# What's in the Numbers? A Review and Analysis of More than 400 Miles of Force Main Inspection and Condition Assessment Data

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## 1. Introduction

Comprehensive condition assessment of wastewater force mains provides significant challenges to owners/operators of collection systems since the ability to shut down or expose the pipeline for a thorough inspection is often impractical due to operational and/or financial considerations. Traditional gravity sewer inspection techniques (i.e. visual based technologies) do not always transfer easily to their wastewater pressure pipe counterparts and visual assessments do not provide the structural condition of force main – something that is critical in determining the true pipe condition. Therefore, a different set of inspection tools and assessment techniques is required for force mains.

The most effective strategy to safely manage a force main inventory is to implement a risk based approach for any data collection, inspection, condition assessment, and management techniques. Using asset risk to guide the management strategies, an owner/operator can ensure they are implementing the right approach, at the right time, with the lowest financial impact. While, recent advances in force main inspection technologies, assessment techniques, and repair/rehabilitation methods now allow for substantial extension of existing asset service life, a risk based approach to their implementation will ensure resources are focused on the correct pipelines. The goal should always be to focus the proper resources in managing the asset while safely getting the most service life out of the force main.

## 2. Background

Wastewater utilities in the United States focus significant resources towards the evaluation of their collection system performance due to regulatory pressure, public health concerns, and a focus on proper asset management practices. Evaluations have primarily focused on the gravity collection system through capacity and condition assessments resulting in rehabilitation and replacement programs often influenced by regulatory drivers. The assessment, rehabilitation, and replacement components provide the utility with the ability to better manage their wastewater water collection system reducing illegal discharges to the environment and protecting public safety. Capacity and condition assessments have become increasingly more effective through advancements in the assessment technologies. Specifically, flow metering, hydraulic modeling, robotic inspection, and trenchless rehabilitation/replacement technology advancements over the past several years have allowed wastewater utilities to efficiently understand the condition of the buried infrastructure as well as effectively extend the useful life and manage these assets. The assessment technology advancements provide higher quality data allowing for a thorough understanding of a collection system's existing capacity, inflow and infiltration sources, as well as operational and structural defects that can be addressed through rehabilitation and/or replacement action. Gravity mains are typically assessed in a programmatic approach known as a sewer system evaluation survey (SSES). A SSES typically follows the following methodology:

- Implementation of a comprehensive flow metering program to identify areas with high wet weather peak flows
- Targeted smoke testing in areas identified by the flow metering program locating potential inflow sources
- Dye testing to confirm smoke testing results (i.e. inflow sources)
- Areas identified with excessive groundwater infiltration through the flow metering program then undergo night flow isolation tests
- Finally, a closed circuit television (CCTV) inspection of pipes with high night flow isolation rates is conducted in order to identify operational and structural defects leading to infiltration as well as pipeline blockages.

While this process and individual techniques are effective in assessing gravity wastewater systems, they do not always transfer easily to the wastewater pressure pipe (force main) system. If a force main can be temporarily taken out of service with internal access provided via an entry port, an inspection can be conducted in order to determine the condition of the pipeline using traditional techniques (including CCTV, SONAR, and/or laser profiling) or technologies to assess the internal corrosion of the pipe. However, since wastewater force mains are generally designed with little to no redundancy or internal pipeline access (taps, entry ports, etc.), these invasive assessment technologies are often not applicable. Plus, external corrosion is a frequent cause of failure for force mains, which will not be assessed through these tradition gravity sewer inspection techniques. Therefore, wastewater force main condition assessment programs need to take a different approach than the SSES protocol outlined above.

It should also be noted that traditional defect coding techniques such as NASSCO's PACP standard do not apply to force mains as visual observations and not the structural capacity of the pipe. For example, Figure 2.1 indicates interior corrosion of a ductile iron force main where the pipeline was removed from service to investigate internal corrosion potential. While corrosion was visible, the extent of the pipe wall loss (e.g. loss of structural capacity) cannot be determined by visual inspection alone. While the inspection identified internal hydrogen sulfide corrosion, it only provided qualitative information, which is not actionable (e.g. quantitative wall thickness). Without quantifying the actual wall loss, an informed decision is not possible and unnecessary repairs may be implemented due to what could be superficial defects. In this example, up to 50% wall loss was observed.

*Figure 2.1 – DIP Deterioration Due to Hydrogen Sulfide Corrosion*

A wastewater utility conducting a force main condition assessment program may take the following approach:

- Conduct an analysis of the collection system force mains to identify the high risk pipelines using a likelihood of failure rating based on the structural and operational condition of the pipeline as well as the consequence of failure rating, which accounts for direct cost, health/environmental, and socio-economic factors. In simple terms, asset management principles define risk as a product of consequence of failure and likelihood of failure (COF x LOF). Unlike what has been the industry standard in years past, this risk assessment should not be used as a replacement strategy but a prioritization of where to collect more data on the pipelines. The reason for this is based on data collected not only by the authors of this paper, but also the Environmental Protection Agency that indicates that between 70% and 90% of the pipe being replaced in the United States has physical life left;

- Based on the risk assessment, develop a risk based inspection and condition assessment strategy that uses technologies, engineering, and analysis that optimizes human and financial resources all while reducing the risk of each pipeline asset to an acceptable level. Figure 2.2 provides a simplified approach to implementing a force main management strategy using a risk base approach. As the risk of each asset increases, the inspection technology resolution as well as the analysis technique complexity increases (these area additive as risk increases). While this also increases the cost of the assessment, the reliability of the information also increases thereby reducing the risk of managing the asset;

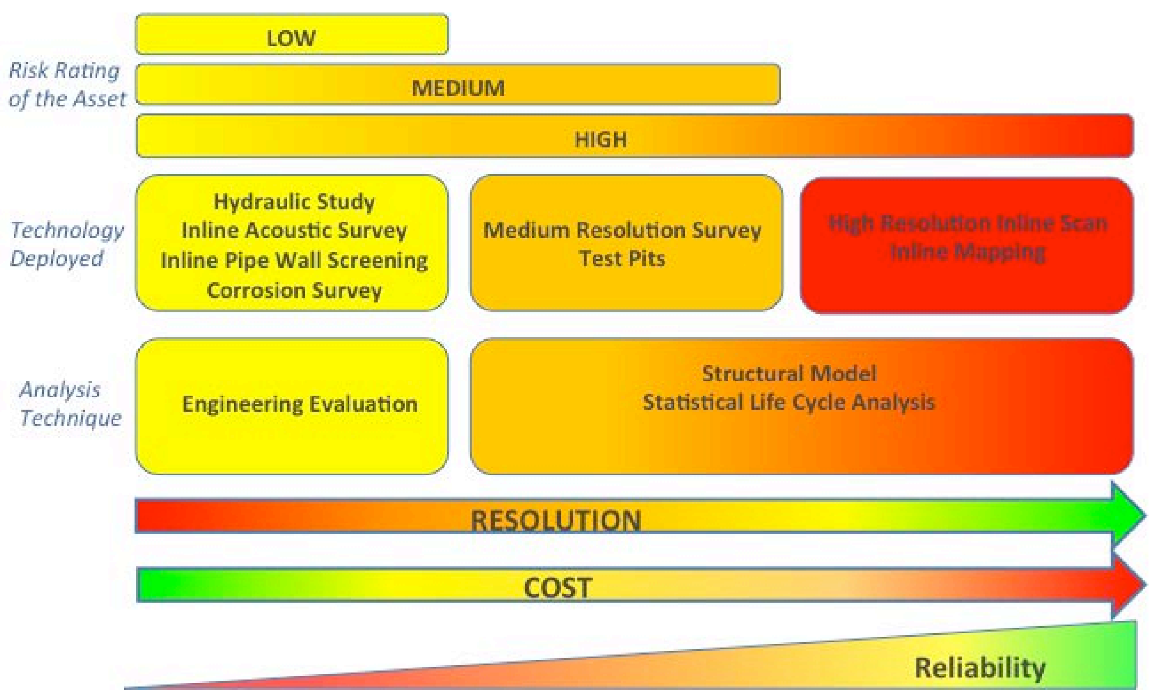


*Figure 2.2 – Simplified Risk Based Management Approach for Force Main Assessment*

- Data from the corrosion source identification and pipe wall integrity techniques can then be used to provide inputs to both structural and statistical analysis. These analyses provide the wastewater utility with the remaining useful life of the force main and will assist in the development of rehabilitation or replacement strategies;

- Once a force mains condition and remaining useful life is known, a comprehensive pipeline management strategy should be developed, which may include future inspection strategies/schedules, rehabilitation or replacement strategies (CIP planning), detailed pipeline data for asset management systems, etc.

Using a risk based approach to pipeline management for more than 500 miles of force mains, data indicates that these critical pipelines typically do not deteriorate or fail systematically along their full length. Instead, deterioration usually consists of localized problems due to environmental or operational factors. Force main inspection and condition assessment data indicates that less than 10% of the pipelines surveyed have indicators of distress while even less (approximately 1%) require repair or replacement to extend their service life. For example, a recently completed a force main condition assessment of nearly 3.5 miles of ductile iron pipe indicated that less than 5% of the force main alignment was found to have gas pockets, which can create conditions for internal corrosion and is the primary cause of ferrous force main failures, but pipe wall assessment measurements reveled the pipe to be of adequate thickness. Installation of air release valves was recommended to evacuate the trapped gas, but no other repairs are required saving the client significant capital and operational resources.

### 2.1. Force Main Inventory and Failure Modes

According to the Water Environment Research Foundation's *Guidelines for the Inspection of Force Mains*, the primary material for force mains in the United States is ferrous materials (cast iron, ductile iron, and steel) at over 60% with concrete being the next highest percentage at over 15%. For the purposes of the discussion provided herein, the focus will be on these materials as they make up over 85% of the United States force main inventory. Figure 2.3 provides a breakdown of the force main material makeup from the WERF report.

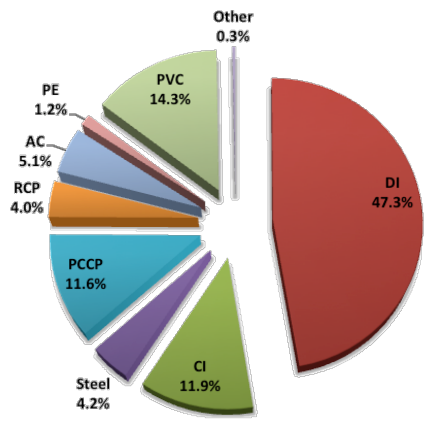


*Figure 2.3 – Force Main Material Breakdown – Data source: Water Environment Research Foundation – Guidelines for the Inspection of Force Mains (2010)*

It is important to note that defects and deterioration of force mains can be wide ranging and may vary from one pipe material to another. Therefore it is often prudent to implement multiple techniques and technologies using on the previously described risk based approach. Too often, inspection techniques and assessment strategies are implemented without consideration of the particular force main characteristics, its threats, and ultimate informational needs for the pipeline. This depletes valuable financial and operational resources without providing the necessary information for managing the pipeline. In a survey of Water Environment Research Foundation (WERF) and the National Association of Clean Water Agencies (NACWA) utility subscriber members, it was found that between 65% and 70% of force main failures are preventable with a comprehensive management program (Figure 2.4). By targeting these primary failure modes with properly selected and implemented inspection and assessment techniques, each force main within the owner/operators inventory can be managed with a low risk of failure.

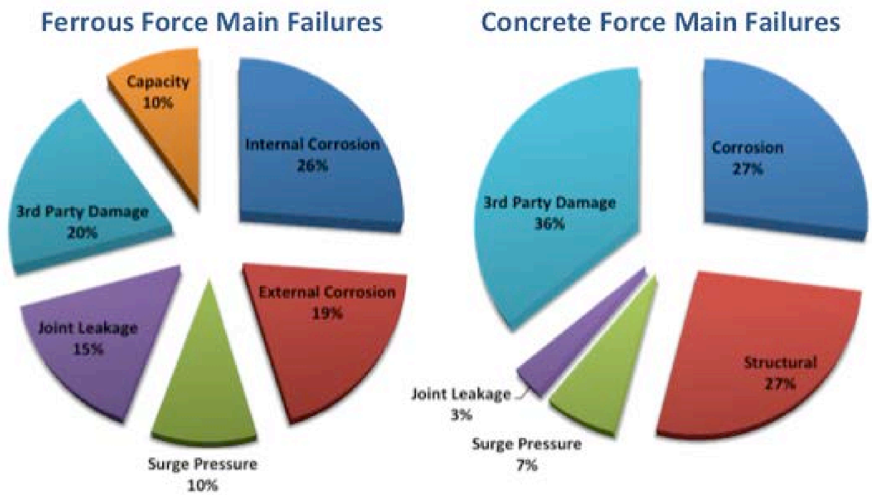


*Figure 2.4 – Force Main Failure Mode Breakdown – Data source: Water Environment Research Foundation – Guidelines for the Inspection of Force Mains (2010)*

The WERF report indicates that nearly 50% of ferrous force main failures (are due to either internal or external corrosion with an additional 25% of failures are due to surge pressure and joint leakage. Similar results are seen with concrete force mains having over 50% of failures due to corrosion or structural deterioration and an additional 10% due to surge pressure and joint leakage. These findings are significant in that utilities can implement a comprehensive force main condition assessment and management program that will address between 60% and 70% of the preventable failures in a scientifically defensible and cost effective manner. Similar results have been validated through inspection, condition assessment, and forensic validation of more than 500 miles of force main assessment.

### 2.2. Force Main Assessment Techniques

Force main inspection technology selection is a key part of any management program and requires a sound technical understanding of the various tools available in the industry. Prior to developing any inspection and assessment planning protocols force main inventories, it is critical for key stakeholders to understand the available technologies used for destructive and nondestructive testing of pressure pipelines._Some of the variables that must be evaluated when selecting technologies for assessing a pipeline may include:

- Force Main Risk
- Pipe Material
- Pipe Diameter and Length
- Operational Constraints
- Pipeline Inspectability
- Cost Efficiency of Technologies
- Technology Limitations
- Ability to Provide Actionable Information

It is important to note that defects and deterioration of force mains can be wide ranging and can vary from one pipe material to another. To identify different defects in force mains, it is often prudent to use multiple techniques and technologies. Too often, inspection techniques and assessment strategies are implemented without consideration of the particular force main characteristics, its threats, and ultimate informational needs for the pipeline. By using this "broad brush approach" to force main assessment, valuable financial and operational resources are often depleted without providing the necessary information for managing the pipeline. Therefore, this paper will not outline various inspection techniques or technologies available in the industry but rather focuses on the overall management approach.

# 3. Remaining Useful Life Analysis

### 3.1 Ferrous Force Mains

In order to predict the likely remaining useful life of ferrous force mains, statistical analyses can be developed that utilizes the inspection data collected as well as the engineering analysis performed that determines the existing condition. In order to perform this evaluation, a minimum amount of data must be collected in order to provide useful, actionable information. This minimum data may include:

1. A required quantity of pipe wall integrity measurements in order to achieve a desired confidence level (e.g. 95%);
2. Adequate data collection methodology to assume the results are representative of the force main;
3. Ability to either predict a deterioration rate based on previously collected data or scientifically defensible assumptions;
4. Structural analysis based on operating conditions, design standards/details, current condition, etc.

Utilizing inspection data and subsequent condition assessment/analysis, a statistical simulation can be conducted to determine the "likely" Rate of Loss and Thickness to Failure can be performed. This analysis can then be used to project when the first failures of the force main based may occur on the data collected and assumptions made. Figure 3.1 below provides a graphical representation of a 36-inch ductile iron force main where an external corrosion survey was conducted along with a desktop analysis to determine locations for test pits. As indicated in the graph, the first failures of the force main are not anticipated for at least 25 years from the day of the last inspection.

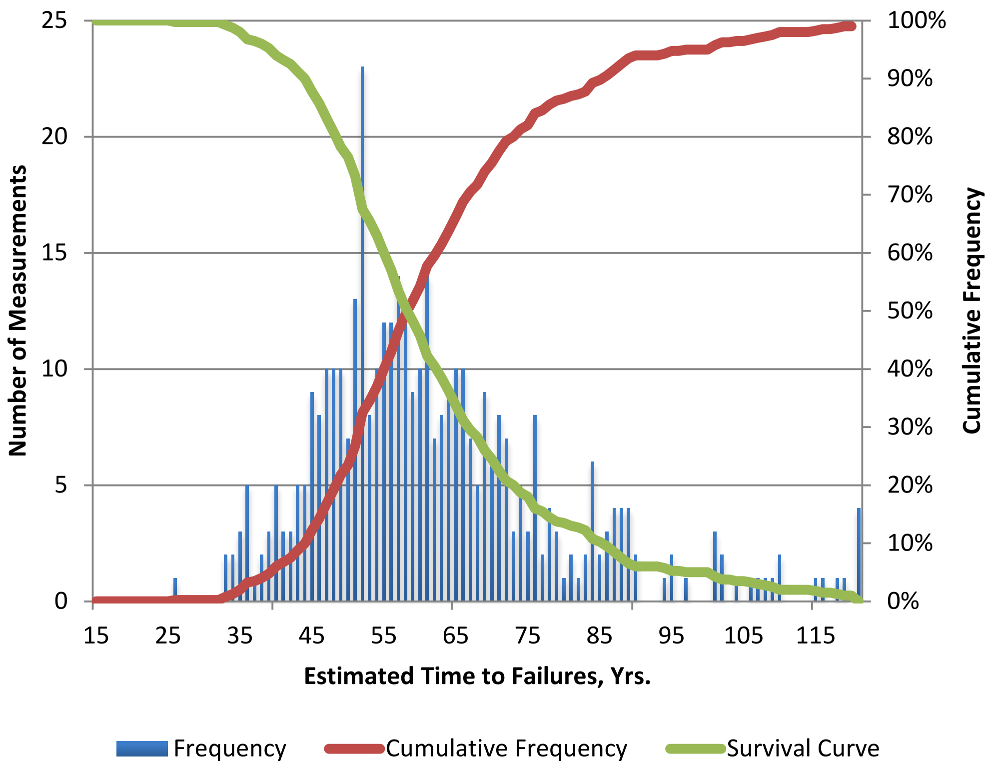


*Figure 3.1. Cumulative Frequency Distribution of Simulated Time to Yield*

Of note, corrosion rates for the force main based on the external corrosion survey results (indirect) versus the pipe wall thickness measurement results (direct) in order to determine the correlation between data. Figure 3.2 below displays two normal probability density functions for each data set indicating little correlation. The pipe wall measurement data set produces a density function with relatively small variance while the soil testing data set has a large variance. The means of each data set also have significant separation. The large variance in the soil testing data is likely due to a large variation in soil corrosivity along the pipe alignment while the small variance in the pipe wall measurement data indicates that the level of external corrosion at the sample locations is relatively consistent. These results highlight the significance of collecting higher resolution data for a high risk asset as the lower resolution data not only predicts failures earlier than the direct measurements but it also has a lower confidence level as it relates to the reliability of the information. Specifically, the corrosion rates based on the soil data indicates the time to failure can range from anywhere between 6 years through 42 years based on the variance in the normal distribution of the data.

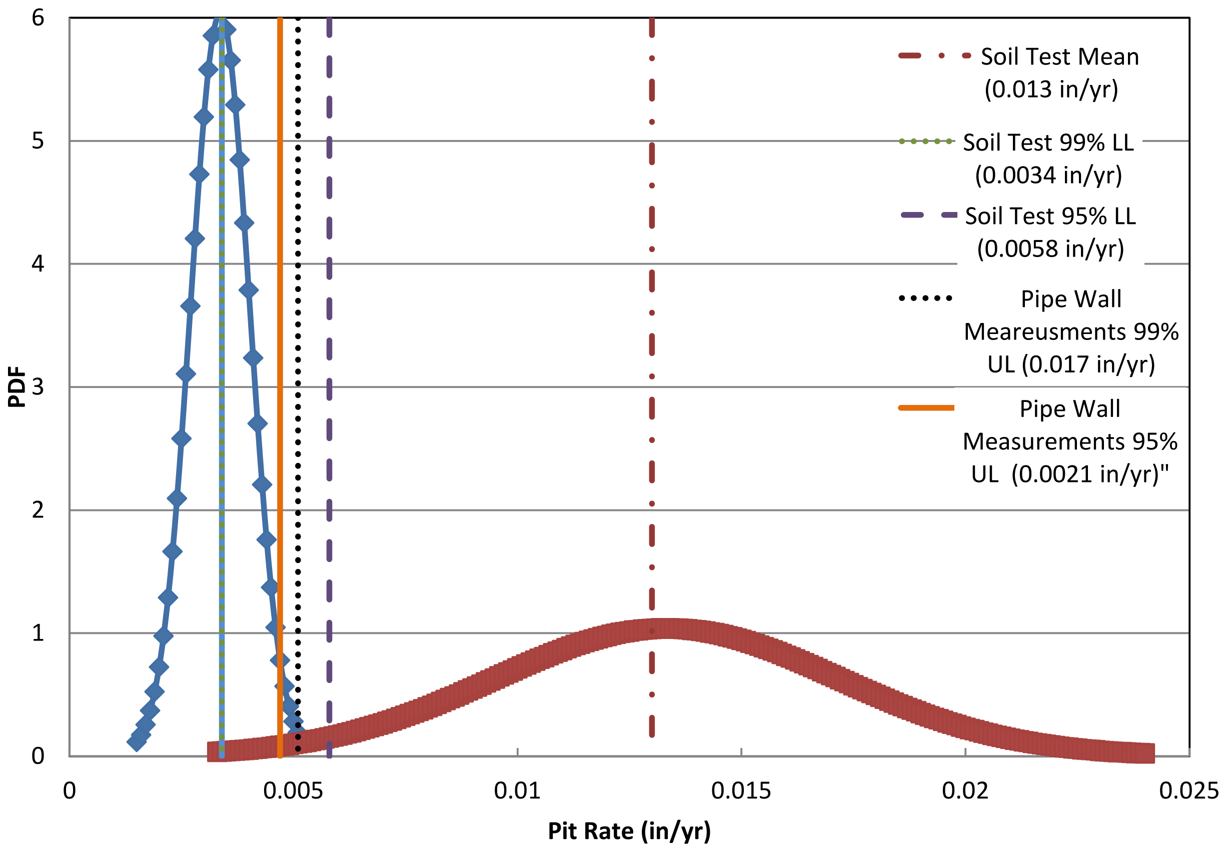


*Figure 3.2 - Distributions of Corrosion Rates Based on Direct versus Indirect Measurement Techniques*

### 3.2. Concrete Force Mains (Prestressed Concrete Cylinder Pipe – PCCP)

A predictive model can be used to estimate when re-inspection intervals, monitoring strategies, and capital planning. This model incorporates historical information, inspection data, the structural analysis, and design/installation information of the subject pipeline while leveraging existing knowledge of force main condition assessment and comprehensive data on real-time monitoring of PCCP at various locations throughout the US.

The predictive model first considers each distress indicator collected during the leak and gas pocket detection and electromagnetic inspections. The distress indicators considered in this analysis may include:

- Number of broken wire wraps
- Number of wire wrap break zones
- Location of wire wrap breaks
- Presence of gas pockets
- Presence of leaks

The magnitude or presence of each distress indicator is related to the condition of each pipe section by use of a condition-state membership matrix. This condition-state membership matrix has been described previously by the author. The condition-state membership matrix that relates the distress indicators listed above to possible condition-states based on PCCP designs, performance curves (structural analysis), history of the force mains, and experiential knowledge. Once the condition rating for each pipe is derived, a deterioration model can be used to simulate pipe degradation. For an individual pipe, this leads to overall degradation via transition from one condition-state to the next until reaching a failed state.

An electromagnetic inspection revealed that 1% of the pipes within the sample force main displayed electromagnetic responses consistent with wire wrap breaks meaning that 99% of the pipeline is likely in excellent or good condition. It is assumed that the force main will continue to degrade and the number of pipes displaying wire wrap breaks (distress) will increase in the coming years. However, the deterioration model does not account for new pipes within the pipeline developing distress. In order to account for new distress within the deterioration model, a comprehensive database of real-time acoustic monitoring wire break data can be used to develop a function that triggers distress in new pipes. The deterioration model can then be used to provide management decision support. An example of the results of deterioration model for a sample force main are shown below in Figures 3.4.

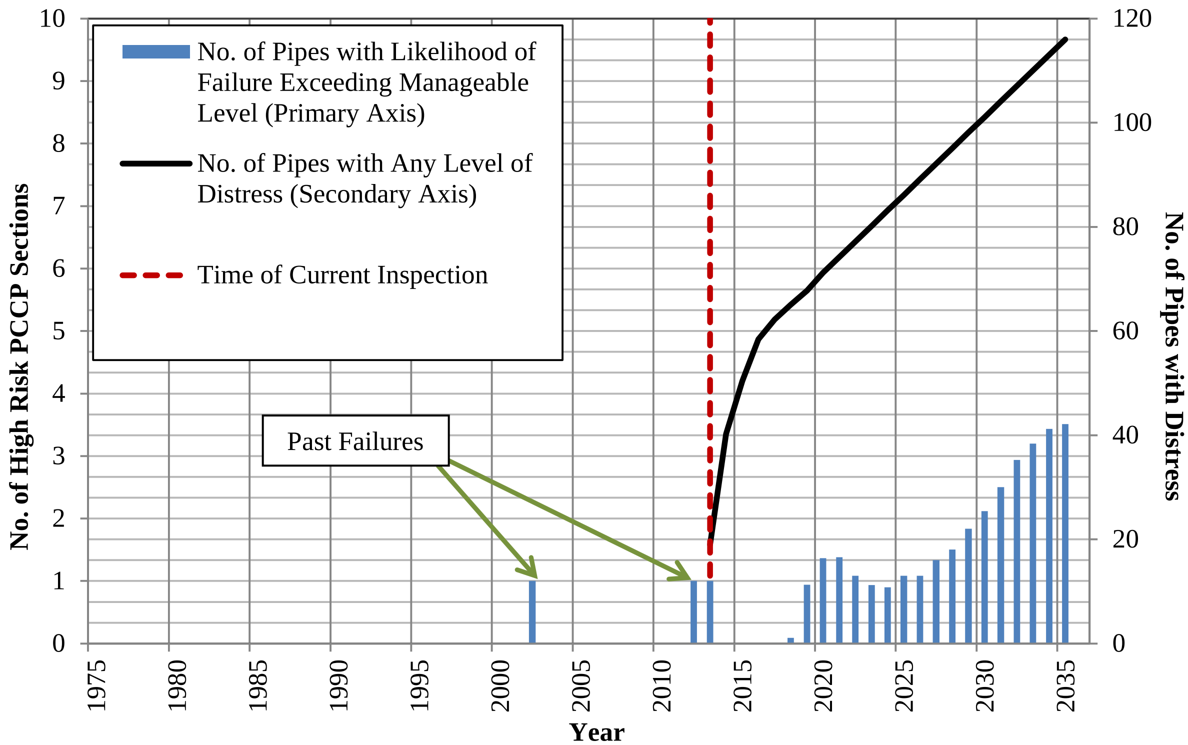


*Figure 3.4 - Results of the time until re-inspection analysis for the Sample Force Main*

Ideally, it is best to re-inspect force mains before a high likelihood of failure develops in any PCCP. Using these criteria, Figure 3.4 indicates that re-inspection of the sample force main should occur in 4 years.

### 3.3 Limitations to the Models

It is important to discuss some of the assumptions and limitations of this analysis. First, this analysis does not guarantee that there will be no force main failures within the time until re-inspection is recommended. Rather, this analysis states that if re-inspection is not completed within the recommended time, there is a higher possibility of force main failure. This analysis considers all degradation rates observed in force mains; however, experiential knowledge dictates that there is considerable variability in the degradation of individual pipe sections, even those within the same pipeline (i.e. it cannot be guaranteed that a pipe section will not degrade faster than previously observed in a pipeline). In addition, this analysis must be re-evaluated if there are operational changes to the pipeline that vary significantly from historic operations. For example, if the flow rate is decreased to a point where significant gas pockets can exist within the force main and possibly lead to $H_2S$ corrosion, the recommended time until re-inspection would be too liberal. Lastly, this analysis does not assume the installation of any monitoring technologies. If the client did decide to install real-time monitoring technology, the recommended time until re-inspection would be overly conservative.

For a comprehensive asset management plan, both the likelihood and consequence of failure should be evaluated. The analysis outlined above only evaluates the likelihood of failure and considers the pipeline condition and engineering analyses. A consequence of failure should evaluate the following costs:

- Social – Including the number of customers affected, number of critical customers affected (hospitals, critical facilities, etc.), and the impact to major roadways;
- Economical – Including the cost of the failure in terms of repairs and compensation for damages;
- Environmental – Including the sensitivity of a failure discharge area and any fines leveed as a results of the failure.

If a consequence of failure analysis is completed and used in conjunction with the likelihood of failure analysis discussed in this section, the risk of the failure of the sample force main can be prioritized and addressed accordingly. However, in lieu of this comprehensive plan, it can be assumed that the consequence of failure of every pipeline is equal and that the likelihood of failure is the dominant factor in determining a condition assessment plan.