RISK-PRIORITISED DISTRIBUTION ASSET MAINTENANCE

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ABSTRACT

This paper describes the work National Grid and its predecessor companies have carried out to establish programmes for the maintenance, generally by replacement, of distribution assets. Prioritisation of resource allocation is based on quantified risk assessment. This quantitative approach provides an objective and consistent method of comparing risk factors that would otherwise need to be assessed on the basis of Engineering Judgement.

The majority of work carried out to date has informed the replacement of iron gas distribution mains, which present a particular risk of incident and injury to the public. The sudden failure of an iron main, by fracture or failure of corrosion product, can release large quantities of gas, creating a risk of fire or explosion. This risk is highest where the release occurs in close proximity to buildings and increases with operating pressure. This paper describes the development of the mains risk prioritisation system (MRPS) to provide a quantified risk value for each iron main in National Grid’s 120,000km mains population.

In 2001, the UK safety regulator, the Health and Safety Executive (HSE), published its enforcement policy for the replacement of iron gas mains. This policy requires gas distribution operators in Great Britain to establish programmes that will enable all iron gas mains within 30 metres of buildings to be replaced over a 30-year period. National Grid has agreed terms with its economic regulator, OFGEM, for the funding of this programme from 2002 to 2007 and makes use of MRPS to prioritise its replacement activity. National Grid has developed procedures and contract agreements that allow an efficient and economic balance to be struck between the reduction of risk to the public and the effective deployment of skilled manpower to carry out the work.

National Grid is developing the risk-based approach for other asset types and has applied the principle to the maintenance of water-sealed gasholders, where environmental and security of supply risks need to be controlled in addition to the risk of injury to the public.

The paper describes how available data can be used to provide a quantified approach to the comparison of risks and the potential benefits of different approaches to the management of risk. Consistency in a numeric evaluation system can support submissions and discussions with Safety and Economic regulators to determine appropriate standards and funding requirements.
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1. INTRODUCTION

Gas markets throughout the World are benefiting from the improvements in technologies that allow the bulk transportation of natural gas in gas or liquid forms. This widening of the availability of gas as a fuel for domestic, commercial and industrial uses has created growth in demand and resultant challenges to maximize the performance of distribution networks. For countries with a long history of gas use, this has brought particular challenges in maintaining and replacing distribution assets that were constructed to store or deliver manufactured gas, yet still provide a large part of 21st Century distribution systems. Metallic main & service pipes and water-sealed gasholders are gradually being replaced by plastic pipe systems and high-pressure storage, but replacement programmes can appear costly when, thankfully, catastrophic failure of the original plant is rare and the risk of injury to individual people is low.

The collection and analysis of performance data and its application in decision support tools can provide a consistent basis for the allocation of resources to enable Asset Managers to deliver an optimal balance between Cost, Risk and Performance. The gathering of data to inform decision-making presents its own challenges, as buried assets cannot be inspected easily and there may be no warning signs that deterioration of the asset or its environment is about to cause a failure with potentially dangerous consequences. A combination of statistical analysis of repair history, data on local environments and theoretical modeling of known failure modes is required in order to develop systems that indicate priorities for repair or replacement.

2. NATIONAL GRID’S GAS DISTRIBUTION NETWORK IN GREAT BRITAIN

National Grid operates a gas distribution system with origins in the late 19th century. Until the introduction of polyethylene pipe systems in the 1970s, iron was the British gas industry's preferred material for distribution mains, with steel used for service pipes and higher pressure pipelines. By the year 2000, the gas distribution networks in Great Britain comprised approximately 120,000km of iron mains, 130,000km of Polyethylene mains and 20,000km of steel mains, together with over 500 water-sealed gasholders, to provide gas supplies to over 20 million gas consumers. The likelihood of failure of individual assets is very low, but the large numbers in use create risks to society and to public confidence in the gas industry.

In June 2005, ownership of the gas distribution systems was divided between four companies, with National Grid retaining just over 50% of the network assets across the central part of England and the remainder being shared between three other major operators.

Figure 1. National Grid UK Gas Distribution Operating Area
This separation of the business brings a new dimension to comparative performance measurement and regulation, with each operator determining standards of performance to meet their customers’ and regulators’ requirements.

National Grid’s distribution mains population totals over 126,000km.

Table 1: National Grid’s Gas distribution mains population in Great Britain (2005)

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Below 75 mbar</th>
<th>75 mbar to 2 bar</th>
<th>2bar to 7 bar</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>55670</td>
<td>9125</td>
<td>525</td>
<td>65320</td>
</tr>
<tr>
<td>Cast &amp; Ductile Iron</td>
<td>50210</td>
<td>2850</td>
<td>0</td>
<td>53060</td>
</tr>
<tr>
<td>Steel</td>
<td>3275</td>
<td>2280</td>
<td>2235</td>
<td>7790</td>
</tr>
<tr>
<td>Total</td>
<td>109155</td>
<td>14255</td>
<td>2760</td>
<td>126170</td>
</tr>
</tbody>
</table>

In addition to the mains detailed in table 1, National Grid operates approximately 11 million individual service pipes, 200 low-pressure gas holders, 1300 pressure regulating installations and 50 off take from the National Transmission System. National Grid also operates the gas transmission pipelines system in Great Britain, 5 LNG storage sites as well as the electricity transmission system in England and Wales.

Two government-appointed bodies regulate the British gas industry’s safety and commercial operating standards, with each body having separate duties. The Health and Safety Executive (HSE) prescribes and enforces legal requirements in relation to the safety of the public and employees for all industries throughout Great Britain. OFGEM (The Office of Gas and Energy Markets) prescribes and enforces the commercial trading arrangements of the gas and electricity industries, establishes allowed revenues for monopoly operators and sets standards for customer services. In designing an asset maintenance strategy, National Grid must implement procedures that meet the objectives of both of its regulators and its own corporate objectives, which include the delivery of its ambition to be the world’s premier Network Services Utility.

The development of a quantitative risk-prioritised approach to maintenance planning can provide an objective means of assessing the benefits likely to be derived from a given level of investment. Where quantitative measures are developed, both the operator and its regulatory bodies can analyse actual or forecast delivery against their objectives to enable comparison with other gas, utility or national expenditure programmes. Such analysis can be used to determine appropriate funding and incentive mechanisms that promote best practice and drive operating efficiencies. When priorities for medium to long-term resource allocation are agreed between operators and their regulators, business plans can be developed with greater certainty, supporting improvements in purchasing and contracting negotiations.

3. DISTRIBUTION SYSTEM DEVELOPMENT AND MAINTENANCE

- Failure Characteristics of Iron and Steel pipes

“Pit cast” is the oldest type of cast iron main in use. These pipes were formed by pouring molten iron into a vertical mould around a central core. In most cases the central core was not perfectly aligned and this caused the wall thickness to vary around the circumference of the pipe, requiring large tolerances and generally providing thick walled pipes. “Spun” cast iron pipes were manufactured by pouring molten iron into a rotating mould. Spun iron pipes have a more constant wall thickness than pit cast, but reduced tolerances allowed by this improved technique formed thinner-walled pipes. Cast iron pipes generally fail by fracturing due to ground loading, though some spun iron pipes have shown evidence of fissure corrosion prior to fracture. The risk of fracture failure in cast iron pipes reduces significantly with pipe diameter as beam strength increases.
Ductile iron pipes, also formed in rotating moulds, have a metallurgy with graphite in spheroidal form, providing greater ductility than cast iron pipes. This improved strength allowed the pipe to be produced with thinner walls than spun iron pipe. The product of ductile iron corrosion has little residual strength, which means that through wall corrosion can form plugs that break out, causing significant leakage. The use of ductile iron pipe was originally expected to provide a balance between fracture and corrosion resistance, but experience suggests that the failure of ductile iron corrosion product can allow gas releases that can be as dangerous as a cast-iron fracture failure.

The properties of steel pipes are well established, with resistance to fracture making steel a widely used material for gas distribution, though corrosion can cause leakage and, in extreme circumstances, total pipe wall loss. Steel pipes used in distribution pressure applications are rarely subjected to stresses which would give concerns about either yield or rupture.

The risk of corrosion failure in steel or ductile iron is mainly a function of soil conditions and the quality of corrosion protection, so is generally independent of pipe diameter. Where new or replacement distribution mains are to be laid in Great Britain, polyethylene is now the preferred material.

- **Mains replacement 1975 to 1999**

  The early 1970’s saw three significant developments that affected the British Gas Industry; the conversion of the entire distribution system from manufactured to natural gas; a series of explosion incidents in 1976 and 1977 that led to a government enquiry; and the development of polyethylene as a suitable material for gas transportation.

  The conversion to natural gas made gas available (and desirable) to a larger population than had previously used manufactured gas. Higher calorific values, the potential for transportation at higher pressures and the prospect of a cleaner, safer, modern fuel gave rise to increasing demands for gas from domestic, commercial and industrial users.

  Following several severe gas explosions over the Christmas and New Year period of 1976/77, the Secretary of State for Energy commissioned an enquiry chaired by Dr P.J. King to examine the circumstances surrounding the incidents and to consider improvements to existing procedures or systems and new measures which might reasonably be implemented to lead to a reduction in such incidents. Dr King recommended that priority should be given to the replacement of higher-risk mains in those locations where a failure could cause a serious incident. The mains targeted were small diameter cast iron and steel mains in the most hazardous locations.

  The development of polyethylene as a pipe material has provided a solution to the failure modes most commonly experienced by metallic pipes. PE has a far higher resistance to fracture than cast iron and does not corrode like steel. PE pipe is so flexible, particularly in small diameters, that it can be provided in coiled form, allowing hundreds of metres to be laid without jointing. This flexibility also allows the pipe to be inserted into the ground using either holes bored by specialist machinery or the bore of the pipe being decommissioned. There are now a wide variety of mains and service insertion techniques, which allow pipelaying and pipe replacement with minimum excavation and reinstatement. This avoidance of excavation and reinstatement costs makes possible the extension or renewal of networks that would be prohibitively expensive if conventional open-cut techniques were used with rigid pipes & frequent joints.

  Between 1975 and 2000, approximately 60,000km of pipe, representing one-third of the 1975 iron gas main population in Britain, was replaced using polyethylene pipe. In accordance with Dr King’s recommendations, this programme replaced small-diameter mains in the most hazardous locations as a priority. Hazard was assessed by surveying the route of mains and identifying places of public assembly (schools, hospitals etc) and properties with cellars, where hazard is increased; and measuring the amount of open ground between the line of the main and the property. Greater amounts of open ground provide opportunity for gas to vent to atmosphere, so reducing hazard.
A series of hazard-based programmes were operated over the last quarter of the 20th century and successfully reduced the frequency of fire and explosion incidents by an order of magnitude. The basis for the programmes was the application of Engineering Judgment to the deployment of available resources. Following privatization of Great Britain’s gas industry in 1985, the exercise of such judgments came under increasing economic examination, as the costs of operating such a programme have to be borne by the gas consumer, whose expectation is that the industry will be operated in an economic and efficient manner, with safety and security of supply delivered in accordance with customers expectations but not at excessive cost. These public interests are represented by OFGEM and are taken into account in five-yearly reviews of the gas transporters allowed revenues. By the year 2000, approximately 120,000km of iron main remained in use throughout Great Britain, the infrequent failure of which give rise to about four serious fire and explosion incidents per annum, with associated injuries to occupants. The dilemma facing the British gas industry and its regulators was either to tolerate this low level of incident and its potentially fatal consequences or to maintain investment in replacement in a way that would further reduce the small residual risk.

- **Development of quantitative risk models**

Consultation with economic and safety Regulators during the 1997 review of allowed revenues indicated that the basis of the hazard-based programme did not provide sufficient quantification of the benefits provided by investment in mains replacement to provide a meaningful cost/benefit analysis. Nor did it make use of the latest thinking in risk assessment methods. It was therefore recommended that a new approach to risk assessment be developed, allowing the production of objective data to inform cost/benefit analysis of various replacement programme scenarios.

Over a three-year period, Transco, the pipeline operator at the time, worked with the HSE, OFGEM and technical advisors to develop a new risk assessment system that was now able to provide a quantified assessment of the risk of incident arising from each of the 1.2 million pipe units that made up its iron mains population. National Grid now uses this Mains Risk Prioritisation System (MRPS) as a key part of its short, medium and long-term replacement planning process.

MRPS uses three key factors to calculate a risk value for each mains unit; the main’s failure factor (assuming failure either by fracture for cast iron or by corrosion for ductile iron or steel pipes); a gas ingress factor; and a consequence factor. Figure 2 below illustrates the data used to calculate each of the factors.

For a cast iron main;

- **The mains fracture factor** is calculated by combining data on the diameter of the main, its individual breakage history and a factor developed from the breakage history of other cast iron mains within a 400metre zone around the main being considered;

- **The gas ingress factor** is calculated by considering the diameter of the main (as this affects the quantity of gas likely to be released from a fracture); the distance between the main and the nearest property; the amount of open ground in that distance; and whether the property has a cellar or a basement. (Cellars can significantly increase the risk of an explosion, as gas is more likely to accumulate in a below ground void and less likely to be detected if the cellar is rarely visited);

- **The consequence factor** is calculated by considering the pressure at which the main is operating (this affects the rate of gas release and therefore the likely rate of gas accumulation in property); and the presence of cellars. The consequence of an explosion in a cellar is likely to be higher than one in an above ground room as there may be no windows to provide overpressure relief at the time of ignition, so the structural damage is generally greater.
The resulting risk value is expressed in units of $10^{-6}$ incidents per kilometre per annum. A typical value for the mains operated by National Grid is about $25 \times 10^{-6}$ incidents per kilometre per annum. An alternative way of expressing this value is that each kilometre of iron main is estimated to present a risk of incident once every 40,000 years. A population of 40,000km of pipe with this risk value would be expected to give rise to one incident per annum, but such a model would not indicate which pipe was most likely to be the cause of the incident. National Grid’s population of pipes has a wide range of risk values. In December 2005, there were less than 700km of mains with risk values in excess of 240. These pipes will form the core of National Grid’s replacement programmes in the next few years.

At present, National Grid operates four MRPS models, assessing risk for cast iron mains with diameters up to 12”, cast iron mains with diameters greater than 12”, ductile iron mains and steel mains. The four models produce risk values that are directly comparable, allowing decisions to be made on the allocation of resources across the material types.

The MRPS models, developed with Advantica, have been developed and validated using advanced statistical techniques and reviewed by independent statisticians.

- **Definition of mains replacement programme requirements from 2000**

  Initial independent economic assessment in the late 1990s suggested that the level of investment necessary to deliver further safety improvements was far higher than normal economic metrics would support. The economic return on the investment required would be considerably lower than expected by shareholders in a fully private enterprise. There is, however, a clear public aversion to the consequences of catastrophic failure, however rare. The UK legal requirements for the maintenance of gas networks do not prescribe particular measures to be taken to ensure integrity, but are “goal setting”, with general requirements to reduce risk “so far as is reasonably practicable” and to maintain pipelines in “efficient working order and in good repair”.

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**Figure 2. Elements of Risk Calculation**

- **Risk Value**
  - **Mains Fracture Factor**
    - Background Breakage Zone
    - Previous Breakage History
    - Diameter of Main
  - **Gas Ingress Factor**
    - Open Ground
    - Proximity to Property
    - Diameter of Main
    - Cellars or Basements
  - **Consequence Factor**
    - Operating Pressure
    - Cellars or Basements

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In assessing the investment required to achieve a reduction in the risk to the public, the HSE carried out a cost/benefit analysis that estimated a cost per incident avoided by accelerating replacement from the average of the 1995 to 1999 rates (approximately 1800km p.a.) to an annual rate of replacement that would allow the remaining population of iron mains within 30 metres of buildings to be replaced over a 30-year period (approximately 3,600km p.a.). The HSE deemed the proposed acceleration to be “reasonably practicable” and have since introduced procedures whereby operators submit annual programmes for HSE approval. Failure by an operator to submit or comply with a programme can result in enforcement action being taken. This approach by the HSE has defined new standards to be achieved by distribution network operators, based on the need for a precautionary approach to network maintenance.

- **Application of MRPS**

Though the MRPS models were developed principally to inform a replacement prioritisation tool, the quantified estimates of risk presented have allowed a range of analysis to be applied to improve several aspects of business performance.

By multiplying each main’s risk value by its length and summing the result, it is possible to estimate the total risk presented by the metallic pipe population or by specific populations, for example by material, diameter or geography. This can be used to identify areas where the risk of incident presented may be significantly different from average values. An example of output from the model indicating the distribution of risk in the National Grid gas network is shown in figure 3 below.

The outputs are used to establish a methodology that identifies the highest priority pipes for a coming year’s replacement programme and identifies pipes that are likely to be high priorities over the next five years. An economic judgment can then be made whether to include all the next five years’ priority pipes in a single replacement project. By applying this principle, a balance can be struck between “top down” replacement of pipes in strict risk order and the efficient deployment of valuable skilled resources. This allows an optimised approach to the overall reduction of risk.

**Figure 3. Example risk profile**

Forecasts of the quantity of risk reduced can be developed for a range of investment scenarios. While the removal of risk of incident is the biggest influence on the selection of pipes, the tool can be used
to assess the effect of replacing particular populations for other reasons. For example, if a Local Authority requests replacement of mains in a street that it is planning to resurface or refurbish, the risk values of the pipes in that street can be reviewed and a decision made on whether it is appropriate to bring forward their replacement in order to avoid replacement works soon after the refurbishment project is completed. Alternatively, if a new replacement technique is being reviewed, the mains that the technique could be applied to can be analysed to determine their priority for replacement and either the economic benefit to be derived or the urgency of completing the development.

The data from the models changes dynamically as new repair and survey data is input. This data can be used to monitor the effectiveness of the programmes being operated and demonstrate the rate of risk reduction. This monitoring data is provided to both the Safety and Economic regulators to inform their discussions on the future of the replacement programmes.

By identifying areas in descending order of local risk, plans can be made several years in advance to recruit and deploy resources in those areas where replacement workloads will be greatest. National Grid has applied this principle to develop an Alliance approach to its contracted replacement works, described in section 4 below.

- **Maintenance of MRPS**

  The data behind MRPS is taken from National Grid’s asset database and specific surveys carried out to maintain the validity of the risk estimates. At present, mains operating at pressures greater than 75mbar are surveyed annually in order to collect information about changes in local environments. (The risk of an incident from a main operating at 2bar is estimated to be 20 times that of a main operating below 75mbar.) Mains operating at pressures below 75mbar are surveyed on a five-yearly cycle.

  The MRPS models are reviewed annually and validated against historical incident and breakage data. Key coefficients that drive the failure, ingress and consequence factors are updated annually in order to ensure that the models make best use of the available data.

- **Development of quantified risk models**

  National Grid is seeking to apply the principles of MRPS to its wider asset population. Though the estimation and management of the risk of a gas release and ignition is very important, other assets can fail in ways that give rise to other risks with serious consequences for the business.

  A good example of this is the application of risk modeling techniques to low-pressure gas holders, where the risks arising from failure of the holder include the risk of an ignited release of gas but also the economic and social risk of a failure to maintain supply during periods of cold weather and environmental risks if the containment of holder water fails and local watercourses are contaminated. In 2005, National Grid implemented a model that takes into account the potential impact of all three of these risks and provides decision support for the prioritisation of maintenance activity on water-sealed low-pressure gas holders.

  As the risks of serious ignition incident from fracture or serious corrosion failure of mains reduce with the progress of the risk-based mains replacement programme, the control of low-volume leakage from mains will increase in priority. Leakage from joints and minor corrosion defects gives rise to about 80% of National Grid’s network emergency work and is a significant source of methane released to atmosphere. An extension to the MRPS models has been developed by Advantica that uses the leakage data held alongside the fracture and corrosion repair data. This extension can estimate the economic value that can be generated by combining a leakage reduction model with the incident reduction model, giving an indication of a wider benefit to be gained by considering both aspects of risk from mains failure. The model can be applied to consider an economic-only replacement programme for Networks where the risk of catastrophic failure of iron or steel mains is negligible and replacement programmes are driven principally by return on replacement investment.
4. THE ALLIANCE APPROACH

The implementation of the HSE’s 30-year programme and the application of the MRPS prioritisation model have allowed National Grid to identify those areas where mains replacement activity will be highest over the next decade. These areas have defined the basis for Construction Alliances with major contractors. These Alliances provide a much stronger relationship between National Grid and its Contractors than conventional Period Contracts, with longer terms, greater certainty of workload and locations and greatly improved planning for investment, recruitment and training. The Alliance contracts have initially been let for eight years, with options to extend for a further five years.

The Alliance approach puts National Grid and Contractor employees into a single unit, combining management and workforce with shared objectives and measures. Work planning is carried out in accordance with National Grid’s procedures for managing risk, but projects can be organized and scheduled in a way that makes best use of the Alliances’ resources.

The Alliances are now in their third operating year and the benefits of improved working are delivering efficiencies in project design and operating practices, together with initiatives to ensure that public and operator safety are maintained at the highest levels when work is carried out in the public highway.
5. RESULTS

The parallel implementations of the September 2001 Health and Safety Executive (HSE) Enforcement Policy describing a 30-year programme to replace all iron gas mains within 30 metres of buildings and the quantified risk assessment tool, MRPS, provided the gas industry in Great Britain with a long term programme with clear direction and high quality decision support. The anticipated costs of this programme are approximately £15 billion. In April 2002, the economic regulator, Ofgem, announced arrangements for funding that enable the British gas industry to recover its costs to deliver the programme and provide incentives for improved operating efficiency. Both of these regulators’ decisions are subject to five-yearly reviews.

In the four years since the commencement of the 30-year programme, National Grid has developed pipe selection procedures that balance the requirements for risk reduction prioritisation with the need for efficient deployment of skilled resources. NG’s contractors are now working in a way that can allow medium- and long-term planning for individual projects and the required manpower.

NG is working to develop equivalent approaches to the management of other key assets where low probability/high consequence failures create significant difficulties in investment decision-making. Advances have been made in the creation of decision support tools for the maintenance of Gasholders, Water Bath Heaters and Steel distribution pipes.

6. CONCLUSION

The implementation of significant safety-based investment programmes can be difficult to justify on the basis of conventional cost/benefit analysis. Such programmes are a key part of a gas business’ operating strategy and high-level decisions must be made. Where a programme’s scale is such that it has a very significant effect on the company’s finances, the regulators responsible for enforcing the operator’s safety and commercial obligations need to be provided with objective analysis of the options available.

The collection of data and its analysis in a way that supports decision-making at the highest level is a significant challenge. The ability to carry out objective analysis of performance is a fundamental requirement, however, in industries where customer charges are increasingly subject to detailed examination.

National Grid believes that it has provided a model that can be applied widely throughout the gas and utility industries to inform both internal and external decisions on investment and asset management.