Fracking Wastewater:

Recommendation for Cost Efficient Wastewater Treatment in the Fracking Industry

by

Shannon Schwingle

A Report Submitted to the Faculty of the

Milwaukee School of Engineering

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Environmental Engineering

Milwaukee, Wisconsin

August 2017

Abstract

The purpose of this paper is to explain a project in which wastewater treatment methods associated with hydraulic fracturing (fracking) were investigated. The goal of the project was to determine the most cost effective treatment method. A review of relevant literature was first conducted in order to develop an understanding of fracking and its technology, as well as associated issues, including fracking chemicals, environmental impacts, and regulatory concerns. Literature was additionally reviewed – and operators in the industry were consulted – in order to identify fracking wastewater treatment methods, practices, technology, and issues. Findings from this review of literature indicated that fracking wastewater characteristics vary from region to region, and even from well to well. As a result, no universal treatment method exists at this time. Instead, a proliferation of treatment methods were identified. Because of this state of affairs, it was recognized that project scope limitations needed to be imposed. These limitations included a focus on geographic region and on treatment methods. Although fracking occurs in several regions of the United States, this project focused on the Marcellus Shale region. A common treatment method and a relatively new method were the criteria employed to select two treatment options. A common treatment method in the Marcellus Shale region is the transportation of fracking wastewater to a centralized wastewater treatment (CWT) facility. A life cycle analysis was conducted in order to compare this treatment method with a new on-site evaporation method, Purestream's Accelerated Vapor Recompression (AVARA) system, in which wastewater can be re-used in a fracking operation. The main finding is that the AVARA option is a more cost-effective method – primarily because the transportation of wastewater entails significant costs. More research is necessary, particularly with a focus on the development of treatment systems that integrate operator feedback and that facilitate greater re-use of fracking wastewater in fracking operations. In addition, new fracking methods need to be developed, which do not rely primarily on the use of water. Such new methods could eliminate the need for fracking wastewater treatment, as well as offer other benefits, such as sustainability and the elimination of some environmental impacts.

Acknowledgments

The author wishes to thank Dr. Frank Mahuta Ph.D., J.D., Professor Gary Shimek, M.L.I.S., and Kenneth Kaszubowski P.E., for their extraordinary advice and support in this research project.

The author would also like to thank the many friends and family members that offered their encouraging words of support. It seemed they always knew when I needed them the most.

To the people that were willing to give the author their time and thoughts on what was given to them to read, thanks are not enough. Your willingness to read the project at various stages was greatly appreciated and that kindness and essential feedback that was given to enable the project to be completed will never be forgotten.

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Nomenclature

Abbreviations

bbl – a unit of measure indicating a barrel in terms of oil, the equivalent of 159 liters.

EPA – Environmental Protection Agency

NORM – naturally occurring radioactive materials

POTW – publically owned treatment works

TDS – total dissolved solids

Glossary

Aquifer – "A body of rock whose fluid saturation, porosity and permeability permit production of groundwater." [1]

Biocide – "An additive that kills bacteria. Bactericides are commonly used in water muds containing natural starches and gums that are especially vulnerable to bacterial attack." [1]

Borehole – "The wellbore itself, including the openhole or uncased portion of the well. Borehole may refer to the inside diameter of the wellbore wall, the rock face that bounds the drilled hole." [1]

Brackish water - Although quantitative definitions of this term vary, it is generally understood that brackish groundwater is water that has a greater dissolved-solids content than occurs in freshwater, but not as much as seawater (35,000 milligrams per liter*). It is considered by many investigators to have dissolved-solids concentration between 1,000 and 10,000 milligrams per liter (mg/L). The term "saline" commonly refers to any water having dissolved-solids concentration greater than 1,000 mg/L and includes the brackish concentration range." [2]

Casing – "Large-diameter pipe lowered into an openhole and cemented in place. The well designer must design casing to withstand a variety of forces, such as collapse, burst, and tensile failure, as well as chemically aggressive brines." [1]

Cement – "The binding material in sedimentary rocks that precipitates between grains from pore fluids. Calcite and quartz are common cement-forming minerals." [1]

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[1] Schlumberger. 2017. Oilfield Glossary. [Internet, WWW]. *Available:* Available from the Schlumberger website; ADDRESS: http://www.glossary.oilfield.slb.com/

[2] USGS. 2017. [Internet, WWW]. *Available:* Available from the USGS website; ADDRESS: https://water.usgs.gov/ogw/gwrp/brackishgw/brackish.html

Derrick – "The structure used to support the crown blocks and the drillstring of a drilling rig." [1]

Effluent – "Liquid waste that is sent out from factories or other places, often into the sea or rivers." [1]

Flowback – "The process of allowing fluids to flow from the well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for cleanup and returning the well to production." [3]

Fracking – "A method of getting oil or gas from the rock below the surface of the ground by making large cracks in it. Fracking is short for "hydraulic fracturing"." [3]

Potable Water – Water that is clean and safe to drink

Produced Water – "A term used to describe water produced from a wellbore that is not a treatment fluid. The characteristics of produced water vary and use of the term often implies an inexact or unknown composition. It is generally accepted that water within the pores of shale reservoirs is not produced due to its low relative permeability and its mobility being lower than that of gas." [1]

Proppant – "Sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment. In addition to naturally occurring sand grains, man-made or specially engineered proppants, such as resin-coated sand or high-strength ceramic materials like sintered bauxite, may also be used." [1]

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[1] Schlumberger. 2017. Oilfield Glossary. [Internet, WWW]. *Available:* Available from the Schlumberger website; ADDRESS: http://www.glossary.oilfield.slb.com/

[1] Cambridge Dictionary. 2017. Dictionary. [Internet, WWW]. *Available:* Available from the Cambridge Dictionary website; ADDRESS: http://dictionary.cambridge.org

Slurry – "A mixture of suspended solids and liquids. Muds in general are slurries, but are seldom called that. Cement is a slurry and is often referred to as such." [1]

Shale – "A fine-grained, fissile, detrital sedimentary rock formed by consolidation of clay- and silt-sized particles into thin, relatively impermeable layers. It is the most abundant sedimentary rock." [1]

Well Pad – "A temporary drilling site, usually constructed of local materials such as gravel, shell or even wood." [1]

[1] Schlumberger. 2017. Oilfield Glossary. [Internet, WWW]. *Available:* Available from the Schlumberger website; ADDRESS: http://www.glossary.oilfield.slb.com/

Chapter 1: Introduction

1.1 The Management of Fracking Wastewater

There is a new gold rush in the United States, but it doesn't involve gold at all. It is the booming industry of unconventional drilling, also referred to as fracking. The act of fracking involves drilling thousands of feet below ground level to a depth where the drill head is then turned horizontally to the target area. Once the target area is reached, a set of explosions are set off in order to break the shale rock, allowing a mixture of sand, water, and chemicals to be used to extract oil and natural gas. The amount of water used in this fracking process can be anywhere from two to six million gallons per well in the Marcellus Shale formation [1].

There are two types of wastewater produced by these wells. After the well is "fracked", some of the water sent down into the well flows back to the surface. This is called flowback water. After the well is put into production, water that has been trapped in the rock also comes to the surface with the gas or oil. This is called produced water. These produced waters can contain high levels of salts and dissolved solids from the rock that surrounded them for so many years [2, 3]. They can also contain radon and barium, which can create further challenges to treatment processes [2, 3]. This study focuses on treatment options for the flowback and produced water from the well.

Hydraulic fracturing -- also known as fracking or fracing -- has been a topic of controversy in recent years, yet its origins can be traced back to the 1860s in Pennsylvania and neighboring states [4]. Basically, in the early years of fracking, a charge was sent down an oil well bore to a determined depth and set off. Fracking's purpose in the oil industry has always been to enhance the ability to recover resources and increase production of wells. Of course, many developments in the technology have occurred since the 1860s. Today, hydraulic fracturing is routinely performed on each site of these unconventional horizontal wells throughout the country and abroad.

On June 14, 2015, the United States Environmental Protection Agency (EPA) released a report on fracking that was over 1,000 pages long with appendices [5]. The purpose of this report was to briefly explore what fracking is, the impacts it has on water resources, and to provide a recommendation for wastewater treatment that is efficient and cost effective. One of the major findings of this report was that each well has very distinct characteristics that make it difficult to design a single treatment method for the wastewater that is created and produced by the well. Additionally, costs of trucking wastewater to centralized wastewater treatment (CWT) facilities proved to be a major factor in the overall costs regardless of method used.

The current process of hydraulic fracturing involves drilling one vertical well that can then have multiple horizontal wells drilled from it in multiple directions to reach trapped oil and gas in tight shale formations. Thus, horizontal drilling has made it possible to reach out in all directions from the vertical well and thus expand the total area from which oil and gas can be extracted. This arrangement of wells requires more water to be used to complete the fracking process. The resulting flowback and produced waters need to be treated before they can be re-used or released into the environment. The challenge presented is how to treat the water efficiently and cost effectively.

The challenge is significant. A fracking site employs millions of gallons of water, requiring decisions about how to handle the water, how to store it (if necessary), and how to treat the water that returns to the surface during and after a fracking job [6]. In this report, a cost analysis was performed that was used to determine the most cost effective treatment option for treating fracking wastewater. A number of on-site treatment technologies exist for fracking wastewater; alternatively the wastewater can be shipped to an off-site facility for treatment [7]. Much of the cost for the off-site option is associated with the cost of trucking [7]. There may be a distance at which it makes economic sense treat the water on-site versus shipping the wastewater to a plant for treatment.

The use of fracking is related to the price and amount of oil the United States at any given time: if oil prices are low and surplus oil is plentiful, fracking in the United States slows down; when prices go back up, and there is more need for oil and natural gas again, fracking is called upon to replenish these reserves. With more fracking comes more water usage, and thus more wastewater is generated. Depending on the location of the well, the composition of the wastewater will vary, and thus specific methods of treatments are typically needed for specific locations.

An option that has been popular to use is the injection of the wastewater back into the earth using deep injection wells [8]. These wells go deep into the earth, below drinking water aquifers, and the wastewater gets pumped into these porous formations. These injection wells have recently been linked to earthquakes in areas where the wells are present [9].

When an injection well is not an option, trucking the wastewater off-site to a centralized treatment facility has been popular [10]. These treatment plants are usually centrally located in areas where multiple shale plays have been identified. Shale plays are geographic formations of rock in which significant accumulations of natural gas or oil are present. Much of the cost associated with this disposal option is for transporting the water to, and sometimes back, from the facility [7].

A developing trend entails treating the water on-site using various methods, typically determined by the composition of the wastewater itself [8]. These methods include physical separation (e.g. filtration), chemical treatment (e.g. precipitation), and evaporation [8, 11, 12]. Lower costs are often associated with these forms of treatment, but that is determined by the ultimate quality of the water required at the end of treatment and trucking distances for off-site disposal options [13]. Depending on whether the water is to be used again, or if it is to be discharged to the environment, these costs can vary dramatically.

There has been concern over the water supply aquifers becoming contaminated by fracking wastewater [14]. Fracking wells can be drilled thousands of feet below the aquifers that are used to produce drinking water, but there is still concern that there could be contamination through the loss of integrity of a well casing, allowing a leak leading to contamination.

Along with aquifer contamination concerns, there are additional environmental concerns that have led to increased regulation of the fracking industry [15]. The federal government so far has asserted little regulatory jurisdiction over fracking, instead leaving it up to the states to decide what regulations, if any, should be passed and enforced with respect to the fracking industry. Recently, there have been more studies by the EPA to better understand the risks and benefits of fracking and how to address these environmental concerns going forward [5]. With respect to its current technological status, fracking is still relatively new, and there is still much to learn about what happens in the process and in the aftermath of developing an unconventional well.

1.2 Purpose of This Project Report

The purpose of this project report is to describe briefly the process of hydraulic fracturing, to explain what impacts it has on water sources, and to provide a recommendation for a wastewater treatment and disposal method that is both cost-effective and efficient.

There are numerous environmental concerns that surround fracking as a method of extracting fossil fuels from tight shale rock formations. Fracking a single well requires using millions of gallons of water under tremendous pressure to fracture rock deep under the surface of the earth [16]. Of all the water used, a portion of it returns to the well head as flowback water. This considerable volume of water needs to be disposed of properly or treated to be used again or released into the environment. Consideration also needs to be given to the water that comes to the surface after the well is in production. This water is termed produced water and often will have a much different composition than flowback water, since produced waters have very high dissolved solids concentrations because of the rock formations surrounding it.

1.3 Organization of This Project Report

This report is organized in the following manner. A summary of the fracking process is presented which includes a discussion of the environmental impacts that occur as a result of this process. A literature review follows with an emphasis on the chemicals used and the treatment technologies available for the wastewater generated by fracking. The treatments are categorized as off-site and on-site. The report also features a review of new and developing technologies for treatment. Next, the discussion turns to the wastewater technologies that were selected for further analysis by means of a life cycle cost analysis (LCCA). This discussion is followed by the results of the LCCA, along with a discussion on how these results were obtained. Finally, the report closes with recommendations concerning wastewater treatment, as well as future research recommendations.

Chapter 2: Background

2.1 What is Fracking?

Fracking is the process of drilling a well into a rock formation and then injecting a mixture of water, sand, and chemicals into the well at a high pressure to create little fissures in the rock so that the trapped gas can be released and captured at the well head [16]. The purpose of fracking is to make accessible the oil and natural gas that is trapped in shale rock formations that had previously been thought to be inaccessible. The development of horizontal drilling has been a game changer in this process to access these shale resources. Origins of fracking can be traced back to the times of the Civil War when a patent was issued to Edward Roberts in 1865 for what he called the exploding torpedo [4]. The torpedo would be lowered into the well close to the oil, where it was exploded, and then the well would be filled with water. This process was credited with increasing well production 1200 percent [4].

In the 1930s, the first innovation in fracking occurred when acid was used instead of nitroglycerin, which made the well less apt to close, and thus increased its production [4]. Modern-day fracking can be credited to Floyd Farris of Stanolind Oil and Gas, who in 1947 began a study on the relationship of the oil and gas production of wells and the pressurization on the wells themselves [4]. This study led to an experiment in Kansas where gelled gasoline and sand was sent 2,400 feet down into a limestone formation, followed by a gel breaker. The experiment did not produce an increase in production for the well, but it did succeed in creating the need to continue experimenting [4]. Two of these experiments were conducted in 1949 by Halliburton, one in Oklahoma and another in Texas [4]. These experiments proved to be more successful and quickly helped lead to the commercialization of fracking.

In the 1960s, fracking was being used in Oklahoma, and grew to include Colorado, New Mexico, and Wyoming through the 1970s [4]. This was significant enough to gain the attention of President Gerald Ford, who called for further exploration in shale formations during his State of the Union address in 1975 to reduce the dependency of the United States on foreign oil imports [4].

Current shale plays in the United States can be seen in Figure 1. The figure shows the many different areas where prospective, and active, plays are located. Many of the lower 48 states are shown to have shale formations that can be explored for production of natural gas and oil.

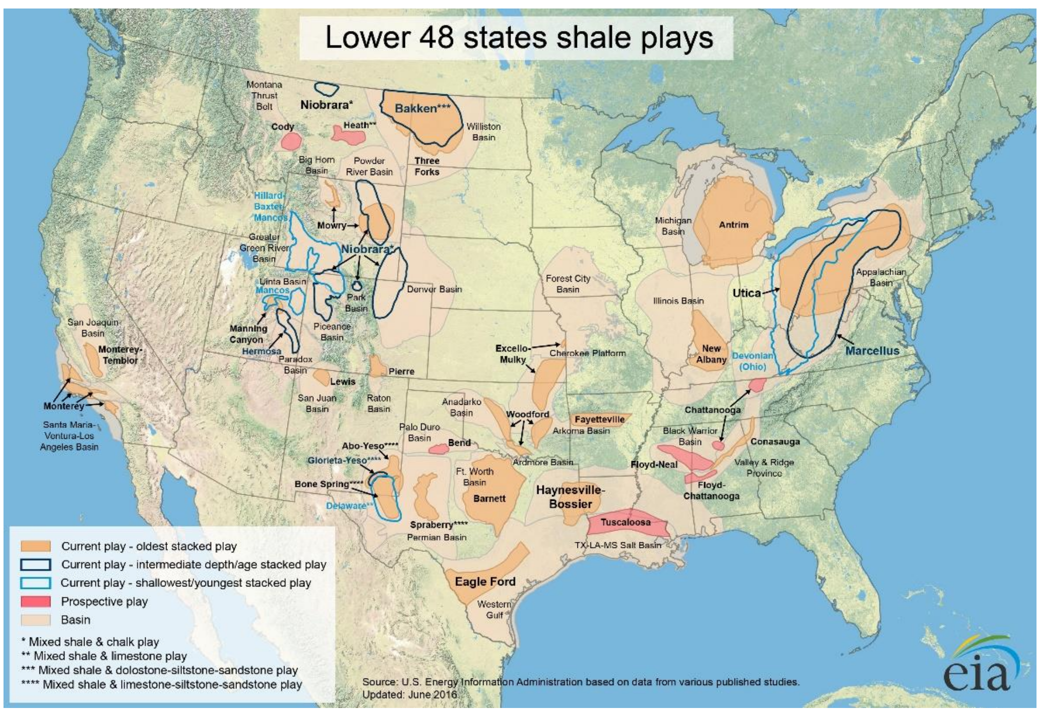

Figure 1: United States Shale Formation Map [17].

The real boom in the fracking industry occurred when horizontal drilling was combined with the fracking operations. This innovation occurred in the 1990s and continued to grow as the demand for oil became greater, creating higher prices and the driving force behind further exploration of fracking as a method to extract oil and gas from shale [4].

2.2 Fracking: Growth and Controversies

In recent years, the development of fracking in the United States has created a boom in drilling wells in regions where there are shale formations that contain what is referred to as natural gas. One of these regions, the Marcellus Shale Formation, is believed to be one of the largest reserves of natural gas in the world with estimates for technically recoverable gas at 3.99 trillion cubic meters to 13.85 trillion cubic meters [1]. This formation lies in the Northeast United States, as seen in Figure 2, under almost all of

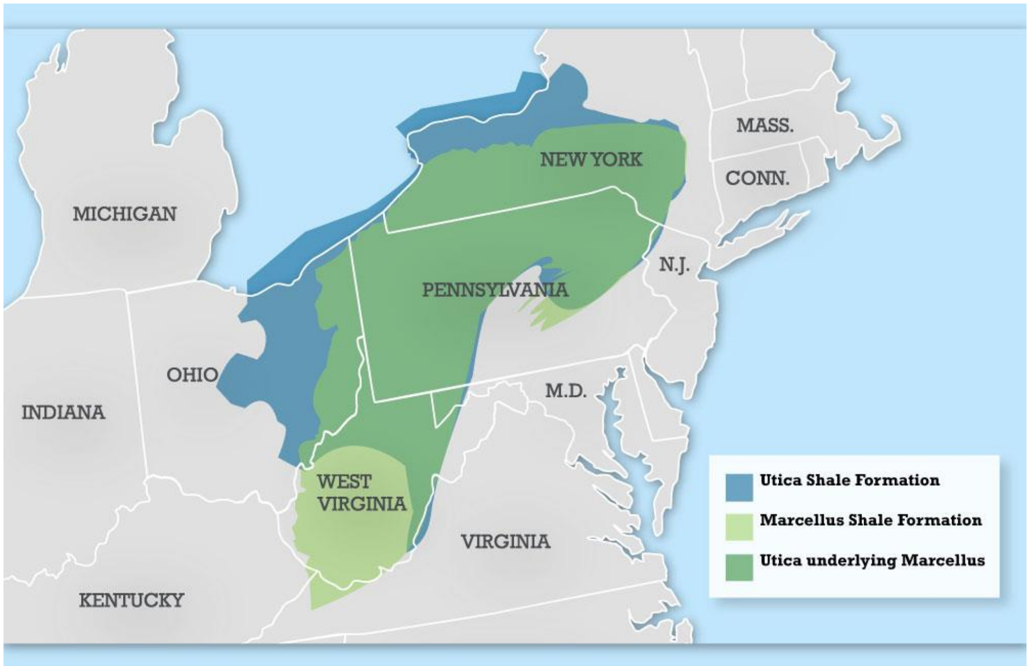

Figure 2: Marcellus Shale Formation Map [18].

West Virginia, well over half of Pennsylvania, and parts of surrounding states. These reserves were thought to be unreachable until the technology of horizontal drilling was developed. With this development, there are wells being drilled in areas that have never before had this type of activity in them. These wells are getting closer and closer to population centers, contributing to the current conflict and controversy that exists around hydraulic fracturing.

One of the topics of concern is that environmental impacts of hydraulic fracturing are not fully understood. These impacts can include anything from the rock fracturing causing earthquakes, to water supply contamination, to people being in danger by just being in the vicinity of a well as a result of air pollution [19]. These uncertainties have influenced some local municipalities to ban fracking operations in their jurisdictions [20].

2.3. How Fracking Works

The process of hydraulic fracturing begins with the construction of a drilling rig on site that will be a temporary structure and used in the process of drilling the well. These drilling rigs are referred to as derricks and are used in both vertical and horizontal wells. This stage of constructing the drill rig takes, on average, three days. Once the derrick is constructed, the vertical well phase can start. This stage takes about 14 days to complete, depending on the depth or location of the target formation for the well. This would be the same type of well for conventional oil drilling or conventional gas drilling. The conventional and unconventional types of wells for gas and oil production are shown in Figure 3.

During the drilling process, steel casing called conductor casing is placed in the well bore.

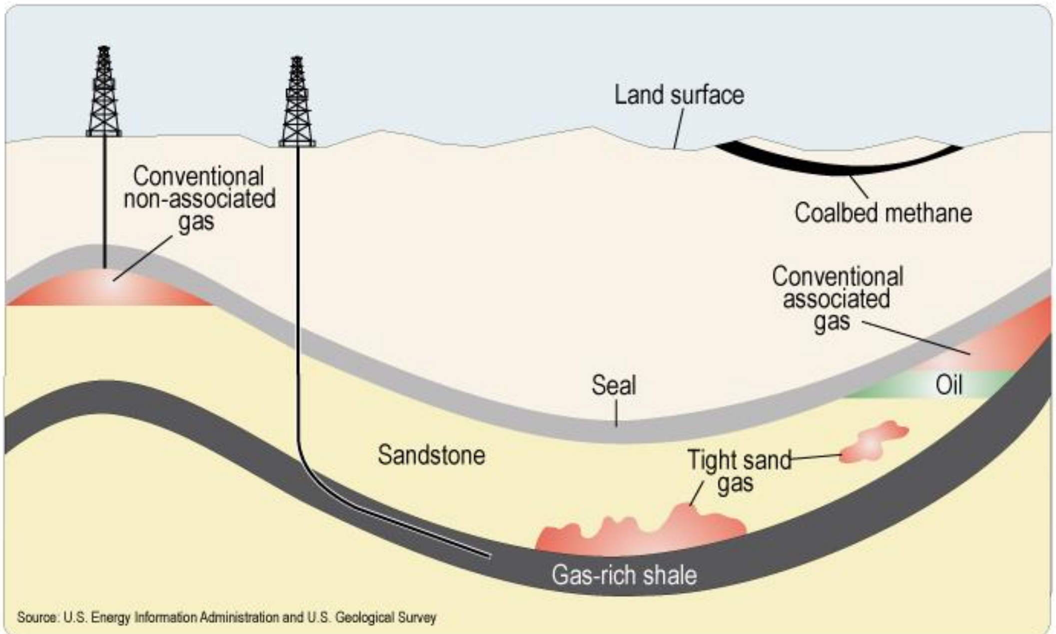

Figure 3: Conventional and Unconventional Gas and Oil Wells [21].

These sections of casings, called “strings”, are cemented into place, forming a bond between the casing and the bedrock and helping to mitigate the potential for contaminant transport along the well bore. On average, Marcellus Shale wells use more than 3 million pounds of steel and cement in this process that eliminates pathways for hydrocarbons to escape [22]. The next stage is to place surface casing, which is separate from the conductor casing, and extends past all potable sources of water. These steel strings are placed to protect underground sources of water. Typically, shale formations that are targeted reside over a mile below the surface, separating them from sources of groundwater by thousands of feet of impermeable rock layers. At around 500 feet above the target formation, the vertical well begins its horizontal trajectory. This point is referred to as “the kick off point”. Well design and location of the shale being targeted dictate the length of the horizontal sections, which may extend 1,000 to 10,000 feet.

As drilling continues in this horizontal direction and as it reaches its targeted depth, production casing is lowered into the well and cemented into place. The section of the well that is next to the horizontal part of the well is referred to as “the heel” and the very end on the horizontal well is referred to as “the toe”. The fracturing stages begin at the toe and work back towards the heel. These stages begin with the perforating of the well to enable hydrocarbons to flow to the surface. This is accomplished by lowering a perforating gun into the well, where it creates a series of small holes that penetrate the production casing, the cement, and the neighboring rock. This series of holes creates areas where the fracturing fluid will enter the formation and create the path through which the hydrocarbons will travel into the well.

The completion phase commences once the drilling is complete and the derrick is removed from the site. This stage usually takes from 3 to 10 days, depending on well design. This is when the actual fracturing of the rock takes place by the injection of a fracking fluid consisting of over 99% water into the well at pressures that range from 10,000-20,000 psi [23]. Within the fluid, there are chemicals and proppant (typically, sand or ceramic material) designed for that specific rock formation and its properties to enable the well to be productive. This fracking fluid, which can vary in composition, is called slickwater. Slickwater helps to facilitate the placement of the proppant in the rock fractures and create a better environment for the gas to travel through. After the slickwater has been sent through the well system, the proppant is pumped into the well to prop open the fractures and facilitate the flow of the gas from the shale rock formations.

Once this procedure is completed, the drillers flush the well with freshwater to remove any excess materials [24]. This water is then returned to the surface and is referred to as *flowback water*. It contains debris left by the perforating process and any excess proppant that didn't find its way into the fractures in the formation. Upon recovery of this flowback water, the well is ready for production. In addition to flowback water, there is also water generated by the well during its lifetime. This water is referred to as *produced water* and is naturally occurring in the shale formation. It can contain natural occurring radioactive particles as well as other minerals and suspended solids that are found in the shale rock formations [25]. Figure 4 provides an overview of the fracking process.

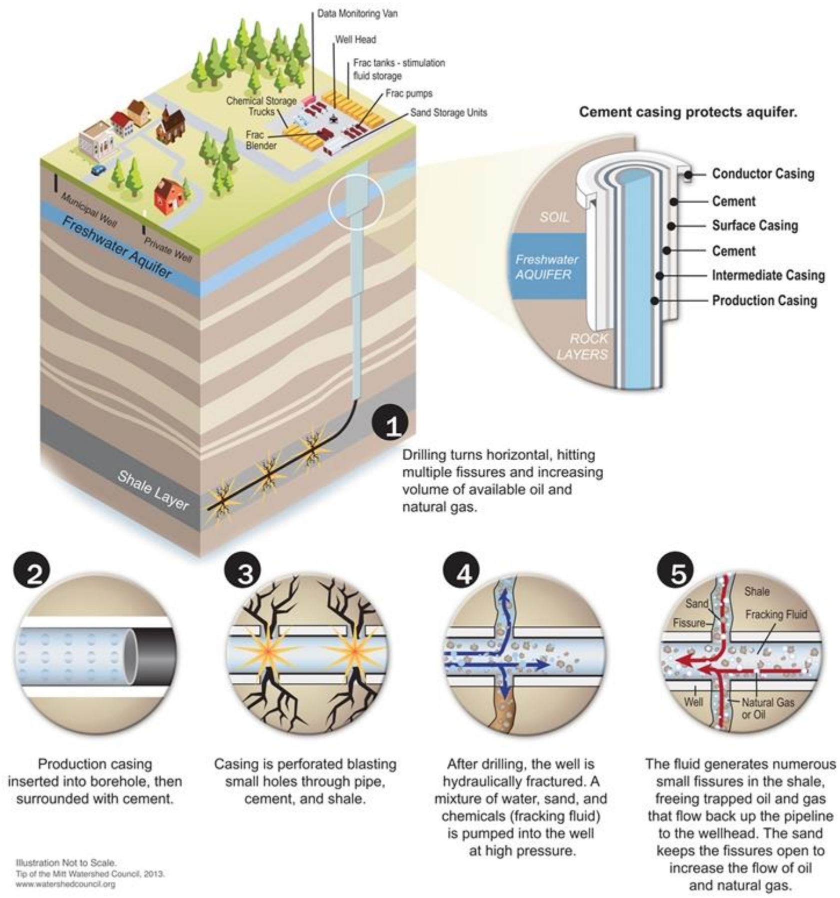

Figure 4: Hydraulic Fracturing Process [26].

This fracturing process is repeated for each stage that the well is designed for. Each fracturing process is referred to as a frac job. There can be up to 40 frac jobs that take place during the development of a well [27].

In the fracking industry, best management practices have developed to include the use of monitoring wells that are being placed around the well pad before, during, and after the hydraulic fracturing process [28]. The monitoring wells are placed before fracturing that provide a water quality baseline in the area before any drilling occurs. If there are any contaminants already present in the water, the oil and gas companies cannot be held responsible for them. Throughout the fracturing process, regulations are in place in certain states to require the sampling of the water at predetermined time intervals to ensure there are no leaks into the groundwater systems [28]. These monitoring wells also provide an early warning system in the event that a casing leak occurs during the production of the well.

2.4. Environmental Impacts Associated with Fracking: Air Pollution, Solid Wastes, Wastewater

The process of fracking and the wastes it generates have raised many concerns with respect to the environmental impact this method of hydrocarbon extraction can have. One of the environmental impacts of concern is the volume of water needed to hydraulically fracture a well. In the Marcellus Shale region, the average volume of water required to fracture a single well is 15,000 m^3 [29]. This water can be obtained by re-using recycled water from previous drilling operations or by using fresh water. The volume needed to fracture any given well depends greatly on the geographical area the well is in and the design of the well itself. The impact that the removal of this volume of water can have on an area depends on the region in which the well is being drilled. This volume of water will have different effects on aquifers and watersheds from different regions, based on the availability of water within the watershed.

Treatment of wastewater from hydraulic fracturing currently includes but is not limited to disposal using injection wells, trucking to off-site treatment facilities, and on-site treatment for reuse or disposal [8]. The composition of the wastewaters from these wells will vary because of the properties of the rock formation into which the well is drilled. For example, Marcellus Shale wells are known to have produced water high in dissolved salts [30]. The different characteristics of the wastewater dictate the type of treatment necessary to reuse or dispose of the wastewater. Each of the above mentioned methods of disposal have a cost associated with them. In the Marcellus Shale Formation in 2012, it is estimated that it costs from $.36 to $.63 per cubic meter to reuse produced water, $.59 to $13 per meter cubed for deep well injection, and $53 to $71 per meter cubed for desalination and treatment for surface water discharge [29]. Government regulations dictate to what degree water needs to be treated to be released back to the environment.

There currently is great debate on whether regulations for hydraulic fracturing should be established by the federal government or by the individual states. In 2005, the Energy Policy Act was passed by Congress. In this act, gas extraction industries were exempted from any federal regulations and any oversight under the Safe Drinking Water Act (SDWA) [31]. In 2009, The Fractured Responsibility and Awareness of Chemicals (FRAC) Act was presented to Congress. The act seeks to amend the SDWA Act to allow the EPA to regulate hydraulic fracturing and require companies to disclose chemicals used in the fracturing process [32]. The Congressional session expired before any action was taken. The FRAC Act has stalled several times since then, and as of the writing of this paper, has yet to be passed [32].

In the state of Pennsylvania, the Oil and Gas Act was passed in 1984 [31]. This act required all new wells to obtain a permit prior to drilling, and it additionally required that all existing wells be registered. It also laid the groundwork to regulate the many aspects of drilling wells, such as bonding, permitting, registration, locations, protection of water supplies, and protection of groundwater [31]. As an amendment to the Oil and Gas Act, the Pennsylvania State General Assembly passed Act 13 into law in February 2012. This legislation created a procedure to collect fees to be used to cover the impacts of drilling. Controversial part of this legislation is that it prevents local municipalities from using zoning ordinances to prohibit drilling [31]. In Pennsylvania, Chapter 95 regulates wastewater treatment requirements for the state. Pennsylvania State Statute 95.2 regulates effluent standards for industrial wastes. This statue states that industrial wastes must meet the following requirements: wastes must feature pH no less than 6 and no greater than 9, except where the wastes are discharged into an acid stream, in which case the pH can be greater than 9; oil bearing wastewaters must not cause a film or sheen of the wastes or shoreline; wastes cannot have more than 15 mL of oil per liter per day on average or have more than 30 mL of oil per liter at any time; water must not contain more than 7 mg per liter of iron [33].

As a part of the fracking industry boom that has happened in recent years, there is controversy over the environmental risks associated with obtaining resources from shale formations. These risks create concerns over groundwater contamination, accidental spills, waste disposal, air quality, the footprint of drilling pads, pipeline placement and safety, and the amount of water used [34].

Well integrity is crucial in protecting the groundwater aquifers against contamination. As explained earlier in this paper, there is a detailed process during drilling to ensure groundwater is protected. Several layers of steel casings that are cemented into place prevent contaminant transport along the well bore into the groundwater. It is important for the operator of the well to follow the procedure and test well integrity throughout the drilling process, as required. Any deviation from this procedure could result in contamination because of well integrity failure [35].

Through the drilling process and life of the well, wastewater is produced. These wastes can be from flowback, or they can be produced from the rock formation itself. The water needs to be collected and treated on-site or shipped elsewhere for treatment or disposal. The method of collection can be in large retention ponds, or tanks on the site of the well pad. Anytime there is storage of a waste, there is the risk of a spill. There is no exception in this case of storing wastewater from hydraulic fracturing. The large ponds are required to have linings on the bottom to help prevent leakage from them. Unfortunately, these linings are susceptible to ripping and accidental leakage occurs as a result [36]. Tanks can develop small cracks and leak after use over time. The pipes used to transport the water from the well to the storage vessel can have leaks. There are any number of ways an accidental spill can occur. The key is to continue to improve the methods and safety procedures on-site to avoid these spills.

Solid wastes are also created in the drilling process in the form of well cuttings. There may also be solid wastes in the retention ponds for the wastewater where the sediments have dropped out of solution. These wastes could contain toxic chemicals used during the fracking process and they can even contain naturally occurring radioactive material or NORM, rendering them radioactive, which means they have to be treated as radioactive waste [25]. Because the drilling process itself brings the wastes to the surface, there is no way around the generation of these wastes with current technology, and they need to be handled and disposed of properly.

An often overlooked environmental concern of fracking is air quality. At any given well pad, there are numerous pieces of equipment that need power to run. Often the power will be provided by generators. There is also the potential for a lot of truck traffic to bring in the water and equipment, as well as to remove the wastes as they are generated. After production begins at the well, there may be what is called “flaring” occurring at the well pad. Flaring is when methane gas is set on fire to burn it off to limit the amount of methane being released into the atmosphere. Methane is a strong greenhouse gas and cannot be allowed to enter the earth’s atmosphere in great volumes [37]. This flaring can have an effect on the air quality at the well pad and also on the surrounding areas. For instance, in the case of Dish, Texas — a small town 35 miles north of Fort Worth, where fracking takes place -- local residents complained to local authorities of illnesses [19]. The local authorities did not take action on these complaints and eventually, the EPA had to investigate the situation. After testing of the air quality in the area and testing of residents’ blood and urine, it was found that people living in the town had toluene and xylene in their blood and urine samples [32]. Toluene and xylene are both hydrocarbons that are used in many household and industrial products as well as cigarettes [32]. Exposure can occur through dermal, ingestion, or inhalation of the substances. No evidence exists that the presence of toluene and xylene are directly attributable to fracking activities, but residents are convinced that a link exists.

The well locations themselves have been moving closer and closer to more densely inhabited areas with the advent of horizontal drilling. The locations of these well pads that are moving closer to communities have so far turned out to be in areas where the inhabitants are of color or living in poverty, rather than in more affluent white locations [38]. Within these areas, there is likely to be less resistance to the application of disposal well permits as there is not often the political backing needed to halt the oil companies from obtaining the permits [38]. The literature indicates that there are many risks associated with the operation of disposal wells, such as contamination of the groundwater, risks of spills in the surrounding area during transportation, increased seismic activity, and general adverse health risks [38].

Another issue associated with the drilling and fracking locations is property values in the surrounding areas. When a location to drill has been secured, there is a lot of heavy equipment that is brought into the area, which puts stress on existing roadways and all neighboring properties. In addition, the risk of spills by tankers, possible groundwater contamination, and air pollution all have an effect on the value of properties in the drilling and fracking area [39]. There have been numerous case studies in which contamination has occurred and people's health has been altered since drilling and fracking has commenced in a given area. Within these areas, the oil and gas companies have tried to discredit findings of the EPA and other groups in relation to the contamination [39].

In order for an entity to remove minerals from below the surface, they have to obtain the mineral rights. Natural gas and oil are treated in the same manner, and as such, it is required that the mineral rights be obtained prior to removal. An interesting situation occurs when the land owner has surface rights but not the mineral rights. These situations are referred to as split estates [40]. Split estates often create uneasiness amongst landowners in a region where fracking has become active because they have little control over what happens to their land and homes when a discovery of resources has been made. Depending on the location, there are few or no laws that will protect a land owner from a company coming in and taking their land from them in order to remove the resources that are held below the surface [41]. Recently, the legal concept of eminent domain has been used successfully by private companies to remove land from landowners so that the companies can develop the land or remove the minerals below it. The process of eminent domain has been successfully employed by drilling companies for fracking operations [41]. The Supreme Court case of Kelo vs. City of New London (Kelo) in 2005 set a precedence for private companies to acquire land. In the case of Kelo, the argument was made that public use was satisfied by the increased taxes that would be collected by the municipality. States have further augmented the phrase public use by adding public purpose to state eminent domain status. Further, hydro fracturing companies can claim common carrier or public utility company (PUC) status under state laws to connect pipeline networks. Challenges have been made in eminent domain cases, but the challenges usually last years, are very costly to the landowner, and often do not result in a halting of the procedure [41].

The development of shale gas wells requires the mobilization of large and heavy equipment to sites usually in rural areas. The equipment is moved to the site by the way of trucks that in many cases exceed normal truck sizes and weights [42]. Many trips of these heavy trucks are necessary to get a well built and ready for production. This above normal traffic in weight and frequency places much stress on roads and in turn can damage them. Much debate has occurred within these state and local transportation departments on how to allot the funds needed to off-set the damage incurred through the numerous heavy trucks traveling on roads that were never meant to handle that type of traffic. There are limited areas of road in Pennsylvania that are under agreements with shale development firms to be reconstructed when visual damage is observed [43]. The other areas of road, however, are left to the states and local municipalities to reconstruct, and in many situations, the state and local budgets are unable to cover the escalating costs. In the case of Texas, they required additional funding through legislative actions that include a House Bill and Senate Bill for a total combined amount of $450 million in funds to be used in counties of increased energy activity [44].

2.5. Environmental Regulations Associated with Fracking

Current regulations for fracking are largely in the states' hands. Pro-fracking states and groups want to keep the federal government out of the process, leaving all regulation in the hands of the states, claiming that federal regulations are redundant, and would cost the industry more money and make unconventional drilling economically less feasible [45]. Anti-fracking groups feel that the states are not doing a very good job of making and enforcing the regulations needed to keep the public safe. There have been accounts of contaminated groundwater and links made to air pollution and illness [32].

Through the years, the fracking industry has been able to avoid federal regulations because it has been declared exempt in regulatory activities. The regulations include the Clean Air Act of 1970, Clean Water Act of 1972, Safe Drinking Water Act of 1974, Resource Conservation and Recovery Act of 1976, Comprehensive Environmental Response, Compensation and Liability Act of 1980, and the Emergency Planning and Community Right-To-Know Act of 1986.

Some states such as New York have taken it upon themselves to ban fracking altogether. In 2010, New York placed a moratorium on hydraulic fracturing and horizontal drilling that was to remain in place until July 1, 2011 [32]. On December 17, 2014, hydraulic fracturing was permanently banned in the state of New York [46]. The basis of the ban was that the city of New York relies heavily on the groundwater that originates in upstate New York. If anything were to happen to that water source, the whole City of New York, among other municipalities, would be in danger of losing their water supply.

Chapter 3: Literature Review

3.1 Chemicals in Hydraulic Fracturing Wastewater

In a fracking operation, of the water volume that is sent down the borehole of the well to do the fracking, chemicals account for less than one percent of that overall liquid volume [47]. These chemicals are there to aid in the recovery of the gas in the well [28]. The chemicals can serve a number of purposes, from reducing scaling in the piping to limiting bacteria growth throughout the well [28]. Based on the location of the well being fracked, and the company doing the fracking, the composition of the chemical mixture can vary greatly. Often, the nature of the chemical mixture is determined by the composition of the rock formation [48]. There is an important resource that registers many of the fracking wells in the United States and lists the chemicals being used at each well site. This resource is a website called Frac Focus, which is a searchable web-based "chemical disclosure registry" available at http://www.fracfocus.org [49]. This website was created by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission to give the public access to information about the chemicals being used in wells in their area. The oil and gas companies doing the drilling are encouraged to participate and to create a more transparent relationship with the public to help clear up the myths that have developed around the hydraulic fracturing industry. The intent of the website is to provide factual information on the sites in the United States where there are wells. It is a registry in which some states are requiring companies to disclose their chemical information in one web-based location that the public can then access. This registry is strictly for the chemicals that are being added to the water prepared by the well operating company and does not include any chemicals or radioactive material that may be picked up from contact with the rock formations on the way back out of the well.

A concern with respect to the materials and chemicals that are coming out of the hydraulically fractured wells is radioactivity [24]. In the process of fracking, the water slurry comes in contact with the rock formations it is traveling through. In these rock formations, there are naturally occurring radioactive materials (NORM), such as radium, which are picked up and returned to the surface at the well head in the wastewater. Not all wells produce these wastes, but at the ones where they do occur, the machinery and equipment that comes into contact with the wastewater have to be cleaned and the radioactive material must be disposed of properly. In Texas, much of the flowback water that contains these radioactive materials is disposed of by directly injecting them deep into the earth in deep injection wells [50]. Such wells are not available in areas such as New York and Pennsylvania [19].

3.2 Off-Site Wastewater Treatment

The amount of water needed to hydraulically fracture any given well nationally averages 20 million liters [19]. The amount of water that will be discharged out of the well as flowback soon after injection is estimated to be around 60%, which means around 12 million of the initial 20 million liters would be available for treatment [51]. For some, the enormous amount of water required to fracture rock might seem shocking. To put these large numbers in perspective, Bitto indicates that currently, close to 95 billion liters of water are needed every year for the hydraulic fracturing industry [52]. As immense as 95 billion liters sounds, it only equates to less than 0.03% of total current water use in the United States [52]. The greater concern with respect to wastewaters produced at the well site of a hydraulic fracturing operation is the content of contaminants in the water and the treatments and disposal of these waters and contaminants [19].

In the late 2000s, when fracking increased in Pennsylvania, the companies performing the fracking captured the wastewater from the wells and then trucked that water to local public wastewater treatment facilities or publicly owned treatment works (POTWs) [36]. These facilities then treated the water and discharged the treated effluent into local streams and water courses. As it turned out, these POTWs were not equipped to properly treat the water that was being brought to them from the fracking wells due to the high levels of total dissolved solids (TDS), heavy metals, and potential for normally occurring radioactive materials (NORM) [36]. This led to water that did not meet discharge standards being released into water courses, thus contaminating those sources. In the spring of 2011, Pennsylvania put an end to this type of disposal by requiring all public wastewater treatment plants to stop accepting fracking wastewater [36]. This action is a main reason for the high percentage of reused water currently being deployed in the Marcellus Shale region [36]. With the oil and gas companies in this region no longer able to send their wastewater to local facilities, they were forced to truck these wastes out of state, which quickly became very costly [36]. The logical option left to them was to create a way to treat or re-use this water at the well site. The percentage of water re-use in the Marcellus Shale formation has been reported to be 87% as recently as the summer of 2014 [51].

3.3 On-Site Wastewater Treatment

As a method for reducing the cost of trucking wastewater off site and long distances to wastewater treatment plants, on-site water treatment has become increasingly popular and necessary. There are a variety of treatment methods available from different companies throughout the United States. Those options include filtration, electrocoagulation, chemical precipitation, distillation and membrane filtration [52]. Depending on the geographic location of the well and the challenges presented by the water being treated, each method will have its place and advantages. There is not one method that will treat all fracking wastewater in the United States, as the rock formations vary in composition and generate different contaminants in the waters produced.

In the Marcellus Shale Region of Pennsylvania, Integrated Water Technologies offers a system called FracPure, in which a three-stage process treats a variety of wastewaters to produce distilled water and beneficial salt products [30]. The company claims that the water produced exceeds EPA and state regulatory standards for drinking water [30].

Forward Osmosis is a membrane technology where water from one solution passes through a membrane to another solution based on the chemical concentration of the two solutions [30]. This method can be especially effective in treating waters that require desalination [30]. The process does not require a lot of energy to complete and it is a low-pressure system. The water is passed through a membrane that separates the water being treated and the draw solution, which will pull the water to be treated through the membrane without additional pressure. The water is processed through a membrane and not vaporized as other treatments require.

As a major player in the shale gas industry, Baker Hughes has conducted a program testing the benefits and cost effectiveness of electrocoagulation as a method to treat wastewater from a fracking site [53]. Seth and Cormer report that "Electrocoagulation is a process that destabilizes suspended, emulsified or dissolved contaminants in a liquid by introducing electrical current, which provides electromotive forces that causes chemical reactions." [53]. Upon the completion of the analysis of the wastewater being produced in the Permian Basin in New Mexico, it was determined that the Baker Hughes H2prO HMD provides the best treatment solution by using electrocoagulation [53]. Baker Hughes has developed units specifically for use in the field to be able to handle travel to sites, where the units can be deployed in as little as one hour.

As a pioneer of the hydraulic fracturing process, Halliburton has developed a service to treat flowback water to be re-used in another fracking operation [54]. This service is called CleanWave and it too uses the electrocoagulation method for treatment. It is a mobile unit that treats up to 26,000 bbl/day using electricity as its power source [54]. A combination of units can be mobilized at any site depending on the volume of wastewater to be treated. The system is extremely versatile in the types of water it can treat, and because multiple units can be used, it provides an expandable service if needed. This versatility also serves an advantage, as there are different kinds of wastewaters produced on-site through the life of a typical fracking well [54]

A thermal process developed by Purestream is called Accelerated Vapor Recompression (AVARA) which heats the wastewater to create a flow of clean steam that is then cooled to water. The AVARA system is a patented proprietary low pressure system that is more energy efficient than its competitors. The system produces distilled water that removes chlorides, total suspended solids, iron, and oil. A concentrated volume of brine is the by-product of the treatment process. Remote monitoring of the system furthers its efficiency by offering 24/7 monitoring. The AVARA system provides a small footprint and rapid deployment capabilities through its self-contained design. The flexibility of the system to be powered by several different energy sources, and to be installed in a plug and play method makes it a fast and convenient method to treat flowback and produced water.

3.4 New and Developing Wastewater Treatment Technologies

As an option that builds on the existing on-site technologies for treating wastewater, a centralized treatment facility for fracking wastewaters is becoming a more economical development for developed areas [55]. With a centralized treatment plant, several well pads can use the plant to cut back on costs associated with an individual plant at each site.

Chapter 4: Methodology

4.1 Fracking Wastewater Treatment

In recent years, there has been increased interest in finding a cost effective and efficient way to treat fracking wastewater. In the process of selecting the technologies to compare in this Master of Science in Environmental Engineering (MSEV) project, many were considered. Ultimately, three technologies were selected that represent a wide range of processes that are currently being used to treat wastewater from fracking. The process of selecting the technologies started with identifying what is currently being used in the industry by fracking companies in the Marcellus Shale formation. To carry out this task, research was performed on the technologies in use currently by fracking companies by consulting research projects and by conducting interviews with current operators. It was determined that because of the high Total Dissolved Solids (TDS) content typically found in fracking wastewater from the Marcellus formation, evaporative technology is a good option to research. It can be adjusted to meet effluent standards for discharge or it can just treat the water enough to be recycled for use again at the well in a later fracking job. Another method is for the operator to recycle the wastewater on-site by performing a rudimentary treatment referred to as "flock and drop" (i.e., precipitation of hardness, metals, and TSS), and then blending this water with new freshwater during stimulation at a well site. This would be temporarily used until the well was no longer being stimulated to produce. At that point, the wastewater would have to be collected and treated elsewhere. Lastly, there are various Central Wastewater Treatment (CWT) facilities in operation throughout the Marcellus Shale formation that accept wastewater from fracking wells. These plants are capable of treating large volumes of water that can either be returned to the operator who dropped it off or treated to be released as effluent into a local stream. A major cost for this treatment process or any treatment process that is off site is the transportation cost. The transportation cost can account for around 60% of the total cost to treat the water [56].

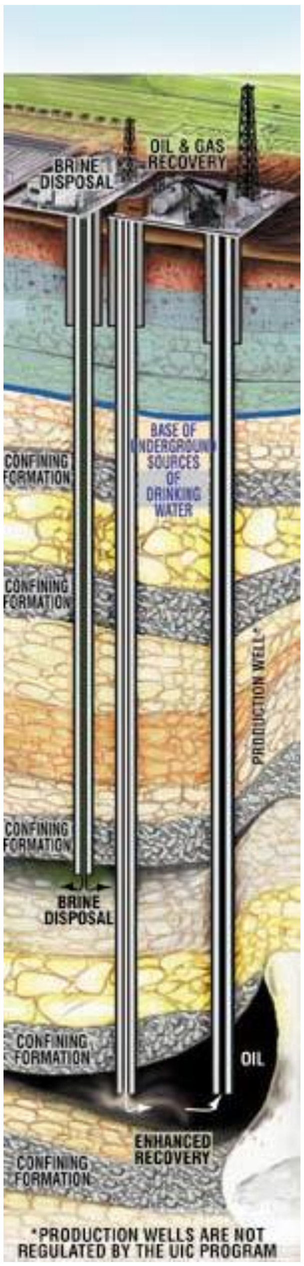

Figure 5: Class II Injection [56].

It is important to keep in mind that the rock formation where each well is drilled is different in composition, and thus, the wastewater being produced by each well is unique. This fact complicates the goal of developing a universal treatment process and is a major reason it has yet to be done. Each well will require a specific plan to treat the water to make it useful to the operator and to be usable again or to be discharged as effluent into a local stream.

Traditionally, Class II injection wells have been the method of choice for operators to dispose of their wastewater [30]. Figure 5 shows a Class II injection well. The use of the well to dispose of wastewater is very cost effective. The issue in Pennsylvania has always been the cost of trucking to one of these wells, because these injection wells are not as common in Pennsylvania as they are in other fracking areas [30]. Thus, injection wells in both Ohio and West Virginia are utilized for this purpose by operators in Pennsylvania [57].

As discussed previously, then, there are numerous ways to dispose of and to treat wastewater created from fracking.

Each method has its advantages and disadvantages. In seeking to reach a recommendation concerning the most cost effective method of treatment, it was determined in this project that a comparison between treatment options would yield fruitful results. However, in order to achieve best results, it was determined that the scope of the comparison needed to be limited by analytically evaluating the popular treatment method of trucking the wastewater to a centrally located treatment facility and a newer evaporation treatment technology called AVARA. The on-site method of "flock and drop" was not considered, as this treatment option is only used when a well is in production, and thus, it does not encompass a full life cycle comparison of wastewater as the selected methods do. Current common practice during fracking operations at a well site, according to Matt Thomas at XTO, is to send the water out to a centralized waste treatment facility to be treated to reduce suspended solids, barium, and heavy metals in order to be able to re-use the water for further fracking activity [56]. The AVARA system uses vapor recompression to remove chlorides and suspended solids, and produces distilled water that can then be re-used or discharged. As the name suggests, vapor recompression enables condensation to occur by increasing pressure, and in turn, the condensation temperature is increased, too.

The treatment method of trucking to a centralized wastewater treatment (CWT) facility is still believed to be the most cost effective way to manage wastewater in the fracking industry [56]. This doesn't mean that companies are not interested in using new technologies if they make sense to their bottom line. The AVARA system could allow for a more cost effective method with less risk of spills.

The Marcellus Shale formation is located in the Northeastern United States. It has been estimated to be one of the largest reserves of natural gas in the world [58]. Until recently, much of the trapped natural gas was unreachable. The development of horizontal drilling has made it possible to recover these trapped reserves. There is a growing concern over the amount of water being used, as well as concern over the environmental implications from the wastewater created. A single horizontal well in the Marcellus formation can use two to six million gallons of water for fracking [1]. A large portion of that water remains underground, with water recovery estimates in the 10% to 50% range [24]. This flowback water contains chemicals that aid in the process of recovering the natural gas. These chemicals consist of <1% of the total water used during the fracking process [24]. After the fracking process is complete and the well is put into production, water continues to make its way to the surface. In the Marcellus formation, this produced water contains high levels of dissolved salts, along with iron, and barium [47]. These high levels of salts create challenges for treating this water for re-use, or for disposal. It is important to understand that the best method of treatment is directly related to the rock formation the water is coming from and can vary greatly.

The processes that were evaluated in this project report are services, and as such, they do not have acquisition costs. The costs that were evaluated were limited to water disposal, water sourcing, transportation of wastes, and chemicals/services used. A deeper investigation of costs would include labor and energy, which are not included as line items in this study.[1]

[1] They are rolled into the service fee charges per barrel of wastewater treated.

A major cost for oil and gas companies is wastewater treatment and management. There are numerous treatment options, and the option that is selected at a site is often done so for multiple reasons. As deep well injection sites become limited, and the costs of using this method go up, operators are looking for other methods to treat and to dispose of their wastewater. As indicated previously, the method used most often in Pennsylvania is to truck the wastewater to a third-party treatment plant, which will perform a "flock and drop" in order to remove barium, heavy metals, and some suspended solids, and which then ships the water back to the site for further use in the stimulation process of the well. An alternative procedure for this method would be to use an on-site treatment method such as AVARA. This process uses vapor recompression to treat water to discharge standards of state and federal regulations. The well operators can use the vented methane to power the plant instead of flaring it off, and the trucking costs are greatly reduced by not having to transport the water back and forth to the site.

4.2 Life Cycle Analysis

Life cycle costing is a method of economic analysis for all costs related to building, operating, and maintaining an energy conservation measure over a defined period of time. This method was implemented in the research and analysis of wastewater technologies that are considered in this research paper. In order to do the life cycle analysis, data had to be gathered from various sources and analyzed for effectiveness.

This report features the comparison of two methods of treating wastewater produced by fracking. No acquisition of equipment was considered in this analysis. Both treatment methods that were analyzed are treated as services with no capital expenditure.

The first treatment method is to truck the wastewater to a Central Wastewater Treatment facility (CWT) and the second method is to use an on-site evaporative technology that will return 75% of the wastewater entered into the system as usable water that can be discharged and 25% of the wastewater is trucked to the CWT, as displayed in Figure 6.

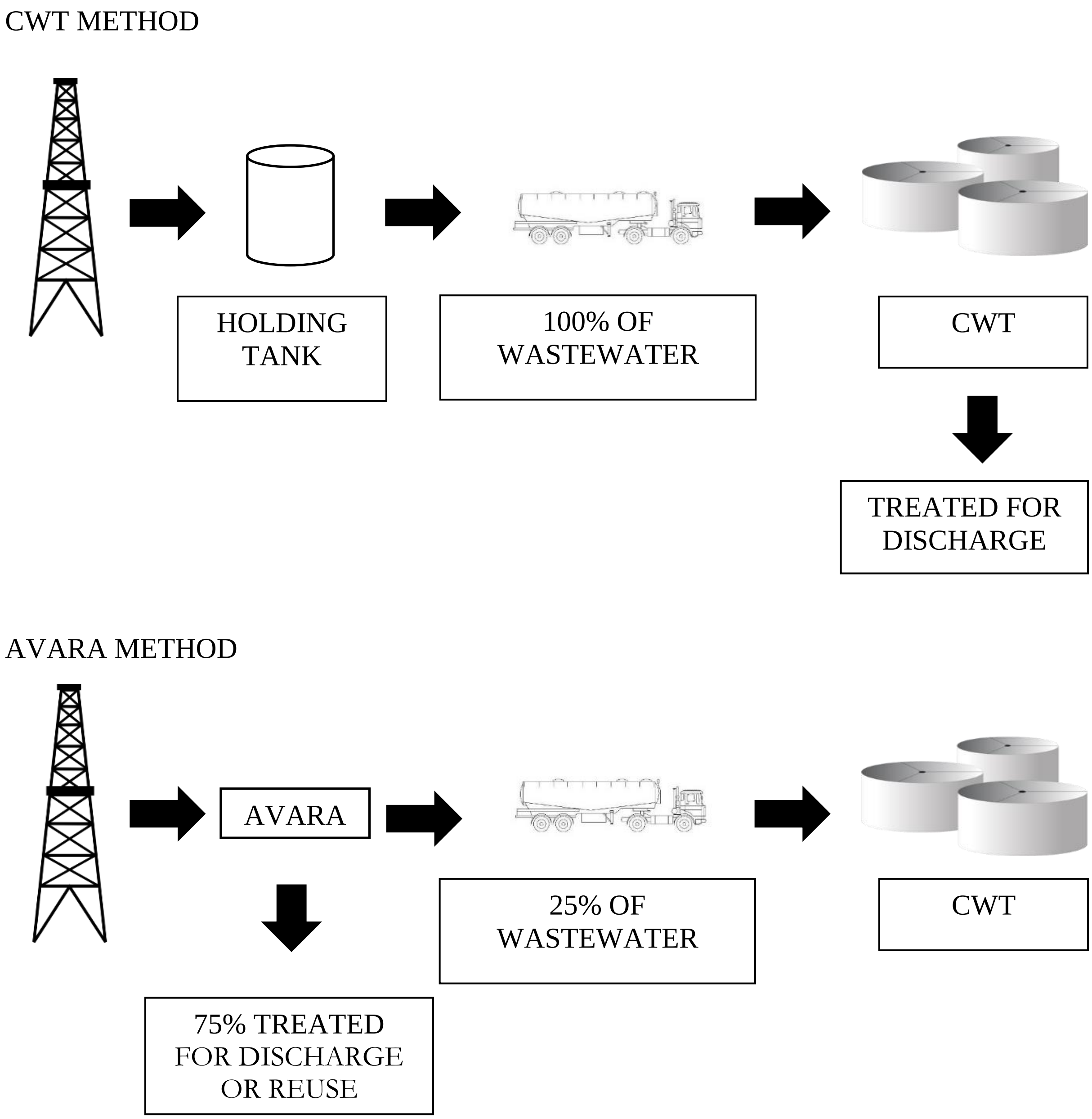

Figure 6: Diagrammatic Overview of the CWT and AVARA Treatment Methods.

Table 1 displays the cost data that were gathered for the CWT and AVARA methods. In this table, costs associated with chemicals and the service to treat the wastewater, sourcing of the clean water, and trucking are displayed for each method.

Table 1: Cost Data [2, 7, 59, 60, 61, 62].

Assumptions for CWT and AVARA Methods		
Water Required to Frack Well	107,143	bbl
Flowback at 15%	16,071	bbl
Produced Water per Year	2,380	bbl
Assumed Distance to CWT	40	Miles
Assumed Distance to Water Source	10	Miles
Assumed Life of Well	20	Years
-AVARA Trucks 25% of Flowback and Produced water volume to CWT		

Cost Data per Bbl of Wastewater	**CWT**	**AVARA**
Chemistry and Service for Treatment	$4.00	$3.25
Trucking in $/mi/Bbl	$0.19	$0.19
Cost of Freshwater	$0.06	$0.06
Energy in kWh/Bbl	N/A	5[1]

[1] Energy costs based on two assumptions: (1) diesel generator efficiency of 40% (2) diesel cost of $2.50 per gallon.

The assumed freshwater supply is based on the availability of surface waters and groundwater in the Marcellus shale play and that oil and gas developers actively want to keep transportation costs to a minimum [63]. When using AVARA for water treatment, 75% of the water put into the system is returned, so it is necessary to source 25% to get back to the original water volume for future fracking jobs. When sending water to be treated at a facility, the option exists to take back that water after it is treated. If the well site were to choose to take the water back, the cost of water would drop significantly for future fracking jobs. It would still be necessary to source some freshwater to make up for some inevitable loss during the treatment process. These options were not included in the analysis of these methods and their costs.

In addition to these tables and cost evaluations, a Net Present Value (NPV) evaluation for the sourcing of water and treatment of wastewater was conducted for the life span of a well. The analysis was conducted for both the CWT and AVARA methods of treatment. The Year 1 costs are driven by the cost of capturing and treating the flowback water in the first 14 days, and capturing and treating the produced water of the well over the life span of the well. The results of the NPV for the CWT and AVARA methods are represented in Table 2. The formula used for the NPV evaluation is the annually fixed formula seen in Equation (1), where PV is the present value, TV is today's value, and UPW in the Uniform Present Worth factor for fixed recurring costs. Equation (2) displays the detailed UPW formula in which *d* is the real discount rate, and n represents the number of years for analysis:

$$PV = TV(UPW), \quad (1)$$

$$UPW = \frac{(1+d)^n - 1}{d(1+d)^n}. \quad (2)$$

The NPV's for the methods further demonstrate that the AVARA method of treatment is the more economical choice for treatment of wastewater.

Table 2: NPV Evaluation [2, 7, 59, 60, 61, 62].

NPV Analysis		
Discount Rate: .06 Planning Horizon: 20 years Initial Investment: $0		
	CWT	**AVARA**
Year 0	0	0
Year 1		
- Flowback Water Treatment	$64,284.00	$52,230.75
- Flowback Water Trucking	$122,139.60	$30,534.90
- Energy Costs for AVARA	N/A	$12,374.67
Year 1 - 20		
- Produced Water Treatment	$9,520.00	$7,735.00
- Produced Water Trucking	$18,088.00	$4,522.00
- Energy Costs for AVARA	N/A	$1,832.60
NPV	$440,082.66	$224,593.91

4.3 Sensitivity Analysis

Sensitivity analysis is a technique used to test how the robustness of an independent variable will impact a particular dependent variable under a given set of assumptions [64]. As assumptions were made in this project that could impact the results of the life cycle analysis, it is important to analyze how the outcome could be influenced by the independent variable. This is a way to scientifically check the integrity of the assumptions of the data used that will influence the outcome, and thus the recommendations, of this report. An example would be to test the integrity of the cost of the chemicals in the AVARA system that would be needed to treat wastewaters with different characteristics. If it is determined that changing these costs would create a significant swing in the overall value that is created by using the AVARA system on-site to treat the wastewater, the use of this system may have to be reconsidered as the cost efficient way to treat wastewater at that particular well site.

It is difficult to estimate the costs of treatment universally, since there are so many factors that come into play when considering water treatment in shale plays. There are characteristics for each shale play, but decisions must be made on a case-by-case basis, and because of this state of affairs, broad assumptions were made in the computing of information in this study. Water needs to be tested before it is re-used to make sure that it is adequately treated. These results can also affect the ratio of freshwater needed to be blended to make the recycled water usable again in fracking. It is important to address the site-specific features of each well before conclusions are derived. Bench and pilot testing may have to be considered before a decision can be made as to what treatment is the best to use. A sensitivity analysis on the life cycle analysis for the costs associated with wastewater was conducted. This analysis calculated the breakeven point for the chemical and service costs for the AVARA method of treatment compared with the central wastewater treatment method. The calculated cost of the chemical and service costs for the AVARA method of treatment was $35 per barrel of wastewater. The conclusion can be made that even if the estimated costs presented in the tables preceding are under estimated, they are still well under the calculated $35 per barrel cost to breakeven with the central wastewater treatment method. As a recommendation for further study, a complete and thorough sensitivity analysis analyzing location of well, characteristics of water treated, characteristics of water to be re-used and costs associated with these should be conducted and has the potential to further determine a cost effective method to treat wastewater in the fracking industry.

Other assessment techniques are also possible. For example, a recent study by Bartholomew and Mauter [65] features the use of a linear programming optimization technique to assess “the trade-offs between financial costs and human health and environmental (HHE) costs for shale gas water management” in the Marcellus play. Bartholomew and Mauter [65] found “significant variation in the financial and HHE costs under different objective functions and regulatory scenarios”.

Chapter 5: Results and Discussion

5.1 Results

Each method of treatment has advantages and disadvantages. As has been discussed, each shale play--and further, each well--has distinct characteristics and the wastewater produced does as well. What may work environmentally and economically for one well may not work at another location.

Table 1 displays costs per unit (bbl) where it is clear to see that trucking will account for a large portion of all costs associated with wastewater treatment. In Table 2, the costs of trucking for the CWT method are shown to account for 63% to 67% of the total costs because of the number of trips the trucks will have to take from the well pad to the treatment center, given the well took 4.5 million gallons of water to frack.

In Tables 2, the costs of trucking for the AVARA method are shown to account for 33% to 38% of the total costs because of the reduced number of trips that are required as a result of the ability of AVARA to concentrate the wastewater produced. It is clear that trucking is a major component in costs associated with drilling and operating a fracking well. The more an operator can do to reduce the trucking component from their costs, the more profitable the well will become over the duration of its life. It is clear that significant savings can be accomplished by reducing trucking costs using the AVARA system.

This project indicates that trucking costs are substantial in any method of wastewater treatment. The more that can be done on-site will significantly lower the costs of any wastewater treatment technology. Many variables are included in a determination of treatment methods for fracking wastewater. In the Marcellus Shale formation, the high levels of TDS are a limiting factor in choice of technology. More companies are trying to produce additives that will enable re-use of wastewater with less treatment and that can still be effective [66]. However, in a time where the public is looking for more transparency in what chemicals are being used, this approach may not be a viable solution going forward.

The desire to reduce trucking costs by limiting the trips required to treat wastewater produced from the 4.5 million gallons of water used from the well, will at the same time contribute to reducing the damage that is occurring on roadways. This situation would produce a win-win situation for Pennsylvania's Department of Transportation. Not only would the costs for repairing roads decrease, the roads would become safer with less truck traffic on roads that were not built to handle that type of traffic. The costs associated for road damage and repair were not considered in the evaluation and NPV for this project.

The synergy created from reducing trucking required for developing and operating an unconventional well would continue on to have an impact on the amount of water sourced, and the air quality in the area of well pads. The re-use of wastewater on-site is not only economical to the operator, it helps to reduce the environmental impact of the quantity of water used, which has been a major concern, especially in areas where water is not as abundant. Air quality in the vicinity of a well pad is another environmental concern often raised by people living in the communities near these wells. The reduction of trucking in an area by a well would have a positive impact on air quality, due simply to the reduced emissions in relation to the number of truck trips required.

Chapter 6: Conclusions and Recommendations

6.1 Conclusion

Hydraulic fracturing is a process that uses a large volume of water at high pressure to fracture rock formations to allow the release of hydrocarbons from these formations to the surface where they are then captured. The large volume of water used needs to be treated prior to being released back into the environment or being re-used in another fracking job. This treatment of wastewater can be very costly to both the oil companies and the environment alike. The key to economical and environmentally safe fracking operations is to determine and to develop a wastewater treatment method that can be cost effective.

Wastewater volume has increased over the last decade because of the increase in the number of wells drilled. During those years, the methods of re-using the wastewater, and treating on-site have shown great gains as opposed to disposal at wells. The distance traveled for wastewater treatment has decreased over this time as well. There has been increasing attention paid to fracking and the regulations associated with the oil and natural gas industry in recent years as production has increased. This attention has produced pressure on the federal government to regulate the industry. Currently, regulation is handled by the states and local governments. Some of the public has argued for more federal regulation, because the perception exists that the regulation in some states does not do enough to keep the public and drinking water safe. The federal government has not shown any interest up to the writing of this paper to change its stance on continuing to allow states to regulate. Wastewater treatment in Pennsylvania has evolved from taking the water to the local POTW for treatment and discharge to local streams to methods allowing re-use of the wastewater through minimal treatment. The amount of trucking required has been significantly reduced as a result, which also results in a more economical method for wastewater treatment. The treatment methods evaluated in this paper include a centralized wastewater treatment facility and treatment on-site for re-use during the fracking operation, along with additional treatment for release at the end of fracking operations. It was found that the cost of trucking is the main cost factor between these two methods.

Because the cost of trucking is so influential on the overall cost of the operation of the well, the recommendation for wastewater treatment in the Marcellus Shale formation in this paper is that the AVARA method should be utilized. Its ability to concentrate the wastewater and reduce trucking costs is a main reason the AVARA method is more efficient. The AVARA system will remain the efficient method compared to the CWT given the large difference in the volume of wastewater that is trucked to be treated in the CWT method.

6.2 Lessons Learned and Limitations

There are numerous factors that go into the decision of how to treat wastewater at any given well at any given time. While conducting the research for this project, it was found that the characteristics of the wastewater varied so greatly from region to region, and even from well to well in the same shale play that it would prove to be difficult to conclude that a single treatment method would be the most efficient and cost effective. The decision to concentrate on the Marcellus Shale formation was thought to be an effective way to focus on a typical type of wastewater. This approach proved to be untrue as more and more literature research was evaluated, and as further development of the project took place.

The technologies for fracking are continuously being evolved and as a result, treatment continues to change. When conducting research on current practices in the field, it was noted that a lot of companies had a preferred way to treat the wastewater, but at the same time, they were all open to new technologies. There is wide understanding in the fracking industry that trucking costs money, so any way that companies can prevent their operations from having to truck something typically evokes interest on the part of companies. Since this is the case, there are numerous new methods being tried in the field. Thus, fracking wastewater treatment is an ever evolving aspect of the industry, which proved difficult to track during the course of this project. As a result, a decision was made to limit the project scope in the wastewater treatment methods. As previously indicated, project limitations include the focus on a specific geographic region (i.e., the Marcellus Shale formation), as well as a focus on two wastewater treatment methods (i.e., transportation to a centralized treatment site and use of the AVARA evaporation technology).

6.3 Recommendations

For the Marcellus Shale formation, there has to be considerable consideration given to the amount of TDS in the wastewater. This state of affairs is one of the characteristics of most wastewaters in this formation. As one moves to other characteristics of the wastewater produced in the Marcellus region, those characteristics become much more individualized with respect to each well. This causes certain methods to become less effective than others. What may work at one well effectively does not at another. For this reason, there should be consideration given to not only the method that will work at that well, but which method would work over a broader range of types of wastewater. The example in this project shows that evaporative technology has the ability to treat many different types of wastewater effectively. The AVARA system in particular can be mobilized to a site and as many units as necessary can be set up to handle different volumes of wastewater.

Even as effective as the AVARA system has proven to be, there should be more research and time given to developing a system that would be efficient and cost effective and capable of handling much larger volumes of water in a small footprint.

6.4 Suggestions for Future Research

The investigation in this project featured the evaluation of just a handful of available technologies currently being used in the oil and fracking industry. There are many others available that were not considered at the time of the writing of this paper, and it is assumed that others may have been developed during the course of this project. Further interviews with operators on-site could prove to hold great value, as their input is invaluable concerning what works and what doesn't work for them currently. There may be certain qualities or processes that are preferred, or not preferred, and consideration should be given to their input during the development of new technologies.

The re-use of fracking water should be further researched and developed. The more that water can be re-used, the less stress that would be placed on local watersheds, and the less potential trucking would have to occur. These two factors could help the image of the fracking industry with the public, and at the same time, lower their bottom line, creating a win-win situation.

Another area that could be researched and developed further would be the actual method of fracking currently being used. The massive quantities of water used during a frac job have created significant environmental stress in certain regions where fracking occurs. There are other methods of fracking that are under development, such as the use of CO_2 instead of water to create the necessary pressure to fracture the shale [67]. This method could help with the pure volume of water used, as well as with the wastewater produced, and should be researched further.

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Engineering

Capstone Report Approval Form

Master of Science in Environmental Engineering – MSEV

Milwaukee School of Engineering

This capstone report, titled “Fracking Wastewater: Recommendation for Cost Efficient Wastewater Treatment in the Fracking Industry,” submitted by the student Shannon Schwingle, has been approved by the following committee:

Faculty Advisor: ______________________________ Date: _______________

Dr. Frank Mahuta, Ph.D, J.D.

Faculty Member: ______________________________ Date: ________________

Professor Kenneth Kaszubowski, P.E.

Faculty Member: _____________________________ Date: _______________

Professor Gary Shimek, M.L.I.S.