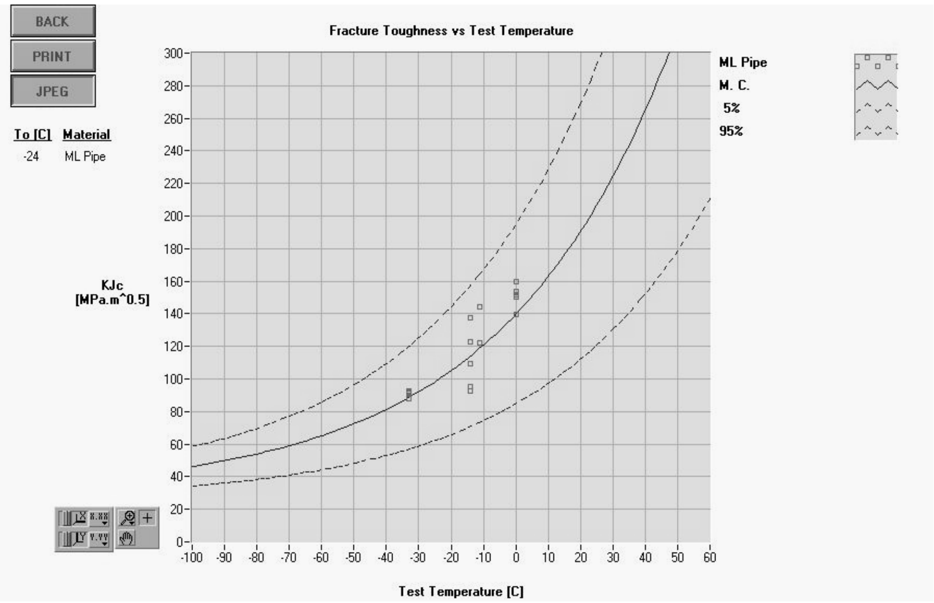


Figure 4: Static fracture toughness (K_{Jc}) values determined from 17 ABI tests conducted on a pipeline steel sample at four test temperatures. The median fracture toughness curve and the 95% and 5% confidence limit curves are shown in the figure.

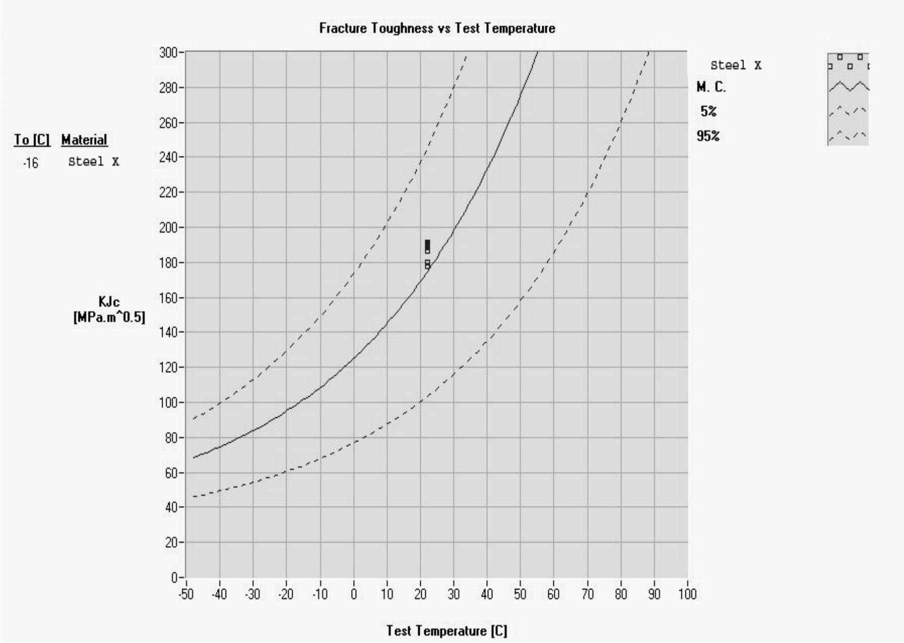
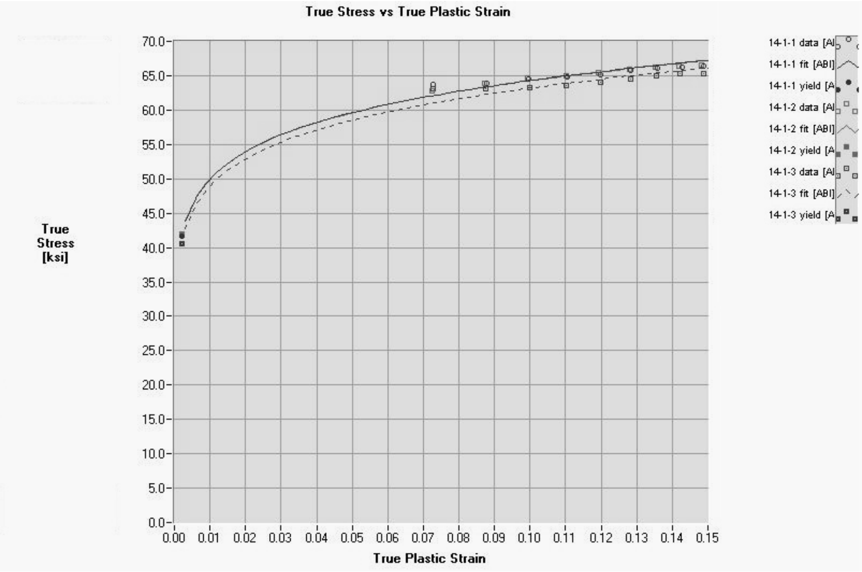


Figure 5: The ABI-determined fracture toughness values, median curve, and the 95% and 5% confidence limit curves obtained from 15 ABI tests at ambient temperature at 4 pipeline locations. The ABI-determined T_o value for the Kerosene pipeline is -16ºC.

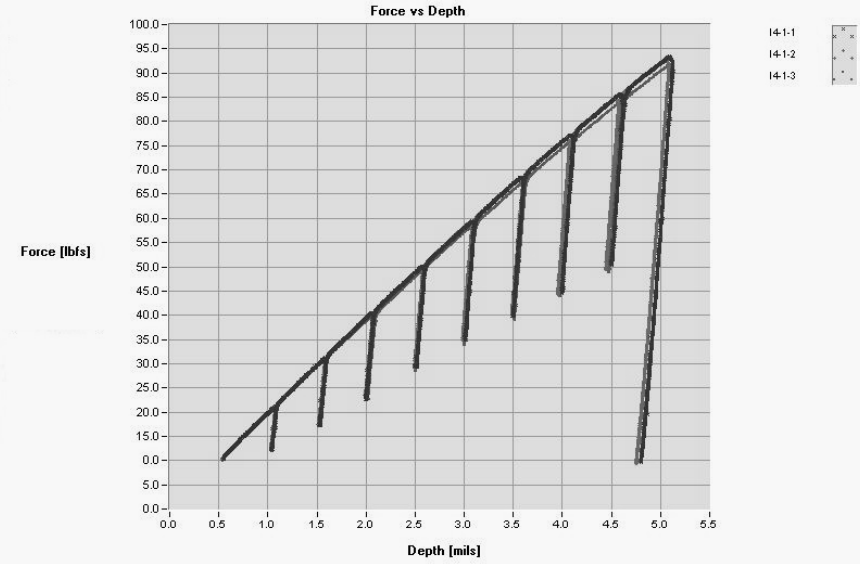
Calculation of Maximum Operating Pressure

The Rstreng software [11] 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 existence 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 were not determined from destructive tension tests or from the nondestructive ABI tests; the maximum safe pressure would only be 86 psi (Fig. 8a) because of the CFR mandatory use of the 24,000-psi value of the yield strength for undocumented steel pipelines. The minimum 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 8b. This pressure is slightly higher than the current operating pressure of 100 psi, indicating that the corroded section must be repaired for safe operation.



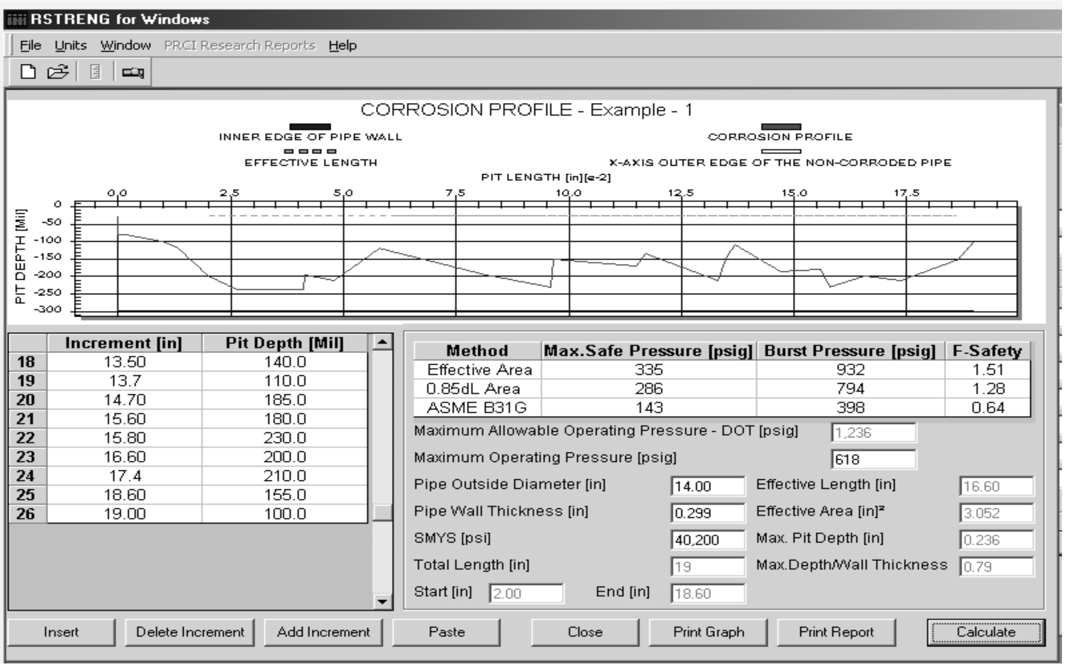
(a)

Figure 6a: 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),



(b)

Figure 6b: 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). (1 lb = 0.454 kg, 1 ksi = 6.895 MPa)

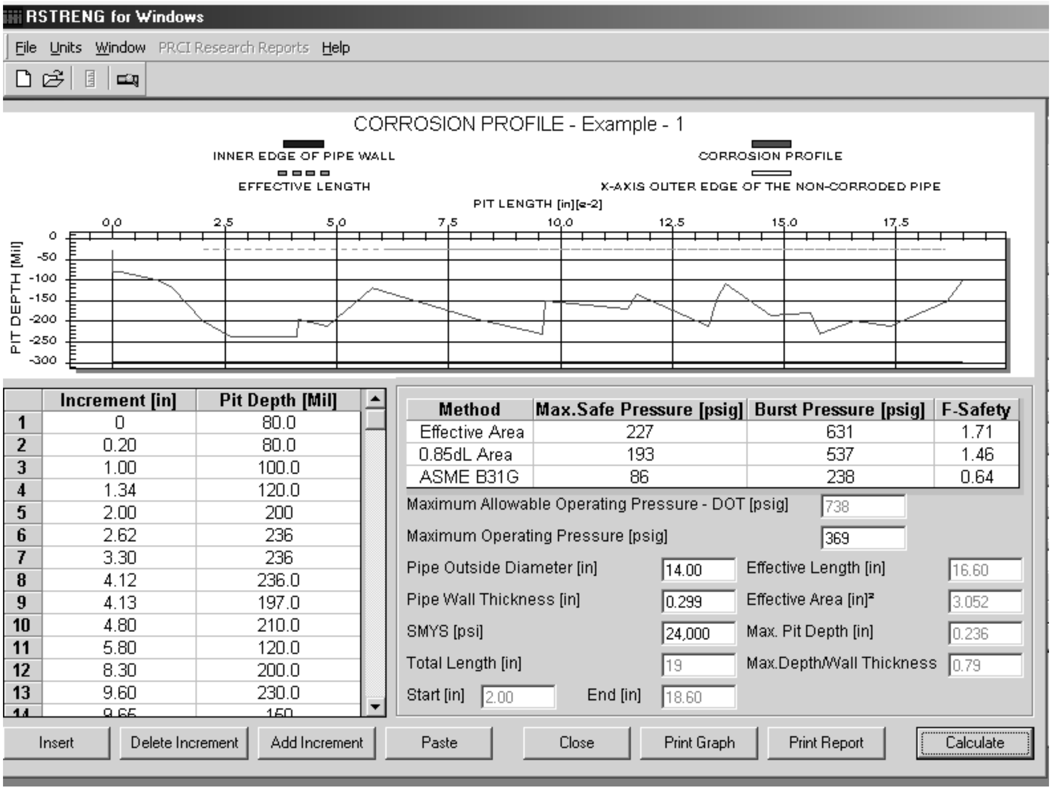


	Increment [in]	Pit Depth [Mil]
18	13.50	140.0
19	13.7	110.0
20	14.70	185.0
21	15.60	180.0
22	15.80	230.0
23	16.60	200.0
24	17.4	210.0
25	18.60	155.0
26	19.00	100.0

Method	Max.Safe Pressure [psig]	Burst Pressure [psig]	F-Safety
Effective Area	335	932	1.51
0.85dL Area	286	794	1.28
ASME B31G	143	398	0.64

Maximum Allowable Operating Pressure - DOT [psig] 1,236
Maximum Operating Pressure [psig] 618
Pipe Outside Diameter [in] 14.00
Effective Length [in] 16.60
Pipe Wall Thickness [in] 0.299
Effective Area [in]² 3.052
SMYS [psi] 40,200
Max. Pit Depth [in] 0.236
Total Length [in] 19
Max.Depth/Wall Thickness 0.79
Start [in] 2.00
End [in] 18.60

Figure 7: A few corrosion pits over a 19-inch long section reduced the maximum safe operating pressure from 618 psi (when no corrosion pitting exists) to 143 psi according to the ASME B31G Code.



	Increment [in]	Pit Depth [Mil]
1	0	80.0
2	0.20	80.0
3	1.00	100.0
4	1.34	120.0
5	2.00	200
6	2.62	236
7	3.30	236
8	4.12	236.0
9	4.13	197.0
10	4.80	210.0
11	5.80	120.0
12	8.30	200.0
13	9.60	230.0
14	9.65	160

Method	Max.Safe Pressure [psig]	Burst Pressure [psig]	F-Safety
Effective Area	227	631	1.71
0.85dL Area	193	537	1.46
ASME B31G	86	238	0.64

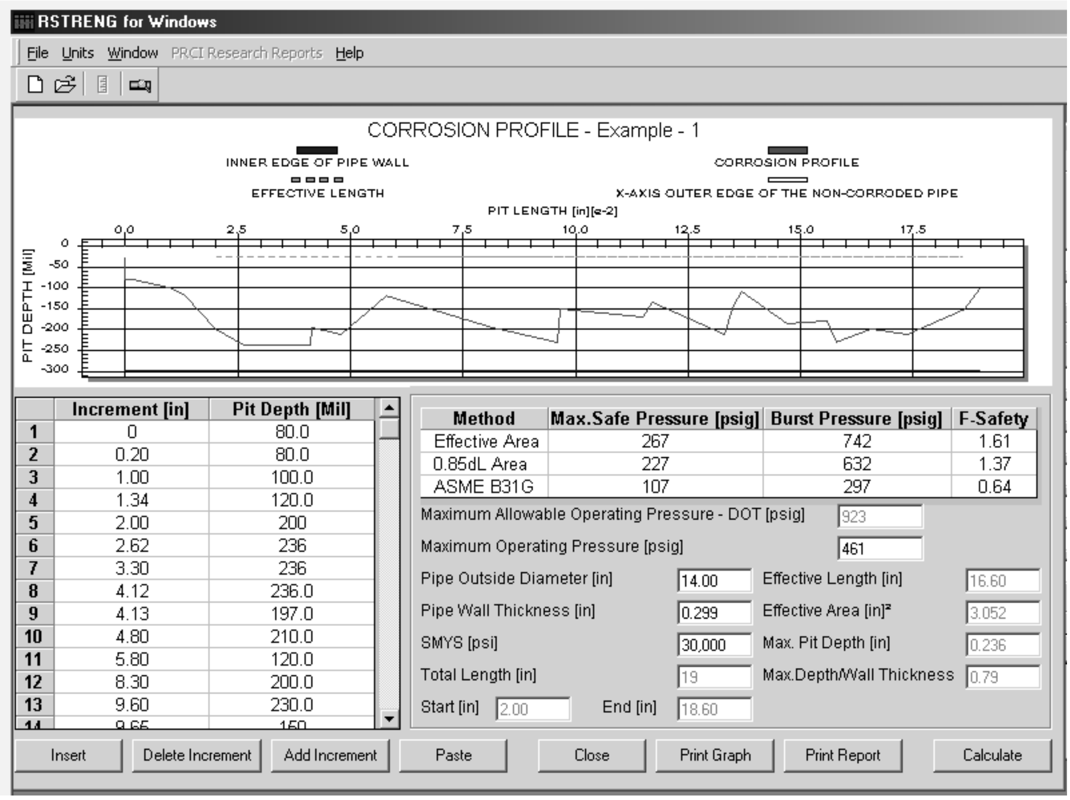
Maximum Allowable Operating Pressure - DOT [psig] 738
Maximum Operating Pressure [psig] 369
Pipe Outside Diameter [in] 14.00
Effective Length [in] 16.60
Pipe Wall Thickness [in] 0.299
Effective Area [in]² 3.052
SMYS [psi] 24,000
Max. Pit Depth [in] 0.236
Total Length [in] 19
Max.Depth/Wall Thickness 0.79
Start [in] 2.00
End [in] 18.60

Figure 8a: 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

Conclusions

The SSM System provides the key mechanical properties (tensile and fracture toughness), from each single ABI test, in a nondestructive and localized fashion without any interruption to the pipeline transmission service.

The results presented in this paper demonstrate the capabilities of the patented Stress-Strain Microprobe® (SSM) system and its Automated Ball Indentation (ABI) test technique to nondestructively measure the tensile and fracture toughness properties of carbon steel pipeline materials in a reliable and accurate manner on samples and components. 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 safe 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 two applications of the SSM system presented here provided the pipeline operators with accurate, nondestructive, ABI-measured fracture toughness and tensile values for deterministic pipeline integrity assessments.



	Increment [in]	Pit Depth [Mil]
1	0	80.0
2	0.20	80.0
3	1.00	100.0
4	1.34	120.0
5	2.00	200
6	2.62	236
7	3.30	236
8	4.12	236.0
9	4.13	197.0
10	4.80	210.0
11	5.80	120.0
12	8.30	200.0
13	9.60	230.0
14	9.65	160

Method	Max.Safe Pressure [psig]	Burst Pressure [psig]	F-Safety
Effective Area	267	742	1.61
0.85dL Area	227	632	1.37
ASME B31G	107	297	0.64

Maximum Allowable Operating Pressure - DOT [psig] 923
Maximum Operating Pressure [psig] 461
Pipe Outside Diameter [in] 14.00
Pipe Wall Thickness [in] 0.299
SMYS [psi] 30,000
Total Length [in] 19
Start [in] 2.00
End [in] 18.60
Effective Length [in] 16.60
Effective Area [in]² 3.052
Max. Pit Depth [in] 0.236
Max.Depth/Wall Thickness 0.79

Figure 8b: 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.

The integration of the SSM measurements with the conventional, non-destructive inspection results (crack/flaw size and/or 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 older pipelines. In addition, the quality of seam welds and girth welds in repair jobs or in new pipeline construction (particularly for high strength grades such as X80 through X120) can be quantified thoroughly from their ABI-measured fracture toughness values as well as from actual ABI-measured tensile properties (required for a true verification of weld over-match design requirements or strain-based design requirements of arctic or earthquake-prone applications).

The SSM measurements should be performed on at least 10% of the total pipeline sections (without documentation) 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.

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