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Enhancing Environmental Performance with Base Fluid Chemistry Selection and Bioremediation Management Techniques for Onshore Applications

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Abstract

Using bioremediation to manage drill cuttings coated with Non-Aqueous Fluids has been an accepted technique for many years. Meeting the challenges of completing projects in a short time frame, within budget and achieving strict closure limits for residual hydrocarbon concentrations has in some jurisdictions been an obstacle. A review of advances in the understanding of drilling fluid chemistry that favor bioremediation is the first step toward attaining success. The additional review of efficient and practical field application of bioremediation is also critical to a successful operation. Finally, understanding soil science targets that allow beneficial reuse of cuttings provides the advantage of onsite management which can reduce truck traffic. This paper will review all three aspects of continued advocacy of bioremediation application for onshore management of drill cuttings.

Introduction

Drill cuttings management is an operation that challenges all operators in onshore drilling operations. The current practice for cuttings management includes solidification onsite and transportation to a local landfill for disposal. This can present both an excessive cost and a potential for spills or other negative environmental consequences.

An alternative approach to the continued generation of cuttings as waste is to redirect resources used to generate and dispose of waste toward the beneficial reuse of the drill cuttings as feed stock for topsoil. Beneficial reuse is a variation of recycling that identifies the end use for a processed byproduct and designs a system of use and treatment that results in the generation of a product that has value instead of a waste that has no value. In the case of drill cuttings and residual mud, one viable and practical product is topsoil that uses the mineralogy of the cuttings combined with macro soil nutrients and organic amendments to enhance soil productivity.[1, 2, 3, 4, 5] Biological treatment, through bioremediation and composting can be a powerful tool to convert inert shale drill cuttings and residual mud components to viable topsoil uses.

A bioremediation process consists of microbial populations found in local soil to consume hydrocarbons found in the base fluid coating the cuttings. This converts hydrocarbons to biomass and helps convert otherwise inert shales to a productive soil or soil amendment. The successful application of the bioremediation process will allow the use of this technology in onshore operations. Meeting the challenges of completing projects in a short time frame, within budget and achieving strict closure limits for residual hydrocarbon concentrations has in some jurisdictions been a challenge.

Defining Soil Science Targets That Allow Beneficial Reuse of Cuttings

The use of drill cuttings as soil or a soil enhancer through a beneficial reuse avenue requires identification of key soil science targets. Through an understanding of what is available in the material and what is needed, the most beneficial treatment and amendments may be developed. The basics of chemistry and physical soil characteristics are listed in Table 1, which summaries a limited review of available literature sources that discuss the basics of soil science targets.[6] While the chemistry of soil is important to optimize, the aspects of soil texture and soil organic material are also very important to soil health. Many of the formations that are drilled to generate cuttings have a high clay content. Using the soil textural chart, it demonstrates that soils that are too high in clay are not as productive as soils that have a stronger balance of sand silt and clay (Fig. 1 and Fig. 2). Use of soil organic material and other soil management techniques can enhance the texture characteristics of the final product.

Recognizing and addressing soil productivity also requires a review of the potential impacts of residual hydrocarbon contamination and other drilling fluid and shale components that could cause low soil productivity. These chemical constituents of concern could result in contaminated soil, contaminated surface water runoff, or contaminated ground water. As with all beneficial reuse projects the upfront recognition and management of these potential risks is critical to the viability of the beneficial reuse of drill cuttings as topsoil. Fortunately, many years of drill cuttings risk management evaluation has resulted in a framework of knowledge of the recognized potential contaminants and pathways to either manage or eliminate risks. Even though the framework of risk management exists, it requires close attention and continued evolution to ensure the successful application on beneficial reuse of drill cuttings as topsoil. While the full review of the potential contaminants and the appropriate risk based chemical and biological limits to manage these risks is beyond the scope of this paper, there are three basic elements of risk mitigation that are summarized below. First, the identification and management of the chemical constituents listed in the Louisiana (Table 2) and Texas (Table 3) limits for reusable material.[7, 8] Beyond the risk based documentation prepared by individual states, the EPA and many state agencies publish risked based soil screening criteria (summarized in Table 4) for many common constituents of concern, including heavy metals and hydrocarbons.[9, 10, 11, 12]

Some of the common themes in Tables 1, 2, 3 and 4 is the control of Electrical Conductivity (EC) and Sodium salts, management of hydrocarbons, and management of heavy metals. Recognizing that these constituents of concern can potentially come from either the drill cuttings or the drilling fluid additives, the beneficial reuse process must be designed in a manner to mitigate and manage these potential hazards.

Further review and discussion of drilling fluid components are discussed in the next section of this paper. The management of salts, hydrocarbons, heavy metals and NORM from drill cuttings can be primarily managed by drilling practices and knowledge of basin characteristics. In many cases, the shale encountered in drilling operations has naturally occurring concentrations of metals, salts, hydrocarbons and NORM. Since they occur similar to background levels, they do not present a risk above regulatory control levels.

Review of Advances in Drilling Fluid Chemistry

Historical advances and development of drilling fluid chemistry have been primarily focused on meeting offshore discharge limitations related to OSPAR and US EPA use and discharge compliance regulations. Environmental performance is routinely designed into offshore drilling fluid products to meet both chemical and biological performance targets. For Synthetic Based Drilling Fluids, the EPA requires base fluids to meet toxicity, biodegradation and PAH.[13] Countries that follow OPSPAR testing requirements also evaluate both toxicity and biodegradation. Applying the same general approach to meeting onshore environmental performance targets for salts, heavy metals and hydrocarbons is an achievable goal.

The focus of this paper is on the use of Non-Aqueous Drilling Fluids (NADFs). However, applying the same targets to Water Based Muds and cuttings is also a valid approach to beneficial reuse. There are three major functional components of NADF that have potential to provide beneficial soil properties or damage the environment. These three include the internal phase of the NADF, the external phase of the NADF and the weight material. A fourth component of NADF is the emulsifier package which is normally represents a small percentage of the overall mass and volume of the drilling fluid. The emulsifier package most commonly uses fatty acids that do not pose a significant environmental risk.

Base Fluids

Base fluids used in NADF commonly include diesel oil and mineral oil. These historical base fluids have limitations that make them less suitable for beneficial reuse NADF formulations. Development of fluid properties specifically designed for onshore use has benefited from development and refinement of base fluid options for offshore. Underpinning the environmental performance and occupational health performance of these base fluids is chemistry. In order to simplify the discussion, many suppliers and operators refer to fluid chemistry in broad terms such as Synthetic or Enhanced Mineral Oils. A closer look at the chemistry reveals there are some key chemical attributes that drive environmental and occupational health performance. The basics of carbon chain distribution, branching, aromatic content, polyaromatic content and other cyclic hydrocarbons impact performance.

The primary difference between onshore and offshore requirements is that offshore base fluids need to biodegrade under anaerobic conditions and onshore fluids can be managed under aerobic biodegradation conditions. This key difference allows the use of paraffinic hydrocarbons onshore. Several papers reviewing the subject of chemistry that drives onshore environmental performance indicators have documented that paraffins that are more linear biodegrade faster, have a lower carbon chain length, and tend to be more bioavailable and biodegrade faster.[14] However, shorter carbon chain length hydrocarbons also have lower flash points a higher potential for vapor generation and are more toxic in the aquatic environment. While it is tempting to pull off-the-shelf data for offshore testing and apply it to onshore product selection, this short cut approach is not likely to address the more relevant chemical and biological terrestrial testing targets. Since occupational health exposures are also critical design targets, it is important to find acceptable occupational health exposure targets as well as acceptable environmental performance targets.

The process of defining and documenting relevant chemical and biological endpoints for application to onshore environments has been evolving for many years. Starting back with the development of Louisiana 29-B testing requirements and limitations, on through more recent studies published by West Virginia that evaluated plant growth and runoff toxicity testing with fresh water daphnia species.[17]

Using the basic approach to evaluating base fluids with terrestrial testing procedures yielded information about common base fluids during the initial development of onshore NADFs. These historical results are summarized in Table 5. Using the basic understanding of branching and hydrocarbon distribution it is both transparent and logical that products containing primarily linear paraffins in the C11-C14 range biodegrade quickly and completely in onshore environments. It is also logical that branched paraffins with higher, >C14 carbon chain distribution are less toxic. It is not the branching that makes them less toxic though, it is the ability to manufacture longer chain length hydrocarbons without them turning to wax that makes branched paraffins less toxic. The data presented in the AADE 01-NC-HO-11 paper from 2001 is still relevant.[1] However, the range of available Enhanced

Mineral Oils and Synthetic Base Fluids has opened up the possibility of more base fluid products that can meet the biodegradation, toxicity and occupational health targets required for beneficial reuse of NADFs.

Recognizing that the critical trends in performance are product independent, the path forward on beneficial reuse base fluid selection will evaluate the best science available to understand the chemistry first and then relate it to particular products. The product should match the science and not the science matching the product. Consequently, the focus of this paper is on better understanding the supportable science driving occupational health exposure risks and environmental performance of onshore base fluids.

A Canadian guidance document (IRP 14) shows both the Total Hydrocarbon THC (100 mg/m3) and also the oil mist limit (5mg/m3).[15] Since the oil mist limit is much lower, it may be the occupational health driver. Oil mist is most likely generated at the shale shaker where the mud is exposed to high g-forces in the shale shaker.

While hydrocarbon chain length distribution is a significant driver for biodegradation rate and toxicity, aromatic hydrocarbons can be generated as a vapor as documented in the LA DEQ Phase III report on oilfield waste.[18] The IRP 14 document contains a model for rig worker exposure with some relatable field data.[15] These and other models can be adjusted to review potential rig site exposure in combination with rig site monitoring studies that support a path forward.

One of the conclusions in SPE 35908 was that that C9-C11 was the source of most of the vapors (C12 was also a big contributor).[14] Therefore, reducing or eliminating C9, C10, C11, or C12 would seem to enhance control of vapor and oil mist generation. Contrasting the SPE 35908 paper is the recent study of crude oil biodegradation in Nigeria that documents, through a biodegradation experiment, the C10-12 fraction of hydrocarbons tends to biodegrade completely, the C12-C16 decreases significantly, the C16-C21 stays nearly the same and the C21-C35 proportionally increases.[16] The paper also documents that the aromatic hydrocarbon fractions biodegrade or disappear in the same proportion to the aliphatic hydrocarbons which are more driven by chain length than chemical structure.[16] That does not mean aromatic content of the base fluid is not an important issue, it means that it is more of an occupational health issue than and environmental issue because if all of the hydrocarbons are biodegraded in the treatment process, there will be not be significance aromatic compounds in the residual soil intended for beneficial reuse.

While most toxicity testing has conventionally occurred on base fluids before they are used and discharged into the onshore environment, there is an opportunity to manage and treat cuttings onsite in a controlled environment before they are released into the biosphere. Using this approach, ongoing development of post treatment chemical and biological tests are evolving. Some of these tests include the use of worms, plant growth and leachate analysis that are introduced later in this paper. There has also been development of screening tools for aquatic testing of leachate using daphnia.[17]

In addition to these biological test methods, conventional chemical testing appropriate for monitoring soil mixtures will be the primary tool for meeting environmental endpoints. The most commonly used general endpoint for hydrocarbons is Method 8015 for TPH (Total Petroleum Hydrocarbons). While it is still being used and recognized in many regulatory jurisdictions, it is often supplemented by more specific testing for hydrocarbon components, or alternative extraction techniques. For simplicity, the information presented in this paper is based on TPH/DRO using method EPA 8015. As ongoing biological and chemical testing develops for the option of beneficial reuse, the focus needs to remain on tests that accurately predict ecologically relevant endpoints that can be practically and accurately measured.

Internal Phase

In the case of onshore drilling fluid design, the internal phase is equally important to the external phase for an NADF environmental performance. Offshore discharges into the marine ecosystem are salt tolerant. Therefore, the inclusion of high conductivity, non-biodegradable salts is not an environmental issue offshore because discharging salt into a saline environment is not harmful. In the terrestrial environment however, salt can have significant negative impacts to soil, surface water, and ground water. In the case of Calcium Chloride and Sodium Chloride, many of the current regulatory controls for Electrical Conductivity and Sodium Absorption Ratio are designed to manage salt contamination issues. Clearly these regulatory controls also impact the soil quality objectives for beneficial reuse. Beyond the targets for soil health, soluble salts can dissolve easily into water and cause surface and ground water contamination.

Concerns for salt contamination are not unique to the oilfield. For example, the need to find cost effective de-icing chemistry that has a low environmental impact has generated several viable alternatives to traditional internal phase brines. The step beyond simply looking at mitigating environmental damage is to look for macro nutrients that are beneficial to soil productivity. With a focus on macro nutrients and soil productivity (while avoiding sodium which does not increase soil productivity), there are a range of options for inclusion in both the drilling fluid design and the biotreatment design. Some of these options were previously presented in SPE 74474 and focused on acetate chemistry.[5] These demonstrated that there are options available that meet drilling fluid performance requirements and also can enhance soil performance. The focus on acetate chemistry has continued in this paper because it provides the opportunity for macro nutrient additions, good drilling fluid performance, and a good occupational health and safety profile.

The evaluation of the finished cuttings product is well served by a combination of chemical and biological testing. While the common use of these tests for oilfield acceptability criteria has not yet been formalized, some of the underlying EPA test procedures including OCSPP 850.4100: Seedling Emergence and Seedling Growth and OCSPP 850.3100 Earthworm sub chronic Toxicity Test can supplement ASTM E1676 Standard Guide for Conducting Laboratory Soil

Toxicity Test With Lumbricid Earthworm *Eisenia foetida*.[19,20,21,22] While these screening tests are useful indicators, longer term tests evaluating plant mass and soil health are also needed to differentiate short term benefits and longer-term benefits associated with various drilling fluid internal phases.

Weight Material

The third core element of drilling fluid design for onshore use is the weight material. Frequently, this component is overlooked in terrestrial testing and evaluation programs because the most common weight material (barite) is inert and would not be considered either detrimental or beneficial. Barium is often used as a residual tracer for drilling fluids and is commonly evaluated in onshore and offshore discharge studies. In some regulatory jurisdictions, barium is a regulated component of drilling fluids discharges. Most notably in the Louisiana and Texas guidelines for a reusable material True Total Barium is a controlled parameter. There are weight material product alternatives for barite and they can be incorporated into beneficial reuse NADF formulations to manage regulatory and non-regulatory requirements. The key concern for weight material design is to ensure that the issue of heavy metal concentrations is managed.

Table 4 documents that risk based heavy metal screening values are common concerns and that other beneficial reuse and bio-solid management programs always include limits for heavy metals.

Efficient and Practical Field Application of Bioremediation

The efficient and practical field application of bioremediation must include personnel that understand the theoretical concepts in addition to having a hands-on training. Concepts include the basics that bioremediation/composting is a controlled, managed, active treatment process that applies microorganisms to transform and degrade organic compounds such as petroleum hydrocarbons. The efficient and practical field application of bioremediation is the pathway to meet the challenges of completing projects in a short time frame, within budget and achieving strict closure limits for residual hydrocarbon concentrations that has in some jurisdictions been an obstacle.

Hands-on training can be performed through smaller scale pilot studies. During such training, the recipient will learn the techniques to manage a pile, the tools to use, and the solutions on how to fix a pile if the operation becomes stagnant due to a multitude of reasons. A pilot study can also establish a baseline evaluation of the bioremediation/composting capabilities of the cuttings containing various sources of drilling fluids.

Once complete, it is critical that the pilot studies can be scaled upwards in order to be incorporated into field operations. This review of techniques for advanced bioremediation consists of practices conducted in a greenhouse set up as part of an onshore environmental research lab. These practices can be scaled up to ambient conditions on a larger scale and ultimately it is believed that these can be brought into the field with similar results.

It is not just a scenario where additional cuttings will be treated, rather the bioremediation concepts must be scaled up and the changes must be understood by all that are participating. Training on pilot studies is paramount in order to provide the baseline understanding but it also allows for the trainee to really grasp the nature of the compost pile and make the theoretical connections that bring about an advanced ability to understand the operations on a larger level. Taking these ideas and expanding them on a larger level is the core of the advanced bioremediation techniques. The hands-on portions described throughout this section occurred at an onshore environmental research lab, based in Houston, Texas, consists of a greenhouse as well as environmental chambers and indoor capabilities. Four studies will be reviewed in this section and will be used to demonstrate how pilot studies can incorporate multiple variables related to the soil science targets described in the previous section.

- Field Cuttings – Lab
- Field Cuttings – Ambient
- Field Cuttings – Multi Pile
- Lab Cuttings – Lab

Bioremediation/Composting Pile Creation

Each of the studies begins with cuttings and the creation of a bioremediation/compost pile. As these are pilot scale, most of the materials are commercially available at local hardware stores. A bioremediation/composting pile requires the following components: drilling fluid/cuttings, peat moss (organic portion and bulking agent), water, fertilizer (for the nutrients - nitrogen and phosphorous), and potassium acetate (nutrients - potassium). These components are added into a commercial cement mixer and mixed for two minutes. They are then transferred into a standard composting tray in the greenhouse. The bioremediation/composting pile needs maintenance multiple times a week in order to replicate field conditions. The piles are turned physically, allowing the moisture, bulking amendments, and nutrients to be mixed and adjusted. Typically, daily parameters are measured in order to control the conditions at the optimal range for bacterial growth and biological treatment.

The following reference test methods were used to monitor the compost piles:

- TPH/DRO: Method 8015B, Diesel Range Organics (DRO) (GC), Protocol SW846.
- INFRACAL: Company Internal Protocol, Test Method 709b for Cuttings Analysis – Oil and Grease, Water and Solids Content.
- Nitrogen Content: Company Internal Protocol, Test Method 0512 for Poly-Plus (PHPA) Determination by Ammonia Extraction.
- Porosity: Company Internal Protocol, WI 0501, Bulk Density and Porosity of Compost, adapted from University of Idaho On-Farm Composting Management Series.
- Moisture Content: Company Internal Protocol, WI 0502, Moisture Content of Compost, adapted from ASTM D2974-14.

- Evaporation: Mass balance.

Field Cuttings - Lab

The initial bioremediation study for review consisted of a 30-gallon compost pile containing field cuttings that were collected from Synthetic Base Drilling Fluid operations in the Marcellus Shale (field cuttings). The base fluid incorporated into the drilling fluid consisted of a synthetic hydrocarbon material. The drilling fluid also incorporated barite as the weight material and calcium chloride as the internal phase. The bioremediation/compost pile was created with peat as the bulking agent and maintained daily.

This study continued for 28 days and served as a training tool opportunity for a field engineer. Secondly, this pilot study was the model that would be scaled up in ambient conditions in the Marcellus Shale area. The trained engineer gained the hands-on understanding that porosity, moisture, and nutrients are key to managing a successful bioremediation/composting pile and that advanced bioremediation techniques are necessary to facilitate biological treatment with increased efficiency.

This initial bioremediation study monitored the hydrocarbon reduction as a tool to provide a snapshot of the conditions of the pile throughout the process. This occurred on a periodic basis, using the INFRACAL instrument, after each pile turn. The initial and final results, however, were conducted at a third-party laboratory. The final outcome resulted in a reduction of the TPH/DRO from 11.7% to 0.86% in a 28-day time period (Fig. 3).

Field Cuttings - Ambient

The subsequent bioremediation/composting study occurred in ambient conditions outside of a controlled onshore environmental research lab. After the hands-on lab training, the engineer returned to the Marcellus Shale area and prepared with the appropriate consumables. Similar drill cuttings were obtained and used as the source area remained the same. This study scaled the pile from 30-gallons to 60-gallons in an effort gauge the impacts of increased volumes on maintenance of the pile and the parameters. The maintenance schedule consisted of turning the pile twice a week remained the same as the lab study. The parameters used to control conditions also remained the same and after review, the results were similar. It was observed that the biological activity appeared to last slightly longer in a larger pile based on temperature profiles compared to the lab study. This study continued for 35 days and served as an example that bioremediation/composting piles can be conducted in ambient conditions. Similar to the initial lab study, the reduction of hydrocarbons was measured throughout the process. The final outcome, based on third-party lab results, showed a reduction of the TPH/DRO from 13.3% to 0.13% in a 35-day time period (Fig. 3).

Field Cuttings - Multi Pile

In both the lab and ambient study, the biological treatment with composting led to a reduction of the TPH/DRO. The biological activity was evident as a driver of reduction and therefore as efficiency of the treatment is based on duration of the bioremediation operation, advancing the speed is necessary. A sequential Multi Pile approach was planned as an initial study to determine various rates. Temperature can be used as a surrogate for bacterial activity and the data loggers measured and tracked multiple readings daily.

Three compost piles were created at different intervals for the Multi Pile approach. The Generation 1 pile was created with field cuttings, similar to the studies above, with biochar used as the bulking agent to create the 30-gallon compost pile. The Generation 1 pile continued for 28 days and resulted in a reduction of the TPH/DRO from 8.42% to 0.09% (Fig. 4). On Day 11, as the Generation 1 pile was at a high level of bacterial activity, 1/6 of the contents were added to a new pile, Generation 2 pile. The Generation 2 pile was also created with field cuttings, and biochar was used to create the 30-gallon pile. The Generation 2 pile continued for 17 days and resulted in a reduction of the TPH/DRO from 6.17% to 0.46% (Fig. 4). The Generation 3 pile was created with 1/12 of the contents of the Generation 2 pile, during Day 10. This pile was created with field cuttings, but peat was used and it was configured as a 20-gallon pile. The Generation 3 pile continued for 28 days and resulted in a reduction of the TPH/DRO from 6.88% to 0.44% (Fig. 4). This pile received less maintenance than the Generation 1 and Generation 2 piles.

For the sequential Multi Pile study, the relative level of temperature differences over ambient conditions were compared. Integrating the temperature difference between ambient temperatures and pile temperatures was calculated as a surrogate for bacterial activity. Using this approach and summing the daily average temperature differences, the different ranking of three piles based on bacterial activity which was: Generation 2 < Generation 1 < Generation 3 (Fig. 5).

The Generation 2 pile shows the ability of the bacteria to replicate rapidly due to the inclusion of the bacteria from the previous pile. A Multi Pile approach could help increase efficiency by reducing the lag time resulting from bacteria growth in a new pile. A comparison of the first 7 days for each pile shows a 31% for Generation 1, 38% for Generation 2, and 57% reduction of hydrocarbons for Generation 3 (Fig. 6). There was supporting evidence that the temperature in the pile increased more rapidly from Generation 1 to Generation 2 to Generation 3. Consequently, using the sequential Multi Pile approach in the field applications is likely to reduce initial lag time and make the composting process more efficient. The Field Cuttings – Lab study was comparable to the Generation 3 pile.

Lab Cuttings - Lab

Pilot studies in the lab can also be conducted with simulated drill cuttings and drilling fluids that are specifically designed to allow analysis of various potential options. This final review of the section will focus on a study consisting of a linear paraffin drilling fluid but with the decision to incorporate an internal phase of acetate and a weight material of calcium carbonate. The study continued for 27 days and resulted in a reduction of the TPH/DRO from 8.97% to 0.32%. The electrical conductivity was measured in the soil samples throughout the study and ranged between 2.6 mS/cm and 3.2 mS/cm.

Following the study, an exploratory biomass evaluation occurred. The bioremediation/composting pile was spread in the composting bin and seeded with a native grass seed mix (sourced online). The seeds germinated and various types of grass grew. As the bin was watered on a daily basis, the leachate was collected to determine EC, Chlorides, and Salinity.

For the "Lab Cuttings - Lab" pile remnants in the greenhouse, the initial EC in the leachate of 6.6 mS/cm (Chlorides 1300 mg/l) was reduced to less than 2 mS/cm (Chlorides 300 mg/l) after nearly 40 days of watering and plant growth (Fig. 7 and 8).

A similar grass growth study was conducted with the "Field Cuttings - Lab" pile remnants described at the beginning of this section. The electrical conductivity was measured in the soil samples throughout the bioremediation/composting portion of the operation and ranged between 7.1 mS/cm and 7.3 mS/cm consistently. When spread in the bin and planted, the leachate initially contained an EC of 58 mS/cm (Chlorides 22,000 mg/l). This was reduced to less than 10 mS/cm (Chlorides 3200 mg/l) after nearly 20 days, and ultimately settled near 5 mS/cm (Chlorides 1,200 mg/l) at the conclusion of more than 90 days of watering and plant growth (Fig. 7 and 8).

The grass emerged and grew in each of these but the EC, Chlorides, and Salinity resulting from the calcium chloride internal phase of the field cuttings had an impact. The grass was collected along with the roots, dried, and weighed for biomass content. The "Field Cuttings - Lab" pile remnants generated 0.6 kg of biomass and the "Lab Cuttings - Lab" pile remnants generated 2.2 kg of biomass (Fig. 9 and 10). Thus, this preliminary biomass evaluation showed a nearly four-fold increase in the alternative internal phase bioremediation/composting pile remnants.

The evaluation of plant growth and water leachate from the plant growth appears to be a useful and information tool that supports the significant benefit of using an alternative internal phase for the drilling fluid.

Findings and Conclusions

Moving from a waste management paradigm to a beneficial reuse paradigm is a challenge. Consequently, the use of the very best drilling fluid design combined with the efficient and practical field application of bioremediation/composting is the pathway to meet the challenge and achieve the targets of successful beneficial reuse of drill cuttings as a soil or soil amendments. Some of the key findings in this study are presented below.

- The use of drill cuttings as soil or a soil enhancer through a beneficial reuse avenue requires identification of key soil science targets. Through an understanding of what is available in the material and what is needed, the most beneficial treatment and amendments may be developed.
- Some of the common themes in between soil science targets and regulatory controls include Electrical Conductivity (EC) and Sodium salts, management of hydrocarbons, and management of heavy metals. Recognizing that these constituents of concern can potentially come from either the drill cuttings or the drilling fluid additives, the beneficial reuse process must be designed in a manner to mitigate and manage these potential hazards.
- While the chemistry of soil is important to optimize, the aspects of soil texture and soil organic material are also very important to soil health.
- There are many ongoing developments with base fluid products being offered for sale in the onshore market. The ongoing evaluation and documentation of base fluid performance indicates that there will be a good selection of products that can meet the requirements for NADFs that can be designed for beneficial reuse.
- Concerns for salt contamination are not unique to the oilfield. For example, the need to find cost effective de-icing chemistry that has a low environmental impact has generated several viable alternatives to traditional internal phase brines. The step beyond simply looking at mitigating environmental damage is to look for macro nutrients that are beneficial to soil productivity.
- There are weight material product alternatives for barite and they can be incorporated into beneficial reuse NADF formulations to manage regulatory and non-regulatory requirements. The key concern for weight material design is to ensure that the issue of heavy metal concentrations is managed.
- The efficient and practical field application of bioremediation is the pathway to meet the challenges of completing projects in a short time frame, within budget and achieving strict closure limits for residual hydrocarbon concentrations that has in some jurisdictions been an obstacle.
- Hands-on training can be performed through smaller scale pilot studies. During such training, the recipient will learn the techniques to manage a pile, the tools to use, and the solutions on how to fix a pile if the operation becomes stagnant due to a multitude of reasons. A pilot study can also establish a baseline evaluation of the bioremediation/composting capabilities of the cuttings containing various sources of drilling fluids.
- It is not just a scenario where additional cuttings will be treated, rather the bioremediation concepts must be scaled up and the changes must be understood by all that are participating. Training on pilot studies is paramount in order to provide the baseline understanding but it also allows for the trainee to really grasp the nature of the compost pile and make the theoretical connections that bring about an advanced ability to understand the operations on a larger level.
- For the sequential Multi Pile study, the relative level of temperature differences over ambient conditions were compared. Integrating the temperature difference between ambient temperatures and pile temperatures was calculated as a surrogate for bacterial activity. Using this approach and summing the daily average temperature differences, the different ranking of three piles based on bacterial activity.
- The grass emerged and grew in each of these but the EC, Chlorides, and Salinity resulting from the calcium chloride internal phase of the field cuttings had an impact. The grass was collected along with the roots, dried, and weighed for biomass content. This preliminary biomass evaluation showed

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Table 1

Basic Soil Science Targets[6]

Composition of Soil	Soils are composed of solid particles which have spaces between them. The solids consist of bits of minerals and organic matter. Between the particles are pore spaces which are filled with air and water. Good agricultural soils have about one-half soil particles and one-half pore space by volume. Ideally, organic matter will account for 5% or more of the weight of soil particles.
Mineral Composition of Soil	Mineral soil particles vary considerably in size. These particles are grouped according to size. Beginning with the smallest sized particles these groups are classified as clays, silts, sand and gravel. This approach is more focused on particle size in the soil matrix than the mineral composition of the soil particle.
Texture	Texture is the proportional amount of each of these groups. Soils consist of mixtures of various size particles. A soil textural triangle is used to determine the textural class of soil according to the percent sand, silt and clay. These three lines will intersect at a point inside the triangle indicating the soil textural type. Note that the word "loam" does not refer to a specific group of particles, but is used to describe mixtures of sand, silt and clay. A target loam soil would contain 45% silt size particles, 35% sand size particles and 20% clay size particles.
Essential Mineral Elements of Soil	Six elements are called macro elements because the plant uses them in rather large amounts. The macro elements are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S).
Cation Exchange Capacity	Cation exchange capacity (CEC) is a measure of the number of adsorption sites in a soil and is an important indicator of the soil's ability to retain and supply cations for plant use. CEC is reported as milli-equivalents per 100 grams of soil (meq/100 g). The CEC of agricultural soils ranges from below 5 in sandy soils with little organic matter to over 20 in certain clay soils and those high in organic matter. A soil with a low CEC has little ability to store nutrients and is susceptible to nutrient loss through leaching.
Sodium Adsorption Ratio	Plants are detrimentally affected, both physically and chemically, by excess salts. Sodium Adsorption Ratio (SAR), along with pH, characterize salt-affected soils. It is an easily measured property that gives information on the comparative concentrations of Na+, Ca2+, and Mg2+ in soil solutions.
Soil pH and Liming	One of the most important aspects of nutrient management is maintaining proper soil pH. Soil pH is a measure of soil acidity. Soil pH is important because it affects the availability of nutrient elements for plant uptake. As the soil pH falls below pH 6.0, the availability of N, P and K, becomes increasingly restricted.
Carbon-To-Nitrogen Ratio	Organic matter is broken down by microbes which use carbon for energy. Microbes are more efficient than crops in obtaining nitrogen from the soil. If there is not enough nitrogen for both the microbes and the crop, the crop will not obtain what it needs.
Organic Material In Soil	Soil organic matter (SOM) improves moisture holding capacity of sandy soils, aeration of clay soils and helps overall tilth of any soil. The break down or decomposition of SOM releases nutrients which can be used by plants. SOM is continuously being produced and broken down by living plants and animals. SOM is broken down by microbes as they consume it for food. Any factor that affects soil microbial activity also affects SOM break down. The resistant materials remain and form the dark colored material called humus. Humus continues to decompose, but at a very slow rate.

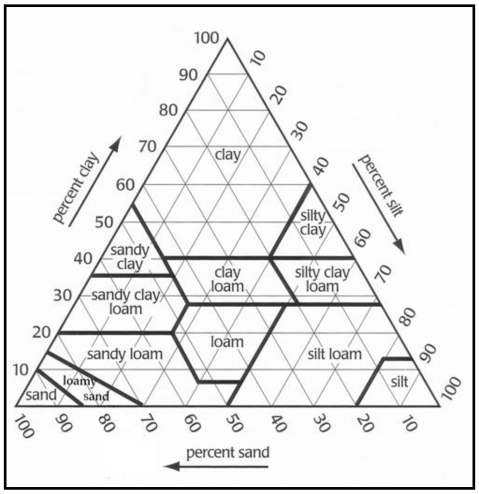

Fig. 1 – Textural Triangle[6]

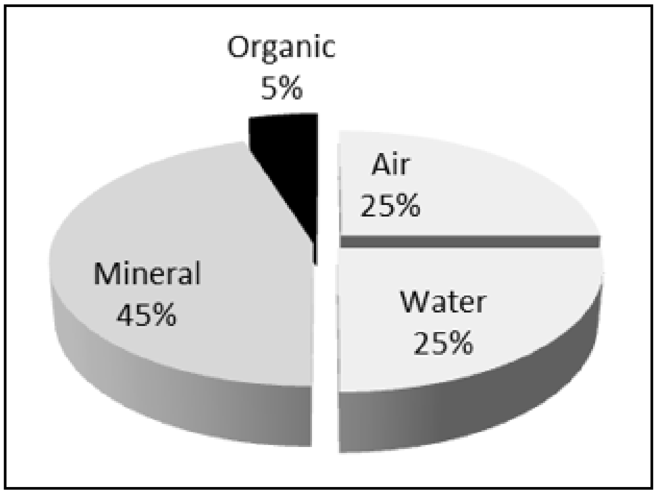

Fig. 2 – Soil Characteristics[6]

Table 2

Testing Criteria for Reusable Material - Lousiana[7]

Parameter	**Limitation**
Moisture Content	< 50% (by weight) or zero free moisture
pH*	6.5 - 9.0
Electrical Conductivity (EC)	8 mmhos/cm
Sodium Adsorption Ratio (SAR)	12
Exchangeable Sodium Percentage (ESP)	15%
Total Barium: Reuse at Location other than Commercial facility	40,000 ppm
Leachate Testing** for:	
TPH	10.0 mg/l
Chlorides	500.0 mg/l
TCLP Benzene	0.5 mg/l
Leachate Testing**:	
Arsenic	0.5 mg/l
Barium	10.0 mg/l
Cadmium	0.1 mg/l
Chromium	0.5 mg/l
Copper	0.5 mg/l
Lead	0.5 mg/l
Mercury	0.02 mg/l
Molybdenum	0.5 mg/l
Nickel	0.5 mg/l
Selenium	0.1 mg/l
Silver	0.5 mg/l
Zinc	5.0 mg/l
NORM	Not to exceed Applicable DEQ Criteria/Limits

Table 3

Permit Application for Reusable Product - Texas[8]

Parameter	Limitation
Moisture Content *ASTM D 2216 or equivalent*	< 50% (by weight) or zero free moisture
pH [1] *EPA Method SW-846 9045C*	6.5 - 9 s.u.
Electrical Conductivity (EC) [2]	8.0 mmhos/cm
Sodium Adsorption Ratio (SAR) [2]	12
Exchangeable Sodium Percentage (ESP) [3]	15
Total Barium [3] - Reuse at Commercial Facility	100,000 ppm
Louisiana Department of Natural Resources (LDNR) Leachate Test Method, 1:4 Solid [3]	
Total Petroleum Hydrocarbons (TPH) [3]	10.0 mg/L
Chlorides [3]	500 mg/L
Toxicity Characteristic Leaching Procedure (TCLP) Benzene *EPA Method SW-846 1311/8021*	0.5 mg/L
Leachable Metals [3] EPA Method SW-846 6010/6020/7000/7470/7471	
Arsenic	0.5 mg/L
Barium	10.0 mg/L
Cadmium	0.1 mg/L
Chromium	0.5 mg/L
Copper	0.5 mg/L
Lead	0.5 mg/L
Mercury	0.02 mg/L
Molybdenum	0.5 mg/L
Nickel	0.5 mg/L
Selenium	0.1 mg/L
Silver	0.5 mg/L
Zinc	5.0 mg/L

1 In addition to the criteria set forth, E&P waste, when chemically treated (fixated), shall be acceptable as reusable material with a pH range of 6.5 to 12 s.u. and an electrical conductivity of up to 50 mmhos/cm, provided such reusable material passes leachate testing requirements for chlorides and metals in VI.D.1. above.

2 LDNR Lab Procedures for Extraction and Analysis of E&P Waste or equivalent

3 LDNR Lab Procedures for Extraction and Analysis of E&P Waste or equivalent

Table 4

Risk Based Heavy Metal Screening Concentrations from State Programs for Voluntary Cleanup Programs and Risk Based Site Closure Programs

Method	Metal	Units	EPA Residential Soil	EPA Industrial Soil	TCEQ Texas Residential Soil	TCEQ Texas Industrial Soil	Texas RRC Commercial Reuse Site Closure	Louisiana DEQ Residential Risk Based Soil Screening	Louisiana DEQ Industrial Risk Based Soil Screening	Oklahoma (Same as EPA) Residential Soil	Oklahoma (Same as EPA) Industrial Soil
Method 6010 ICP AES	Arsenic	mg/Kg	0.68	3.00	24	200	10	12	12	0.68	3.00
Method 6010 ICP AES	Barium	mg/Kg	15000.00	220000.00	8100	120000	10000	550	14000	15000.00	220000.00
Method 6010 ICP AES	Cadmium	mg/Kg	71.00	980.00	52	810	10	4	100	71.00	980.00
Method 6010 ICP AES	Chromium	mg/Kg	120000.00	1800000.00	33000	120000	100	12000	310000	120000.00	1800000.00
Method 6010 ICP AES	Lead	mg/Kg	400.00	800.00	500	1600	200	400	1400	400.00	800.00
Method 6010 ICP AES	Selenium	mg/Kg	390.00	5800.00	310	4900	10	39	1000	390.00	5800.00
Method 6010 ICP AES	Silver	mg/Kg	390.00	5800.00	97	2300	200	39	1000	390.00	5800.00
Method 7471A Manual Cold Vapor AA	Mercury	mg/kg	11.00	46.00	8.3	19	10	2	61	11.00	46.00

Table 5

Biodegradability of Various Base Fluids[1]

Treatment	% Reduction of Hydrocarbons	Biodegradability Rank
C_{11-14} LP	97	1
C_{12-13} LP	94	2
Ester	91	3
Isomerized Tetradecene C_{14} (IO)	83	4
Diesel	61	5
Branched Paraffin	43	6

Table 6

Toxicity of Various Base Fluids[1]

Treatment	Water Toxicity	Animal Toxicity	Alfalfa Phytotoxicity*		Toxicity Rank
	Microtox IC_{50}	% Earthworm Survival	% Seed Emergence	% Root Elongation	
Branched Paraffin	106	100	95	107	1
C_{11-14} LP	98.5	100	96	134	2
C_{12-13} LP	65.9	100	95	120	3
Isomerized Tetradecene C_{14} (IO)	61.7	100	101	144	4
Diesel	10.3	0	7	2	5
Ester	5.9	0	0	0	6

*Seed Emergence and Root Elongation test results are normalized to Control test values of 100.

Table 7

Biodegradability, Toxicity & Electrical Conductivity of Untreated and Bioreactor-Treated Cuttings 6% w/w Loading on topsoil from Southern Alberta Grassland[1]

System	Biodegradability (65 days)	Animal Toxicity		Alfalfa Phytotoxicity*			Relative Electrical Conductivity (after 65 days)
	% Loss of Extractable Hydrocarbons	% Springtail Survival	% Earthworm Survival	% Seed Emergence	% Root Elongation	% Shoot Mass	
Formulation A	98	80	100	100	149	97	1.0
Formulation N	98	87	93	4	11	47	4.0
Std. Diesel /$CaCl_2$ / Barite Formulation	68	0	0	3	8	25	4.9
Formulation A with Barite	99	90	100	100	108	105	0.8
Bioreactor-Treated Cuttings, Form. NA	-	93	100	109	134	129	-
Bioreactor-Treated Cuttings, Form. N	-	73	100	113	116	121	-

*Phytotoxicity test results are normalized to Control test values of 100.

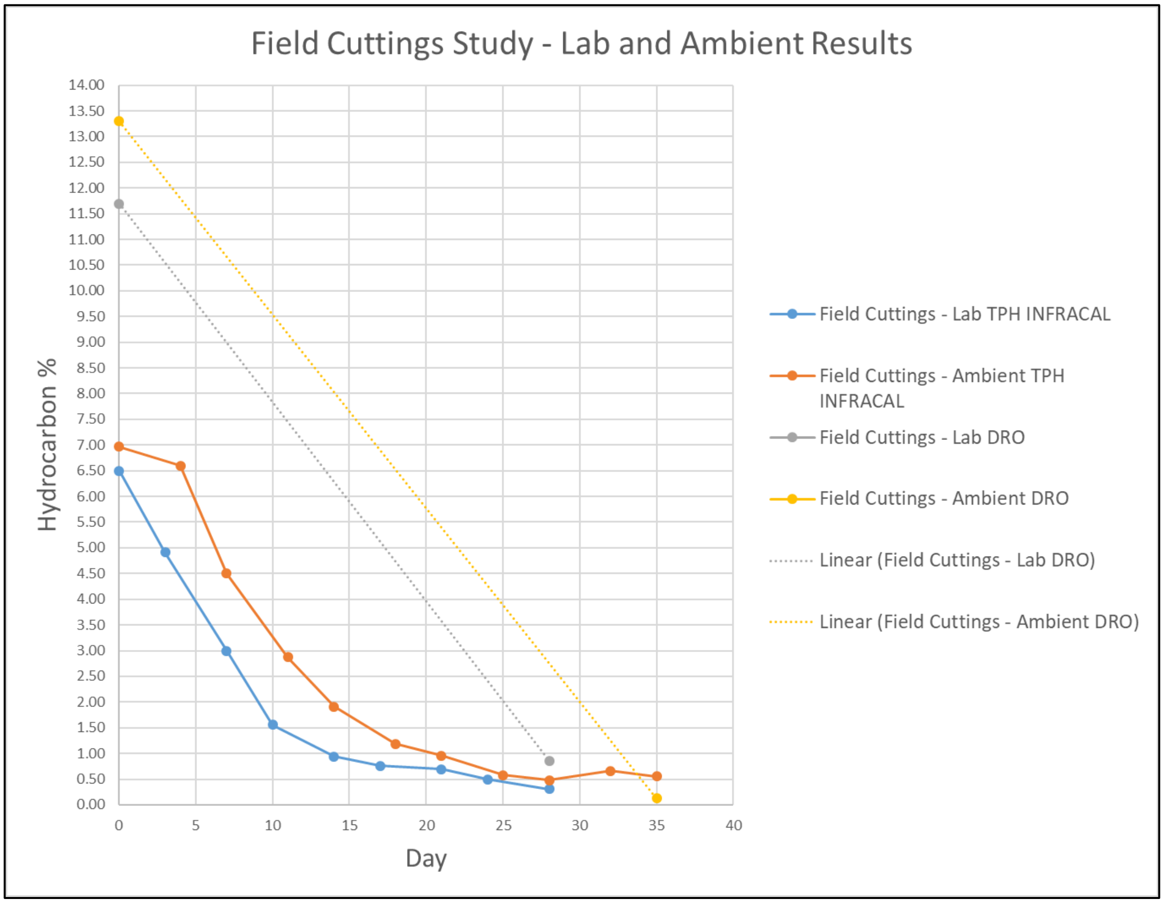

Fig. 3 – Field Cuttings Study – Lab and Ambient Results

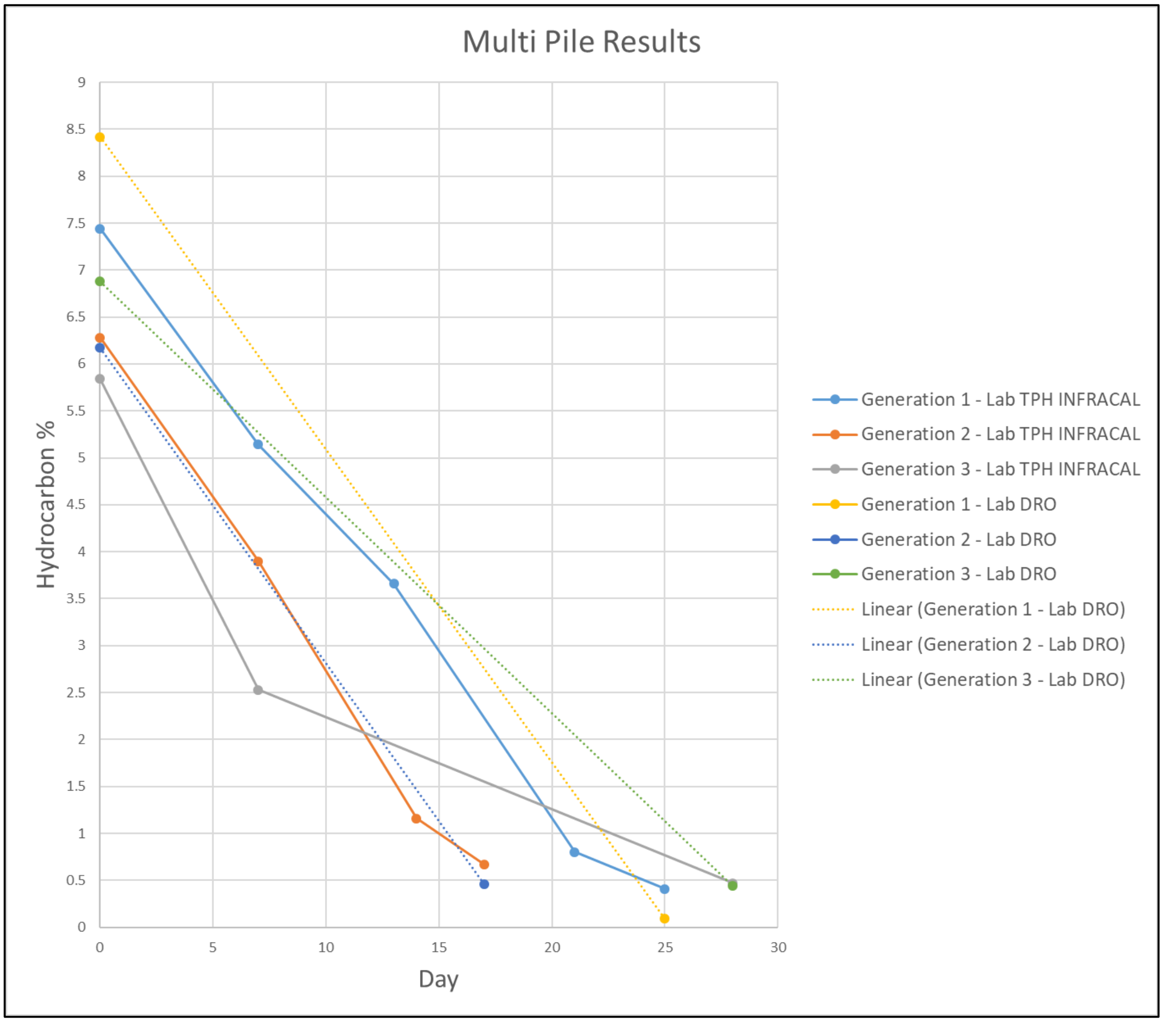

Fig. 4 – Multi Pile – Lab Results (Generation 1, 2, and 3)

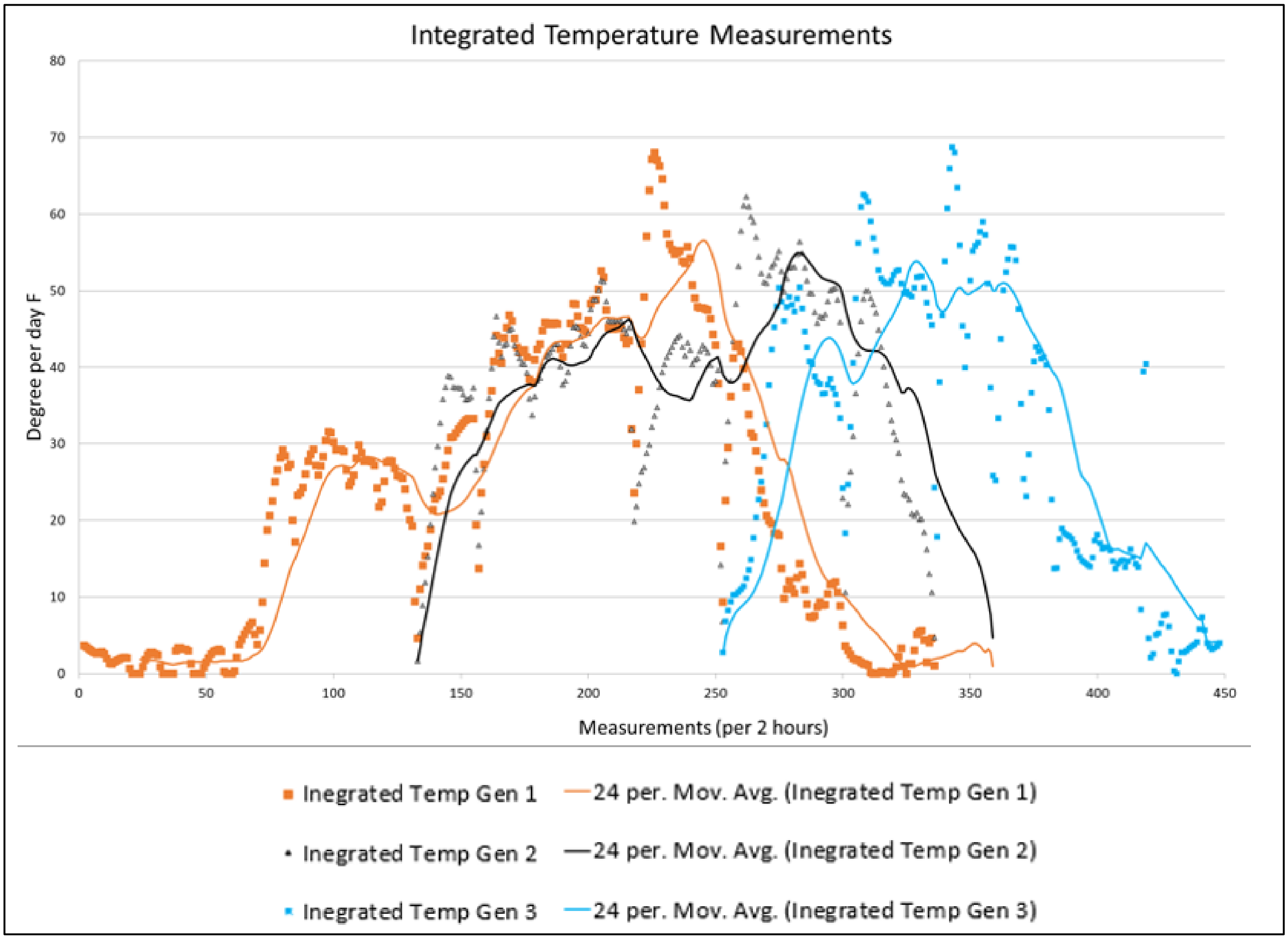

Fig. 5 – Integrated Temperate Measurements for Multi Pile

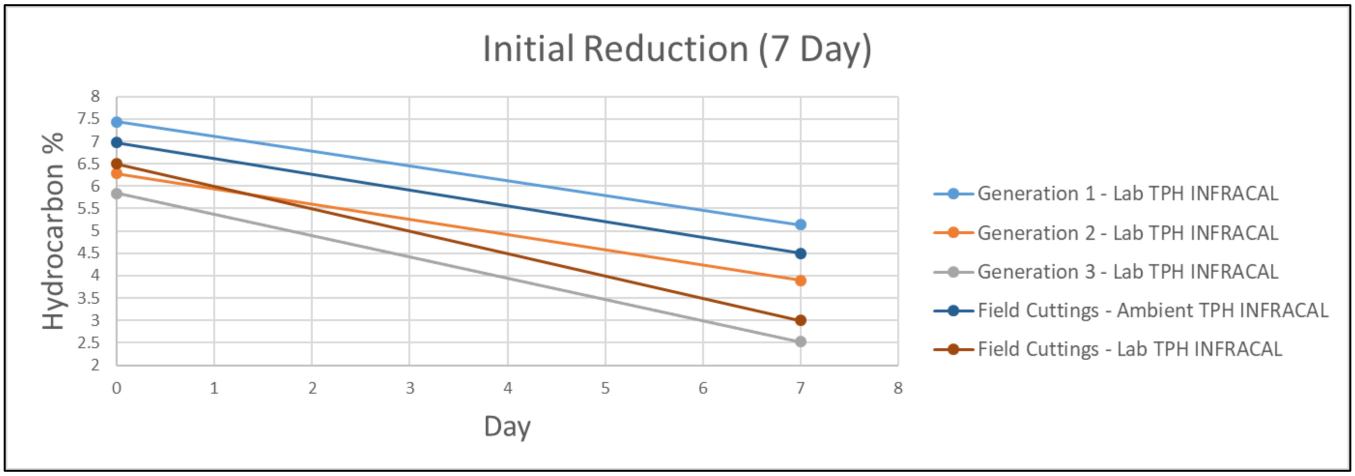

Fig. 6 – Initial Reduction

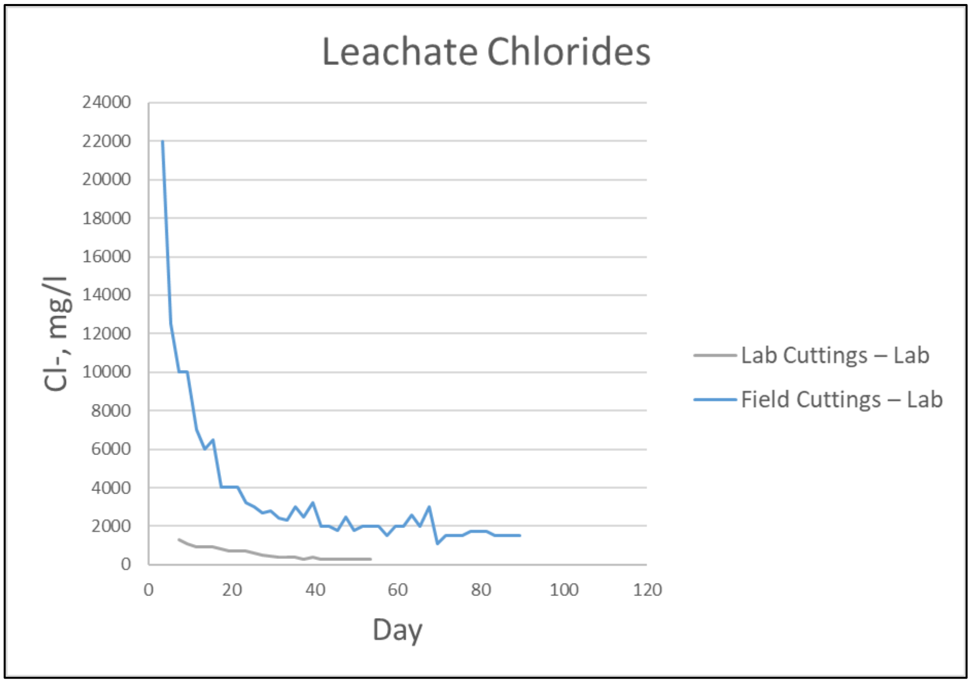

Fig. 7 – Leachate Chlorides

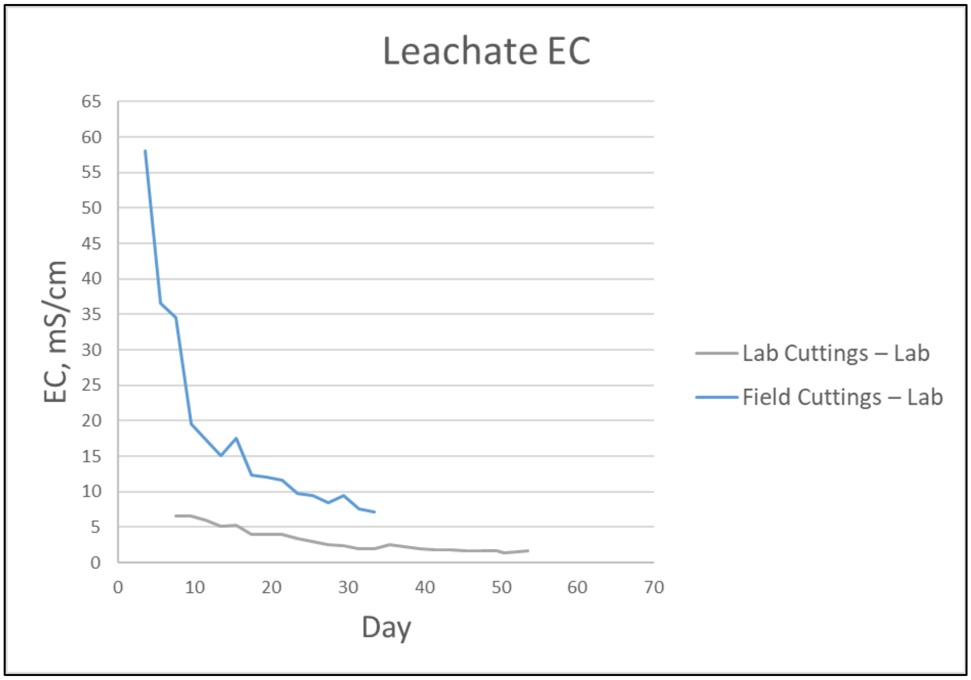

Fig. 8 – Leachate Electrical Conductivity

Fig. 9 – "Lab Cuttings – Lab" pile (bin 2, left); "Field Cuttings – Lab" pile (bin 3, right); Center pile is outside the scope of this paper.

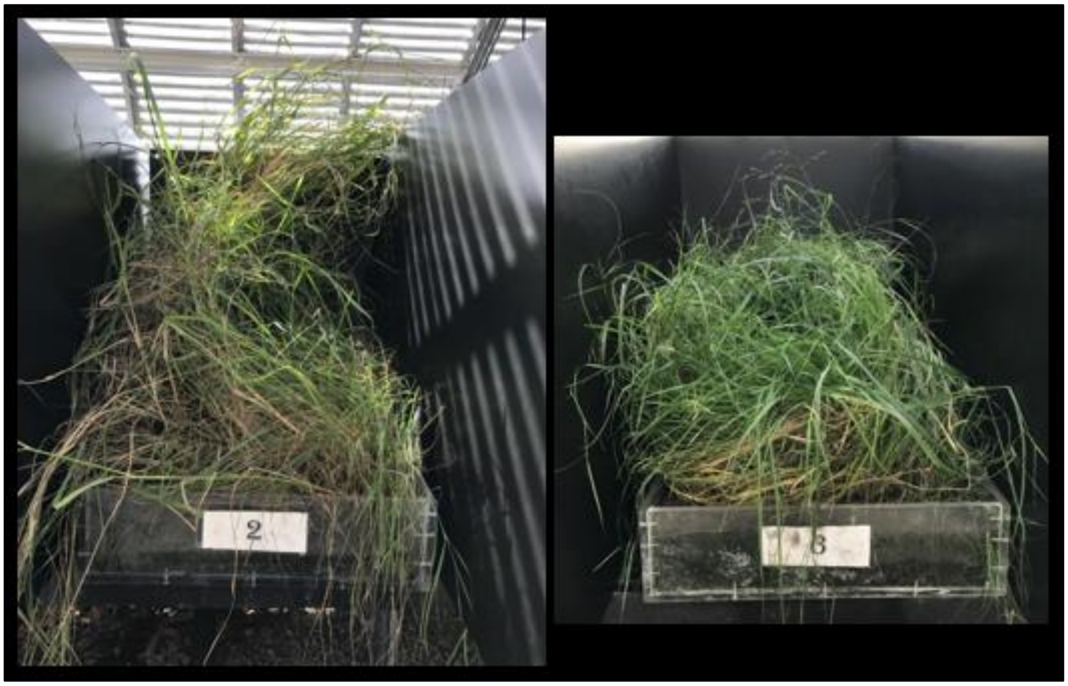

Fig. 10 – Multi Pile – "Lab Cuttings – Lab" pile (bin 2, left); "Field Cuttings – Lab" pile (bin 3, right);