STATISTICAL ANALYSIS OF EXTERNAL CORROSION ANOMALY DATA OF CASED PIPE SEGMENTS

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EXECUTIVE SUMMARY

Cased pipe segments are generally believed to be very safe; however, external corrosion compromising the integrity of the cased pipes does exist. The primary types of external corrosion include atmospheric corrosion and corrosion by electrolyte. The external corrosion by electrolyte occurs when cathodic protection (CP) is shielded, for instance, by the casing wall, by the insulator spacers, or by accumulation of mud/deposits in the casing-carrier pipe annulus. When a metallic short is present, any CP benefit could be completely eliminated.

When external corrosion on a pipe occurs, it is incumbent on operators applying the External Corrosion Direct Assessment (ECDA) procedure to understand the severity of the corrosion, if present, and to provide guidance into how operators should respond. A key step towards developing an ECDA procedure for cased pipe segments is understanding the statistical relationships between the corrosion anomalies identified using In-Line Inspection (ILI), which can determine the size and location of the corrosion anomalies within casings, and operational conditions of the pipeline. The results of the statistical relationships obtained from piggable cased pipe segments can be applied toward developing a strategy for non-piggable cased pipe segments, assuming corrosion conditions are similar.

This study addresses the significance of corrosion damage, for which a statistical analysis of ILI data of cased pipe segments from seven pipeline operators was performed. The evaluation also included investigating the effects of metallic and electrolytic shorts on the corrosion of cased pipe segments, summarizing results from a review of failure incidents of cased pipe segments during the past 22 years, and performing an assessment of the preferential location of a peak anomaly on a cased pipe segment.

The results from the above study will provide a technical basis for the determination and prioritization of cased pipe segments for examination as part of the ECDA program.

Severity of the ILI Anomalies to the Integrity of Cased Pipe Segments

The following statistical analysis was to understand the severity of the peak corrosion anomalies to the integrity of cased pipe segments containing the anomalies. The following items were investigated:

- The percentage of cased pipe segments that contain a peak anomaly with a depth of 20% or greater of the pipe wall thickness (wt),
- The percentage of cased pipe segments that contain a peak anomaly with a depth of 80% wt or greater,
- The distribution of FP/MAOP, where FP and MAOP denote, respectively, failure (or burst) pressure (FP) and maximum allowable operating pressure (MAOP) of a pipe segment.

For the 2733 cased pipe segments for which ILI data was received for this study, slightly less than 10% (272 cased pipe segments) contain peak anomalies with a depth

of 20% wt or greater. Only one cased pipe segment has a peak anomaly with a depth exceeding 80% wt (84% wt).

For the statistical analysis below, unless stated otherwise, it considers only the deepest (or peak) anomaly on a cased pipe segment and requires that the anomaly depth be no less than 20% wt. It is noted that in accordance with the modified ASME B31G (Reference: ANSI/ASME B31G-1991(R2004) Manual for Determining the Remaining Strength of Corroded Pipelines: a Supplement to B31, Code for Pressure Piping, ANSI/ASME) no repair action is necessary for anomalies of less than 20% wt except to arrest the active corrosion. This reduces the population of cased pipe segments considered for statistical analysis down from 2733 to 272, or approximately 10%. Of the total population of 272 peak anomalies (or cased pipe segments) used in this study, the following was observed.

For a specific pipe segment, the relative severity of one or more anomalies can be evaluated from the *Failure Pressure (FP)*, which accounts for the effect of both the *anomaly depth* and *length*. However, this *FP* alone is not very useful for comparison between different pipe segments because it depends on pipe nominal wall thickness, diameter, and the steel property. Thus, a better way for measuring the relative severity of anomalies on different pipe segments is the use of *FP/MAOP*, or Factor of Safety, which approximately does not depend on the pipe nominal wall thickness (t), diameter (D), or steel property (such as SMYS – specified minimum yield strength, which is proportional to flow stress) because both *FP* and *MAOP* are proportional to the term: $\mathrm{SMYS}\frac{2t}{D}$, following ASME B31G. Therefore, in this project *FP/MAOP* is used to compare the severity of damage associated with ILI-indicated anomalies for all cased pipe segments received, for this study, from all seven operators, irrespective of pipe diameter and wall thickness.

It was found that only 5 peak anomalies of the total of 272 cased pipe segments have an *FP/MAOP* less than 1.39 (scheduled repairs), accounting for 1.8%. The lowest *FP/MAOP* of all anomalies is 1.28. It is noted that these five anomalies do not include the deepest one (84% wt) whose *FP/MAOP* is rather large, 1.64, owing to its small length (0.79 inch). The pipe segment containing this anomaly is required to be replaced to prevent leaks in accordance with the ASME B31G criteria.

Excluding the cased pipe segment with the deepest anomaly, the total number of cased pipe segments is reduced to 2732. Of the 2732 cased pipe segments, the percentage accounted for by the 5 anomalies scheduled for repair drops to 0.18%, suggesting that an overwhelming majority of cased pipe segments do not need any repair action based on the modified ASME B31G criteria. It is cautioned that this conclusion can be affected by the original design factor of the cased pipe segments. For road and railroad cased pipe segments, ASME B31.8 recommends a design factor of 0.72 (or 1/1.39) for both Div. 1 and Div. 2 of Class 1 except for private roads of Div. 1 for which the design factor is recommended as 0.8.

For about 46% of all anomalies, the *FP/MAOP* falls within 1.7 - 2.1, inclusive. The average is 2.1 and the median is 2.0. This high average ratio reinforces that cased pipe segments are, in general, in excellent condition.

A further statistical analysis of *FP/MAOP* was needed to examine whether the severity of individual peak anomalies (when present) have any preferential distribution along the carrier pipe, or whether this ratio, or the peak anomaly severity, is higher near the end of the casing or inside on the cased carrier pipe segments.

For the above investigation, the distributions of the number of anomalies vs. *FP/MAOP* were compared for five ranges of *shortest distance* from either end of the casings (0-5 feet, 5-10 feet, 10-20 feet, 20-50 feet, and over 50 feet). The statistical result of the *shortest distance* is presented in the last section of this summary. Since the distributions are very close to each other and are of the same shape, it can be concluded that the severity of individual peak anomalies to the pipeline integrity do not appear to depend on their locations along the cased pipe segments. As a simple example, for cased pipe segments on the same pipeline (with the same carrier pipe diameter, wall thickness, operating condition), this non-preferential distribution of *FP/MAOP* can be understood as: the peak anomalies have similar sizes (depth and length) regardless of their being located near the ends of the casing or inside.

Caution should be taken when the above statistical results, as well as statistical results to be presented below, are used. They are not applicable to isolated events, such as anomalies generated in very unusual circumstances. Also, limitations of the ILI data must be clear. It is known that the ILI tools have resolution limits in determining the anomaly depths and lengths. One operator also found that ILI tools can misidentify casings.

The Effects of Metallic and Electrolytic Shorts

A reexamination of the data in the Office of Pipeline Safety (OPS) report on casing study (OPS, Technical Division, Interoffice Report-Project No. 87-6, May 10 (1988)) shows that among a total of 1,043 casings, the number of non-shorted casings (a subtotal of 862 casings) was more than 4 times that of shorted casings. However, only 2.4% of non-shorted casings had anomalies compared with 12.7% for the shorted casings. Thus, it is apparent that shorted casings are significantly more susceptible to corrosion than non-shorted casings. In reaching its conclusion that “A shorted casing does not enhance or reduce corrosion activity on carrier pipe,” OPS neglected the fact that the non-shorted casings were significantly more numerous than the shorted casings, which should be considered when the susceptibility of short to corrosion is assessed.

An analysis of the data available for SwRI’s study shows that the number of non-shorted casings (a subtotal of 157 casings) is approximately five times more common than that of shorted casings (a subtotal of 28 casings). The percentage of shorted casings with anomalies (16 out of 28, or 57.1%) was 4 times greater than non-shorted casings with anomalies (21 out of 157, or 13.4%). This finding is consistent with the new analysis of the previous OPS Study data.

One operator provided data to SwRI’s study that included the respective effect of metallic short, electrolytic short, and clear casings (no electrolyte in casings) on the external corrosion of carrier pipes in casings. For 139 casings considered (not including the 9 casings whose short-status is unknown), it was found that the presence of external corrosion for metallically shorted or electrolytically shorted casings is consistently higher than if casings lack electrolyte in the annulus.

Review of Historical Incidents of Cased Pipe Segments

A review of reportable pipeline incidents of cased pipe segments between August 7, 1984 and November 8, 2006 in the OPS database shows that among 11 incidents identified, 5 were known to be caused by corrosion, 3 by excavation, and 3 by unknown causes.

Of the 5 corrosion incidents, 3 resulted from atmospheric corrosion. Thus, atmospheric corrosion should be carefully considered when cased pipe segments are determined and/or prioritized for examination.

Distribution of Anomalies from Ends of Casings

A total of 1357 casings were considered for this particular analysis (lengths of the other 1376 casings were not provided for this study). Of the 1357 casings, 73% have a length in the range of 30-120 feet. The average is 104.3 feet and the median 71.6 feet. Two casings have lengths greater than 800 feet (1028 feet and 1585 feet); 11 casings between 500 feet and 800 feet, inclusive, accounting for 0.81%. Of the 1357 casings, 24.1% of the casings were shorter than 50 feet, 53.1% were shorter than 75 feet, 68.1% were shorter than 100 feet, 93.6% of the casings were shorter than 250 feet and 99.2% of the casings were shorter than 500 feet.

For the 272 cased pipe segments, which contain a peak anomaly with a depth of 20% wt or greater, the average casing length is 136.5 feet, greater than if the casings (1357 in number), which contain no anomaly or contain a peak anomaly but less than 20% wt in depth, are included. The statistical analysis below was based on the 272 cased pipe segments. The preferential location of the peak anomaly on a cased pipe segment was investigated.

For the *shortest distance* of anomalies from either end of the cased pipe segment, it is found that the number of anomalies decreases as the *shortest distance* increases. Beyond 60 feet, this number is small and sparsely distributed, particularly after 110 feet. Approximately 22% of all anomalies are within 2 feet, 45% within 10 feet, 62% within 20 feet, and only 13% are located beyond 60 feet.

The above analysis of using the *absolute shortest distance* has the drawback that far fewer cased pipe segments are counted when the *shortest distance* is large. Since the lengths of cased pipe segments vary widely from 17.4 feet to 1584.8 feet, with the average length of 136.5 feet, a *"relative" shortest distance*, or the ratio: *shortest distance/casing length*, provides an unbiased description of how anomalies are distributed along individual cased pipe segment.

A statistical analysis of *shortest distance/casing length* showed a preferential distribution of anomalies to occur within the first 2% length of the cased pipe segment, accounting for roughly 20% of all (272) anomalies. Beyond 2%, the anomalies are relatively uniformly distributed along the cased pipe segments.

Using the average casing length of 136.5 feet, the preferential distribution distance from either end of the casings is roughly 2% × 136.5 feet = 2.7 feet, which is consistent with the analysis using *"absolute" shortest distance*, that 25% of anomalies are located within 3 feet from either end of the casing. Thus, the true preferential distribution of anomalies in casings is within 3 feet, on average, from either end of the casing, although it must be noted that still, a significant majority, or 75%, of the anomalies are located beyond 3 feet.

The significance of this preferential distribution peak anomalies may be interpreted as, on average, from excavation of 3 feet from each end of the casing, an operator would gain 25% confidence in locating the peak anomaly of a cased pipe segment. Although this 25% is not large, without this knowledge of preferential location for peak anomalies, or assuming anomalies are randomly located on the cased pipe segment, it would require excavation of 10 times this length, or 30 feet from each end of the cased pipe segment, in order to gain the same confidence of locating the peak anomaly.

The *anomaly depth* and *length* were also statistically analyzed. For the *anomaly depth*, the average is 27.4% wt, the maximum is 84% wt, and the median is 25% wt; for the *length*, the average is 2.6 inches, the minimum 0.2 inch, the maximum 17.9 inches, and the median 1.6 inches.

CLARIFICATION OF RELEVANT TERMS AND ABBREVIATIONS IN THE REPORT

Definition of Relevant Terms

Anomaly: A corrosion defect on carrier pipe in casings indicated from ILI runs, which, in the context of this report, is the same as an anomaly indication.

Anomaly depth: Perpendicular to the pipe wall surface, the greatest depth of an anomaly relative to the original surface.

Anomaly length: In the axial direction, the length of an anomaly.

Clear casing: No metallic short and no electrolyte in the casing and carrier pipe annulus.

Corrosion: External corrosion of carrier pipe in casings.

Electrolytic short: A condition that electrolyte is filled partially or fully in the casing-pipe annulus and by conducting current through the annulus electrolyte; the potential difference between the casing surface and the carrier pipe holidays is significantly reduced from if they were isolated.

Factor of Safety: or *FP/MAOP*, used to measure the extent of threat to pipe safety by a corrosion anomaly, and for Class 1 location of road and railroad crossings, it is required in ASME B31.8 to be in general no less than 1.39 (or 1/0.72) for the design MAOP.

Failure Pressure (FP): or *burst pressure*, calculated following ASME B31G or Modified ASME B31G.

Isolated casing: No metallic connection between the casing and the carrier pipe, but *electrolytic short* can be possible when the annulus is partially or fully filled with electrolyte.

Maximum Allowable Operating Pressure (MAOP): Depending on class location, it is normally defined as: coefficient × SMYS, where the coefficient is in general 0.72 for Class 1 location of road and railroad crossings based on ASME B31.8.

Metallic short: Direct, physical metallic connection between casing and carrier pipe.

Peak anomaly: or *maximum anomaly*, the deepest anomaly on carrier pipe in a casing. In the context of this report, the depth is 20% wt or greater.

Piggability: a condition that a cased pipe segment can be in-line inspected.

Short: *Metallic short* if not otherwise specified.

Shortest distance/casing length: or *"relative shortest distance"*, the ratio of the shortest distance of a peak anomaly to the total length of the casing.

Shortest distance: The smaller distance between the location of the peak anomaly on carrier pipe and either end of the casing.

Abbreviations

AGA: American Gas Association.

CP: Cathodic protection.

DOT: Department of Transportation of the U.S.

ECDA: External corrosion direct assessment, a methodology.

FP/MAOP: Factor of Safety, used to measure the extent of threat to pipe safety by a corrosion anomaly.

FP: Failure (or burst) pressure.

INGAA: Interstate Natural Gas Association of America.

ILI: In-line inspection.

LRGW: Long Range Guided Wave.

MAOP: Maximum allowable operating pressure.

OPS: Office of Pipeline Safety, under DOT.

SMYS: Specified Minimum Yield Strength.

wt: Wall thickness.

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This report was edited and formatted by Ms. Lori Salas of Southwest Research Institute.

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[1] Mr. Alan Eastman of Mears Group helped with obtaining the data from Kinder Morgan.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

1.0 BACKGROUND AND OBJECTIVES

1.1 Background

Cased pipe segments are generally believed to be very safe since the time-independent threats, including third party excavation and outside force damage, are largely eliminated. However, external corrosion of carrier pipes in casings still poses a threat to pipeline safety. Understanding the causes and characteristics of carrier pipe corrosion in casings is an important step forward to better management of corrosion threats of cased crossings.

Carrier pipes in casings can suffer external corrosion in various forms, including:

- atmospheric corrosion on carrier pipe at coating holidays, exposed to air in the carrier-casing annulus,
- corrosion of the carrier pipe at the coating holidays in direct contact with electrolyte,
- localized corrosion due to galvanic coupling, concentration cells, the presence of bacteria, etc.

Understanding the external corrosion threats of the carrier pipes in casings will provide a technical basis for determination and prioritization for examination of cased pipes under an operator's Integrity Management Program.

Many factors can affect the integrity of cased pipe segments, including: differences in design of casings, steel or weld types, year of installation, extensions of casings to accommodate road work, historical interruptions of CP, historical leaks, historical shorts and clearance of shorts, bare or coated carrier or casing pipes, types and conditions of coatings on either carrier or casing pipes, local weather conditions, seasonal changes (temperature and rain falls), soil electrolyte corrosivity, local atmosphere corrosivity related to geographical locations such as coastal or grass/forest lands vs. desert, industrial areas vs. agricultural areas, and issues such as stray currents, third party damage, natural disasters (e.g., earthquake, hurricane, flooding), etc.

The investigation of the effects of all above factors on the external corrosion of cased pipe segments is beyond the scope of this project. This project focuses on a statistical analysis of the ILI anomaly data provided by seven operators and an evaluation of the effects of metallic and electrolytic shorts on the external corrosion of cased pipe segments.

Some operators' field experiences suggest trends, such as corrosion anomalies tend to be located near the ends of cased pipe segments. Quantifying these trends requires a broad database of observations. To ensure this is an industry-wide phenomenon, it is important to build up a significant database from different companies and statistically analyze the data. To this end, operators submitted a significant collection of ILI data of cased crossings gathered over the past several years to Southwest Research Institute® (SwRI®) for review and interpretation. This information formed a database from which trends were developed for a population representative of typical industry cased pipelines. This general statistical result from piggable cased pipe segments can then be used for determining and prioritizing the unpiggable cased pipe segments that require examination utilizing other techniques.

This work also includes a review of the past reportable incidents of cased pipe segments due to external corrosion. Understanding the causes of these notable failures can provide lessons learned and are helpful for better managing the integrity of cased pipe segments for the future.

1.2 Objectives

The following items will be presented in an effort to further the understanding of external corrosion on cased pipe segments:

- Overall statistical analyses of cased pipe segments with or without anomalies;
- Statistical analyses of ILI data to assess corrosion threats of carrier pipes in casings:
    - Distribution of anomaly indications vs. distance from either end of a cased pipe segment,
    - Distribution of anomaly depths and lengths,
    - Distribution of FP/MAOP for anomalies,
    - Percent of corroded cased pipe among all cased pipe segments for this study (%), and
    - Effect of "electrical" and "electrolytic" shorts on corrosion;
- Summary of historical reportable corrosion incidents in cased pipe segments.

2.0 ILI DATA COLLECTION AND ANALYSES

2.1 Data Format

A standard template for collecting ILI data was developed by the operators, as shown in Table 2-1. This data format was intentionally made simple (not include very many integrity-threatening factors as stated in Section 1.1) because it was realized that collecting field data was voluntary and could be time-consuming if not focused on only the parameters intended for this study.

Although it was supposed that the data format specified in Table 2-1 would be followed, several companies provided either a raw ILI data sheet (requiring the data to be extracted and then further processed into the proper format) or incomplete data. For data sets where the failure/burst pressures (FP) were missing, ASME B31G[1] and Modified B31G[2] were used to calculate the FPs to complete the dataset. The calculated results were shown to be consistent with FPs given for other anomalies with similar depths and lengths.

2.2 Data Analyses

2.2.1 Overall Statistics

A total of seven companies contributed their ILI data to this project, which was nearly all obtained from pig runs since 2004. One company provided only data for cased pipe segments with anomaly depths of 20% wt or greater, while other companies provided data for all cased pipe segments including those with no anomalies or with anomalies of any depth. Therefore, these different data sets had to be categorized before statistical analyses could be conducted. Table 2-2 shows the number of cased pipe segments (or casings) received from the seven individual companies with various anomaly depths.

In Table 2-2, the combination of A and B accounts for more than 64% of the 2733 cased pipe segments received. Among the total of 2733 cased pipe segments, 2461 either do not have an anomaly or have anomalies with a depth less than 20% wt (require no repair action following Modified B31G criteria), accounting for 90% of the entire population. Only one cased pipe segment has an anomaly depth exceeding 80% wt (require replacement of this pipe segment in order to prevent leaks following ASME B31G criteria), accounting for 0.04% of the total cased pipe segments.

Slightly less than 10% of the total 2733 cased pipe segments, or 272 cased pipe segments, contain anomalies with depths between 20% and 80% wt (scheduled repair following Modified B31G criteria). The breakdown for the number of cased pipe segments with anomaly depths between 20% and 80% wt (including 20% wt) is also shown in Table 2-2.

Figure 2-1 provides a visual demonstration of the casing data of Table 2-2. The cased pipe segment with an anomaly depth greater than 80% wt is hardly seen (blue color), while the casings with anomaly depths less than 20% wt accounts for a huge majority (green color). Overall, there is a significant reduction in the number of the cased pipe segments as the anomaly depth increases.

2.2.2 Limitations of the Data

When reading or interpreting the statistical data above and below, one must keep in mind the limitations of the data. All of this data was obtained using ILI tools, whose accuracy in finding and sizing anomalies depend on many factors including, but not limited to: the types of pigging tools used and their detection limits[3]; the qualification, competence and experience of the personnel using the tools; and the quality of the software used to process the data. Also, depending on the procedures of the service company and the requirements of the operators, the results obtained can differ.

One significant factor that can be overlooked is the misidentification of casings (or cased pipe segments) by the ILI tools. To verify whether the pigging runs, indeed, identified its casings correctly, Company D used Geographic Information System (GIS) and maps to independently check those casings identified from pig runs. For a limited set of casing data provided to this study (117 casings), this company found that approximately 44% of the "casings" identified by the pig turned out to not be actual casings. Among a total of 117 casings identified by pig runs, it was found that 65 were confirmed casings, 32 confirmed non-casings, and 20 unlikely casings. Only the confirmed 65 casings were used in this study.

According to this operator, one reason for the misidentification by pig runs could be attributed to how the pigs and/or data analysts identify a "casing". It appears that when the pig experiences certain conditions, like an extended "extra-metal" reading, it registers it as a casing even though that may not be the case. Alternatively, the pig may go through a casing but not record it, possibly because the casing is significantly larger than the pipe, and therefore, there is little or no magnetic signal jump from the pipe to the casing. Although there does not seem to be a pattern as to when the pig misidentifies or misses a casing, this company's data showed that it was highly likely that if the pig registered either an "eccentric start" or "eccentric end" to the casing, that casing did not actually exist (73% of the "eccentrics" were not actual casings). However, this only accounts for 31% of the misidentified casings, and thus, there are likely other factors that could attribute to the pig misidentification. Some other minor discrepancies, like one casing being identified as three adjacent casings, were also seen when comparing the pig data against GIS and maps.

It is unknown if the above problem also exists in the data provided from other companies (Company A claimed that its pig runs accurately located its casings). It is not within the scope of this work to verify the true casings for all other companies without them providing with such information. However, the sample of the confirmed casing data from Company D, even though the size is not large, can be used to independently check whether the total casing data is representative by comparing the casing data distributions as shown in Figure 2-2, where the data set of Company D and the total casing data are highlighted.

In general, the cased pipe segments with either no anomaly or with the peak anomaly depth less than 20% wt (green color), and those with an anomaly depth between 20% wt and 80% wt, including 20% wt (combined orange and dark red portions), are consistent. A discrepancy is the percentage of the cased pipe segments with a peak anomaly between 40% wt and 80% wt, which is more obvious for Company D than the total. As can be seen in Figure 2-2, the distribution of anomaly depth for the other companies varies differently.

To further confirm that the total casing data is valid in representing the anomaly distribution without being affected by misidentification of casings by pig runs, a more detailed comparison of the anomaly distribution of Company D vs. the total casing data is presented in Table 2-3, where a breakdown of the peak anomaly depth for every 10% wt interval between 10% and 80% wt is shown. The accumulated distribution of the anomalies is presented in Figure 2-3.

Figure 2-3 shows that the distributions of Company D and the total casing data are consistent overall. The consistency, to some extent, supports that the overall casing data may not be significantly distorted by any misidentification of the pig runs, if indeed that is a problem.

Using the total casing data, statistical analyses of the anomaly data on cased pipe segments are presented next.

2.2.3 Characteristics of the ILI Peak Anomalies

For the statistical analyses below, only the anomaly with a peak depth not less than 20% wt, and that is the deepest anomaly of a cased pipe segment (i.e., one anomaly per cased pipe segment), was counted and used. For anomalies below 20% wt in depth, modified ASME B31G recommends no repair actions except to arrest the active corrosion. The deepest anomaly of a cased pipe segment is used in an effort to examine the statistical nature of the most severe corrosion damage anomaly on a cased pipe segment and to avoid any preferential treatments of the cased pipe segments that contain many more anomalies than others.

The problem with using the deepest anomaly to represent the severest on a cased pipe segment is that the deepest anomaly may not necessarily be the most severe because the severity of an anomaly also depends upon its length. For casings on a pipeline section with the same carrier pipe diameter, wall thickness and operating conditions, the severity of an anomaly can be measured by failure (or burst) pressure (FP) because FP has included the effect of both the anomaly length and depth. The drawback is that for casings on different pipe sections with different carrier pipe diameter or wall thickness, FP alone is not a proper basis for comparing the anomaly severities. Therefore, only the Factor of Safety, which is defined as the ratio of FP to MAOP and is independent of pipe diameter and wall thickness, can be best used.

Although an alternative to using the deepest anomaly could be the use of the anomaly of greatest FP/MAOP on a cased pipe segment, the data provided is insufficient for this analysis.

Statistical analyses of a few key variables identified as the most useful for this project are described in the following sub sections.

2.2.3.1 Anomaly Distribution based on *Shortest Distance* from either End of Casing

Figure 2-4 shows the number and cumulative percentage of anomalies vs. *shortest distance* from either end of the casing. In Figure 2-4(a), a sharp decrease of the number of anomalies (represented by the height of blue columns) is shown as the *shortest distance* increases. Beyond 60 feet, the number becomes small and sparsely distributed, particularly after 110 feet. The number of anomalies within 60 feet account for 87% (shown on the pink curve).

Figure 2-4(b) is a portion of (a) focusing on the *shortest distances* closer to the end of the casing. Among a total of 272 anomalies, 62% are within 20 feet of a casing end. Within 2 feet, this percentage is 22%; 45% within 10 feet, and 54% within 15 feet. Only 16% of the anomalies are located beyond 50 feet.

The use of *"absolute" shortest distance* above has its drawback in determining the distribution of anomalies along cased pipe segments. When the shortest distance is large (such as 500 feet), only anomalies on carrier pipe deep in those long casings (greater than 1000 feet) can be counted; far fewer anomalies compared to anomalies whose shortest distance is small. In Section 5.0, it will show that the casing length varies widely from 17.4 feet to 1584.8 feet, with the average of 136.5 feet. Therefore, the above analysis of using *"absolute" shortest distance* masks the true distribution of the anomalies along the length of individual cased pipe segments, and overestimates the percentage of anomalies very near the ends of cased pipe segments.

A more objective statistical description of how the peak anomalies are distributed along the length of individual cased pipe segments is the use of *"relative" shortest distance*, defined as the ratio of shortest distance to the total casing length, or *shortest distance/casing length*.

Figure 2-5 shows that the first 2% of the length (or very near the ends of cased pipe segments) accounts for roughly 20% of the anomalies. The anomalies along the rest of the cased pipe segments are distributed relatively uniformly as demonstrated by the dotted blue line, which passes nearly most of the pink data points. This indicates that a preferential distribution of anomalies only occurs very near the ends of cased pipe segments, or the first 2% length of the cased pipe segment. Further into the casings, the distribution of anomalies is relatively uniform along the longitude of cased pipe segments.

With the average casing length being 136.5 feet, the preferential distribution distance from either end of cased pipe segment is calculated to be: 2% × 136.5 feet = 2.7 feet, which is approximately consistent with the 25% of anomalies within 3 feet from ends of cased pipe segments as shown in Figure 2-4, where an overestimation of 5% is shown. However, it must be noted that although there appears to be a preferential distribution of anomalies to very near the ends of the cased pipe segments, still 75% of the anomalies are located over 3 feet away from the ends into the cased pipe segment.

The significance of the above result of preferential location of a peak anomaly on a cased pipe segment may be interpreted as, on average, excavation of only 3 feet from each end of the casing, an operator would gain approximately 20 - 25% of confidence in locating the peak anomaly of a cased pipe segment. Although this confidence level is not high, without this knowledge of preferential location of anomalies, or assuming anomalies are randomly located along the cased pipe segment, it would require excavation of approximately 10 times this length, or 30 feet, in order to gain the same confidence. The cost associated with the extended excavation could be dramatically higher considering the particular locations of casings, normally under road, highway or railway crossings.

2.2.3.2 Anomaly Distribution Based on *Maximum Anomaly Depth*

Figure 2-6 shows the number and cumulative percentage of anomalies vs. *maximum depth* (% wall thickness). Here, the first column and second column from the left represent anomalies whose depths are at 20% wt and at 21% wt, respectively. Since only cased pipe segments with peak anomaly depths not less than 20% wt are used in the entire section of 2.2.3, no anomaly is less than 20% wt in depth.

Figure 2-6 shows that approximately 52% of anomalies (pink curve) are within the first 5% span of maximum depth, between 20% wt -25% wt, inclusive. Within the next 5% span (between 25% wt - 30% wt, including 30% wt), this percentage drops sharply to 23%. Greater than 30% wt depth, the anomalies account for only 24%.

The average depth is 27.4% wt, the maximum 84% wt, and the median depth is 25% wt.

2.2.3.3 Anomaly Distribution Based on *Anomaly Length*

Figure 2-7 shows the number and cumulative percentage of anomalies vs. *anomaly length.* Slightly more than 60% of anomalies have a length of less than 2 inches, and only 11% have a length of more than 5 inches.

The average length is 2.6 inches, the minimum 0.2 inches, the maximum 17.9 inches, and the median length is 1.6 inches.

2.2.3.4 Anomaly Distribution Based on *FP/MAOP*

The severity of damage to the cased pipe integrity by corrosion anomalies can be reflected by the Factor of Safety, or the ratio: *FP/MAOP*, which is independent of an individual pipe's nominal wall thickness (t), diameter (D), and steel properties (SMYS), because both FP and MAOP are proportional to the term: $\mathrm{SMYS}\frac{2t}{D}$, based on ASME B31G or modified ASME B31G. Thus, *FP/MAOP* can give an unbiased estimate of the threat of corrosion anomalies to different pipe sections (with different t or D) from different operators. In this ratio, only the corrosion threats contributed by the anomaly geometry and dimensions are accounted for.

A plot of the number and cumulative percentage of anomalies vs. *FP/MAOP* is shown in Figure 2-8. Only 5 anomalies of the total of 272 have FP/MAOP less than 1.39 (require repair action or lower MAOP following Modified B31G), which, interestingly, do not include the deepest anomaly (84% wt) whose FP/MAOP is rather large, 1.64, due to its small length (0.79 inch). Following ASME B31G criteria, the pipe segment containing this anomaly requires replacement to prevent leaks. For all anomalies, the lowest FP/MAOP is 1.28.

Excluding this deepest anomaly, 98.2% of the remaining anomalies require no repair action according to Modified B31G, if class locations are not considered. For crossings of roads or railroads with casings, ASME B31.8[4] recommends a design factor of 0.72 (or 1/1.39) for both Div. 1 and Div. 2 of Class 1 except for private roads of Div. 1 where the design factor is recommended as 0.8.

To account for all cased pipe segments received for this study, a total of 2733, of which the majority either do not contain an anomaly or contain a peak anomaly less than 20% wt in depth, 99.82% of all the cased pipe segments do not require repair action, accounting for an overwhelming majority of the casings received for this study.

Figure 2-8 also shows that 46% of all anomalies have *FP/MAOP* falling within 1.7-2.1, inclusive. The average is 2.1 and the median is 2.0. This high average ratio reinforces that the cased crossings are overall in excellent condition.

It is useful to use *FP/MAOP* to determine if the damage severity of an individual anomaly is preferentially located near the ends of the cased pipe segment, similar to preferential location of anomalies along cased pipe segments (Section 2.2.3.1).

Figure 2-9 shows the distribution of anomalies vs. *FP/MAOP*, calculated using the number of anomalies within every 0.1 interval of *FP/MAOP* divided by the subtotal number of the anomalies within an interesting range of *shortest distance* from the ends of cased pipe segments (0-5 feet, 5-10 feet, 10-20 feet, 20-50 feet, and over 50 feet). The number of anomalies within the above five ranges is approximately the same.

Figure 2-9(a) shows the percent distribution of anomalies vs. FP/MAOP for each range, with a dot to replace the blue column bars used before. Figure 2-9(b) is the cumulative distribution of anomalies vs. FP/MAOP, or integration of Figure 2-9(a) followed by normalization to 100%.

It is quite clear that the patterns for the five different distance ranges are similar to each other in both figures. Since the difference in the distribution for the five different distance ranges reflects levels of the corrosion damage severity along cased pipe segments, the similarity of the five distributions (representing different distances along the cased pipe segments) indicates that the damage severity of individual anomalies do not depend on locations.

As a simple example to understand above non-preferential location of the damage severity of peak anomalies represented by *FP/MAOP*, casings on one pipeline with the same carrier diameter, wall thickness, operating condition may be used. Then, this non-preferential distribution of *FP/MAOP* means that the peak anomalies have similar sizes (depth and length) regardless of their being located near the ends of casings or inside.

Table 2-1. Format Used to Collect ILI Data from Operators for this Project

Pipeline Segment	MP	Casing #	ILI Year	Corrosion > 20%	Max Peak Depth (% WT)	Length of Anomaly (in)	Casing Length	Shortest distance from casing end	Predicted Burst Pressure	PF/ MAOP	Class Location	Diameter	MAOP	W.T.	SMYS	% SMYS	Shorted?

Table 2-2. Overall Statistical Analyses of Casing Data

Company name	A	B	C	D	E	F	G	Total
Total Casings	559[2#1]	1200[2#2]	149[2#3]	65[2#4]	36	376	348[2#2]	**2733**
d[#] <20% wt	509	1056	116	57	31	364	328	**2461**
% of total	91.06	88.00	77.85	87.69	86.11	96.81	94.25	**90.05**
20%=< d <30%	34	117	20	5	3	8	14	201
30%=< d <40%	13	25	8	1	0	3	3	53
40%=< d <80%	3	2	4	2	2	1	3	17
20%=< d <80%	50	144	32	8	5	12	20	**271**
% of total	8.94	12.00	21.48	12.31	13.89	3.19	5.75	**9.92**
d >=80%	0	0	1	0	0	0	0	**1**
% of total	0.00	0.00	0.67	0.00	0.00	0.00	0.00	**0.04**

Table 2-3. Comparison of Confirmed Casing Data from Company D with Total ILI Data

Anomaly depth interval	**10%=<d<20%**	**20%=<d<30%**	**30%=<d<40%**	**40%=<d<50%**	**50%=<d<60%**	**60%=<d<70%**	**70%=<d<80%**	**80%=<d**	**Total**
Company D: no of anomalies (Ndi)	5	5	1	1	1	0	0	0	13
Nd/(total no of anomalies of D)x100%	38.5%	38.5%	7.7%	7.7%	7.7%	0.0%	0.0%	0.0%	100.0%
All companies: total no. of anomalies (Nti)	139	201	53	11	3	2	1	1	411
Nt/(total no of anomalies)x100%	33.8%	48.9%	12.9%	2.7%	0.7%	0.5%	0.2%	0.2%	100.0%
Anomaly depth range	>=10%	>=20%	>=30%	>=40%	>=50%	>=60%	>=70%	>=80%	
Company D: no of anomalies (Ndc)	13	8	3	2	1	0	0	0	
Ntc/(total no of anomalies)x100%	100.0%	61.5%	23.1%	15.4%	7.7%	0.0%	0.0%	0.0%	
All companies: total no. of anomalies (Ntc)	411	272	71	18	7	4	2	1	
Ntc/(total no of anomalies)x100%	100.0%	66.2%	17.3%	4.4%	1.7%	1.0%	0.5%	0.2%	

[2#1] Two casings provided have identical casing number (Casing 401).

[2#2] Only casings with anomalies were provided. This total casing number was given by the company contact.

[2#3] This total was determined directly from the spreadsheet data provided by Company C who missed one casing count (Pipeline Segment A) in its summary data to be shown in Section 3.3.

[2#4] Two casings provided have identical casing number (Segment L 142S, Casing 114C)

[#] d is the anomaly depth in terms of wall thickness (wt).

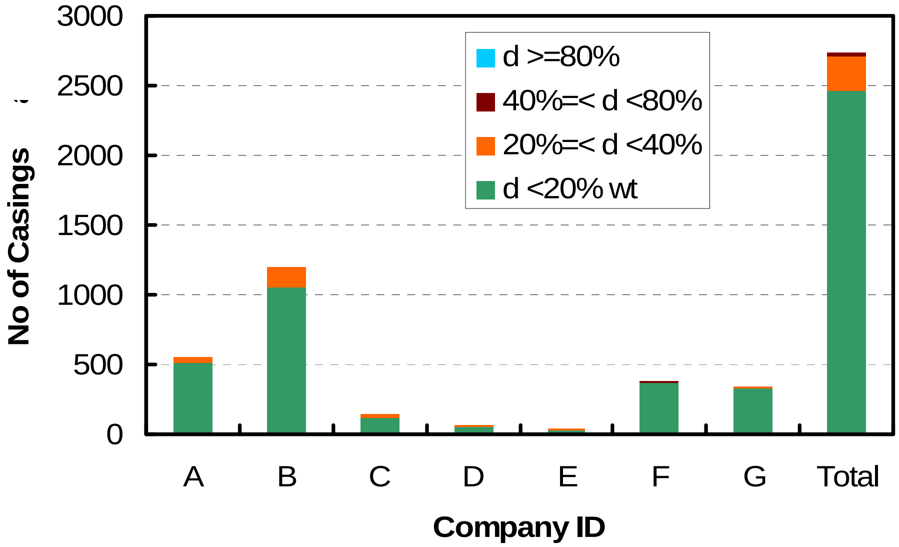


Figure 2-1. Distribution of the number of casings with different depths of anomalies obtained from individual companies and their total.

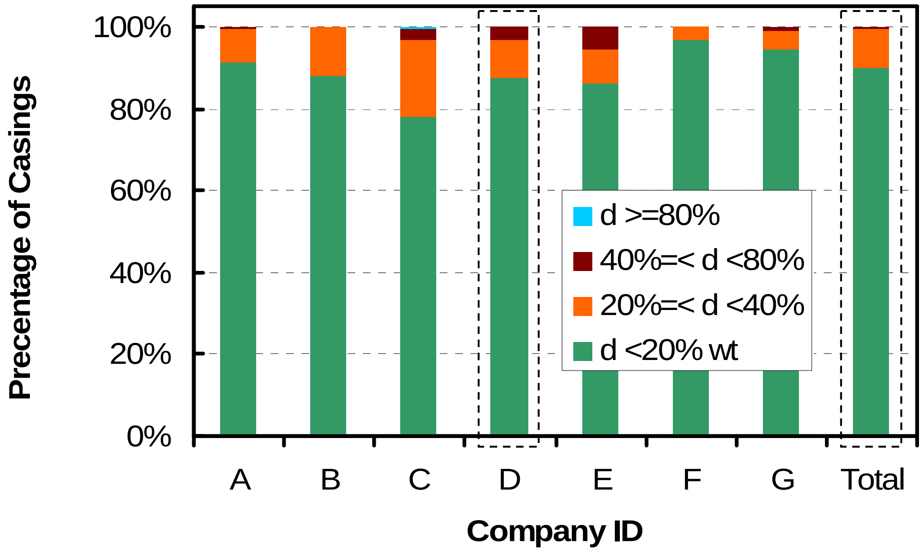


Figure 2-2. Distribution of the number of casings with different depths of anomalies obtained from individual companies and their total.

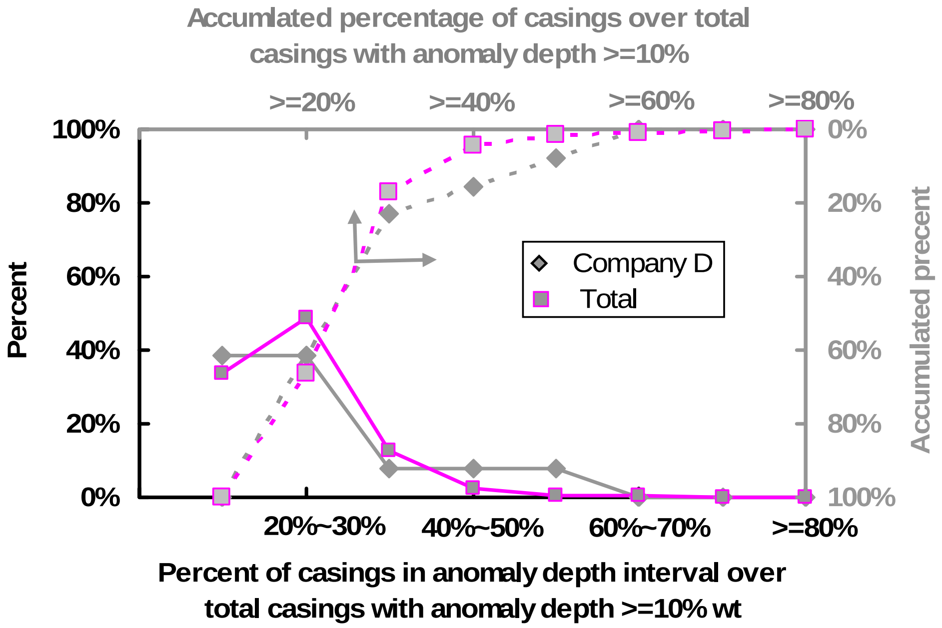
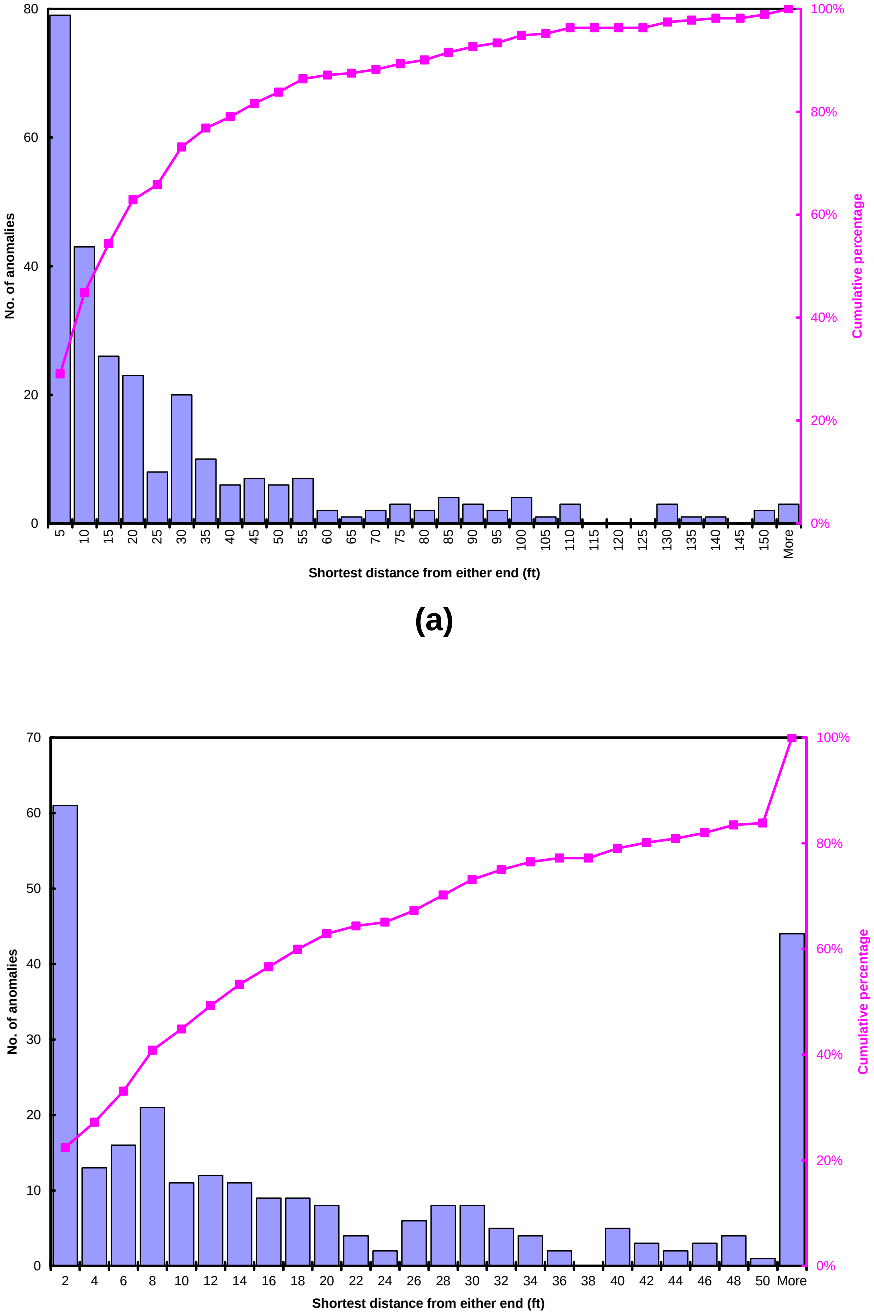


Figure 2-3. **Comparison of confirmed casing data from Company D with ILI casing data from all companies in term of percentage of casings over the total casings for intervals (left and bottom axes) or for ranges (top and right axes) of anomaly depth.**



(a)

(b)

Figure 2-4. **The number and cumulative percentage of peak anomalies vs. the shortest distance from either end of casings: (a) overall view, and (b) nearer the ends of casings. Only the deepest anomaly in a casing with its depth not less than 20% wt is used for this analysis, same for Figures 2-5 – 2-9.**

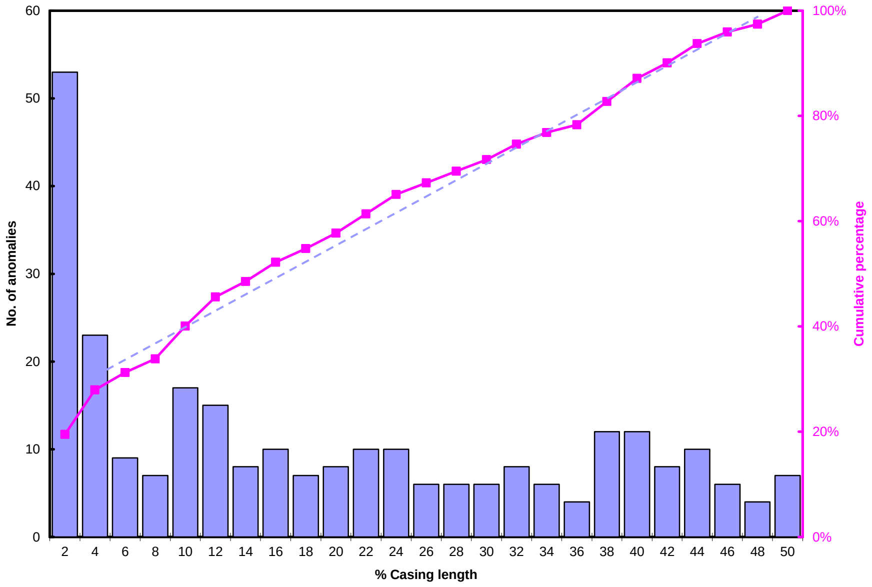


Figure 2-5. **The number and cumulative percentage of peak anomalies vs. the percentage of the shortest distance from either end of casings over the longitude of cased pipe segments.**

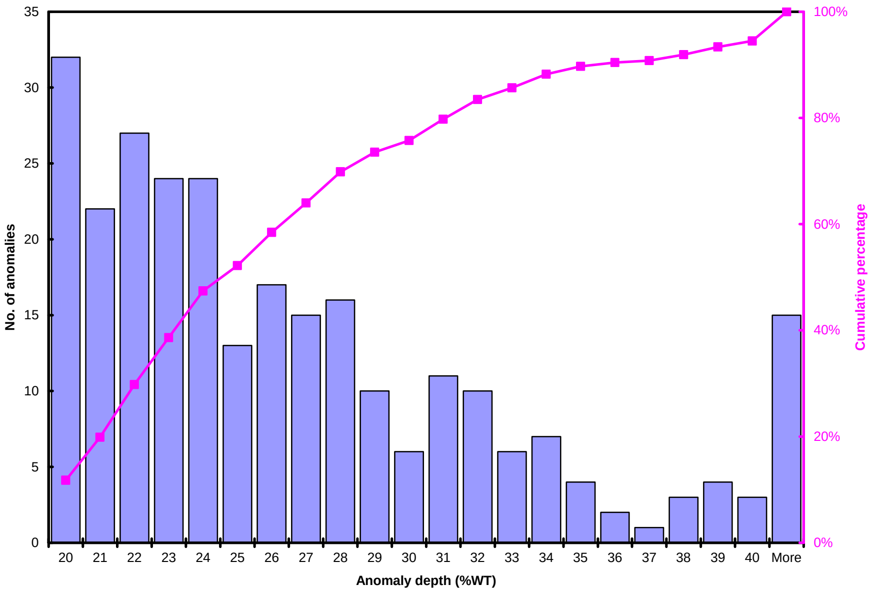


Figure 2-6. **The number and cumulative percentage of peak anomalies vs. maximum peak depths in % of wall thickness.**

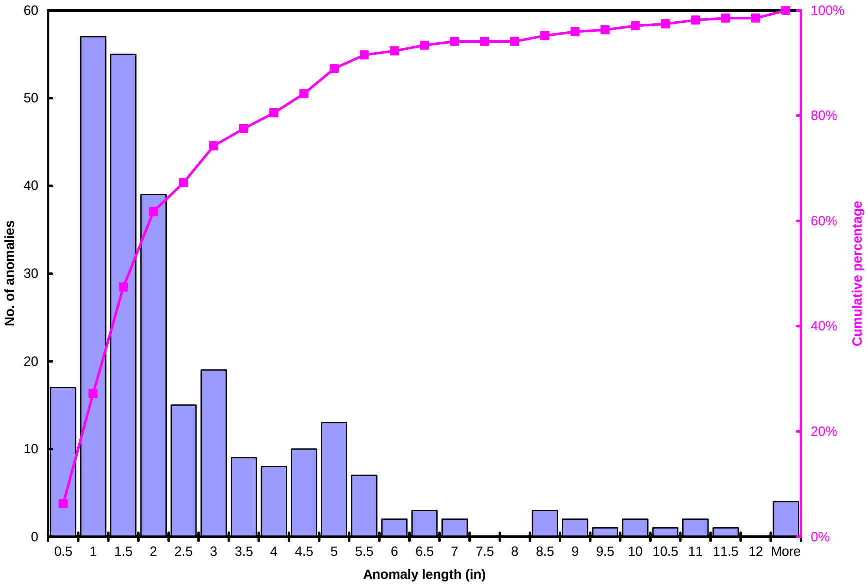


Figure 2-7. **The number and cumulative percentage of peak anomalies vs. anomaly length in inches.**

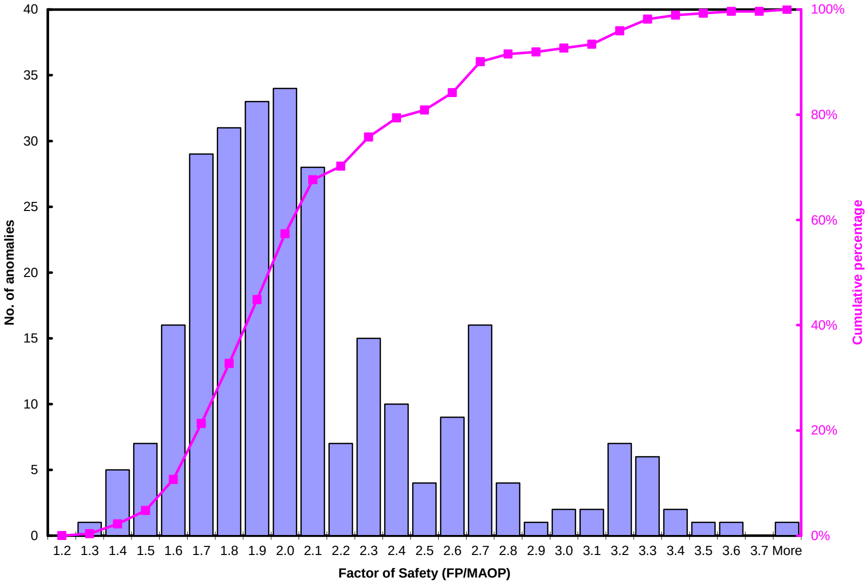
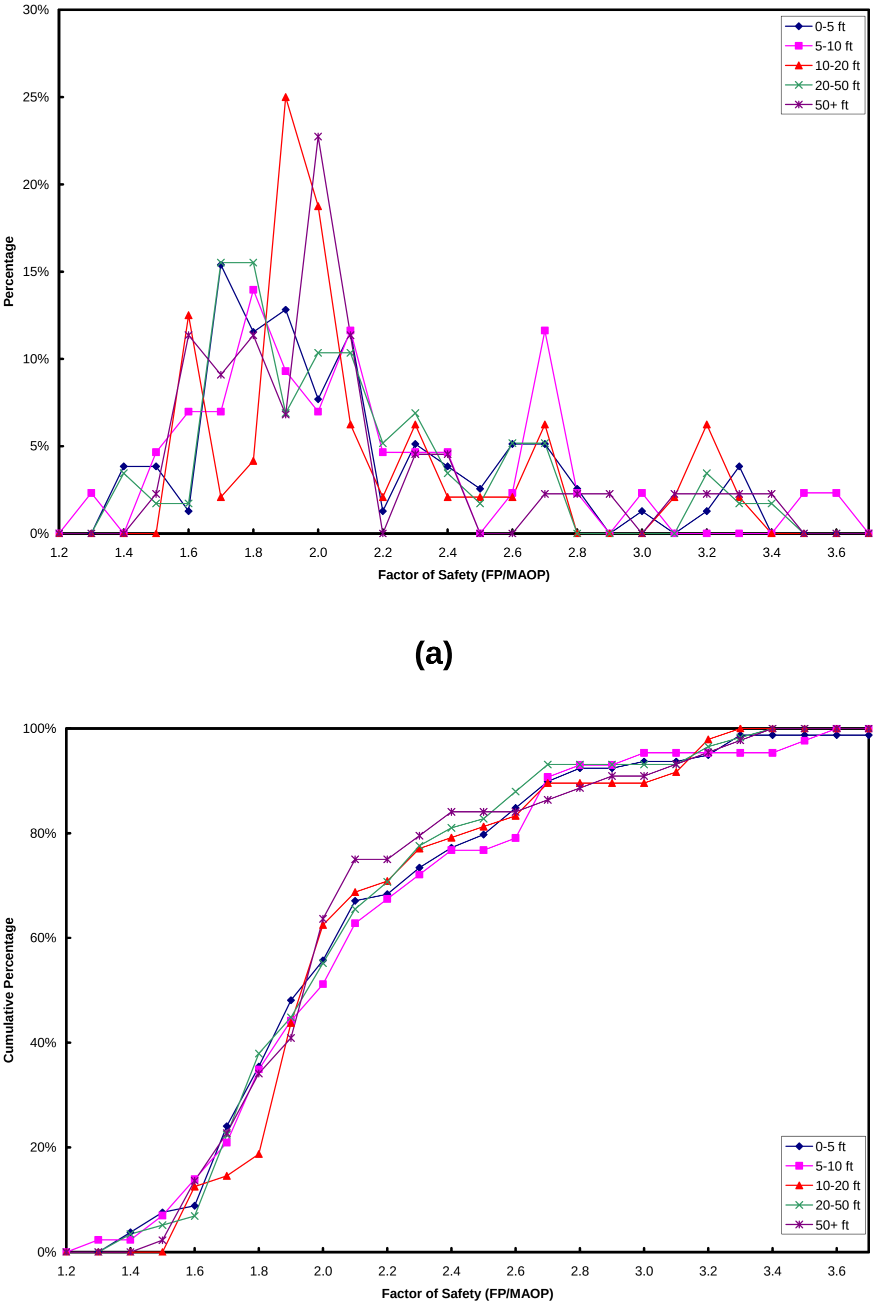


Figure 2-8. **The number and cumulative percentage of peak anomalies vs. Factor of Safety or the ratio of failure pressure (FP) and MAOP.**



(a)

(b)

Figure 2-9. **The distribution of anomalies vs. FP/MAOP, calculated using the number of anomalies within every 0.1 interval of FP/MAOP divided by the subtotal number of anomalies within the ranges of shortest distance from either end of the casing: 0-5 feet, 5-10 feet, 10-20 feet, 20-50 feet and greater than 50 feet. For each range, the number of anomalies is roughly the same.**

3.0 REVIEW OF THE PREVIOUS OPS REPORT AND EFFECT OF SHORTS

3.1 Review of the Previous OPS Report (1988)[5]

The 1988 OPS report[5] documented that a previous casing study stated that "A shorted casing does not enhance or reduce corrosion activity on carrier pipe". This statement was made based on a statistical analysis of ILI anomaly data obtained at that time, which, however, seems to contradict what is normally understood, that a metallic short can adversely increase the chances of carrier pipe corrosion because of its possible elimination of any CP benefits. CP could otherwise be received by the carrier pipe if the casing and carrier pipe are metallically isolated and electrolyte is partially or fully filled in their annulus. This concept will be discussed in more detail in Section 3.3. In this report, the terminology "short" means "metallic short" if not otherwise noted.

The ILI data for cased pipe segments in the 1988 OPS report was reexamined and the new analyzed result is summarized in Figure 3-1. Among a total of 1,043 casings, the non-shorted casings (a subtotal of 862 casings or 83% of total casings) are four times more numerous than the shorted casings (a subtotal of 181 casings or 17% of total casings). Although the number of cased pipe segments with corrosion anomalies (anomaly depth was not specified in the report) for non-shorted casings (21 casings) is just slightly less than that for shorted casings (23), the percentage of non-shorted cased pipe segments with anomalies among its subtotal (2.4%, or 21 over 862) is rather much smaller than the percentage of shorted casings (12.7%, 23 over 181), suggesting that shorted casings are significantly more susceptible to corrosion than non-shorted casings.

The statement of the 1988 OPS report[5] resulted from a comparison of the percentage of non-shorted cased pipe segments with anomalies (21 casings) over the total cased pipe segments with anomalies (44 casings). Anomalies were found on 47.7 % of the non-shorted cased pipe segments and on 53.3 % of shorted cased pipe segments. However, this comparison neglected the fact that the non-shorted cased pipe segments were four times more than the shorted cased pipe segment, which should be considered when the susceptibility of the shorted or non-shorted casings to corrosion was compared.

The higher susceptibility of shorted cased pipe segment to corrosion suggests that a metallic short does increase the chances of external pipe corrosion and thus, shorted casings should be considered to receive prioritization for integrity assessment.

3.2 Comparison of OPS Report Result with Result of this Study

Only companies B, C, E, and G provided data for shorted and non-shorted casing data, and companies C and E also provided data including the presence or absence of corrosion peak anomalies. Therefore, only can the C and E data be used to determine the respective susceptibility of shorted and non-shorted cased pipe segments to corrosion.

A summary of the data is presented in Table 3-1, where both the total casings, including those without anomalies on the carrier pipe, and the casings with a peak anomaly depth of 20% wt or greater on the carrier pipe are included for both shorted and non-shorted casings.

The numerical value of Table 3-1 is graphically presented in Figure 3-2(a), to show an easy comparison with Figure 3-1. There are several similarities between the data shown in the two pictures:

- The non-shorted casings (a subtotal of 157 casings) are four times more than the shorted casings (a subtotal of 28 casings).
- The number of non-shorted casings with the carrier containing corrosion anomalies (21 casings) is similar to that for shorted casings (16 casings).
- The percentage of non-shorted casings with the carrier containing anomalies (13.4%, 21 over 157) is much smaller than the percentage of shorted casings (57.1%, or 16 over 28).
- The percentage of non-shorted casings with the carrier containing anomalies (21 casings), roughly 56.8% (21 over 37), is similar to the percentage of shorted casings, or 43.2% (16 over 37).

Consistent with the result of the new analysis of the OPS Report data, the result obtained using data of this study shows that short can significantly increase the corrosion susceptibility of carrier pipe in casings.

A further investigation of the second bullet, and thus, the fourth was conducted based on ILI data for cased pipe segments from Companies B, C, E, and G, as shown in Table 3-2 and Figure 3-2(b).

Among the total 201 cased pipe segments with anomalies, the non-shorted cased pipe segments (172 casings or percentage 86%) are five times more than that of shorted cased pipe segments, instead of roughly the same based on the OPS report[5] (Figure 3-1) or data from companies: C and E (Figure 3-2(a)). This suggests the fourth bullet may not be a common result.

3.3 Mechanisms and Corrosion Effects of Shorts

Some casings are bare and some coated; some isolated from the carrier pipe, some electrically shorted or electrolytically coupled to carrier pipe. These casings present either little, partially, or fully CP shielding problems to the carrier pipe. Depending on the level of electrolyte in the annulus, atmospheric corrosion or corrosion in electrolyte of the cased pipes can be an issue. Corrosion of a cased pipe segment with the annulus filled with non-electrolyte material was not a subject of this study. The data provided to this study did not contain information about whether the annulus was filled with non-electrolyte material.

As shown in Figures 3-3(a) and (b), the pipe surface at holidays exposed to air would suffer atmospheric corrosion, regardless of the casing being isolated or shorted. If no electrolyte is present in the annulus or the electrolyte level below the pipe bottom, as shown in Figure 3-3(a), there is no pathway for CP to reach the pipe holidays. Thus, CP is completely ineffective. If the pipeline is, however, partially (Figure 3-3(b)) or fully (Figure 3-3(c)) submerged in electrolyte, CP current could reach the pipe surface in direct contact with the electrolyte and can become effective, although the effectiveness would be higher if the casing were absent. The polarization resistances at both the casing inner and outer surfaces must be overcome in order for the CP current to pass through the casing wall.

When the casing and the pipe are electrically shorted, the absence of potential gradient between the inner surface of the casing and the carrier pipe surface at holidays would lead to complete ineffectiveness of CP, as shown in Figure 3-3(d). This would also be true for the case shown in Figure 3-3(b) if the carrier pipe and casing were shorted.

3.4 One Operator's Field Experience on the Effect of Shorts and Other Parameters

3.4.1 Criteria for Shorts

One operator conducted detailed casing studies that included an investigation of the effect of metallic short, as well as electrolytic short, on the corrosion of carrier pipe. Already loosely defined earlier, an electrolytic short is a condition where electrolyte is filled in the casing-pipe annulus and the potential difference between the inner (or outer, if the potential difference is negligible) surface of casing and carrier pipe holidays is small or negligible due to the current flow through the annulus electrolyte.

In this company's Operating and Maintenance Procedures, shorts were determined according to the following procedure and criteria:

- When the casing/soil potential vs. $Cu/CuSO_4$ and pipe/soil potential vs. $Cu/CuSO_4$ has a difference less than 50mV, it was considered that the casing and carrier pipe are either metallically or electrolytically shorted;
- Panhandle Eastern tests[6] are performed on all casings with less than 50mV difference to determine the type of short;
- Casings with a resistance less than or equal to 0.08 ohms are considered metallically shorted;
- Casings with a resistance greater than 0.08 Ohms are considered electrolytically shorted;
- A large resistance would indicate the casings are clear; no metallic short and no electrolyte in the annulus.

Although, in general, the casing potential is more positive than the pipe potential, when a reverse situation occurs, the operator's experience suggests the following circumstances may have generally occurred:

- A galvanic anode connected to the casing.

- An impressed current groundbed is located nearby and the casing is receiving current from the groundbed due to interference issues.
- Error in the casing-to-soil reading due to resistance in the mechanical connection to the casing.

3.4.2 Field Test Data and Data Analyses

This company provided comprehensive casing data, including data other than requested for this study. This additional information includes separating casings into metallically shorted (Mshort), electrolytically shorted (Eshort) and clear (Clear), and having correlated corrosion anomalies on cased pipe segments vs. 500 feet outside away from each end of the casing.

This data resulted from five pipeline segments (A, B, C, D, E) containing a total of 148 casings[3#1], of which the short-status of nine casings was unknown and not used in the study for the effect of shorts.

Table 3-3 is a summary of cased pipe segments containing low depth anomalies (≥ 10% wt) and higher depth anomalies (> 30% wt). For both types of anomalies, the percentage of electrolytically or metallically shorted casings is consistently higher than when compared to clear casings (no electrolyte in annulus and no metallic short). Due to the locations of the pipe segments (South and Southeast Texas), the company believed that the casing-pipe annulus should contain water all year round, not just in the rainy seasons as in some other parts of the United States, as the water tables in South and Southeast Texas are typically much higher than rest of the U.S. Historically, casings which are clear, typically remain clear from reading to reading and there are not, generally, wide variations in casing to soil potentials from reading to reading. Electrolytically shorted casings, generally, consistently track the potential of the carrier pipe.

Table 3-4 shows the ratio of anomalies on each cased pipe segment relative to anomalies located within 500 feet outside away from either side of the casing. For clear casings, there is a low ratio of external anomalies located outside within 500 feet from both ends of the casings compared to the inside of the casings, indicating low tendency of corrosion of the carrier pipe inside casings than outside. In contrast, electrolytically shorted cased pipe segments contain a higher number (compared metallically shorted casings) of external anomalies on the inside of the carrier pipe than outsider 500 feet from both ends of the casings.

Prior to offering an explanation of the above result, it would be useful to understand how CP functions under both electrolytic- and metallic-short conditions. By definition, CP works on the carrier pipe both inside and outside of the casing under electrolytic short. On the contrary, under metallic short, CP on the carrier pipe is not effective inside the casing due to the low electric resistance of metallic contact, and becomes less effective (than the case of electrolytic short) outside of the casing due to the large bare surface area of the casing, which competes for CP current with, and depress the CP current to, the holidays of the coated carrier

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[3#1] One casing in Pipeline Segment A was not counted based on spreadsheet data.

pipe outside casings. The result is to increase corrosion anomalies on the carrier pipe both inside and outside of the casing (in comparison with electrolytic short).

For the similar number of metallically and eletrolytically shorted casings, although the metallically shorted casings showed more anomalies on the carrier pipes 500 feet outside from both ends of the casings, compared to electrolytically shorted casings. The number of anomalies on the carrier pipes inside of the casings is rather small on metallically shorted casings compared to electrolytically shorted casings, inconsistent with increased anomalies by metallic short as explained above. The explanation can be that the metallically shorted casings also contain casings that are metallically shorted but contain no electrolyte in the annulus. Such casings function the same as clear casings with low number of corrosion anomalies inside casings. Thus, the corrosion anomalies on carrier pipes inside casings with metallic shorts could be higher than in the table if all the casings contain electrolyte in the annulus.

Coal tar enamel was present as coating on four pipe sections. The other pipe section was coated with fusion bonded epoxy (FBE). There were a total of 24 casings on the FBE coated pipe section and none of them contained any external metal loss indications on the carrier pipe within the casings. All of the casings were clear except for one, which is metallically shorted. The absence of indications could be related to a combination of the non-shielding nature of FBE coatings, quality of coating application and/or the quality of installation (limited or no damage during installation). Thus, the type of coatings should be taken into account when cased pipe segments are prioritized in a pipeline integrity program.

Root-cause analysis from prove-up excavations was reviewed where available by this operator. For two of the pipe sections, both had casing excavations where root cause analysis could be performed. In both instances the casing spacer damaged the carrier pipe coating. Figures 3-4 and 3-5 showed two examples of corrosion under insulator spacers.

Table 3-1. ILI Casing Data of Only Companies C & E: Total Casings and Total Shorted or Non-shorted Casings, with or without Anomalies, for Determining the Effect of Short on Corrosion

Company name	C	E	Total
Total casings	149	36	185
Casings with >=20% anomalies	32	5	37
Total non-shorted casings (N1)	121	36	157
Casings with >=20% wt anomalies (Nc1)	16[*#]	5	21
Nc1/N1x100%	**13.2%**	**13.9%**	**13.4%**
Total shorted casings (N2)	28	0	28
Casings with >=20% wt anomalies (Nc2)	16	0	16
Nc2/N2x100%	**57.1%**	**N/A**	**57.1%**
Total casings with >=20% wt anomalies for C and E (Nct=Nc1+Nc2)			37
Nc1/Nctx100%			**56.8%**
Nc2/Nctx100%			**43.2%**

Table 3-2. ILI Casing Data of Only Companies B, C, E & G: Total Casings and Total Shorted or Non-shorted Casings with Anomalies, Insufficient for Determining the Effect of Short on Corrosion

Company name	B	C	E	G	Total
Total Casings with >= 20% wt Anomalies	144	32	5	20	**201**
Non-shorted Casings	132	16[*#]	5	19	**172**
% of total	91.7%	50.0%	100.0%	95.0%	**85.6%**
Shorted Casings	12	16	0	1	**29**
% of total	8.3%	50.0%	0.0%	5.0%	**14.4%**

[*#] Include 3 casings whose short status is unknown.

Table 3-3. One Operator's Casing Data with Statistical Analyses for Total Casings, Metallically Shorted, Electrolytically-shorted, or Non-shorted Casings with or without Anomalies

	All Casings		Casings containing Minor Indications (>10% wt)		Higher level indications (>30% wt within casings)	
	#	Percent	#	Percent	#	Percent
Total Casings	*148*	*100*	*30*	*20.3*	*12*	*8.1*
Clear Casings	95	64.1	9	**9.5**	3	**3.2**
Eshort Casings	22	14.9	8	**36.4**	5	**22.7**
Mshort Casings	22	14.9	12	**54.5**	3	**13.6**
Unknown Casing Status	9	6.1	1	11.1	1	11.1

Table 3-4. The Operator's Casing Data with Statistical Analyses for Indications inside Casings vs. Those within 500 ft from Both Ends of the Casings

	All Casings		Total Ratio of Indications Inside Casing vs Within 500ft for casings containing indications		Total Ratio of Indications Inside Casing vs Within 500ft for all casings	
	#	Percent	Inside/Outside	Outside/Inside	Inside/Outside	Outside/Inside
Total Casings	148	100	308/347	347/308 (1.1:1)	308/611 (0.5:1)	611/308 (2:1)
Clear Casings	95	64.1	27/116 (.23:1)	116/27 (4.2:1)	27/321 (0.08:1)	321/27 (11.9:1)
Eshort Casings	22	14.9	173/8 (21.6:1)	8/173 (.05:1)	173/32 (5.4:1)	32/173 (0.18:1)
Mshort Casings	22	14.9	94/216 (.44:1)	216/94 (4.9:1)	94/250 (0.38:1)	250/94 (2.66:1)
Unknown Casing Status	9	6.1	14/7 (2:1)	7/14 (0.5:1)	14/8 (1.75:1)	8/14 (0.57:1)

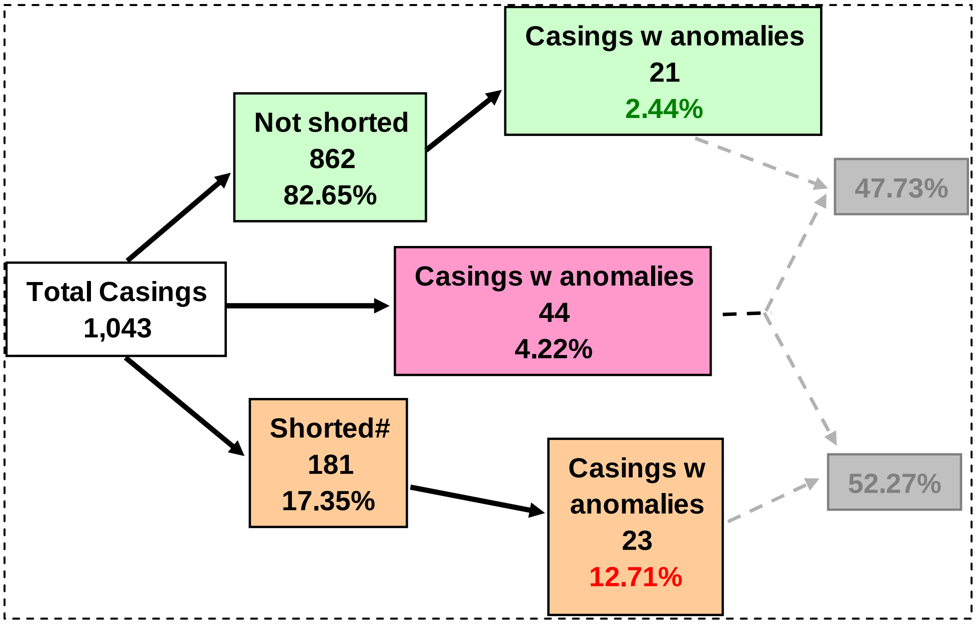
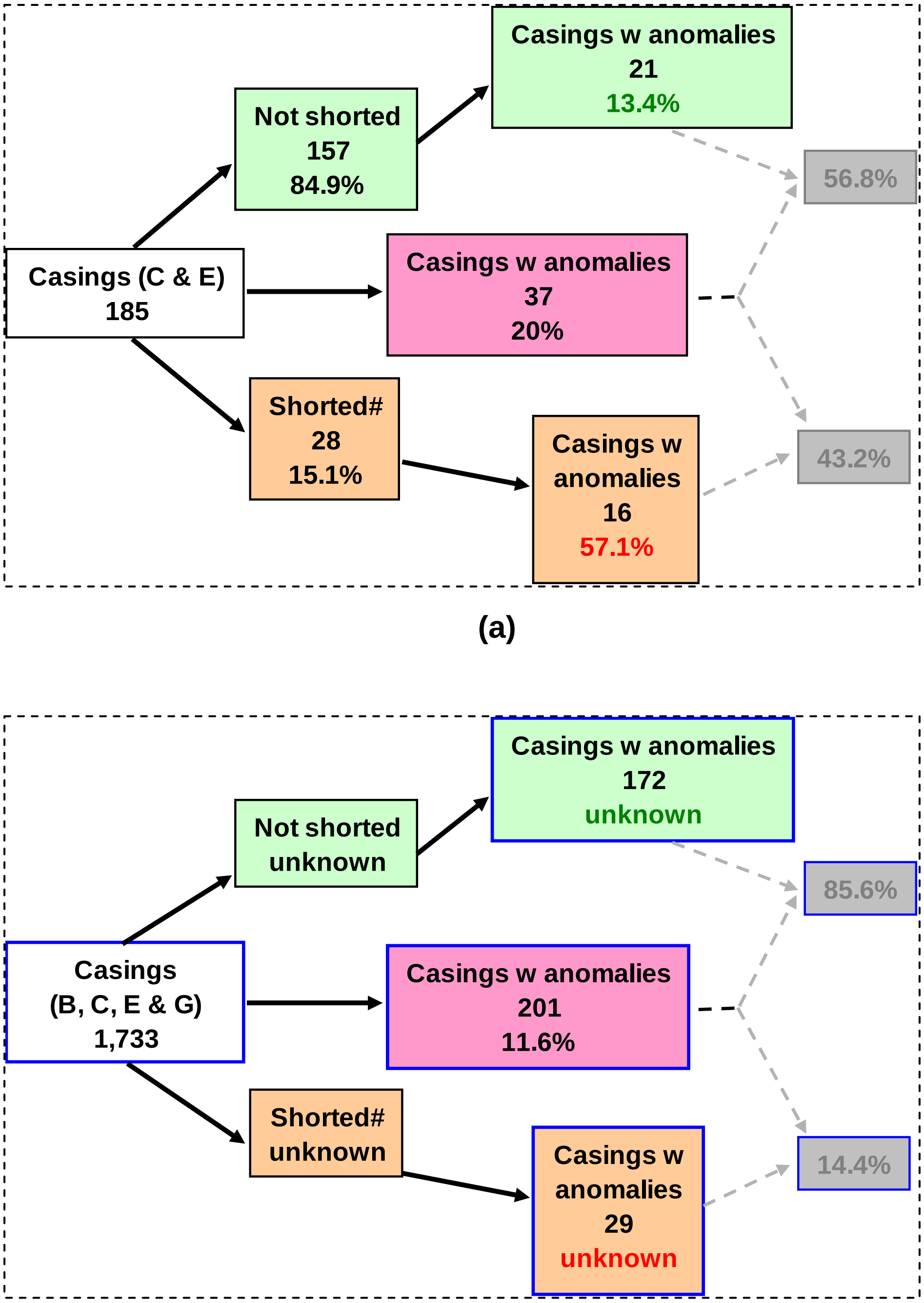


Figure 3-1. New analysis of the ILI casing data extracted from the 1988 OPS study on casings. [3#1]

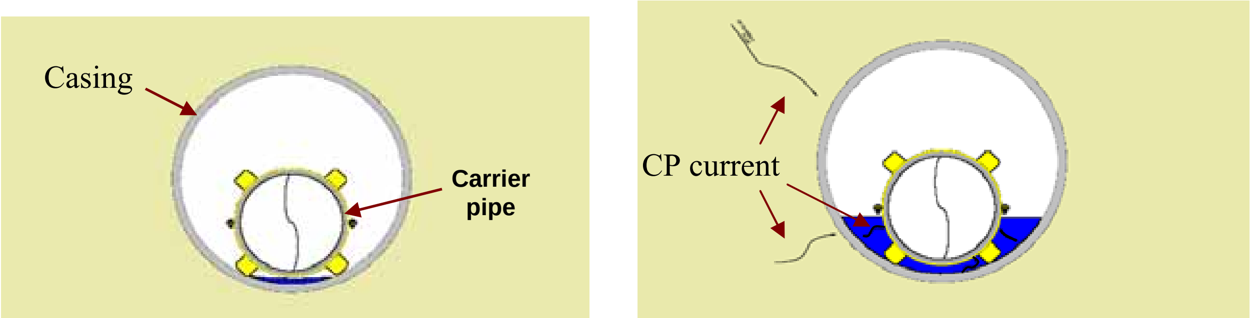
[3#1] Anomaly peak depth was not reported.



(a)

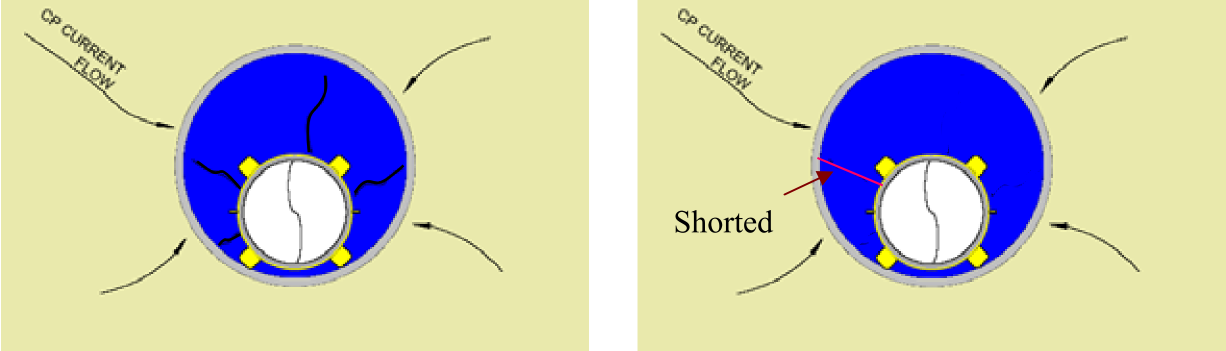
(b)

Figure 3-2. Analysis of the ILI casing data for this current study: (a) for Companies C and E only, and (b) for Companies: B, C, E and G. The latter data is insufficient to determine the effect of short on corrosion.



(a) Isolated casing. Dry or water below the carrier pipe. No CP current reaches to the pipe surface.

(b) Isolated casing. Annulus partially full of electrolyte. Holidays on bottom of pipe submerged receive CP current.

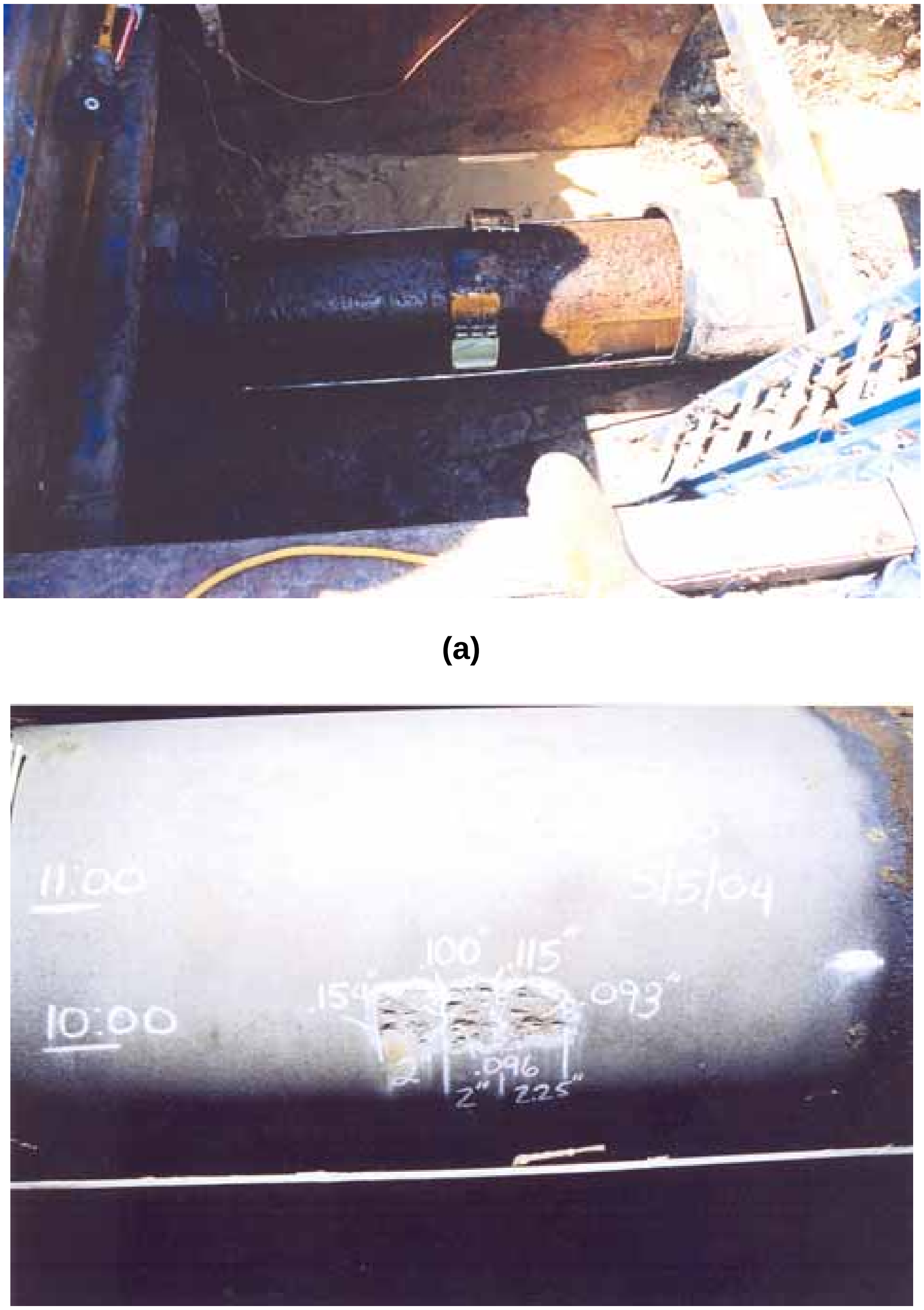


(c) Isolated casing. Annulus full of electrolyte. All holidays receive CP current.

(d) Shorted casing. Annulus full of electrolyte. Holidays of pipe receive zero CP current.

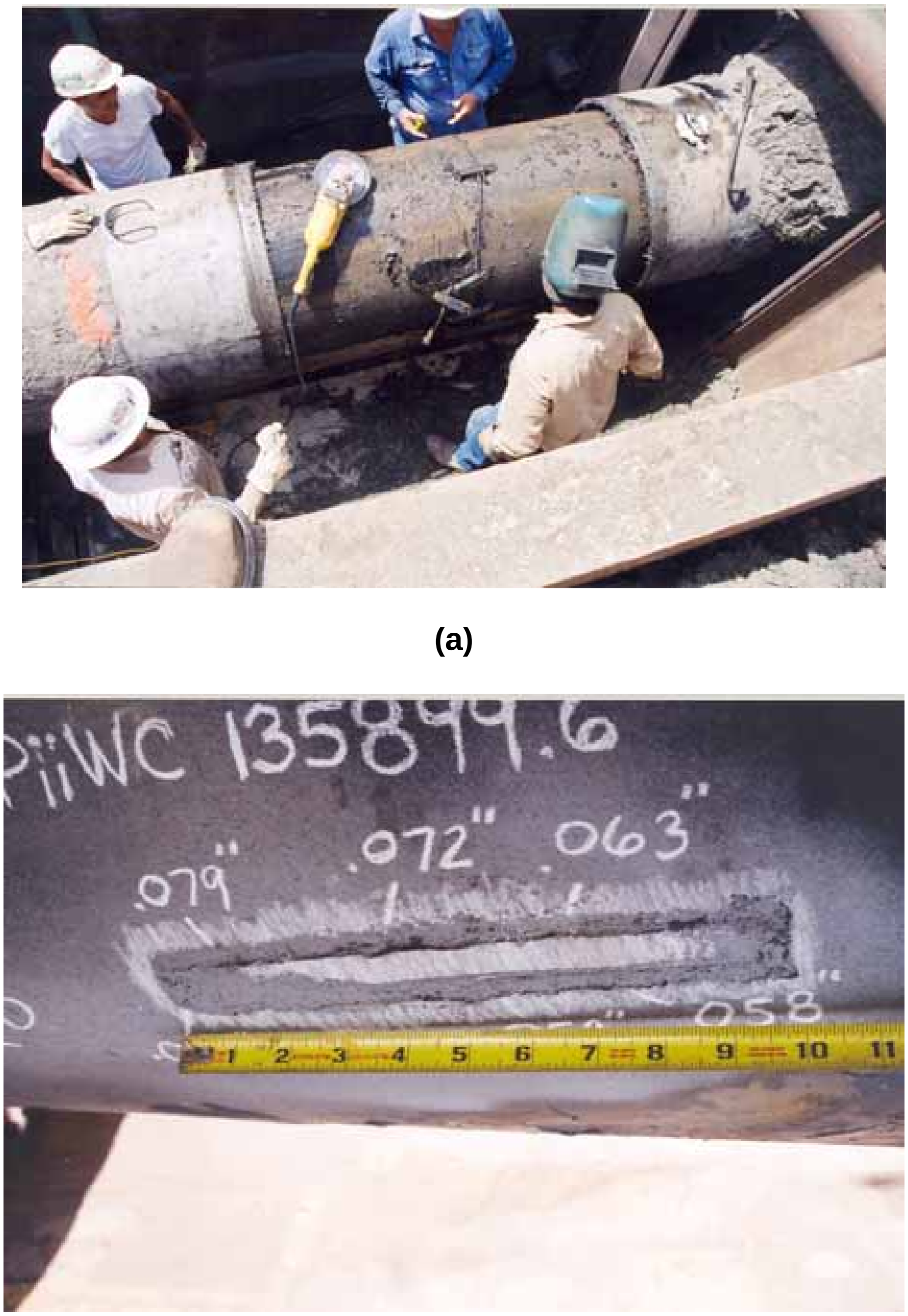
Figure 3-3. Schematic diagrams to demonstrate conditions of shorts. See descriptions under each sub-figure.[3#2]

[3#2] Diagram modified from a presentation of Mr. Earl Kirkpatrick at NACE Conference 2006.


(a)

(b)

Figure 3-4. Corrosion beneath a plastic casing spacer: (a) overall picture, and (b) the ridges in the corrosion that match up with the spacer stand-offs.



(a)

(b)

Figure 3-5. Corrosion beneath wood pieces attached by wire between them used as casing spacers: (a) overall picture, and (b) the outline of the wood spacer matches the corrosion.

4.0 REVIEW OF HISTORICAL REPORTABLE INCIDENTS IN CASED PIPE SEGMENTS

A review of reportable natural gas pipeline incidents involving casings in the OPS-record database was conducted for incidents occurring between August 7, 1984 and November 8, 2006. However, it would be useful to describe two incidents reported in the OPS report (1988) to gain an understanding of real corrosion incidents involving casings[5].

4.1 Two Incidents Reported in the OPS Report (1988)[5]

4.1.1 Colonial Pipeline Company (1980, Hazardous Liquid Pipeline)

An incident occurred on March 6, 1980 in a Colonial Pipeline Company's 32 inch diameter liquid pipeline inside a cased highway road crossing in Virginia. This failure resulted in an estimated loss of 8000 barrels of aviation kerosene. Although no one was killed or injured, 5,000 fish and small animals were killed because of the failure. The cleanup of the polluted farm land, streams, river banks and reservoirs continued for several months. It was later determined that the casing involved with the failure had been electrically shorted to the carrier pipe for 10-12 years. Metallurgical examination of the failure led to the following conclusion.

"… the failure occurred at an area near the bottom of the pipe that had been thinned by corrosion. Apparently, the corrosion resulted from ground water leakage past the pipe-to-casing seal and into the annular space between the pipe and casing, where shielding effect of the casing would mitigate against obtaining adequate CP in this area…." It was also reported that: "The fact that the casing was shorted to the pipe may have prevented a small amount of CP current from entering the annular space, but the effect on the overall rate of attack probably was small."

This OPS report regarded the metallic short as a minor factor to the incident, while the shielding effect was treated as the major cause. In fact, it is likely that the shielding effect resulted mainly from the short as discussed in Section 3.3 of this report and thus, short can likely be a key factor resulting in the incident. Recent experimental tests[7-9] showed the sufficient CP can be achieved on the carrier pipe if the casing-pipe annulus is filled with electrolyte and the casing and pipe isolated. Direct metallic short could remove the CP benefit and allow free corrosion to occur.

4.1.2 Texas Eastern Gas Pipeline Company (1985, Natural Gas Pipeline)

This incident was detailed in the National Transportation Safety Board (NTSB) report of February 18, 1987[10], where detailed investigation of the failure was reported. In the OPS report (1988), it was reported that the incident occurred on April 27, 1985 when a 30 inch diameter natural gas pipeline of the Texas Eastern Gas Pipeline Company ruptured under Kentucky State Highway 90. The escaping gas ignited and burned an area about 700 feet long and 500 feet wide. Five persons in one house were killed and three others burned as they ran from their mobile home. There was extensive damage to buildings, construction equipment, and other property.

The corrosion was attributed to several factors. The NTSB report[10] stated the probable cause of the accident to be "… unsuspected and undetected atmospheric corrosion …" Atmospheric corrosion occurs on a pipeline where moisture from the air, along with contaminates, come into contact with exposed metal.

This casing was located about 2 miles downstream of a compressor station with the line temperatures in the range of 140 - 160 °F. With high heat, the coating was badly damaged. With the presence of vents and the consistently higher line temperatures than the local temperature, cyclic water condensation occurred on the carrier pipe ,which provided electrolyte necessary for the atmospheric corrosion.

4.2 DOT Reportable Pipeline Incidents in Casings between August 1984 to November 2006

The DOT reportable incident database was provided by AGA and the Process Performance Improvement Consultants, LLC, covering the period from August 7, 1984 to November 8, 2006.

A search of casing incidents by using the keyword "casing" or "cased" found a total of 11 incidents occurred in cased crossings during this period of the time. These incidents are summarized in Table 4-1.

Among the 11 incidents, 5 were known to be caused by corrosion as highlighted in orange in the table. For the rest, excavation damage accounted for 3, including the cause of "damage by test". The other 3 incidents were noted in the database for causes as either unknown or miscellaneous. This result indicates that corrosion and excavation can be the primary causes of the carrier failures in casings.

Of the 5 corrosion incidents, 3 resulted from atmospheric corrosion (Natural Gas Pipeline Co. of America, Texas Eastern and Columbia Gulf Transmission).

Table 4-1. DOT Reportable Pipeline Incidents in Casings between August 1984 to November 2006

Incident date	Company name	Class Location	Offshore/Onshore	Incident Type (Leak, Rupture, Other)
4/27/1985	Texas Eastern Pipeline Company*	1	ONSHORE	RUPTURE
8/16/1988	AMOCO GAS CO	3	ONSHORE	LEAK
3/18/1992	NATURAL GAS PIPELINE CO OF AMERICA	1	ONSHORE	LEAK
9/13/2006	COLUMBIA GULF TRANSMISSION	1	ONSHORE	LEAK
10/16/2006	SOUTHERN STAR CENTRAL GAS PIPELINE I	N/A	ONSHORE	LEAK
7/9/1985	WESTAR TRANSMISSION CO	1	ONSHORE	OTHER
2/8/2002	ENOGEX INC (EX. MUSTANG FUEL CORP)	1	ONSHORE	RUPTURE
01/07/03	SOUTHERN CALIFORNIA GAS CO	3	ONSHORE	LEAK
04/23/03	EL PASO FIELD SERVICES	1	ONSHORE	OTHER (Road casing vent leaking)
8/22/2003	PACIFIC GAS & ELECTRIC CO	1	ONSHORE	LEAK CAUSED BY LONGITUDINAL TEAR
6/18/2005	COLUMBIA GULF TRANSMISSION	N/A	**OFFSHORE**	LEAK

Incident State	Type of pipe	PIPE_COAT	PRTYR	NPS	WALLTHK	CAUSE_TEXT
KY	TRANSMISSION SYSTEM	COATED	1952	30	0.375	**CORROSION**
TX	TRANSMISSION SYSTEM	COATED	1961	12	0.22	**CORROSION**
NE	TRANSMISSION SYSTEM	COATED	1942	26	0.25	**CORROSION**
LA	INTERSTATE	COATED	1954	30	0.5	**CORROSION, EXTERNAL**
KS	INTERSTATE	COATED	1971	20	0.26	**CORROSION, EXTERNAL**
TX	TRANSMISSION SYSTEM	N/A	1963	20	0.25	DAMAGE BY TEST
OK	INTRASTATE	N/A	1970	20	0.25	THIRD PARTY EXCAVATION DAMAGE
CA	INTRASTATE	N/A	1947	12	0.22	MISCELLANEOUS
TX	INTRASTATE	N/A	1971	12	0.22	MISCELLANEOUS
CA	INTRASTATE	N/A	1931	8	0.25	THIRD PARTY EXCAVATION DAMAGE
LA	INTERSTATE	N/A	N/A	18	0.41	UNKNOWN

VIS_EXAM_TEXT	COR_CAUSEO	Corroison type	CPYR
GENERAL CORROSION	***ATMOSPHERIC INSIDE CASING***		N/A
LOCALIZED PITTING Corrosion (external)	GALVANIC		1961
LOCALIZED PITTING Corrosion (external)	OTHER	***ATMOSPHERE***	1942
GENERAL CORROSION	***ATMOSPHERIC INSIDE OF CASING***		1954
GENERAL CORROSION	DISBONDED COATING IN AREA SHIELDED BY CASING		1971
			N/A
			N/A
			N/A
			N/A
			N/A
			N/A

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* This incident of Texas Eastern was included in the table based on data in the NTSB report[10].

5.0 DISTRIBUTION OF CASING LENTGH

Section 2.2.3.1 for determining the preferential location of the peak anomaly on a cased pipe segment, underlined the significance of understanding the distribution of casing Length. A statistical analysis of casing lengths is undertaken for all casings received for this study (Figure 5-1(a)), and for casings that contain anomalies with a depth of 20% wt or greater (Figure 5-1(b)).

Of the 2733 casings surveyed for this study, a total of 1357 casings were considered for the analysis in Figure 5-1(a). The lengths of other 1376 casings for this study were not provided. Of the 1357 casings, Figure 5-1(a) shows that 73% have a length in the range of 30 - 120 feet. The average is 104.3 feet and median 71.6 feet. Two casings have lengths greater than 800 feet (1028 feet and 1585 feet); 11 casings between 500 feet and 800 feet, inclusive, accounting for 0.81%.

Based on the 1357 casings surveyed, 24.1% of the casings were shorter than 50 feet, 53.1% were shorter than 75 feet, 68.1% were shorter than 100 feet, 93.6% of the casings were shorter than 250 feet, and 99.2% of the casings were shorter than 500 feet.

For the 272 cased pipe segments that contain peak anomalies with a depth of 20% wt or greater, the casing length varies widely from 17.4 feet to 1584.8 feet, with the average of 136.5 feet and the median 93.0 feet (Figure 5-1(b)). Both the average and median are respectively greater than those (1357 casings) which also included casings that contain no anomaly or contain peak anomalies less than 20% wt in depth. For these 272 casings, 15.8% are shorter than 50 feet, 40.4% shorter than 75 feet; 54.4% less than 100 feet; 69.1% less than 150 feet; 89.0% less than 250 feet; and 98.9 less than 500 feet.

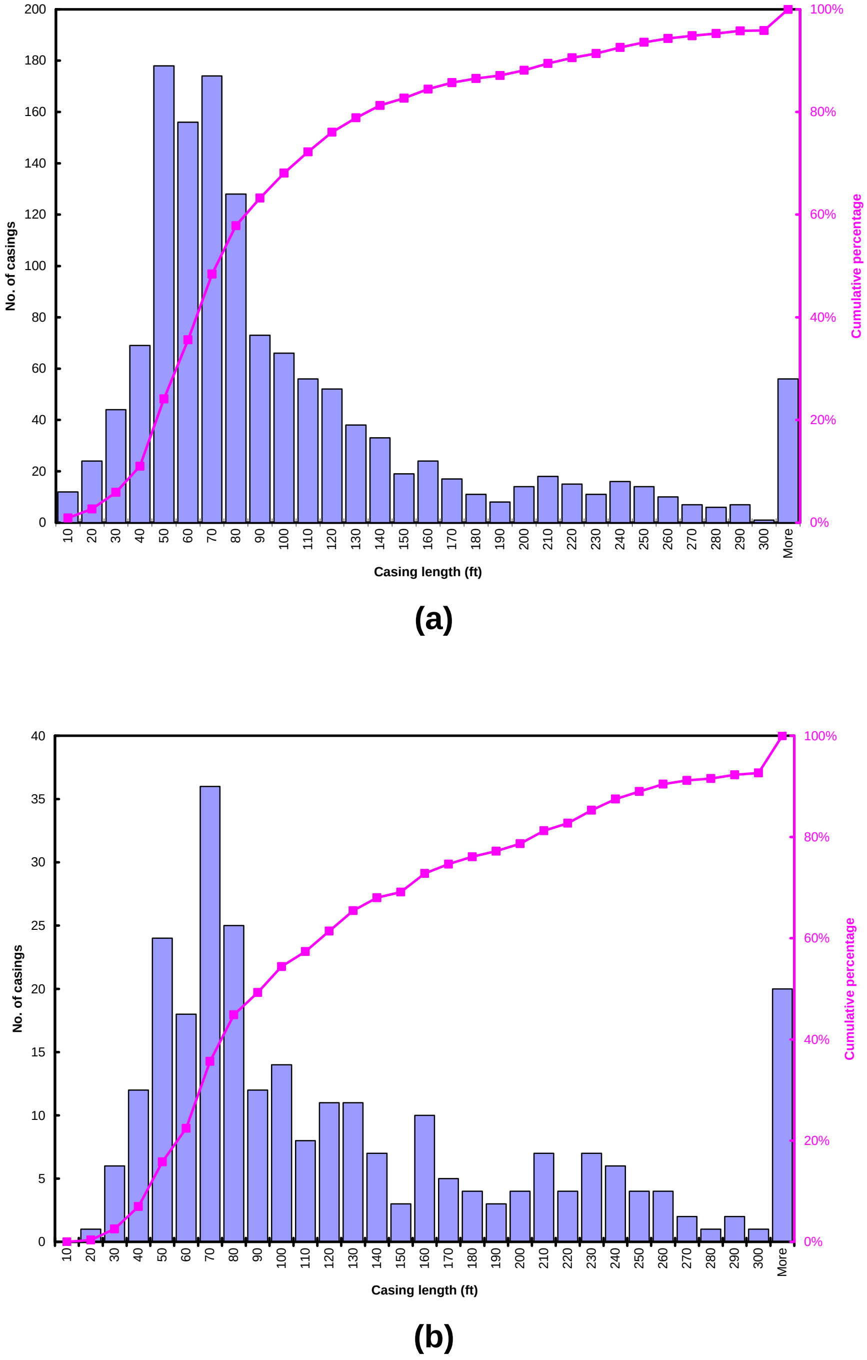

Figure 5-1. **Distribution of Casing Lengths (a) for all casings with or without anomalies, and (b) for casings with a peak anomaly depth not less than 20% wt.**

6.0 CONCLUSIONS

For the total of 2733 casings received for this study, only slightly less than 10% of them (272 casings) contain anomalies, on the carrier pipes, with a depth of 20% wt or greater. Only one cased pipe segment contains an anomaly whose depth is greater than 80% wt.

The preferential location of anomalies on carrier pipe inside casings is 2% of the casing length, or approximately 3 feet on average, from either end of the casing. Beyond 3 feet, the peak anomalies are relatively uniformly distributed. This preferential location contains 25% of the peak anomalies; the peak anomaly has over 10 times likelihood to be located here than any other place on the carrier pipe with the same area.

Only five peak anomalies of the total of 272 cased pipe segments have an *FP/MAOP* less than 1.39 (scheduled repairs), accounting for 1.8%. These five anomalies do not include the deepest one (84% wt) whose *FP/MAOP* is rather large, 1.64, owing to its small length (0.79 inch). The pipe segment containing this anomaly is required to be replaced to prevent leaks in accordance with the ASME B31G criteria.

Excluding the cased pipe segment with the deepest anomaly, the total number of cased pipe segments is reduced to 2732. Of the 2732 casings, the percentage accounted for by the 5 anomalies scheduled for repairs drops to 0.18%. An overwhelming majority of cased pipe segments do not need any repair action based on modified ASME B31G criteria. It is cautioned that this conclusion can be affected by the original design factor of the cased pipe segments.

The distributions of *FP/MAOP*, reflecting the severity of individual peak anomalies to the pipeline integrity, are independent of locations along the cased pipe segments, i.e., the severity of individual anomalies does not have a preferential distribution along the cased pipe segment.

The new analysis of the OPS 1988 report data and the analysis of new data provided for this study show that shorted-casings are significantly more susceptible to corrosion than that of non-shorted casings. In reaching its conclusion: “A shorted casing does not enhance or reduce corrosion activity on carrier pipe,” OPS neglected the fact that the non-shorted casings were significantly more numerous than the shorted casings.

One operator’s field data for a limited number of 139 casings suggests that metallically shorted casings or electrolytically shorted casings are more prone to resulting in carrier pipe corrosion than clear casings (no electrolyte in the annulus).

A review of reportable pipeline incidents in casings between August 7, 1984 and November 8, 2006 in the OPS-record database shows that among 11 incidents identified, 5 were known to be caused by corrosion, 3 by excavation, and 3 by unknown causes. Of the 5 corrosion incidents, 3 resulted from atmospheric corrosion. Atmospheric corrosion attributes to more than half of corrosion failures in the past.

The above analyses are based on ILI results provided by the seven operators, which may have variance due to several factors (e.g., tool resolution limits).

7.0 RECOMMENDATIONS

ILI external anomaly data of cased pipeline crossings were analyzed. However, the severity of the corrosion anomalies to the integrity of the cased pipe segments relative to the uncased sections outside of the casings is not known until a comparison of the severity of the anomalies on the two different sections of the carrier pipelines is conducted. AlthoughSection 3.4.2 of this report showed a comparison of anomaly distribution between inside and 500 feet outside from each end of the casings, the limited data set may not be sufficient to represent the industry. It is suggested that more data from a number of operators is provided for similar analysis but focusing on FP/MAOP.

The different effects of metallic short, electrolytic short and no short on external corrosion should be studied further with more data sets.

The effect of dielectric fillers, such as wax petrolatum on the external corrosion of cased carrier pipe, and the long-term performance of the fillers need to be understood. This is a subject that was not scoped in this work.

The effect of different coating types, age of casings, interruption of CP, and other factors not touched above, are also important in a pipeline integrity program.

8.0 REFERENCES

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10. NTSB, “Pipeline Accident Report – Texas Eastern Gas Pipeline Company Ruptures and Fires at Beaumont, Kentucky, on April 27, 1985 and Lancaster, Kentucky, on February 21, 1986”, Report No. NTSB/PAR-87/1, Report Date: February 18, 1987.