FINAL REPORT

ORPHAN AND ABANDONED WELL RESEARCH NEEDS ASSESSMENT

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ABSTRACT

This report reviews and discusses potential research topics associated with the abandonment of oil and gas wells, referred to as orphan wells. Orphan wells are of interest and importance as there are hundreds of thousands of them across Canada, with the responsibility for these sites falling to each province or territory. Of particular relevance to CanmetENERGY Devon are issues surrounding the reclamation of well sites, and the contaminants that may enter the soil and ground water from the wells. This report focuses upon specific contaminants including hydrocarbons, salt, herbicides and sterilants, with a review of current research and information regarding remediation. The information in this report will be used to initiate new research proposals and activities at CanmetENERGY to better address risk assessment practices and the remediation of orphan well sites. The primary focus of the research needs identified relates to the understanding of soil and groundwater contamination and how to remediate contamination.

CONTENTS

TABLES

FIGURES

DEFINITIONS

In this report terminology consistent with the Alberta Government in reference to orphaned and abandoned wells was used (GOA 2017):

Abandoned well: A well that has been sealed with a bridge plug and cement, cut off below ground and capped with a vented cap. This definition applies regardless of the owner of the well. An abandoned well may or may not be orphaned (defined below).

Bridge plug: A metal plug used to seal a wellbore.

Inactive well: A well where no oil or gas has been produced for at least one year. Production may have stopped due to economic reasons, or if the reservoir has become depleted. The well may or may not return to production.

Orphan: A well or facility that does not have a private owner.

Reclamation: The process of returning a well site to having soil and vegetation conditions similar to those that existed before it was disturbed.

Remediation: The process of cleaning up contaminated water and soil. A site must be cleaned up until it meets relevant regulatory guidelines.

1.0 INTRODUCTION

Across Canada there are hundreds of thousands of oil and gas wells. Many of these wells are located in the Western Canada Sedimentary basin in Alberta, British Columbia, Saskatchewan, Manitoba, the Northwest Territories and the Yukon Territory; however there has been oil exploration in every province and territory at some time (CAPP 2018). These wells are drilled to depths ranging from several hundred meters to thousands of meters, depending on the purpose of the well and the target reservoir(s). Wells may produce natural gas, natural gas liquids, oil, water, or a combination of these fluids. Regardless of the depth of completion, when a well is no longer economically viable, and the operator decides to abandon the well, any equipment on the site must be removed, the borehole abandoned, the soil remediated and the site reclaimed (AER 2014; AER 2018c). The process of well abandonment is when a well is sealed with a bridge plug and cement to seal the wellbore, and the well casing is cut off below ground (GOA 2017). In Alberta, an inactive well is one that has not produced for up to 12 months. A well may become inactive if it becomes uneconomic, either because the resource has been depleted or because the value of the resource has dropped and it costs more to extract the product than it can be sold for. In Alberta, there are approximately 180,000 active wells, 83,000 inactive wells and 69,000 abandoned wells (GOA 2018). Site remediation involves the removal of contamination in soil and water that may exist at the well site and reclamation eventually returns the affected land to a productive landscape.

In 2014, the price of oil dropped significantly, and over the last four years there have been many oil and gas companies which have gone bankrupt. The wells that these companies owned are termed orphan wells, as they no longer have an owner. As of January 2019, there are 3127 orphan wells for abandonment in Alberta (OWA 2019). Whether abandoned wells are owned by a company or are orphaned, impacted sites must still be remediated and reclaimed. The cost of cleaning up these wells is high, with the liabilities in the billions to tens of billions of dollars (CBC 2019; FP 2017).

During the lifetime of a well there is the potential for a variety of impacts to surrounding soil and water. Drilling fluids may be released to the environment, and these drilling fluids may include saline water and hydrocarbons from the well. A spill may occur as a rapid release during an accident, or gradually over time. In the event that soil or groundwater becomes contaminated at a site, the site will need to be remediated to be compliant with provincial guidelines (AEP 2016a; AEP 2016b). Following the abandonment of the well, the site must be assessed for contamination. If there is contamination of the soil, the contamination will need to be remediated to comply with regulatory requirements. Common sources of contamination at orphaned well sites include salts, hydrocarbons, herbicides and sterilants. A variety of methods may be used to remediate these contaminants. One of the most common remediation methods is soil excavation and landfilling. While this method is quick and effective, it can be very costly, and means contaminated soil must be stored in an appropriate landfill elsewhere. There are a variety of other types of methods that can be used to remediate contaminated soils and ground waters, depending upon the contaminant type and situation, including: soil leaching and washing; *in situ* chemical oxidation; bioremediation; soil vapour extraction and thermal treatment. Once a well site has been remediated it may be reclaimed with vegetation.

The objective of this literature review was to assess the state of research related to the abandonment, characterization of contaminants, remediation and reclamation of oil and gas well sites. While this is a potential issue in many parts of Canada, this review focused most of its attention on Alberta.

It should be noted that the objectives of this report are focused on the engineering and scientific aspects of these issues and are not focused on the legislative aspects related to site ownership, responsibility and regulations. Furthermore, in writing this review limited published information related to specific challenges at well sites was found.

1.1. WELL SITE ACTIVITIES

During the life of a well there are numerous stages of activities (CAPP 2014). Prior to selection of a well site, there may have been seismic exploration to select a site. Once a site has been selected, well site activities include:

1. **Well site preparations**: This may include construction of access roads, site access, site excavation, construction of well pad, drilling of a pilot hole.
2. **Drilling and subsurface resource evaluation**: The well is drilled and various geological and geophysical methods are used to evaluate resource potential of the formation.
3. **Well completion and optimization**: In this stage the drilling rig is removed, and the production casing is inserted into the well and perforated at the depth of interest. At this

stage the formation may be stimulated using hydraulic fracturing to increase the permeability to allow the flow of hydrocarbons.

4. **Production and maintenance**: This is the main period of operation of a well, when oil or gas is produced.
5. **Site closure and reclamation**: When the well is no longer operational, the well must be abandoned, soils remediated and the site reclaimed.

Some of these activities have a greater potential to impact soil, water and biota than others, and during site preparation, vegetation may be removed and in some cases, a well pad may be constructed.

During the drilling, resource evaluation, completion and optimization phases, there is a great deal of activity at a well site. At a drill site there are a range of materials that could potentially be sources of contamination. One example is drill cuttings, which may become contaminated with fracturing-related chemical additives, or from the formations they interact with. Wells are commonly stimulated with hydraulic fracturing, where water with a variety of additives is injected down the borehole to induce fractures within the target formation (or reservoir), allowing for an increased production of oil and gas due to the greater induced permeability of the fractured geological material. Following fracturing, the induced pressure is decreased and injected water, formation water, solids and gases return from the formation as flow back. Over time water known as produced water returns to the formation. Flow back and produced water may contain elevated dissolved ion content, residual hydraulic fracturing chemicals, and a variety of natural and introduced organic compounds. If these liquids are spilled, they have the potential to impact soil and groundwater (Drollette et al. 2015; Funk et al. 2019).

During the production and maintenance phases, there is also the potential for spills of produced water and hydrocarbons. At some sites, herbicides and sterilants have been used to control vegetation during the period of active resource extraction, and there is the potential for these to remain in soils and sediments in the vicinity of the well or wellpad (AER 2018a). While there are a variety of methods that can be used to remediate contaminated soils, it is not uncommon for material to be excavated and taken away (Bernesky 2013). Once contaminated soil has been removed, the site needs to be reclaimed. The processes for identifying contamination are outlined in Section 4.

2.0 WELL ABANDONMENT

A well is considered to have been abandoned once the well has been permanently dismantled, with production zones plugged, and the well cut and capped approximately 2 m below the ground surface (GOA 2017). The objective is to permanently seal the well in order to prevent the migration of fluids between different zones in the subsurface and/or to the surface. The first step to sealing a borehole is to remove any downhole equipment (*e.g.* production tubing, downhole pumps, and packers (IEA 2018)). Once all of the equipment has been removed, the wellbore needs to be cleaned to remove scale and other debris. The well can then be plugged to prevent the migration of fluids and gases (Figure 1). It is common for a bridge plug to be placed in the well, which is cemented in place (AER 2019a). In Alberta the thickness of this plug is dependent upon depth, ranging from a minimum thickness of 30 m above 1500 m depth, to a minimum thickness of 60 m below 1500 m depth (AER 2018c). There are various different technologies used to plug a well, including the balanced plug method, cement squeeze method, bailer dump method and two plug method (IEA 2018). Once all zones have been plugged, the well is filled with fresh water to ensure long term integrity. Following this, the top of the well is cut off below ground, and a vented cap is installed.

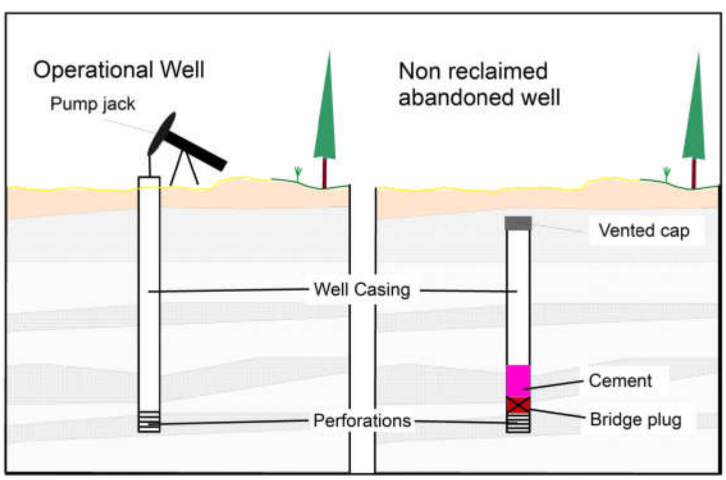

Figure 1 – Schematic diagram of the differences between an operational well and an abandoned well at a non-reclaimed site

If the abandonment process is not carried out successfully there is the potential for the oil or gas to migrate between reservoir formations, or even into groundwater. If during operation a well develops a serious leak (>300 m^3/day of gas) it must be fixed within 90 days, while smaller less-serious leaks must be addressed prior to abandonment (AER 2003). The definition of a serious leak is defined within ID 2003-01 (AER 2003). Following abandonment, remediation and reclamation, the site can be returned to its previous use. In some cases, houses have been built over the top of abandoned wells. If the abandonment was successful, there may never be a problem, however in some cases the well may begin to leak, which becomes a safety hazard (Wingrove 2010).

3.0 ASSESSMENT OF ABANDONED WELL SITES

A company must clean up any contamination that well site activities may have caused. To determine the reclamation requirements for abandoned oil and gas facilities, the site must go through multiple environmental impact assessment steps. These steps are Phase 1, Phase 2 and Phase 3; following Phase 3, the site may be reclaimed (AE 2001).

Phase 1: The first assessment step involves the collection of information on activities conducted at the site that may have resulted in contamination. It also includes a site visit to identify any visual evidence of potential contamination and possible sources of that contamination. Potential sources of contamination include flare pits, wellheads, drilling waste sumps, storage tanks, etc. Common contaminants include salts, metals, extractable hydrocarbons, polyaromatic hydrocarbons (PAH), benzene, toluene, ethylbenzene and xylene (BTEX), herbicides, methanol, glycol, etc. (AE 2001). The objective of the Phase 1 assessment is to screen the area and to determine if there is a need for a Phase 2 (*i.e.* more detailed) assessment.

Phase 2: The second phase of environmental assessment is determined based upon the outcome of the Phase 1. This phase may include soil and water sampling to establish the presence or absence of adverse environmental effects on soil and/or water (AE 2001). In Alberta, the results of the Phase 2 assessment are compared with Alberta Tier 1 Remediation Guidelines (AE 2001). In most cases Tier 1 guidelines are applicable. In some cases more site specific information is incorporated and Tier 2 guidelines are used, or an Exposure

Control approach may be used. Exposure control is when ongoing monitoring is conducted to monitor risks.

Phase 3: The third phase of an environmental assessment includes identifying how to remediate previously identified contamination, conducting a hazard assessment, conducting remediation and validating that remediation efforts were successful (AE 2001). Once Phase 3 is complete, a remediation certificate may be applied. Once the site is reclaimed, a Reclamation Certificate is applied. In Alberta, the Alberta Energy Regulator conducts audits of Reclamation Certificates. Since 2014, 133 audits have been conducted with a pass rate of 84% (AER 2019b).

4.0 CONTAMINANTS OF CONCERN

Based on the activities that may occur at a well site described in Section 1.1, there are a variety of contaminants that may be identified during the Phase 2 site assessment. As mentioned previously, these may include salts, hydrocarbons, metals and sterilants (AE 2001). The Alberta "*Phase 1 Environmental Site Assessment Guideline for Upstream Oil and Gas Sites*" lists common contaminants associated with different well site activities (Environment 2001). In this section we discuss possible remediation technologies associated with these contaminants. Many of these contaminants also occur at other contaminated sites, such as metals and hydrocarbons.

4.1. SALINIZATION

Salt contamination is possibly the most problematic form of contamination at abandoned well sites, and can pose a significant challenge to the remediation of abandoned well sites (Evans and Pollard 2019; Johnson 2019). Oil and gas are commonly produced from formations at depths of hundreds to thousands of metres below ground. At these depths formation water is generally saline, with high concentrations of dissolved ions (Connolly et al. 1990; Hitchon et al. 1995). Sodium and chloride are commonly elevated in these waters. If these waters are spilled, soils and ground waters may become contaminated with salts. It is worthwhile noting that the salinity of these spilled produced waters can be many times greater than that of ocean water. Excess salt in soil can have numerous environment impacts, including degradation of the physical properties of the soil, inhibited plant growth, and decreased groundwater quality (Greenberg et al. 2007; Hamid et al. 2007). Plants may be the most significantly impacted by increased salinity because it is more difficult for plants to uptake water and nutrients in the presence of high salinity (Qadir et al. 2003). The extra salinity also makes the regrowth of vegetation in the area difficult, resulting in bare soil and soil erosion.

There is potential for Na^{+} ion exchange with Ca^{2+} ions sorbed to soil particles. If this occurs, there is the potential that mobile Na^{+} ions will be decreased, and that soils will be degraded by the displacement of Ca^{2+} and Mg^{2+} from clays. The Cl^{-} ion is generally expected to be a conservative tracer. While Cl^{-} may enter water via weathering of NaCl, and to some degree atmospheric deposition, it is not consumed in biological or chemical reactions (Appelo and Postma 1999). Cl^{-} has a high solubility, meaning it is one of the last ions to precipitate out of solution (Prothero and Schwab 1996). Column experiments using radioactive tracers have shown that in general Cl^{-} is not retarded when the pH is greater than 6 (Appelo and Postma 1999). Some studies have suggested that Cl^{-} may behave non-conservatively in forested ecosystems (Svensson et al. 2012; Viers et al. 2001). (McCarter et al. 2018) investigated the potential for sorption of Cl^{-} in peat, with the results suggesting there may have been some minor sorption, but it was concluded to be insignificant compared to overall concentrations.

The Subsoil Salinity Tool is a computer model that can be used to determine Alberta Tier 2 soil remediation guidelines for salts, including chlorides, below the root zone (ESRD 2014). If chloride behaves non-conservatively, this model may be overly cautious, meaning soil may be remediated when it does not pose an environmental risk. This may result in different environmental impacts from remediating the soil.

4.2. HYDROCARBONS

There are a wide range of hydrocarbon contaminants which may be present at an abandoned oil and gas well site resulting from resource development and/or unintentional spillage or leakage. These include: alcohols (methanol, glycol), extractable hydrocarbons, polyaromatic hydrocarbons (PAH), benzene, toluene, ethylbenzene, xylene (BTEX) and purgeable hydrocarbons.

Alcohols are organic compounds containing one of more –OH groups. They may be used as drilling additives to act as a product stabilizer or winterizing agent (FracFocus 2016). Some organic molecules with alcohol groups can act as surfactants, which can increase the solubility of other organics in water. Some alcohols themselves are contaminants, the simplest of which is methanol (AEP 2016). Alcohols in general may also be important, as they have the potential to affect how other contaminants are transported (Bouchard 1998; Rao et al. 1991).

Purgeable and extractable hydrocarbons are distinguished only by their molecular weight and carbon number, and are so named by the techniques used to analyse them in environmental matrices such as soil (USDHHS 1999). Purgeable hydrocarbons correspond to C_6 to C_{10-12}, and extractable hydrocarbons generally fall under C_{8-12} to C_{24-26} and higher. A common division of hydrocarbons for analysis is into four fractions: F1-F4, where F1 contains C_6-C_{10}, F2 contains C_{10} to C_{16}, F3 contains C_{16} to C_{34} and F4 contains C_{35+} hydrocarbons. Purgeable hydrocarbons are analyzed by purge-and-trap gas chromatography, while extractable hydrocarbons are extracted and concentrated from samples using solvents. PAHs describe hydrocarbons with two or more aromatic rings, and could fall within these categories, depending on their carbon number. Risks at well sites from these types of hydrocarbons are deleterious effects on local plant and animal life, as well as potential human health hazards (Abdel-Shafy and Mansour 2016; API 2001; Polycyclic Aromatic Hydrocarbons (PAHs); What Health Effects Are Associated With PAH Exposure? 2013). Additionally, it is worth noting that metals can be present in trace amounts in hydrocarbon mixtures, with persistent environmental effects and, in some cases, poorly understood mobility (Dong et al. 2013; El-Tokhi and Mostafa 2001; Mulligan et al. 1999).

BTEX is the group name for a special class of hydrocarbons that is distinguished because of these hydrocarbons high solubility, and toxicity to both humans and animal life. They are polar, volatile, and can easily travel in groundwater (Mitra and Roy 2011; Yang et al. 2017). BTEX is also a common air pollutant which may be used as an indicator of air quality.

One of the impacts of hydrocarbon contamination of soils is the development of hydrophobic soils (Roy et al. 1999). Hydrocarbons may coat soil grains, making them repel water, meaning the soil cannot retain water needed for vegetation growth. Hydrophobic soils can be a problem at abandoned well sites (Polet 2007).

4.3. DRILLING WASTE

During drilling, drilling waste, which is a mix of cuttings, drilling mud, formation fluids and drilling additives, is produced (AER 2016). Depending on the composition of the drilling mud, it may be disposed of by different means. The waste itself can also be highly variable, adding an extra layer of complexity to proper remediation. In some cases waste can be land sprayed, or disposed in forested land, while other waste may need to be treated or disposed of down a borehole or in a landfill. During environmental assessments of the well sites for closure compliance, there is a review of how drilling waste has been disposed. Drilling waste can be a source of contamination on abandoned sites, and specific concerns include potassium chloride muds and inverts (oil-based drilling mud).

Drilling waste is sometimes placed in a pit or sump. Modern regulations restrict the use of sumps to nonhydrocarbon-based drilling waste, in clayey soils (Halla 2007). Modern regulations require that material placed in sumps should be characterized for parameters such as pH, total petroleum hydrocarbons, BTEX etc. (GOA 2012). In the past, flare pits were used to store and burn disposed-of oil field wastes and petroleum hydrocarbon (PHC) (Cheng et al. 2004). In Alberta, flare pits were banned in 1996 due to the potential to impact the environment. There are many sumps in Canada, however, and it is unclear how much of a problem historical and/or poorly managed sumps represent.

4.4. HERBICIDES AND STERILANTS

A variety of herbicides and soil sterilants are used at well sites. These are used to stop the growth of noxious weeds, and keep vegetation down to minimize risks from wildfire (WCES 2019). With repeated use, there is the potential for well sites to become contaminated with herbicides and sterilants used at the site, for example: dicamba, atrazine, bromacil, diuron, linuron, simazine and tebuthiuron (AE 2001; Rakewich and Bakker 2017). InnoTech Alberta has been investigating research needs related to remediating and reclaiming soils contaminated with sterilant residues (InnoTech Alberta 2018).

5.0 REMEDIATION METHODS

There are many different remediation methods that can be applied to the clean-up of contamination at abandoned well sites; however there is limited literature describing case studies at abandoned wells. The appropriate remediation method is dependent on the type and quantity of the contaminant(s), site characteristics (*e.g.* geology, hydrology, hydrogeology, and hydrogeochemistry), local receptors and where the contaminant is in soil and/or groundwater. A remediation method may work given one scenario, but not for another. Contamination can also be caused by dumping of additional wastes at the site including substances such as fatty acid ethoxylates, fatty acid amines, used lubricants/hydraulic fluids, fuel, uncured concrete, and metal scrap. Remediation can be complicated by a lack of distinct marking at sites, which makes finding them difficult. In this section we describe some methods that may be useful to remediating contaminated groundwater and soils.

Remediation methods for both soil and groundwater may be separated into two broad categories, *in situ* or *ex situ*. *In situ* treatment occurs at the site in the ground, whereas for *ex situ* treatment soil or water is excavated or pumped to be treated. *Ex situ* methods include excavation and disposal, or treatment, such as leaching and washing (FRTR 2007). *Ex situ* treatments result in greater certainty and uniformity for the effectiveness of treatment, but generally involve managing a large amount of material and some challenges with keeping the contamination contained.

As the name would suggest, *in situ* treatments are conducted in place. The advantage of *in situ* treatment is that ground or soil is treated without excavation of material, resulting in cost savings (FRTR 2007). The drawback of *in situ* methods is that they commonly take longer, and that there may be variability in the effectiveness. *In situ* methods may take advantage of natural degradation processes in soil or water, resulting in a decrease in concentration of a contaminant (Brandy and Well 2008). Organic contaminants may also leave the system by volatilization from the soil to the atmosphere. Contaminants may become unavailable if they are adsorbed by clays, oxides, and organic matter, or alternatively they may be chemically broken down or biodegraded. Physical treatment of soils includes techniques such as soil vapour extraction, multiphase extraction and thermal desorption (Jierui 2018). Chemically treating soil can involve the use of oxidants. Oxidants are used to react with contaminants in soil to create more benign compounds with less environmental impact. The desired end products of such a treatment are water and carbon dioxide (Jierui 2018).

The US Federal Remediation Technology Roundtable provides a remediation technologies screening matrix to help select a remediation technology (FRTR 2007). Some of these remediation methods are discussed further below. There are many methods, and this review cannot cover all possible methods. Selecting a remediation method requires balancing the chemical impact of contamination with the possible environmental issues caused by physically or chemically disturbing the ground.

5.1. SOIL EXCAVATION

A common site remediation method is soil excavation, commonly also known as "*dig and dump*" (EEBR 2019). Contaminated soil is excavated from a site and transported away. This technique is relatively quick and removes the contaminant from the site, meaning compliance with regulations can be achieved. While this method is effective, it means the contaminated material must be transported and stored in an appropriate facility (COMCO 2019). The contaminant remains, but the material has been moved and disposed of in an appropriate landfill. This method of remediation also requires the transport of large volumes of contaminated soil, and fresh, non-contaminated material must be transported to the site. This may mean many truckloads of soil are transported with the potential for other environmental and social impacts, including fuel consumption and CO_2 emissions. Because of the drawbacks of the dig and dump soil treatment, it is desirable to increase the use of alternative remediation methods, especially in environments that are difficult to reclaim, such as grasslands or peat bogs (Johnson 2019).

5.2. SOIL LEACHING AND WASHING

Soil leaching and washing is a common treatment for oil and gas sites (Jierui 2018). Soil washing either concentrates contamination into a smaller volume by grain size separation, or dissolves the contaminant into the water solution (FRTR 2007). For example, washing is often conducted by washing the soil with calcium and magnesium (*e.g.* calcium may be added as gypsum) (Jierui 2018). This results in ion exchange of sodium and calcium/magnesium to help remove the excess ions from the soil.

5.3. *IN SITU* CHEMICAL OXIDATION

In situ chemical oxidation can be used to treat soil and groundwater. The method involves using an oxidant such as permanganate, persulfate, peroxide or ozone to oxidize organic contaminants (ITARC 2005). The method may be applied to a variety of contaminants, including some expected at abandoned well sites including: benzene, toluene, ethylbenzene, and xylenes (BTEX); total petroleum hydrocarbons (TPH); polyaromatic hydrocarbons (PAHs); and organic pesticides (insecticides and herbicides). One case study tested *in situ* chemical oxidation at a former oil and gas compressor station where groundwater was contaminated with bromacil and dicamba herbicides, as well as residual petroleum hydrocarbons (Rakewich and Bakker 2017). The method appeared to be successful at removing residual petroleum hydrocarbons, but did not remove bromacil; some decrease in dicamba was observed.

5.4. BIOREMEDIATION

Biological remediation, or bioremediation, makes use of microorganisms and plants to consume or transform contaminants into other chemicals (Brandy and Well 2008). In some cases, the bacteria that are native to the soil or water degrade a contaminant; in other cases a different bacteria which has been identified to consume the contaminant is added. For example, a certain strain of bacteria has been found to consume perchloroethene and can be added to water to induce biodegradation, although the vinyl chloride by-products is also a known human carcinogen (ATSADR 2011; Ellis and Anderson 1997). Alternatively, amendments, such as fertilizer, can be added to increase the rates of biodegradation. Another form of bioremediation is phytoremediation, where plants and associated fungal and bacterial communities are used to either break down contaminants, or bioaccumulate them. At the time of writing, bioremediation in the form of soil excavation and aeration to increase biodegradation is a remediation method reported to be used by environmental consultants (Luther 2019). However, at abandoned well sites, high salt concentrations are common, which may limit the effectiveness of biodegradation (Jierui 2018).

5.5. SOIL VAPOUR EXTRACTION AND THERMAL TREATMENT

Soil vapour extraction is a method for *in situ* extraction of volatile contaminants. A vacuum is applied to the soil to increase volatilization of volatile organic compounds; this method does not remove non-volatile compounds (FRTR 2007). Another *in situ* method is thermal treatment, which can be used to increase volatilization and breakdown of contaminants. Thermal desorption has been used to treat soil contaminated with the herbicide Tebuthiuron (Lin 2009).

5.6. MONITORED NATURAL ATTENUATION

Monitored natural attenuation is not actually a remediation technology, but a method to monitor a site while concentrations decrease by natural processes. The concentrations and extent of contaminants are measured over time, based on the hypothesis that the concentrations will decrease without artificial intervention. In some cases natural attenuation is sufficient to contain contamination (Chiu et al. 2013), however in other cases natural attenuation is occurring at a site, but is not sufficient to bring concentrations down to guideline levels (Choi and Lee 2011).

6.0 RECLAMATION AND CLOSURE

Following remediation, a site must be reclaimed. Reclamation involves replacing soil on the site, restoring the drainage and revegetating. Once the site has been reclaimed, the soil has to have the correct properties and be of sufficient quantity; vegetation also needs to be of the appropriate quantity and quality (AER 2019c). Problems during reclamation may include having trouble getting the desired species of plants to grow, weeds, and in some cases hydrophobic soils (Polet 2007).

The Alberta Energy Regulator has been encouraging ‘area based closure’, where multiple operators may work together towards closure of an entire area (AER 2018b). This may result in cost savings of up to 40% for the operators. Savings are realized by having similar work being done at multiple sites at the same time.

7.0 RESEARCH NEEDS IDENTIFIED BY OTHER ORGANISATIONS

In this report we have focused on well site practices and their potential for contamination and remediation methods for some contaminants. Many of the challenges associated with the abandonment, remediation and reclamation of abandoned well sites are related to legislation/regulation and logistics. For example, a site located in a remote area may be difficult and therefore costly to access.

Other organizations have also identified areas for improvement in the abandonment, remediation and reclamation regulatory process as well as greater technical understanding. In 2018, InnoTech Alberta hosted a workshop titled “*Harnessing the Innovation System to Support Efficient Upstream Oil and Gas Wellsite Assessment, Remediation and Reclamation*” which focused on identifying ways of improving well abandonment, reclamation and remediation (Levy et al. 2018). Many of the challenges identified in this workshop related to legislative challenges and practical logistical challenges.

The workshop summary is publically available; here we summarize some of the challenges identified (Levy et al. 2018). During the abandonment, remediation and reclamation process there are multiple stakeholders which may include, amongst others, the well owner, land owner, contractors, and the province. Doing the work to reclaim a site can be very expensive, and significant savings can be achieved through doing multiple sites at one time (area based closure), as highlighted above; however it is sometimes for companies to collaborate. Furthermore, there can be tight time windows with report due dates to meet regulations as well as limitations in when sites can be accessed due to seasonal considerations. Other challenges relate to companies choosing the lowest bidder for Phase 1 and 2 assessments and some information being missed. Furthermore historical information on sites may be missing, especially in cases where the site has changed owners throughout its lifetime. Additionally, some companies may sell older wells to other companies who are less inclined to undertake abandonment, remediation and reclamation, and alternatives to soil excavation are often not seen as cost-effective. At the reclamation stage legislative challenges relate to repeat justifications for non-routine treatments.

In some cases addressing these challenges requires new technical information or technology, however many could be addressed by modified regulations and guidelines and through increased collaboration.

The Petroleum Technology Alliance Canada (PTAC) has identified a range of areas for increased technical knowledge (PTAC, 2019). The gaps identified by PTAC relate to topics the organization sees as important and may potentially fund. These gaps relate to three topic areas: regulatory guidelines/ directives/ policies/ criteria; risk assessment; and reclamation and remediation technology advancement. Many of the research needs identified by PTAC relate to the knowledge needed for development of risk based guidelines, including information on background concentrations of contaminants and their bioavailability. PTAC also identifies improved remediation methods as a research need. The research needs identified by PTAC are summarized in Table 1.

Table 1 – Summary of some of the research needs identified by PTAC (modified from (PTAC 2019))

Regulatory Guidelines/Directives/Policies/Criteria

- Organics
    - Understand appropriate protection of various exposure pathways
    - Fate and transport assessment methods.
    - Clarity on Alberta Guideline assumptions
- Inorganics
    - Background metals and salts in soils database.
    - Fate and transport mechanisms.
    - Risk based remediation guidelines for some metals.
- Other
    - Understand Phase I ESA calculations for drilling waste.
    - Outcome-based reclamation criteria.

Risk Assessment

- Improved understanding of bioavailability of contaminants to allow determination of risk based remediation endpoints.
- Field screening methods to allow for more rapid site investigations.
- Tools (*e.g*. software and models) to calculate site specific Tier 2 remediation guidelines.

Reclamation and remediation technology advancement

- Improved methods for assessing risk and remediating petroleum hydrocarbons in fractured bedrock.
- Remediation methods for petroleum hydrocarbons, salts, and metals in wetlands.
- Groundwater remediation methods (*in situ* and *ex situ*) for petroleum hydrocarbons and salts.
- Technologies for longer term remediation time frames.

8.0 SUMMARY AND RECOMMENDATIONS

Salts, hydrocarbons and herbicides are common contaminants at abandoned wells sites. These contaminants are not unique to oil and gas sites. Soils and groundwater may become contaminated with salts from soil salinization over time (RECARE 2018), road salt, and salt water intrusion (GC 2017). Hydrocarbon contamination may occur from leaky storage tanks at homes and gas stations, or spills during transport (Freeze and Cherry 1979). Herbicide contamination may also be associated with agriculture.

While many of the contaminants at abandoned well sites are similar to what is found at other contaminated sites, there are some differences. The prevalence of salt contamination at abandoned wells may reduce the remediation options. For example, bioremediation may remove hydrocarbons at a site, but it will not remove salts. Another challenge is that abandoned wells may be remotely located, meaning all materials and equipment have to be transported to the site. Some sites can only be reached during winter when the ground is frozen. Furthermore, trucking material from a site can become very costly.

Below we summarize the research needs we have identified. This is not intended to be a comprehensive list, but rather a high-level summary of potential topic areas for further in-depth investigation. Any further studies will have to combine geology, chemistry and engineering to create a multi-disciplinary and multi-faceted approach that has a holistic understanding of the research problem and ways to solve it.

Salt: Salt contamination of soil is potentially the biggest issue at abandoned well sites. While salt contamination sounds like a simple issue, there are many challenges to be addressed to improve the understanding of contamination in the subsurface and alternative remediation methods. Some topics include:

- What are the pore water concentrations of salt vs. what is leachable by natural processes?
- Better tools to predict how salt will move in the subsurface.
- Better methods to remediate soils contaminated with salts, and identify which methods are most effective for different types of salt.

Hydrocarbons: Many abandoned oil and gas well sites are contaminated with hydrocarbons. Soil remediation guidelines are based on soils that are coarse or fine grained (AE 2001). While grain size provides a good initial indicator, other properties, such as mineralogy, have a significant impact on the leachability of hydrocarbons due to the sorption of hydrocarbons on different soil particles. Tests to demonstrate the differences in leachability of hydrocarbons in different soils may be used to inform guidelines focused on risk rather than simply concentration. It may also be informative to examine persistence and leachability of hydrocarbons based on their size, structure and source, in order to better assess remediation that is needed.

Sterilants: The sterilant Bromacil is used to control vegetation at well sites. While it may degrade in soil (EXTOXNET 1993), in some studies it has been found to be persistent in soils and water (Hebb and Wheeler 1978; Rakewich and Bakker 2017). Improved methods for remediating soil and water affected by bromacil and other steriliants (Drozdowski 2018) would be beneficial. Exploring alternatives for vegetation control that do not involve sterilants is another possible area of research.

Remediation: Sites are commonly remediated by soil excavation. This method is costly and impacts the environment at the site because of the large amount of material transported to and from the site. Soil fill has to come from another site, so soil conservation is also of concern. It is desirable to identify environmentally-friendly alternative methods for remediation at contaminated oil and gas well sites.

Sumps: There are many sumps with drilling waste in Canada, from oil and gas drilling. There is uncertainty surrounding how much of a problem sumps represent. Further research is needed to better understand challenges related to sumps. Some questions that exist are: What is needed to characterize sumps? Are there characteristics that determine if a sump will be problematic or not?

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