White Paper

The Effect of Pipe Expansion on Fusion Bonded Epoxy Coatings

Energy Pipeline Industry
Pipe Quality Action Plan
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This white paper is the product of work conducted by an ad-hoc group formed to study and evaluate the effect of expansions that have been observed in line pipe on fusion bond epoxy coatings. This was one of eight work groups created to address a broader set of pipe quality issues. The members of the work group were:

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Purpose

The purpose of Work Group 8 was to explore the impact that pipe expansion has on Fusion Bonded Epoxy Coatings. Upon organization, the work group decided to approach this along three work activities.

- Past industry papers and testing on the subject of coating expansion were researched and summarized in a white paper[1]. This included previously unpublished field data were collected on coating condition of pipeline segments, which permanently expanded during field hydrostatic tests.
- Pipe coated with plant applied Fusion Bond Epoxy underwent burst testing during which the coating was evaluated at incremental levels of strain.
- Additional samples of coated pipe underwent tensile and bend testing to demonstrate the strain levels at which the coating showed signs of strain and cracking.

Goals

The goal of Work Group 8 was to demonstrate the level of strain that Fusion Bonded Epoxy can undergo before the coating becomes strained and ultimately reflects cracking~~.~~ A second goal was to evaluate the effect of strain as manifested as stress marks and ultimately, cracking, on coating performance.

Historical Testing

The first activity of Work Group 8 took was to review and evaluation of Pipeline Research Council International (PRCI), the Gas Research Institute (GRI – predecessor of GTI), the Gas Technology Institute (GTI), NACE, and the International Pipeline Conference (IPC) publications and determine what historical work, if any, had been done on the performance of coatings on pipe subsequently expanded or strained. The white paper which discussed this research was written by Process Performance Improvement Consultants, LLC and entitled "Flexibility (Strain Limit) of Fusion Bonded Epoxy Coatings"[1]. Substantial work on coating flexibility has been done, however; to date little work has been completed on the effect of coating expansion on FBE coatings. However, both Spectra Energy and TransCanada have recently looked at how coatings perform once subjected to strain through expansion.

- The Spectra Energy report[2] studied coating performance after being subjected to bending and how film thickness played a role in the flexibility of the coating. All of the strain levels in this report are expressed as permanent strain. The tests showed that, as expected, the coating remained intact at the 2.5°/PD (degrees per pipe diameter). Additional testing showed with the four-point bend method that no cracking was seen in the coating when bent to 3°/PD in either tension or compression. There was some decrease in adhesion (observed through the knife adhesion test) observed on strained coating; however, this did not impact the results of cathodic disbondment testing or hot water soak testing. The report found that FBE, used in conjunction with Cathodic Protection Systems, still provides a corrosion barrier as long as the coating is intact.

- The TransCanada report[3] looked at the percent strain a coating can undergo before signs of strain or cracking are observed. At film thicknesses of 14 to 20 mils FBE coating was subjected to a strain of 9% (total surface strain per ASTM A370-09) before cracking was observed.

Current Testing

The second work activity the group undertook was to develop a test series to demonstrate FBE coatings' ability to handle a certain amount of strain. Three sets of tests were completed: these consisted of tensile testing, bend testing, and burst testing of fusion bond epoxy coated pipe samples.

Description of test samples and conditions

- All samples were from coated pipe and the test specimens were longitudinal straps.
- The pipe coated for testing was 42 in. OD spiral welded pipe with a wall thickness of 0.541 in. (API Spec. 5L X70).
- The tensile straps were prepared per ASTM A370-9a and were 14 x 2.25 x 1.5 in.
- The bend straps were prepared per NACE RP0394 and were 8 x 1 in.
- The bend and tensile testing were carried out at ambient temperatures between 65˚F and 72˚F
- The presence of holidays was determined by the use of a wet sponge coating holiday detector set at 67.5 volts.
- Fusion Bonded Epoxies from two material manufactures were used: 3M SK6233 and Valspar 2000. These were applied at thicknesses ranging between 14 and 26 mils.
- The FBE coating was applied and tested to El Paso Specification UC200. The FBE coatings used achieved CSAZ245-20.02 certification which requires a 3°/PD bend be made at -30°C with no cracking of the coating. The 3°/PD bend equates to a strain level of 2.61% total strain (elastic plus permanent set).

Types of Strain Relevant to Data in this Paper[4]

The main topic of this paper is the amount of strain that an FBE coating can withstand before showing signs of damage. It is important to recognize that there are various ways to measure strain, and this paper includes strain data that from various sources using different methods to measure or calculate strain. In general, strain is either *Total Strain* or *Permanent Strain*.

Differentiating between these two types of strain is important, as the level of Permanent Strain on the coating is more relevant to the strain seen in pipe expansion. Throughout this paper the strain seen in a bend strap is referred to in units of °/PD (degrees per pipe diameter), and the type of strain data (permanent or total) is indicated.

The definitions of *Total Strain* and *Permanent Strain* are given below and referenced to how this was calculated. The differences between the two types of strain and how they are calculated are shown in more detail in Appendix A.

- *Total Strain*- The total amount of strain a coating is subjected to before the load is released and the steel substrate springs back. This includes both plastic and elastic deformation.

- *Permanent Strain*- This is the plastic strain remaining after release of the force used in bending, hydrostatic testing, pipe expansion in the mill, or tensile testing. On coated straps, this is most easily measured by determining the bend radius of the strap after release of the bending force, and using an equation such as in NACE RP0394-2002 Appendix H Section H4.3 or in Appendix A of this paper (which was actually the basis for the NACE test method). Bend severity is usually designated and measured in degrees per pipe diameter, because this was the traditional way for operators of field bending machines to measure the strain of their bends. This usage carried over into the standards for bending of coated straps. In order to further make the two numbers comparable (i.e. field bend severity and coated strap bend severity), both give the strain along the neutral axis of the pipe or strain. Appendix A of this paper explains this in more detail. Strain in °/PD is 1.146 times the strain in percent.

The strain measured in tensile testing is always in percent, and is measured at the surface. When determining yield strength, the strain includes both elastic and plastic components. However, within this paper, the strain is measured after release of tensile force, and hence is only the permanent strain. Another way to look at this is via the stress-strain curve for steel. As the tensile strap is pulled, the stress and strain increase along a straight line with a slope called the elastic modulus (also referred to as Young's modulus). At some point, the graph deviates from linearity as the steel plastically deforms. If the test is stopped before breakage, and tensile load released, then the strap shrinks back along the slope of the elastic modulus. Thus the amount of permanent strain (after load release) is less than the total strain experienced under the maximum load. The amount of elastic strain reduction (referred to as "spring back" on bends) is significant, on the order of 0.5% (~ 0.6 °/PD).

The strain of hydrostatic testing can be measured while the pipe is under pressure, and this would be total strain (both elastic and plastic components). But the hydrostatic test strain data in this paper were determined after pressure release, and thus represent permanent strain.

Mandrel bending of coated straps, such as in specifications like NACE RP0394-2002, Appendix H Section H4.2, or CSA Z245.20, section 12.11, represent total strain. These numbers are higher than the permanent strain values. . This method is easier for the coating applicator or manufacturer to meet a specification because the target strain is met BEFORE elastic spring back. However, total strain is not directly comparable to the amount of strain that the coating must withstand in field cold bends, which is measured AFTER spring back. Based on tests done at Tennessee Gas Pipeline some years ago on X52 and X60 pipe, the amount of spring back is 0.4 to 0.6 °/PD. Higher-strength pipe may have a greater amount of spring back, depending on the shape of the stress-strain curves for the pipe steel. If the amount of elastic spring back is 0.6 °/PD, then a CSA mandrel bend of 2.5°/PD would be equivalent to only 1.9 °/PD permanent bend. Conversely, a 2.5 °/PD permanent strain such as determined by the Tennessee Gas (Tenneco) / NACE template method would require a mandrel bend to a total strain of 3.1 °/PD. *The importance of permanent strain is reflected in NACE RP0394, Table 4, where the acceptance criterion for flexibility of straps from production test rings is specifically "permanent strain".*

It would be beneficial to the pipeline industry if the various coating standards and customer specifications were more consistent in their treatment of strain requirements for coating.

Tensile Test Summary

The complete result tables for the tensile tests can be found in Appendix B. In summary, the tensile testing was conducted at two facilities in the following manner. The tensile test straps were prepared per ASTM A370-9a and placed in the tensile tester. Each strap was slowly elongated while watching for signs of strain on the coating. The elongation continued until cracking in the coating was observed. For the purpose of these tests stress marks are defined in the coating is defined as 'small white lines appearing in the coating' and a pictorial example are seen in Figure 1;

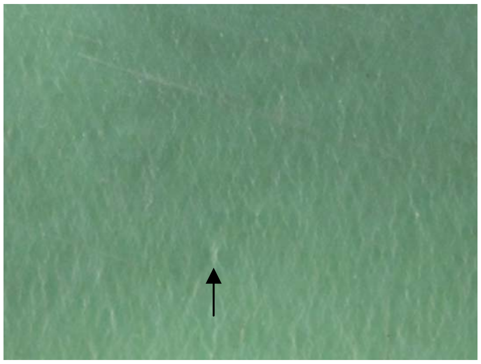


Figure 1

The bend straps were placed in the test rig and the strain gauge was attached as seen in Figure 2 and elongated. As the straps were elongated measurements were taken at pre-determined points of strain, Figure 3.

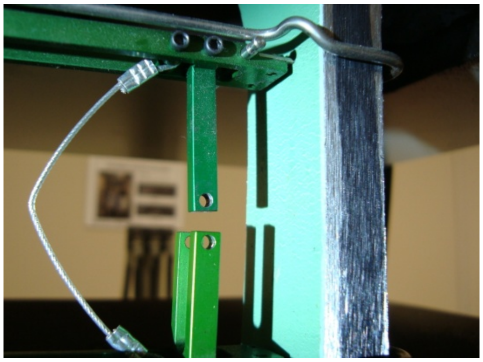


Figure 2

Figure 3

The testing stopped when cracks were observed visually in the coating. Holidays in the coating were verified by a wet sponge jeep set at 67.5 volts. Examples of the types of cracking seen are shown in Figures 4 and 5.

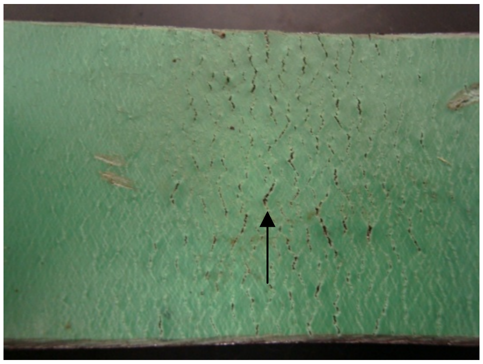


Figure 4

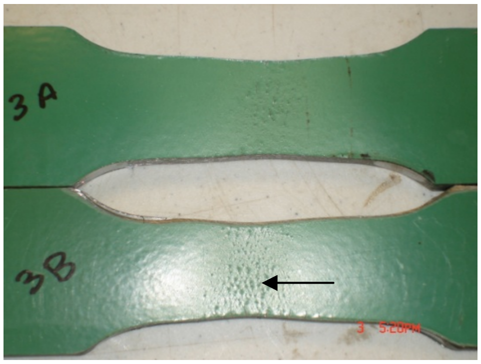


Figure 5

The tensile testing showed that signs of stress in the coating are not observed until strains in excess of 10% are applied to the strap. Cracking or the creation of holidays does not begin until strain levels in excess of 14% are seen. It should be noted that the tensile straps were flattened prior to tensile testing, which could create strains on the coating before the tensile testing.

Bend Test Summary

The complete bend test results can be found in Appendix C. In summary, the bend tests were carried out using NACE RP0394 with a combination of the four-point and mandrel bending methods. The severity of bend resulting in stress marks and cracking was first determined by using the four-point bend method outlined in NACE RP0394-2002. From this estimate the proper size mandrels were determined. To ensure reproducibility of the bend these mandrels were used for the remaining bends. The samples had an effective strap thickness, which was between 0.560 in and 0.580 in.

We found that a four inch radius mandrel creates signs of stress in the coating, will generate permanent strain levels between 7.3°/PD and 7.6°/PD total strain depending on strap thickness (Figures 7 and 8).

Figure 7

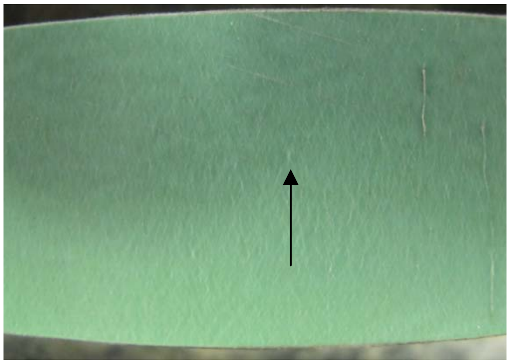


Figure 8

When attempting to create a crack in the coating using the four-point bend method, the strap had to be bent almost 180° before cracking was observed. While creating this failure mode it, should be noted that the time it takes to complete the bend is important; too fast a bend rate can result in disbondment of the coating in the area of the bend. For this experiment, the bend was completed in a 20 to 30 second time frame. Due to the extreme degree of bend required to show cracking a mandrel was made from a piece of 1 in. radius bar stock (Figure 6). This resulted in permanent strain levels between 27.17°/PD and 27.82°/PD total deflection. A wet sponge holiday detector was used to determine the presence of holidays; refer to Figures 9 and 10.

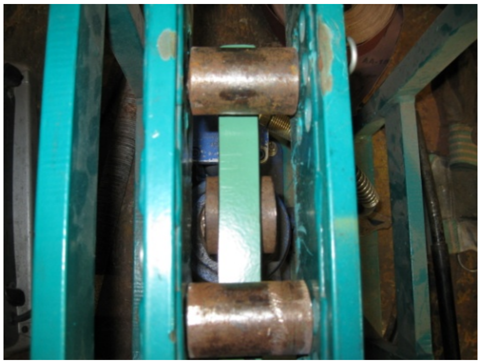


Figure 9

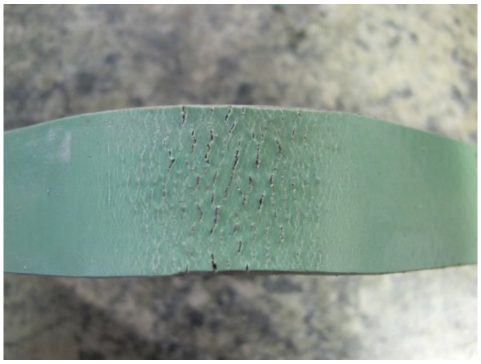


Figure 10

The coating elongation for two samples at each bend severity was determined by marking the straps at uniform intervals and measuring the distance along the arc between the marks both before and after the bend. The results of these measurements can be found in Appendix C1. It should be noted that all bend straps were taken in the longitudinal direction. Additional testing could be conducted to see if there are any changes in how the coating performs when circumferential straps are bent.

While completing the bend tests, the impact of damage to the coating, such as a gouge (Figure 11), were also studied. It was found that a gouge in the coating, that did not penetrate through the coating, could create a stress riser for a coating crack to initiate and propagate when put under strain. This effect of the stress riser was reduced by applying a two-part liquid repair epoxy to the damaged area prior to bending. In this instance initially the repair material showed no signs of cracking (Figure 12) when bent with the 1-inch radius mandrel, however, after resting for a one week period cracks and holidays (Figure 13) did appear in the coating.

Figure 11

Figure 12

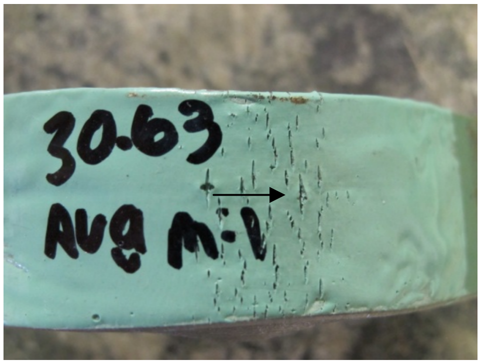


Figure 13

Field Testing of Coating

Through the course of the research and testing the group posed the question, 'How do we test the coating in the field in the event it has undergone expansion?' After thorough discussion, the consensus was that an Owner Company should use its existing coating inspection techniques described in its procedures for pipeline rehabilitation. In the event that no procedures have been developed to determine the suitability of a coating during pipeline rehabilitation, the following tests are recommended.

1) Cross Hatch Adhesion Test - Use the method outlined in ASTM D6677 and perform a cross-hatch adhesion test with a knife pick.
2) Holiday Detection - Due to the difficulties to determine the proper test voltage for coating, which has been in service subjected to differing conditions, it is recommended that holiday detectors are set per NACE RP0490. The voltage should be set or verified per section 3, and tested by using an artificial holiday.
3) Cure- It is not generally recommended that the cure of the coating be checked via DSC (Differential Scanning Calorimeter) after long term exposure. The reason for this recommendation is that exposure to the environment, high operating temperatures, and moisture can produce cure

results, which are false or misleading. In the event that the cure of the material is in question, the Owner Company should work with the Material Supplier to develop a valid procedure for verifying the cure of the coating in question.

Burst Test Summary

The purpose of the testing was to analyze the coating integrity during the burst testing. Burst testing was performed on six coated pipes submitted by two different pipe mills. Each mill submitted three coated pipes: each mill had applied a different FBE coating. Three pipes were coated with 3M SK6233 and the remaining three were coated with Valspar 2000. The pipe was welded together in strings of three pipes, each string being comprised of the same coating. The outer diameter of the pipe was then measured at pre-determined locations to determine the baseline diameter. The pipe was then pressurized to 80%, 105%, and 110% of the specified minimum yield strength (SMYS), and depressurized at each increment to re-measure the diameter. The FBE coating was inspected visually and with a coating holiday detector between pressurization intervals through the course of the hydro test.

No loss of coating integrity was visually identified nor did the holiday detector show any areas of exposed bare metal between pressurization intervals on either pipe string prior to rupture. After reaching the 110% of SMYS, the sections were taken to burst pressure. Upon completion of the test, the outer diameter was measured. All these measurements can be found in Appendix D, followed by a pictorial summary of the pipe sections and rupture sites. Up to 110% of SMYS the coating showed no signs of strain or cracking; however, after the pipes were taken to burst, signs of strain could be seen through the length of the coating to various degrees. The observed strain marks ranged in size from 1/16 to ¾ inch in length throughout different areas of each pipe string, with the longest indications adjacent to the rupture origins. Figures 14 and 15, page 9, show the types of strain marks seen at areas marked Section T (2.63% expansion) and Q (3.2% expansion), respectively. (The raw data can be found in Appendix D2 Joint P3 and pictures of the burst test can be found in Appendix D3.)

At the rupture sites, the coating was fractured in either a “puzzle piece” pattern or a “strip” pattern parallel with the direction of the stress marks (Appendix D3). The exact cause of the differences in how the coating failed at the rupture site can only be speculated about at this point. Holiday detection was performed after both burst tests on the entire OD surface of each pipe string. It should be noted that only the areas immediately surrounding the rupture site caused the coating to crack and/or disbond.

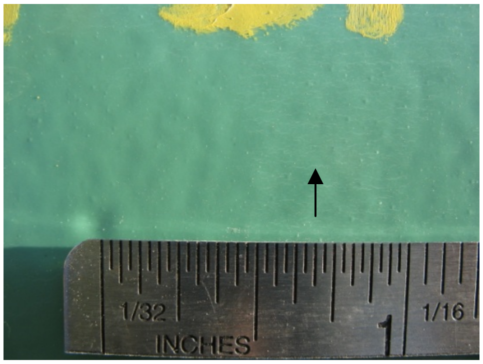


Figure 14

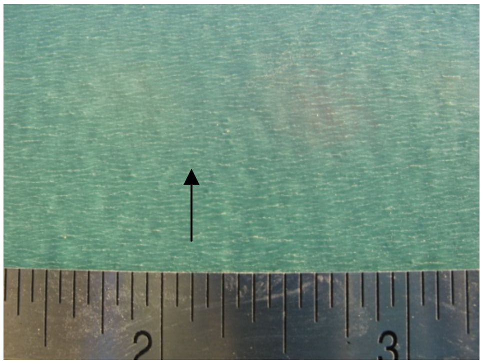


Figure 15

Field Observations

Two operators who have recently excavated pipelines and observed expansions in the pipe have provided some initial feedback on their findings. It was found in both cases that visual signs of stress in the coating were present. Despite these stress marks seen in the coating, no loss of adhesion was observed.

Excavation 1

Stress marks and cracking were observed over approximately half of a pipe joint at one location that measured 3.06% expansion (permanent strain), Figure 16. The coating showed good adhesion as reflected by a cross-hatch test. Holidays were identified and after visual inspection, were verified as shovel dings and damage from probing made during initial excavation.

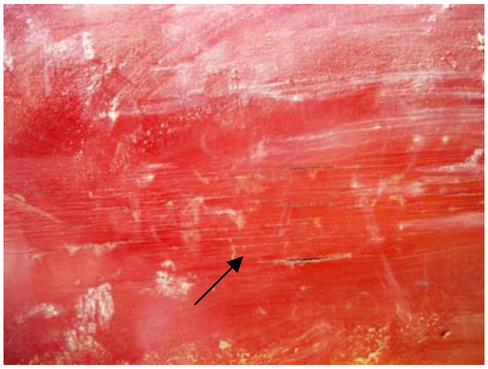


Figure 16

Excavation 2

Signs of initial stress (stress marks) Figure 17, in the coating were observed at two localized expansions on the pipe. A picture was taken at the location of largest expansion, which was 1.73% (permanent strain).

Figure 17

Conclusions

The testing conducted by Work Group 8 on coated samples which were subjected to varying levels of strain by tensile, bend, and burst testing show that Fusion Bonded Epoxy coating does not begin to show signs of stress until strain levels reach levels that well exceed the minimum required to generate plastic deformation of the steel substrate. It was concluded that a correlation between the strain from tensile testing and strain from bend testing needs more data points which should include additional coating and steel thicknesses.

To ensure reproducibility it is important that the bend and tensile testing be conducted at a temperature ranging from 65°F to 75°F. The temperature range of 65°F to 75°F was chosen to make results comparable to those seen in hydrostatic testing. From the testing conducted, it appears that dramatic deformation (greater than strain levels of 7%) in the steel substrate is required before visual defects were observed in the coating.

Fusion Bonded Epoxy coatings are designed to handle certain levels of strain and tested for their abilities to do so. This is outlined in CSA Z245.02, which requires them to be bent to a 3°/PD bend at -30°C and pass Cathodic Disbondment Testing with the coating in strain. Additionally, historical experience shows that even in instances where adhesion of the coating may be compromised, the coating will still provide a level of protection when used in conjunction with a Cathodic Protection System.

The group recommends to the pipeline industry that the various coating standards and customer specifications should be more consistent in their treatment of strain requirements for coating.

The work group also recognizes that this study is not inclusive of all coatings currently used for pipelines. A more extensive study may be appropriate to learn the effects of expansion on;

1) other coatings such as abrasion resistant overlays, liquid coatings, and repair materials and
2) the effect of specific strain levels related to the following industry standard tests; Cathodic Disbondment, Moisture Permeation, and Adhesion.
3) Look at how coatings perform when strained at varying temperatures, mainly less than 40°F. The goal being to make testing comparable to lower temperature hydrostatic testing.

Appendix A

Tennessee Gas (Tenneco Gas) MQ-852 Coating Bend Tests

COATING BEND TESTS

1. GENERAL

Bend tests are conducted to assure that the coating has adequate flexibility for field usage. Bend flexibility is related to the degree of coating cure. The ANSI B31.8 Code for Gas Transmission and Distribution Piping Systems (1975 edition) limits field bend severity of pipe 12 3/4 in. and larger to 1.5° per pipe diameter (¶841.231 (a)). This 1.5°/PD standard is the measure of permanent strain (that is, the amount of bend after springback). The 1986 ANSI/ASME B31.8 Code (¶841.231) allows 1.9°/PD for 20 in. and larger pipe, and greater bend severity for smaller diameters (up to 3.2°/PD for 12 3/4 in. pipe). Reel barge strains can amount to as much as 3.7°/PD total strain (before springback). Such severe strains would only occur with larger pipe and small spools (e.g., 12 3/4 in. OD and 32 ft diameter spools). With good lay practice (larger spools and/or dummy pipe to increase the effective spool diameter), the maximum total strain would still be 2.5 to 3.0°/PD. This corresponds to a permanent strain of about 2.3 to 2.8°/PD. (The amount of springback is dependent upon the yield strength of the pipe. The above conversion from total to permanent strain assumed average grade B yield strengths; high strength pipe may have a springback of up to .5 °/PD.)

Appendix 1 demonstrates the derivation of the relationship between strain and bend parameters.

2. PROCEDURE

2.1. Adequate Number of Straps
A pass and a fail must always be obtained to insure specification compliance. Therefore, obtain six straps when using the four-point jig. When using the mandrel method, three straps are adequate. [NOTE: Use one strap to determine foam and contamination.] The size of the straps should be approximately 1 in. by 8 in.

2.2. Measure the thickness of the specimens with a micrometer and file or grind the stress raisers (e.g., notches along edge of strap) before cooling.

2.3 The specimens must be held at 0 F for for at least one hour when placed in a freezer. If a freezer is not available that can reach 0 F, then a CO_2 fire extinguisher or dry ice may be used. The CO_2 (dry ice) method can cause the straps to cool down to -109 F; such low temperatures can cause a bend test failure which might have otherwise passed at 0 F. Therefore, the specimen must be allowed to "warm" up to 0 F, and a contact pyrometer must be used to determine specimen temperature. To determine final temperature, place the probe of the contact pyrometer on the steel (do not take a reading on the coating since an erroneous higher temperature may be read there, due to low thermal conductivity of the coating which permits only slow chilling of the probe). Bend the straps within 30 seconds after the straps reached 0 F or were removed from a freezer that maintained a temperature of 0 F. The flexibility of the coating will increase as the temperature increases.

2.4 Examine each bent strap immediately after bending using 40X magnification. A crack, fissure, tear, or delamination of the coating constitutes a failure. Defects lying within 0.1 in. of the strap edge are excluded from consideration. "Stretch marks" do not constitute failure, but should be noted on the inspection report. Additionally, when using a four point jig, a crack 1/8 in. to either side of the pin contact point is acceptable.

2.5 Our specification requires 1.5°/PD permanent (arc match method) or 2.5°/PD total (mandrel method) bend at 0 F. To confirm coating bendability, calculate the strain for the straps which passed the test, using the method in 3.1 for mandrel bends or the method in 3.2 for the four point bend.

3. <u>DETERMINATION OF STRAIN</u>

Several methods are in use for determining strain; all have some degree of error. Therefore, only bends made with either a four point jig (using the arc match method) or the mandrel method are acceptable. Any deviation from the following two methods must not be allowed.

3.1 MANDREL BEND

A minimum <u>total</u> strain of 2.5°/PD is required when using this method.

This method bends the strap over a mandrel with a given curvature. Mandrels must be changed as wall thickness changes to maintain the same strain.

3.1.1 The following equation can be used to choose a mandrel radius that will produce a 2.5°/PD or greater bend. The solution to the equation may not be a standard mandrel radius. In such cases, choose a mandrel radius that is equal to or <u>less than</u> the solution to the equation. [The mandrel number (which is usually stamped on the mandrel) can be multiplied by 0.375 inch to obtain the mandrel radius.]

$$R = 22.42t$$

where R = radius of mandrel
t = thickness of coated strap

Appendix 2 is a chart showing what the strain would be for various wall thicknesses bent on various mandrel radii. Strain is given in both the usual °/PD and in Engineering terms [$\varepsilon(\%)$].

3.1.2 Use the following equation to determine °/PD once the mandrel radius has been chosen.

$$°/PD = \frac{57.3\ t}{(R + t/2)}$$

where t = thickness of coated strap
R = radius of mandrel

3.1.3 View the specimen microscopically for failure. See ¶2.4 for failure criteria.

3.1.4 Since this is <u>total</u> strain, and springback varies with yield strength, the <u>permanent</u> strain should be subsequently measured by the arc match method. This will also insure that the correct mandrel radius was used. <u>When using the arc match method</u>, keep in mind that only a minimum of 1.5°/PD is required.

3.1.5 <u>Most Common Errors When Using This Method</u>

a. Using the wrong mandrel.
b. Not adding half the strap thickness to the mandrel radius when performing the calculation. Errors up to 6% can result by omitting half the strap thickness in the calculation.
c. Using nominal wall rather than actual strap thickness. Two joints of pipe with the same nominal wall thickness could differ in actual wall thickness by as much as 27 1/2% and still be within the API linepipe specification.
d. Using "shims" to change strap thickness; shims will only change mandrel radius, and this affects the calculated strain less than the strap thickness does.

3.2 ARC MATCHING METHOD

A <u>permanent</u> strain of 1.5°/PD is required when using this method.

This method can be used on straps bent either with a <u>mandrel</u> or <u>four point jig</u>. The principle is simply matching the outside curvature of the bend with arcs of a known curvature (bend radius). The procedure is as follows:

3.2.1 When using a four point jig, continue bending until failure occurs. Note the ram position. Repeat the bend test, with approximately 1/4 to 1/2 inch less ram travel, and inspect microscopically for signs of failure. If none are found, measure strain on both the pass and fail and record the results. If the second bend has failed (See Section 2 for Failure Criteria), repeat with even less ram travel until both a pass and a fail are obtained.

3.2.2 Select a portion of the bent strap with relatively even curvature (no tangents or breakover points) and mark two "hashmarks" about 1 1/2 to 2 1/2 in. apart, on the external coating.

3.2.3 Select an arc from Appendix 3 with approximately the same curvature and lay the edge of the bent strap on the page <u>with the two hashmarks aligned to intersect the arc</u>. [Note: If the strap edge is not perpendicular to the outside of the bend, the strap must be canted until the outside surface of the bend is perpendicular to the page.]

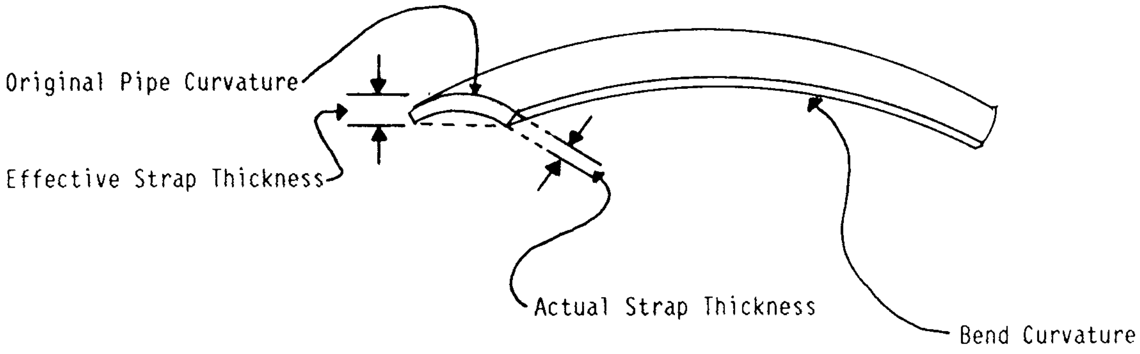
3.2.4 If the portion of the strap between hashmarks lies above the drawn arc, one moves to a smaller radius arc, or vice versa. Within a short time, you should be able to tie down the actual arc curvature between two drawn arcs. Pick the one with the smaller bend radius (giving the vendor the benefit of the doubt) and note the arc radius.

3.2.5 Calculate <u>permanent</u> strain with the following equation:

$$\text{o/PD} = \frac{57.3\ t}{R - t/2}$$

where t = thickness of coated strap
R = bend radius to outer curve of strap (arc)

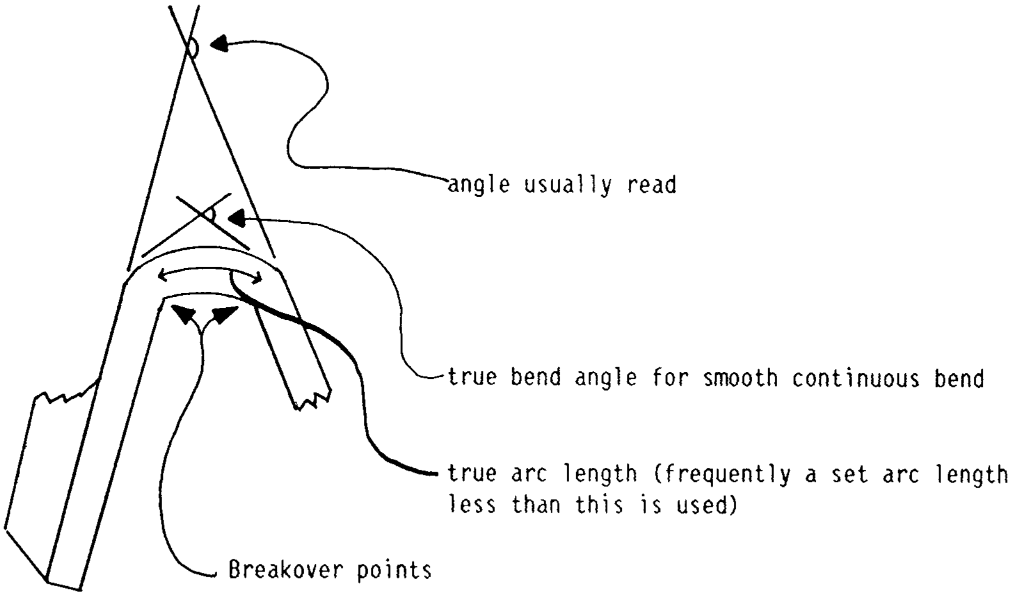
3.2.6 On small diameter pipe, "effective strap thickness" should be used. Strain is dependent on distance to the neutral axis, and thus any lift-off from the mandrel caused by transverse curvature adds to the effective thickness used for the bend strain calculation, as shown below.



3.2.7 Most Common Errors When Using this Method

a. Using nominal wall rather than actual strap thickness. Two joints of pipe with the same nominal wall thickness could differ in actual wall thickness by as much as 27 1/2% and still be within the API linepipe specification.

b. Four point benders often use an inclinometer on the straight strap ends, or a graphical extrapolation of the straight strap ends after bending to develop strain data. Results from this method are frequently two times or more the true value. The usual error sources are (1) use of strap ends for bend angle determination (this gives a greater angle reading than actually exists along the smooth part of the bend, since the breakover angles are included, as shown in the sketch below) and (2) use of the wrong arc length.



$$^\circ/\text{PD} = \frac{A}{l/t}$$

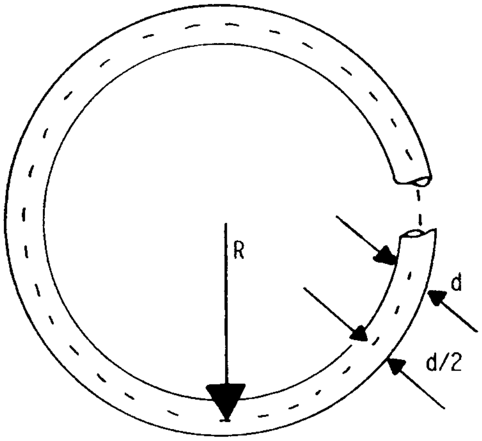
where A = bend angle
l = arc length
t = thickness of coated strap

APPENDIX 1
BEND STRAIN DETERMINATION

Use concept of pipe bent into a circle:

It is assumed that (1) the neutral axis is along the pipe centerline and (2) the circumference of the neutral axis equals the original pipe length before bending.

R = neutral axis bend radius
d = pipe diameter
ε = strain
$\varepsilon(\%)$ = strain in percent



ENGINEERING TERMS

$$\varepsilon = \frac{\text{Outer circumference} - \text{Neutral axis circumference}}{\text{Neutral axis circumference}}$$

$$\varepsilon = \frac{2\pi(R + d/2) - 2\pi R}{2\pi R} = \frac{R + d/2 - R}{R}$$

$$= \frac{d/2}{R}$$

$$= 0.5\,\frac{d}{R}$$

$$\varepsilon(\%) = 100\varepsilon = 50\,\frac{d}{R}$$

FIELD TERMS

$$°/PD = \frac{\text{Number of degrees per circle}}{\text{Circumference of neutral axis in increments of pipe diameter}}$$

$$°/PD = \frac{360}{\frac{2\pi R}{d}}$$

$$= 57.3\,\frac{d}{R}$$

GENERAL NOTES

1. The same derivation and equations apply to strap bends, except that strap thickness (t) is substituted for pipe diameter:

$$\varepsilon(\%) = 50\,\frac{t}{R}$$

$$°/PD = 57.3\,\frac{t}{R}$$

2. Note the relationship between "$\varepsilon(\%)$" and "°/PD" :

$$°/PD = 1.15\varepsilon(\%)$$

or

$$\varepsilon(\%) = 0.87\ °/PD$$

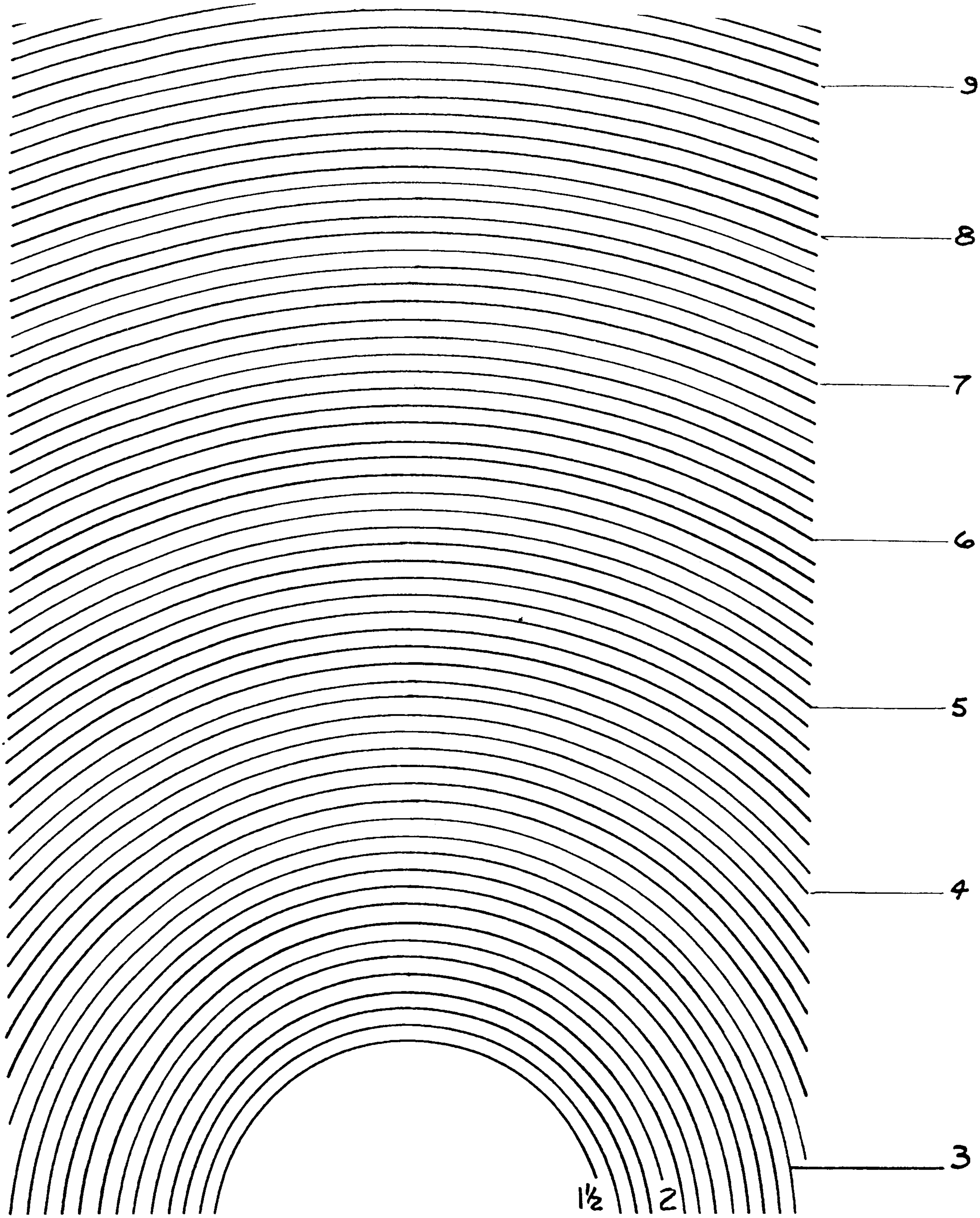
APPENDIX 2

DEGREES/PIPE DIAMETER (°/PD) AND STRAIN (%) AS
A FUNCTION OF WALL THICKNESS AND MANDREL RADIUS*

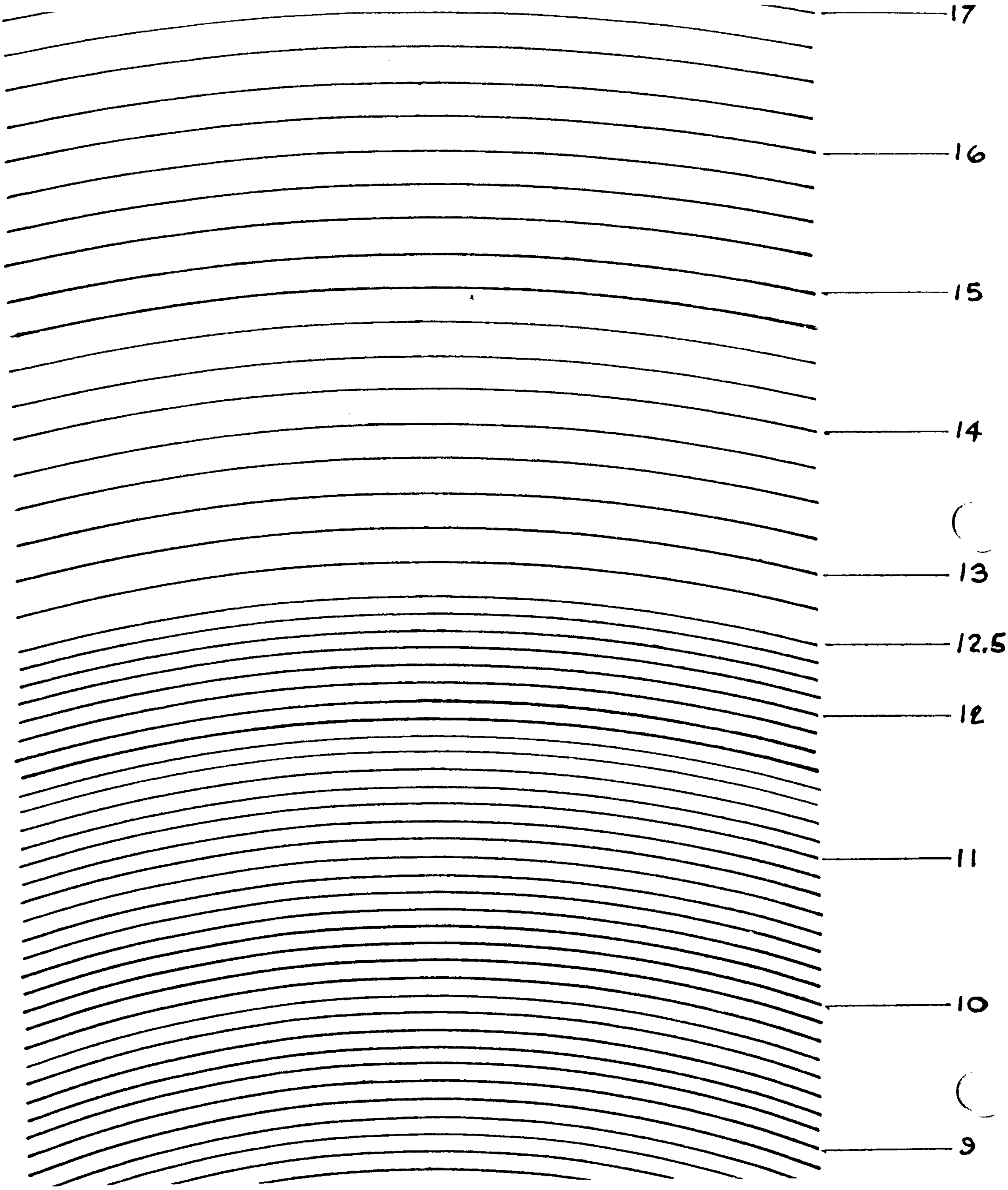
WALL THICKNESS	MANDREL RADIUS (MANDREL NUMBER)											
	3.00 in.(8)		3.750 in.(10)		5.625 in.(15)		7.50 in.(20)		9.375 in.(25)		11.25 in.(30)	
	°/P.D.	% ε	°/P.D.	% ε	°/P.D.	% ε	°/P.D.	% ε	°/P.D.	% ε	°/P.D.	% ε
.188	3.48	3.04	2.80	2.45	1.88	1.64	1.42	1.24	1.14	.993	.950	.829
.203	3.75	3.27	3.02	2.64	2.03	1.77	1.53	1.34	1.23	1.07	1.02	.894
.219	4.04	3.52	3.25	2.84	2.19	1.91	1.65	1.44	1.32	1.15	1.10	.964
.250	4.58	4.00	3.70	3.23	2.49	2.17	1.88	1.64	1.51	1.32	1.26	1.10
.281	5.13	4.47	4.14	3.61	2.79	2.44	2.11	1.84	1.69	1.48	1.41	1.23
.312	5.66	4.94	4.58	3.99	3.09	2.70	2.34	2.04	1.88	1.64	1.57	1.37
.344	6.21	5.42	5.03	4.39	3.40	2.97	2.57	2.24	2.06	1.80	1.73	1.51
.375	6.74	5.88	5.46	4.76	3.70	3.23	2.80	2.44	2.25	1.96	1.88	1.64
.406	7.26	6.34	5.89	5.14	3.99	3.48	3.02	2.64	2.43	2.12	2.03	1.77
.438	7.80	6.80	6.32	5.52	4.29	3.75	3.25	2.84	2.62	2.28	2.19	1.91
.469	8.31	7.25	6.74	5.89	4.59	4.00	3.47	3.03	2.80	2.44	2.34	2.04
.500	8.82	7.69	7.16	6.25	4.88	4.26	3.70	3.23	2.98	2.60	2.49	2.17
.562	9.81	8.56	7.99	6.97	5.45	4.76	4.14	3.61	3.33	2.91	2.79	2.44
.625	10.8	9.43	8.82	7.69	6.03	5.26	4.58	4.00	3.70	3.23	3.10	2.70
.688	11.8	10.3	9.63	8.40	6.60	5.76	5.03	4.39	4.06	3.54	3.40	2.97
.750	12.7	11.1	10.4	9.09	7.16	6.25	5.46	4.76	4.41	3.85	3.70	3.23
.812	13.7	11.9	11.2	9.77	7.71	6.73	5.89	5.14	4.76	4.15	3.99	3.48
.875	14.6	12.7	12.0	10.4	8.27	7.22	6.32	5.51	5.11	4.46	4.29	3.74
.938	15.5	13.5	12.7	11.1	8.82	7.70	6.74	5.89	5.46	4.76	4.59	4.00
1.000	16.4	14.3	13.5	11.8	9.36	8.16	7.16	6.25	5.80	5.06	4.88	4.26
1.062	17.2	15.0	14.2	12.4	9.89	8.63	7.58	6.61	6.14	5.36	5.17	4.51
1.125	18.1	15.8	15.0	13.0	10.4	9.09	8.00	6.98	6.49	5.66	5.46	4.76
1.188	18.9	16.5	15.7	13.7	11.0	9.55	8.41	7.34	6.83	5.96	5.75	5.02
1.250	19.8	17.2	16.4	14.3	11.5	10.0	8.82	7.69	7.16	6.25	6.03	5.26

*(Mandrel number here is actual mandrel radius divided by 0.375 in.)

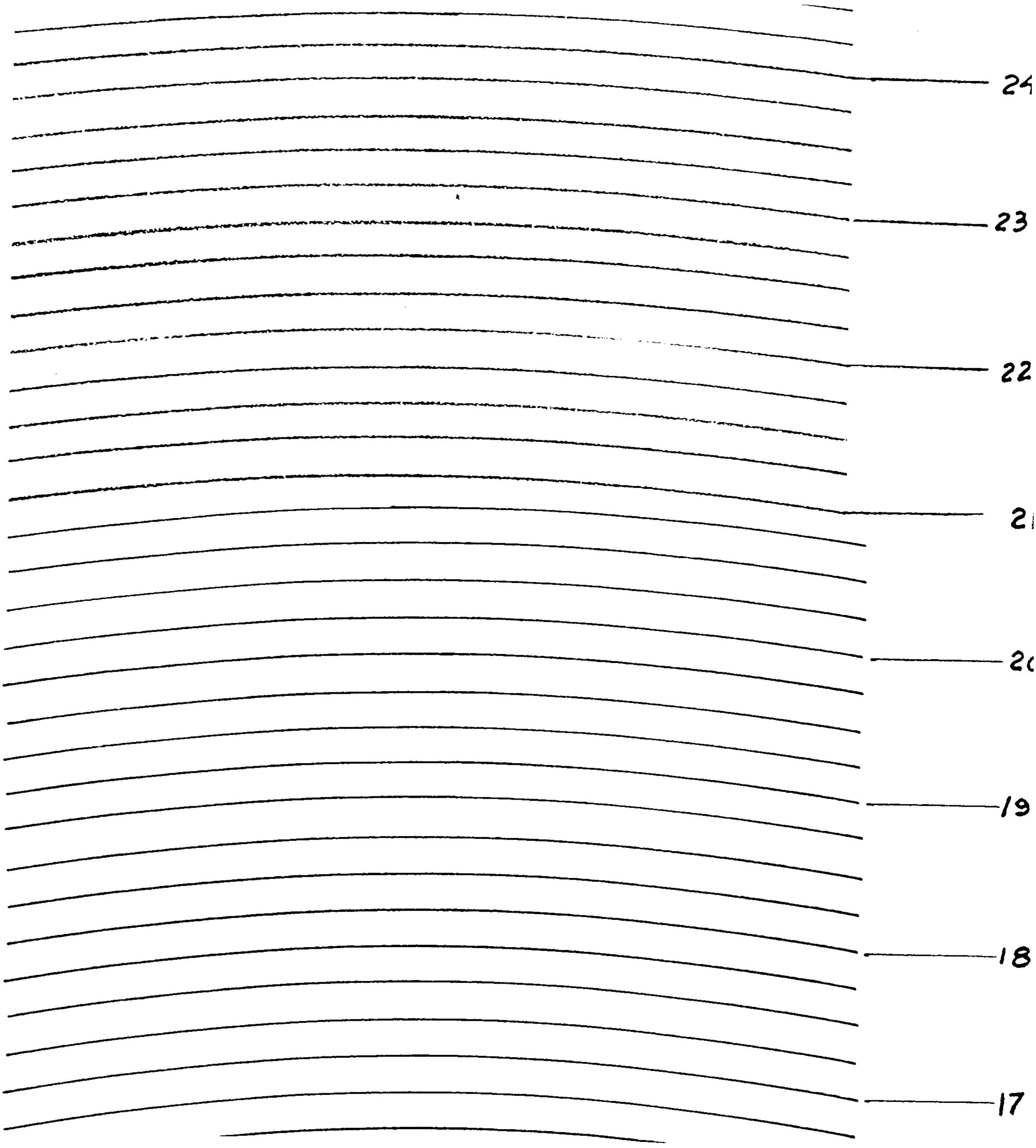
APPENDIX 3



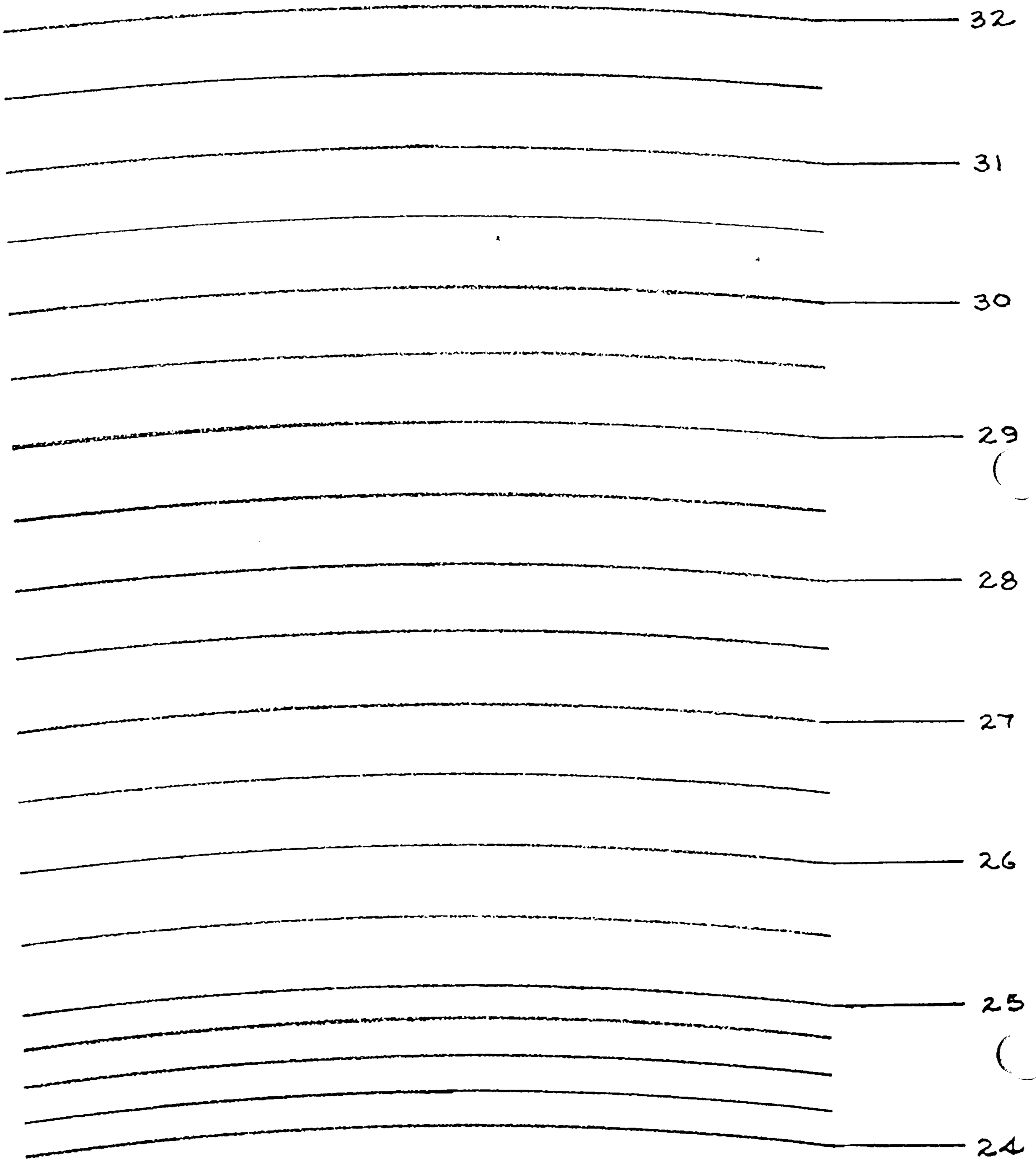
APPENDIX 3



APPENDIX 3



APPENDIX 3



Appendix B

Valspar 2000 Sample No. 3 A : PIPE NO. A09004912				
Tensile Strap (Coating Thickness 17.5 – 19.7 mils)				
% Strain	Thickness, inch	Elongation	Visual	Remarks
0.00%	0.560	2.00	ok	--
1.90%	0.559	2.038	ok	--
1.95%	0.559	2.039	ok	--
2.10%	0.559	2.042	ok	--
3.70%	0.559	2.074	ok	--
6.15%	0.545	2.123	ok	--
13.10%	0.537	2.262	Small fracture , No holiday	--
16.20%	0.525	2.324	Stress Crack, Holiday	Failed

Valspar 2000 Sample No. 3 B : PIPE NO. A09004912				
Tensile Strap (Coating Thickness 17.5 – 19.7 mils)				
% Strain	Thickness, inch	Elongation	Visual	Remarks
0.00%	0.560	2.00	ok	--
1.40%	0.558	2.028	ok	--
3.25%	0.557	2.065	ok	--
2.75%	0.555	2.055	ok	--
3.85%	0.553	2.077	ok	--
6.70%	0.545	2.134	ok	--
11.25%	0.537	2.225	ok	--
17.40%	0.530	2.348	Stress mark , No holiday	--
22.60%	0.511	2.452	Crack, Holiday	Failed

Appendix B, cont.

3M SK6233 SAMPLE 1-A PIPE NUMBER 901830-H
Tensile Strap (coating thickness 24.1 to 25.1 mils)

% Strain	Thickness, inch	Elongation	Visual	Remarks
1.55%	0.567	2.031	OK	--
3.10%	0.554	2.062	OK	--
4.65%	0.543	2.093	OK	--
9.60%	0.531	2.192	OK	--
12.80%	0.513	2.256	OK	--
16.00%	0.494	2.32	Stress mark , No holiday	--
19.20%	0.488	2.384	Stress mark , No holiday	--
21.85%	0.461	2.437	Crack	Holiday

3M SK6233 SAMPLE 1-B PIPE NUMBER 901830-H
Tensile Strap (coating thickness 24.1 to 25.1 mils)

% Strain	Thickness, inch	Elongation	Visual	Remarks
0.00%	0.569	2	OK	--
0.75%	0.562	2.015	OK	--
1.55%	0.559	2.031	OK	--
3.10%	0.551	2.062	OK	--
6.25%	0.542	2.125	OK	--
7.80%	0.538	2.156	OK	--
10.95%	0.521	2.219	Stress mark , No holiday	--
17.55%	0.49	2.351	Crack	Holiday

Appendix C1

Elongation Measurement of Bend Straps							
Sample No	Effective Strap Thickness	Radius of Mandrel Used	Start	Finish	Elongation	*Percent Elongation	Total Strain ˚/PD
R1	.574	4	.352	.378	.025	7.10%	7.67
R2	.570	4	.350	.378	.028	8.00%	7.62
R3	.570	1	.341	.4825	.141	41.34%	25.42
R4	.568	1	.349	.5040	.155	44.41%	25.35

All measurements are in inches
Strain in °/PD is calculated using the formulas found in NACE RP0394

Appendix C2

Bend Strap Evaluation							
Sample No	Coating Type	Effective Strap Thickness	Coating Thickness (Mil)	Radius of Bend	Permanent Strain ˚/PD	ε (%)	Stress/ Crack
4-1 A09003306	Valspar	.577	15	4.75	7.41	6.45	Stress
4-2 A09003306	Valspar	.570	15	4.75	7.31	6.36	Stress
4-3 A09004575	Valspar	.582	16	4.75	7.48	6.51	Stress
4-4 901830	3M	.590	18	4.75	7.59	6.60	Stress
1-1 A09804912	Valspar	.586	16	1.5	27.82	24.20	Crack
1-2 A09804912	Valspar	.577	17	1.5	27.29	23.74	Crack
1-3 A09004575	Valspar	.577	15	1.5	27.29	23.71	Crack
1-4 901830	3M	.575	19	1.5	27.17	23.64	Crack

All measurements are in inches
Strain in °/PD is calculated using the formulas found in NACE RP0394
Engineering Strain ε(%) is calculating by using the formula found in Tennessee Gas Specification PIT 5-852 dated April 30, 1984 where a relationship between Strain in °/PD is related to Engineering Strain. The formula for this is listed below;

$$\varepsilon(\%) = 0.87 \times \left({}^{\circ}\!/_{PD} \right)$$

Appendix D1

Location		Distance (ft)	Initial Diameter (in)	Diameter Change at Stress Levels				
				80%	100%	105%	110%	142%
3M SK6233 Joint BC1 901818	A	5	42.079	42.116	42.125	42.118	42.125	43.136
	B	10	42.065	42.096	42.096	42.100	42.114	43.225
	C	15	42.051	42.087	42.087	42.089	42.088	43.359
	D	20	42.107	42.135	42.135	42.135	42.140	43.136
	E	26	42.133	42.173	42.180	42.170	42.175	43.180
	F	30	42.122	42.169	42.155	42.161	42.163	44.064
3M SK6233 Joint BC2 901813	G	35	42.100	42.187	42.140	42.140	42.139	43.621
	H	40	42.068	42.111	42.112	42.112	42.112	43.507
	I	45	42.056	42.094	42.088	42.093	42.091	43.637
	J	50	42.050	42.084	42.085	42.084	42.087	43.591
	K	55	42.040	42.086	42.080	42.080	42.078	44.063
	L	61	42.047	42.083	42.080	42.082	42.080	44.318
3M SK6233 Joint BC3 901830	M	65	42.061	42.098	42.103	42.099	42.105	Rupture
	N	69	42.110	42.135	42.131	42.142	42.140	44.437
	O	75	42.087	42.122	42.122	42.125	42.131	44.437
	P	80	42.084	42.119	42.119	42.119	42.120	43.932
	Q	85	42.103	42.142	42.138	42.138	42.138	43.717
	R	90	42.088	42.137	42.125	42.125	42.133	43.724
	S	96	42.088	42.113	42.110	42.114	42.119	43.645

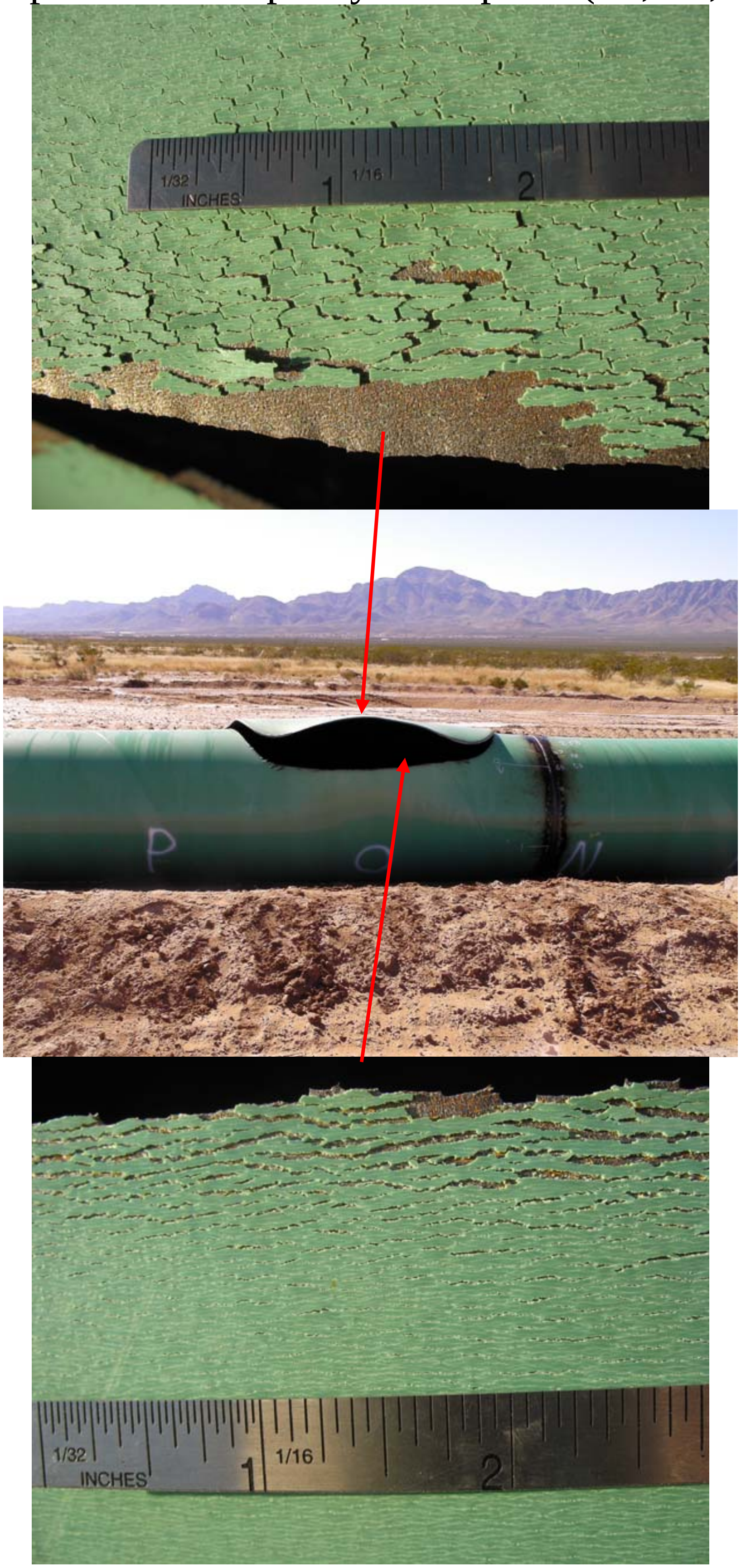
Appendix D2

Location		Distance (ft)	Initial Diameter (in)	Diameter Change at Stress Levels				
				80%	100%	105%	110%	138%
Valspar 2000 Joint P1 A09003306	A	7	42.152	42.183	42.195	42.196	42.192	42.185
	B	10	42.141	42.186	42.189	42.188	42.181	42.182
	C	15	42.157	42.213	42.211	42.188	42.189	42.190
	D	20	42.172	42.234	42.232	42.204	42.208	42.215
	E	25	42.132	42.182	42.173	42.176	42.169	42.207
	F	31	42.100	42.145	42.140	42.136	42.144	42.178
	G	35	42.051	42.066	42.065	42.078	42.085	42.270
Valspar 2000 Joint P2 A09004575	H	39	42.138	42.186	42.176	42.173	42.175	42.900
	I	45	42.120	42.165	42.161	42.165	42.170	42.628
	J	50	42.136	42.206	42.183	42.190	42.190	42.530
	K	55	42.119	42.166	42.172	42.162	42.162	42.469
	L	60	42.137	42.184	42.168	42.175	42.175	42.510
	M	66	42.097	42.134	42.145	42.139	42.134	42.759
Valspar 2000 Joint P3 A09004912	N	71	42.133	42.208	42.183	42.178	42.179	Rupture
	O	75	42.118	42.160	42.155	42.154	42.152	Rupture
	P	80	42.120	42.161	42.166	42.157	42.160	43.758
	Q	85	42.111	42.177	42.164	42.160	42.155	43.484
	R	90	42.106	42.158	42.146	42.145	42.142	43.170
	S	95	42.103	42.148	42.141	42.144	42.134	43.091
	T	101	42.112	42.154	42.181	42.150	42.150	43.222

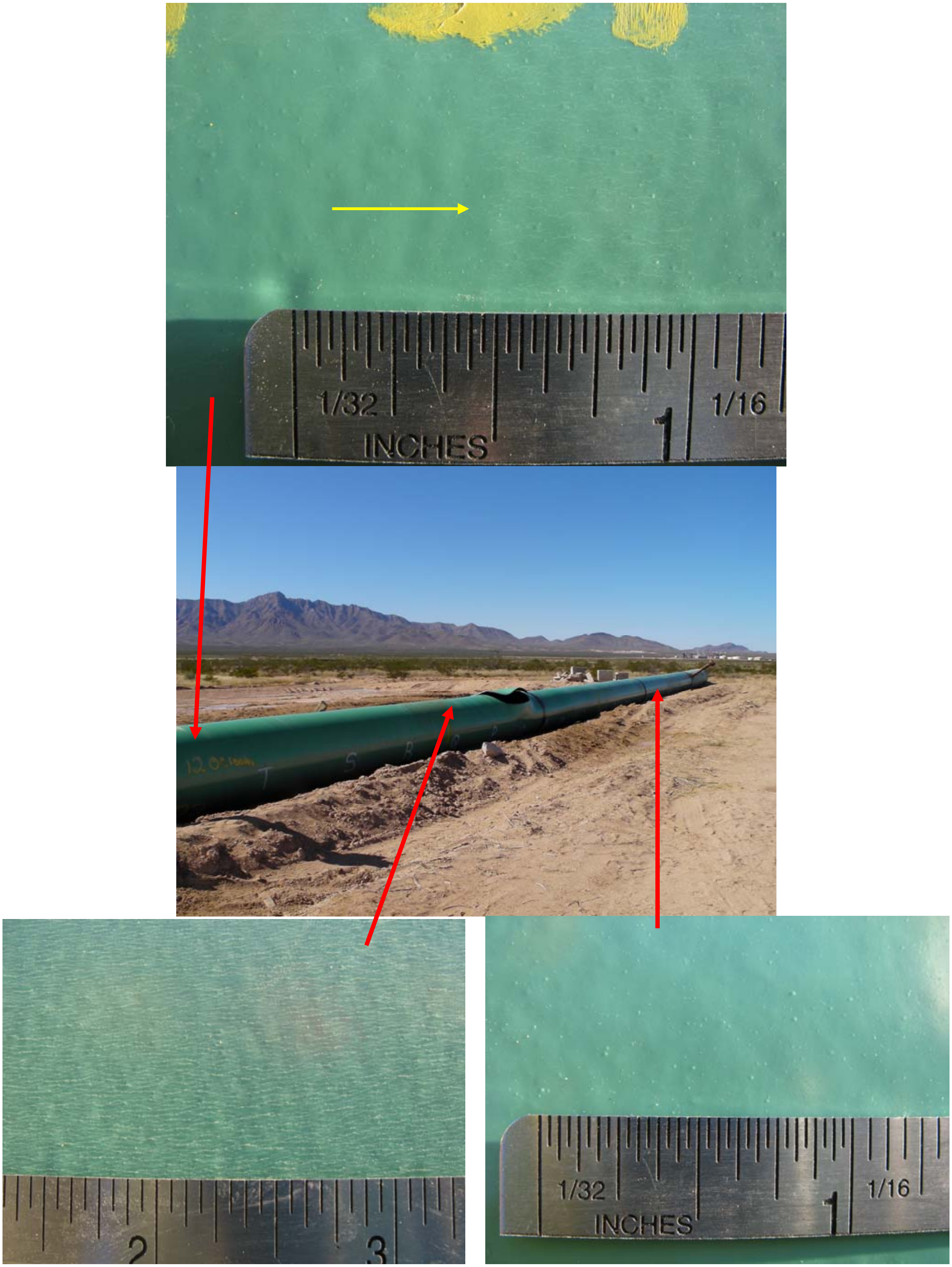
Appendix D3

Burst Test Pictures

Valspar Coated Pipe Hydro-rupture (P1, P2, P3)

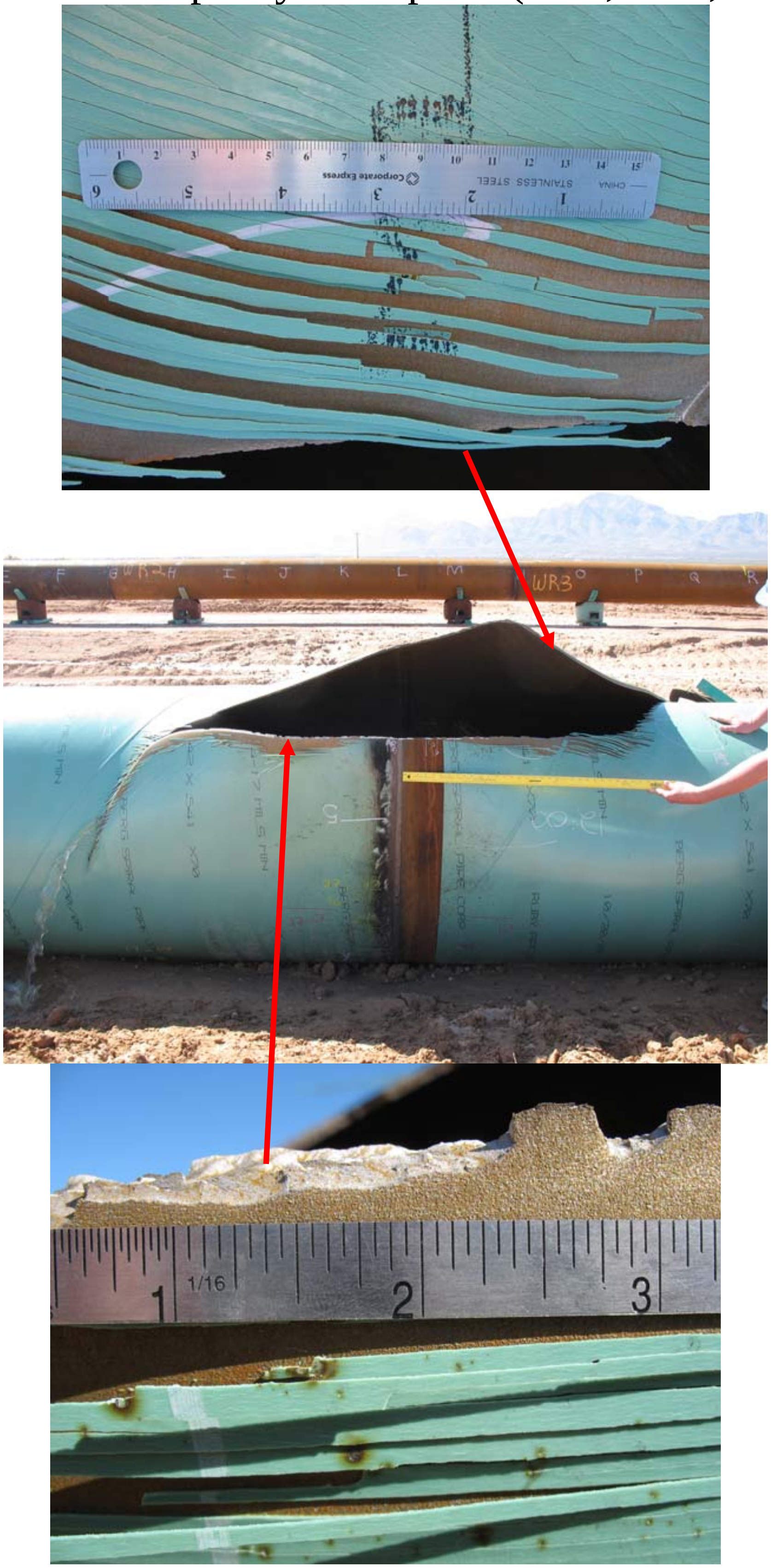


The above image of the Valspar coated pipe after hydro rupture. The red markers indicate where along the fracture site images were taken. The torn coating took on a “puzzle piece” type morphology which appeared to flow parallel to the micro-cracking on the pipe body.

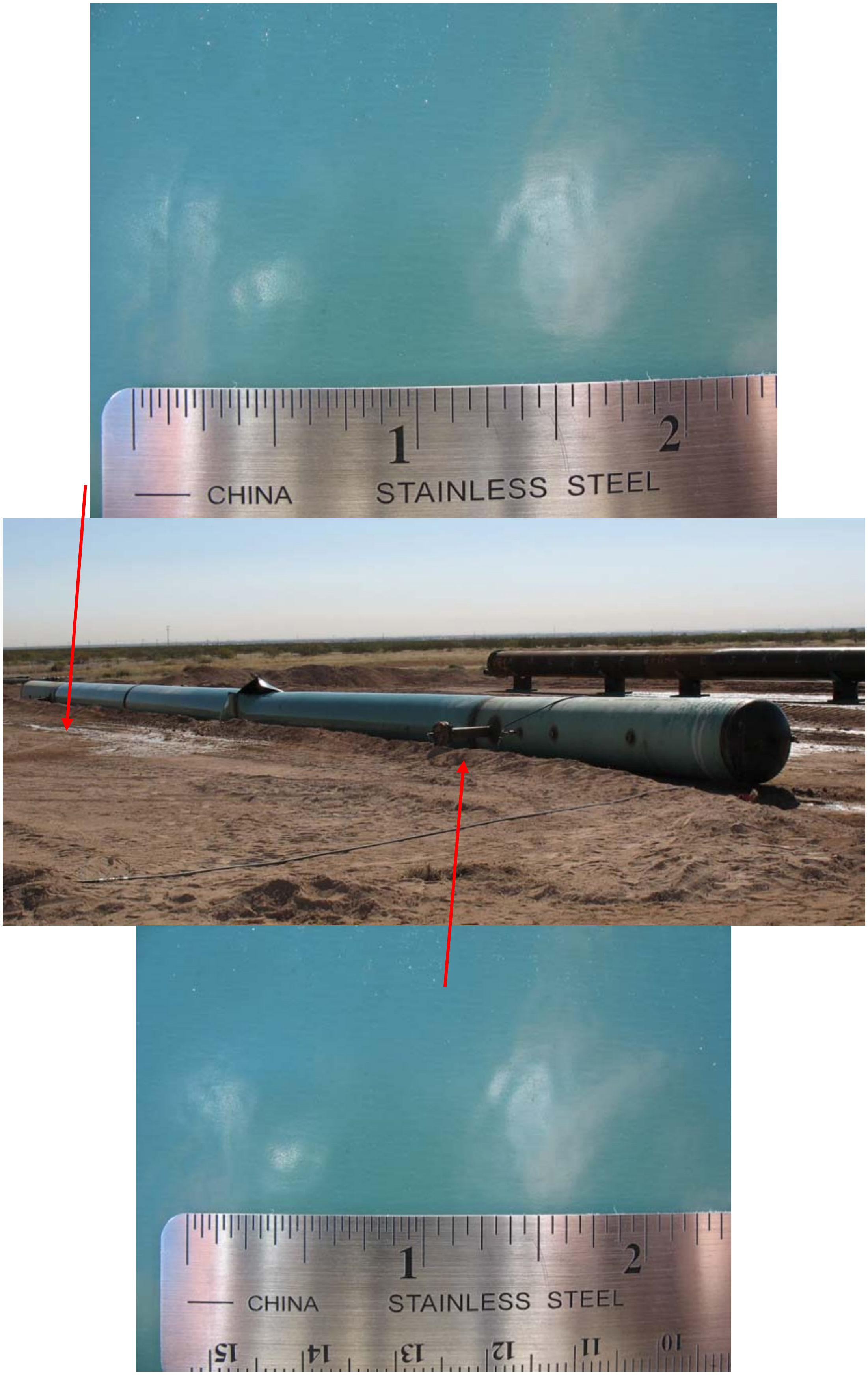


The above images of the micro-cracks observed on the coating pipe body illustrated by the red and yellow markers. The micro-cracks extended approximately 40ft. upstream and downstream of the rupture site, after which undamaged pipe coating was visually observed.

3M Coated Pipe Hydro-rupture (BC1, BC2, BC3)



The above images of 3M coated pipe adjacent to the rupture site. The red markers illustrate the location on the pipe where the images were taken. The torn coating took on a strip type morphology which ran parallel to the direction of the micro-cracks observed on the failed pipe.



The above images of the micro-cracks observed on the coated pipe body illustrated by the red markers. The 3M coated pipe displayed micro-cracks through the entire pipe body, the cracks ran axially along the pipe. Regions adjacent to the end cap girth welds did not display the observed micro-cracking due to the increase strength and thickness of the end caps.

References and Further Reading

1. Process Performance Improvement Consultants, LLC "Flexibility (Strain Limit) of Fusion Bonded Epoxy Coatings", November 22, 2009, Mark Hereth and Keith Leewis, P-PIC

1. Corinth Pipe for Spectra Energy "Evaluation of Bending Performance of High DFT Coatings"
Dated January 3, 2008
Provided by: Stephen Rapp, Spectra Energy

2. RAE Engineering and Inspection Ltd. For TransCanada "Determination of Coatings Deformation Limit in Tensile Strain"
Dated September 15, 2009
Provided by: Robert Worthingham, TransCanada

3. Explanation of Types of Strain Relevant to Data in this Paper
Provided by: David Sokol, Consulting Metallurgist

Referenced Standards

ASTM A370-09a Standard Test Methods and Definitions for Mechanical Testing of Steel Products

ASTM D6677-07 Standard Test Method for Evaluating Adhesion by Knife

El Paso Corporation UC200 Plant Applied External Fusion Bonded Epoxy Pipe Coating

NACE RP-0394 – 2002 Application, Performance, and Quality Control of Plant Applied Fusion-Bonded Epoxy External Coating – Appendix H sets out the test requirements.

NACE RP-0490-2001 Standard Recommended Practice-Holiday Detection of Fusion Bonded Epoxy External Pipeline Coatings of 25- to 760 um (10 to 30 mils)

Tennessee Gas (Tenneco Gas) Test Procedure MQ-852 Coating Bend Tests
    Dated April 30, 1984
    Background information on the Engineering Strain Calculation
    Provided by: David Sokol, Consulting Metallurgist

Tensile and Burst Testing were coordinated and conducted by ElPaso. For additional information contact Matt Dabiri, ElPaso

Bend Testing was conducted at Commercial Coating Services International Ltd. For additional information contact Neil Hruzek, CCSI