AN ECONOMIC APPROACH TO DETERMINING THE PERFORMANCE CAPABILITY OF GAS DISTRIBUTION PIPELINES

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ABSTRACT

Many low pressure gas distribution systems around the World were constructed over a long period and contain a wide variety of pipe materials that may represent some degree of potential risk. The likelihood of gas leakage is principally influenced by the potential for structural failure or localized through-wall corrosion. The potential consequences of failure are principally related to the location of the pipeline and the potential for escaping gas to enter any adjacent buildings.

Patterns of pipeline failure have been recognized in the past and the potential risks associated with failure have been controlled by the strategic replacement of pipe sections or entire pipelines. In the UK, the failure of grey iron and ductile iron gas pipes has resulted in the implementation of various strategic replacement policies. To date, the replacement strategies for gas distribution pipelines have generally not involved any targeted inspection or condition assessment. The UK water industry has necessarily introduced the strategic replacement of small diameter grey iron pipes to resolve very similar failure patterns to those seen in the gas industry. However, the water industry has developed strategies for identifying candidates for replacement which involved localized condition assessment of the pipe system.

The condition assessment process developed and applied by AESL involves establishing the structural condition of relevant sections of pipeline based on selective inspection. As the outcome of an inspection is likely to be related to factors affecting the local area of the inspection, the condition of longer sections of pipelines can be estimated by analysis of results from other areas, using modeling techniques that are statistically appropriate.

Experience shows that, due to inadequate corrosion protection, low pressure gas and water distribution pipelines often suffer from widespread corrosion defects. AESL have developed/patented tools and technologies to inspect these pipelines, allowing localized inspection of the internal and external condition of short lengths of the pipe wall. The inspection tools use high flux magnetic inspection techniques and operate on the outside of the pipe; above ground pipes tend to be readily accessible but excavation is required to access below ground pipelines. To date, AESL has carried out more than 2,000 condition assessments of individual sections of pipelines, or complete pipelines, split approx 400 large diameter and 1,600 small diameter, at sites throughout the UK, Europe and Australasia. The assessments were part of a validation process prior to re-commissioning or as routine ongoing structural assessments of operational networks.

All inspection sites, past and current, are mapped onto AESL's central server, with display icons that define individual aspects of the condition assessment or the project under which the assessment was carried out. AESL can interrogate and analyze all past inspection data, to provide ongoing reviews of experience, to assist in the interpretation of other data, etc. Customers can access inspection data from their own condition assessment projects, during and following the work, and are provided with Internet access to appropriate inspection results, condition assessment outputs, background data, photographs, etc.

This paper summarizes developments in technology and practice targeted towards a better understanding of the operating conditions and performance of low pressure distribution pipelines in current service. The technologies and practices have had extensive use in the UK water industry and have contributed substantially to the required conditions of service being achieved, within existing financial targets. The potential of these technologies and practices is now being recognized within the UK gas industry, where safety critical performance is a much more prevalent issue.
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1. INTRODUCTION

Gas distribution systems currently in operation around the World are extensive and many were constructed over a period of more than 100 years. However, the transportation of gas, even at relatively low pressures, across an urban environment represents a degree of potential risk and requires sound asset management, targeted at eliminating leakage. The likelihood of gas leakage is principally influenced by the potential for structural failure or localized through-wall corrosion. The potential consequences of failure are principally related to the location of the pipeline and the potential for escaping gas to enter any adjacent buildings.

Patterns of pipeline failure have been recognized in the past and the potential risks associated with failure have been controlled by the strategic replacement of pipe sections or entire pipelines. In the UK, the failure of grey iron and ductile iron gas pipes has resulted in the implementation of various strategic replacement policies. To date, these replacement strategies for gas distribution pipelines have generally not involved any targeted inspection or condition assessment.

The UK water industry has necessarily introduced the strategic replacement of small diameter grey iron pipes to resolve very similar failure patterns to those seen in the gas industry. However, the water industry developed strategies for identifying candidates for replacement which involved localized condition assessment of the pipe system. Originally, an intrusive inspection process was applied but, more recently, Advanced Engineering Solutions Ltd (AESL) have developed and applied technologies and strategies allowing non-intrusive inspection and condition assessment of distribution pipes. These processes, which are equally applicable to gas distribution pipelines, are discussed in this paper.

2. GAS DISTRIBUTION PIPELINES - FAILURE PATTERNS AND RISK

The majority of distribution pipelines operate within an urban environment and the potential consequences of any failure can be substantial. The majority of gas distribution systems have been in operation since the mid 19th century, at least. Over such a long period, a range of pipe materials were necessarily used for construction; pit and spun cast grey iron were used for many years, followed by spun cast ductile iron. Recognizing the very long life of cast iron, both grey iron and ductile iron do deteriorate structurally and both have been the target of strategic replacement.

Risks associated with pipeline operation are typically quantified by multiplying together various factors representing the likelihood of a failure occurring and the potential consequences of that failure. Potential consequences are usually related to the type and usage of buildings adjacent to the section of pipeline. Generally, failure predictions for grey iron distribution pipelines have been based on historical failure patterns, and replacement has been concentrated on small diameter pipes of 75 mm to 300 mm diameter. The main argument for targeting the replacement of small diameter grey iron pipe is illustrated in Figure 1.

![Figure 1: Failure Rate v Nominal Diameter - Grey Cast Iron Pipe](image-url)
Figure 1 shows the relationship between pipe diameter and failure for grey iron pipe within a UK water distribution system. The failure profile is very similar to that seen in grey iron gas distribution pipes and shows that the pipe failure rate is broadly proportional to the pipe diameter, the number of recorded failures increases as the pipe diameter reduces. Gas and water distribution pipelines operate at relatively low pressure and the external loading regimes are usually more significant. Thus, the relationship between failure numbers and pipe diameter can ultimately be related to differences in pipe bending strength and the influence of time related corrosion. The UK gas industry solution to this problem was the strategic replacement of small diameter grey iron pipe.

The problem of localized corrosion in ductile iron pipe has been recognized for a number of years and, following a number of UK failures with serious consequences, a blanket replacement strategy was introduced. Whilst similar localized corrosion may occur in ductile iron water pipes, the outcome is usually isolated leakage, with no serious consequences, and thus replacement of ductile iron water pipe does not yet appear to be a significant issue.

3 WATER PIPELINES - FAILURE PATTERNS AND CONDITION ASSESSMENT

3.1 Small Diameter Water Distribution Pipes

The UK water industry suffers significant failure levels in its small diameter grey iron pipelines. However, a significant difference between the UK gas and water industries is the much higher percentage of 75 mm and 100 mm pipe within water distribution networks; pipe diameter is usually selected to ensure appropriate flow rates through the network. In some systems, 75 mm and 100 mm pipes represent 60% to 70% of the entire network, making the targeted replacement of all small diameter pipes somewhat impractical. The water industry has therefore introduced strategies allowing more focused selection of pipes within categories requiring maintenance or replacement.

The historical usage of grey iron pipe is very similar within the UK gas and water industries. However, the consequences of any failure of a water pipe rarely involve safety issues but are largely financial and related to the cost of supply failures and the repair of third party damage. The likelihood of failure within gas and water pipes is similar, but it should be recognized that water pipes corrode both externally and internally, potentially increasing the overall rate of deterioration. However, internal corrosion can also result in unacceptable reductions in water quality, which can require system refurbishment activities even where there is no leakage.

For these reasons the UK water industry undertakes a strategic assessment of the likelihood of failure of small diameter grey iron pipe. Inspections and structural condition assessments are used as inputs to the process, to identify sections of pipe where replacement is the economic solution. These assessments were initially carried out intrusively, on small sections of pipe cut from the parent pipe, resulting in substantial costs and water quality issues. AESL then developed external inspection tools capable of providing the same pipe integrity data non-intrusively, without cutting or otherwise damaging the pipe. Non-intrusive condition assessment processes are now routinely carried out on both small and large diameter water pipes.

The main output required from the condition assessment process is to determine the remaining service life for any asset, before leakage or structural failure occurs, and a minimum of 30 years remaining life is often the required target. The condition assessment outputs are therefore used to define the actual remaining life that is likely, in order permit a decision as to whether a pipeline is to remain in service, is to require relining (non-structural lining) or is to be replaced.

The AESL process automatically transfers data from inspection tools on site, directly to the Company offices, processes the site data, assesses the structural life of the pipeline and maps the overall conclusions. Site maps and pipe assessments can also be used to optimize the definition of future inspection requirements, since they already outline differences within the loading regimes and corrosivity environments local to the sites that are inspected, as shown in Figure 2.
3.2 Large Diameter Water Distribution Pipes

Although distribution systems typically contain substantially more small diameter pipes than large diameter, the larger diameter pipes are operationally more important. They are also more valuable because of the potential cost of replacement and thus blanket replacement strategies are not valid. Some degree of condition assessment is an obvious method of correctly focusing optimum maintenance and replacement expenditure. This is an accepted philosophy in many water industries around the world and the potential benefits of assessing low pressure pipelines are beginning to be recognized within the gas industry.

Many, if not most, large diameter water mains run for considerable distances across country in order to supply local small distribution diameter systems. The distances involved inevitably mean that a wide variety of corrosion mechanisms and drivers may be active along the length of the pipeline. However, the most obvious sections where conditions vary are usually crossings, where water pipelines cross over roads, railways, canals, rivers, etc, via bridges, or cross under, via tunnels. Failure of the pipeline at these crossings can be particularly problematic due to access difficulties, the nature and size of the road, railway, etc, being crossed and the possible consequences if a pipeline failure results in the road, railway, etc, being damaged or even closed to traffic. For these reasons, AESL have inspected many such critical crossings, as well as other less critical pipeline sections, using developments of the processes outlined below.

4. THE CONDITION ASSESSMENT PROCESS

Experience from existing pipelines shows that many, if not the majority, of large diameter grey iron pipes provide an actual operating life that is significantly longer than the expected design life. The actual service life achieved will depend upon a number of factors, but it will be greatly influenced by the level of over-design that was traditionally incorporated into the initial design, arising from a reliance on manual design calculations and various safety factors that were traditional used as a means of compensating for variabilities in materials and manufacturing techniques. As steel and ductile iron pipes were manufactured using more modern techniques, their designs would have been less conservative, with fewer compensating factors, and their actual operating life is usually much closer to...
the expected life predicted at the time of their initial design. Figure 3 illustrates the life cycle of a typical pipeline.

Typically, design and construction faults can, and often do, result in initial failure levels that are higher than expected, often relatively early in the post commissioning phase. Thereafter, the problems are identified, rectified, and the pipeline begins its normal service life, during which it begins to respond to its environment. The AESL approach to condition assessment considers the pipeline's in-service performance commencing after any initial failure trends have been resolved. The end of a pipeline's service life is characterized by an increasing trend in the number of leaks and other failures, to a level which, for operational or financial reasons, is unacceptably high.

Under similar conditions, corrosion rates for iron and steel pipelines could be expected to be similar. If a constant corrosion rate is applied to a range of typical cast iron pipes, the theoretical time to failure by perforation shows a pattern that is dependant on the pipe wall thickness, which is directly related to the nominal diameter. However, this is not the case in practice, because of the potentially wide variabilities in pipe corrosion protection materials and site corrosion drivers, corrosion rates can vary significantly, both along the length of any given pipeline and between apparently similar pipelines. The inspection and condition assessment of individual pipelines, or sections of pipelines, can be used to highlight those pipelines or sections that are performing to a better or lesser degree than the relevant norms, allowing future maintenance expenditure to be focused and prioritized accordingly.

The condition assessment process developed and applied by AESL involves establishing the structural condition of relevant sections of pipeline based on selective inspection. As the outcome of an inspection is likely to be related to factors affecting the local area of the inspection, the condition of longer sections of pipelines can be estimated by analysis of results from other areas, using modeling techniques that are statistically appropriate.

Pipe wall deterioration is limited by the performance of the pipe corrosion protection system applied (coating, wrap, cathodic protection, etc) and the aggression of the site corrosion drivers (soil chemistry, moisture content and soil resistivity). Site inspections therefore require assessment or measurement of the condition of the corrosion protection system and the aggressivity of the corrosion drivers, as well as the condition of the pipe wall. The overall condition assessment process also involves using the site data to define pipe sections for which local inspection outputs can be validly applied and to define appropriate locations where these sections should be inspected.
4.1 Where To Inspect

Soil maps, where available, can be used to better understand soil corrosivity and potential differences along the route of a pipeline, with a view towards identifying pipe sections where the maximum corrosion rate is likely to occur. However, the use of imported backfill around a pipe during and after its construction may influence or limit the application of soils maps to the process.

AESL use pipe coating surveys, above ground and in-ground, to help identify variations in coating condition and hence potential differences in pipe wall condition. Survey instruments for pipe coatings are usually designed to trace specific defects in an otherwise sound coating. Distribution mains are often coated to a poor standard, frequently with inadequate materials, which makes the identification of individual defects both difficult and unnecessary. AESL operate proprietary equipment, including pipeline current mapping tools, which are designed to identify individual coating defects see Figure 4. Using whatever tools are appropriate, the pipeline is surveyed and the output data is analyzed in a way which allows assessment of the general coating condition, as well as the identification of areas of apparent differences and significant individual defects. This approach allows subsequent pipe inspections to be focused towards locations which include areas where there are variations in pipe coating condition. Selecting these locations improves the overall accuracy and relevance of the inspection data and allows a more realistic assessment of areas where the remaining service life of the pipeline may differ, including the potential for short term failure.

4.2 Soil Condition Assessment

The condition of the soil in contact with any exposed area of pipe wall is always a significant factor in defining the type, degree and rate of corrosion which can occur. It is therefore standard practice to take soil samples and to carry out a series of site and laboratory tests to help define the overall corrosion potential. Correlations across a range of soil types and properties can help to define corrosion levels and potential variations. Hence soil test results must always be considered on the basis of a background understanding of their relevance to corrosion predictions. Overall, estimating the corrosivity of soils along the route of a pipeline can substantially assist the condition assessment process and help identify sections of pipe which have similar corrosion drivers and of sections of ground/soil which have similar corrosion properties.

Having studied and applied a range of standard techniques for soils assessment, AESL currently favors the French standard AFNOR A05-250. This standard defines a very practical method which uses fundamental and accessible soil properties to define potential corrosivity. Quantitative
outputs are always required, wherever possible, and this standard does help define quantitative estimates.

4.3 Coating Condition Assessment

Pipe coating inspection for distribution pipelines is not yet a developed science and most coating inspection tools are limited in accuracy and range, especially the various techniques and instruments used in above ground surveys to identify coating defects. As an input to the overall pipeline condition assessment process, coating condition surveys should provide quantitative outputs of coating condition, wherever the pipeline is inspected.

The approach taken by AESL is to define a notional grid (fixed size) around the pipe at the point of inspection, and to assign all locations where coating condition is assessed with a positional reference to the grid. Thus all data is defined to precise positions at the pipe surface, all defects can be aggregated and all potential corrosion effects can be related to surface area. This approach is currently visual but does provide a quantitative output and the position of pipe coating defects and pipe surface defects can be compared by overlaying the inspection grids. The condition assessment process for any pipeline will certainly be improved if the condition of the coating along sections of the pipe can be interpreted from local inspections and long term corrosivity trends can be predicted. This process of local coating inspection is always carried out as part of the full condition assessment process.

4.4 Pipe Wall Condition Assessment

Most pipeline inspection technologies have been targeted at ensuring the integrity of safety critical gas, oil and chemical pipelines, usually operating at high pressure. Such pipelines are typically manufactured using high quality steels and are usually well coated to provide reliable corrosion protection, often including active cathodic protection systems. Pipe wall inspection systems are therefore often focused towards identifying and sizing significant individual defects, or relatively small numbers of defects rather than attempting to give an overall assessment of potential corrosion arising from all coating defects that are present. An overall assessment of potential corrosion would require the whole of the pipe wall to be inspected, and is generally achieved using pig mounted NDT systems.

Experience shows that, due to inadequate corrosion protection, low pressure gas and water distribution pipelines often suffer from widespread corrosion defects. AESL have developed/patented tools and technologies to inspect these pipelines, allowing localized inspection of the internal and external condition of short lengths of the pipe wall. The inspection tools use high flux magnetic inspection techniques and operate on the outside of the pipe; above ground pipes tend to be readily accessible but excavation is required to access below ground pipelines. To date, AESL has carried out more than 2,000 condition assessments of individual sections of pipelines, or complete pipelines, split approx 400 large diameter and 1,600 small diameter, at sites throughout the UK, Europe and Australasia. The assessments were part of a validation process prior to re-commissioning or as routine ongoing structural assessments of operational networks.

AESL have developed a range of inspection tools for the external inspection of metallic pipes from 75 mm diameter upwards; the largest pipeline inspected to date is 2,500 mm nominal diameter. All AESL pipe inspection tools are high flux magnetic devices, utilizing an array of field sensors to scan the imposed magnetic fields for anomalies indicating metal loss, and separate proximity sensors to indicate the positions of areas of significant metal loss relative to the internal and external surfaces of the pipe wall. The tools are operated by a small PC/PDA device which downloads the raw inspection data, processes and visualizes images of any pipe wall defects present, then transmits the data back to the main AESL office - see Figure 5. The pipe wall defects found by the inspection tool are then located on the pipe, cleaned, photographed and their size is checked by physical measurement. Finally, wherever the existing corrosion protection coating has been damaged during the pipe inspection, the area of damage is repaired, patched or recoated to a standard that has been agreed with the pipeline operator.
AESL’s inspection tools for larger diameter pipes are similar in principle and operation to the smaller tools, but the full circumference of larger pipes is not inspected in a single scan. Only part of the surface is scanned at any one time and the process is repeated to scan the full pipe circumference - see Figure 6. All inspection tools are designed to be compact and portable, suitable for use in confined spaces, tunnels, etc, and operated from access platforms, scaffolding, ladders, etc.

Once a basic magnetic inspection tool is manufactured, further development is undertaken during initial use, to extend the range of application, refine the accuracy and improve the operator response of the tool, as well as to make the tool more rugged for field use. This development is customer focused and is usually carried out on an on-going basis of continuous improvement. Other inspection instruments used within the overall condition assessment process are largely proprietary, including ultrasonic tools, pipe coating inspection instruments, pipeline current mapping transmitters/receivers, differential GPS systems and antennae, etc.
The physics of the inspection process and hence the outputs of the inspection tools depends upon the metallurgy and structural quality of the metallic pipe, including the consistency and overall quality of the pipe surface. In particular the inspection of large diameter grey iron pipe can be problematic; the material is not homogenous and the pipe wall thickness is often very substantial. Ductile iron and steel pipes are less problematic, have better metallurgical properties, thinner pipe walls and are easier to inspect. For these reasons, AESL often use conventional ultrasonic inspection techniques to calibrate their magnetic tools against thick wall pipe, and, where necessary, to assist in sizing complex defects.

4.5 Statistical Analysis

Statistical models can be used at several stages of the condition assessment process. Firstly, modeling is used to define the appropriate number of locations where inspections are to be carried out and the level of inspections required at each location; this is a function of the expected defect and failure regimes. Statistical analysis can also be used to ensure that condition assessment outputs are of adequate quality, a process which can also involve the analysis of historical data and relationships between corrosion mechanisms, pipe depth, age and material of pipe, soil type and coating type.

The patterns of corrosion occurring along a pipeline influence the accuracy of the condition assessment process. For example ductile iron and steel appear to exhibit a greater randomness in the degree of corrosion that ultimately occurs. In these circumstances, analysis of the factors influencing pipeline performance, as well as pipe wall inspection outputs, is more critical.

In any statistical analysis, data distributions are fitted to measured populations of defects to confirm their mathematical validity and to predict the numbers, and depths, of defects along the pipeline and their failure probability. A range of statistical distributions may be considered, including extreme value analysis.

4.6 Communications and Mapping Technology

Part of AESL’s technology development process has been targeted at recording the location of all pipe inspections, to ensure that geographical data is reliably recorded and easily analyzed. To meet this requirement, all AESL inspection tools are fitted with a GPS location system, the output from which links the entire condition assessment strategy and forms the basis of a comprehensive audit trail. Inspection data, including a GPS tag, is transmitted from the inspection site directly to the AESL offices, so analysis can be undertaken in parallel with the inspection, allowing details of the inspection to be redirected, if necessary.

All inspection sites, past and current, are mapped onto AESL’s central server, with display icons that define individual aspects of the condition assessment or the project under which the assessment was carried out. AESL can interrogate and analyze all past inspection data, to provide ongoing reviews of experience, to assist in the interpretation of other data, etc. Customers can access inspection data from their own condition assessment projects, during and following the work, and are provided with Internet access to appropriate inspection results, condition assessment outputs, background data, photographs, etc.

5. CONCLUSIONS

This paper summarizes developments in technology and practice targeted towards a better understanding of the operating conditions and performance of low pressure distribution pipelines in current service. The technologies and practices have had extensive use in the UK water industry and have contributed substantially to the required conditions of service being achieved, within existing financial targets.

The potential of these technologies and practices is now being recognized within the UK gas industry, where safety critical performance is a much more prevalent issue.