

Evaluation and Remediation of Potential Environmental Contaminants in Alberta Oil and Gas Well Sites

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Abstract

When the first oil well was drilled in Alberta in 1914, it shaped Alberta's future in the global economy. As it developed into the world's third largest oil reservoir and with booming oil and gas industries, Alberta became the heart to Canadian Energy. It is estimated that there are around 450,000 oil and gas wells that have been drilled throughout the province since 1963. However, some oil and gas well sites were with minimum or without regular management resulting in the high potential of local soil and water contamination by hazardous materials in the well sites. These contaminants include soil sterilant herbicides, heavy metals, salts, petroleum hydrocarbons, and drilling fluids that are generated from oil and gas development and drilling activities. These contaminants present in soils and groundwater are potential health threats to the wild and human lives.

Several soil and groundwater remediation technologies have been studied for decades. Physical remediation technologies, such as soil vapor extraction, dual phase extraction, and electro-kinetic technologies; chemical remediation technologies, like insitu chemical oxidation, soil washing; as well as bioremediation and phytoremediation have been applied in real life scenarios. Each of them has the ability and capacity to degrade or stabilize single or multiple contaminants that are present in oil and gas well sites across Alberta.

Understanding the soil and site contaminant characteristics, considering the social economic factors, as well as implementing cost effective, environmentally friendly remediation technologies, are the key to achieving successful remediation.

Acknowledgement

I would like to greatly thank and acknowledge my supervisor, Dr. Les Lavkulich at the University of British Columbia for his strong support and valuable suggestion not only throughout the Master of Land and Water Systems program, but also with the final project. Thank you for giving me the opportunity to pursue this project, for all your encouragement that always inspired me further to do better. I would also like to thank Dr. Hans Schreier and Dr. Sandra Brown for being on the supervisory committee for this project and the final presentation.

I would like to thank the guidance and teaching from Dr. Tariq Siddique at the University of Alberta. The knowledge that you shared opened the door for me to see the world of soil science. This strong academic knowledge eventually helped me to develop my passion for soil and the groundwater remediation fields.

Next, I would like to thank Senior Soil Scientist Dr. Leonard Leskiw from Paragon Soil and Environmental Consulting Inc, and Dr. Anne Naeth from the University of Alberta for their valuable advice and assistance.

Finally, I would like to thank Mr. Bike and Mrs. Menggentuya, and Mr. Iftekhhar Rahid for their love and support.

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1. Introduction

1.1 Oil and Gas Industries in Alberta

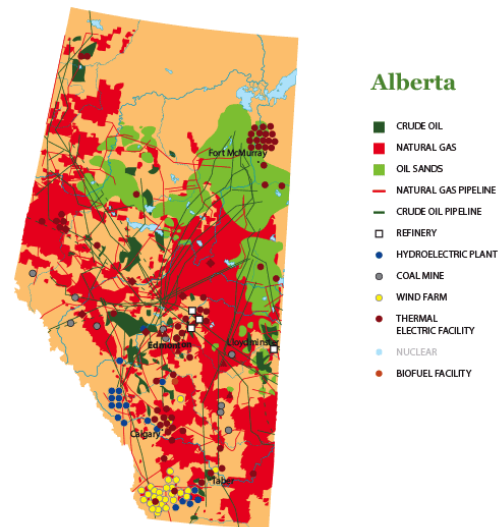
Alberta is a western Canadian province (Figure 1) enriched with a diverse resources portfolio including natural gas, coal, mineral, and the most famous, Alberta oil. Over one hundred years ago, on 1914, May 14th, the first Alberta oil well was drilled, which turned Alberta's fortunes (Hussain, 2014). This meaningful extraction well, not only led to the exploration of fossil fuels beneath the ground, but also opened the potential of the land in providing bulk oil productions and other economic benefits in the future. According to the geological surveys in 2012 (OPEC), Alberta is the third largest oil reservoir in the world following Venezuela and Saudi Arabia. The total oil reserved in Alberta is around 170 billion barrels (BBL), (Figure 3).

Figure 1. Map of Alberta, Canada



Source: Government of Canada

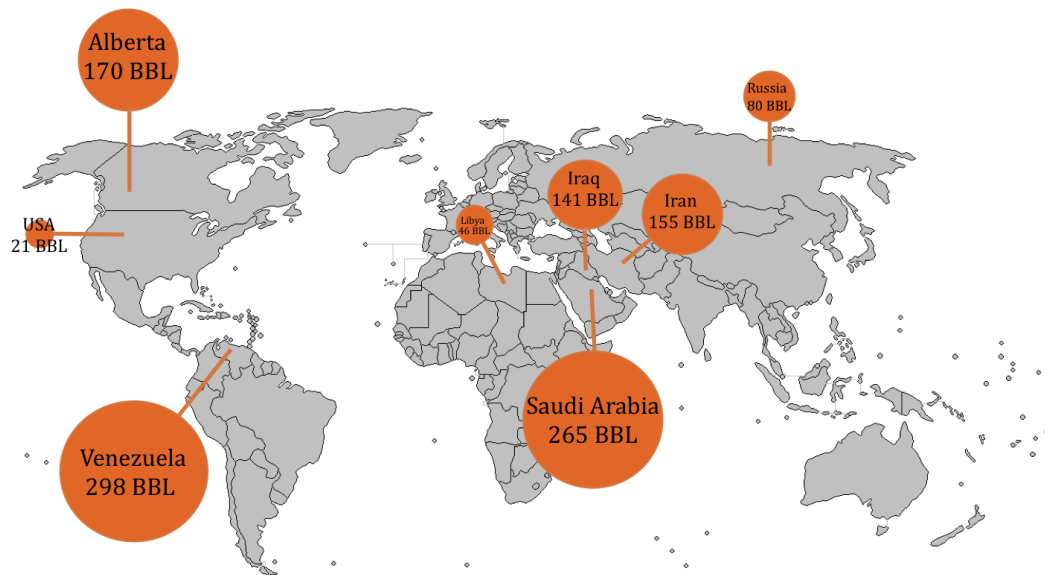
Figure 2. Alberta Natural Resources Distribution



Source: Richard Matthews

With thousands of oil wells drilled and billions of barrels of oil extracted, Alberta sits at the heart of Canadian energy. The energy industry provides tremendous opportunities for companies to involve in the extraction and processing of Alberta's energy resources (Government of Alberta, 2018). Production and export of local oil and gas have become the most critical economic profit to the province.

Figure 3. World Oil Reserves.

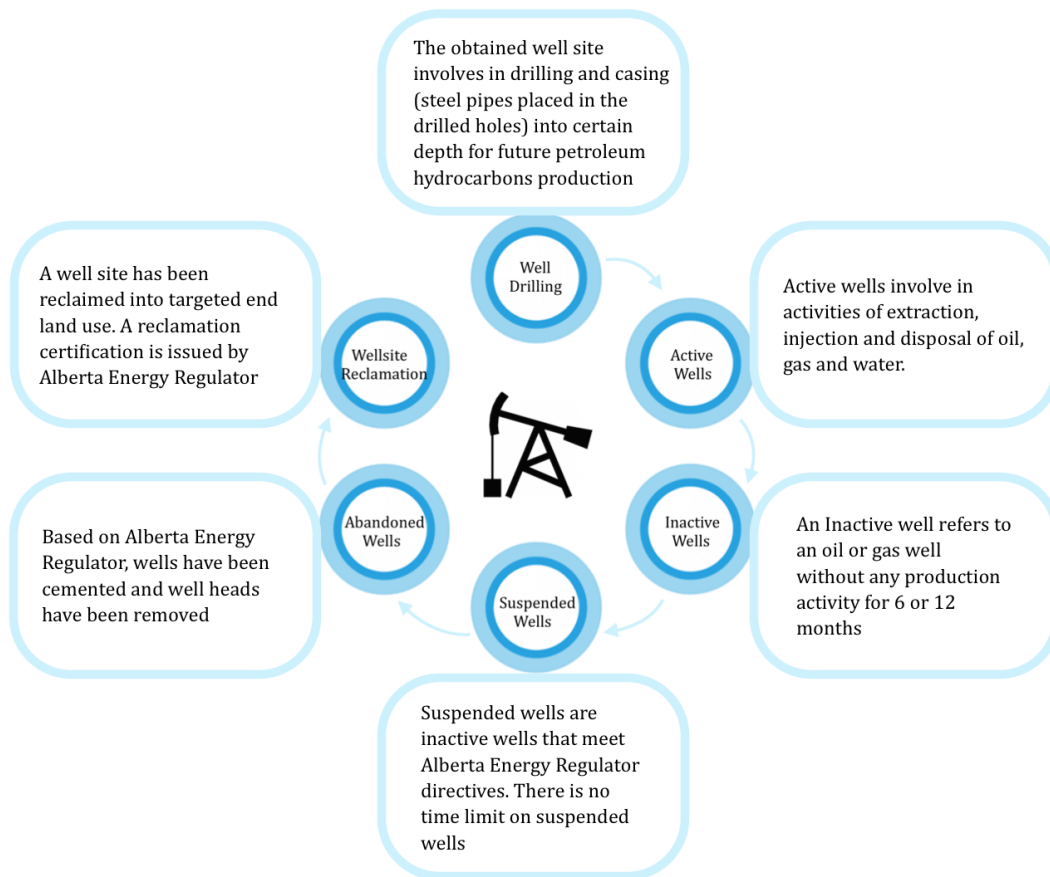


The potential wealth of Alberta's resources provided strong economic incentives to the oil and gas industries, which are constantly exploring for and extracting oil and gas through various industrial activities (Figure 2). The famous of explorations is Albertan Oil Sands, located in northern Alberta, which underlie a total of 142,200 km² of lands in Peace River, Athabasca, and Cold Lake regions (Alberta Energy, 2018). Since 1963, there have been more than 440,000 oil and gas wells drilled throughout the province (Alberta Energy Regulator 2018). By 2017, there was 442,000 km of pipelines operating solo within the boundaries of Alberta (Alberta Energy Regulator, 2017). There are also extended pipelines across provinces and even nations to distribute Alberta crude oil and natural gas to resources demanding areas within and beyond the boundaries of Canada.

1.2 Alberta Oil and Gas Wells

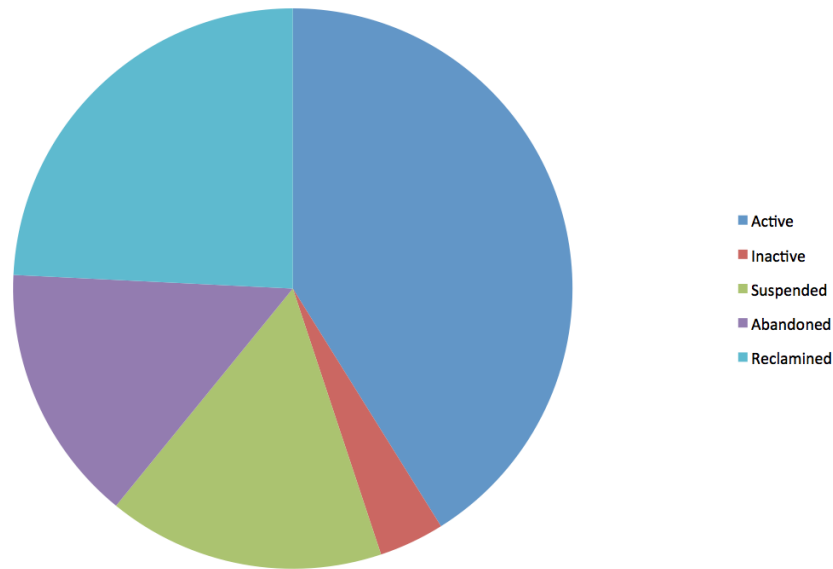
The regular life cycle of Alberta's oil and gas wells involves a series of development stages. It starts with well drilling on a suitable field with reserved petroleum. Once the well is completely drilled to the licensed depth, the well becomes active in producing petroleum hydrocarbon products. The productivities of a well decrease over time, until it reaches its inactive stage. However, it may take decades to reach the stage in which the Alberta Energy Regulator considers the well as an inactive well. The inactive well undergoes various precautionary measures and then transforms into a suspended stage, where there is no time limit for well suspension. The suspended well, without any production value, is then recognized as an abandoned well. (Dachis & Shaffer et, 2017) (Figure 4).

Figure 4. Life Cycle of Oil and Gas Wells in Alberta



Since 1963, approximately 450,000 oil wells have been drilled throughout Alberta. These wells are at variable stages of their life cycle (Government of Alberta, 2018). By May 2017, there were around 185,000 (41%) active wells, 17,000 (4%) inactive wells, 72,000 (16%) suspended wells, 67,000 (15%) abandoned wells and around 109,000 (25%) reclaimed wells (Dachis & Shaffer et al, 2017) in Alberta (Figure 5). However, some oil wells end up to become orphan wells; oil wells which have no legally responsible or financially able party to deal with their proper abandonment and the reclamation of their site” (Dachis & Shaffer et al, 2017), at any time of a well life cycle under the influence of external legal and socio-economic factors.

Figure 5. Distribution of Oil and Gas Wells at Their Variable Life Stages



1.3 Emerging Issues

Lack of laws and regulations, as well as some negative industrial behavior and responses, have led to a complex situation in Alberta oil and gas industries. Eventually, these complexities have imposed difficulties to reclaim these contaminated active, inactive, suspended and abandoned oil and gas well sites in Alberta.

In the past, the lack of established rules and regulations of the Alberta Government failed to provide detailed and specific steps and timelines for the development and reclamation of well sites. Basically, the drilling of oil and gas wells and subsequent abandonment of these well sites without reclamation practices were not controlled by laws and regulations. This changed in the 1970's, when federal and provincial governments started introducing legislation such as the Oil and Gas Conservation Act, Alberta Land Conservation Act, The Land Surface Conservation and Reclamation Act, Indian Oil and Gas Act (Schmidt, 1975). These Acts provide detailed benchmarks, restrictions, and guidelines for oil extraction and reclamation activities.

From an industrial perspective, cleaning up contaminated well sites is not a priority of Alberta oil and gas industries. To oil and gas companies, remediation and reclamation processes do not generate any economic benefits; rather, remediation and reclamation deduct a portion of generated economic profits.

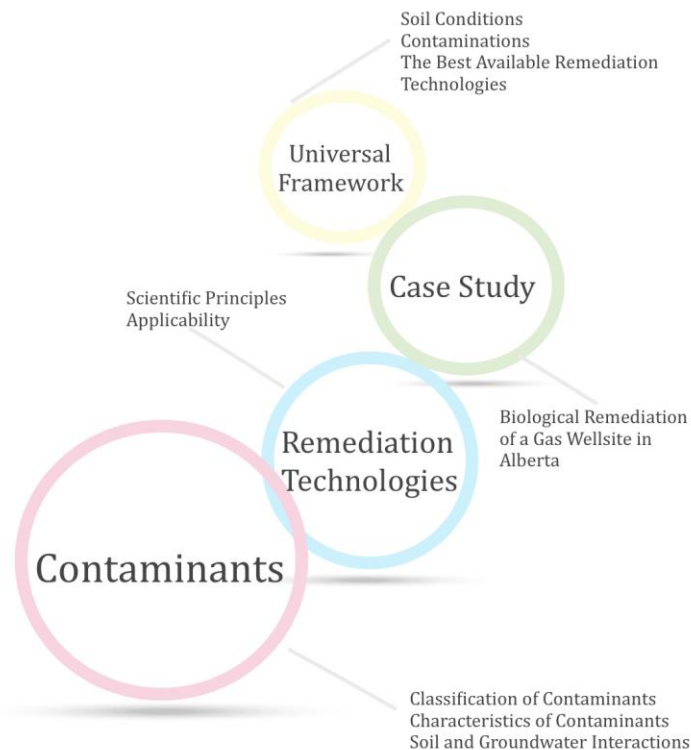
The oil and gas activities led Alberta's economy to reach its peak in 2012. However, Alberta experienced a dramatic economic downturn in 2015 (Mueller, 2016), which failed in balancing the supply and demand of the oil and gas in the market. As a result, small companies went bankrupt. They did not have the financial resources to operate, or even reclaim oil extraction wells.

1.4 The victims

These oil and gas wells in Alberta have potential to threaten the health of the local land, water, wildlife, and human population. Once the well site management fails to regulate well developments and petroleum hydrocarbon extraction activities, soil and groundwater have the potential to be polluted by the well site contaminants including sterilant herbicides residue, drilling mud and drilling additives, heavy metals and salt, as well as toxic petroleum hydrocarbons. Eventually, these contaminated lands and water fail in their ecological functions in terms of providing a healthy ecosystem, and secure drinking and irrigation water sources.

2. Objectives

Figure 6. Project Objectives



The first objective of this study was to classify the potential environmental hazards that exist at Alberta oil and gas well sites. Then present and evaluate the interaction of hazardous materials with soil and groundwater.

The next objective is to describe the situation in detail by presenting and explaining the best currently available technologies applied in remediation projects, in terms of degrading and transforming well site contaminants, into stable and environmental non-hazardous chemicals.

Evaluating a real world example of oil and gas well site remediation in Alberta is the next focus. This study includes a detailed evaluation of site contaminants and the applied targeted remediation technologies.

With all the available information, the major purpose of this paper is to develop a universal framework to inform audiences of the best available remediation technologies based on the identification of specific well site contaminants, and the soil and groundwater conditions. This framework will benefit the public, environmentalists, and government policymakers in helping them to gain a better understanding of oil and other petroleum extraction well sites.

3. Methods

The primary evaluation was made through literature reviews. Literature reviews provided scientific information of the variable contaminants generated during oil and gas exploration and extraction activities. The detailed scientific principles of current remediation technologies in degradation and transformation well site contaminants was also synthesized from scientific literature.

Personal dialogues with environmental consulting experts, university professors, stakeholders, and public communities were conducted to acquire additional information about real world scenarios of well site remediation across Alberta. This evaluation provides additional expectations from field experiences, to support scientific information.

4. Results

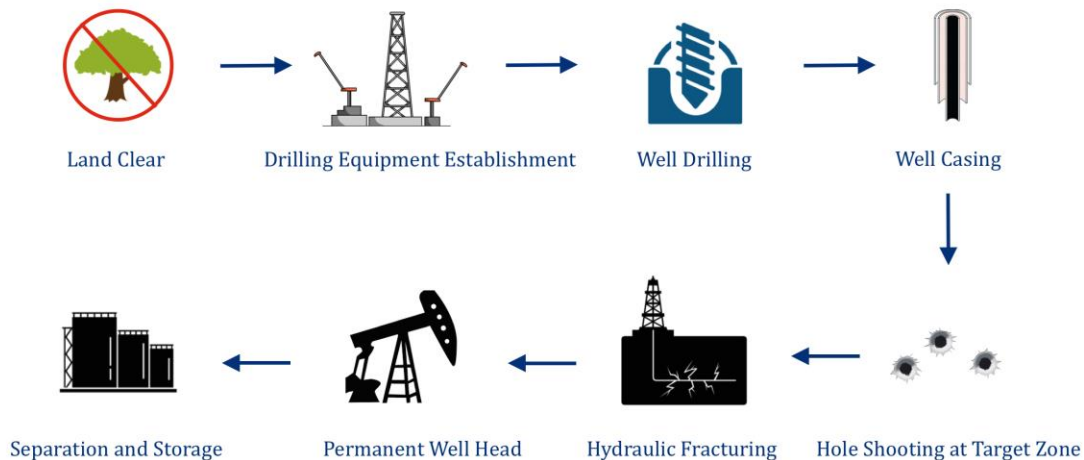
4.1 Potential Environmental Hazardous Assessments

4.1.1 Oil Well Drilling and Operation Processes

The potential environmental hazards that exist in the Alberta oil and gas well sites are directly related to well drilling and production processes, where these processes either utilize or generate toxic chemicals on site. In order to explore the pollutants associated with oil well sites, identifying the origins of these chemicals associated with oil drilling processes is necessary.

Oil well drilling processes involve multiple stages of complicated and rigorous works. The process starts with the planning phase, which focuses on the location of wells, research on the potential reserves, environmental assessments, and cost projections. Once the underlying geological materials and reserves are identified, the optimal location to drill wells is determined (Aresco LP, 2018).

Figure 7. Well Drilling Processes



Once the drilling sites are confirmed, site clearing is needed. Sterilants herbicides are generally applied onsite to permanently kill plants. Soil disturbance with heavy equipment then creates access roads for workers and onsite equipment loadings. In this case, drilling rigs and equipment are transported to the site, and a reserve pit is dug for drilling mud and cuttings disposal. A close looped system is installed on site to manage return fluids, and separate drilling solids and fluids through physical

mechanisms centrifuge, linear motion shakers, and mud cleaners, so that fluids can be reused and recycled (Aresco LP, 2018).

Once the site facilities are ready, the drilling rig is placed and drilling equipment is connected to the power system and pressurized piping systems. Then, a hole to the surface casing is drilled and the drill bit connected at the end of the drill pipe moves down to the ground (Aresco LP, 2018). During this process, drilling mud and chemical additives are continuously pumped into the hole to lubricate the bit and flush the cuttings to the land surface. Then, the drill bit and pipe are removed from the hole, the surface casing and cement are placed into the hole to isolate fresh water zone from drilling contamination. Then a well head and blowout preventer are placed at the surface of the well, followed by a smaller diameter drill and pipe to further complete intermediate drilling beneath the previous drilling position. Continuous drilling activity is needed until the drill reaches the geological layers containing the oil and gas reserve. The drills and pipes are then removed, and production casing is introduced to the entire length of the hole. In this case, cement and the casing in the hole fill the hole between the production casing and drilled holes to stabilize and strengthen the pipe (Aresco LP, 2018).

At the ground surface, the drilling rig is no longer needed. A “perf” gun is lowered to the targeted zone with applied pressure. It shoots holes through steel casing and cement into the target geological formation layers. Then the “perf” gun is removed. Next, specialized equipment to produce hydraulic fractures is used by injecting water, sand and a small amount of chemical into the well holes under the extremely high pressure. When the mixtures reach the target zone, they travel through the shoot holes and reach permeable shale causing fractures and cracks. Sands eventually are stuck into these fractures and cracks. Petroleum hydrocarbons are released through these sand-filled paths and tubes, and brought up to the surfaces. Fractural fluid is also known as flow back liquid. The flow back liquid is a mixture of water, petroleum hydrocarbon, dissolved salts and heavy metals. It flows back to the surface, and is then treated and reused in hydraulic fracturing jobs (Aresco LP, 2018).

At the end, a production tubing is placed in the hole to allow oil and gas to flow upwards, then a permanent well head, a pump jack, oil storage tanks and associated equipment are installed on site (Aresco LP, 2018). The extracted petroleum hydrocarbons are then transported to the tank for separation and storage.

4. 2 Contaminants Classification and Soil Interactions

4.2.1 Soil Sterilants Herbicides

During the initial industrial activities of land clearing, standing vegetation and under storage shrubs need to be removed completely to prohibit any chance of regrowth. To do this, chemical sterilants, commonly used in oil and gas industries, are applied to destroy all forms of living organisms including trees, pests, and pathogens in the soil. The toxicity of sterilants can cause harm not only to the “undesired” organisms, but the “desired” organisms as well. The high toxicity of these chemicals not only achieves “total kill” of soil organisms, but also may cause great harms to human beings as the “non-targeted species” (Skelly & Donaldson, 2011).

Sterilant products consist of active chemicals including atrazine, bromacil, diuron, prometon, simazine and tebuthiuron (Skelly & Donaldson, 2011). These products can be adsorbed on soil mineral surfaces, thus they are highly resistant in the soil and can last for decades. In addition, most of sterilants herbicides are highly soluble. They are readily dissolved into irrigation and rain water (Skelly & Donaldson, 2011). As water moves through soil vertically and horizontally, the chemicals are carried to different geological locations.

4.2.2 Drilling Fluids and Drilling Fluid Additives

Drilling fluids are mixtures of water with clay, water with silicate, water with polymers, or clay with hydrocarbons, as drilling fluid additives (Table 1) are mixed with drilling fluids to control the fluid characteristics (Dinwoodie, 2017).

Table 1. Lists of Drilling Additives

pH and alkalinity control	Lost circulation materials (LCM)
Bactericides	Lubricants
Corrosion inhibitors	Polymer stabilizers/breakers
Defoamers	Shale control inhibitors
Emulsifiers	Surface active agents
Filtrate reducers	Thinners, dispersants
Flocculants	Viscosifiers
Foaming agents	Weighting agents

Sources: Dinwoodie, 2017

Drilling fluids and additives are applied during the well drilling processes. As drill bits lower through the land, high density gel-like drilling fluid is injected into the well hole to lubricate and cool the drilling bit, clean the bottom of the hole, carry the left over cuttings to the land surface, and stabilize the hole with control of subsurface pressure (Dinwoodie, 2017). Eventually, drilling fluids, additives, and drilling cuttings are carried to the surface. These all are stored in the open sump that has been dug for holding returned liquids and solid materials from the drilling holes.

The chemical characteristics of drilling fluid and additive mixtures have negative impacts on the soil and water. Generally, water based drilling fluids, which contain water with clay or silica, are environmentally friendly. However, the drilling additives mixed with these non-toxic drilling fluids can be corrosive and toxic. The potential toxicants include bactericides, corrosion inhibitors, de-foamers, emulsifiers and de-emulsifiers, foaming agents, lubricants, polymer stabilizer or breakers, shale control inhibitors and surfactants or detergents (Dinwoodie, 2017). In addition to the drilling additives, the oil-based drilling fluids which contain polymers or diesel have certain degrees of toxicity. They have strong abilities to adsorb on the soil particle surfaces. Once they are in a water saturated condition such as groundwater, they can either float on the surface water or sink at the bottom of the water body based on their density. In most cases, small amounts of diesel and polymers can be naturally degraded within a few years.

4.2.3 Salts

Salt contamination is one of the primary issues in oil and gas well sites. During the hydraulic fraction processes, around 2,500,000–4,200,000 gallons (Gruber, 2013) of high-pressured water with selected chemical additives is injected into each well to enhance water flow and oil and gas production. The water is injected into the well initially, of which a portion of the water called “flowback” immediately returns back the well surface (Earthworks, 2015). The rest of the water, which either penetrate into the geological formation or returns to the surface after a long period of circulation, is called “produced water” (Kassotis & Tillitt et al, 2016). Both of the flowback and produced water contain variable geological materials such as radioactive materials, heavy metals, hydrocarbons, and primarily naturally occurring salts from shale materials. Due to the dissolution of the geological formation materials, constantly increased the concentration of Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^{2-} , Na^+ , K^+ , Ca^{2+} , Ba^{2+} , Mg^{2+} , Fe^{2+} , and Sr^{2+} and released of insitu brines are found in both flowback and produced water (Haluszczak & Rose et al, 2013). The flowback water, which contains an extremely high amount of salts, (Pichtel, 2016) is 5 to 10 times concentrated than seawater (Haluszczak & Rose et al, 2013).

For the produced water receiving soils, a high concentration of soluble mono-charged salts such as Na^+ , K^+ can lead to dispersed soil structure. These mono-charged cations are able to neutralize the negative charge of the single clay particle, however, they fail in bridging two clay surfaces (particles) together due to the limited number of charge carried by cations. From a macro-view perspective, dispersed saline soils fail to have healthy physical properties. The dispersed soil particles primarily affecting the formation of stable soil aggregates. In this case, the poorly structured soil aggregates fail to form macrospores within and between aggregates, which in turns affect water conductivity through soil profiles. For saline soils, soil pores are dominated by micropores formed between the soil particles. Due to the high osmosis potential and matrix potential of soil, water molecules are either surrounded with dissolved salt or adsorbed to the soil particle, thus water stored in microspores is hard to be taken up by plant roots. Eventually, saline soils with poor soil structure and low permeability will restrict plants growth and regeneration (Abrol & Yadav et al, 1988).

4.2.4 Petroleum Hydrocarbons

Petroleum hydrocarbons are one of the contaminants that exist in multiple stages of the oil and gas extraction and production processes. During the well drilling process, diesel, common mixtures of petroleum hydrocarbons, is applied as an oil based drilling fluid. Some of the lubricating agents, applied as drilling additives, are also forms of hydrocarbons. Eventually, the drilling fluids and carried cuttings are placed into the onsite sump. As mentioned previously, the resultant water that is brought up to the well surface contains mixtures of environmentally hazardous materials inducing significant amounts of hydrocarbons and dissolved gases. As hydrocarbon products are extracted and stored on site, there are potential risks of petroleum hydrocarbons leakages and spills from the knock-out tanks or flare pit.

Petroleum hydrocarbons consist of a mixture of hundreds of organic compounds (Seddique, 2015). Individual compound differs greatly in its toxicity and persistence in the environment (Ver, 2017). Based on their boiling points, they are classified into F1 to F4 fractions (Figure 8), while based on their chemical structures, they are broadly classified into aliphatic and aromatic hydrocarbons (Figure 9).

Figure 8. Petroleum Hydrocarbon Frictions and Examples

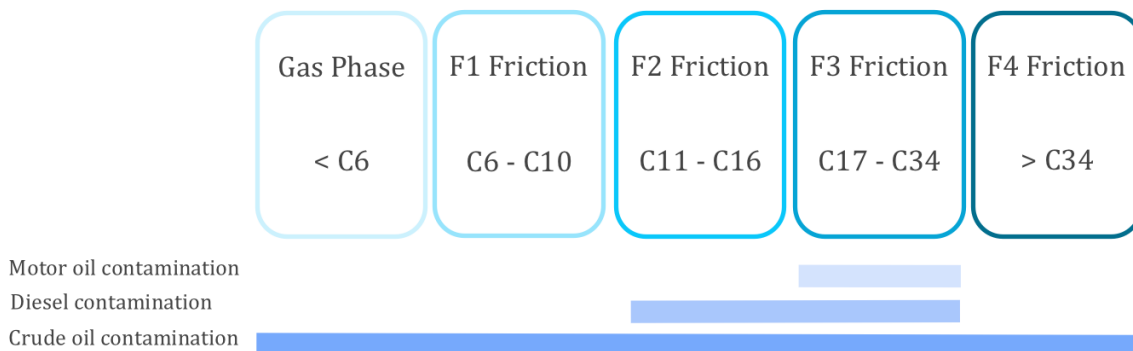
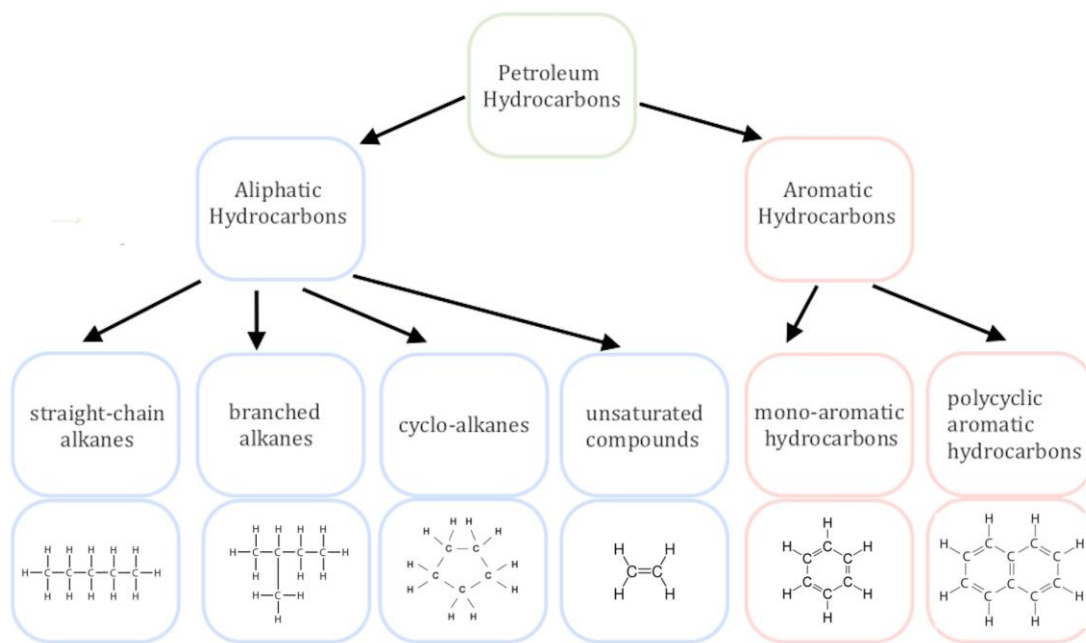


Figure 9. Petroleum Hydrocarbons Classification and Examples



The challenge for the local environment is when compounds like BTEX (Benzene toluene, ethylbenzene and xylene) and PAHs (polycyclic aromatic hydrocarbons) pollute the land and water. Small molecule hydrocarbons are the most toxic but volatile and short lived (Ver, 2017). For example, a compound like benzene present in 1 L of refined oil can contaminate 1 million L of water (Seddique, 2015). Compared to light weight hydrocarbons, large molecule hydrocarbons are less toxic but much more persistent in the environment.

In the soil matrix, the residual petroleum hydrocarbons have a strong ability to be adsorbed on soil particles. Once they are adsorbed on the mobile particles, they can be carried into either surface or ground water. Due to their hydrophobic characteristic and density, most hydrocarbons either float on the water surface (Light Non Aqueous Phase Liquid) or sink at the bottom of water bodies (Dense Non-Aqueous Phase Liquid).

4.2.5 Heavy Metals

The hydraulic fracturing water that is brought to the surface carries not only dissolved salts, but also variable heavy metals from the geological formations. Generally, oilfield produced water contains heavy metals such as mercury and lead, and metalloids such as arsenic (Fakhru'l-Razi & Pendashteh et al, 2009). Other common metals that may be found onsite are Ba, Cd, Cr, Cu, Pb, Hg, Ni, Ag, Zn, Al, B, Fe, Li, Mn, Se, and Sr (Lebas & Shahan, 2013).

Another source of heavy metals getting into the soils is from well site equipment, such as a rusted well-head. Metals like Fe and Al form oxidized rusts once they are exposed to air and rainwater. With time, these metals are dissolved by the rainwater and contaminate the surface soil. The concentrations of oil field heavy metals vary depending on formation geology and the age of the well.

In the soil matrix, heavy metals can either adsorb to soil particles and sediment surfaces, or they can be dissolved by water. Heavy metals are active contaminants due to their active chemical properties. Since most of the heavy metals are transitional metals such as Fe, As, Se, Ur, they change their oxidation state and toxicity based on the soil pH and redox potential. Comparatively, metals that are bonded with S, CO_3^{2-} are less mobile and less toxic compared to dissolved free cations such as Se^{2-} , Fe^{2-} . Heavy metals can also bond to organic matter and form chelates, which are chemical compounds that react with metal ions to form a stable water-soluble complex (Drugs, 2018). These metal-organic complexes increase metals mobility so that heavy metals can translocate within the soil matrix. The environmental concerns with heavy metals are their toxic and bioaccumulative impacts. Heavy metals contaminated water can harm organisms if that water is linked to their supply of drinking and irrigation water.

4. 3 Available Well Site Remediation Technologies

In order to reclaim an oil and gas well site completely and successfully, with the eligibility to apply a reclamation certificate, the site must be assessed and remediated

to meet the required standards in accordance with the Alberta Tier 1 Soil and Groundwater Remediation Guidelines (Appendix 1) or the Alberta Tier 2 Soil and Groundwater Remediation Guidelines (ESRD, 2014). Remediation of mixtures of complex contaminants like heavy metals, salt, herbicides and petroleum hydrocarbons require immediate attention, as they are environmental and human health hazards.

Remediation of Alberta's oil and gas well sites ethically does not include the "dig and dump". This means the transfer of contaminated soils from the infected location to another location, such as a landfill or a waste collecting facility, is not accepted. These waste transfer processes do not directly solve the contaminant issue, rather, putting other geological areas under certain degrees of environmental risks.

The available technologies for remediating contaminated oil and gas well sites can be classified into insitu and exsitu technologies based on site disturbance in terms of translocation of contaminated soil for treatments. While, they also can be classified into physical, chemical and biological remediation based on their scientific principles. Each remediation technology is unique in addressing one or multiple contaminants. A range of remediation technologies can be mixed and matched to achieve the maximum effect in well site remediation.

4. 3. 1 Physical Remediation Technologies

Soil Vapor Extraction

Soil vapor extraction, an insitu technology, can be applied to the contaminated soil unsaturated (vadose) zone. This technology is also called insitu soil venting, insitu volatilization or enhanced volatilization (Siddique, 2015).

Applicability

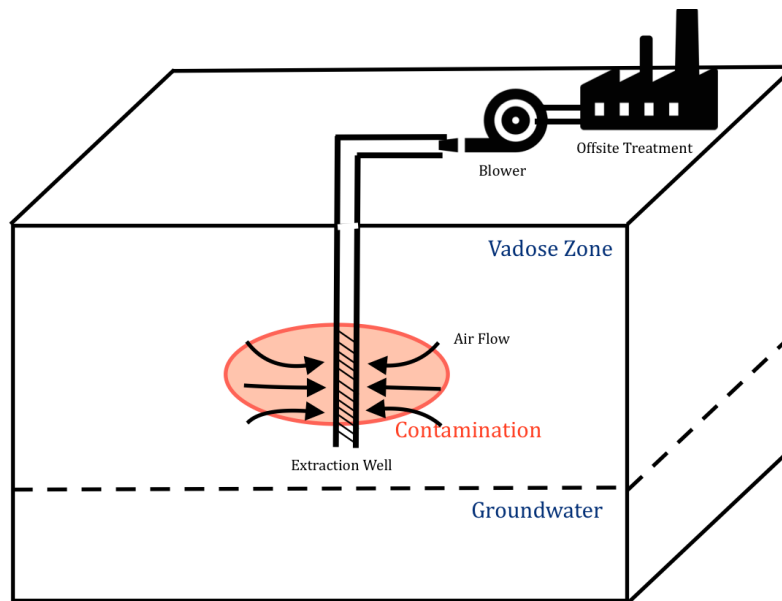
Soil vapor extraction technology can effectively remove volatile organic contaminants, including gasoline, BTEX (benzene, toluene, ethylbenzene and xylene), PCE (tetrachloroethylene) and TCE (trichloroethylene) (Siddique, 2015). However, it is not suitable for remediation of heavy petroleum hydrocarbons since they are not volatile. Based on soil texture, the applicability of soil vapor extraction declines as soil texture change from coarse (sand and gravel) to fine (clay or silt).

Principle

During soil vapor extraction processes, a group of extraction wells is placed into a soil unsaturated zone. A negative pressured vacuum is applied through the extraction

wells to extract volatile and semi-volatile organic compounds from the soil, and leave a clean soil behind. The contaminants that are extracted go through off-site treatments such as combustion and chemical oxidation (Figure 10)

Figure 10. Soil Vapor Extraction Process



Multiphase Extraction

Multiphase extraction is also called dual phase extraction (DPE) or two phase extraction (TPE) (Siddique, 2015). This technology is applied to remove contaminants from both soil saturated (groundwater) and unsaturated zones.

Applicability

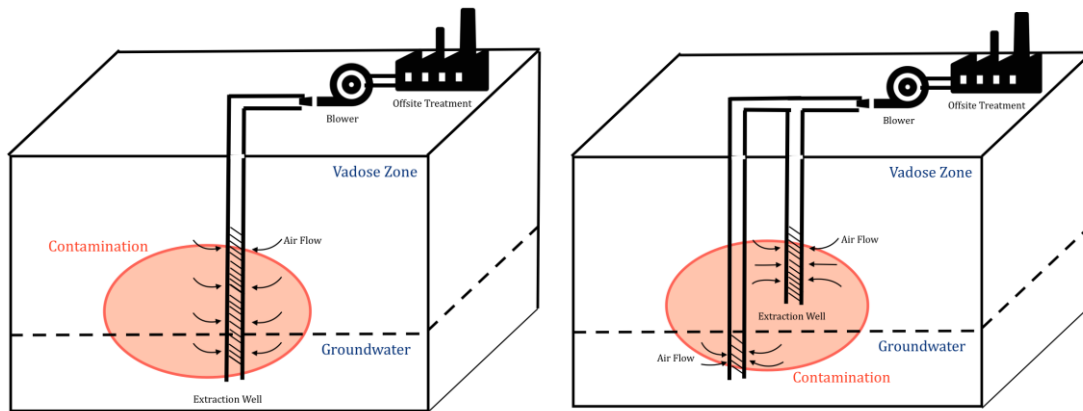
Multiphase extraction can effectively remove halogenated volatile organic compounds, aromatic volatile organic compounds, total petroleum carbons, and floating products (Light Non Aqueous Phase Liquid) on the surface of groundwater.

Principle

A single pump system is used to extract vaporized and groundwater contaminants together by a single extraction tube under the applied negative vacuum pressure. A dual pump system requires two extraction wells to be placed into the groundwater and unsaturated zone with applied negative vacuum pressure. Under the negative pressure, the subsurface pump extracts contaminated groundwater, while surface

blower extracts contaminants in a vapor phase. The extracted liquid and vapor contaminants are treated offsite, and the treated groundwater is disposed or re-injected back to the subsurface (Figure 11).

Figure 11. Multiphase Extraction Process



Thermal Desorption

Thermal desorption technology extracts soil contaminants by heating the soil to a certain temperature in a thermal desorber. The applied high temperature allows vaporization and separation of the well site contaminants from the soil (Nelson Environmental, 2015). These vaporized contaminants are converted into carbon dioxide and water as the end products.

Applicability

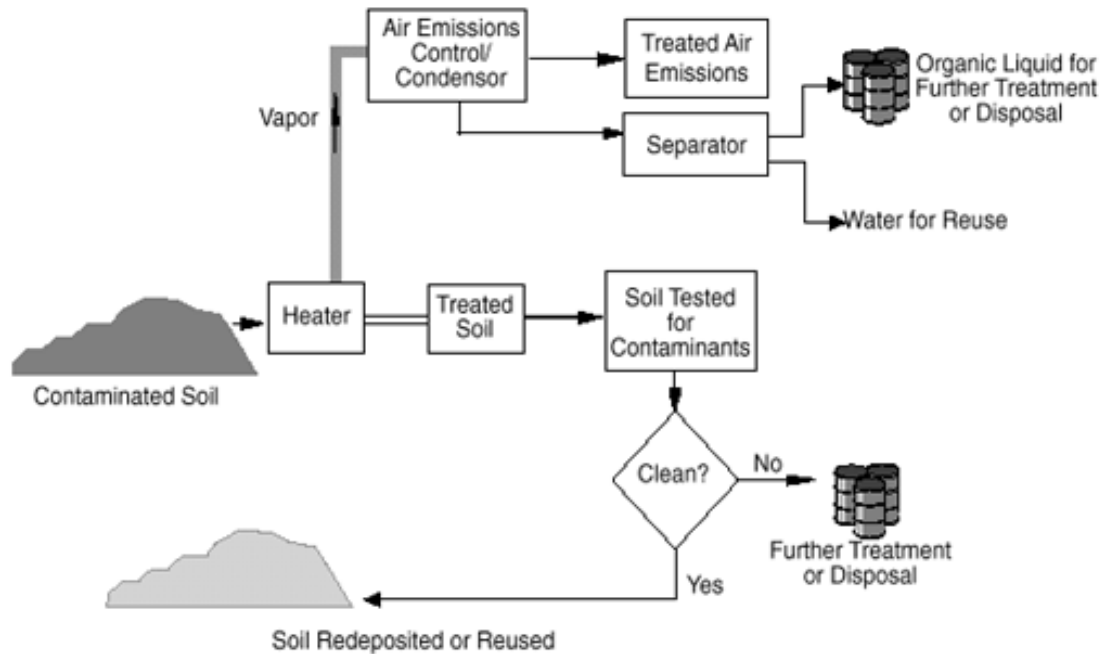
Thermal desorption is one of the fastest technologies to remove soil volatile and semi volatile organic compounds including gasoline, BETX (benzene, toluene, ethylbenzene and xylene), chlorinated organic compounds, PAHs (polycyclic aromatic hydrocarbons) and herbicides (Qu, 2010).

Principle

The process of thermal desorption starts with the excavation of contaminated soils and transportation of soils to onsite thermal desorption equipment. After the soil is prepared or homogenized, it is placed in the thermal desorber. The thermal desorber is mobile and uses rotary kiln desorption. When contaminated soil enters the rotating drum, organic contaminants vaporize at high temperatures around 200 to 500 °C (Nelson Environmental, 2015). The “bag house” does the collection of dust and other gaseous objects from the thermal desorber. These vapor contaminants are finally destroyed by the afterburner. 870 °C of heat is used to convert the last portion of any contaminant into carbon dioxide and water vapor (Nelson Environmental, 2015).

After the gasification and combustion of the contaminants, the soil is cooled, rehydrated and stockpiled (Figure 12).

Figure 12. Thermal Desorption Process.



Source: United States Environmental Protection Agency

Electro-kinetic Technology

Electro-kinetic technology is an insitu soil remediation technique that utilizes direct current to control migration of contaminants in the soil through electromigration, electroosmosis, and electrophoresis (Cameselle et al. 2013; Ghosh et al. 2011; Lee et al. 2014; Wei et al. 2016).

Applicability

Electro-kinetic technologies are able to remove radioactive elements, toxic anions, petroleum hydrocarbons, ion-organic complexes, chlorinated organic compounds, and PAHs (polycyclic aromatic hydrocarbons), but most effective in removing metal contaminants (Qu, 2010). Electro-kinetic technologies are targeted to low permeable clay soils. Generally, ions in the clay soil have low mobility, however, the mobility is greatly enhanced under the electro-kinetic potential. The efficiency of electro-kinetic technologies in removing Hg, Ni, Mn, Zn, Pd, Cd, Cr, Co from kaolinite reaches 85% to 95% (Qu, 2010).

Principle

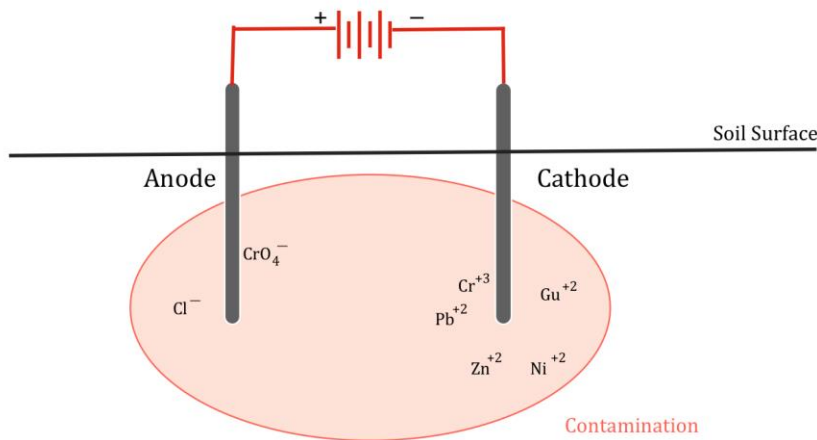
The most important reaction in Electro-kinetic technologies is electrolysis of water molecules. The end products H^+ produced from anode reaction reduces surrounding soil pH, while OH^- generated at cathode increases surrounding soil pH.

Anode reaction: $H_2O \rightarrow 2H^+ + \frac{1}{2} O_2(g) + 2e^-$

Cathode reaction: $2H_2O + 2e^- \rightarrow 2OH^- + H_2(g)$

Electromigration is a process where ions and ion complexes in the soil move towards the opposite electrode under the applied current (Qu, 2010). In this case, cations or cation-organic complexes migrate towards the cathode, while anion and anion-organic complexes move towards the anode (Figure 13). Electroosmosis forces water in the soil pores to move from anode to cathode by the electro-kinetic force. In this case, non-ion contaminants carried by the electroosmosis fluid is removed. Under the effect of electrokinetic potential, charged particles and colloids, with adsorbed contaminants on them, are forced to move towards the electrodes (Qu, 2010). Eventually, the accumulated contaminates near the electrodes can be removed through precipitation, electroplating, and ion exchange reactions (Qu, 2010).

Figure 13. Electro-kinetic Technologies



4. 3. 2 Chemical Remediation

Chemical remediation involves applications of chemicals to the contaminant infected soils and groundwater. Chemical reactions between applied chemical and contaminants can degrade or detoxify contaminants into environmentally friendly

end products. The effective remediation technologies used in oil and gas well site are soil washing and insitu chemical oxidation.

Soil Leaching and Washing

Soil leaching and washing technologies enhance cation exchange, dissolution and migration of contaminants in the soil matrix via application of soil amendments or chemical solvents. This technique can be applied both insitu and exsitu.

Soil amendment

Inorganic calcium and magnesium soil amendments are effective in remediating soil salinity issue at oil and gas well sites. Gypsum is the most common chemical substance that is applied to adjust the physical and chemical properties of salt accumulated soils (Bischoff et al, 2017). Other effective soil amendments are limestone and magnesium carbonate.

Adding these amendments can improve soil structure, balance osmotic water potentials, and ionic potentials, and increase nutrient availability in the soil (Bischoff et al, 2017). Soils with high concentrations of mono cation salts, like sodium and potassium, have a dispersed structure. This is because saline soils are neutralized by monovalent cations with large molecular radius. This results in weak interactions between clay particles (Figure 14). However, sodium and potassium on clay particles can be replaced by divalent cations, such as calcium from gypsum. Replacement of sodium by calcium occurs through cation exchange reactions. The smaller radius of calcium creates stronger interactions between clay surfaces, and results in clay aggregation (Figure 15). To achieve remediation, this process also requires applications of a large amount of water to flush down the exchanged salts to the deeper soil horizons or groundwater, and leaving a non-salt affected root zone.

Figure 14: Dispersed Soil Structure VS Flocculated Soil Structure

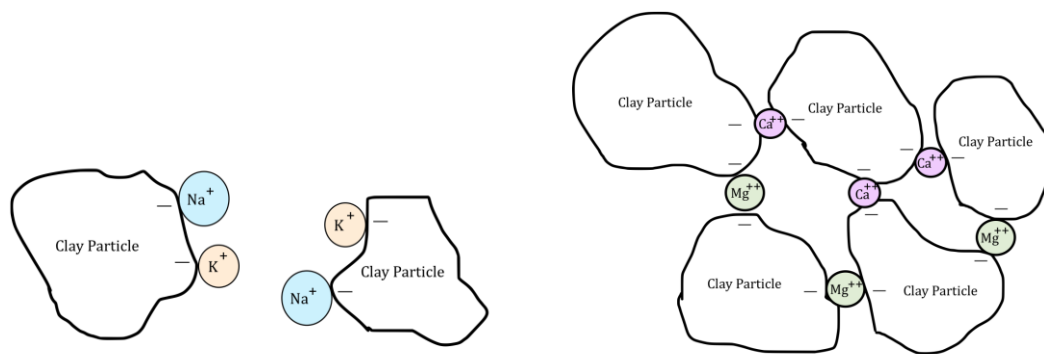
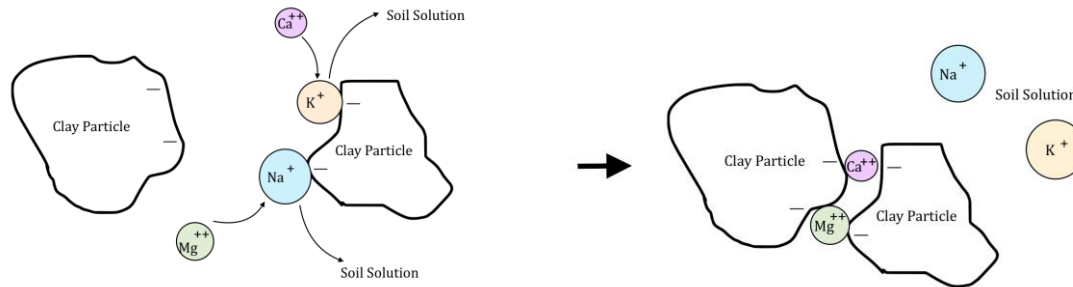


Figure 15: Soil Exchange Reaction: Divalent Cations Replace Monovalent Cations



Soil solvent

Soil surfactants target on oil well produced organic and inorganic contaminants like heavy metals, petroleum hydrocarbons, drilling additives and herbicides that are strongly adsorbed on the soil particles.

During the soil washing processes, chemical solvents are injected or sprayed to contaminated soils in order to enhance dissolution, complexation, and mobility of organic and metal contaminants, as these chemical reactions change the chemical and physical properties of targeted contaminants.

Surfactants target to mobilize organic contaminants such as petroleum hydrocarbons, herbicides, and other organic chemical additives that cover around the soil particles. Surfactants increase the aqueous solubility of organic compounds due to solubilization of surfactant micelles (Cheah et al, 1998). Organic acids like citric, itaconic, fumaric, pyruvic and acetic acids and EDTA can increase the mobility of adsorbed or dissolved heavy metals by forming ion-organic complexes (Siddique, 2015). Eventually, the dissolved various organic contaminants and heavy metals that are attached to organic acids, can be extracted or flushed down to the groundwater for further treatment.

Insitu Chemical Oxidation

Chemical oxidation remediation is an insitu technology involving applications of chemical oxidants into the contaminated soil and groundwater through injection wells. The injected oxidants oxidize well site contaminants into environmental friendly end products such as water and carbon dioxide.

Applicability

Insitu chemical oxidation technology is excellent in immediate remediation of organic pollutant in both soil saturated and unsaturated zones. For oil and gas recovery, it is effective in degrading petroleum hydrocarbon and herbicides that are highly

resistant in soil. The most common chemical oxidants used for soil remediation are permanganate salts (NaMnO_4 , KMnO_4), peroxide (H_2O_2), ozone (O_3), and persulfate salts ($\text{Na}_2\text{S}_2\text{O}_8$, $\text{K}_2\text{S}_2\text{O}_8$) (Siddique, 2015).

Principle

All oxidants react with organic contaminants through oxidation and reduction reactions. During the reaction, one or more electrons are transferred from an electron donor, such as an organic contaminant, to an electron acceptor, such as an oxidant. The electron transfer produces radicals, which are highly reactive chemical species with an odd number of valence electrons (Siddique, 2015). These newly produced radicals oxidize organic contaminants in soil and water, resulting in conversion to water, methane, and carbon dioxide.

4. 3. 3 Biological Remediation

Biological remediation technologies utilize plants, soil microorganisms, and enzymes produced by these biomes to degrade or transform well site contaminants. Biological remediation technologies can be applied both insitu and exsitu.

Biological remediation is not significant in oil and gas well sites that have been contaminated by high concentrated salt due to the high osmotic potential. However, there are scientific articles that have indicated that certain microorganisms and plant species, which are able to tolerate and adapt high concentration of salt, can be used for heavy metal transformation and petroleum hydrocarbon degradation (Lee, 2016).

Bioremediation

Bioremediation technologies have been studied for decades and have proven that organic contaminant can be degraded by activities of soil microorganisms under both aerobic and anaerobic conditions. It is important to know that nature has the ability to digest contaminants in a positive way. To degrade petroleum hydrocarbons including BTEX (benzene, toluene, ethylbenzene and xylene), gasoline and monoaromatic hydrocarbons, bioremediation can be achieved via oxidation reaction under the aerobic conditions (soil unsaturated zone), and reduction reaction under the anaerobic conditions (groundwater). Soil temperature, soil water content and soil pH play important roles in microorganism survivals, growth, reproduction and metabolism.

Principle

In order to mineralize petroleum hydrocarbons by the activities of soil microorganisms, microorganisms require an energy source for the biomass synthesis, an electron source and a carbon source for ATP (energy) synthesis, and terminal electron acceptors for receiving electrons that are generated during the biochemical reactions.

Soil organisms can be classified as autotrophs and heterotrophs based on their sources of carbon, electrons, and energy. Autotrophs are microorganisms which synthesize food themselves by utilizing inorganic forms of carbon (CO_2) as the carbon source, the surrounding inorganic matters as electron sources, as well as chemical reactions, the heat and solar energy, as energy sources. The terminal electron acceptors for autotrophic microorganism are generally inorganic compounds, for example, NH_4^+ , Fe^{2+} , S^{2-} and Mn^{2+} (Sidiqqe, 2015).

Heterotrophs are microorganisms that utilize organic carbons that have been synthesized by autotrophs as carbon and electron sources, and energy produced in chemical reactions as the energy source. In this case, heterotrophs are the key microorganism groups that degrade pollutants like petroleum hydrocarbons and herbicides. The terminal electron acceptors for heterotrophs are inorganic compounds rich in O element such as O_2 under the oxic condition, NO_3^- , NO_2^- , MnO_2 , FeOOH under the suboxic condition, and SO_4^{2-} and CO_2 under the anoxic condition (Sidiqqe, 2015).

During a series of biochemical reactions between organic matters and heterotrophic microorganism, electrons generated from degradation of contaminated organic matters go through the electron transport chain which synthesis ATP (energy), and eventually accepted by terminal electron acceptors. Under the oxic or the aerobic condition, the electron acceptor O_2 undergoes a reduction reaction, and gains electrons, reduces in oxidation state and eventually bonds with H^+ to form water. Under the anaerobic (suboxic and anoxic) conditions, terminal electron acceptors NO_3^- , NO_2^- , MnO_2 , FeOOH , SO_4^{2-} and CO_2 gain electrons, reduce the oxidation states and form N_2 , Mn^{2+} , Fe^{2+} , S^{2-} , and CH_4 . For organic matter, the electron and carbon sources of microorganisms, are eventually mineralized or degraded into water and carbon dioxides or methane.

Table 2. Anaerobic Bioremediation Information

Oxic	Eh=440mV	Oxidation	$\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$
Suboxic	Eh= 280~230mV	Nitrate reducing condition	$\text{CH}_2\text{O} + \text{NO}_3^- \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{N}_2$
	Eh=380~230mV	Manganese reducing condition	$\text{CH}_2\text{O} + \text{MnO}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{Mn}^{2+}$
	Eh=150~80mV	Iron reducing condition	$\text{CH}_2\text{O} + \text{Fe}(\text{OH})_3 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{Fe}^{2+}$
Anoxic	Eh=-150~-160mV	Sulfate reducing condition	$\text{CH}_2\text{O} + \text{SO}_4^{2-} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{S}^{2-}$
	Eh=-150~-250mV	Methanogenesis	$\text{CH}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{O} + \text{CH}_4$

The sequences of reduction reactions are directly controlled by the soil redox potential (Eh: the oxygen level), and indirectly related to the concentration of terminal electron acceptors in the soils. When the soil is in the oxic conditions with redox potential greater than 414mV, O_2 is the dominant electron acceptor. Once the oxygen is depleted, redox potential drops to a suboxic condition, where the condition first favors NO_3^- and MnO_2 , then favors FeOOH as electron acceptors. Moreover, if redox potential reaches anoxic condition or the above electron acceptors are depleted, SO_4^{2-} and CO_2 will become the dominant electron acceptors (Siddique, 2015). From the perspective of presence and concentration of terminal electron acceptors, terminal electron acceptors which have a higher concentration in the soil solution will become dominant in the reactions. In order to complete electron transport, terminal electron acceptors only function if the soil redox potential reaches ideal conditions for each terminal electron acceptor. Otherwise, the oxidation and reducing reactions will not be initiated and petroleum hydrocarbons will not be degraded due to dysfunctional or inactive terminal electron acceptors.

Phytoremediation

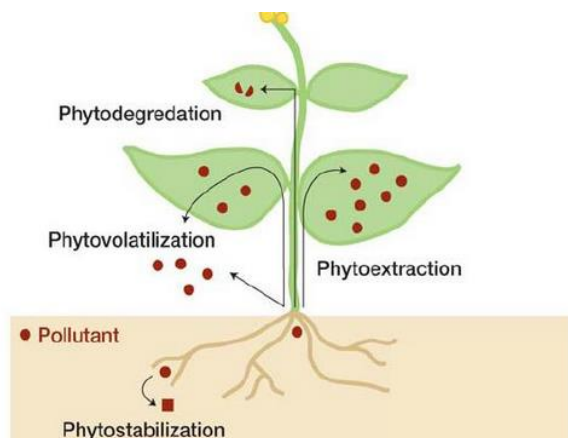
Phytoremediation can be defined as “the efficient use of plants to remove, detoxify or immobilize environmental contaminants in a growth matrix (soil, water or sediments) through the natural biological, chemical or physical activities and processes of the plants” (Peuke & Rennenberg, 2005). This requires plants growing in a contaminated matrix for a required growth period in order to remove contaminants from the root zone or facilitate immobilization and detoxification of the pollutants (UNEP, 2002). Once remediation is completed, the plants can be harvested, processed and disposed of.

Principle

The removal of oil and gas produced wastes petroleum hydrocarbons and heavy metals can be achieved through phytostabilization, phytodegradation,

phytovolatilization, phytoextraction, and plant growth promoting rhizobacteria (PGPR).

Figure 16. Phytoremediation Processes



Source: *Debating Sciences*

Phytostabilization process avoids mobilization of heavy metals and limits their diffusion in the soil matrix. During this process, metals are incorporated into the lignin of cell walls, root cells, or into humus. In this case, metals become insoluble by the direct action of root exudates and subsequently trapped in the soil matrix (Galal, Ghazi elt, 2017).

Phytodegradation is a process to mineralize contaminants into non-toxic inorganic compounds through activities of soil microorganisms, which are present in the pores between soil particles and plant roots. In this process, plant roots metabolism products, and surrounding soil conditions like optimum moisture, and oxygen levels, enhance microorganism activities.

Phytovolatilization is the process whereby plant absorbs and volatilizes heavy metals such as Hg and As (Qu, 2010) and petroleum hydrocarbons such BTEX (benzene, toluene, elthybenzene and xylene). These contaminants in mobile forms can be absorbed by roots, and converted into non-toxic forms within the plant tissues and then released into the atmosphere.

Phytoextraction is the process mainly applied to heavy metals such as Cd, Ni, Cu, Zn, Pb Se, and As (Qu, 2010). Plant roots absorb heavy metals. Metals are further translocated and accumulated in aerial parts of plants. A plant that accumulates a large number of heavy metals can be harvested.

For all three remediation processes, organic acids such as EDTA can be added to enhance metals complexation. This will decrease the toxicity of heavy metals to plants and increases the mobility of heavy metals for plant uptake.

Plant growth promoting rhizobacteria (PGPR) plays important role in promoting phytoremediation. These bacteria inhabit the plant root and influence plant growth positively by increasing nutrient availability to plants with fixed N, soluble phosphate and iron that has been sequestered by bacterial siderophores (Seddique, 2015). Plants with better health and vigor conditions will be more effective in contaminant extraction, transformation, and volatilization.

4. 4 Case Study

4. 4.1 Reason for Choosing Case Study

As mentioned above, salt contamination is the primary issue that exists in Alberta's oil and gas well sites. Fortunately, remediating salt contaminated soils by soil washing technology is not as difficult compared to other organic and metal contaminants. This is because onsite chemicals like petroleum hydrocarbons, metals and herbicides have various chemical structures (vary in compounds) and forms (dissolved, adsorbed, precipitated), which require applications of complicated remediation techniques. Comparatively, the magnitude and effect of petroleum hydrocarbons contamination are greater than metals and herbicides contaminations in oil and gas extraction sites, since extracted petroleum hydrocarbons have high potential to enter into the surrounding environment by accidental tank breakage and leakage.

Petroleum hydrocarbon contaminated soils and groundwater can be degraded or extracted in various ways with applications of current technologies. However, the natural attenuation of petroleum hydrocarbons by activities of soil microorganisms has been applied during the past few decades. This insitu, cost effective and environmentally friendly biological remediation can effectively degrade hydrocarbons under aerobic and anaerobic soil conditions with several biological and chemical reactions. The naturally occurring processes are highly active in the soil and groundwater that are enriched with a high level of O_2 , NO_3^- , SO_4^- , Fe and Mn oxides, and CO_2 as electron acceptors.

Based on the above information, a real life scenario of biological degradation of petroleum hydrocarbons in Alberta gas well site is examined as the case study in this paper. This case study is based on several scientific papers: Seasonal Recharge and Replenishment of Sulfate Associated with Bioremediation of Hydrocarbon Plume;

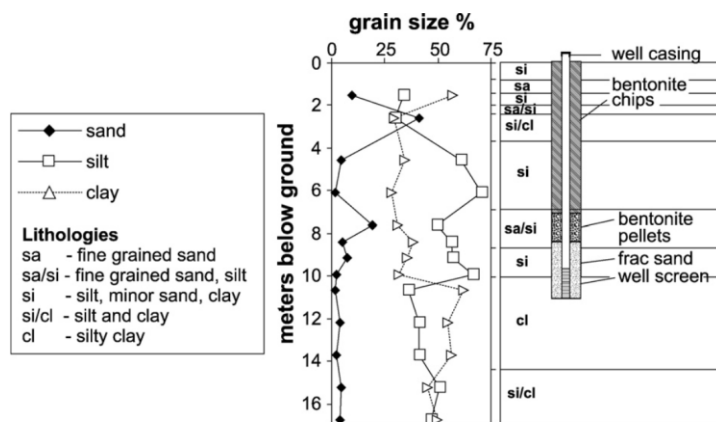
Microbial Reduction of Sulfate Injected to Gas Condensate Plumes in Cold Groundwater; and Bacterial Sulfate Reduction in Biodegradation of Hydrocarbons in Low-Temperature, High-Sulfate Groundwater, Western Canada by Dale R. Van Stempvoort, James Armstrong, and Bernhard Mayer.

Due to the ownership of oil and gas wells within the study area, the detailed location, and previous site investigation reports will not be included in the following descriptions.

4. 4. 2 Study Site

According to Van Stempvoort, Armstrong and Mayer (2002 and 2006), the study site is a gas well site in a small farmland of prairie region in northern Calgary, Alberta. The gas well site has existed since 1972. The landscape of the site is hummocky glacial terrain with dominated glacial deposits of silt and clay up to 17 meters in depth (Figure 17). The bedrock in this area is Cretaceous and Tertiary, which consist of sandstone, siltstone, shale and minor coal below 30 meters of the surface.

Figure 17. Site Soil Information



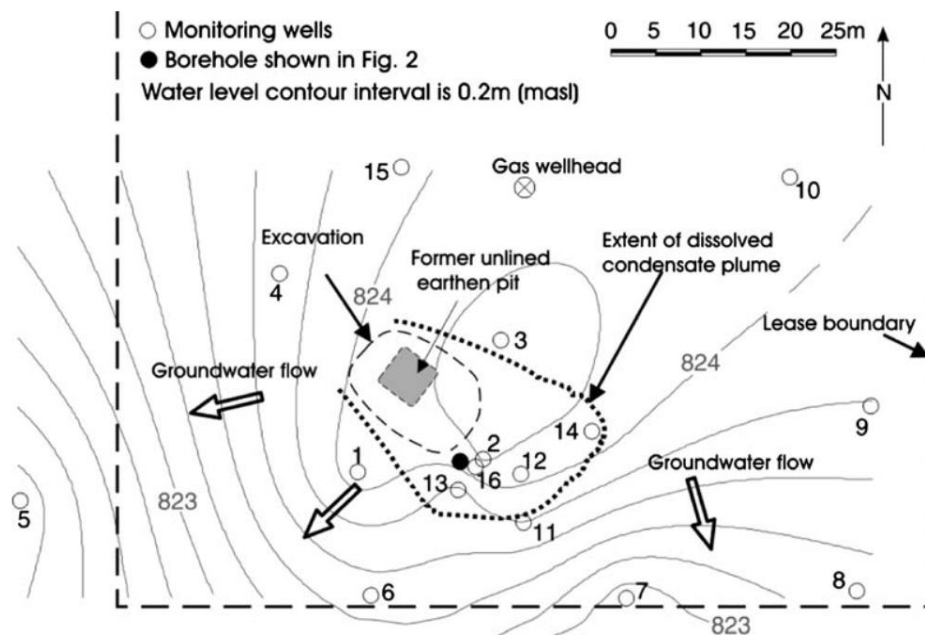
Source: Dale Van Stempvoort, James Armstrong and Bernhard Mayer

From the 1970s to the 1990s, natural gas condensate and production water were occasionally discharged to an unlined earthen pit, which was 5 m across, 1m deep and with a surrounding earth berm approximately 0.4 m high. These contaminants infiltrated through the soil profiles and reached groundwater. In 1996, soil analysis indicated the site contained an elevated concentration of chloride and “oil & grease” at a concentration of 2460 mg/L and 646 mg/L. In 1997 and 2001, the contaminated soil below the pit was excavated twice, however, the complete excavation was limited

by the presence of oilfield production equipment (Van Stempvoort, Armstrong & Mayer, 2002).

In 1999, there were the 14 monitoring wells installed on site to a depth of 12- 18 m. In 2002, two injection wells were installed (#15 and #16) for field injection experiments. The data from the monitoring wells (#1–#14) indicated that a plume of hydrocarbons was detected in the groundwater near the water table. The forms of hydrocarbons were light non-aqueous phase liquid (LNAPL), a group of hydrocarbon compounds that are not soluble in water and less dense than water (Siddique, 2015). Based on the monitoring data, the total light non-aqueous phase liquid contaminated area was 100 to 200 m². The hydrocarbons consist of 85% of C₆ to C₁₀, 7% of C₃ to C₅ and 7% C₁₁ to C₁₆ compounds. The groundwater temperature at the site was between 5°C to 6 °C (Van Stempvoort, Armstrong & Mayer, 2002).

Figure 18. Contaminated Area, Monitoring and Field Injection Wells



Source: Dale Van Stempvoort, James Armstrong and Bernhard Mayer

In 1999, sample tests of monitoring well #2 indicated that there were visible hydrocarbons and volatile compounds at 4 to 10 m and 3 to 13 m below the ground surface. While, monitoring well #12, #13 and #14 had lower levels of hydrocarbons (Van Stempvoort, Armstrong & Mayer, 2002).

In 2011, the sample analysis showed that BETX (benzene, toluene, ethylbenzene and xylene) and other hydrocarbons in monitoring well #2 and #12 remained at the

similar levels as 1999. However, the LNAPL (light nonaqueous phase liquid) level was observed to be constantly increasing in well #2 from 0.5 cm in 1999 to 55 cm in 2011. Moreover, hydrocarbons were not detected in monitoring well #13 and #14, where wells were at a low level of hydrocarbons in 1999. Well analysis in 1999 also showed that high level of sulfate ($>1000\text{mg/L}$) was present in the majority of the wells, however well #2 has the lowest level approximately 30mg/L in 2002 (Van Stempvoort, Armstrong & Mayer, 2002).

Groundwater was constantly monitored and analyzed. The monitored objectives included major ions Ca, Mg, Na, K, SO_4^- , Cl, HCO^- , total dissolved Fe and Mn, BTEX (benzene, toluene, elthybenzene and xylene), total petroleum hydrocarbons (C_3 to C_{10}), total extractable hydrocarbons ($\text{C}_{11}\text{-C}_{60}$), ^{34}S , and ^{13}C (Van Stempvoort, Armstrong & Mayer, 2002).

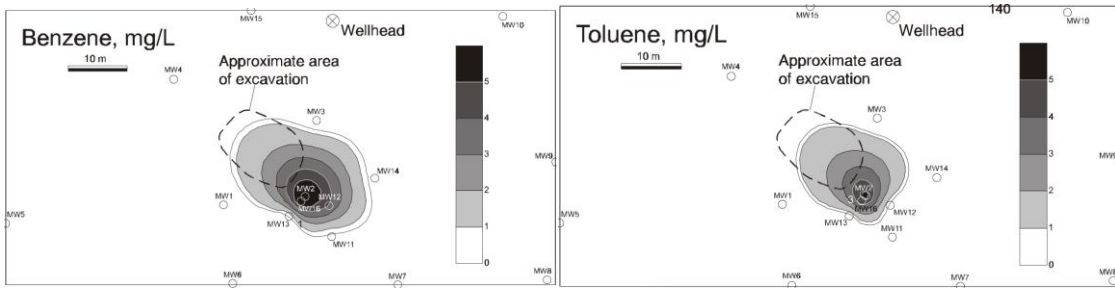
In order to compare the sulfate reduction rates of monitoring wells #2 and #16, 20L of sulfate solution mixed with 1820mg/L K_2SO_3 and 18.3g/L NaBr was injected into the well #16 in 2012 June (Van Stempvoort, Armstrong & Mayer, 2002).

4. 4. 4 Results of Case Study

Natural Attenuation Of Hydrocarbons

In June of 2002, the average groundwater temperature was 5 to 6 °C where the water temperature was cooler for insitu biological remediation compares to other sites. However, there was evidence that natural attenuation of hydrocarbon occurred at the site. As shown in Figure 19, the change in the concentration of BTEX (benzene, toluene, elthybenzene and xylene) along the flow path indicates hydrocarbon degradation was occurring in the groundwater. By comparing benzene and toluene, the evidence showed that natural attenuation of toluene was relatively greater than benzene, although benzene was also degraded over time (Van Stempvoort, Armstrong & Mayer, 2002).

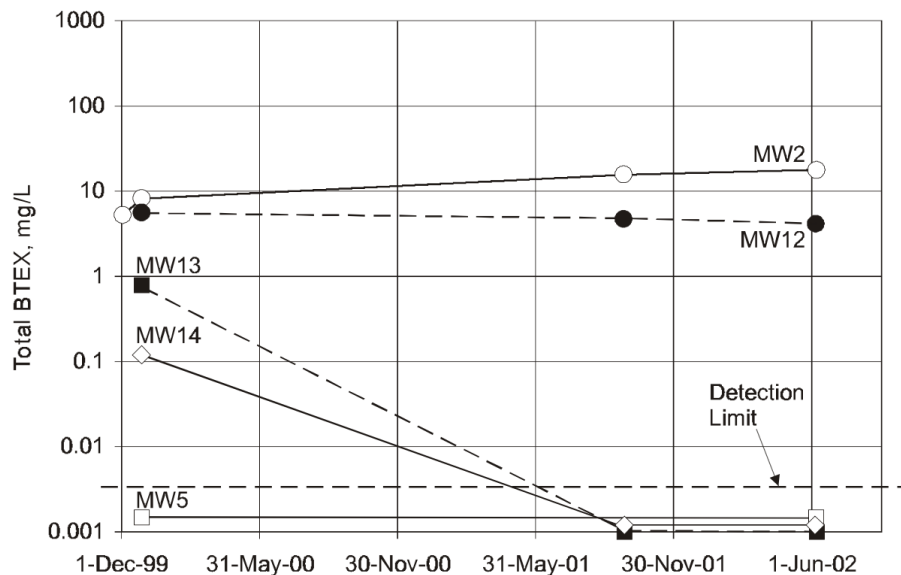
Figure 19. Benzene and Toluene Degradation



Source: Dale Van Stempvoort, James Armstrong and Bernhard Mayer

By comparing the total concentration of BEXT (benzene, toluene, ethylbenzene and xylene) between monitoring wells over time, Figure 20 shows that BTEX (benzene, toluene, ethylbenzene and xylene) concentration in the source of contamination plume (monitoring well #2) increased from Dec, 1999 to Jun, 2002. There is a high possibility that the increases were related to increasing amounts of free product of LNAPL (light non-aqueous phase liquid). In comparison, monitoring wells #13 and #14 that are away from the core of the plump showed a sharp decline until BTEX concentration reached 0 in Nov, 2001 as natural attenuation of hydrocarbons occurred on site.

Figure 20. BTEX (Benzene, Toluene, Ethylbenzene and Xylene) Degradation

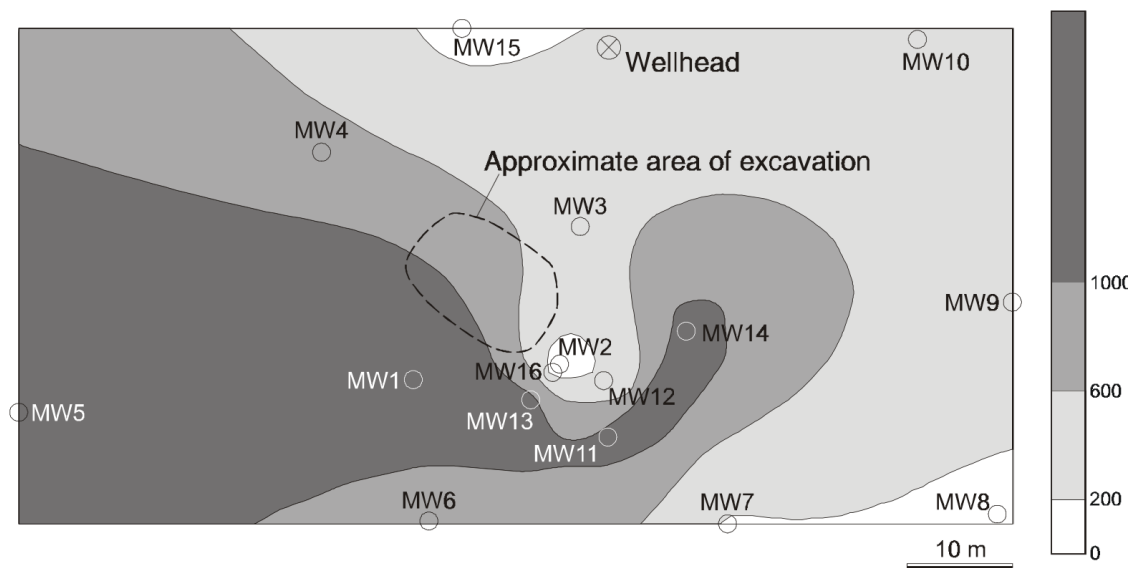


Source: Dale Van Stempvoort, James Armstrong and Bernhard Mayer

Terminal Electron Acceptors

Sulfur is one of the main terminal electron acceptors in heterotrophic bioremediation of petroleum hydrocarbons in anoxic conditions (groundwater). In this study site, sulfate in unsaturated soils was dissolved by the periodical discharge of groundwater. However, in 2002, the concentrations of dissolved sulfate in groundwater greatly differed among the monitoring wells that covered the entire petroleum hydrocarbon contaminated area. Sulfate levels were lowest in the most contaminated area (monitoring well #2 and #16), and were highest in the southwest corner of the contaminated plump (Figure 21 and Table 3). The lowest concentration of sulfate present in well 2 and 16 indicates that the majority of dissolved sulfate was utilized and transformed into other forms of compounds due to the extremely intensive activity of sulfate-reducing bacteria. Thus the terminal electron acceptor in the core of the contaminant plump was assumed to be sulfate (Van Stempvoort, Armstrong & Mayer, 2002).

Figure 21. Site Sulfate Distribution



Source: Dale Van Stempvoort, James Armstrong and Bernhard Mayer

Table 3. Terminal Electron Acceptors

Dissolved indicator	Background wells outside of the hydrocarbon plume (MW-4, 5, -6, 7, 8, 9, 15)		Wells near plume margin, in vicinity of excavated pit (MW-1, 3, 11, 12, 13, 14)		Wells in the core of the hydrocarbon plume (MW-2, 16)	
	average	range	average	range	average	range
oxygen ¹ (mg/L)	3.9	1 to 8.7	1.6	0.3 to 6.5	0.4 (MW-16)	na ²
nitrate (mg/L)	26.8	0.14 to 118	15.5	0.01 to 78	0.14	0.01 to 0.27
sulfate (mg/L)	433	77 to 1,300	984	267 to 1,760	48.9	2.7 to 95.1
sulfate $\delta^{34}\text{S}$ ‰	-7.7	-9.6 to -6.8	-8.2	-5.4 to -10.4	-6.7	-4.4 to -9.0
total Fe (mg/L)	0.19	0.03 to 0.67	3.1	0.04 to 15.5	398	351 to 445
total Mn (mg/L)	0.262	0.01 to 0.53	1.84	0.04 to 4.55	23.4	16.6 to 30.2
methane (mg/L)	na	< 0.002 to 0.002	na	< 0.002 to 3.0	na	na
bicarbonate (mg/L)	520	425 to 617	1148	697 to 1,770	6,840	6,580 to 7,100
DIC $\delta^{13}\text{C}$	-12.1	-10.1 to -15.0	-19.3	-12.8 to -29.6	-14.2	-10.4 to -17.9

¹ *in-situ* on June 14, 2002; all others sampled June 5-7, 2002 and analyzed in laboratory ² na = not available

Source: Dale Van Stempvoort, James Armstrong and Bernhard Mayer

From the experiment results (Van Stempvoort, Armstrong & Mayer, 2002), Table 3 indicates that there was evidence that other terminal electron acceptors also played a key role in biodegradation of hydrocarbons. Since there was a significant concentration of dissolved oxygen shown in some locations of the contaminated plump, indicating the presence of insitu aerobic bioremediation. Evidence of nitrate reduction indicated that nitrate is the secondary terminal electron acceptors in this contaminated site since the dissolved nitrate levels were relatively low at the core of plump compare to the concentration shown in gas well locations.

Iron and manganese oxides are important terminal electron acceptors in bioremediation. In this experiment, the highest concentrations of both metal oxides were shown at the core of plump. The groundwater analysis indicated that iron and manganese reduction had occurred onsite, and reduced metals might have exchanged with soil particle surface minerals or formed complexes with sulfide (Van Stempvoort, Armstrong & Mayer, 2002).

The reduction of dissolved CO₂ under methanogenesis condition also indicates insitu natural degradation of hydrocarbons under activities of methanogenesis microorganisms. According to Van Stempvoort, Armstrong & Mayer, (2002), the dissolved CO₂ was highest in the core of plump, wells #2 and #16 (>6500mg/L). While #1, #12, #13 and #14 surrounding the core of plump also showed an elevated concentration of dissolved CO₂ (>1000mg/L). The presence of a high concentration of CO₂ comes from biodegradation of hydrocarbons, where organic carbon was converted into inorganic carbon. However, the end product CO₂ was then converted into CH₄ through biological activities under the anoxic condition.

Rate of Sulfate Reduction

During the biological remediation of hydrocarbons-contaminated groundwater, sulfate is the dominant terminal electron acceptor and sulfate reduction is the dominant biochemical reaction. To compare the speed of sulfate reduction and hydrocarbon degradation via biological activities at the core of the polluted area, the sulfate reduction rates were compared between monitoring well #2 and #16 (anthropogenic sulfate injection).

According to Van Stempvoort, Armstrong & Mayer (2002), in the monitoring well # 2, the concentration of sulfate was reduced from 1570mg/L in Dec 1999 to 30.3mg/L on Jul 2002. Total 1540ml of sulfate was reduced within 21 months with a reduction rate of 2.4mg/L per day. Meanwhile, monitoring well 16, with an additional injection of sulfate in summer 2002, showed that a large fraction of injected sulfate was reduced over time. About 1.9 % sulfate had been reduced by the first 8 days, 10.8 % over 22 days, and 36.7 % over 57 days. The sulfate reduction rate was around 6mg/L per day. According to Aharon and Hu (2002), as well as Habicht and Canfield (1997), the microbiological activities of sulfate reduction in marine sediment porewater is around 0.01 mg/L per day and approximately 700mg/L per day in shallow algal mats. As compared to both conditions, the core of the hydrocarbon plump reached the middle of the overall range of biological sulfate reduction activities.

4. 4. 5 Additional Bioremediation Analysis

In order to achieve biological remediation of lightweight hydrocarbons in this gas well site, both soil and contaminants conditions need to be optimal. In this study, the naturally occurring high concentration of sulfate, as well as presence of Mn and Fe oxides, nitrate, oxygen, and carbon dioxides are the key terminal electron acceptors that were directly involved in the biochemical reactions of hydrocarbons mineralization. Without these terminal electron acceptors, the series of reactions would never occur, and further hydrocarbon degradation wouldn't be initiated onsite. The low concentration of lightweight hydrocarbons in the groundwater did not impose a high level of toxicity to the anaerobic soil microorganisms, but rather served as the food source (carbon source) for microorganism growth, development, and reproduction. With various electron acceptors and sufficient carbon source, the sulfate reduction rate is still limited. This is because of the depletion of dissolved sulfate, and the low groundwater temperature.

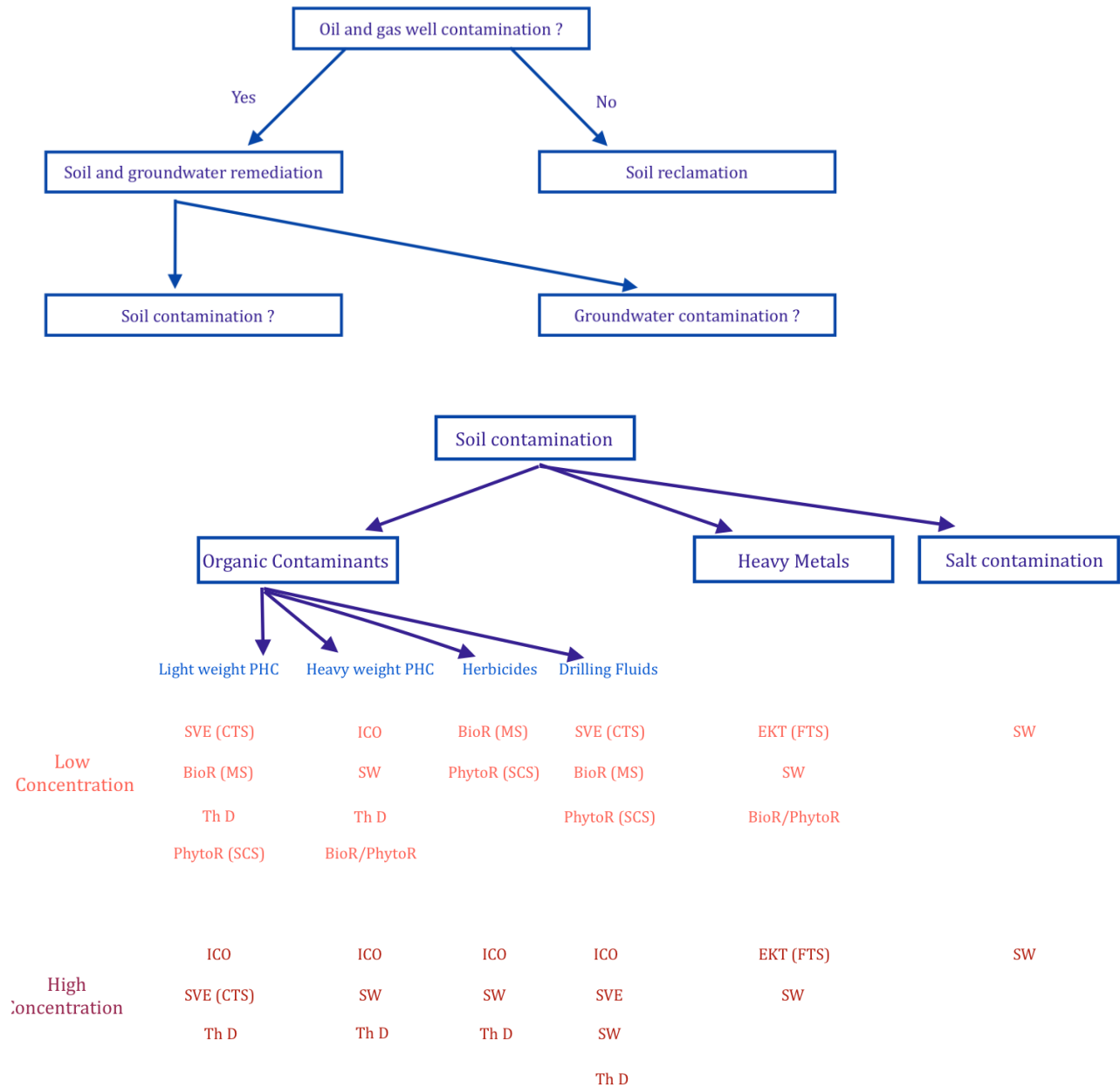
Natural attenuation of hydrocarbons through soil microorganism's activities is green technology from a sustainable development perspective. Compared to physical and chemical remediation technologies, bioremediation can reach permanent remediation without risks of re-pollution or re-contamination. Moreover, the insitu degradation processes have the least negative impacts on the soils and groundwater compared to physical and chemical remediation technologies which may have heavy machinery or equipment onsite. Moreover, the biological remediation technologies are cost-effective, since no input or minimum input is required to achieve contaminant removal. According to Qu (2010), the cost for the bioremediation is 30 % to 50% of the cost that is used in chemical and physical remediation.

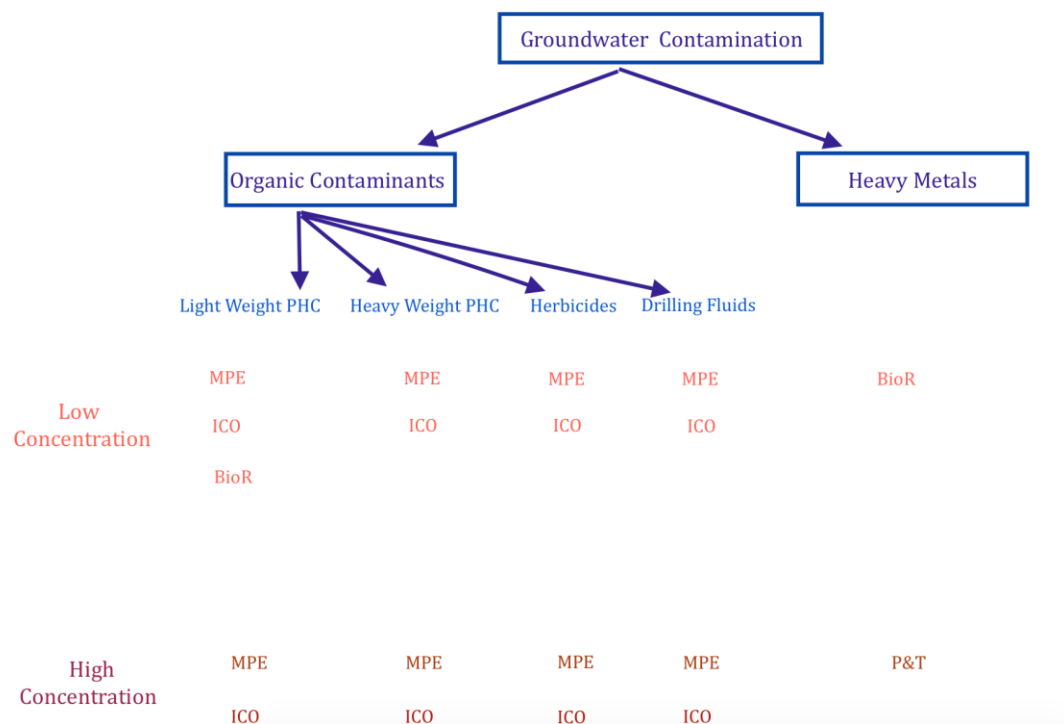
However, not all remediation of oil and gas well site contaminants can be remediated by biological activities. Bioremediation can be applied to certain contaminants rather than all contaminants. It can be easily restricted by the type and concentration of the contaminants onsite. Moreover, compared to physical and chemical remediation, biological remediation is relatively slow. The complete remediation of hydrocarbons may take years or even decades.

5. Discussion

From a scientific perspective, remediation of Alberta oil and gas well site contaminants requires a holistic understanding of both soil and contaminant conditions. Here, an oil and gas well site remediation framework is developed based on the integrations of the above knowledge about well site contaminant classification, soil and well site contaminant interactions, as well as reviews of remediation technologies. The purpose of the oil and gas well site remediation framework is to guide public audiences to the best available remediation technologies that can be applied in oil and gas well site by utilizing the information on the framework.

Figure 22. Soil Remediation Framework





PHC=Petroleum Hydrocarbons SVE=Soil Vapor Extraction BioR=Bioremediation PhytoR=Phytoremediation ICO=Insitu Chemical Oxidation
 SW=Soil Washing Th D=Thermal Desorption EKT=Electron Kinetic Technology MPE=Multiphase Extraction P&T=Pump and Treat
 CTS=Coarse Textured Soil FTS=Fine Textured Soil MS=Moisten Soil SCS=Shallow Contaminated Soil

This flow chat indicates well site soil and/or groundwater contaminations and their targeted remediation technologies at the slightly higher concentration (low concentration) and highly exceeds concentration (high concentration) conditions. Both groups of contaminants concentrations are compared to the benchmark concentrations in Alberta Tier 1 and 2 Soil and Groundwater Remediation Guideline (Appendix 1).

If multiple contaminants are present onsite at the same time, overlapping remediation technologies are recommended, since this overlapping single technology is able to treat multiple contaminants. When the contaminated site situation becomes over complicated, where one single technology fails to treat all contaminants, two or more remediation technologies can be mixed and matched in order to be more effective in removing well site contaminants.

6. Summary and Recommendations

The oil and gas industries in Alberta have significantly contributed to local and national economic growth. Beyond the economic benefits exist some negative environmental issues. The mixture of residue wastes generated from the oil and gas extraction well sites are the major environmental hazards to the surrounding soil and groundwater. Further, petroleum hydrocarbons, salty water, heavy metals, and other chemicals can easily create a “dead zone” to the environment. Fortunately, remediation of soil and groundwater can solve these emerging issues.

To utilize the effective remediation technologies available, it is necessary to understand the presence of site-specific contaminants, their chemical, physical and biological characteristics, and their interactions in the soils and groundwater. Moreover, evaluating soil conditions including soil texture, groundwater depth, redox potential, geological formations and mineral compositions also play a key role in the remediation technology choice and implementation.

In real life scenarios, the implementation of remediation practices on contaminated oil and gas well sites needs to take into account socioeconomic factors. Stakeholders, like the governments, landowners, well owners, environmental companies, social committees and even the general public who have a strong voice can influence the decision-making of well site remediation. Moreover, the amount of budgets for the oil and gas well site is another key factor in terms of influencing the final remediation technologies.

In order to achieve sustainable development with integrations of all environmental, social and economic factors, and to meet the expectation of “Green Trends”, introducing and implementing cost effective, site specific, environmentally friendly technologies like bioremediation and phytoremediation need to be encouraged and promoted in Alberta oil and gas well sites.

7. Appendix

Appendix 1. Alberta Tier 1 Soil and Groundwater Remediation Guidelines

Soil Type	Fine					Coarse					Notes
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	
Unit	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	
General and Inorganic Parameters											
pH (in 0.01M CaCl ₂)	6-8.5	6-8.5	6-8.5	6-8.5	6-8.5	6-8.5	6-8.5	6-8.5	6-8.5	6-8.5	1
Cyanide (free)	0.9	0.9	0.9	8	8	0.9	0.9	0.9	8	8	2
Fluoride	200	200	200	2,000	2,000	200	200	200	2,000	2,000	1
Sulphur (elemental)	500	500	500	500	500	500	500	500	500	500	3
Metals											
Antimony	20	20	20	40	40	20	20	20	40	40	1
Arsenic (inorganic)	17	17	17	26	26	17	17	17	26	26	
Barium (non-barite)	750	750	500	2,000	2,000	750	750	500	2,000	2,000	2
Barite-barium	10,000	10,000	10,000	15,000	140,000	10,000	10,000	10,000	15,000	140,000	4
Beryllium	5	5	5	8	8	5	5	5	8	8	1
Boron (hot water soluble)	2	2	2	2	2	2	2	2	2	2	1
Cadmium	3.8	1.4	10	22	22	3.8	1.4	10	22	22	2
Chromium (hexavalent)	0.4	0.4	0.4	1.4	1.4	0.4	0.4	0.4	1.4	1.4	2
Chromium (total)	64	64	64	87	87	64	64	64	87	87	2
Cobalt	20	20	20	300	300	20	20	20	300	300	1
Copper	63	63	63	91	91	63	63	63	91	91	2
Lead	70	70	140	260	600	70	70	140	260	600	2
Mercury (inorganic)	12	6.6	6.6	24	50	12	6.6	6.6	24	50	2
Molybdenum	4	4	4	40	40	4	4	4	40	40	1
Nickel	50	50	50	50	50	50	50	50	50	50	2
Selenium	1	1	1	2.9	2.9	1	1	1	2.9	2.9	2
Silver	20	20	20	40	40	20	20	20	40	40	1
Thallium	1	1	1	1	1	1	1	1	1	1	2
Tin	5	5	5	300	300	5	5	5	300	300	1
Uranium	33	23	23	33	300	33	23	23	33	300	
Vanadium	130	130	130	130	130	130	130	130	130	130	2
Zinc	200	200	200	360	360	200	200	200	360	360	2
Hydrocarbons											
Benzene	0.046	0.046	0.046	0.046	0.046	0.078	0.073	0.073	0.078	0.078	5
Toluene	0.52	0.52	0.52	0.52	0.52	0.12	0.12	0.12	0.12	0.12	5
Ethylbenzene	0.11	0.11	0.11	0.11	0.11	0.21	0.21	0.21	0.21	0.21	5
Soil Type	Fine					Coarse					Notes
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	
Unit	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	
Xylenes	15	15	15	15	15	28	12	12	28	28	5
Styrene	0.68	0.68	0.68	0.68	0.68	0.80	0.80	0.80	0.80	0.80	
F1	210	210	210	320	320	210	24	24	270	270	6
F2	150	150	150	260	260	150	130	130	260	260	6
F3	1,300	1,300	1,300	2,500	2,500	300	300	300	1,700	1,700	6
F4	5,600	5,600	5,600	6,600	6,600	2,800	2,800	2,800	3,300	3,300	6
Acenaphthene	0.32	0.32	0.32	0.32	0.32	0.38	0.38	0.38	0.38	0.38	
Anthracene	0.0046	0.0046	0.0046	0.0046	0.0046	0.0056	0.0056	0.0056	0.0056	0.0056	
Fluoranthene	0.032	0.032	0.032	0.032	0.032	0.039	0.039	0.039	0.039	0.039	
Fluorene	0.29	0.29	0.29	0.29	0.29	0.34	0.34	0.34	0.34	0.34	
Naphthalene	0.014	0.014	0.014	0.014	0.014	0.017	0.017	0.017	0.017	0.017	
Phenanthrene	0.051	0.051	0.051	0.051	0.051	0.061	0.061	0.061	0.061	0.061	
Pyrene	0.034	0.034	0.034	0.034	0.034	0.040	0.040	0.040	0.040	0.040	
Carcinogenic PAHs	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	IACR<1.0	7
Benz[a]anthracene	0.070	0.070	0.070	0.070	0.070	0.083	0.083	0.083	0.083	0.083	8
Benz[b]fluoranthene	6.2	6.2	-	-	-	6.2	6.2	-	-	-	8
Benz[k]fluoranthene	6.2	6.2	-	-	-	6.2	6.2	-	-	-	8
Benz[ghi]perylene	-	-	-	-	-	-	-	-	-	-	
Benz[a]pyrene	0.60	0.60	0.70	0.70	0.70	0.60	0.60	0.77	0.77	0.77	8
Chrysene	6.2	6.2	-	-	-	6.2	6.2	-	-	-	8
Dibenz[a,h]anthracene	-	-	-	-	-	-	-	-	-	-	-
Indeno[1,2,3-c,d]pyrene	-	-	-	-	-	-	-	-	-	-	
Halogenated Aliphatics											
Vinyl chloride	0.014	0.0083	0.0083	0.014	0.014	0.020	0.00034	0.00034	0.0043	0.0043	
1,1-Dichloroethene	0.15	0.15	0.15	0.15	0.15	0.24	0.021	0.021	0.24	0.24	
Trichloroethene (Trichloroethylene, TCE)	0.054	0.054	0.054	0.054	0.054	0.081	0.012	0.012	0.081	0.081	5, 11
Tetrachloroethene (Tetrachloroethylene, Perchloroethylene, PCE)	0.69	0.69	0.69	0.69	0.69	0.77	0.16	0.16	0.77	0.77	
1,2-Dichloroethane	0.025	0.0062	0.025	0.025	0.025	0.041	0.0027	0.0027	0.033	0.033	
Dichloromethane (Methylene chloride)	0.10	0.052	0.10	0.10	0.10	0.095	0.048	0.095	0.095	0.095	
Trichloromethane (Chloroform)	0.0029	0.0029	0.0029	0.0029	0.0029	0.0030	0.0010	0.0010	0.0030	0.0030	
Tetrachloromethane (Carbon tetrachloride)	0.037	0.013	0.013	0.037	0.037	0.062	0.00057	0.00057	0.0069	0.0069	

Soil Type	Fine					Coarse					Notes
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	
Unit	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	
Dibromochloromethane	0.91	0.12	0.91	0.91	0.91	1.5	0.12	0.27	1.5	1.5	
Chlorinated Aromatics											
Chlorobenzene	0.61	0.39	0.39	0.61	0.61	1.1	0.018	0.018	0.22	0.22	12
1,2-Dichlorobenzene	0.097	0.097	0.097	0.097	0.097	0.18	0.18	0.18	0.18	0.18	12
1,4-Dichlorobenzene	0.051	0.051	0.051	0.051	0.051	0.098	0.098	0.098	0.098	0.098	
1,2,3-Trichlorobenzene	0.26	0.26	0.26	0.26	0.26	0.31	0.26	0.26	0.31	0.31	
1,2,4-Trichlorobenzene	0.78	0.78	0.78	0.78	0.78	0.93	0.23	0.23	0.93	0.93	
1,3,5-Trichlorobenzene	1.9	1.9	1.9	1.9	1.9	3.6	0.13	0.13	1.3	1.3	
1,2,3,4-Tetrachlorobenzene	0.042	0.042	0.042	0.042	0.042	0.050	0.050	0.050	0.050	0.050	
1,2,3,5-Tetrachlorobenzene	0.37	0.37	0.37	0.37	0.37	0.70	0.10	0.10	0.70	0.70	
1,2,4,5-Tetrachlorobenzene	0.19	0.19	0.19	0.19	0.19	0.37	0.052	0.052	0.37	0.37	
Pentachlorobenzene	3.7	3.7	3.7	3.7	3.7	4.5	4.5	4.5	4.5	4.5	
Hexachlorobenzene	3.6	0.80	3.6	3.6	3.6	7.0	0.50	0.50	6.0	6.0	
2,4-Dichlorophenol	0.0029	0.0029	0.0029	0.0029	0.0029	0.0034	0.0034	0.0034	0.0034	0.0034	
2,4,6-Trichlorophenol	0.19	0.19	0.19	0.19	0.19	0.37	0.37	0.37	0.37	0.37	
2,3,4,6-Tetrachlorophenol	0.039	0.039	0.039	0.039	0.039	0.047	0.047	0.047	0.047	0.047	
Pentachlorophenol	0.024	0.024	0.024	0.024	0.024	0.029	0.029	0.029	0.029	0.029	5
Dioxins & Furans	0.00025	0.000004	0.000004	0.000004	0.000004	0.00025	0.000004	0.000004	0.000004	0.000004	9
PCBs	1.3	1.3	22	33	33	1.3	1.3	22	33	33	5
Pesticides											
Aldicarb	0.041	0.012	0.041	0.041	0.041	0.065	0.012	0.065	0.065	0.065	12
Aldrin	5.9	3.4	3.4	5.1	5.9	11	3.4	3.4	5.1	11	
Atrazine and metabolites	0.0088	0.0088	0.0088	0.0088	0.0088	0.010	0.010	0.010	0.010	0.010	
Azinphos-methyl (Guthion)	0.41	0.41	0.41	0.41	0.41	0.75	0.75	0.75	0.75	0.75	
Bendiocarb	0.14	0.14	0.14	0.14	0.14	0.21	0.21	0.21	0.21	0.21	
Bromacil	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	13
Bromoxynil	0.044	0.044	0.044	0.044	0.044	0.052	0.052	0.052	0.052	0.052	13
Carbaryl	1.9	1.9	1.9	1.9	1.9	3.6	3.6	3.6	3.6	3.6	12
Carbofuran	0.68	0.082	0.68	0.68	0.68	1.2	0.089	1.2	1.2	1.2	12
Chlorothalonil	0.0084	0.0084	0.0084	0.0084	0.0084	0.010	0.010	0.010	0.010	0.010	
Chlorpyrifos	49	3.2	49	49	49	95	3.8	95	95	95	12
Cyanazine	0.12	0.029	0.12	0.12	0.12	0.21	0.032	0.21	0.21	0.21	12, 13
Other Organics											
Soil Type											
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Notes
Unit	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	
2,4-D	0.43	0.10	0.43	0.43	0.43	0.67	0.10	0.67	0.67	0.67	12
DDT	0.7	0.7	12	12	12	0.7	0.7	12	12	12	5
Diazinon	2.2	2.2	2.2	2.2	2.2	4.2	4.2	4.2	4.2	4.2	12
Dicamba	0.50	0.12	0.50	0.50	0.50	0.79	0.12	0.79	0.79	0.79	12, 13
Dichlofop-methyl	2.0	0.079	2.0	2.0	2.0	2.4	0.095	2.4	2.4	2.4	
Dieldrin	0.59	0.59	0.59	0.59	0.59	1.1	1.1	1.1	1.1	1.1	
Dimethoate	0.0058	0.0028	0.0058	0.0058	0.0058	0.0055	0.0027	0.0055	0.0055	0.0055	
Dinoseb	2.8	1.4	2.8	2.8	2.8	5.5	1.7	5.5	5.5	5.5	12
Diquat	11	11	11	11	11	21	21	21	21	21	
Diuron	1.9	1.9	1.9	1.9	1.9	3.5	3.5	3.5	3.5	3.5	
Endosulfan	0.0013	0.0013	0.0013	0.0013	0.0013	0.0015	0.0015	0.0015	0.0015	0.0015	
Endrin	2.4	2.4	2.4	2.4	2.4	4.7	4.7	4.7	4.7	4.7	
Glyphosate	0.054	0.054	0.054	0.054	0.054	0.049	0.049	0.049	0.049	0.049	
Heptachlor epoxide	0.039	0.039	0.039	0.039	0.039	0.076	0.010	0.010	0.076	0.076	
Lindane	0.31	0.11	0.31	0.31	0.31	0.60	0.13	0.60	0.60	0.60	12
Linuron	0.051	0.051	0.051	0.051	0.051	0.059	0.059	0.059	0.059	0.059	13
Malathion	0.82	0.82	0.82	0.82	0.82	1.3	1.3	1.3	1.3	1.3	12
MCPA	0.42	0.026	0.42	0.42	0.42	0.66	0.025	0.66	0.66	0.66	12, 13
Methoxychlor	0.046	0.046	0.046	0.046	0.046	0.056	0.056	0.056	0.056	0.056	
Metolachlor	0.048	0.048	0.048	0.048	0.048	0.055	0.055	0.055	0.055	0.055	
Metribuzin	0.024	0.012	0.024	0.024	0.024	0.028	0.014	0.028	0.028	0.028	
Paraquat (as dichloride)	1.1	1.1	1.1	1.1	1.1	2.2	2.2	2.2	2.2	2.2	
Parathion	7.2	7.2	7.2	7.2	7.2	14	14	14	14	14	12
Phorate	0.075	0.075	0.075	0.075	0.075	0.14	0.14	0.14	0.14	0.14	
Picloram	0.024	0.024	0.024	0.024	0.024	0.022	0.022	0.022	0.022	0.022	
Simazine	0.033	0.033	0.033	0.033	0.033	0.038	0.038	0.038	0.038	0.038	13
Tebuthiuron	0.046	0.046	0.046	0.60	0.60	0.046	0.046	0.046	0.60	0.60	12, 13
Terbufos	0.080	0.080	0.080	0.080	0.080	0.15	0.15	0.15	0.15	0.15	
Toxaphene	3.3	3.3	3.3	3.3	3.3	6.3	4.8	4.8	6.3	6.3	
Triallate	0.0077	0.0077	0.0077	0.0077	0.0077	0.0092	0.0092	0.0092	0.0092	0.0092	
Trifluralin	0.038	0.038	0.038	0.038	0.038	0.045	0.045	0.045	0.045	0.045	
Other Organics											
Soil Type											
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Notes
Unit	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	
Aniline	0.36	0.36	0.36	0.36	0.36	0.60	0.60	0.60	0.60	0.60	12
Bis(2-ethyl-hexyl)phthalate	34	34	34	34	34	41	41	41	41	41	
Dibutyl phthalate	0.54	0.54	0.54	0.54	0.54	0.65	0.65	0.65	0.65	0.65	
Dichlorobenzidine	4.2	4.2	4.2	4.2	4.2	8.1	8.1	8.1	8.1	8.1	
Diethanolamine	2.0	2.0	2.0	2.0	2.0	3.5	3.5	3.5	3.5	3.5	14
Diethylene glycol	10	10	10	10	10	15	15	15	15	15	
Diisopropanolamine	14	14	14	14	14	17	17	17	17	17	5
Ethylene glycol	60	60	60	60	60	62	62	62	62	62	5
Hexachlorobutadiene	0.026	0.026	0.026	0.026	0.026	0.031	0.0067	0.0067	0.031	0.031	
Methanol	9.0	9.0	9.0	9.0	9.0	0.75	0.75	0.75	0.75	0.75	
Methylmethacrylate	1.3	1.3	1.3	1.3	1.3	1.8	0.10	0.10	1.3	1.3	
Monoethanolamine	20	20	20	20	20	10	10	10	10	10	14
MTBE	0.044	0.044	0.044	0.044	0.044	0.062	0.046	0.046	0.062	0.062	
Nonylphenol + ethoxylates	5.7	5.7	5.7	14	14	5.7	5.7	5.7	14	14	5
Phenol	0.0028	0.0014	0.0028	0.0028	0.0028	0.0024	0.0012	0.0024	0.0024	0.0024	5
Sulfolane	0.18	0.18	0.18	0.18	0.18	0.21	0.18	0.21	0.21	0.21	5
Triethylene glycol	100	100	100	100	100	150	150	150	150	150	

Soil Type	Fine					Coarse					Notes
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	
Unit	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	(Bq/g)	
Radionuclides											
Uranium-238 Series (all progeny)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	10
Uranium-238 (²³⁸ U, ²³⁴ Th, ²³⁴ mPa, ²³⁴ U)	10	10	10	10	10	10	10	10	10	10	10
Thorium-230	10	10	10	10	10	10	10	10	10	10	10
Radium-226 (in equilibrium with its progeny)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	10
Lead-210 (in equilibrium with ²¹⁰ Pb and ²¹⁰ Po)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	10
Thorium-232 Series (all progeny)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	10
Soil Type	Fine					Coarse					Notes
Land Use	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	Natural Area	Agricultural	Residential/ Parkland	Commercial	Industrial	
Thorium-232	10	10	10	10	10	10	10	10	10	10	10
Radium-228 (in equilibrium with ²²⁸ Ac)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	10
Thorium-228 (in equilibrium with its progeny)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	10
Potassium-40	17	17	17	17	17	17	17	17	17	17	10

Source: Alberta Tier 1 Soil and Groundwater Remediation Guidelines

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