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Dent Study

FINAL REPORT

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This report is intended to serve as a technical resource for OPS and State pipeline safety inspectors evaluating operators' integrity management (IM) programs. Inspectors consider information from a number of sources in determining the adequacy of each IM program. Development of this report was funded via a Congressional appropriation specifically designated for implementation of IM oversight. This and other similar reports are separate and distinct from the work products associated with and funded via OPS's R&D Program.

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List of Acronyms

DSAW	Double submerged-arc welded
ET	Eddy-current testing
FEA	Finite-element analysis
GRI	Gas Research Institute
HF-ERW	High-frequency electric-resistance welded
ILI	In-line inspection
LF-ERW	Low-frequency electric-resistance welded
MFL	Magnetic-flux leakage
MT	Magnetic particle testing
NDE	Nondestructive examination
NPS	Nominal pipe size
PRCI	Pipeline Research Council International
PT	Penetrant testing
SCC	Stress-corrosion cracking
UT	Ultrasonic testing

Executive Summary

This report documents a study of the potential effects of dents on the integrity of both gas and liquids pipelines. The focus of this study was dents located between the 4 o'clock and 8 o'clock positions commonly referred to as "bottom-side" dents. However, several aspects of dents in general (i.e., issues germane to bottom-side dents as well as other dents) were also reviewed and, for completeness, are reported herein.

The parameter used to determine severity of a dent is usually depth. In fact, depth as a percent of diameter is the only dent geometry parameter currently mentioned in 49 CFR 192 and 195 for evaluating the disposition of dents (all dents with depths greater than 6 percent of the nominal pipe diameter must be repaired or removed).

However, depth is not always the most useful parameter for determining if a dent presents a threat to pipeline integrity. Evaluating the significance of flaws or defects from a fitness-for-purpose standpoint, which compares the severity of the flaw against the acceptance criterion for a critical state, may be more informative. Where the flaw is characterized as a deformation, the local strain in the material may be a relevant criterion for judging its severity.

A methodology for calculating strain in dents similar to that presented in ASME B31.8-2003 is presented in Section 3.2.

A potentially important phenomenon that should be considered when evaluating the integrity impact of a dent is possible pressure-cycle fatigue of the dent. This can occur when a dent is free to flex back and forth between various depths in response to fluctuations in the internal pressure of the pipeline. This subject is discussed further in Section 3.3.

A brief review of in-line inspection (ILI) technology with regards to sizing and evaluating dents was conducted and is discussed in Section 4. The most common ILI tools for sizing and evaluating dents are the latest generation of caliper, or geometry, tools. These tools have multiple mechanical fingers that travel along the inside surface of the pipeline and record the deflections of the fingers resulting in a "map" of the surface, facilitating examination of deformation magnitude, shape, and location. However, since third-party type dents that have undergone rerounding are typically on the order of 1 percent of the diameter in depth, which is at or below the threshold for reliable detection by many caliper tools, these tools may not be the best method for general detection of dents. Other ILI tools, such as magnetic-flux leakage (MFL) and ultrasonic (UT) tools commonly used to assess metal-loss, are also able to locate dents. Although these tools do not reliably size the depth of dents, they can be used to infer the length and width dimensions of some dents. Neither MFL nor UT tools will reliably detect metal-loss indications within the curvature of dents with any significant severity, however MFL and UT tools have been used successfully by pipeline operators to detect dents with gouges and bottom-side dents affected by corrosion.

Multiple nondestructive examination (NDE) methods are applicable for direct examination of dents to assess integrity. These NDE methods include: visual examination, penetrant testing (PT), magnetic particle testing (MT), shear wave UT and eddy current testing (ET).

Mitigation options discussed in Section 5.3 include: grinding to remove defects in a shallow dent, installation of a composite wrap repair, installation of a sleeve, or replacement of the pipeline section.

A recommended procedure for inspection of dents is presented in Section 5 and a review of pertinent regulations and industry standards is presented in Section 6.

Finally, a series of decision diagrams to aid in evaluating dents and determining appropriate mitigation, as required, were developed and are presented in Section 7. A number of reference documents are also listed at the end of the report.

1 Introduction

This report was developed in accordance with the Statement of Work and proposal submitted in response to RFP for Technical Task Order Number 10 (TTO 10) entitled *“Bottom-Side Dent Study”*.

Dents in pipelines are a common result of third-party damage or backfill loads over hard spots beneath the pipeline. While dents are common, failures from dents alone (i.e., dents without additional surficial mechanical damage such as scratches and gouges) are relatively uncommon. Dents with additional surficial mechanical damage are typically caused by third-party actions and result in immediate failure approximately 80 percent of the time (Rosenfeld, 2001). In the remainder of mechanical damage events, damage is not severe enough to cause immediate failure, but if the damage is not repaired it may result in failure at a later time if the internal pressure is raised sufficiently, if corrosion develops in the damaged material, or due to pressure-cycle fatigue. Pressure-cycle fatigue is caused by the dent cyclically rebounding or “rerounding” under internal pressure fluctuations (in other words, the indentation flexes in and out in response to variations in operating pressure).

On the other hand, dents without additional surficial mechanical damage or “plain dents” are not an immediate threat to pipeline integrity. They can, however, create a longer-term integrity issue due to the development of ancillary problems (e.g., coating damage, shielding from cathodic protection, corrosion, stress-corrosion cracking (SCC), hydrogen cracking, or punctures due to continued settlement). In some cases, plain dents can also fail due to pressure-cycle fatigue.

Pressure-cycle fatigue failure of dents is most common in “unrestrained” or “unconstrained” dents, i.e. those that are not prevented from rerounding under the effects of internal pressure by the soil surrounding them. Conversely, dents that are prevented from rerounding, such as dents caused by rocks in the ditch, are considered “restrained” or “constrained”. However, in cases where there are closely spaced restrained dents, the saddle-shaped area between the dents is actually unrestrained and thus may be susceptible to pressure-cycle fatigue failure even if the dents themselves are restrained (Rosenfeld, 2002(b)).

Regardless of the cause of the dent, if any restraining force is removed, such as when a rock dent is exposed and the rock removed, the dent is then unrestrained and subjected to possible fatigue damage.

Pressure-cycle fatigue failure of dents is more likely to occur in liquid lines, compared to gas lines, due to the more cyclical operating pressure spectrum.

Numerous publications, many resulting from actual tests or field observations, are available. However, a simple damage assessment criterion that accurately portrays failure potential has not been developed due to the complex nature of the problem. Nevertheless, much has been learned regarding the multitude of factors that are important when considering the appropriate response to pipeline dents.

Since dents with and without associated surficial mechanical damage are fairly common, there is a need to address the ability of pipeline operators to detect and evaluate occurrences, including bottom-side dents, in the context of integrity management.

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2 Background

Office of Pipeline Safety incident records for liquid lines from 1968 through 2003 and gas lines from 1970 through 2003 were analyzed in an attempt to quantify the number of incidents related to dents that have occurred in the United States. This review only identified seven incidents in liquid lines (out of 8,721 reported) and two incidents in gas lines (out of 24,150 reported) where specific reference to failure at a dent had occurred. There was not sufficient data to determine whether any of these were bottom-side dents, or even simply plain dents. However, one of the documents identified during a literature search indicated one of the dents on a liquid line was actually a bottom-side dent that failed due to corrosion fatigue from an area of near-neutral pH SCC (Johnston, 2002).

Further review of the incident records identified an additional seven incidents in liquid lines and one incident in a gas line where reference was made to damage due to rocks. It is a reasonable assumption that the majority of these incidents also had associated dents, and were likely bottom-side dents.

Thus, the total number of incidents suspected to be associated with dents based on this review is 14 out of 8,721 for liquid lines (<0.2%) and three out of 24,150 for gas lines (<<0.1%).

The one confirmed bottom-side dent failure resulted in an estimated release of 11,644 barrels of crude oil and resulted in approximately $12.6 million in damage. The total estimated liquid release for all 14 incidents was 17,423 barrels with approximately $14.9 million in damage.

This analysis is somewhat inconclusive since the incident data available on the OPS FOIA On-line Library for both gas and liquids lines does not report failures at dents as a separate category/cause. Some of the incidents included in the above summary were identified based on information captured in other fields. Consequently, the incidents included in the above summary may not represent all failures at dents, however, the summary does seem to reveal that failures from dents are not a significant portion of pipeline incidents.

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3 Dent Characterization and Parameters Affecting Pipeline Integrity

3.1 Scope Statement

“Discuss the various mechanisms whereby dents might affect pipeline integrity and evaluate the more relevant of the numerous parameters that would be utilized to assess an existing dent. Discuss efforts that have been undertaken to predict failure of dents.”

Assuming that a dent survives the initiating force, failure may occur at a later time due to:

- damage to the coating, allowing localized corrosion resulting in a stress concentration.
- mechanical damage to the pipeline itself, resulting in a stress concentration.
- fatigue due to fluctuations in pressure.

The ability of an ILI tool to detect metal-loss indications within the curvature of a dent is dependent on the sensor suspension system. This is discussed further in Section 4. Pressure-cycle fatigue is discussed further below.

While depth of a dent, its location, and the presence of metal loss are the parameters for assessment in 49 CFR 192 and 195, the latest version of ASME B31.8 has introduced the concept of assessing dents based on strain. These issues are discussed in the following sections.

3.2 Discussion on Strain in Dents

The parameter typically used to determine severity of a dent is depth. In fact, depth as a percent of diameter is the only dent geometry parameter currently mentioned in 49 CFR 192 and 195 for evaluating the disposition of dents (all dents with depths greater than 6 percent of the nominal pipe diameter must be repaired or removed).

However, depth is not always the most useful parameter for determining if a dent presents a threat to pipeline integrity. Evaluating the significance of flaws or defects from a fitness-for-purpose standpoint, which compares the severity of the flaw against an acceptance criterion for a critical state, can be more informative. Where the flaw is characterized as deformation, the local strain in the material may be a relevant criterion for judging its severity.

3.2.1 ASME B31.8 Strain Criterion

The latest version of ASME B31.8 (2003) acknowledges this concept and provides strain acceptance criterion, as well as a method for estimating the strain in dents. This estimation procedure and justification for the strain acceptance criterion are discussed below.

The strain in a thin plate bent to a radius *R*, is given by the equation $\varepsilon = {}^{t}\!/_{R}$, where *t* is the thickness of the plate. Line pipe is proof tested during the manufacturing process, which redistributes and relieves some residual forming stresses. Therefore, this equation must be modified to correctly estimate the strain due to denting in a manner that reflects the strain in the pipe wall in the circumferential direction as zero if perfectly round. This modified equation takes the form of:

$$\varepsilon_1 = t\left(\frac{1}{R_0} - \frac{1}{R_1}\right)$$ **Equation 3.1**

where:

R_0 is the original outside radius of the pipe,

R_1 is the indented radius of the outside surface of the pipe, and

t is the wall thickness.

Radii are positive if measured from the direction of the center of the pipe, that is, radius R_1 would be positive if the denting only results in "flattening" of the pipe. The radius would be negative if, in fact, the dent is actually reentrant (i.e., the curvature of the pipe has been reversed). This is shown graphically in Figure 3.1.

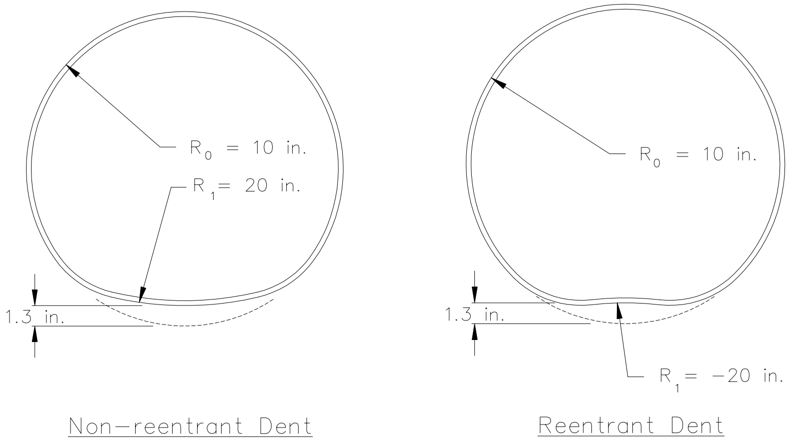

Figure 3.1 Non-reentrant Versus Reentrant Dents

The calculation of strain in the longitudinal direction is essentially the same as for a flat plate; however, to be consistent with the sign convention defined for the circumferential direction (both strain and radii), the formula takes the appearance:

$$\varepsilon_2 = -\frac{t}{R_2}$$ **Equation 3.2**

where:

R_2 is the radius of curvature of the outside surface of the pipe in a longitudinal plane through the dent. Based on the sign convention discussed above, this value is generally always a negative number.

There is an additional strain to consider in the longitudinal direction, extensional strain, which is the strain due to the actual elongation of the material through the dent and is calculated using the formula:

$$\varepsilon_3 = \frac{1}{2}\left(\frac{d}{L}\right)^2$$ **Equation 3.3**

where:

d is the depth of the dent, and

L is the length of the dent.

The above formula is an empirical estimate that was benchmarked against a limited number of finite element analyses.

Once these values are calculated, the resultant strains on the inside and outside pipe surfaces are computed as:

$$\varepsilon_i = \sqrt{\varepsilon_1{}^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2}$$ (inside surface) **Equation 3.4**

and

$$\varepsilon_o = \sqrt{\varepsilon_1{}^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2}$$ (outside surface) **Equation 3.5**

3.2.2 Discussion of ASME Criteria

The equations given in ASME B31.8, and shown here as equations 3.1 through 3.3, develop the component strains in the circumferential and longitudinal directions. The through-thickness strain is assumed zero. Equations 3.4 and 3.5 serve the function of reducing the components developed to a scalar. Reduction to a scalar allows the criteria to be consistently evaluated and applied to any combination of the component strains.

The methodology is the same as used to develop a scalar stress value for criteria for pipe stress evaluation. There are two generally accepted empirical criteria for prediction of yielding of ductile metals: maximum-shearing-stress theory (Tresca theory), and the maximum-distortion-energy theory (von Mises theory). These are both used in pipeline regulations as well as in pipe stress analytical software packages.

The **Effective Stress** calculated using the von Mises Theory (sometimes erroneously referred to as the "von Mises stress") is:

$$\sigma_{effective} = \left(\frac{1}{\sqrt{2}}\right)\cdot\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

For a plane stress state, $\sigma_3 = 0$, therefore substituting this into the above equation:

$$\sigma_{effective} = \left(\frac{1}{\sqrt{2}}\right)\cdot\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - 0)^2 + (0 - \sigma_1)^2} \quad \Rightarrow \quad \sigma_{effective} = \left(\frac{1}{\sqrt{2}}\right)\cdot\sqrt{(\sigma_1 - \sigma_2)^2 + \sigma_2{}^2 + \sigma_1{}^2}$$

Expanding terms:

$$\sigma_{effective} = \left(\frac{1}{\sqrt{2}}\right) \cdot \sqrt{\sigma_1{}^2 - 2\sigma_1\sigma_2 + \sigma_2{}^2 + \sigma_2{}^2 + \sigma_1{}^2}$$

And gathering like terms:

$$\sigma_{effective} = \left(\frac{1}{\sqrt{2}}\right) \cdot \sqrt{2 \cdot \left(\sigma_1{}^2 - \sigma_1\sigma_2 + \sigma_2{}^2\right)} \quad \Rightarrow \quad \sigma_{effective} = \sqrt{\sigma_1{}^2 - \sigma_1\sigma_2 + \sigma_2{}^2}$$

The "effective stress" is a uniaxial stress that produces the same octahedral shear stress as the actual principal stresses.

Similarly, **Effective Strain,** as defined in a description for a course on *Plastic Deformation at Large Strain, High-Strain Rate, High Temperature* given at the University of Minnesota, is:

$$e_{effective} = \left(\frac{\sqrt{2}}{3}\right) \cdot \sqrt{(e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2}$$

Where e_1, e_2, and e_3 are the strains in the principal directions. For the pipe problem, we will take the circumferential and longitudinal directions as the principal directions. The through-wall strain is assumed zero. Thus, for the inside surface:

$e_1 = \varepsilon_1$ (from Equation 3.1)
$e_2 = \varepsilon_2 + \varepsilon_3$ (from Equations 3.2 and 3.3)
$e_3 = 0$

Substituting this in the above:

$$e_{effective} = \left(\frac{\sqrt{2}}{3}\right) \cdot \sqrt{[\varepsilon_1 - (\varepsilon_2 + \varepsilon_3)]^2 + [(\varepsilon_2 + \varepsilon_3) - 0]^2 + (0 - \varepsilon_1)^2}$$

Expanding terms:

$$e_{effective} = \left(\frac{\sqrt{2}}{3}\right) \cdot \sqrt{\varepsilon_1{}^2 - 2\varepsilon_1(\varepsilon_2 + \varepsilon_3)^2 + (\varepsilon_2 + \varepsilon_3)^2 + (\varepsilon_2 + \varepsilon_3)^2 + \varepsilon_1{}^2}$$

Collecting like terms:

$$e_{effective} = \left(\frac{\sqrt{2}}{3}\right) \cdot \sqrt{2\varepsilon_1{}^2 - 2\varepsilon_1(\varepsilon_2 + \varepsilon_3)^2 + 2(\varepsilon_2 + \varepsilon_3)^2} \quad \Rightarrow$$

$$e_{effective} = \left(\frac{\sqrt{2}}{3}\right) \cdot \sqrt{2\left(\varepsilon_1{}^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3)^2 + (\varepsilon_2 + \varepsilon_3)^2\right)} \quad \Rightarrow$$

$$e_{effective} = \left(\frac{2}{3}\right) \cdot \sqrt{\varepsilon_1{}^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3)^2 + (\varepsilon_2 + \varepsilon_3)^2}$$

This last equation can be seen to be Equation 3.4 preceded by a constant.

For the outside surface, the same process is used but with:

$e_1 = -\varepsilon_1$ (from Equation 3.1)

$e_2 = -\varepsilon_2 + \varepsilon_3$ (from Equation 3.2 and 3.3)

$e_3 = 0$

Thus, Equations 3.4 and 3.5 are analogous to the stress-based von Mises Theory. While the normal formulation of the theory is for determining the effective **stress** in a body subjected to biaxial or triaxial loading such as a pipeline, the empirical formulae given by Equations 3.4 and 3.5 are strain based. They form the same function of reducing a multiaxial-state to a reference scalar in a consistent formulation.

3.2.3 Example

The following example shows both the applications of Equations 3.1 through 3.5, as well as illustrates that strain is sometimes a better indicator of dent severity than depth alone. The example is of a pipeline with a diameter of 20 inches and a wall thickness of 0.312 inches. Results produced by application of Equation 3.1 for a series of values for R_1 ranging from 10 inches to –2 inches is shown in Figure 3.2. Note that the initial value of R_1 is equal to the value of R_0 in this example, and the calculation results in a zero strain value, which is expected based on the premise that line pipe is essentially strain relieved subsequent to the manufacturing process. As the shape of the dent proceeds from just a slight flattening of the pipe to essentially a flat spot, the radius R_1 increases from the original outside radius to essentially infinite radius (zero curvature). Once the dent becomes reentrant, the radius R_1 becomes negative and increases until it approaches zero, such as at a crease, and the strain values become very large. If the strain capacity of the material is exceeded, tearing of the metal will occur and the pipeline will fail. The concept of change in sign of R_1 as the dent goes from non-reentrant to reentrant is illustrated in Figure 3.1. A further illustration is provided in Figure 3.3. While all the dents depicted have the same depth, as the dent becomes, what is intuitively, more severe, the curvatures increase and the absolute value of the radii decrease. Increased strains would be associated with the more acute dent forms.

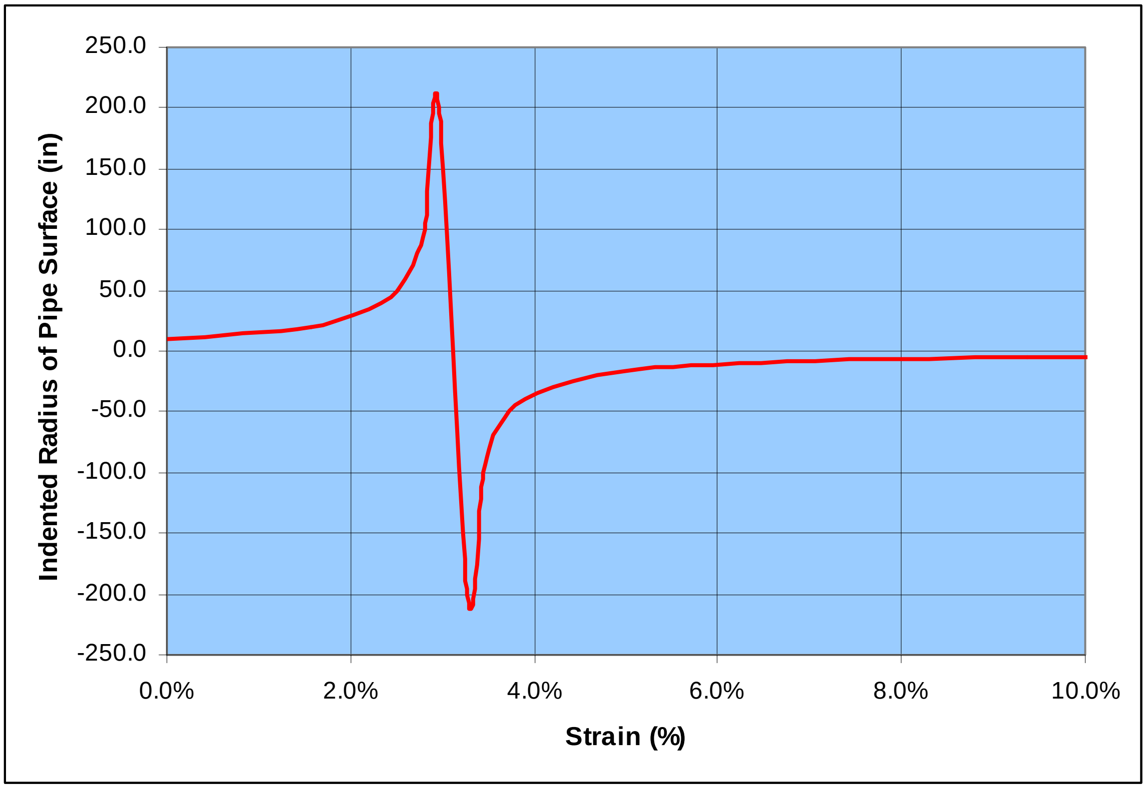

Figure 3.2 Results from Equation 3.1 for Various Values of R_1

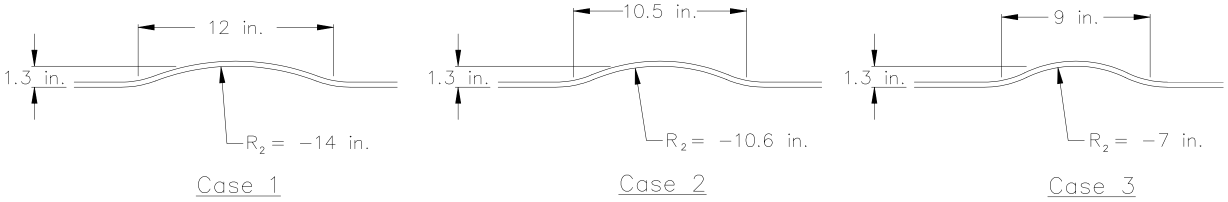

Figure 3.3 Example Dent Profiles

Strain calculations were completed for a 1.3-inch-deep reentrant dent, as shown on the right side of Figure 3.1, for each case of longitudinal length and curvatures depicted in Figure 3.3. The basic parameters for input into the various strain equations are given in Table 3.1. Calculation results for Equations 3.1 through 3.5 are presented in Table 3.2.

Table 3.1 Dent Parameters

Parameter	Case 1	Case 2	Case 3
Depth, d (inches)	1.3	1.3	1.3
Length, L (inches)	12	10.5	9
Pipe radius, R_0 (inches)	10	10	10
Dent radius, R_1 (inches)	-20	-20	-20
Dent radius, R_2 (inches)	-14	-10.6	-7

Table 3.2 Strain Calculation Results

Equation	Case 1		Case 2		Case 3	
	in/in	%	in/in	%	in/in	%
3.1	0.0468	4.68%	0.0468	4.68%	0.0468	4.68%
3.2	0.0223	2.23%	0.0294	2.94%	0.0446	4.46%
3.3	0.0059	0.59%	0.0077	0.77%	0.0104	1.04%
3.4	0.0546	5.46%	0.0596	5.96%	0.0721	7.21%
3.5	0.0495	4.95%	0.0515	5.15%	0.0577	5.77%

Once strains have been calculated, they must be compared to a strain criterion. The latest version of ASME B31.8 establishes the allowable strain in dents at 6 percent. This value is based, in part, on the fact that both ASME B31.4 and B31.8 allow up to approximately 3 percent strain to be induced in the pipe wall during field bending (calculated as the change in pipe length along the intrados or extrados of the bend divided by the original unbent length, or D/2R where R is the average radius of the bend at the neutral axis, see Table 3.3). In addition, it has been observed that the likelihood of cracks in deformation seems to increase where material strain exceeds approximately 12 percent (Rosenfeld, 2001). Therefore, 6 percent was chosen as an appropriate strain criterion.

Table 3.3 Allowable Strains in Field Bends

Diameter (in)	Deflection of Longitudinal Axis (deg)	Minimum Bend Radius	Radius at Neutral Axis (in)	Arc Length of Neutral Axis (in)	Radius at Extrados (in)	Arc Length of Extrados (in)	Resulting Strain (percent)
12.75	3.2	18D	229.5	12.82	235.875	13.17	2.8%
14	2.7	21D	294	13.85	301	14.18	2.4%
16	2.4	24D	384	16.08	392	16.42	2.1%
18	2.1	27D	486	17.81	495	18.14	1.9%
20	1.9	30D	600	19.90	610	20.23	1.7%

Review of the calculation results for Equations 3.4 and 3.5 show that even though the depth of the dent exceeds six percent of the outside diameter of the pipe ($0.06 \times 20 = 1.2$ inches) for this example, the strain may or may not exceed the 6 percent criteria, depending upon the actual measured radius of curvature of the pipe wall. The results are consistent with what normal judgment would indicate, that is, a dent relatively deep for its length is worse in terms of the strains associated with deformation than one with the same depth spread out over a greater length and width of pipe surface.

3.3 Pressure-Cycle Fatigue

As discussed in Section 1, a restrained dent is one that is constrained by some physical means and cannot rebound to its original contour. Unrestrained dents, such as those caused by a blunt impact, will normally rebound nearly completely due to the internal pressure of the pipeline once the impacting force is removed.

The main concern with unrestrained plain dents is pressure-cycle fatigue. This is a result of high local bending stresses associated with the dent fluctuating with operating pressure cycles (i.e., as the internal pressure increases, the dent tends to flatten, which is also known as rerounding, and as the pressure decreases, the dent tries to resume its initial geometry. Much research has been completed on demonstrating or predicting the pressure-fatigue characteristics of dents (Rosenfeld, 2001).

The fatigue performance of dents is affected by several factors. For unrestrained dents, fatigue life has been shown in analytical models to:

- decrease with increasing initial depth (Alexander, 1997),
- decrease with increasing pressure cycle range (Alexander, 1997),
- increase with mean pressure level,
- decrease with increasing initial local strain (Kiefner, 1999),
- decrease with increasing dent width-to-depth ratio (Rosenfeld, 1997),
- decrease with increasing pipe D/t ratio (Fowler, 1993), and
- decrease with increasing SMYS (Fowler, 1993).

This last effect is due to the dent in low-SMYS material being more likely to reround plastically to a shallower residual depth than would a similar dent in a high-SMYS material of the same thickness, and thus undergo smaller elastic fluctuations from pressure cycles, leading to a longer life compared to the deeper residual depth (Rosenfeld, 2001)[1].

Tests have shown that plain dents having residual depths of 2 percent or less of the pipe diameter exhibited fatigue lives between 10^5 and 10^6 cycles of pressure producing hoop stress levels between 36 and 72 percent of SMYS (Rosenfeld, 2001). Due to the low number of pressure cycles typically experienced by gas pipelines, this is likely equivalent to an indefinite life for most gas pipelines (regardless, this does not alleviate the need for gas operators to address the requirements of 49 CFR 192.917 (e)(2)). However, as some liquid pipelines operate with pressure spectra several orders of magnitude more aggressive than most gas pipelines, pressure-cycle fatigue of dents is a valid concern.

Given the same size and shape, restrained dents typically have at least an order of magnitude greater fatigue life than unrestrained dents. In one series of tests, restrained dents up to 18 percent of the pipeline diameter survived hundreds of thousands of pressure cycles between 36 and 72 percent of SMYS without failure (Alexander, 1997). In additional studies conducted by the Texas Transportation Institute in cooperation with OPS, the fatigue lives of restrained versus unrestrained dents were compared as part of a larger project evaluating the fatigue behavior of dents (Texas Transportation Institute 1997). A comparison of the fatigue lives of restrained versus unrestrained dents determined in the Texas study is presented in Figure 3.4. Based on these results, there is justification for not excavating rock dents, at least on pipelines that are susceptible to pressure cycle fatigue, even though not excavating them will necessitate addressing long-term corrosion control and monitoring issues mentioned in Section 1.

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[1] This notion is based on theoretical considerations that may be outweighed by other important advantages associated with higher-strength pipe, such as improved toughness. It is not intended to suggest that low-strength pipe is categorically superior to high-strength pipe in resisting mechanical damage.

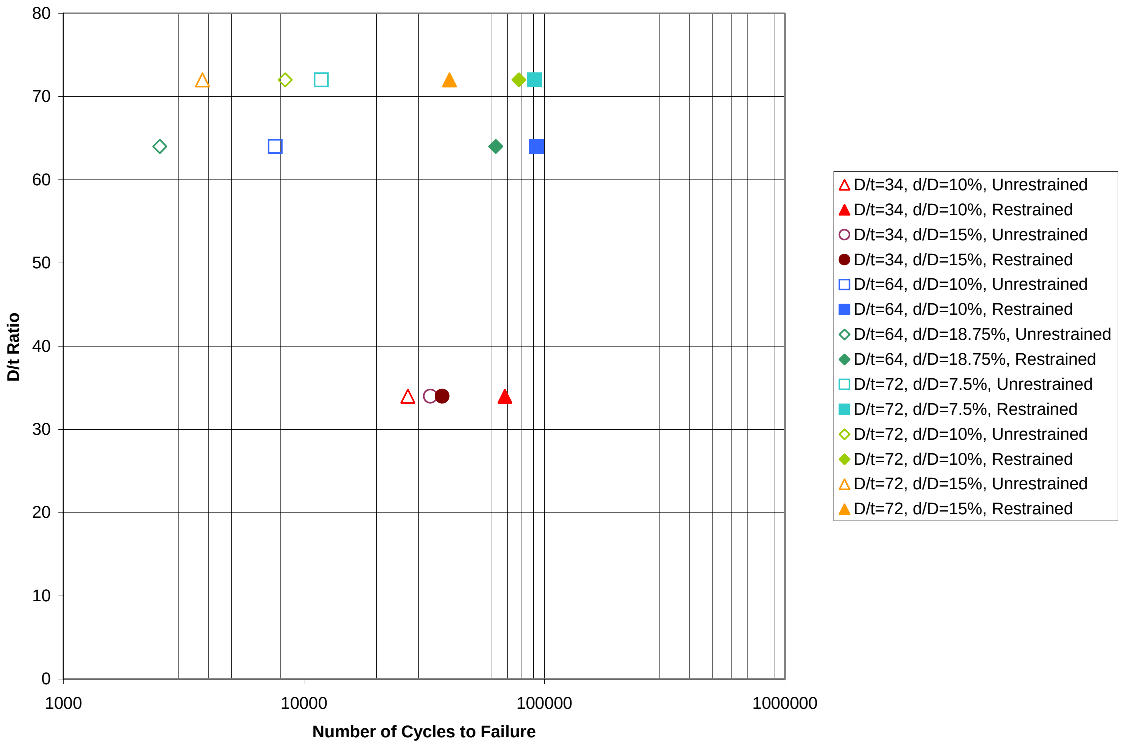

Figure 3.4 Comparison of Fatigue Lives for Restrained versus Unrestrained Dents

An important exception(also mentioned in Section 1) is if there are two closely spaced (less than or equal to one pipe diameter) restrained dents with a flattened or saddle-shaped area between them. The flattened area between the dent centers may be susceptible to pressure-cycle fatigue since it can be effectively unrestrained and thus flexes in response to pressure cycles. In this situation, further investigation is warranted. If this is confirmed in the field, the best response would be to install a full-encirclement sleeve around the feature. The concern for this condition is much greater for liquid pipelines due to their more severe pressure-cycling characteristics. However, one failure in a gas pipeline in 2002 is thought to have been caused by SCC in the saddle area between two dents.

The study of pressure cycle fatigue is a topic of ongoing work effort.

3.4 Dents on Welds

Tests conducted by Battelle and British Gas indicate that burst strength could be adversely affected by dents on seams of low-frequency electric-resistance welded (LF-ERW) line pipe and double submerged arc-welded (DSAW) line pipe, and that fatigue life is also adversely affected (Rosenfeld, 2001). Later testing indicates that fatigue life for dents in seams of high-frequency electric-resistance welded (HF-ERW) line pipe is nearly as good as in the body of the pipe (Alexander, 1997).

Additional testing demonstrated that dents affecting girth welds, ERW seams, and DSAW seams all have similar fatigue performance; as a group they tend to fail in about a half-order of magnitude fewer cycles as compared to plain dents in the body of the pipe (Kiefner, 1999).

These results are for pipelines having sound, ductile welds, and therefore are not representative of LF-ERW, electric-flash welded, lap-welded or other seam types that may be susceptible to brittle fracture. Girth welds were assumed to meet the minimum requirements of API Std 1104, or at least be generally sound electric welds. No tests of dents on oxy-acetylene welds have been described in the literature.

For the reasons discussed above, the recommended strain limits are reduced in welds. ASME B31.8 recommends an upper limit on strain of 4% for dents affecting ductile welds. ASME B31.8 further indicates that dents affecting non-ductile welds (e.g., oxy-acetylene welds) are not allowed and must be repaired.

3.5 Prediction of Failure at a Dent

In the US, extensive research has focused on issues related to remaining strength and service life of damaged pipelines. The goal of this work has been to develop inspection, maintenance, and monitoring criteria. On the other hand, the majority of research conducted in Europe has focused on the parameters of ultimate damage resistance (e.g., the force required to puncture the pipe) with the main goal of developing damage-resistance criteria for design of new pipelines, or for specifying size limits on equipment operating near pipelines.

In excess of four hundred tests related to dents, gouges, puncture, rerounding, burst, and fatigue have been performed on pipe samples with various diameters, wall thicknesses, and materials. However, even with this amount of information, clear understanding of the underlying damage mechanisms and development of accurate predictive models has not been completely achieved.

A number of studies on plain dents using finite element analysis (FEA) have been conducted. The main issue with FEA is that the model must account for both material and geometric nonlinearities. Accurate modeling of material nonlinearities hinges on the stress-strain relationship of the material, which is most certainly altered by the denting and rerounding process. Another issue is the difficulty in establishing a suitable failure criterion for use in evaluating the FEA results.

Nevertheless, these tests and studies provide a basis to support empirical guidelines that can be used by operators until better understanding of the dent behavior is available. A list of references and other pertinent documents is given in Section 8.

4 ILI Technology for Sizing and Evaluating Dents

4.1 Scope Statement

“Evaluate the reliability of current ILI technology for locating and characterizing dents. Discuss potential benefits of comparing subsequent ILI tool runs, and evaluate the potential benefits of comparing data from different types of ILI tools.”

4.2 Using MFL Tool Data to Evaluate Deformations

MFL tools have been run in pipelines for the last thirty years to reliably detect metal loss anomalies. Although the primary purpose of these tools is to detect and quantify metal loss, they also respond to deformation anomalies and may be used to locate the deformations and to assess their characteristics. MFL tools do not directly measure the reduction in pipe diameter due to the deformation, but do respond to any sharp portions of the deformation by the sensors “lifting off” the inside pipe surface. This creates a magnetic field change, thus causing a signal response. The sensitivity to deformation detection is somewhat based on the type of sensor assembly, the size of the sensors, and the type of sensors. MFL tools may not produce a signal response due to deformations that are almost all ovality or pipe that is gradually egged with no sharp contour changes. Deformations that are composed of only ovality are rarely integrity concerns. Deformations with sharp contour changes (those that may contain potential integrity issues) can be reliably detected by an MFL tool. The proper analysis of the MFL raw data is the key to gaining information about the deformation anomalies. The longitudinal length may be determined by measuring the length of pipe where there was sensor disturbance. The circumferential width may be determined by the number of channels or sensors affected. In many cases, there is a relationship between the depth of a symmetrical deformation and the circumferential width.

Deformations that cause significant sensor disturbance should be further assessed. The assessment may consist of further MFL data scrutiny to determine the area affected and whether there are any indications of metal loss within or adjacent to the deformation. Deformations that are sharp or that have more than one peak will cause a significant sensor disturbance on the MFL data. Deformations with more than one peak have been found to be susceptible to cracking on some pipeline systems.

Metal loss creates a different change in the magnetic flux field and thus different signals than deformation “lift off.” Deformations that contain metal loss may be distinguished due to their combined (metal loss and deformation lift-off) signals from deformations that do not contain metal loss (these will only have lift-off signals). Deformations that have a small radius of curvature and thus a steep slope may cause significant lift-off of the MFL sensors such that the ability to detect metal loss is reduced or overcome. Deformation with a small radius of curvature would cause a significant signal response, and therefore, should be recommended for evaluation or correlation with a geometry tool inspection.

If the tool vendors are expected to identify deformation with a small radius of curvature, the MFL ILI specifications should specify that the ILI vendor report deformations with significant signal response and deformations with metal loss during the MFL analysis. The analysis of deformations should be reviewed by the operator’s integrity management staff to verify that the ILI vendor properly interpreted deformation anomalies.

4.3 Using UT Tool Data to Evaluate Deformations

The detection and extent of deformation anomalies may be obtained by careful analysis of the signals recorded by UT tools. The circumferential and longitudinal extent of deformation anomalies may be obtained. As a UT transducer passes over a deformation, any sharp contour changes will cause a change in the UT transducer angle such that the sound waves do not return to the transducer and a loss of signal is recorded. The loss of signal patterns can be interpreted to provide information about the characteristic's deformation anomalies. Deformations that do not contain a small radius of curvature or steep slopes may only cause an increase in the stand-off distance (the distance from the ultrasonic transducer and the inside pipe surface). Ultrasonic data may be used to approximate the magnitude of deformation anomalies based on the arc-degrees circumferentially affected on the pipe that cause a loss of signal. Physical measurements obtained from sample excavations are correlated with the ultrasonic data to validate the process.

The ultrasonic data may be correlated with a multi-channel deformation tool to demonstrate that the process is valid and that the predicted deformation magnitudes and patterns were consistent. One drawback to the use of ultrasonic wall measurement tools for deformation analysis is that on those deformations that cause a loss of signal, wall thickness measurements are not recorded for the portion of the deformation where the transducers experienced loss of signal. On those deformations where an increase in the stand-off distance is experienced, wall thickness measurements will still be recorded, and an analysis for metal loss may be obtained.

4.4 Using Geometry Tools to Evaluate Deformations

Multiple geometry tool configurations are available from ILI vendors that can provide various levels of detail. They can generally be grouped into two categories: single-channel tools and multi-channel tools. Modern geometry tools are reliable for locating and characterizing deformation anomalies. A multi-channel geometry tool is recommended for detailed analysis. A metal-loss tool or direct examination is required to determine if metal loss is associated with the deformation anomaly.

Single-channel tools that only give distance traveled and the minimum pipeline diameter are useful on new construction projects or on line segments that have never been pigged. These tools offer simple operation, low inspection cost, the ability to pass large reductions, and rapid analysis of the geometrical data. The drawbacks to the use of these tools are numerous. They offer limited information, no orientation of the deformation on the pipeline, no way to discern the circumferential extent of the deformation, and reduced ability to perform strain or stress calculations from the results.

Multi-channel tools provide additional data such as orientation, width of the deformation, and the ability to make longitudinal and circumferential strain calculations based on the rate of change in each geometry sensor. Design and spacing of the sensing fingers or paddles determines the circumferential resolution of a caliper tool. Conventional resolution calipers were typically designed with the same number of fingers as the nominal pipe size (NPS), such as 12 fingers or 20 fingers for NPS 12 or 20 pipelines, respectively. The spacing between the sensing fingers is approximately pi or 3.14 inches when the number of sensors equals the NPS. Later, higher resolution caliper tools were designed with spacing as small as approximately ¾ inch. Caliper tools have been designed with narrow (rod-like) fingers or paddles, with a tip contour matching the inside surface. Radius-tipped paddles provide more coverage of the inside surface than narrow fingers, but the radius tips tend to average the width of the deformation. Conversely, narrow fingers may provide greater resolution of the contour, but do not record deformation that passes between adjacent fingers.

Linear resolution of deformation contour is related to the sampling rate. Sampling rate may be determined by lapsed time or travel distance. When the sampling rate is determined by lapsed time, the resolution can be affected by variations in velocity as the tool traverses the pipeline. When the sampling rate is determined by travel distance (as determined by the odometer), rapid acceleration or deceleration can cause odometer slippage and introduce errors in resolutions. Linear sampling at intervals of 0.25 inch and less can be characterized as high linear resolution, while sampling at intervals of 1 inch and greater can be characterized as low linear resolution.

Deformation anomalies are normally made up of a sharp portion that is normally referred to as the dent and an egged portion on the periphery of the dent that is normally referred to as ovality. In some cases, the pipeline may not contain a dent and the reduction in pipe diameter is attributable solely to ovality. Ovaled pipe normally is not an integrity concern as long as the diameter reduction will not affect the operation of the pipeline or the running of ILI tools.

4.5 Potential Benefits of Comparing Data from Different Types of ILI Tools

Metal-loss tools may be used to determine the existence of deformation anomalies (particularly those that are prone to integrity issues). The metal-loss tools will provide the approximate size of the deformation. The approximate seriousness of the deformation can be inferred by the extent that the metal-loss tool reacts while traveling over the deformation. To conservatively use a metal-loss tool as the sole deformation inspection tool may result in the excavation of deformations that would not otherwise require excavation. Additional information such as deformation depths and the ability to calculate strains may be obtained by running a geometry tool. None of the available geometry tools can identify external metal loss. Consequently, determining if metal loss is present requires excavation for direct examination or running a metal loss tool. A potential benefit of combining a metal-loss tool with a geometry survey may be the ability to cost effectively screen deformations based on magnitude, strain, and metal- oss. The correlation of the metal-loss tool with the geometry tool could lead to improved selection of deformation for excavation and potentially fewer deformations that require remediation.

4.6 Potential Benefits of Comparing Subsequent ILI Tool Runs

One potential benefit of comparing subsequent tool runs is that changes in deformation magnitudes or profiles may be discovered and deformations may be evaluated to determine if they have suffered metal loss since the previous inspection. Another potential benefit would be to detect deformation anomalies that were not present on the previous inspection and therefore have developed since the previous inspection. A comparison of the tool data is recommended to fully compare tool runs, as opposed to simply a comparison of report spreadsheets, in case anomalies are inadvertently missed on one of the inspections.

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5 Field Inspection and Mitigation

5.1 Scope Statement

“Evaluate the various methods for inspection and mitigation of dents. Develop a recommended procedure for inspection of dents for the purpose of determining whether mitigation is required.”

5.2 Inspection Methods

There are several techniques for performing NDE of pipelines. The following sections discuss the NDE methods most applicable for inspection of dents.

5.2.1 Visual Examination

Visual inspection is the oldest and most common form of NDE. Visual inspection is a quick and economical method for detecting and sizing flaws that are visible on the pipeline’s exterior surface. The reliability of visual inspection depends upon the training and experience of the inspector, as well as the inspection protocol and acceptance criteria. The inspector must be trained to identify critical flaws and compare them with the acceptance criteria.

The main disadvantage of visual inspection is that the surface to be inspected must be relatively clean and accessible to the unaided eye. Surface preparation can range from wiping with a cloth to blast cleaning and treating with chemicals to reveal the surface condition. Typically, visual inspection lacks the sensitivity of other surface NDE methods.

5.2.2 Penetrant Testing

Penetrant testing (PT) is one of the most widely used NDE methods and is used to reveal surface breaking flaws by bleedout of a colored or fluorescent dye from flaws. Widespread use of PT can be attributed to two main factors, which are its relative ease of use and its flexibility.

The technique is based on the ability of a liquid to be drawn into a "clean" surface breaking flaw by capillary action. After a period of time, called the "dwell," excess surface penetrant is removed and a developer applied. The developer acts as a "blotter" to draw the penetrant from the flaw to reveal its presence. Colored (contrasting) penetrants require illumination with adequate white light, while fluorescent penetrants must be used in darkened conditions and illuminated with an ultraviolet "black light."

It is essential that the component is carefully cleaned first, otherwise the penetrant will not be drawn into the defect. If surface penetrant is not fully removed before application of the developer, misleading indications will result.

PT is used to inspect for flaws that break the surface of the material being examined such as fatigue cracks that may develop within a dent. It is capable of detecting surface breaking flaws that would not be observed by the unaided eye.

Like all NDE methods, PT has both advantages and disadvantages. The primary advantages and disadvantages when compared to other NDE methods for inspection of dents are summarized below.

Primary Advantages

- The method has high sensitivity to small surface discontinuities.
- Large areas can be inspected rapidly and at low cost.
- Indications are produced directly on the surface of the pipe and constitute a visual representation of the flaw.
- Aerosol spray cans make penetrant materials very portable.
- Penetrant materials and associated equipment are relatively inexpensive.

Primary Disadvantages

- Precleaning is critical as contaminants on the surface can mask defects.
- Metal smearing from machining, grinding and grit or vapor blasting must be removed prior to PT.
- The inspector must have direct access to the surface being inspected.
- Surface finish and roughness can affect inspection sensitivity.
- Multiple process operations must be performed and controlled.
- Post cleaning of acceptable parts or materials is required.
- Chemical handling and proper disposal is required

5.2.3 Magnetic Particle Testing

Magnetic particle testing (MT) is an NDE method primarily used to detect surface breaking flaws. MT can also be used to locate near sub-surface flaws that are essentially perpendicular to the surface; however, its effectiveness quickly diminishes as the depth of a defect increases or size decreases.

MT uses magnetic fields and small magnetic particles, such as iron filings to detect flaws in components. The magnetic particles can be applied dry or wet; suspended in a liquid, colored, or be made fluorescent for visual contrast against a background. The technique uses the principle that magnetic lines of force (flux) will be distorted by the presence of a flaw in a manner that will reveal its presence. The flaw (for example, a crack) is located from the "flux leakage" following the application of fine iron particles to the area under examination. There are variations in the way the magnetic field is applied, but they are all dependant on the above principle.

Surface irregularities and scratches can give misleading indications. Therefore, it is necessary to ensure careful preparation of the surface before MT is undertaken.

5.2.4 Ultrasonic Shear Wave Testing

UT uses sound waves of short wavelength and high frequency to detect flaws or measure material thickness. Usually, pulsed beams of high frequency ultrasound are used via a handheld transducer (probe) which is placed on the specimen. Any sound from the pulse that is reflected and returns to the transducer (like an echo) is shown on a screen, which gives the amplitude of the pulse and the time required to return to the transducer. Flaws anywhere through the specimen thickness may reflect sound back to the transducer if orientation is suitable. Flaw size, distance, and reflectivity can be interpreted by a technician having appropriate training and experience.

5.2.5 Eddy-Current Testing

Eddy-current testing is an electromagnetic technique and can be used for crack detection. When an energized coil is brought near to the surface of a metal component, eddy currents are induced into the specimen. These currents set up a magnetic field that tends to oppose the original magnetic field. The impedance of the coil in close proximity to the specimen is affected by the presence of the induced eddy currents in the specimen.

When the eddy currents in the specimen are distorted by the presence of the flaws, the impedance in the coil is altered. This change is measured and displayed in a manner that indicates the type of flaw.

5.3 Remediation Techniques

Depending on the severity and condition of a dent, several remediation options are available: grinding of defects in shallow dents, installation of composite wrap repairs, installation of a welded steel sleeve, or replacement of the pipeline section. It is common practice to reduce the pressure to no more than 80 percent of the recent high operating pressure level prior to initiating repairs, especially where there is significant uncertainty as to the nature and severity of the defect. Such a reduction maintains the minimum margin of safety implied in the basis for design and operation with a minimum hydrostatic test pressure of 90 percent SMYS and operation at 72 percent SMYS. Pressure reductions of other magnitudes, either above or below this level, may be justified depending on the nature of the defect (e.g., it is normally possible to have a fairly good idea of the severity of corrosion, and thus one can determine the most prudent reduction).

5.3.1 Grinding

Grinding mechanical damage in shallow dents to a smooth contour was determined to be a feasible method to restore the integrity of a pipeline in research published by the Pipeline Research Council International (PRCI) and the Gas Research Institute (GRI). Bottom-side dents rarely involve mechanical damage, although occasionally it is seen in conjunction with contact from either a very sharp and hard rock, or from some type of construction equipment capable of penetrating beneath the pipeline.

Grinding is used as a repair technique for removing mechanical damage, including cracks and SCC, in the pipe body. It has been shown that corrosion in a dent does not behave any “worse” than corrosion in the pipe body. Therefore, it would be reasonable to perform light grinding to a smooth contour to convert mechanical damage or SCC in a rock dent to “metal loss,” provided the resulting metal loss is not greater than would be allowed for corrosion. In fact, ASME B31.8-2003 states:

> “External mechanical damage including cracks, may be repaired by grinding ou the damage provided any associated indentation of the pipe does not exceed a depth of 4% of the nominal pipe diameter. Grinding is permitted to a depth of 10% of the nominal pipe wall with no limit on length. Grinding is permitted to a depth greater than 10% up to a maximum of 40% of the pipe wall, with metal removal confined to a length given by the following formula:

$$L = 1.12\left[(Dt)\left(\left(\frac{a/t}{1.1a/t - 0.11}\right)^{2} - 1\right)\right]^{1/2}$$

where

D = nominal outside diameter of the pipe, in.

L = maximum allowable longitudinal extent of the ground area, in.

a = measured maximum depth of ground area, in.

t = nominal wall thickness of pipe, in.”

ASME B31.8-2003 also states:

> “Dents containing stress corrosion cracking may be repaired by grinding out the cracks to a length and depth permitted in para. 862.213 for corrosion in plain pipe.”

This would have to be followed by appropriate coating repairs. Grinding might not be recommended as a means of mitigating a fatigue crack or partial puncture crack discovered in a bottom-side dent. This is because there is potential for the crack to be fairly deep with respect to the pipe wall, and continued operation could cause a fatigue crack to reinitiate. The acceptability of grinding as the primary means of mitigation is contingent on verification that the remaining thickness of pipe wall is adequate per B31.8, B31G or other approved criteria.

5.3.2 Composite Wrap Repairs

Composite wrap repairs have been shown to extend the lives of pipes affected by damage when compared to damage with no repairs, when correctly installed in the appropriate situations. This type of repair may be appropriate for reinforcing a dented pipeline once a mechanical defect has been fully removed by grinding. It may also be used for dents with corrosion flaws since the failure mechanism in this case is bulging of the thinned area and therefore only reinforcement is required. In general, hardenable filler materials must be used in gaps between the pipe surface and the composite wrap in order to immobilize the defect. A material such as fast-curing polyester epoxy resin is suitable and commonly used for this purpose, but other filler materials have also been used. If the possibility for pressure-cycle fatigue is suspected, the use of composite wrap repairs would not be appropriate as a permanent repair, as experiments have shown that progressive changes in dents continue beneath the wraps when subjected to additional pressure cycles.

5.3.3 Pipeline Sleeves

The use of full-encirclement steel reinforcing sleeves with ends left unwelded (Type A sleeves) could also be appropriate for any dent-related condition that is not already leaking and a crack or possible crack is not left in place. As with the composite wrap repair, the use of a hardenable filler in any gaps between the pipeline and the sleeve is necessary.

A full-encirclement steel containment sleeve with ends welded to the pipeline (Type B sleeve) could be appropriate for virtually all dent-related defects. It is unnecessary to use a hardenable filler since the sleeve will contain any leak resulting from continued flaw extension in service, but the filler would make for a better repair and would probably prevent flaw extension altogether.

A pipeline affected by large bottom-side dents may be too distorted for a conventional steel sleeve to be installed with a tight fit, which could impair the sleeve's effectiveness. The same is true with repairing buckles. Commercially-made sleeves having an expanded center section are available for encapsulating leaking couplings or other devices, and might be usable over a distorted pipeline section. The annular space could be filled with grout, or left open, provided the ends of the sleeve are welded to the pipeline.

Another style of sleeve that can be used in such situations is the grout-filled shell. The oversized shell is installed with jack screws so as to clear the deformed pipe section. The open annular ends are dammed with a moldable epoxy putty, and the full interior space between the shell and pipe filled by pumping in a flowable grout. The type of grout depends on the application, but for reinforcing dents the main performance characteristic is that the grout have some compressive strength so it could be epoxy-based or cement-based. If the pipeline coating is generally well-adhered, it may be unnecessary to fully remove the original coating within the sleeved length of pipe except to the extent necessary to inspect the dent and halt any corrosion that may have occurred. The end treatment can be molded and finished to produce a suitable taper for application of an exterior coating over both the sleeve and the adjacent pipe surface. Such repairs have been shown to be capable of reliably containing line pressure when suitably engineered.

5.3.4 Pipe Replacement

Complete replacement of the damaged pipeline section is an option.

5.4 Recommended Inspection Procedure

5.4.1 Preliminary Examination and Measurements

1. Reduce internal pressure to 80 percent of the operating pressure at the time the dent was discovered.
2. Expose the pipeline section to be examined.
3. Manually clean the pipeline to remove all dirt and loose material on the dented section and a minimum of two pipe diameters on either side of the dent.
4. Visually examine the dented area for evidence of corrosion, gouges, cracking, or coating damage. If found, make detailed notes documenting the size, shape, and locations of the defects for comparison after coating removal.
5. Photograph the dent from at least two angles.
6. Record detailed measurements of the dented area, including:
    a. Total axial length
    b. Depth (difference between the original, undeformed pipe surface and the indented surface) at the apparent apex of the dent.
    c. Width (perpendicular to the pipe axis) as the distance separating points of either side of the apex of the dent having depths equal to one half of the maximum depth.

   d. Maximum radius of curvature in both the longitudinal and circumferential directions (this can be easily measured utilizing a contour gage).
   e. Minimum and maximum "diameters" of the deformed pipe at a maximum of 4-inch increments along the pipeline axis.
   f. Deviations of the pipeline from straight.
   g. Record locations of girth and/or longitudinal seams in relationship to the dent apex, to the extent possible.

5.4.2 Remove Coating

1. Remove coating from the deformed area and a sufficient distance on either side to perform a complete examination of the dent.
2. Clean the exposed pipeline surface to near white condition per SSPC SP-10 in accordance with operator's procedures.

5.4.3 Detailed Examination

1. Visually examine the entire deformed area following coating removal for any evidence of a gouge, groove, crack, arc burn, or other stress-concentrating defect.
2. Ultrasonically examine the dent for any loss of wall thickness or evidence of crack or other discontinuity.
3. Perform MT or PT of the deformed area.
4. Perform shear wave UT examination of the dented area if defects are noted. If a crack indication is discovered by UT examination, verify with radiographic examination.
5. If desired, dent contours can be transferred to spreadsheets or physical curvature templates for estimating strain levels.

6 Pertinent Regulations, Industry Standards and Industry Recommended Practices

The following regulations and industry standards were reviewed for this report:

- 49 CFR 192 *Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards*
- 49 CFR 195 *Transportation of Hazardous Liquids by Pipeline*
- ASME B31.4-1998 *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquid*s (1998)
- ASME B31.4-2002 *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquid*s (2002)
- ASME B31.8-1995 *Gas Transmission and Distribution Piping Systems* (1995)
- ASME B31.8-2003 *Gas Transmission and Distribution Piping Systems* (2003)
- API Publication 1156 *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines* (1997)
- API Standard 1160 *Managing System Integrity for Hazardous Liquids Pipelines* (2001)

6.1 49 CFR 192

49 CFR 192 Subpart O, *Pipeline Integrity Management*, requires operators to take prompt action to address anomalous conditions discovered through integrity assessment as described in §192.933, which states in part:

> “(d) *Special requirements for scheduling remediation.*—(1) *Immediate repair conditions.* An operator's evaluation and remediation schedule must follow ASME/ANSI B31.8S, section 7 in providing for immediate repair conditions. To maintain safety, an operator must temporarily reduce operating pressure in accordance with paragraph (a) of this section or shut down the pipeline until the operator completes the repair of these conditions. An operator must treat the following conditions as immediate repair conditions:
>
>> (i) A calculation of the remaining strength of the pipe shows a predicted failure pressure less than or equal to 1.1 times the maximum allowable operating pressure at the location of the anomaly. Suitable remaining strength calculation methods include, ASME/ANSI B31G; RSTRENG; or an alternative equivalent method of remaining strength calculation. These documents are incorporated by reference and available at the addresses listed in appendix A to part 192.
>>
>> (ii) A dent that has any indication of metal loss, cracking or a stress riser.
>>
>> (iii) An indication or anomaly that in the judgment of the person designated by the operator to evaluate the assessment results requires immediate action.
>
> (2) *One-year conditions.* Except for conditions listed in paragraph (d)(1) and (d)(3) of this section, an operator must remediate any of the following within one year of discovery of the condition:

> > (i) A smooth dent located between the 8 o'clock and 4 o'clock positions (upper 2/3 of the pipe) with a depth greater than 6% of the pipeline diameter (greater than 0.50 inches in depth for a pipeline diameter less than Nominal Pipe Size (NPS) 12).
> >
> > (ii) A dent with a depth greater than 2% of the pipeline's diameter (0.250 inches in depth for a pipeline diameter less than NPS 12) that affects pipe curvature at a girth weld or at a longitudinal seam weld.
>
> (3) *Monitored conditions.* An operator does not have to schedule the following conditions for remediation, but must record and monitor the conditions during subsequent risk assessments and integrity assessments for any change that may require remediation:
>
> > (i) A dent with a depth greater than 6% of the pipeline diameter (greater than 0.50 inches in depth for a pipeline diameter less than NPS 12) located between the 4 o'clock position and the 8 o'clock position (bottom 1/3 of the pipe).
> >
> > (ii) A dent located between the 8 o'clock and 4 o'clock positions (upper 2/3 of the pipe) with a depth greater than 6% of the pipeline diameter (greater than 0.50 inches in depth for a pipeline diameter less than Nominal Pipe Size (NPS) 12), and engineering analyses of the dent demonstrate critical strain levels are not exceeded.
> >
> > (iii) A dent with a depth greater than 2% of the pipeline's diameter (0.250 inches in depth for a pipeline diameter less than NPS 12) that affects pipe curvature at a girth weld or a longitudinal seam weld, and engineering analyses of the dent and girth or seam weld demonstrate critical strain levels are not exceeded. These analyses must consider weld properties.”

6.2 49 CFR 195

Integrity management is discussed in 49 CFR 195.452 and describes actions that an operator must take to address integrity issues in subpart (h), which states in part:

> “(4) *Special requirements for scheduling remediation.*
>
> (i) *Immediate repair conditions.* An operator's evaluation and remediation schedule must provide for immediate repair conditions. To maintain safety, an operator must temporarily reduce operating pressure or shut down the pipeline until the operator completes the repair of these conditions. An operator must calculate the temporary reduction in operating pressure using the formula in section 451.7 of ASME/ANSI B31.4 (incorporated by reference, see § 195.3). An operator must treat the following conditions as immediate repair conditions:
>
> > (A) Metal loss greater than 80% of nominal wall regardless of dimensions.
> >
> > (B) A calculation of the remaining strength of the pipe shows a predicted burst pressure less than the established maximum operating pressure at the location of the anomaly. Suitable remaining strength calculation methods

> include, but are not limited to, ASME/ANSI B31G ("Manual for Determining the Remaining Strength of Corroded Pipelines" (1991) or AGA Pipeline Research Committee Project PR-3-805 ("A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe" (December 1989)). These documents are incorporated by reference and are available at the addresses listed in §195.3.
>
> (C) A dent located on the top of the pipeline (above the 4 and 8 o'clock positions) that has any indication of metal loss, cracking or a stress riser.
>
> (D) A dent located on the top of the pipeline (above the 4 and 8 o'clock positions) with a depth greater than 6% of the nominal pipe diameter.
>
> (E) An anomaly that in the judgment of the person designated by the operator to evaluate the assessment results requires immediate action.

(ii) *60-day conditions.* Except for conditions listed in paragraph (h)(4)(i) of this section, an operator must schedule evaluation and remediation of the following conditions within 60 days of discovery of condition.

> (A) A dent located on the top of the pipeline (above the 4 and 8 o'clock positions) with a depth greater than 3% of the pipeline diameter (greater than 0.250 inches in depth for a pipeline diameter less than Nominal Pipe Size (NPS) 12).
>
> (B) A dent located on the bottom of the pipeline that has any indication of metal loss, cracking or a stress riser.

(iii) *180-day conditions.* Except for conditions listed in paragraph (h)(4)(i) or (ii) of this section, an operator must schedule evaluation and remediation of the following within 180 days of discovery of the condition:

> (A) A dent with a depth greater than 2% of the pipeline's diameter (0.250 inches in depth for a pipeline diameter less than NPS 12) that affects pipe curvature at a girth weld or a longitudinal seam weld.
>
> (B) A dent located on the top of the pipeline (above 4 and 8 o'clock position) with a depth greater than 2% of the pipeline's diameter (0.250 inches in depth for a pipeline diameter less than NPS 12).
>
> (C) A dent located on the bottom of the pipeline with a depth greater than 6% of the pipeline's diameter.
>
> (D) A calculation of the remaining strength of the pipe shows an operating pressure that is less than the current established maximum operating pressure at the location of the anomaly. Suitable remaining strength calculation methods include, but are not limited to, ASME/ANSI B31G ("Manual for Determining the Remaining Strength of Corroded Pipelines" (1991)) or AGA Pipeline Research Committee Project PR-3-805 ("A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe" (December 1989)).

> > These documents are incorporated by reference and are available at the addresses listed in §195.3.
> >
> > (E) An area of general corrosion with a predicted metal loss greater than 50% of nominal wall.
> >
> > (F) Predicted metal loss greater than 50% of nominal wall that is located at a crossing of another pipeline, or is in an area with widespread circumferential corrosion, or is in an area that could affect a girth weld.
> >
> > (G) A potential crack indication that when excavated is determined to be a crack.
> >
> > (H) Corrosion of or along a longitudinal seam weld.
> >
> > (I) A gouge or groove greater than 12.5% of nominal wall.
>
> (iv) *Other conditions.* In addition to the conditions listed in paragraphs (h)(4)(i) through (iii) of this section, an operator must evaluate any condition identified by an integrity assessment or information analysis that could impair the integrity of the pipeline, and as appropriate, schedule the condition for remediation. Appendix C of this part contains guidance concerning other conditions that an operator should evaluate."

6.3 Comparison of 49 CFR 192 and 49 CFR 195 Regarding Dents

As shown in the previous sections, 49 CFR 192 and 49 CFR 195 differ to a degree on the disposition of anomalies. 49 CFR 192 places anomalies into one of three categories: immediate repair conditions, one-year conditions, and monitored conditions; while 49 CFR 195 defines immediate conditions, 60-day conditions, 180-day conditions, and other conditions. A comparison of the designated condition for the various types of dent related anomalies is given in Table 6.1.

Table 6.1 Comparison of 49 CFR 192 and 49 CFR 195 Regarding Dents

Anomaly	49 CFR 192 Condition	49 CFR 195 Condition
A dent that has any indication of metal loss, cracking or a stress riser.	Immediate	Upper 2/3 of the pipe — Immediate Lower 1/3 of the pipe — 60-day
A dent with a depth greater than 6% of the nominal pipe diameter.	Upper 2/3 of the pipe — One-year[1]. Lower 1/3 of the pipe — Monitored	Upper 2/3 of the pipe — Immediate Lower 1/3 of the pipe — 180-day
A dent with a depth greater than 3% of the nominal pipe diameter on the upper 2/3 of the pipe.	Not defined	60-day
A dent with a depth greater than 2% of the nominal pipe diameter on the upper 2/3 of the pipe.	Not defined	180-day
A dent with a depth greater than 2% of the pipeline's diameter that affects pipe curvature at a girth weld or at a longitudinal seam weld	One-year[1]	180-day
[1] Can be downgraded to a monitored condition providing engineering analyses of the dent demonstrate that critical strain levels are not exceeded. In the case of a dent affecting a weld, the weld properties must also be considered.		

6.4 ASME B31.4

As of July 14, 2004, 49 CFR 195 incorporates by reference ASME B31.4-1998. Paragraph 451.6.2 "Disposition of Defects" defines dents that should be removed or repaired as:

a. Dents which affect the pipe curvature at the pipe seam or at any girth weld

b. Dents containing a scratch, gouge, or groove;

c. Dents exceeding a depth of ¼ in. (6 mm) in pipe NPS 4 and smaller, or 6% of the nominal pipe diameter in sizes greater than NPS 4;

ASME B31.4-2002 added a fourth condition requiring repair or removal of dents.

d. Dents containing external corrosion where the remaining wall thickness is less than 87.5% of that required for design.

Revising the reference in §195.3 to the current edition of ASME B31.4 would have no practical effect unless §195.452 (h), which identifies a dent with any indication of metal loss as a repair condition, were also revised.

6.5 ASME B31.8

Both 49 CFR 192 and 49 CFR 195 currently incorporate ASME B31.8-1995 by reference. Dents discovered during installation are discussed in section 841.243, which states:

> "(a) A dent may be defined as a depression which produces a gross disturbance in the curvature of the pipe wall (as opposed to a scratch or gouge, which reduces the pipe wall thickness). The depth of a dent shall be measured as the gap between the lowest

> point of the dent and a prolongation of the original contour of the pipe in any direction.
>
> (b) A dent, as defined in para. 841.234 (a), which contains a stress concentrator such as a scratch, gouge, groove, or arc burn shall be removed by cutting out the damaged portion of the pipe as a cylinder.
>
> (c) All dents that affect the curvature of the pipe at the longitudinal weld or any circumferential weld shall be removed. All dents that exceed a maximum depth of ¼ in. in pipe NPS 12 and smaller, or 2% of the nominal pipe diameter in all pipe greater than NPS 12 shall not be permitted in pipelines or mains intended to operate at 40% or more of the specified minimum yield strength. When dents are removed, the damaged portion of the pipe shall be cut out as a cylinder. Insert patching and pounding out of the dents is prohibited."

Paragraph 841.243 limits all dents to a maximum depth of only 2 percent of the nominal diameter, but paragraph 841 is in Chapter IV, entitled Design, Installation, and Testing, which implies that paragraph 841.243 applies only during new construction to manage contractor performance.

Chapter V Operating and Maintenance Procedures contains paragraph 851 Pipeline Maintenance. The following requirements for paragraph 851.4 would apply for managing pipeline integrity.

> "…Smooth dents in existing pipelines do not require repair unless they:
>
> a. contain a stress concentrator, such as a scratch, gouge, groove, or arc burn;
> b. affect the curvature of the pipe at the longitudinal weld or a circumferential weld; or
> c. exceed a maximum depth of 6% of nominal pipe diameter."

In the 2003 edition of ASME B31.8, paragraph 851.4 was completely revised and now states in paragraph 851.41:

> "(a) Dents are indentations of the pipe or distortions of the pipe's circular cross section caused by external forces.
>
> (b) Plain dents are dents that vary smoothly and do not contain creases, mechanical damage [such as described in 851.41(c)] corrosion, arc burns, girth, or seam welds.
>
> (c) Mechanical damage is damage to the pipe surface caused by external forces. Mechanical damage includes features such as creasing of the pipe wall, gouges, scrapes, smeared metal, and metal loss not due to corrosion. Cracking may or may not be present in conjunction with mechanical damage. Denting of the pipe may or may not be apparent in conjunction with mechanical damage.
>
> (d) Plain dents are defined as injurious if they exceed a depth of 6% of the nominal pipe diameter. Plain dents of any depth are acceptable provided strain levels associated with the deformation do not exceed 6% strain. Strain levels may be calculated in accordance with Appendix R or other engineering methodology. In evaluating the depth of plain dents, the need for the segment to be able to safely pass

> an internal inspection or cleaning device shall also be considered. Any dents that are not acceptable for this purpose should be removed prior to passing these devices through the segment, even if the dent is not injurious.
>
> (e) All external mechanical damage with or without concurrent visible indentation of the pipe is considered injurious.
>
> (f) Dents that contain corrosion are injurious if the corrosion is in excess of what is allowed by para. 862.213, or if they exceed a depth of 6% of the nominal pipe diameter.
>
> (g) Dents that contain stress corrosion cracks or other cracks are injurious.
>
> (h) Dents that affect ductile girth or seam welds are injurious if they exceed a depth of 2% of the nominal pipe diameter, except those evaluated and determined to be safe by an engineering analysis that considers weld quality, nondestructive examinations, and operation of the pipeline are acceptable provided strain levels associated with the deformation do not exceed 4%. It is the operator's responsibility to establish the quality level of the weld.
>
> (i) Dents of any depth that affect non-ductile welds, such as acetylene girth welds or seam welds that are prone to brittle fracture, are injurious."

Paragraph 851.42 goes on to state:

> "(a) Injurious dents and mechanical damage shall be removed or repaired by one of the methods below, or the operating pressure shall be reduced. The reduced pressure shall not exceed 80% of the operating pressure experienced by the injurious feature at the time of discovery. Pressure reduction does not constitute a permanent repair."

Even though ASME B31.8-2003 is not currently referenced in 49 CFR 192, the requirements of this edition are generally aligned and compatible with 49 CFR 192.

6.6 API 1156

API 1156 and its addendum present results from numerous experimental and finite element analyses to determine the effects of smooth dents and rock dents on the integrity of liquid petroleum pipelines. The report provides conclusions related to potential significance of dents detected by ILI both in terms of severity and location, as well as information on dent behavior and the potential failure mechanisms.

From an operator's point of view, the most useful piece of information in this report is probably Appendix C of the Addendum, which contains a field guide for the assessment of dents and buckles that includes methods for prioritizing these anomalies based on ILI results and assessment techniques based on excavation and examination.

6.7 API 1160

API Standard 1160, contains information about dents in Appendix A "Anomaly Types, Cause, and Concerns." Section 9.6 "Strategy for Responding to Anomalies Identified by In-Line Inspections" states:

> "An operator shall take action to address pipeline integrity concerns identified during the evaluation of in-line inspection data. If a condition exists on the pipeline that presents an "immediate concern"…the operator shall initiate mitigative actions within five days in order to continue to operate the affected part of the system. Mitigation action is based on regulatory requirements, company guidelines, and assessment of risk.
>
> When a pipeline is inspected by an in-line inspection tool, the final results of the inspection should be provided to the operator within six months. However, certain types of potential defects should be brought to the operator's attention through a preliminary report…"

The descriptions of what constitute an "immediate concern" are slightly different than the "Immediate" conditions in the CFR provisions; however, there are close parallels in most cases. Once an "immediate concern" is identified, Section 9.6 states:

> "Mitigative action…shall be based on in-line inspection data analysis without excavation verification. Temporary mitigative action(s) shall be initiated as soon as possible; within five days of receipt of the preliminary in-line inspection report and shall remain in place until the anomaly can be excavated and assessed. Permanent mitigative action such as repairs, if required, should be accomplished within thirty days of receipt of the preliminary in-line inspection report."

7 Conclusions and Recommendations

While the main purpose of this report was to evaluate the effect of bottom-side dents on pipeline integrity, the discussion expanded somewhat naturally to include additional issues pertaining to integrity assessment of dents. Flow charts were prepared to illustrate the dent evaluation process for 49 CFR 192, 49 CFR 195, ASME B31.4-2002 and ASME B31.8-2003. These flow charts are presented as Figure 7.1, Figure 7.2, Figure 7.3, and Figure 7.4, respectively. A suggested dent evaluation process that expands on the ASME B31.8 recommended practice and could be applied to both gas and liquid pipelines was also prepared and is presented as Figure 7.5.

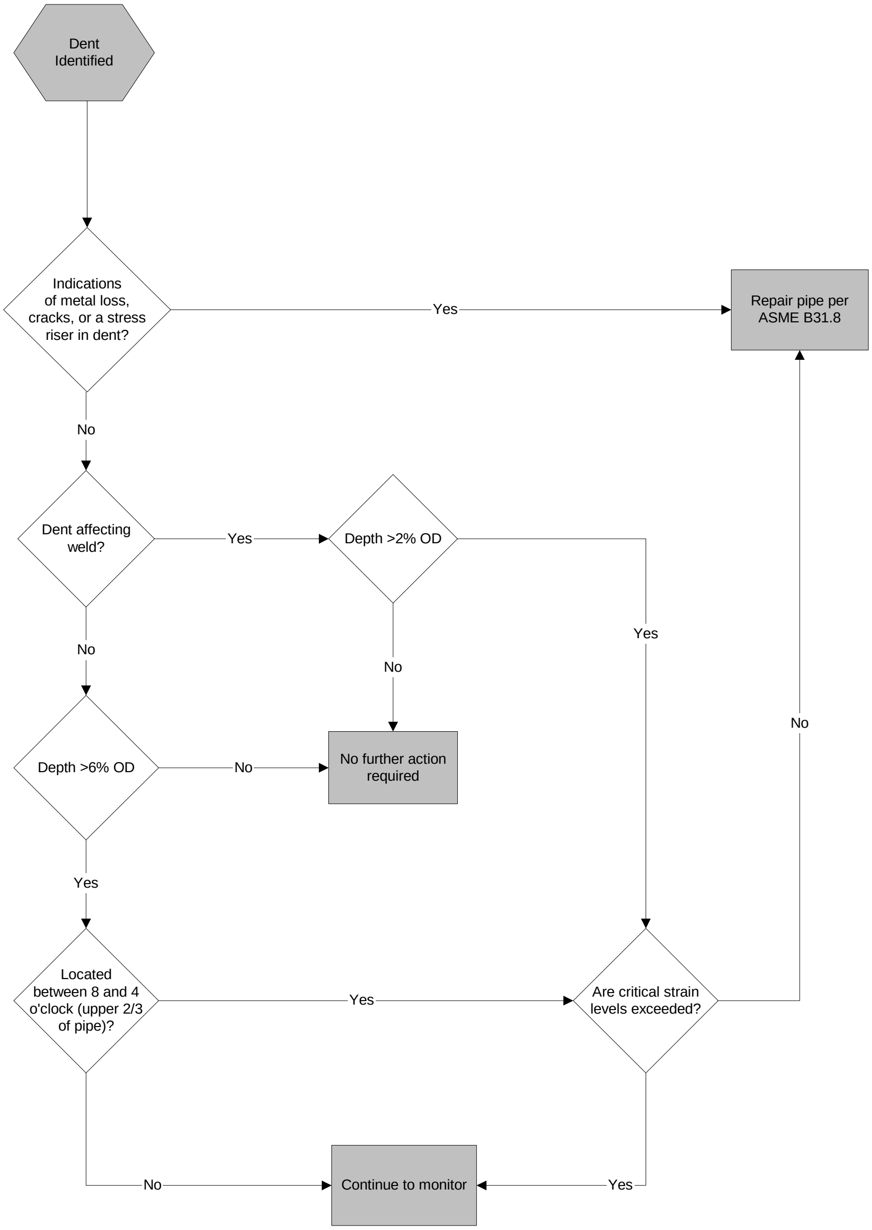

Figure 7.1 49 CFR 192 Dent Evaluation Process

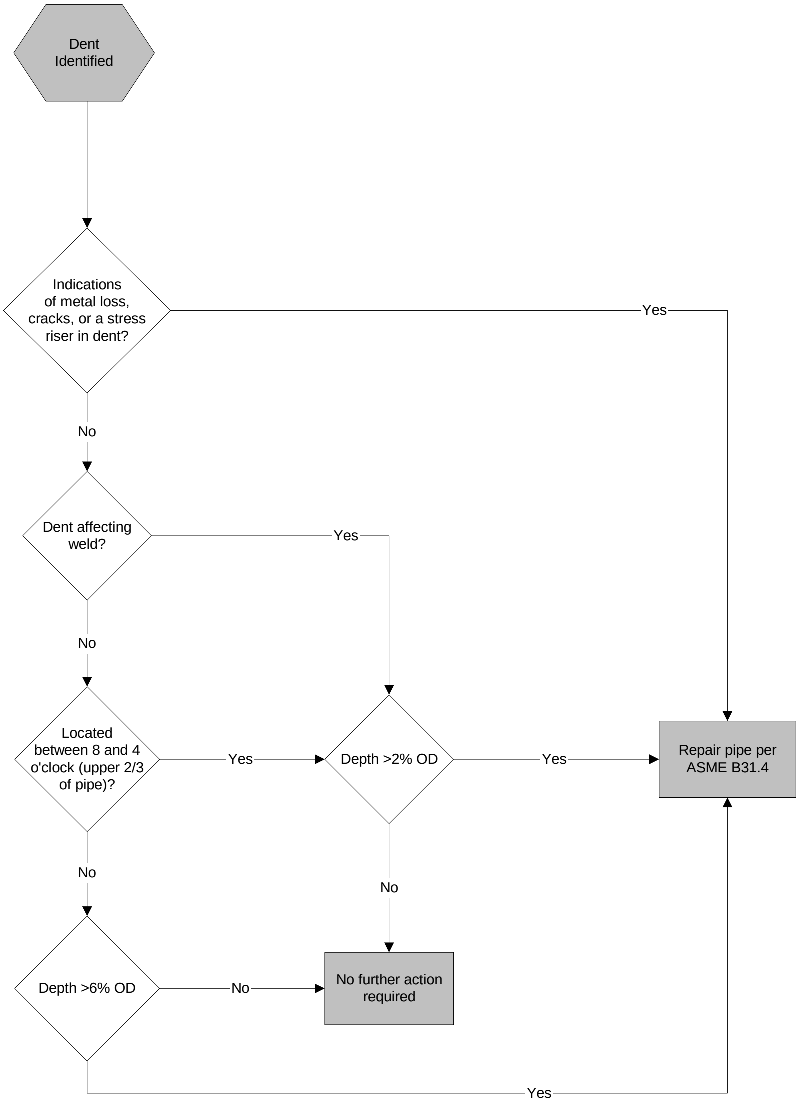

Figure 7.2 49 CFR 195 Dent Evaluation Process

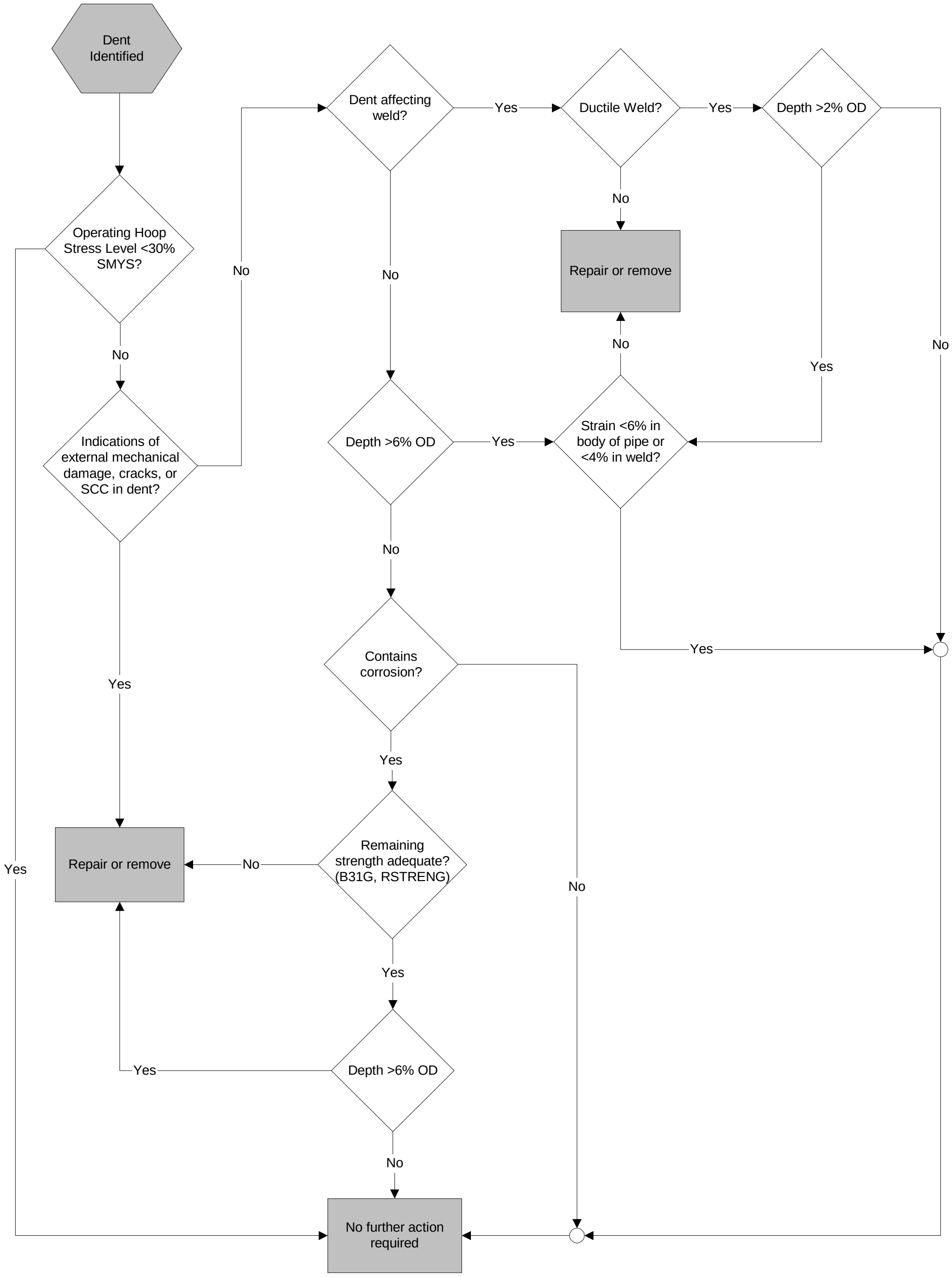

Figure 7.3 ASME B31.8-2003 Dent Evaluation Process

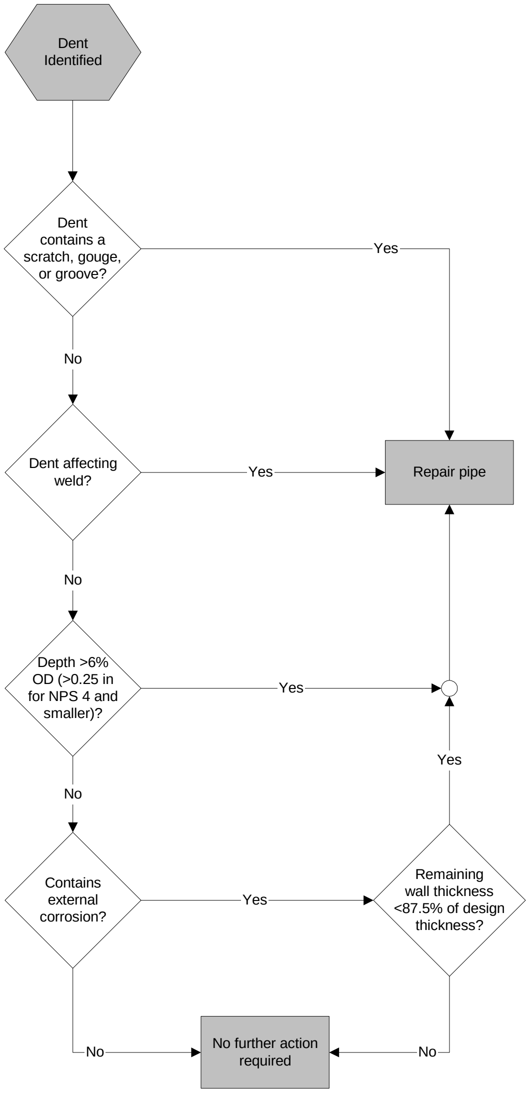

Figure 7.4 ASME B31.4-2002 Dent Evaluation Process

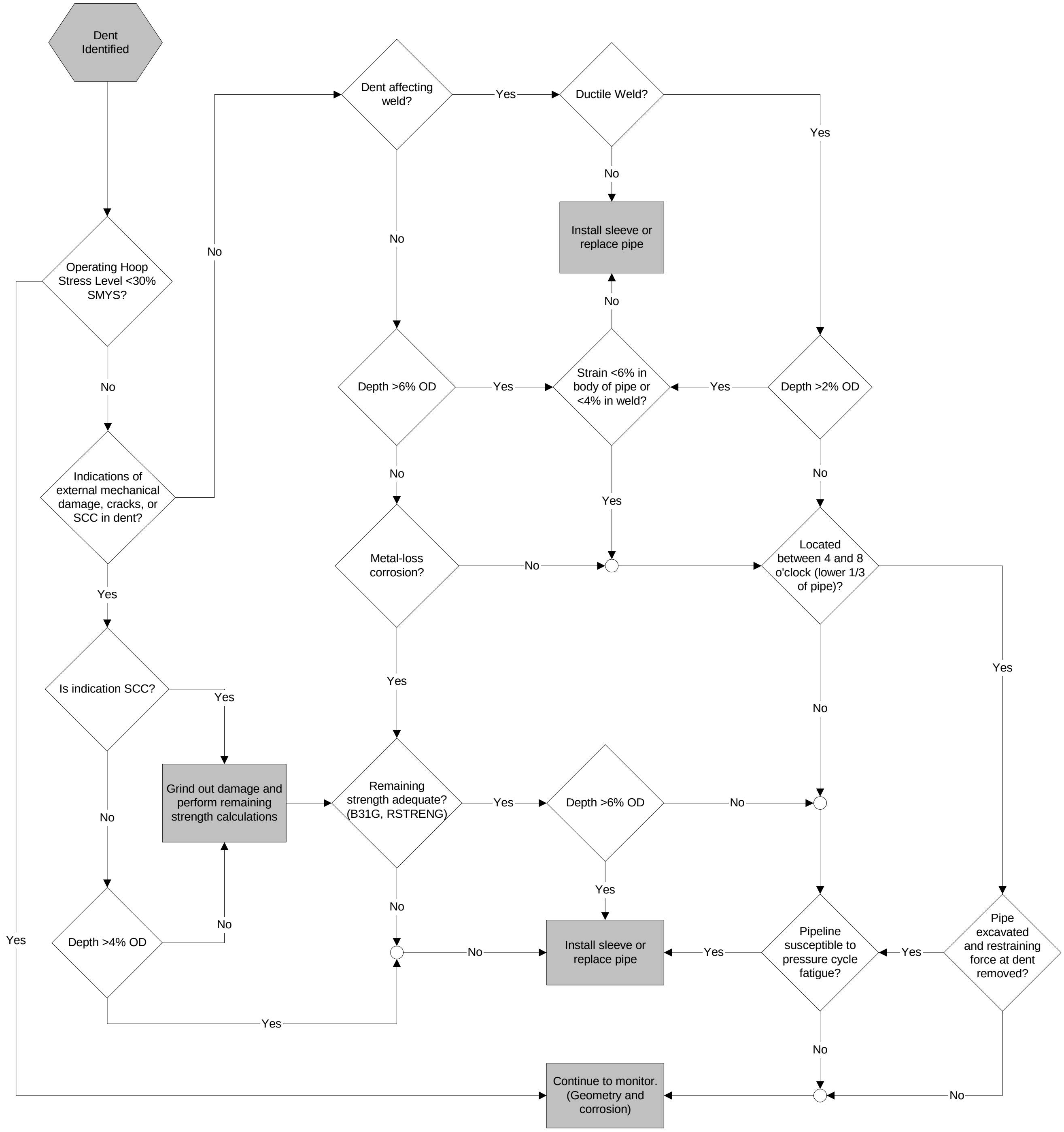

Figure 7.5 Suggested Dent Evaluation Process

By following this procedure, dents are only subjected to the strain criterion if they exceed some deformation limit. Based on the examples shown in Section 3, it is apparent that the strain criterion could be violated even below the deformation limit. Therefore, it is recommended that the strain criteria be considered by for use by operators even for dents that meet the existing depth acceptance criteria.

The main difference between the suggested dent evaluation process and the ASME B31.8 process is the additional check for susceptibility to pressure-cycle fatigue for all situations except restrained bottom-side dents. This exception is based on research data, which indicates that if a dent is subjected to pressure cycling, the remaining life is typically on the order of one order of magnitude higher if the dent is restrained (as is typical for bottom-side dents) than if unrestrained. The potential benefits of leaving a dent in a pipeline (subject to pressure-cycle fatigue or not) must be weighed against the level of effort required for additional monitoring to ensure the pipeline's integrity is not compromised. Monitoring activities must account for the myriad of ancillary problems that may develop (e.g., coating damage, shielding from cathodic protection, corrosion, stress corrosion cracking, hydrogen cracking, or punctures due to continued settlement).

8 References

1. Alexander, C.R., and J.F. Kiefner, *"Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines"*, API Publication 1156, November 1997.
2. Burkhardt, G. L., "*Technology Status Assessment For Development Of Nonlinear Harmonic Sensors For Detection Of Mechanical Damage"*, National Energy Technology Laboratory, January 2002.
3. Fowler, J.R., and R.R. Ayers, *"Acceptability of Plain Dents for Offshore Pipelines"*, PRC/EPRG 9th Joint Technical Meeting on Line Pipe Research, May 1993.
4. Johnston, D. C., *"Using In-Line Inspection to Address Deformations Containing Near-Neutral pH Stress Corrosion Cracking"*, ASME 4th International Pipeline Conference, 2002.
5. Kiefner, J.F., and C.R. Alexander, *"Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines (Phase 2)"*, Addendum to API Publication 1156, October 1999.
6. Rosenfeld, M. J., *"Proposed New Guidelines for ASME B31.8 on Assessment of Dents and Mechanical Damage"*, Gas Research Institute, May 2001
7. Rosenfeld, M. J., *"Factors to Consider When Evaluating Damage on Pipelines"*, Oil & Gas Journal, 2002(b).
8. Texas Transportation Institute, *"Fatigue Behavior of Dented Petroleum Pipelines–Task 4"*, 1997.

8.1 Other Pertinent Documents

1. Eiber, R. J., W.A. Maxey, C.W. Bert and G.M. McClure, *"The Effects of Dents on the Failure Characteristics of Line Pipe"*, PRCI Catalog No. L51403, May 1981.
2. Rosenfeld, M. J., *"Development of a Model for Fatigue Rating Shallow Unrestrained Dents"*, PRCI Catalog No. L51741, September 1997.
3. Rosenfeld, M. J., *"Investigations of Dent Rerounding Behavior"*, ASME International Pipeline Conference, 1998.
4. Rosenfeld, M. J., *"Guidelines for the Assessment of Dents on Welds"*, PRCI Catalog No. L51810, December 1999.
5. Rosenfeld, M. J., J. W. Pepper, and K. Leewis, *"Basis of the New Criteria in ASME B31.8 for Prioritization and Repair of Mechanical Damage"*, ASME 4th International Pipeline Conference, 2002(a).