The UK Mains Replacement Methodology and its role in Reducing Leakage Repairs

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Background

Mains replacement is in use in gas companies throughout the world as a way of removing mains made of older mains materials, such as cast iron, and replacing them with mains of newer materials, such as polyethylene. This has the advantage of reducing leakage from older materials, some of which may lead to gas entering property and causing ignition/explosion incidents.

The way in which mains are identified for replacement varies from company to company. In an ideal situation, those main most likely to leak in the future should be targeted first. The way in which this future behaviour is predicted will determine how effective a replacement scheme is in reducing future leakage.

Since the late 1970's, the national distribution gas company for the UK at that time (British Gas), began a programme of targeted mains replacement of cast iron and small diameter steel mains. The programme was in response to gas industry and public concern about gas leakage, in particular leakage likely to track into property and cause an ignition incident. This first programme was superseded by various improved schemes which became more focused as more data became available. The most recent methodology, MRPS (Mains Risk Prioritisation Scheme) developed by GL Nobel Denton in 1999, was based upon statistical data and was designed to generate a likelihood of both leaks and ignition incidents, for each individual mains unit. The methodology was scrutinised by the UK safety regulator, the Health and Safety Executive, throughout its development and the methodology was endorsed by them on completion.

This paper describes the formulation of this approach, which was implemented by all four UK gas distribution companies in 2000 and continues to be in use currently. In 2002, a 30 year mains replacement programme was put in place which aims to replace all ferrous mains within 30 metres of property in a 30 year period, ending in 2032. The methodology developed by GL Noble Denton is the primary tool used to direct this programme.

Aims

The primary aim of MRPS was to identify ferrous mains within 30 metres of property at higher risk of gas ingress and ignition. The methodology generates two separate measures for each pipe. The Risk Score is a measure of the ignition incident rate in terms of incidents per km per year and the Condition Score is a measure of the leak rate in terms of leak repairs per km per year, irrespective of their likelihood of gas ingress.

Because the UK programme is driven solely on risk, and the requirements to reduce ignition incidents, the pipes are selected by Risk Score. If the primary aim of a distribution company is to reduce leak repairs, pipes should be selected by Condition Score.

The main subject of this paper is the use of MRPS to reduce one element of unaccounted gas, namely leakage from deterioration of ferrous mains, but reference to incident reduction will also be covered to a lesser degree.

Methods

The methodology applied to formulate the Risk and Condition Scores is based upon statistical analysis, primarily multivariate regression, to generate a numerical link between pipe characteristics and previous leakage behaviour and future leakage. The data analysed consists of large quantities of historical data from UK gas distribution records over a period of 20 years. The data provides three separate sources of information on each individual mains unit; one relating to the pipe itself, age, diameter etc, one relating to leakage behaviour of other pipes in the vicinity, and one relating to previous leak repairs on that specific pipe.

One of the most important factors within the model is the Background Failure Zone around each pipe. These are areas of higher than average fracture, joint leak or corrosion behaviour, and are generated by plotting previous leaks geographically and converting to a leak rate per km by standardising by the length of pipe in the area. Figure 1 below shows an example of these zones (for corrosions) for an area in the north of England.

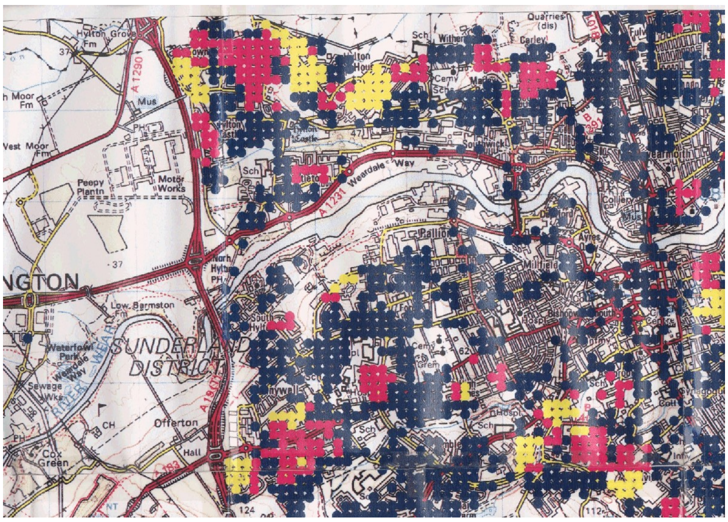

Figure 1 - An example of Background Corrosion Zones

In all cases, corrosion leaks are specifically those leaks which cause gas to escape from the mains as a result of through wall corrosion. They do not include partial corrosion through part of the wall. The areas coloured blue are classed as a low rate of corrosion leaks, referred to as Low Background Corrosion Zones or BCZs. Red areas are medium rates or Medium BCZs, and yellow areas are high rates or High BCZs. The banding of zones is specified in advance and is designed to ensure that reasonable numbers of pipes fall into each category. Where no zones are shown, it is due to no pipes being in the area, or the pipes there are all Polyethylene (PE). The equivalent zones from fractures and joint leaks are Background Breakage Zones or BBZs and Background Joint Zones or BJZs respectively. A pipe can fall into different bands depending upon the behaviour of neighbouring pipes. For example, a pipe can lie in a high BBZ because it is laid in an area of higher than average fracture rate, but may lie in a Low BCZ because the other pipes in the vicinity have a low level of corrosion leaks.

Areas of high BCZ (corrosion) are probably due to localised areas of corrosive soil type. Areas of high BBZ (breakage) are probably due to localised ground movement or traffic loading. Areas of high BJZ (joint) are probably due to localised ground movement or perhaps an area of substandard jointing. The Background Zones act as a proxy for other, underlying factors, which are difficult to measure separately, thus the Zones measure the effect of the underlying factors rather than attempting to measure the original cause. In some cases, an area may have experienced a higher than average level of fractures due to localised ground movement many years in the past. In the intervening years, most of the mains in that area may have been replaced due to lying in a High Background Breakage Zone. If the BBZ is recalculated on the current population, it may drop down to a lower zone because most of the mains, and associated fractures have been removed. However, the underlying cause of the elevated breakage rate, localised ground movement, still exists. In this situation, and all similar situations, the Background Zone is not allowed to drop down to a lower level.

The calculation of zones is applied to all metallic mains but different zones apply to different materials. Cast iron (CI) mains can fail due to fracture, joint leaks or corrosion and therefore each CI main has its own BBZ, BJZ and BCZ. Ductile Iron (DI) and steel mains can fail through corrosion or joint leaks, so each DI and steel main has its own BCZ and BJZ.

The process carried out to generate the Condition Scores is described in this paper as a generic process – a separate but identical process is applied to each leak type in turn but using different data, namely leakage from a corrosion hole, leakage from a fracture, or leakage from a leaking joint. For the CI model, the Condition Score is the sum of the three individual components, modelling fractures, corrosions and leaking joints. For DI and steel, it is the sum of two components, modelling corrosions and leaking joints.

The generic process consists of several stages which are listed below:-

1. Take a time point a year prior to the data extract, and work back from that time point to determine failure history.
2. Use the current year as the time period for ‘future’ behaviour.
3. Allocate all the pipes in a given population by previous failure history and Background Zone, according to the rules above.
4. From previous analysis, it has been shown that the most common type of pipe are those with no previous failures, which also fall into the Low Background Zone. Typically, this is likely to be approximately 90% of the population.

5. Plot this sub-group of pipes by age in one year bands. Use this information to determine age bands which ensure that reasonable numbers of pipes fall into each band.
6. Calculate the 'future' leak rate for pipes in these age bands from the historical data and determine a statistical link between these age bands and 'future' leakage behaviour for this sub-group of pipes.
7. For the remaining categories, not in this sub-group, determine a statistical link between Background Zone and previous leak history.

With regard to step 4 above, Figure 2 illustrates a typical age distribution for steel pipes. It can be seen that steel mains range from an age of over 70 years to dates much more recent, within the last 20 years. Where there are peaks in the distribution, this is due to some pipes being retrospectively tagged with a date of laying which has been recorded as the nearest decade rather than the specific year. This data extract was for pipes in use in 2007. The peak at 27 years relates to a laid date of 1980. The peaks at 37, 47, 57, 67, and 77 relates to laid dates of 1970, 1960, 1950, 1940 and 1930.

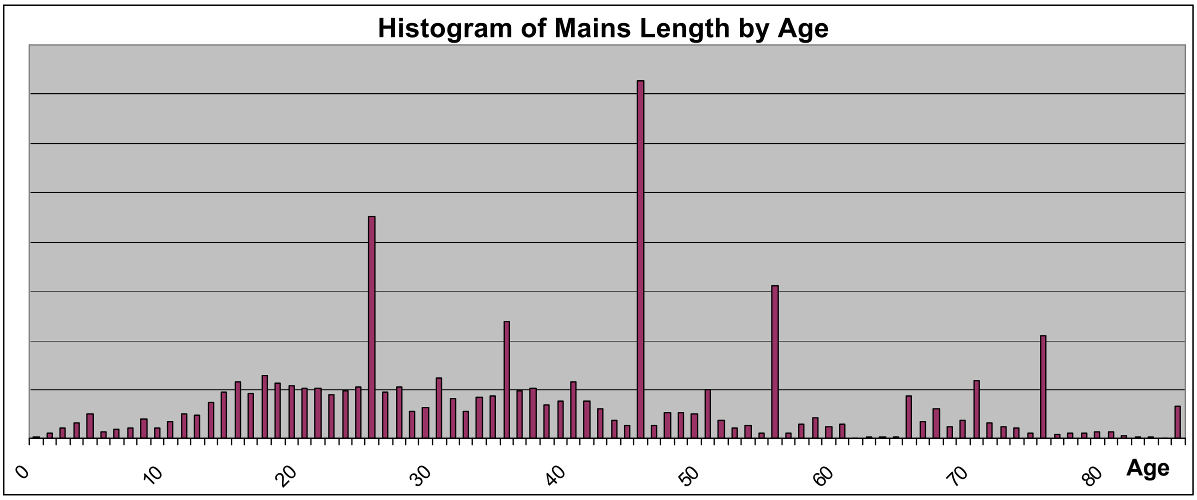

Figure 2 - Histogram of Mains Length by Age

As described in step 6 above, this distribution is then used to group pipes into age bands, and the 'future' failure rate for each band is generated from leak data in the current year. Figure 3 shows typical data points linking leak rate and age of pipe and the fitted curve around those points.

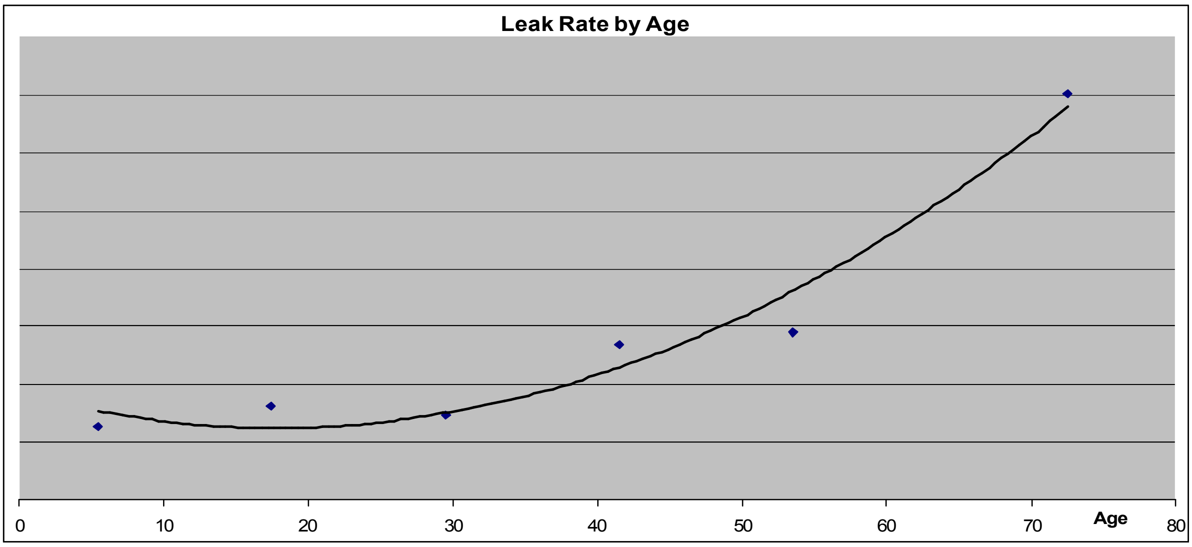

Figure 3 - Leak Rate by Age

The relationship illustrated in Figure 3 is important because it is used to model a large proportion of the mains population, namely those pipes which have not experienced any previous failures and lay in the lowest Background Zone. Other prioritisation schemes will tend to rank pipes with previous failures at the top of the list but will typically only identify less than 10% of the population in use. This type of method will therefore rank the remaining 90% of pipes all the same.

For the remaining pipes not covered by this relationship, namely those which have experienced previous failures, a statistical link between Background Zone and previous failures as inputs, and ‘future’ leak rate as the output, was generated. The Background Zones are already banded into Low, Medium and High. The failure rate bands are normally specified as ‘no previous failures’, 1 previous failure’ and ‘more than 1 previous failure’. For the fracture component of the Condition Score, the fractures are confined to the previous 5 year time period only. For the corrosion component, any previous corrosions are considered, and for joint leaks, any previous joint leaks are considered.

The following figure, Figure 4, shows typical relative weightings between Background Zones, and previous failures, based upon analysis of real data.

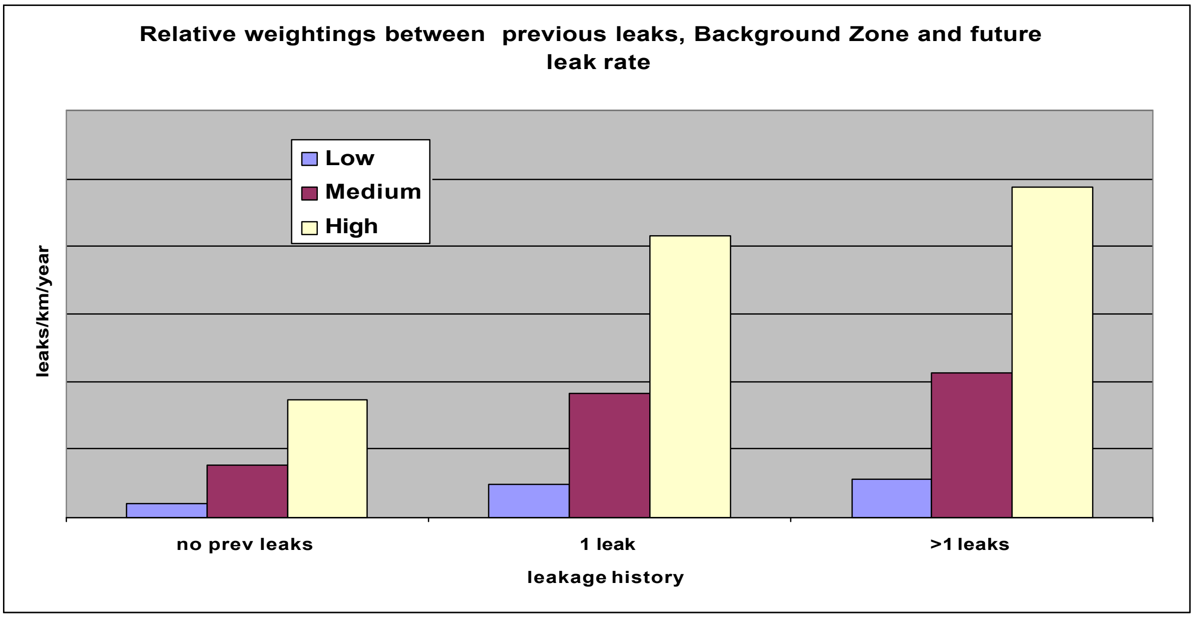

Figure 4 – Relative weightings between previous leaks, Background Zone and future leak rate

The weightings shown above can be used as part of the calculation of Condition Score, for pipes which have previously experienced a leakage failure. For pipes which have not experienced a leakage failure, an additional weighting, related to the age of the pipe, is included.

This process has been applied systematically to generate three separate components of the Condition model, namely the Mains Fracture Factor (MFF) which models future breaks and uses data on previous breaks and Background Breakage Zones (BBZ) ; the Mains Corrosion Factor (MCF) which models future corrosion leaks and uses data on previous corrosion leaks and the Background Corrosion Zones (BCZ); and the Mains Joint Factor (MJF) which models future joint leaks and uses data on previous joint leaks and Background Joint Zones (BJZ). In addition to these common elements, the MFF for Cast Iron pipes also includes a contribution from diameter as there is a strong inverse relationship between diameter and fracture rate. The sum total of all three components is the Condition Score and represents the overall failure rate of an individual pipe in terms of leaks/km/year, where leaks includes fractures, corrosion leaks and joint leaks. It is important to note that one other mode of failure, namely interference damage (otherwise referred to as 3rd party damage), is not included within this model as it is not considered to be a deterioration model of failure.

Results

The analysis discussed in the previous section describes how a theoretical measure of future leak rate is obtained from producing a statistical link between Background Zone, previous leaks, age and future leaks. This section describes how this theoretical measure was tested against real data to determine how accurate the model was at predicting the future number of leaks from a given population. The population selected consisted of a sample of 36000 distribution mains, in operation, from across the UK.

The process whereby the methodology was tested consisted of several stages, as follows:-

1. Take a point in time 1 year prior to the data extract.
2. Apply the Condition Model to all pipes, thereby generating a Condition Score for each pipe, in terms of leaks/km/year.
3. Take the Condition Score of each pipe and multiply by its length to generate a leaks/year measure.
4. Sum all of these individual measures to calculate the total number of predicted leaks from that population for the following year.
5. Examine the data to extract the actual total number of leaks on those pipes in the following year.
6. Compare the 2 figures to determine the accuracy of the model in predicting future leaks.

Table 1 below summarises the results arising from analysis of this sample of mains.

Total number of pipes in sample	36000
Total length of pipes	3509km
Total Number of predicted leaks in current year based on Condition Score for previous year.	899
Total number of actual leaks in current year	888

Table 1 – Summary of sample data and results from verification of Condition Model

The previous table demonstrates that the overall level of leakage arising from a set of pipes has been closely predicted from the Condition Scores. It is important to note that the model does not predict which individual pipes are going to leak as the output is not a binary measure i.e. leak or no leak, rather it predicts the likely level of leaks for an amalgamated group of pipes. Thus the tool can be used to assess how many leaks may be removed from the system by replacing particular set of pipes. This should enable a gas distribution operator to determine the best pipes to target for replacement to give the greatest reduction in future leaks. A further advantage of using the methodology is to be able to compare current replacement policies with this new methodology to determine the likely improvement.

Comparison of prioritisation results

Three separate methods of prioritisation were applied to these pipes. The first consisted of entirely random selection, the second consisted of selecting pipes according to the number of previous leaks on that subset alone, and the third consisted of selecting pipes based upon their Condition Score.

The sample of pipes was chosen to be representative of a full population, i.e. a whole range of pipes, in good and poor condition. Many gas distribution companies are currently working on a replacement programme covering many years - typically a company may choose to replace all metallic mains over a 20 year period say, i.e. replacing 5% of the system each year. If the order in which these mains is replaced is random, then removing 5% of the total population is likely to result in a population which would generate approximately 5% of the annual leaks occurring in the following year. By introducing some kind of prioritisation, where those mains having the highest number of previous leaks are removed first, this should remove a greater percentage of leaks than random replacement alone.

The sample of data was used to simulate the difference in future behaviour based upon three different methods of prioritisation.

For the first simulation, 5% of pipes were removed from the original 36000, by selecting them at random. Again, the selection of pipes was carried out as if it was the previous year. This same sub-population was then examined to extract the number of leaks which actually occurred on those 5% of pipes, in the following year (current year). This process was then repeated for a 20 year period, each year resulting in a further 5% of the population being removed each year.

For the second simulation, 5% of pipes were removed from the original 36000, by selecting them based upon the highest number of leaks prior to the date of selection. This same sub-population was then examined to extract the number of leaks which actually occurred on those pipes in the following year. Again, this process was then repeated for a 20 year period, each year resulting in a further 5% of the population being removed each year.

For the final simulation, 5% of pipes were removed form the original 36000, by selecting them based upon their Condition Score, which takes into account previous leaks, as well as age and Background Zone (and for Cast Iron pipes, the diameter). Again, the number of actual leaks occurring on this sub-population in the following year was extracted and the process repeated for a 20 year simulation.

In each case, the number of leaks at the start of the 20 year period is the same – in this case, 888. The total number of leaks at the end of the 20 year period is zero as all pipes have been removed at this point. The rate at which the level of leaks drops year on year reflects the effectiveness of the prioritisation process, and also the level of costs associated with leak repairs. Leak repairs are usually unplanned events which attract higher workload costs, as the repair may be carried out outside normal working hours which carry a premium. The safety aspect is of course, also important, as any uncontrolled leak has the ability to track through the ground, and in some cases may track into property, presenting a potentially serious hazard.

Figure 5 below shows how leaks should reduce over time using the two methods of prioritisation and random removal. It can be seen that replacing mains based on previous leaks alone will remove leaks from the system more effectively than the random approach, but that the application of the Condition Model within MRPS will be even more effective than using previous failure history alone. As previously stated, all three methods have the same start and end level.

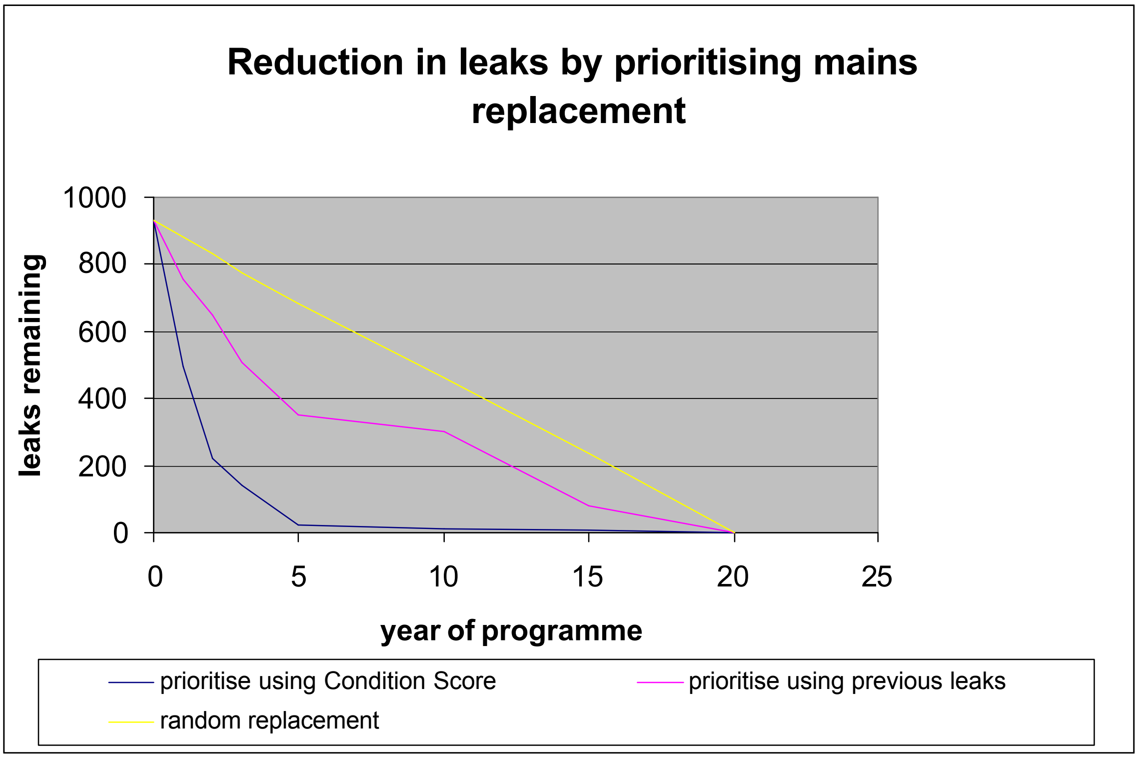

Figure 5 - Comparison of prioritisation methods

Figure 5 demonstrates the effectiveness of the Condition model compared to the practice of replacing mains with the greatest number of previous leaks. The 20-year program removes 5% of pipes, in terms of length, each year. In year 1, using the Condition model to identify this subset of pipes, almost 50% of the leaks which would have occurred in the following year have been avoided. This compares with a reduction of nearly 20% using previous leakage alone. The random replacement, as expected, has removed 5% of the following year's leaks. These results are very different from one another; the use of the Condition model is significantly better at identifying pipes at risk of leaking compared with using previous leakage behaviour alone.

Extension of the Condition model to consider risk of ignition incident

All of the discussion so far in this paper has considered the application of GL's Condition Score methodology to metallic pipes and its impact upon leakage reduction. Of course, any leak from a gas distribution pipe has the ability to track into any nearby property, presenting a potentially serious hazard.

The model currently in use in the UK is an extension of the Condition model, to model the likelihood of gas ingress and ignition. This is known as the Risk Model. Once again, the two further stages have been built up from analysis of historical data. For the gas ingress stage, data on previous leaks and their resulting leakage path, i.e. gas in property, has been analysed to link particular pipe and location characteristics to the proportion of leaks which will enter property.

The characteristics considered are diameter (in the case of cast iron pipes), distance of the pipe from nearby property (proximity), the presence of cellars in nearby property, and whether the ground between the pipe and nearby property is sealed (tarmac, concrete etc) or unsealed (loose gravel, grass etc). Once again, the use of multivariate analysis has allowed an auditable, numerical link to be made between the four input variables and the output, in terms of gas ingress per leak.

The third and final stage in the process, the likelihood of ignition, makes use of two input variables, presence of cellars, and operating pressure. The presence of cellars will increase both the likelihood of gas tracking into property, but also the likelihood of severe property damage and/or injuries and fatalities should the accumulating gas find a source of ignition. The operating pressure is linked to the time it takes for gas to build up to a flammable mixture without detection. Previous analysis has shown that mains operating at Medium Pressure (75mbar to 2 bar) are likely to be at least 10 times more likely to cause an ignition incident than identical mains operating at Low Pressure (<75mbar), should gas track into property.

The output of the Condition Model is leaks/km/year for each individual mains unit. The output for the Risk Model is ignition incidents/km/year for each mains unit. The product of the Risk Score and the length of a pipe results in a measure of ignition incidents per year for each pipe. Just like the Condition Model, the sum total of these values across the whole population in use will generate a measure of predicted incidents per year. In the UK, the average level of actual incidents over recent years is around 1 or 2. In some years, the level is zero.

Because the occurrence of ignition incidents is low, the trend can be difficult to measure over a short time period. In these circumstances, it is more difficult to compare the actual level of incidents with the predicted level, but the application of the Risk Score over the last 10 years (since 2000) has resulted in a 53% reduction in the annual incident rate, for a corresponding 25% reduction in the mains population over the same period. Thus, given a reasonable time period over which to compare its effectiveness, the Risk Model has also been shown to be effective at reducing risk, just as the Condition Model has been shown to be effective at reducing leakage.

As the purpose of this paper was to describe the use of modelling to reduce leakage, the development of the weightings for the Risk Model are not described here in detail, but Figure 6 below shows the typical relationship between proximity, open ground and gas ingress rate as determined from analysis of real data. As can be seen from the graph, the likelihood of gas ingress increases the closer the pipe is laid to nearby property and the presence of sealed ground increases the rate of gas ingress rate compared to open ground. These findings follow engineering judgement but the value of using real data to produce these relationships is that it generates defendable, auditable, objective weightings.

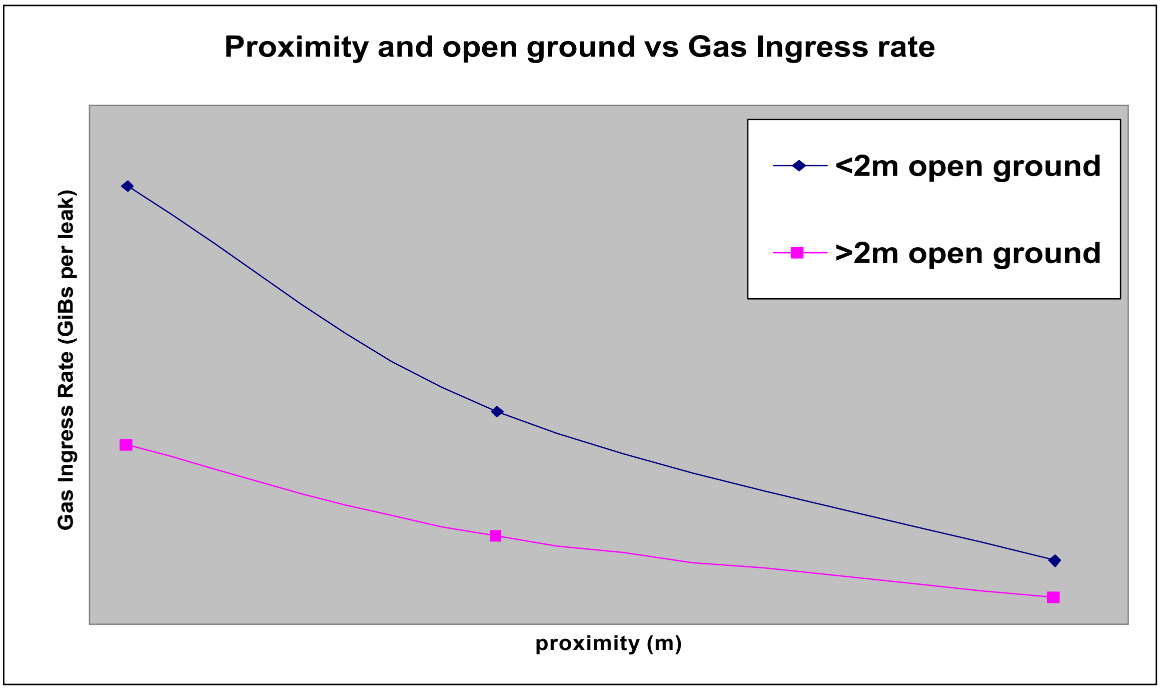

Figure 6 - Statistical link between proximity, open ground and gas ingress rate

Conclusions

This paper has discussed the challenges faced by gas distribution companies in terms of leakage and has proposed a solution which has already been developed and is in use in the UK. The methodology described within the Condition Model has been shown to be effective in targeting metallic pipes for replacement, ideally before they leak. The methodology has been shown to be more effective than using leak history alone as a ranking tool. The advantages of moving to a more effective method of leak identification are several, as listed below :-

1. Gas distribution companies could reduce the level of mains replacement carried out but still achieve the same reduction in leakage.
2. Gas distribution companies could keep the same level of mains replacement but reduce leakage quicker.
3. Gas distribution companies would have a much greater understanding of the number of expected leak repairs in future years, thus managing their resources much more effectively.
4. A more auditable method of identification and prioritisation would allow gas distribution asset managers to present a clear and robust business plan to senior managers, regulators and other stakeholders, when challenged to defend their expenditure on leakage reduction and associated mains replacement.
5. An extension of the Condition Model (the Risk Model) could be applied to metallic mains to identify and prioritise mains for replacement which are at greater risk of gas ingress into property and ignition incident.