Institution: University of Surrey		
Unit of Assessment: 12 Engineering		
Title of case study: Advancing Trunk Main Assessment and Strategy in the Water Industry		
Period when the underpinning research was undertaken: 2000 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr Michael Mulheron Professor Paul Smith Dr Hal Belmonte Dr David Jesson	Reader Professor Post-Doctoral Researcher Post-Doctoral Researcher	16/04/1984 – present 01/09/1986 – present 19/02/2002 – 31/12/2004 20/03/2006 – present
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Networks of ageing cast iron trunk mains are key in the supply of drinking water to millions of consumers worldwide, and any interruption in supply associated with pipe failure, catastrophic or otherwise, is undesirable operationally and problematic, both socially and environmentally. Consequently, network operators seek to reduce the occurrence of failure by proactively targeting and replacing high-risk mains. Accurately determining where and when a pipe needs repair and where asset life may be prolonged for decades is a desired strategy for water utilities globally. Experimental data and the associated physical and empirical models from research at the University of Surrey are being used to inform asset and risk management and form a key part of Thames Water's 2015-2025 trunk main strategy.

2. Underpinning research (indicative maximum 500 words)

The UK water industry operates a supply and distribution network consisting of an ageing, predominantly cast iron infrastructure. Research at Surrey carried out by Professor Paul Smith, Dr Mike Mulheron, and others over more than 20 years (1997-present), into both small diameter (distribution main) and large diameter (trunk main) cast iron water pipes, has led to a detailed understanding of how these assets behave after long periods in service.

Early work on distribution main pipes **[R1, R2]** was key to developing an understanding of the behaviour of cast iron and the role of aqueous corrosion (graphitisation) on material strength and pipe performance. An important insight was that there are two distinct defect populations present within cast iron pipes in service, one relating to the microstructure of the cast iron (reflecting casting method and quality) and the second arising from in-service degradation processes, such as graphitisation **[R1]**. Subsequent work, with Dr Hal Belmonte, developed a (Weibull) statistical approach, based on the strength of small samples from the network, to inform the asset management of the distribution pipe network at both street and area level **[R2]**.

The underlying understanding of changes in material and pipe behaviour over time informed the work on trunk mains, which began in 2006 and was then supported further (2011) through a 4-year, £1.2M project funded by industry and complemented by two EPRSC EngD studentships. This led to new insights into the morphology of cast iron corrosion and its spatial distribution in actual pipes in service **[R3]**. A key finding was that where the layer of graphitised material is of uniform thickness, the associated strength reduction is modest, but where the penetration is more localised, the strength reduction can be significant, e.g., a depth of graphitisation extending to 10% of the wall thickness can produce a 50% loss in strength. This was transformative, in terms of understanding, for a sector that has historically worked with a traditional loss-of-section approach to determining residual strength. It was also shown that the extent and morphology of the graphitisation can vary significantly (at the sub-metre level) within a single section of pipe. Based on this knowledge, the appropriate application of simple strength-of-materials and fracture mechanics approaches were found to provide reasonable bounds for the residual strength data measured experimentally **[R3]**.

The models were refined in subsequent work, in particular through the more robust incorporation of the pipe geometry into the fracture mechanics analysis, and applied to representative pipe elements **[R4]**. The revised model has been shown to provide a useful assessment of the residual load capacity of pipe in a trunk main; this was demonstrated by generating failure envelopes based on assumed defects at particular locations around the circumference of a pipe. Further, a case study demonstrated the potential to apply this methodology to a specific example. Such an approach explains why a slowly deteriorating pipe can suddenly and catastrophically fail when neither the internal pressure nor external loading has changed.

The understanding developed in these studies has influenced the asset management tools used by the industry. Critically, this work has led to a growing realisation that there is a significant technical challenge to be addressed in developing non-destructive testing techniques for buried pipe assets to enable the condition to be assessed with adequate accuracy. This was highlighted in a paper **[R5]**, which reviews the origins and morphology of graphitisation (including new data sets), the consequences for defining accurate and up-to-date condition assessment protocols and hence the type and urgency of rehabilitation strategies. The work demonstrates conclusively that understanding the integrity/life expectancy of water networks requires non-destructive evaluation of large diameter cast iron trunk mains, with particular reference to the kinds of defects that are likely to be present and the issues that make assessment difficult.

3. References to the research (indicative maximum of six references)

[R1] K.Atkinson, J.Whiter, P.A.Smith and M.Mulheron, (2002) Failure of small diameter cast iron pipes, *Urban Water*, 4, 263 - 271. DOI: 10.1016/S1462-0758(02)00004-3

[R2] H.M.S.Belmonte, M.J.Mulheron, P.A.Smith, A.Ham, K.Wescombe and J.T.Whiter, (2008) Weibull based methodology for condition assessment of cast iron water mains and its application, *Fatigue and Fracture of Engineering Materials and Structures*, 31, pp.370 - 385. DOI: 10.1111/j.1460-2695.2008.01233.x

[R3] D.A.Jesson, H.Mohebbi, J.Farrow, M.J.Mulheron and P.A.Smith, (2013) On the condition assessment of cast iron trunk main: The effect of microstructure and in-service graphitisation on mechanical properties in flexure, *Materials Science and Engineering A*, 576, pp.192 - 201. DOI: 10.1016/j.msea.2013.03.061

[R4] A.Fahimi, T.S.Evans, J.Farrow, D.A.Jesson, M.J.Mulheron and P.A.Smith, (2016) On the residual strength of aging cast iron trunk mains: Physically-based models for asset failure, *Materials Science and Engineering A*, 663, pp.204-212. DOI: 10.1016/j.msea.2016.03.029

[R5] A.Rainer, T.F.Capell, N.Clay-Michael, M.Demetriou, T.S.Evans, D.A.Jesson, M.J.Mulheron and P.A.Smith, (2017) What does NDE need to achieve for cast

iron pipe networks, *Infrastructure Asset Management*, 4(2), pp.68–82. DOI: 10.1680/jinam.16.00020

4. Details of the impact (indicative maximum 750 words)

Thames Water supplies 2.6 billion litres of water every day through 31,400 km of water mains to nine million customers. The potable water network includes 3,600 km of trunk mains up to 60 inches in diameter. A trunk main is a large diameter main carrying potable water under high pressure from treatment works and reservoirs to the distribution network. Trunk mains were laid up to 200 years ago and are predominantly made of cast iron **[S1]**.

Major cities such as London have significant subterranean property and infrastructure, in particular basements, as well as a high population density. Consequently, a trunk main failure has the potential to cause significant damage to property and major disruption to water supply and travel. There is evidence of a gradual increase in burst rates of larger trunk mains over time, and avoiding trunk main failures is a top priority as evidenced by the launch of the Thames Water trunk main strategy (2015-2025) and associated action plan in 2017 **[S2]**. The implementation phase began in October 2017, with the changes and improvements continuing as business as usual thereafter.

Thames Water's Managing Director for water said: "*I'm confident that once delivered, our action plan will improve the way we manage our trunk mains and that through collating better information about our network, coupled with better risk modelling, we can reduce the impact on our customers*." **[S3]**

The asset life-cycle of trunk mains is not fully understood and may range from decades to centuries. Targeted repair provides affordable and less disruptive solutions to achieve low levels of bursts whilst avoiding unnecessary replacement of all buried pipes. This provides significant operational savings in water and reduced street excavation, raw materials and carbon emissions.

Thames Water had a strategy for trunk mains with investment of £147m in the period 2015-2020 and a further £97m added in 2017. This includes expenditure on increased monitoring, replacement of high consequence mains, information gathering, technology development, development of condition, and deterioration models. Thames Water has been working extensively with the University of Surrey to support these initiatives, in particular with technology development and condition, deterioration and risk models **[S4]**.

The Thames Water strategic review document **[S2]** sets out an investment strategy from 2015 to 2025, including an ongoing programme of work with the University of Surrey to understand corrosion, confirm deterioration rates, and the causal factors that lead to trunk main failure **[R3, R4, R5]**.

A consequence and probability model has been developed to understand and predict trunk main deterioration for asset management purposes. This allows Thames Water to determine an appropriate replacement rate and level of investment to manage the trunk network effectively.

Thames Water's Asset Investment Manager (AIM) Risk Model has been developed in conjunction with the University of Surrey and comprises a consequence of failure model and a probability of failure model. Combining these models results in an overall risk ranking of trunk mains to be created consisting of over 100,000 individually ranked mains **[S4]**.

The Risk Model allows Thames Water to target investment (£49m per annum from 2015-2020) under multiple serviceability and budgetary constraints, running scenarios to help plan their investment or communicate the cost of improving specific measures to the business.

"*The outputs of the AIM Risk Model are used primarily to influence investment decisions, however the rankings influence a large number of decisions and plans in the business. As an example, the*

High Consequence Mains and Valves lists influence operational strategies and steers priorities for maintenance through AMP6 [Asset Management Plan].” **[S4]**

The probability of trunk main failure is dependent on pipe condition, which the work with the University of Surrey has shown to be highly variable and localised **[R3, R5]**. Thames Water requires better assessment of the condition of cast iron trunk mains in order to increase the efficiency of mains replacement activities and reduce the risk to their customers and stakeholders. However, there is currently little incentive for the development of in-pipe condition assessment devices by contractors due to the current rates of investment. To promote such development, Thames Water is now investing in a Trunk Main Research Rig to enable a detailed evaluation of in-pipe devices without risk to the customers or the trunk main network **[S1]**. Thames Water went out to tender for a design, build and operation contract in February 2018. The Research Rig is due to be commissioned in the first half of 2021.

Thames Water’s Lead Water Network Scientist has said, “*Thames Water's long term partnership with the University of Surrey has been key to shaping our strategy for managing our critical cast iron water and wastewater assets, including our decision to build an innovative £1.2 million testing facility.*” **[S5]**

If initial validation is successful, suppliers will be invited to test their devices on the test rig and devices proving to be successful on the rig will then be tested on the network on buried mains. The University of Surrey research will impact all UK and global water utilities through UK Water Industry Research (UKWIR), international access to the Pipe Test Rig and sharing of real-world results conducted in trunk mains under many cities.

In summary, cast iron trunk mains are a critical asset for the water industry globally. The long term, ongoing collaboration between Thames Water and the University of Surrey has led to an understanding of these critical assets’ performance, operational risk and life-cycle. The results of the collaboration are key factors in the development of Thames Water’s current strategies to manage these assets and has informed the £350m AMP7 capital programme which includes the monitoring and refurbishment of trunk mains **[S6]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Thames Water Conference Presentation, March 2019 “In pipe condition assessment of cast iron trunk mains” corroborates Thames Water’s new approach: https://twenty65.ac.uk/media/editor/Thames%20Water%20presentation%20Twenty65%202019%2C%20Tim%20Evans%2C%20Trunk%20mains%20WEB%20v1.1.pdf

[S2] Thames Water Trunk Mains Strategic Review Final Report, Oct 2017. Section 6.2 https://www.thameswater.co.uk/about-us/regulation/trunk-mains-review

[S3] Water Industry News Article, October 2017 https://wwtonline.co.uk/news/thames-water-sets-out-action-plan-to-minimise-trunk-mains-bursts

[S4] Thames Water Trunk Mains Forensic Review Final Findings Report, 24th March 2017, Surrey work referred to in Introduction and sections 3.1.4, 3.2.1 and 3.2.3 https://www.thameswater.co.uk/media-library/home/about-us/regulation/trunk-mains-review/trunk-mains-forensic-review.pdf

[S5] Testimonial from Lead Water Network Scientist (PDF)

[S6] Thames Water AMP7 capital investment announcement https://www.thameswater.co.uk/about-us/newsroom/latest-news/2020/may/amp7-capital-programme-suppliers-announced