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Soil and Groundwater Remediation Technologies for Former Gasworks and Gasholder Sites

CL:AIRE

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Grangetown Gasworks, Cardiff (Courtesy of O. Lancaster).

Disclaimer

This report has been prepared by CL:AIRE for the Energy Innovation Centre. It has been prepared with the support of Wales & West Utilities and is a report about Soil and Groundwater Remediation Technologies for Former Gasworks and Gasholder Sites. It is not a definitive guide as to how the remediation of former gasworks and gasholder sites should be undertaken. CL:AIRE strongly recommends that individuals/organisations interested in remediating gasworks retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

This report on soil and groundwater remediation technologies for former gasworks and gasholder sites is the output of a research project conducted by CL:AIRE for the Gas Distribution Network (GDN) companies. The project was funded by Wales & West Utilities (WWU) partnered with the Energy Innovation Centre.

The report describes the key issues and contaminants that the GDNs are currently facing. It identifies five main types of contaminated sites that exist on the GDNs inventory as follows:

- General redundant sites;
- Operationally constrained sites, containing infrastructure and live services;
- Sites that have immediate borders with surface waters;
- Small, remote, low value sites; and,
- Sites that have shared source structures/part-ownership.

The report describes the main soil and groundwater technologies that are currently available to treat the common contaminants associated with former gasworks and gasholder sites. It categorises them as *in situ*, *ex situ*, and traditional civil engineering methods. The report considers which of these technologies are likely to be appropriate on the five types of sites above, but the discussion comes with an important caveat and concentrates solely on their general technical suitability.

The report focuses on soil and groundwater remediation in the UK and internationally so that lessons can be learned from other jurisdictions on how different stakeholders remediate their former gasworks and gasholder facilities.

The regulatory framework of the UK is described and includes recent changes in legislation and what potential legislative impacts and drivers may impact the GDNs in the future.

It is apparent from the information gathered in the report that there are contaminants that are difficult to treat using commercially available technologies – spent oxide and gas purification wastes, coal tar and water gas tar. The report also highlights some new innovative technologies that have been developed that should be of interest to the GDNs.

CONTENTS

1. UNDERSTANDING THE PROBLEM

1.1 INTRODUCTION

Gas was manufactured and produced in the UK from 1792 until 1981 when the last gasworks was closed. This was due to the conversion to natural gas from 1967 which took 10 years to complete. The production of ‘Town Gas’ was a complex, multi-stage process that varied from site to site. Understanding the manufactured gas plant processes assists in the investigation and remediation required at these sites. In general, five major processes were used to produce town gas:

- Coal carbonisation;
- Carburetted water gas;
- Oil gas;
- Coke oven gas; and
- Gas reforming.

Coal carbonisation was the most common process used in the UK for gas manufacture and provided the base load for gas manufacture. However, it was ineffective at handling periods of sudden high demand when a quick response was required. Such demand had to be supplied from additional storage capacity. To meet the requirement for rapid gas production, another process was successfully refined in America called “Water Gas”. The process worked by cyclically heating and then steaming coke in a vessel to produce water gas, which consisted primarily of hydrogen and carbon monoxide. This became more commonly used in the 1890s to meet the demand for rapid gas production. The drawback with this method was the relatively poor quality of gas it produced. To improve the quality of the gas, it could be enriched by injecting oil into the carburettor, a process known as **Carburetted Water Gas (CWG**). Water gas plants could produce gas much more rapidly (within 1-3 hours) than traditional coal carbonisation plants, allowing gas companies to meet peak demand more effectively. This process was commonly used on larger town and city gasworks to supplement coal gas supplies, but also later used on medium-sized gasworks throughout the UK. The third process was known as **Oil Gas**. Oil was originally used to make gas in the early 19th century as a competitor to coal gas. Its success was short lived due to limited supplies of whale oil. Oil gas did gain use on the railways, where the gas was suitable for lighting carriages. In the 1950s, gas started to be produced directly from petroleum based oils using processes such as SEGAS. **Coke Oven Gas** was produced as a by-product by some coke ovens. Where available (e.g. South Wales and County Durham) this gas was purchased in bulk by gas companies, leading to many gasworks in those areas ceasing gas manufacture. On a small number of gasworks (e.g. Beckton), coking ovens were built for gas manufacture. During the 1960s and 1970s, a new process called **Gas Reforming** was developed which manufactured Town Gas from refinery by-products such as butane and naphtha. The process broke down these more complex compounds into carbon monoxide, hydrogen and methane.

Figure 1.1 shows details of town gas production from coal and Figure 1.2 illustrates the production of gas from coal and the manufacture of by-products on a large gasworks, showing the process from the mining of the coal to the distribution in the gas mains.

For further information on the history and operation of gasworks, see Gasworks Profile A: The History and Operation of Gasworks (Manufactured Gas Plants) in Britain (CL:AIRE, 2014) and Department of Environment Industry Profile: Gas works, coke works and other coal carbonisation plants (HMSO, 1995). For technical guidance on the management of contaminated land including how to investigate, assess and manage the risks, see https://www.gov.uk/government/collections/land-contamination-technical-guidance.

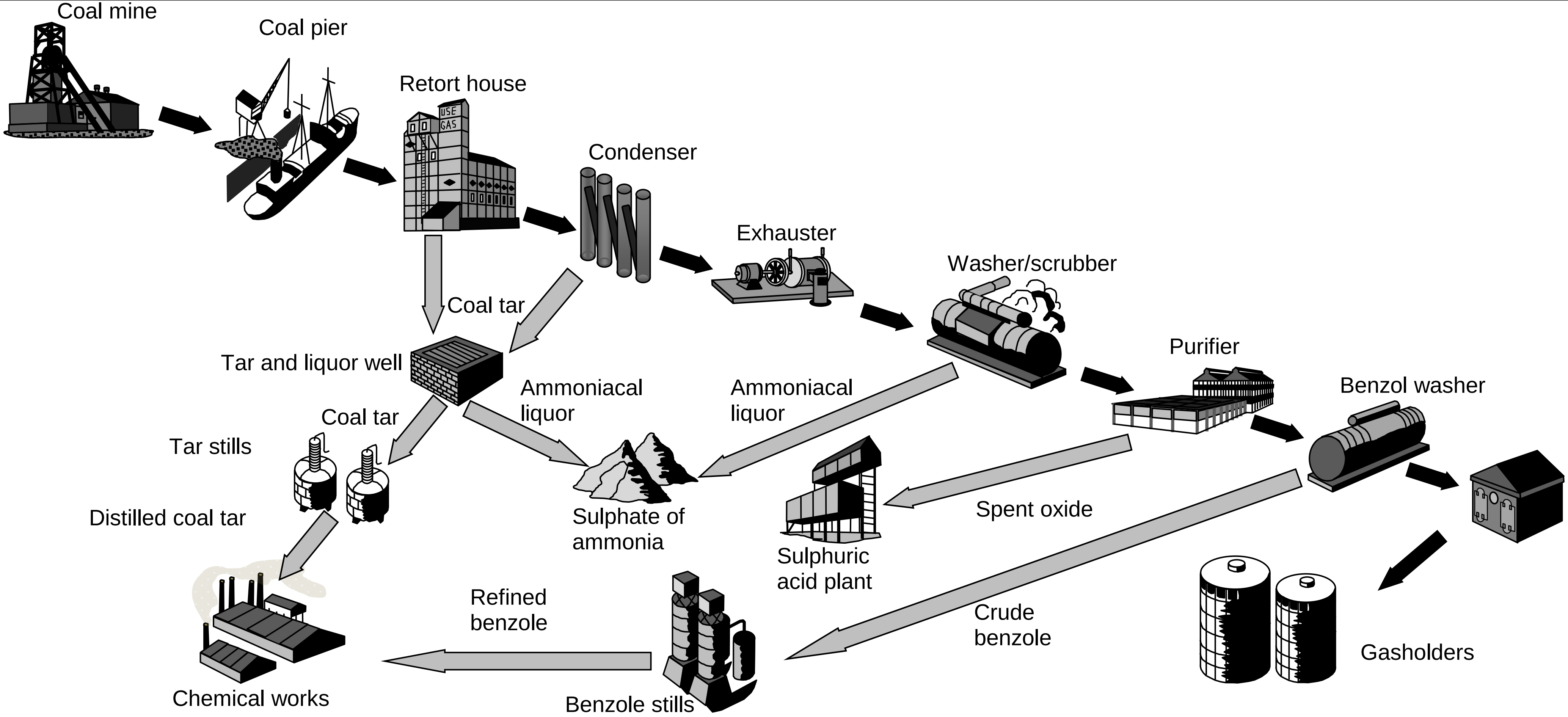

Figure 1.1: The production of town gas from coal. The black arrows show the progress of the gas through the plant and the grey arrows show the processing of the by-products. (Source: Russell Thomas (CL:AIRE, 2014))

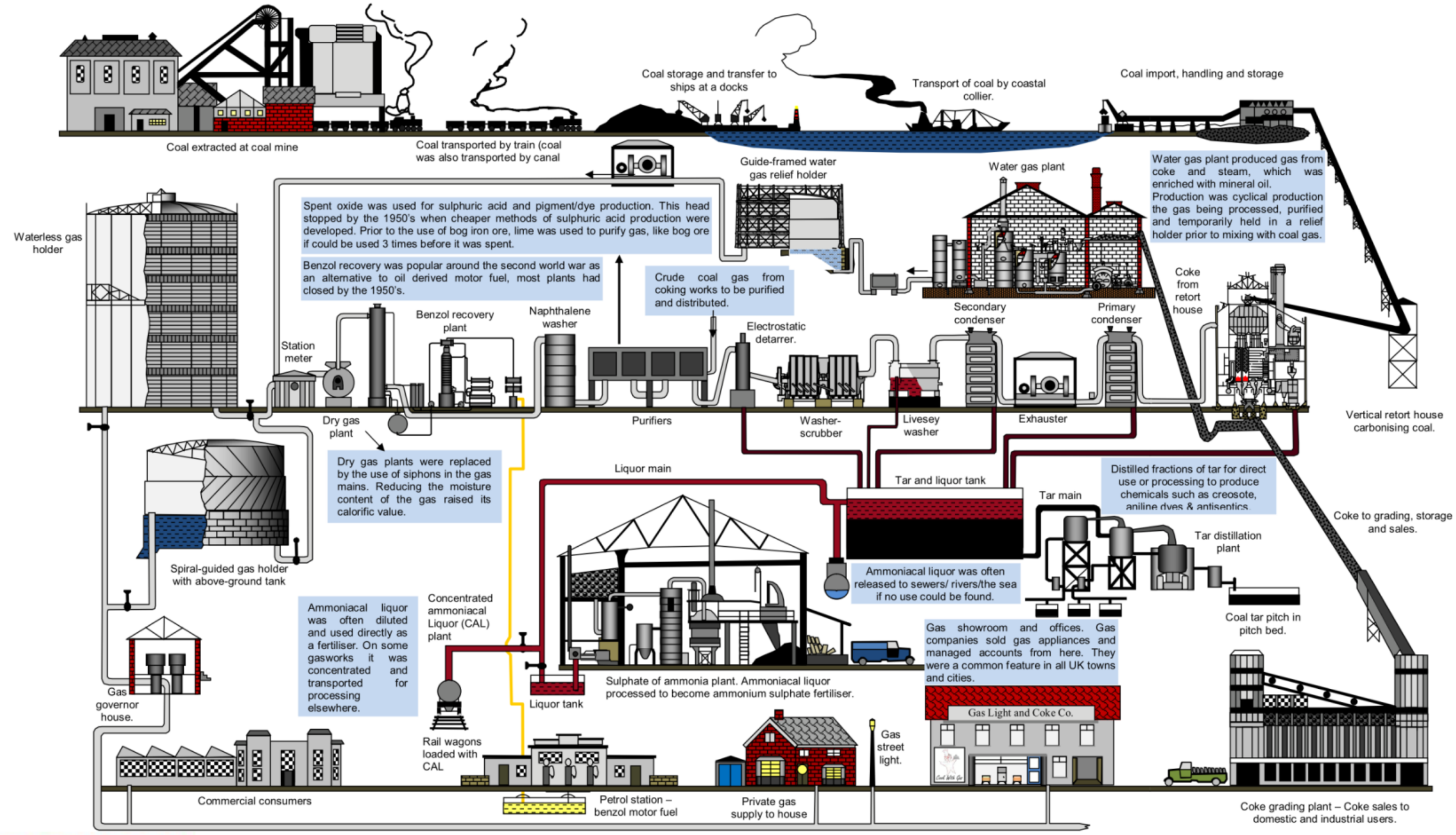

Figure 1.2: The production of gas from coal and the manufacture of by-products on a large gasworks, showing the process from the mining of the coal to the distribution in the gas mains. (Source: Russell Thomas (CL:AIRE, 2014))

1.2 WASTES AND POTENTIAL CONTAMINANTS OF CONCERN

The contaminants on a site depend largely on the history of the site and the type of materials that were produced on it. Many by-products and waste materials were produced as a result of gas manufacture. These included coal tars, oils, sludges, purifier wastes (spent oxide and foul lime), ash, coal dust, coke and ammoniacal liquors. Many waste products were recovered and were used in other industries. However, over time, economic circumstances sometimes dictated that no market existed for some of these by-products, which meant that they were disposed of on site or in nearby landfills. Those that were disposed on site are now being discovered during site investigation to support voluntary risk management or land development. Many of the waste products, such as tars, commonly remain in the soil matrix. When tars (a non-aqueous phase liquid, NAPL) enter groundwater, they are primarily dense (DNAPL) and sink to the base of an aquifer, although some light tar fractions (LNAPL) can float on a water body. Many of the principal wastes can be identified visually or by the odour they emit. For example, tar oils are easily identifiable as black, odorous ooze and the purifier waste spent oxides, which contains up to 50% sulphur and distinctive iron cyanide complexes (formed during the removal of hydrogen cyanide), are recognisable by their intense colours, such as Prussian blue or Berlin green and distinctive odour. Table 1.1 provides a summary of the principal waste types at gasworks sites and Table 1.2 provides the principal contaminants of interest at these sites.

For further information on the composition of by-products and wastes produced during the manufacture of gas, see CL:AIRE (2014) and HMSO (1995).

Table 1.1: Summary of the principal waste types at gasworks sites (Source: Adapted from Department of Environment & Conservation, New South Wales 2005)

Principal waste type	**Source**	**Distinguishing characteristics**	**Likely chemical groups**
Coal tar Tar oils	Separated from gas and liquors at various stages of the purification processes.	Dark brown to black colour Strong phenolic odour May be present as non-aqueous phase liquids, either dense (DNAPLs) or light (LNAPLs) Lower melting point than petroleum tars Different phases have low to high density and viscosity	PAHs Petroleum hydrocarbons, including BTEX Phenols
Spent oxides (including complex cyanides)	Used to remove sulphur during gas purification.	Strong sulphurous odour Distinctive Prussian blue or Berlin green colour when weathered/oxidised Brown/grey/black/green, very dusty when not weathered/oxidised Granular appearance Iron staining common	Complex cyanides Free cyanides Metals Thiocyanate Sulphur (acidic forming sulphuric acid)
Ash, Clinker residues (glassy material)	By-products of carbonisation.	Fine granular material (ash) or glassy smooth irregular lumps. Brown to black	PAHs Metals
Coke, cokebreeze	Furnace residues.	Spongy granular material of low density. Light grey in colour	PAHs Metals
Light oils Drip oils	Light oils used around all machinery and as scrubbing agent in recovery process. Drip oils condensed from gas	Oily smell and appearance	Petroleum hydrocarbons, including BTEX
Ammoniacal recovery wastes	Nitrogen removal during gas purification processes	Ammoniacal odours Fine powders or sludges	Phenols, ammonium compounds, nitrates, sulphates, sulphides, PAHs and cyanides.
Asbestos	Used as lagging around many of the ‘hot’ processes and pipes. Commonly present in a wide range of Asbestos Containing Materials (ACMs) such as cement board and insulating board.	Fibrous to powdery texture, grey-white/blue/greenish colour (crystalline)	Asbestos
Lead, mercury, zinc	Lead from batteries, pipelines, paint, etc. Mercury sometimes used in metering switches.	Generally not visible other than mercury, which, where present, is a dense metallic silver liquid, typically seen as ‘pin heads’ in soil.	Metals

Table 1.2: Principal contaminants of interest at gasworks sites (Source: Adapted from Department of Environment & Conservation, New South Wales 2005)

Inorganic compounds	**Metals and metalloids**	**BTEXs**	**Phenolics**	**Polycyclic aromatic hydrocarbons (PAHs)**
Ammonia	Aluminium	Benzene	Phenol	Acenaphthene
Cyanide	Antimony	Ethyl benzene	2-Methylphenol	Acenaphthylene
Nitrate	Arsenic	Toluene	4-Methylphenol	Anthracene
Sulphate	Barium	Total xylenes	2,4-Dimethylphenol	Benzo(a)anthracene
Sulphide	Cadmium			Benzo(a)pyrene
Thiocyanate	Chromium			Benzo(b)fluoranthene
	Copper			Benzo(g,h,I)perylene
	Iron			Benzo(k)fluoranthene
	Lead			Chrysene
	Manganese			Dibenzo(a,h)anthracene
	Mercury			Fluoranthene
	Nickel			Fluorene
	Selenium			Naphthalene
	Silver			Phenanthrene
	Vanadium			Pyrene
	Zinc			Indeno (1,2,3-cd) pyrene

2. ESTABLISHING THE CURRENT SITUATION OF FORMER GASWORKS IN THE UK

2.1 INTRODUCTION

There is no single list or accurate record of historical UK gasworks sites currently available although the National Gas Archive http://www.gasarchive.org/ and National Gas Museum http://www.nationalgasmuseum.org.uk/ do contain a wealth of information, as do many regional archives and libraries.

Hatheway and Doyle published a summary list in 2006 (Hatheway and Doyle, 2006), estimating that there could be between 12,920 to 20,355 sites across the whole of the UK where various coal carbonisation and other manufactured gas residuals and wastes could be present. Many of these sites existed as a result of supporting industries such as railways, refineries, coke works and collieries forming a patchwork of gasworks across the UK. Gradually as commercial gasworks became established around towns and cities, the smaller sites became abandoned. With the nationalisation of the gas industry in 1947 and the establishment of twelve regional gas boards, many of the smaller plants were closed due to rationalisation and the improvements in higher pressure gas distribution from centrally located urban stations.

Of the extensive number of sites quoted by Hatheway and Doyle (2006), it is believed that approximately 4,000 were gasworks/gas storage sites. Of the ~4,000, ~1,000 are thought to be in full or part ownership of the Gas Distribution Network (GDN) companies and the other ~3,000 remaining sites are in public (Local Authorities) and private (residential, commercial, industrial or developer) ownership or have been developed since the survey was undertaken (see Table 1 of Hatheway and Doyle, 2006).

The sites in the ownership of the main GDN companies include the gasholder stations, sites that have been impacted by gasworks waste or on industrial sites associated with the former gasworks.

To understand and manage liabilities and risks to the environment, GDN companies are able to categorise their site ownership in the following way:

- General redundant sites;
- Operationally constrained sites, containing infrastructure and live services;
- Sites that have immediate borders with surface waters;
- Small, remote, low value sites; and
- Sites that have shared source structures/part ownership.

As part of this exercise, GDN companies have worked with Ofgem (UK Gas and Electricity Regulator) to agree the terms “Statutory Remediation” and “Non-Statutory Remediation”. This has helped set a point of reference for helping the GDN companies prioritise the sites that they deem to require remediation and secure the revenue that is required for remediating the sites.

Statutory Remediation

Statutory remediation is the work required to satisfy the minimum legal requirements for a site’s current use, which reduces the contaminated land risks to a point whereby the site no longer presents significant risks of significant harm to human health, controlled waters and the wider environment. (O. Lancaster pers.comms.)

Non Statutory Remediation

Non-statutory remediation is the work required to satisfy the minimum legal requirements for a site’s proposed change of land use, which incorporates a greater scope of work and more *stringent standards to be achieved, which reduces the contaminated land risks to a point whereby the site no longer presents significant risks of significant harm to human health, controlled waters and the wider environment for the proposed change of land use. (O. Lancaster pers.comms.)*

The GDN companies site portfolios range in size and complexity with sites typically ranging from 0.002 to 4.4ha.

2.2 DRIVERS FOR REMEDIATION

GDN companies are required by environmental legislation to manage their long term liability and assets (see section 4.3). Therefore they have to generate outline statutory programmes for a regulatory period during the business planning stage and by doing so they commit to delivering a number of remediation projects each year. Once revenue is set for remediation, the GDN companies then generate a detailed annual programme; however this can be subject to change due to influences outside of their control e.g. neighbouring developments occurring or local regulatory requirements.

Wales & West Utilities (WWU) has embedded the consideration of climate change forecasts into the delivery of all land management projects (Lancaster, 2013). Usually this is a qualitative assessment, however detailed quantitative assessment has been used to derive remedial targets acceptable in future climate scenarios and also to identify additional contaminants of concern. Climate change has been a stand-alone driver to remediate to statutory standards under future climate conditions, as well as being a contributory driver that has resulted in the broadening of the scope of works and volumes requiring treatment. The UK Climate Impacts Programme (UKCIP) have published their forecasts (UK Climate Projections 09 or UKCP09), which are available from http://ukclimateprojections.metoffice.gov.uk/21708. The 'Guiding Principles for Land Contamination 2' (Environment Agency, 2010) contains a section on technical advice for incorporating UKCP09 forecasts into controlled waters risk assessment (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/297454/geho1109brgz-e-e.pdf).

GDN companies used to receive money to spend on remediation for a fixed five year regulatory period. However, the current regulatory period is an eight year period running from 2013-2021 during which each GDN has committed to undertake a number of site investigation and remediation projects, known as Outputs, for a fixed budget. GDNs can only commit to do remediation projects within the budgetary period. The overall aim is to reduce the risk profile of the contaminated land portfolio as far as possible towards non-statutory or low risk categories, with higher risk sites being dealt with as and when constraints are removed and opportunities arise or when budget is available.

WWU has carried out 22 remediation projects of various sizes in the five year regulatory period 2008-13. They are in the process of undertaking a further programme of remediation with a similar number of remediation projects in the current eight year period 2013-21.

Pre-31st March 2012, most remediation projects involved excavation and disposal, commonly known as 'dig and dump', when landfill tax exemption was in place (see section 4.2.1). Since the abolition of landfill tax exemption, WWU has utilised off-site treatment centres, on-site bioremediation (*ex situ*), stabilisation and solidification (*in situ* and *ex situ*), High Vacuum Extraction and materials management by using the Definition of Waste: Development Industry Code of Practice (DoWCoP) (inc. capping system) (see section 4.3.1 for details on DoWCoP), segregation and one instance of river bank rebuild.

3. ESTABLISHING THE CURRENT SITUATION OF FORMER GASWORKS INTERNATIONALLY

3.1 INTRODUCTION

It is worthwhile considering how other developed countries approach remediation of their contaminated land, what their drivers are and whether the UK can learn from them. It is particularly interesting with respect to other European countries as the UK's environmental legislation is derived from the same European Directives. As part of this research CL:AIRE used its international contacts within the following countries/organisations; USA, Australia, Canada, Netherlands, Taiwan and the Common Forum to ask about how remediation of gasworks is undertaken in these countries, how sites are regulated, whether guidance has been developed and if case studies are available. Information was received from the countries listed in Table 3.1, but none of the responses were very detailed. Appendix A provides the questionnaire that was sent to these countries.

As part of this research, a request was also sent to the secretariat of the Common Forum (European Regulators Forum), but they declined to circulate the questionnaire as they had recently received a similar request from Dr Russell Thomas who was collating European-wide information for a presentation that he was giving at a 2014 conference titled "Manufacturing Gas Industry Europe". Dr Thomas kindly shared his presentation and feedback that he received to assist in this work. Summaries of France and Belgium are included in the results below.

Table 3.1: Countries contacted and sources of information

Country	Source of Information
USA	United States Environmental Protection Agency
Australia	South Australia Regulatory Agency
Canada	Canadian National Energy Board
Netherlands	Dutch Ministry of Infrastructure
Taiwan	No response
European Regulators Forum - Common Forum	France & Belgium

Detailed below is a summary of the main information supplied by the different countries contacted. Although responses were not detailed, it does show that many countries legacy gasworks sites have remained in public ownership and the remediation is being driven and managed by their regulators even if there is no immediate environmental risk. This is quite different to the UK as a more pragmatic approach is taken and land contamination is addressed voluntarily or dealt with through the planning system if there is no immediate environmental risk (See section 4.3 for legislative details for England and Wales).

3.2 USA

The Environmental Protection Agency (EPA) is the regulatory agency of the U.S government that was established to protect human health and the environment. It writes guidance and is also responsible for enforcing regulations that are based on government laws.

The number of former manufactured gas plants and coal tar sites was estimated in 2004 by the EPA to be in the range of 30,000 – 45,000 (EPA, 2004) and are in public and private ownership. EPA published guidance in 1999 on how practitioners should address soil and groundwater contamination in "*A Resource for MGP Site Characterization and Remediation:*

Expedited Site Characterization and Source Remediation at Former Manufactured Gas Plant Sites" (http://www.clu-in.org/s.focus/c/pub/i/606/).

The main drivers for remediation of gasworks sites are development pressure and regulatory intervention. However, there is not a national programme to systematically remediate the sites. The remediation is not managed centrally, with different EPA programmes managing different site remediation's such as the Superfund programme. This is an environmental programme that was established to address abandoned hazardous waste sites and where they publish case studies for all to learn from. An example of one such case study is publically available to download at:
http://www.clu-in.org/download/remed/hyopt/application/rses/superfund_rses/FinalHastingsMay13.pdf.

EPA uses a broad selection of technologies available to it depending on the problem that is being faced and does not focus on one remedy for their gasworks, much in the same way as the UK.

3.3 CANADA

National Energy Board (NEB) Canada has been established to protect the environment from those effects resulting from NEB-regulated facilities. The NEB has developed the Remediation Process Guide for the gas industry to follow and to facilitate well documented and successful remediation. The goal of this guide is to provide a clear process for submitting appropriate remediation information to the NEB. It applies to NEB-regulated facilities under the "*National Energy Board Act"* (NEB Act) and the "*Canada Oil and Gas Operations Act* "(COGOA) and applies to:

- remediation of residual contamination in soil and groundwater to an appropriate standard;
- remediation of all spill sites whether the spill is reportable or not;
- off-site contamination remediation; and
- historical contamination events.

The Remediation Process Guide is freely available and can be accessed at http://www.neb-one.gc.ca/clf-nsi/rsftyndthnvrnmnt/nvrnmnt/rmdtnprcssgd/rmdtnprcssgd-eng.html.

3.4 AUSTRALIA

Site contamination in Australia is regulated by each individual state and therefore each state has its own standards and guidelines. Unfortunately responses were not received from each state, only from South Australia and New South Wales.

South Australia Environment Protection Authority (EPA) confirmed that it knows of at least 10 (5 metropolitan and 5 regional) gasworks with investigation underway to identify others. Currently South Australia does not have its own published guidance on how to treat soil and groundwater contamination associated with gasworks but relies and references New South Wales guidance (http://www.epa.nsw.gov.au/resources/clm/gasworks05237.pdf).

Most of the former gasworks which operated in South Australia were operated by the former South Australian Gas Company – a private company that operated under a public Act. Therefore, it is anticipated that the Australian Government will be responsible for the assessment and remediation of these sites, however, liability is still being determined.

As in other countries, the driver to remediate these sites is predominantly development driven with residential development being the highest priority.

To date the main remediation techniques that have been employed so far in South Australia are capping, excavation, and the introduction of groundwater exclusion zones (where no groundwater wells can be drilled). However, it is understood that this is likely to change in the future.

3.5 NETHERLANDS

Within the Netherlands there is a government funded remediation programme currently underway (2002-2015) to tackle remediation of 148 gasworks which are mainly in public ownership. Prior to this, several hundreds of sites have been remediated by local provincial governments as part of development projects.

Information about the programme is available at: http://www.rwsleefomgeving.nl/onderwerpen/bodem-ondergrond/bodemsanering/publicaties/gasfabrieken with a number of case studies written up but published in Dutch http://www.soilpedia.nl/Webpaginas/soilpedia_home.htm

Most of the sites have been redeveloped as the former gasworks sites have been mainly close to town and city centres and therefore provincial governments are keen to bring these brownfield sites back into beneficial reuse.

3.6 FRANCE

Awareness of risks from former gasworks started in 1990/1991 and in 1996, a 10 year protocol was developed to investigate France's 500 former gasworks that were still owned by the two state owned Gas and Electricity companies (Gaz de France (GdF) and Électricité de France (EdF)).

Sites were prioritised according to their potential impacts on human health and the environment and remediated if required. Since 2007 the regulator (Ministry for the Environment) requires the former operator to be responsible for remediation and they are required to ensure that contaminated sites are remediated. This is by removal of the primary sources (tanks etc), removal of soil sources that may affect water or food production and to ensure that the sites are suitable for their future use.

3.7 BELGIUM

Belgium is split into three regions (Flanders, Wallonia and Brussels-Capital), but responses were only received from Flanders. Flanders has an extensive programme of gasworks investigation and remediation being led by OVAM (Public Waste Agency of Flanders which is responsible for waste management and soil remediation) but being paid by the former owners, current site owners or OVAM (public), with the aim to have remediated all former gasworks by 2027.

4. DRIVERS AND LEGISLATIVE POSITION

4.1 INTRODUCTION

Remediation of contaminants in soil and groundwater associated with gasworks and gas storage facilities has significantly changed due to the implementation of European legislation. This section details the changes in legislation over the last five years and what potential legislative impacts and drivers may be further impacting the GDNs that they will need to be aware of.

4.2 EUROPEAN LEGISLATION

This section identifies the key European directives that are currently in place in England, Wales and Scotland that are used to manage land contamination and groundwater and that have been transposed into English, Welsh and Scottish legislation. See Table 4.1 for details.

Table 4.1: Summary of European legislation relating to soil and groundwater and its transposition into English, Welsh and Scottish legislation

Key Current European Directives	**Requirements**	**England, Wales and Scotland Transposition**
Landfill Directive (99/31/EC)	Control of disposal of waste to landfill to prevent or reduce negative effects on the environment	Landfill (England and Wales) Regulations 2002 amended 2004 Landfill (Scotland) Regulations 2003 & The Landfill (Scotland) Amendment Regulations 20134 The Environmental Permitting (England and Wales) Regulations 2010
Waste Framework Directive (2008/98/EC)	Recovery or disposal of waste without causing danger to humans or the environment	The Environmental Permitting (England and Wales) Regulations 2010 The Hazardous Waste (England and Wales) Regulation 2005 The Waste (England and Wales) Regulations 2011 amended 2012 The Waste (Scotland) Regulations 2011 Waste Management Licensing (Scotland) Regulations 2011
Water Framework Directive (2000/60/EC)	Prevention and control of groundwater pollution (i.e. preventing input of hazardous substances and limiting input of non-hazardous pollutants). Permitting of discharges and disposal of listed substances. Control of the release of listed	The Water Environment (Water Framework Directive) England and Wales) Regulations 2003 The Environmental Permitting (England and Wales) Regulations 2010 The Water Environment and Water Services (Scotland) Act 2003 is the

	substances to groundwater.	enabling act for the European Water Framework Directive. The Water Environment (Controlled Activities) (Scotland) Regulations 2011 amended 2013 The Water Environment (Groundwater and Priority Substances) (Scotland Regulations 2009 Water Resources Act England and Wales 1991 Water Resources Act (Scotland) 2013 Anti-Pollution Works Regulations 1999 (England and Wales) Anti-Pollution Works (Scotland) Regulations 2003
Environmental Liability Directive (2004/35/EC)	Prevention and remedying of environmental damage	The Environmental Damage (Prevention and Remediation) Regulations 2009 – England and Wales The Environmental Liability (Scotland) Regulations 2009
Integrated Pollution Prevention and Control Directive (2008/1/EC)	Permitting of industrial activities with a high pollution potential	The Environmental Permitting (England and Wales) Regulations 2010 Pollution Prevention and Control (Scotland) Regulations 2012 amended 2014

4.2.1 LANDFILL DIRECTIVE

The Landfill Directive was published in 1999 (1999/31/EC), and transposed fully in England and Wales into national legislation through the Landfill Regulations (England and Wales) in 2002 and subsequently amended in 2004. In Scotland the directive was transposed in 2003 as Landfill (Scotland) Regulations. It was introduced step by step to allow industry to adapt, however it has had a major impact in the way the countries have approached remediation of land contamination. This directive aimed to prevent or reduce as far as possible negative effects on the environment from the landfilling of waste, by introducing stringent technical requirements for waste and landfills and setting targets for the reduction of biodegradable waste going to landfill. Historically the UK practiced what is known as co-disposal, whereby hazardous and non-hazardous wastes would be landfilled together within the same landfill. Since July 2004, landfills were divided into three classes:

- Landfills for hazardous waste;
- Landfills for non-hazardous waste; and
- Landfills for inert waste.

Typically, hazardous sites can only accept hazardous waste, non-hazardous sites can only accept non-hazardous waste and inert sites can only accept inert wastes. However, some non-hazardous sites will accept stable non-reactive hazardous wastes (e.g. asbestos).

In October 2007 a ban on the disposal of liquid wastes to landfill and the requirement of pre-treated materials only was introduced. This treatment needed to include a physical, thermal, chemical or biological process - which can include sorting - to change the characteristics of the waste to reduce its volume, reduce its hazardous nature, facilitate its handling, or enhance its recovery.

Alongside the implementation of the directive and to encourage recycling, in 1996 the UK government introduced a landfill tax. However, certain industries were exempt as the government was mindful that as the use of remediation technologies was not very advanced in the UK it could have a detrimental effect on development. Therefore to not cause a major impact to the development sector (but to start encouraging local authorities to implement recycling of municipal waste) landowners/developers/contractors that were carrying out reclamation of contaminated land to facilitate a development were permitted exemption from landfill tax. Exemption applicants qualified up until 30 November 2008 and were permitted to use these exemptions up until March 2012. After this date full landfill tax was applied and subsequently the volume of contaminated soil going to landfill has reduced and alternative remediation options have become more cost effective to use.

Since April 2011 the higher rate of landfill tax (more polluting soils) has increased each year by a rate of £8 per tonne, leading to an increase from £24 per tonne in 2007 to the current rate of £82.60 per tonne in April 2015. This rate will not fall below £80 from April 2014 to April 2020 (HMRC, 2015). The lower rate (that has no biodegradable material) is £2.60 per tonne for less polluting non-hazardous soils.

The Landfill Directive was later amended in 2004 and 2005 to transpose the requirements of the European Commission Council Decision 2003/33/EC on Waste Acceptance Criteria. These are the standards set by the landfill's permit that stipulates what type of waste it is able to accept. This provision was re-transposed as part of the Environmental Permitting (England and Wales) Regulations 2007 and subsequently amended in 2010.

In Scotland, the Landfill (Scotland) Regulations came into force in 2003 implementing most requirements of the Landfill Directive (99/31/EC). The regulations were subsequently amended in 2013 with the waste acceptance criteria being stated in "Criteria and Procedures for the Acceptance of Waste at Landfills (Scotland) Direction" in 2005.

The Landfill (Scheme Year and Maximum Landfill Amount) Regulations 2004 and Landfill Allowance Regulations (Scotland) 2005 implement Section 4 of the Waste and Emissions Trading (WET) Act 2003 making an allocation of allowances of biodegradable municipal waste (BMW) to landfill to local authorities for each scheme year. Allowances may potentially be banked, borrowed or transferred subject to approval by the Scottish Environmental Protection Agency (SEPA). The Landfill allowances Trading Scheme is currently suspended in Scotland.

4.2.2 WASTE FRAMEWORK DIRECTIVE

With the implementation of the revised Waste Framework Directive (2008/98/EC) in England and Wales in 2010 and Waste (Scotland) Regulations in 2011, there was again a step change in the approach to soil remediation. The directive was introduced and provided an overarching legislative framework for the management of waste. It outlined the hierarchy which should act as a "priority order" in waste prevention, legislation and policy.

The primary aim of the Waste Framework Directive is the protection of human health and the environment and necessary measures are required to be taken to ensure that waste is recovered or disposed of without endangering human health and without using processes or methods which could harm the environment.

The directive then sets out a range of recycling and reuse targets, for both household and construction and demolition (C&D) waste.

The targets in the Directive are:

- to recycle or prepare for reuse 50% of household waste by 2020; and
- to reuse, recycle or recover 70% of non-hazardous C&D waste by 2020.

Therefore with stricter and more costly landfill targets and disposing of waste to landfill, this provided an added incentive for the development industry to start to invest more time and effort into undertaking more remediation on site. An alternative to landfilling and following the Waste Framework Directive was to use the Definition of Waste Development Industry Code of Practice (DoWCoP). This is a voluntary system whereby material does not fall into the waste system by being discarded (see section 4.3.1 for more details). The DoWCoP is only applicable to England and Wales.

In Scotland the implementation of the revised Waste Framework Directive (2008/98/EC) came into force in Scotland in 2011 as Waste (Scotland) Regulations.

The Waste (Scotland) Regulations 2011 and the Waste Management Licensing (Scotland) Regulations 2011 place a duty on all persons who produce, keep or manage waste, including Local Authorities, to apply the waste hierarchy.

4.2.3 WATER FRAMEWORK DIRECTIVE

In December 2000 the Water Framework Directive was adopted and came into force in England and Wales in 2003 through The Water Environment (Water Framework Directive) England and Wales Regulations. The aims of this Directive are to:

- Prevent further deterioration of aquatic ecosystems;
- Protect, enhance and improve the aquatic environment;
- Promote sustainable water use;
- Provide further protection to the aquatic environment; and
- Ensure the progressive reduction of pollution of groundwater and prevent its further pollution.

The Directive requires Member States to establish river basin districts and for each of these a river basin management plan. The Directive envisages a cyclical process where river basin management plans are prepared, implemented and reviewed every six years.

The Water Framework Directive places a restriction on pollutants directly being input in the groundwater and that all necessary measures must be taken to prevent the input of hazardous substances and to limit inputs of non-hazardous pollutants so as to avoid pollution.

In Scotland the Water Environment and Water Services (Scotland) Act 2003 is the enabling act for the Water Framework Directive, which introduced a new integrated approach to the protection, improvement and sustainable use of the water environment. The Water Environment (Controlled Activities) (Scotland) Regulations 2005 (CAR) (now superseded by The Water Environment (Controlled Activities) (Scotland) Regulations 2011) introduced controls on previously unregulated activities.

4.2.4 ENVIRONMENTAL LIABILITY DIRECTIVE

The Environmental Damage (Prevention and Remediation) Regulations implement the European Liability Directive which came into force in England on 1 March 2009, 6 May 2009 in Wales and 24th June 2009.

‘Environmental damage’ has a specific meaning in the Regulations, covering only the most serious cases. Existing legislation with provisions for environmental liability remains in place.

The emphasis of this legislation is on a business/operator identifying when there is an imminent threat or actual damage occurring to the environment and taking immediate action.

Enforcing authorities will determine whether there is environmental damage and decide on the necessary remedial measures. Determining environmental liability is the last resort. The emphasis is on business proactively putting in place appropriate pollution prevention measures so that imminent threats and damage do not arise.

The Regulations only apply to damage after the Regulations came into force (not historical), and they only apply to operators of economic activities. However action can be taken if for example drilling a borehole through a tar tank causes the release of tar into a previously uncontaminated aquifer) since the regulations came into force – i.e. a new action on a historic source causing historic contamination to damage the environment further.

‘Environmental damage’ refers to:

- Adverse effects on the integrity of a Site of Special Scientific Interest (SSSI) or on the conservation status of species and habitats protected by EU legislation outside SSSIs;
- Adverse effects on surface water or groundwater consistent with a deterioration in the water’s status (Water Framework Directive term); and
- Contamination of land that results in a significant risk of adverse effects on human health.

There is liability without the need to show fault for activities that include:

- A Environmental Permit;
- Discharges to water;
- Groundwater discharges;
- Water abstraction or impoundment;
- Using pesticides, biocides or dangerous substances;
- Using and releasing Genetically Modified Organisms; and
- Transporting dangerous goods.

There is also liability where an operator has intended to cause damage or has been negligent but only for damage to SSSIs or EU species or habitats.

There are certain exemptions such as damage caused by acts of terrorism or natural disasters or damage falling within certain international conventions (e.g. oil pollution) (Defra, 2009).

In Scotland, the European Environmental Liability Directive 2004/35/EC (ELD) were transposed into The Environmental Liability (Scotland) Regulations in 2009.

The regulations in England, Scotland and Wales do not replace any existing laws therefore ordinary day-to-day activities/accidents will continue to be dealt with under existing legislation.

4.2.5 INTEGRATED POLLUTION PREVENTION AND CONTROL DIRECTIVE

The Integrated Pollution Prevention and Control (IPPC) Directive aims to minimise pollution from various industrial activities throughout the European Union. Operators of certain industrial installations that are covered by the directive are required to obtain an environmental permit from the authorities in EU countries. These permits provide operational measures to control emissions to the environment.

In England and Wales the European Directive has been transposed into the Environmental Permitting (England and Wales) Regulations 2010 and they set out a system to control pollution from any installation or mobile plant carrying out specified activities through permits, inspections and control of emissions. It covers the inclusion of best available techniques (BAT) and standard rules in permits and replaces (revokes) previous PPC legislation.

In Scotland the IPPC Directive has been transposed into the Pollution Prevention and Control (Scotland) Regulations 2012, In addition the Pollution Prevention and Control (Scotland) Amendment Regulations 2014 amend the PPC regulations 2012 and transpose Directive 2012/27/EU (The Energy Efficiency Directive). The new Schedule 1A applies to specified installations and requires a cost-benefit analysis to be carried out for the purposes of the Energy Efficiency Directive. There is also a requirement for new permits for solvent activities to include a requirement to inform SEPA of an incident or accident that could significantly affect the environment.

4.2.6 FUTURE EUROPEAN LEGISLATION

The Soil Framework Directive was formally withdrawn in May 2014 by the European Union (EU), however from recent discussions with Defra, it is understood that they are waiting to hear from the EU what action may be taken as it is understood that the EU still intend to take EU level action on soils. EU member states have been asked to reflect as soon as possible on how soil quality issues could be addressed, using a targeted and proportionate risk-based approach within a binding legal framework.

The reason the directive was unpopular with key EU countries (who created a blocking minority) was the requirement for member states to compile a list of contaminated sites with a programme for remediation. It was felt that this was not appropriate as the UK has an established legal framework to deal with land affected by contamination and it felt that this would be disproportionately expensive for the benefit it would bring.

4.3 DOMESTIC LEGISLATION

England and Wales have developed an approach to dealing with land contamination developed around three principles (Environment Agency, 2013):

- Ensuring new development and land uses are protected from existing contamination – through the planning system or voluntary remediation (Town and Country Planning Acts and Regulations);
- Ensuring that existing development and land uses are protected from existing contamination – the contaminated land regime (Part 2A); and
- Ensuring that no new contamination is created – Environmental Permitting Regulations, Environmental Damage Regulations and Water Resources Act.

Similar principles also exist in Scotland as well.

Detailed below in Table 4.2 is the key domestic legislation that impacts land affected by contamination in addition to the European Legislation that is set out in section 4.2.

Table 4.2: Key domestic legislation that impacts land affected by contamination

Domestic Legislation	Requirements
Environmental Protection Act 1990 : Part 2A Contaminated Land Statutory Guidance 2012 (England and Wales) **The Contaminated Land (Scotland) Regulations 2000 amended 2005**	• Local Authorities are under a duty to inspect their areas to identify contaminated land causing pollution or significant harm. • Require action to make land suitable for current use using an agreed strategy. This can be voluntary or through an enforcement notice or carried out by regulators.

Introduced as a means of dealing with the legacy of contaminated land arising from the historical use of land.	
Environmental Permitting Regulations 2010 (England and Wales) **The Water Environment (Controlled Activities) (Scotland) Regulations 2011** • Permits require the prevention of contamination and clean up to a high standard.	• Allows regulators to set permit conditions and enforce them. • Permits can require remediation and a site may be required to be returned to a satisfactory state. • Remediation activities may need permitting. • Requires the prevention of hazardous substances being discharged to the groundwater causing pollution.
Environmental Damage Regulations 2009 (England and Wales) **The Environmental Liability (Scotland) Regulations 2009** Aim to prevent environmental damage.	• Preventing new land contamination that will damage water or health. • If damage does occur, comprehensive clean-up will be required (often to pre-incident conditions) to species, habitats, water environment and land. • Can also include for compensation.
Town and Country Planning Act 1990 (England and Wales) **Town and Country Planning (Scotland) Act 1997** • Planning and Development Control	• Contamination is a planning consideration and conditions can be imposed requiring assessment and remediation as part of the planning conditions. • Developers responsibility to address contamination

4.3.1 DEFINITION OF WASTE: DEVELOPMENT INDUSTRY CODE OF PRACTICE

The Definition of Waste: Development Industry Code of Practice (DoWCoP) (CL:AIRE, 2011) provides a clear, consistent and efficient process which enables the reuse of excavated materials on-site or their movement between sites however it is only applicable in England and Wales. The process is voluntary and supports the sustainable and cost effective development of land and provides an alternative to Environmental Permits or Waste Exemptions.

The DoWCoP enables:

- Direct transfer and reuse of clean naturally occurring soil materials between sites;
- Conditions to support the establishment/operation of fixed soil treatment facilities; and
- Reuse of both contaminated/uncontaminated materials on their site of origin and between sites within defined Cluster project.

The principles for the reuse of material as non-waste are:

- Protection of human health and the environment;
- Suitability for use, without further treatment;
- Certainty of use; and
- Quantity of material.

If materials are dealt with in accordance with the DoWCoP the Environment Agency (EA) and Natural Resources Wales (NRW) considers that those materials are unlikely to be waste if they are used for the purpose of land development. This may be because the materials were never discarded in the first place, or because they have been submitted to a recovery operation which has been completed successfully so that they have ceased to be waste.

Further information can be obtained from www.claire.co.uk/cop.

In Scotland, SEPA has published regulatory guidance – Promoting the sustainable reuse of greenfield soils in construction in March 2010. This guidance does not cover contaminated soils, it covers natural topsoil and subsoil only. Contaminated soils are covered by SEPA's Land Remediation and Waste Management Guidelines:
http://www.sepa.org.uk/waste/waste_regulation/guidance__position_statements.aspx

5. DESCRIPTION OF EXISTING TREATMENT TECHNOLOGIES AND PROCESSES

5.1 INTRODUCTION

Soil and groundwater remediation technologies have developed significantly in the last 10 to 15 years in the UK. This section will describe the main *in situ* and *ex situ* soil and groundwater technologies that are currently available to treat the common contaminants associated with former gasworks and gasholder sites. The information is summarised in a series of tables, which include a brief description of each technology and an applicability matrix, which provides a general indication of the likelihood that a technology will be able to treat a particular contaminant. Figure 5.1 gives an example of the applicability matrix, with an explanation of the terms used.

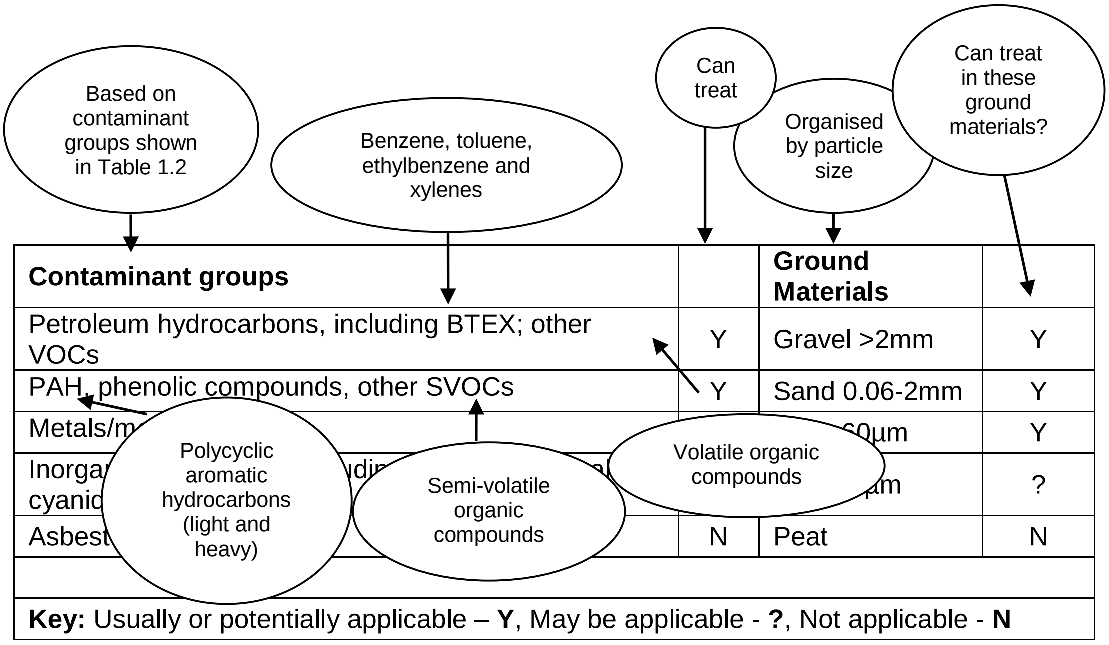

Figure 5.1: Explanation of the applicability tables in this section

The tables in this section are adapted for contaminants typically found on former gasworks sites from information provided in Defra's Contaminated Land Remediation Report (Defra, 2010), which was compiled and authored by CL:AIRE. Additional descriptive information can be found in the Defra document.

The purpose of this section is to guide the reader to which technologies might be suitable for particular contaminants. It is by necessity a simplification to aid understanding. Contaminant behaviour may differ depending on other contaminants or chemical compounds present, the concentration of the contaminants, whether the contaminants are distributed in the soil/strata or in the groundwater, and the type of surface and subsurface ground materials. Former gasworks sites are complex and appropriately skilled personnel will be required to perform bench, pilot and treatability testing where appropriate to assess a number of remedial options. Ultimately, the final judgement will be based on cost, track record, sustainability impacts (environmental, social, and economic), availability of equipment and each site will be considered on a case-by-case basis.

5.2 *IN SITU* TREATMENT TECHNOLOGIES

In situ technologies treat contaminants in the subsurface, without excavation of the contaminated soil or abstraction of contaminated groundwater. Depending on the technology used, there can be a need for surface collection and treatment of contaminants transported in gas or water. *In situ* methods are reliant on a detailed understanding of the site geology, hydrogeology and contaminant properties to ensure that the reagents and contaminants can make effective contact. *In situ* methods can often avoid excessive environmental impacts and costs associated with excavation and abstraction, but they are likely to require pilot and treatability studies to fully understand if a particular technique will be effective at a site.

The following *in situ* technologies are described further below:

- Chemical treatment;
- Enhanced bioremediation;
- Flushing;
- Monitored natural attenuation;
- Permeable reactive barriers;
- Sparging;
- Stabilisation/solidification;
- Thermal treatment; and
- Venting.

There are examples of other *in situ* methods being used on former gasworks sites and to treat the types of contaminants that are typically found on these sites, but these are not in common use and are not discussed here (e.g. electro-remediation, phytoremediation and vitrification).

Chemical treatment

Technology description

Chemical treatment involves the addition of chemicals to soil or groundwater to either oxidise or reduce the contaminants by degrading them, reducing their toxicity, changing their solubility, or increasing their susceptibility to other forms of treatment. Oxidation, rather than reduction, is the more common approach to treat contaminants typically found on former gasworks sites.

Chemical oxidation can be effective for the degradation of a wide range of organic contaminants. It involves the injection of liquid or gaseous chemical compounds to the subsurface. Some organic compounds will undergo partial degradation and can then be treated by other methods, such as bioremediation. Common oxidants include ozone, permanganate, hydrogen peroxide, catalysed hydrogen peroxide (e.g. Fenton's reagent), sodium persulphate and sodium percarbonate.

Remediation timescales are typically <1 year and one of the key considerations is ensuring adequate contact between contaminants and reagents within the treatment zone.

Less commonly, chemical treatments can be applied to soil or groundwater *ex situ* to treat excavated soil or pumped groundwater at the surface.

Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	?	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	N	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Enhanced bioremediation

Technology description

Bioremediation uses microorganisms to degrade organic contaminants to non-toxic by-products or transform inorganic contaminants to less mobile or less toxic forms. Microbial activity can be stimulated or enhanced by adding microorganisms (in a process called bioaugmentation) or amendments such as air, nutrients and chemical reagents (in a process called biostimulation).

Organic compounds common to former gasworks sites are typically degraded in the presence of oxygen under aerobic conditions. Some petroleum hydrocarbons can be degraded anaerobically (in the absence of oxygen), although anaerobic degradation is most commonly associated with the bioremediation of halogenated compounds.

Enhanced bioremediation can be used to treat both soil and groundwater although it can be difficult to apply to a heterogeneous subsurface and toxic intermediate breakdown products may be formed.

Remediation timescales are typically between 6 months to 3 years.

Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	?	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	N	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Flushing
Technology description Flushing involves the application (by injection or spraying) of aqueous solutions to the ground. Aqueous solutions can be any of the following: treated groundwater, acids, alkalis, chelating agents, surfactants and solvents. These solutions may dissolve the contamination and/or stimulate *in situ* biodegradation and *in situ* redox reactions. After flushing, the solution is recovered using wells or trenches and is treated at the surface to remove contaminants using a water treatment plant. Remediation timescales are typically between 6 months to 3 years. Both organic and inorganic compounds can be treated depending on the aqueous solution used. However, a good understanding of site geology and hydrogeology is required to prevent loss of contaminant and soil flushing solution beyond the capture zone.
Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	Y	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	N
Asbestos	N	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable **- ?**, Not applicable – **N**			

Monitored natural attenuation
Technology description Monitored natural attenuation (MNA) is a risk management approach to confirm that natural processes are reducing the load, concentration, flux or toxicity of contaminants within a specified timescale. Attenuation processes include biodegradation, chemical degradation, sorption, immobilisation, dispersion and dilution, any or all of which may result in a reduction in contaminant load, concentration, mobility or toxicity. Although considered a monitoring activity, there is a requirement to extensively characterise the site being managed, and then collect lines of evidence to demonstrate that attenuation processes are occurring and will continue to occur in order to meet the site remedial objectives within the agreed time frame. This may require modelling. MNA requires significant depth of understanding of local geology and hydrogeology, a long term commitment to monitoring and a contingency plan if the contaminants or groundwater do not behave as predicted. Remediation timescales are highly dependent on the contaminants in question and the remediation design but are typically between 1-30 years.
Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	?	Sand 0.06-2mm	Y
Metals/metalloids	?	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	N	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable **- ?**, Not applicable **- N**			

Permeable reactive barriers
Technology description A permeable reactive barrier (PRB) is an engineered treatment zone placed in the saturated zone to remediate contaminated groundwater as it flows through. It allows the passage of water and contains reagents that cause the degradation or removal of contaminants. The use of different reactive media within the reactive zone of a PRB allows the treatment of a wide variety of groundwater contaminants. Reactive media could include zero-valent metals, chelators, sorbents or microbes. The mechanisms involved may be sorption, oxidation/reduction, precipitation, fixation, and biodegradation. PRBs require significant understanding of local geology and hydrogeology and remediation timescales are typically >10 years.
Applicability to contaminants and ground materials

Contaminant groups		Ground Materials	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	Y	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	N	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable **- ?**, Not applicable – **N**			

Sparging
Technology description Sparging involves the injection of air into the groundwater (i.e. to the saturated zone) using vertical wells which promotes volatilisation and/or biodegradation of contaminants from soil, water and the vapour phase. Volatilisation is the partitioning of contaminants into the air as it moves upwards through the water. Biodegradation occurs as the microorganisms are stimulated by the supply of oxygen. Sparging is commonly used in conjunction with vapour extraction and collection techniques at the surface, most commonly vacuum extraction or soil vapour extraction. Ozone can be added to improve performance and may result in contaminant removal via oxidation. Sparging requires a good understanding of site hydrogeology, the nature and extent of contamination and the physical/chemical properties of the contaminants themselves. Care should be taken to avoid the risk of contaminant mobilisation or spreading of the contaminant plume. Remediation timescales are typically between 6 months to 3 years.
Applicability to contaminants and ground materials

Contaminant groups		Ground Materials	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	N	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	N	Clay <2µm	N
Asbestos	N	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable **- ?**, Not applicable **- N**			

Stabilisation/solidification

Technology description

Stabilisation/solidification (S/S) is a remediation technology that relies on the reaction between reagents and the soil matrix to reduce the mobility of contaminants. Common reagents used in S/S are cements, pozzolans (such as pulverised fly/fuel ash), ground granulated blastfurnace slag, lime-based binders (calcium oxide or hydroxide) and organophilic clays.

Stabilisation involves the addition of reagents to a contaminated material (e.g. soil or sludge) to produce more chemically stable constituents; and *solidification* involves the addition of reagents to a contaminated material to impart physical/dimensional stability in order to contain contaminants in a solid product and reduce permeability to air and water.

In situ S/S relies on efficient mixing of the reagents with the soil, which is typically conducted by mechanical mixing (e.g. use of augers, backhoes, blenders or mass stabilisation tools).

S/S can be used to treat recalcitrant organic and inorganic contaminants but reagent delivery and effective mixing can be difficult to achieve *in situ*. Remediation timescales are typically <1 year.

Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	Y	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	Y	Clay <2µm	Y
Asbestos	Y	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable - **N**			

Thermal treatment

Technology description

Thermal treatment involves raising the temperature in the ground to enhance the mobility of organic contaminants in both the saturated and unsaturated zones which can facilitate their recovery and treatment.

There are four main methods for *in situ* heating: injection (steam or hot air); electrical resistance heating; electromagnetic heating (radiofrequency or microwave); thermal conductive heating (using wells heated by electricity or hot gas). These methods have differing ranges of applicability for contaminants and soil and groundwater conditions, treatment efficiencies, and cost. Also, they all require some form of recovery operation, such as by venting and/or pumping, followed by treatment at the surface (e.g. by activated carbon; thermal or catalytic oxidation).

Buried objects or utilities may cause operating problems and the enhanced mobility of contaminants might lead to migration outside the treatment zone. Remediation timescales are typically <1 year.

Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	?	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	N	Clay <2µm	Y
Asbestos	N	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Venting
Technology description Venting is a general term for a number of technologies such as soil vapour extraction, dual phase extraction, multi-phase extraction, bioventing and bioslurping. It involves the movement of air through the unsaturated zone via extraction and/or injection wells to promote volatilisation and/or biodegradation of contaminants from soil and the vapour phase. Volatilisation is the partitioning of contaminants into the air as it moves through the water. Biodegradation occurs as the microorganisms are stimulated by the supply of oxygen. Bioventing occurs when an optimised air flow rate is used to provide enough oxygen to maximise biodegradation and minimise volatilisation. Bioslurping combines elements of both bioventing and vacuum-enhanced free-product recovery to simultaneously remove light non-aqueous phase liquid (LNAPL) and bioremediate soils. Dual vapour extraction, dual-phase extraction or multi-phase extraction involves the use of a high vacuum system to remove contaminated groundwater, LNAPLs and hydrocarbon vapour from the subsurface, which are then treated at the surface. Remediation timescales are typically between 6 months to 3 years.

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	N	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	N	Clay <2µm	?
Asbestos	N	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable - **N**			

5.3 *EX SITU* TREATMENT TECHNOLOGIES

Ex situ treatment technologies treat contaminants above the surface, either in excavated soil or abstracted groundwater. Compared with *in situ* remediation, it is easier to ensure effective mixing of reagents and contaminants, and process optimisation and verification are more straightforward. This has an impact on remediation timescales, which are generally shorter for *ex situ* than *in situ* methods. Conversely, excavation and/or pumping are likely to increase costs and *ex situ* methods require space on the surface and can have a greater impact on the ground environment.

In addition to being treated on the site of origin, excavated soil can be transported to dedicated off-site soil treatment facilities (STFs). Several technologies can be operated at a STF, which increases the types of contaminants and range of materials that can be treated. Once contaminated material has been treated it typically does not return to the site of origin but is used as daily cover or capping material at the STF. The exception to this is where the STF is acting as a hub site as part of a defined Cluster project (CL:AIRE, 2011, 2012).

The following are the main *ex situ* technologies used to treat contaminants typically found on former gasworks sites:

- Biological treatment;
- Soil washing and separation processes;
- Stabilisation/solidification; and
- Thermal treatment.

Biological treatment
Technology description Biological treatment involves the use of microorganisms, commonly bacteria or fungi, to transform or degrade contaminants to non-toxic or less toxic by-products. Several different biological treatment configurations are available: biopiles, windrow turning, landfarming, composting, slurry-phase bioreactors. Microbial activity can be stimulated or enhanced by adding microorganisims (in a process called bioaugmentation) or amendments such as air, nutrients and chemical reagents (in a process called biostimulation). Biological treatment can result in complete organic contaminant degradation, however, heavier organic compounds (e.g. heavy PAH) are difficult to degrade. Soils can often be reused after treatment. Remediation timescales typically range from <6 months to 3 years.
Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	N	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	N	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Soil washing
Technology description Soil washing is a separation treatment process in which soil particles which "host" the majority of the contamination are separated from the bulk soil fractions in a series of aqueous treatment steps (usually with water only). The separated contaminants then go to hazardous waste landfill or are further treated by chemical, thermal or biological processes. Soil washing works via physical separation and/or dissolution processes. For example, differences between physical properties such as particle grain size, settling velocity, specific gravity, surface chemical behaviour and rarely magnetic properties are exploited. Soil washing is unlikely to be economically viable if there is a clay and silt content of greater than 40%. Treatability studies will be required to assess the potential effectiveness of soil washing. Remediation timescales are typically <6 months.
Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	Y	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	?	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable - **N**			

Stabilisation/solidification

Technology description

Stabilisation/solidification (S/S) is a remediation technology that relies on the reaction between reagents and the soil matrix to reduce the mobility of contaminants. Common reagents used in S/S are cements, pozzolans (such as pulverised fly/fuel ash), ground granulated blastfurnace slag, lime-based binders (calcium oxide or hydroxide) and organophilic clays.

Stabilisation involves the addition of reagents to a contaminated material (e.g. soil or sludge) to produce more chemically stable constituents; and *solidification* involves the addition of reagents to a contaminated material to impart physical/dimensional stability in order to contain contaminants in a solid product and reduce permeability to air and water.

Effective mixing of contaminants and binder is critical to performance success. *Ex situ* mixing can involve one of three main methods: plant processing, direct mixing, and in-drum processing.

S/S can be used to treat recalcitrant organic and inorganic contaminants. Remediation timescales are typically <6 months.

Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	Y	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	Y	Clay <2µm	Y
Asbestos	Y	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Thermal treatment

Technology description

Thermal treatment involves the use of heat to destroy organic contaminants or enhance their mobility and facilitate their recovery and treatment. Thermal treatment can be two stage (thermal desorption of contaminants followed by secondary treatment) or in a single stage (incineration).

In thermal desorption, soils are heated in specialised treatment units or piles at temperatures up to 600°C at which a wide range of organic contaminants volatilise. In a rotary kiln, soils can be heated directly or indirectly. In an excavated soil pile, heater and extraction wells are layered into the pile and heat the soil by thermal conduction. Heater wells are heated by electricity or hot gas. A moving air stream within the thermal treatment unit or pile captures the contaminants and directs them to secondary treatment units where the contaminants are either destroyed or trapped prior to subsequent treatment or disposal.

Incineration involves the thermal destruction of contaminants in a combustion chamber at high temperatures up to 1300°C which means a wider range of contaminated materials, higher concentrations of contaminants and those that are harder to treat. However, incineration can be expensive with high energy costs. Remediation timescales for both options are typically <6 months.

Applicability to contaminants and ground materials

Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	N
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	?	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	?	Clay <2µm	?
Asbestos	?	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable - **N**			

5.4 TRADITIONAL CIVIL ENGINEERING METHODS

Traditional civil engineering methods are still commonly used as part of a remediation approach, but rather than being the only approach, they are used in combination with the *in situ* and *ex situ* methods described in the previous sections. The types of civil engineering approaches that are commonly used can be grouped into containment measures and excavation/abstraction measures.

Containment measures isolate the contaminated materials using barriers or cover systems which prevent exposure of the surrounding environment. Excavation and abstraction measures rely on the removal of soil and groundwater respectively, which then needs to be disposed of or subjected to treatment. Pumping groundwater may also be used as a means of hydraulic control i.e. lowering the water table to isolate contamination.

The main advantage of excavation and off-site disposal is that it removes the contaminants (and the risk they pose) from the site. However, high costs associated with handling and transporting large volumes of material, and the noise and nuisance of vehicle movements to local populations, means that alternative remedial solutions are often sought. Selective excavation and physical separation of like-for-like materials for stockpiling, testing and reuse (or disposal) is an important process for maximising reuse on site.

In 2011, CL:AIRE published the Definition of Waste: Development Industry Code of Practice, which has facilitated the reuse of excavated materials on-site and their movement between sites (see section 4.3.1). It ultimately reduces material going to landfill and the requirement for material to be brought back onto site and has resulted in environmental, economic and social benefits (CL:AIRE, 2013, 2014).

Civil engineering methods are applicable to a range of ground conditions and contaminant types, they can be rapidly deployed and use established and proven engineering techniques.

6. CASE STUDIES OF EXISTING TREATMENT TECHNOLOGIES AND PROCESSES

This section of the report presents case studies of remediation technologies that have been used to treat soil and groundwater on former gasworks and gas storage facilities. A case study has been included if it has had some degree of third party evaluation, rather than including case studies from practitioners in the UK whose claims of success cannot be substantiated. In most cases, the case study has originated from a CL:AIRE publication (evaluated by the CL:AIRE Technology and Research Group, a panel of experts from industry, regulatory and academic backgrounds), a journal publication (peer-reviewed), or a Brownfield Briefing Innovation Award (judged by a selection of industry experts).

Table 6.1: UK case studies of remediation technologies used on former gasworks sites in the UK (presented in chronological order by publication date).

Site location	Technologies used	Main contaminants treated	Comments/Reference
Basford, Nottingham	Soil washing	PAH, phenolics, ammonia and complex cyanides	CL:AIRE TDP2 Report. 2003. ISBN 0-9541673-6-8.
Unnamed site, northwest England	Air sparging	BTEX, phenols, PAH	CL:AIRE TDP9 Report. 2004. ISBN 0-9541673-8-4.
Unnamed site, northwest England	Bioremediation (ex situ)	PAH	Slurry phase bioreactor pilot trial. CL:AIRE TDP4 Report. 2004. ISBN 1-9056046-05-7.
Portadown, Northern Ireland	Permeable reactive barrier	BTEX, ammonium, sulphate	Biological PRB. CL:AIRE Case Study Bulletin (CSB3). 2005
Wharf Lane, Solihull	Chemical oxidation (in situ)	Benzene, PAH, TPH, cyanide, arsenic, ammoniacal nitrogen	Fenton's Reagent. Land Contamination & Reclamation, 14 (2), 189-193. 2006. DOI 10.2462/09670513.774
High Wycombe Gasworks	Soil washing, bioremediation (ex situ)	Naphthalene, benzene, xylenes, phenols, ammonium	Land Contamination & Reclamation, 14 (2), 241-246. 2006. DOI 10.2462/09670513.712
Dartford, Kent	Monitored natural attenuation	PAH from highly weathered coal tars	Land Contamination & Reclamation, 14 (2), 283-287. 2006. DOI 10.2462/09670513.714
Wymondham, Norfolk	Hydraulic control	PAHs, TPHs, metals, asbestos and phenols	Groundwater lowering. Land Contamination & Reclamation, 14 (2), 382-387. 2006. DOI 10.2462/09670513.740
Unnamed sites in south east and south west England	Permeable reactive barrier	Ammonium	Biological PRB. Land Contamination & Reclamation, 14 (2), 525-531. 2006. DOI 10.2462/09670513.756
Tunbridge Wells Gasworks	Bioremediation (ex situ), stabilisation (ex situ)	PAH, TPH, BTEX, phenols, cyanide and ammonia	Biopiles and in-ground barrier. "Best use of combined treatment systems" at Brownfield Briefing Remediation

			Innovation Awards 2006. http://www.southerntesting.co.uk/jwtb/assets/files/pdf/case_studies/Brownfield%20Briefing%20Award%20Twells%20GWS.pdf (accessed October 2014)
Dundee and Leven Gasworks, Scotland	Low temperature thermal desorption and Cluster project	PAH, phenols, TPH, cyanide	"Most innovative remediation method" at Brownfield Briefing Remediation Innovation Awards 2007. http://www.ihbrown.com/app/uploads/download/new/DundeeGasworksPhase2.pdf (accessed October 2014)
Clough Road Gasworks, Hull	Bioremediation (ex situ)	PAH, TPH, phenols	Advanced biotreatment (use of surfactants), biophysical treatment. Best use of combined treatment systems" at Brownfield Briefing Remediation Innovation Awards 2007. http://www.yclf.org.uk/download.php?docId=0000000028&inline=true (accessed October 2014)
Lossie Green, Elgin, Scotland	Soil washing	Arsenic, tar, cyanide	"Most sustainable remediation project" at Brownfield Briefing Remediation Innovation Awards 2007. http://www.nottingham.ac.uk/~evzard/envgeotech/eg2008/Bullen&deBon.pps (accessed October 2014)
Chertsey, Surrey	Bioremediation (ex situ)	BTEX, phenols, PAH, TPH	Vented biopiles housed in poly-tunnels. "Best use of a single treatment technique" at Brownfield Briefing Remediation Innovation Awards 2008. http://www.brownfieldbriefing.com/case-study/tamdown-win-bio (accessed Oct 2014)
Unnamed site, south west England	Permeable reactive barrier	PAH, BTEX, phenol, cresol, complex cyanide	Biological sequential reactive barrier. CL:AIRE TDP17. 2008. ISBN 978-1-905046-14-0.
Hampton Court Gasworks, Greater London	Bioremediation (in situ and ex situ), stabilisation, venting, thermal treatment (in situ), flushing, chemical oxidation.	DNAPL coal tar, BTEX, PAH.	A multi-phased in situ approach to DNAPL recovery. Runner Up "Best use of a combination of remediation techniques" at Brownfield Briefing Remediation Innovation Awards 2008. http://www.southerntesting.co.uk/jwtb/assets/files/pdf/case_studies/Brownfield%20Briefing%20Award%20Teddingto

			nGWS.pdf (accessed October 2014).
Unnamed site, south London	Thermal treatment (ex situ)	Coal tar	Thermally enhanced total fluids pumping system for tar recovery. “Most sustainable remediation project” at Brownfield Briefing Remediation Innovation Awards 2009. http://www.brownfieldbriefing.com/features/sustainable-gasworks-site (accessed October 2014)
Crindau Gasworks, Newport, South Wales	Flushing	Coal tar	Surfactant flushing. “Best conceptual design” at Brownfield Briefing Remediation Innovation Awards 2010. http://www.ciwem.org/knowledge-networks/networks/contaminated-land/newsletter-issue-3-october-2010/assessment-and-conceptual-remediation-scheme-design-for-the-former-crindau-gasworks,-newport,-south-wales.aspx (accessed October 2014)
Unnamed site, east England	Automated pumping	DNAPL	“Best low carbon remediation technique” at Brownfield Briefing Remediation Innovation Awards 2010. From Winners Brochure, available from Brownfield Briefing.
Aldershot Gasworks	Multi-phase extraction, stabilisation/solidification (in situ), sludge reactor,	LNAPL, DNAPL, ammonia	“Most Sustainable and Low Carbon Remediation Project” at Brownfield Briefing Remediation Innovation Awards 2011. http://www.brownfieldbriefing.com/news/aldershot-gasworks (accessed October 2014)
Gould St, Manchester	Stabilisation/solidification (in situ, ex situ)	Spent oxide	Highly commended for “Best in situ treatment” at Brownfield Briefing Remediation Innovation Awards 2011. http://www.ashremediation.co.uk/pdfs/Soil_Stabilisation.pdf (accessed October 2014)
Partington, Runcorn, Prescot, Warrington	Bioremediation (ex situ), stabilisation and Cluster project	Typical gasworks contaminants	Focus on the Cluster element rather than the technologies used at the hub site. CL:AIRE Case Study Bulletin (CSB11). 2013.
Ammanford Gasworks,	Stabilisation/Solidification and the Development Industry Code of Practice	Cyanide, petroleum hydrocarbons and	“Best re-use of materials” at Brownfield Briefing Remediation Innovation

Carmarthenshire, Wales		coal tar impacted material.	Awards 2013. http://www.brownfieldbriefing.com/sites/www.brownfieldbriefing.com/files/Winner's%20Brochure%202013.pdf (accessed October 2014)
Beckton Gasholder, London	*In situ* grouting and NAPL recovery	NAPL	"Best conceptual design" at Brownfield Briefing Remediation Innovation Awards 2014. http://www.brownfieldbriefing.com/sites/www.brownfieldbriefing.com/files/Winner's%20Brochure%202014.pdf (accessed April 2015)

Only one third party evaluated case study was submitted as part of the questionnaire sent to CL:AIRE's international contacts. An internet search was also conducted to find others, resulting in one additional case study. Both these are from the US Environmental Protection Agency and are shown in Table 6.2 below.

Table 6.2: Case studies of remediation technologies used on former gasworks sites in the USA (presented in chronological order by publication date).

Site location	**Technologies used**	**Main contaminants treated**	**Comments/Reference**
Fairfield Former Manufactured Gas Plant, Iowa	Monitored natural attenuation	Coal tar	2012. EPA 542-R-12-004. http://epa.gov/tio/download/remed/rse/optimizationreview_fairfield_aug2012.pdf
Second Street Subsite, Nebraska	Soil vapour extraction, thermal treatment (ex situ), pump and treat, in-well stripping, bioremediation (in situ)	BTEX, PAH	2013. EPA 540-R-013-017. http://www.clu-in.org/download/remed/hyopt/application/rses/superfund_rses/FinalHastingsMay13.pdf

7. TECHNOLOGY GAPS

7.1 INTRODUCTION

The aim of this section is to identify contaminants that are currently not able to be treated by commercially available technologies. However, based on the technology reviews and compilation of case studies that were undertaken and presented in sections 5 and 6, the evidence suggests that all contaminants typically found on former gasworks sites are treatable from a technical perspective. By no means is this to suggest that all contaminants will be treated on a particular site as technical feasibility is only one of a number of factors that needs to be considered. The mixture and concentrations of contaminants and the type of ground materials will affect the ability of a technology to be effective, often along with hydrogeological conditions, but these are purely technological factors. The actual decision-making process regarding the site will involve consideration of the risk drivers, clean-up criteria and the end use of the site, environmental impacts, social considerations, remediation timescales and often, fundamentally, the financial cost.

Having said this, the research has identified three contaminant types that could be considered more difficult to treat than others, and which are often removed from site and disposed of in hazardous waste landfills rather than treated on or off site: spent oxide material and two types of tar. These are discussed in more detail below.

7.2 SPENT OXIDE AND GAS PURIFICATION WASTES

Spent oxide is a waste from the gas purification process. Ferric oxide was used as a purifying agent and on becoming saturated with sulphur, cyanide and organic sulphur compounds, the ferric oxide was said to be “spent”. Blue Billy and foul lime were purification wastes produced in a similar way. Blue Billy resulted from reacting the gas with wet lime, whereas foul lime came from the reaction of the gas with hydrated lime. Blue Billy was a noxious and a toxic waste which had been dumped in water courses resulting in numerous pollution incidents, for this reason it was phased out by the mid-19th century. Spent oxide was phytotoxic and used as weed killer, whereas foul lime was a very effective fertiliser once it had been weathered.

The composition of spent oxide and foul lime is similar; up to 6% of the total weight is cyanide, predominantly in the form of thiocyanate and complex metal cyanides, approximately 3-9% iron, 0.08-0.36% manganese, 2-3% sulphate and 36-60% free sulphur (CL:AIRE, 2014). The high percentage composition of sulphur within these wastes, means that they have a high loss on ignition and readily burn. Spent oxide in particular can spontaneous combust if rapidly exposed to air from an anoxic state.

Opinion is divided on whether these solid gas purification wastes can be remediated other than by excavation and removal to landfill. Spent oxide can be treated effectively through thermal desorption, this rapidly destroys any cyanide present within the material. Given the proportion of sulphur present in the material any resulting off-gases are highly laden with sulphur dioxide which makes their treatment difficult and calls into question the economic and environmental benefits of such a treatment method.

Section 6 provides one case study of the successful S/S treatment of spent oxide material, and there are other case studies (not peer-reviewed) that also demonstrate effective treatment. However, from discussions with several practitioners, even those who have demonstrated such success, there are doubts as to whether this treatment will be effective in all cases, due to the elevation of pH that occurs with S/S, and the mobilisation of some of the contaminants (e.g. cyanide) as a result of this. This remains an area for more technology development.

7.3 COAL TAR

Coal tars are an extremely complex mixture of organic compounds. Within coal tars, the main contaminants are PAH; phenolic compounds (e.g. phenol, cresol, xylenol); BTEX compounds; aromatic and aliphatic petroleum hydrocarbons; oxygen, nitrogen and sulphur heterocyclic compounds, e.g. carbazole, dibenzofuran, azobenzene, carbon disulphide; inorganic components, ammonium, cyanide and sulphur-based compounds (CL:AIRE, 2014).

Neat coal tar and coal tar impacted materials are treatable using both *in situ* and *ex situ* technologies, in fact many of the technologies described in section 5 show applicability for the contaminants listed above, evidenced by the case studies in section 6. However, the heavier organic compounds (e.g. large-ringed PAH) can be particularly recalcitrant to biodegradation and the time and cost to treat them effectively may not be acceptable in the current market. Neat coal tar can be sent to a waste oil recovery company and reprocessed into a fuel product for use in cement kilns or power stations. Coal tar impacted material can be taken to landfill if it passes the waste acceptance criteria, however, this is typically only after pre-treatment due to the materials high total organic carbon content. Pre-treatment will use thermal methods (thermal desorption or incineration) or stabilisation/solidification. Developing a technology to effectively and expediently remediate the most recalcitrant fraction of coal tar contamination remains an area for further research.

7.4 WATER GAS TAR

Carburetted Water Gas (CWG) tars like coal tars were also complex mixtures of organic compounds similar in composition to coal tars but in different proportions; they contained a higher proportion of petroleum based components sourced from the enriching process which gasified oils (CL:AIRE, 2014). CWG tars had different physical properties to coal tars, their density often was similar to water making them Neutral Non Aqueous Phase Liquids (NNAPL) and they could readily emulsify. Due to their NNAPL nature, CWG tar plumes are more able to migrate in groundwater forming extensive plumes.

The emulsions formed by CWG tar, were where fine droplets of water would become incorporated in the tar (the reverse could also occur). The characteristics of these tar and water emulsions could be quite different to the characteristics of the water and tar separately. As water content increased, the tars became more viscous and they could be composed of up to 85% water (CL:AIRE, 2014). The ability to form emulsions often makes recovering water gas tars from groundwater very difficult and there is an opportunity here for further research to improve the current recovery process.

8. INNOVATIVE TECHNOLOGY DEVELOPMENT

8.1 INTRODUCTION

The aim of this section is to assess whether there are any new innovative technologies undergoing development or pilot testing that may be applicable to treating contaminants found on former gasworks sites. Two new technologies were found, a thermal method utilising smouldering combustion and an injectable colloidal technology for dissolved organic contamination in groundwater. These will be discussed in sections 8.2 and 8.3 using the same description format and applicability matrix used in section 5. In the course of the research, many technology vendors were identified which claimed to have new technologies, but on closer inspection these tended to be modifications of existing technologies or combinations of existing technologies as part of a treatment train approach. Although these are not new technologies *per se* they are still innovations and some examples are given in section 8.4.

It should be noted that some of the technologies in this section, unlike those in section 6, have not been subjected to third party evaluation (that could be found). Therefore the claims of effectiveness that are presented must be taken on board with this in mind.

8.2 STAR / STARx

STAR / STARx
Technology description STAR is an *in situ* thermal technology based on the principles of smouldering combustion, where the contaminants are the source of fuel. The process is sustained by the addition of air through a well to the treatment zone and is initiated through a short duration, low energy "ignition event." Once the process is initiated (ignited), the energy of the reacting contaminants is used to pre-heat and initiate combustion of contaminants in adjacent areas, propagating a combustion front through the contaminated zone in a self-sustaining manner (i.e., no external energy or added fuel input following ignition) provided a sufficient flux of oxygen is supplied. Active control of the combustion front is maintained by the oxygen supply. STAR can treat materials impacted by coal tar, creosote, or petroleum hydrocarbons at soil concentrations equal to or greater than approximately 3,000 mg/kg Total Petroleum Hydrocarbons (TPH) within silty sand or coarser geologic units. STAR can be applied both above and below the water table. STARx is an *ex situ* version of the STAR technology and is carried out in fabricated reactor systems or in engineered soil piles depending on throughput requirements, available footprint, and treatment time requirements. These systems are ideal for stockpiles of contaminated soils, sites where surficial soils are contaminated, or for waste oils and sludges. With waste oils and sludges, the STARx process includes the admixing of a porous matrix (e.g., coarse sand) to facilitate the self-sustained smouldering process. This is a necessary step to transform waste materials that will not burn on their own, to a mixture that will smoulder in a self-sustaining (i.e. low energy) process.

Applicability to contaminants and ground materials			
Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	?	Silt 2-60µm	?
Inorganic compounds, including acids, alkalis, salts, cyanides	N	Clay <2µm	?
Asbestos	N	Peat	N
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Further information:
C. Switzer, P. Pironi, J.I. Gerhard, G. Rein, and J.L. Torero. Volumetric scale-up of smouldering remediation of contaminated materials, Journal of Hazardous Materials 268,51-60, 2014. DOI: 10.1016/j.hazmat.2013.11.053.
Vendor website: http://savronsolutions.com

8.3 PlumeStop COLLOIDAL BIOMATRIX

PlumeStop

Technology description
PlumeStop is a patented *in situ* technology that works by rapidly removing dissolved organic contamination from groundwater and destroying it through accelerated biological degradation. As a result, contaminants in the groundwater can be reduced to non-detect within days or weeks.

PlumeStop is an injectable colloidal remediation technology composed of dispersive agents, 1 to 2 micron activated carbon sorbent and additives. The technical innovation allows for wide dispersion of a sorptive medium in the aqueous subsurface. The product has a dual function; it sorbs contaminants, quickly removing them from the mobile phase (‘PlumeStop’), and provides a high surface area matrix favourable for microbial colonisation and growth (‘Biomatrix’). Contaminant availability within a risk pathway is therefore reduced while at the same time contaminant destruction is accelerated. The product can be applied in combination with compatible controlled release electron donors/acceptors.

PlumeStop is effective on most organic groundwater contaminants including hydrocarbons, a wide variety of other VOCs and SVOCs.

Applicability to contaminants and ground materials			
Contaminant groups		**Ground Materials**	
Petroleum hydrocarbons, including BTEX; other VOCs	Y	Gravel >2mm	Y
PAH, phenolic compounds, other SVOCs	Y	Sand 0.06-2mm	Y
Metals/metalloids	N	Silt 2-60µm	Y
Inorganic compounds, including acids, alkalis, salts, cyanides	N	Clay <2µm	?
Asbestos	N	Peat	?
Key: Usually or potentially applicable – **Y**, May be applicable - **?**, Not applicable – **N**			

Vendor websites:
http://www.regenesis.co.uk/wp-content/files_mf/141015_reg_plumestop_broc_web.pdf
http://regenesis.com/products/plumestop-colloidal-biomatrix/

8.4 EXAMPLES OF RECENT TECHNOLOGY ADAPTATION

In Situ Geochemical Stabilization
In Situ Geochemical Stabilization (ISGS™) technology utilises a permanganate-based solution to geochemically stabilize dense non-aqueous phase liquids (DNAPL) in the aquifer.

Permanganate and other proprietary reagents are mixed into an aqueous solution that can be injected into an aquifer either through existing wells or direct push technology. As the solution migrates through the treatment area it oxidises contaminants yielding partial mass removal. The ISGS technology also reacts with contaminants in the treated area thereby coating NAPL surfaces with stable mineral precipitates that reduce mass flux.

A product sheet providing further information can be found at the following link:
http://www.peroxychem.com/media/104118/peroxychem-isgs-product-sheet-10-01-esd-14fnl.pdf

Anaerobic Biological Oxidation
Anaerobic bio-oxidation (ABOx) is a technology to treat groundwater contaminated with dissolved hydrocarbons in which non-oxygen electron acceptors are applied to metabolise. Sulphate-mediated ABOx can be an effective strategy for dissolved plumes at former gasworks sites. (Engineered Anaerobic Biooxidation at Two Manufactured Gas Plant Sites. R. Sillan, H. Stevens, and R. Ferree. ARCADIS U.S. – presented at the Ninth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterrey, 2014).

ARCADIS also has UK case studies which treated petroleum hydrocarbons using ABOx, although these were not on former gasworks sites. (Application of Engineered Anaerobic Bio-Oxidation for Groundwater Remediation – Pilot Trial. A. Waduge, C. MacLeod and Mark Webb. ARCADIS UK – presented at Remediation Technologies and their Integration in Water Management symposium, Barcelona, 2012)

Four Stage Gasholder Sludge Treatment
An innovative way of managing gasholder sludge from multiple sites as a cluster project has been developed by WWU, in collaboration with Eneotech Environmental Technology, using a four stage treatment process (caustic washing, centrifugal processing, biological treatment and chemical stabilisation) to enable sludge to be transformed into a material suitable for sustainable re-use through the DoW CoP (CL:AIRE, 2011).
http://events.igem.org.uk/download/20140916gasholders-39recording-the-end-of-an-era39/_/CC_024/88256376_Oliver_Lancaster.pdf/ (slides 38-45)

Capping Solution for Contaminated Sediments
Former gasworks sites are often located next to watercourses and hence may have severely contaminated river sediments. An engineered capping solution that can prevent DNAPL migration has been designed and is described in detail at the following link:
http://www.trcsolutions.com/NewsRoom/Articles/Documents/TRC-Brownfield-Solutions-Article-November-2013.pdf

9. CONCLUDING REMARKS

The objective of this research project was to produce a report on soil and groundwater remediation technologies for former gasworks and gasholder sites for the GDNs.

The report has described the key issues and contaminants that the GDNs are currently facing. It has identified five main types of contaminated sites that exist on the GDNs inventory as follows:

- General redundant sites:
- Operationally constrained sites, containing infrastructure and live services:
- Sites that have immediate borders with surface waters;
- Small, remote, low value sites; and
- Sites that have shared source structures/part-ownership.

The report has described the main soil and groundwater technologies that are currently available to treat the common contaminants associated with former gasworks and gasholder sites. It is possible to consider which of these technologies are likely to be appropriate on the five types of sites above, but the discussion comes with an important caveat and concentrates solely on the general technical suitability of the technologies to the sites identified by the GDNs. It assumes that a risk from contaminated soil or groundwater has been identified (in relevant pollutant linkage (source-pathway-receptor) terms) following an appropriate risk assessment. It is acknowledged that for an actual site, multiple site-specific factors will come into play which means that each site must be considered on a case-by-case basis.[1]

In situ techniques and civil engineering methods can typically be applied to soil and groundwater to treat the source of contamination, break the pathway, or protect the receptor, while the *ex situ* methods that have been described are only applicable to treat the source of contamination (either on or off site) in the soil following excavation.

- General redundant sites

In addition to contamination already present in the soil and groundwater, the contamination in the above and below ground structures (e.g. tanks and associated pipework) needs to be investigated and monitored to ascertain the level of contamination and these structures may need to be removed. Any of the *in situ*, *ex situ* or civil engineering methods could be used on these types of sites.

- Operationally constrained sites, containing infrastructure and live services

Assuming the whole site is operationally constrained there may be reluctance for safety reasons to break into the ground to excavate the soil using *ex situ* and civil engineering options, and for the same reasons *in situ* thermal techniques would not be considered near live gas plant. The use of other *in situ* technologies may be appropriate as they can be designed to allow operations to continue while they work. However, they all require some in-ground installation of boreholes for treatment or monitoring, or for the application of the technology itself.

In reality, there are likely to be areas on an operational site which are not impacted by infrastructure and live services, which may be amenable to *ex situ* technologies (including off-site treatment) and civil engineering methods. Similarly, it is possible to find a site which is large enough that *in situ* thermal techniques can be used safely, at a considerable distance away from the live plant, as long as appropriate risk mitigation measures are put in place.

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[1] Page 23 of Model Procedures for the Management of Land Contamination, CLR11 (Defra, Environment Agency, 2004) states "**Site-specific factors** All remediation options have advantages and limitations that make them more or less applicable in any particular case and a wide range of site-specific technical factors determine which remediation options are most appropriate. Some of these factors relate to the nature of the relevant pollutant linkages, such as the type, amount, lateral and vertical distribution of pollutants and affected media, and the properties of pathways. Others relate to the general characteristics of the site, such as its size, location, accessibility, topography and wider environmental setting, and the existence (or proposed construction) of buildings and other structures. The current or intended use of the site also needs to be taken into account to ensure that remediation does not compromise soil functions, including geotechnical properties. Other factors also affect the choice of the most appropriate option. These include the legal and commercial context within which the site is being handled; the views of key stakeholders (such as site owners, purchasers, funders, regulators and the local community), and the costs and benefits of using any particular option."

- Sites that have immediate borders with surface waters

If there is a risk of contamination impacting surface waters bordering the site, then once the contamination source is removed using *in situ, ex situ*, or civil engineering methods, technologies to mitigate the movement of contaminants towards the surface waters (or other receptors) will need to be deployed and these are likely to be *in situ* techniques. If there is a surface water receptor adjacent to the site then a PRB could be placed to treat groundwater before it reaches the receptor. These sites may also involve in-river works to excavate the bank and construct protection measures (see Ammanford case study in Table 6.1).

- Small, remote, low value sites

Excavation and off-site treatment at a STF can be an important option for those small and remote sites with no space to treat on site or with small volumes that mean many technologies are not financially viable. It could also be possible to follow the DoWCoP and establish a Cluster project if a number of sites could be brought together. Bringing smaller sites forward with larger ones as part of a Cluster could make them viable (CL:AIRE, 2013). If there is no financial driver or time pressure to remediate the site, MNA might be considered as an appropriate option.

- Sites that have shared source structures/part ownership

From a technology perspective, these sites can be managed as described for general redundant sites above. However, legal and commercial factors will need to be managed to account for the part-ownership issues. Temporary works may need to be considered to remediate part of a source in isolation from the remainder.

The report has focused on soil and groundwater remediation in the UK and internationally so that lessons can be learned from other jurisdictions on how they remediate their former gasworks and gasholder sites.

The regulatory framework of the UK has been described and includes recent changes in legislation and what potential legislative impacts and drivers may be further impacting the GDNs.

It was apparent from the information gathered in the report that there are contaminants that are difficult to treat using commercially available technologies – spent oxide and gas purification wastes, coal tar and water gas tar. The report also highlighted some new innovative technologies that have been developed that should be of interest to the GDNs.

10. REFERENCES

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APPENDIX A

Questionnaire template

Questions to International Centres of Excellence

CL:AIRE is producing a brief report entitled "Soil and groundwater remediation technologies for gas works and gasholder sites" on behalf of one of the UKs largest gas distribution network company. As part of this work we are reaching out to other countries that have historical gas works to understand how they have approached remediation of these types of sites.

Therefore we would like to know the following. If you do not know, are you able to signpost me to where I may be able to gather this information from?

1. Do you know how many former gas manufacturing sites are within your country?
2. Do you have any publically available published guidance on how you are required to address the potential for soil and groundwater contamination associated with gas works?
3. How are the gas works sites owned - publically, privately or a mixture?
4. What are the drivers to remediate the sites? E.g. development pressure, regulatory intervention
5. Is there a national programme within your country to remediate former gas works sites?
6. Are you aware of any written case studies of former gasworks remediation that is publically available?
7. What technologies are successfully used to remediate contaminants associated with gasworks sites in your country?
8. Are there any case studies where innovative techniques have been used?