

**A Novel Water Treatment Technology for
Applications in Hydraulic Fracturing, March
2016**

**A Preliminary
Technology Assessment Report
March 2016**



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Executive Summary

Introduction: Electrocoagulation (EC) is an emerging technology that combines the functions and advantages of conventional coagulation, flotation, and electrochemistry in oily water and wastewater treatment by providing a quantitative appreciation of the mechanism of interactions between themⁱ. Based on the principles of electrolysis a simplified EC system may contain single or multiple metal electrodes in the form of anode-cathode pairs and may be connected in either a monopolar or a bipolar modeⁱⁱ. Metals released from the anode during electrolysis cause coagulation of pollutants aiding their separation from water. The optimum process conditions in an EC such as current densities, treatment times, pH etc., are established to achieve high contaminant removal efficiencies. However, one of the challenges limiting the efficiency of EC is the need for the regular cleanup of the fouled electrodes, which causes an intermittent shut-down and a re-start of the EC process.

The ECO II project funded by PTAC/NRCAN was aimed at overcoming this challenge. An ultrasonic system was tested and the process optimized by Easwara to clean the electrodes effectively during the EC treatment of frac flow-back water without their removal from the treatment device. The results of the ECO II project have been reported in Easwara's Final draft report. This preliminary technology assessment is based on the Easwara's Final draft report and specific clarifications provided by Easwara via email correspondence.

Objectives: The overall objective was to determine the efficacy of the Ultrasound (US) in reducing electrode fouling during the EC treatment process. The specific objectives were as follows: (i) to optimize an US system for the effective cleanup of the fouled electrode; and (ii) to test EC for the removal of target contaminants such as total suspended solids, total hardness, heavy metals and total petroleum hydrocarbons from frac flow-back water.

Description of Experiments: The experiments were conducted at the laboratories in the Department of Chemical and Petroleum Engineering, and the Centre for Environmental Engineering Research and Education, University of Calgary. The frac flow-back water used in the experiments was obtained from hydraulic fracturing operations at Progress Energy's Pond, in North Western Alberta. The EC cell incorporating the US transducer was tested using frac flow-back water in a process that included two steps. The first step involved the experimental optimization of the US for the cleanup of the fouled electrodes and the second step tested the efficiency of electrocoagulation for the removal of target contaminants such as suspended solids, hardness, and heavy metals and emulsified oil. The testing included the treatment of the frac flow-back water at different US regimens where the optimum operational parameters for improving EC efficiency were determined.

Results: The results of the first step of the EC process incorporating the US transducer showed the visual removal of scale deposition from EC anode completely. An ultrasound exposure at 480 Watts and frequency of 25 kHz for a time duration between 1 and 3 minutes and at a distance of 5 mm between the US transducer and the EC electrode provided the most optimum result. The results of the second step of the EC process showed a removal of suspended solids, oil and hardness from frac flow-back water up to 90%. The application of carbon dioxide gas bubbled into water during the EC process increased the removal of total hardness in water from 50% to 90%. The removal of heavy metals iron and barium was not supported with comparative before and after treatment results.

Technology assessment: The assessment of the results associated with the specific objective (i) showed that optimization of the US process for the rapid clean-up of the anode during the EC treatment of the frac flow-back water tested was highly effective. The assessment of the results associated with specific objective (ii) showed that the EC treatment for removal of total suspended solids, total hardness, and total petroleum hydrocarbons from frac flow-back water was successful. The removal of heavy metals such as iron and barium could not be verified because it not supported by comparative results before and after the treatment.

An assessment of the overall results showed that when Easwara's US process was combined with the EC treatment, a major drawback associated with electrode fouling could be overcome successfully without the extraction of electrodes as opposed to the current practice which requires the intermittent stopping of the EC treatment process for the extraction, clean-up and re-installation of the electrodes. Relevant technology details have been outlined in the Technology Assessment Summary.

Executive Technology Assessment Summary	
Technology Key Parameters	Description
Technology Type	Easwara's Innovative Ultrasonic process with Electrocoagulation
Treatment efficiency associated with the reduction of target contaminants	The treatment efficiency showed that the following was achieved; reduction in total hardness of 90% as calcium carbonate (CaCO ₃); A 97% decrease in Nephelometric Turbidity Units (NTU) indicating a reduction of TSS; and a 97% removal of total petroleum hydrocarbons (TPH) representing a reduction of emulsified oil from frac flow-back water.
De-fouling of the electrode	A complete de-fouling of the electrode (anode) was achieved with an US process at 480W and 25 kHz, between 1 and 3 minutes
Infrastructure considerations	Infrastructure considerations are not available in the report. Experiments were conducted in a laboratory
Electrical/Power requirements	The power applied for the US treatment was up to 480 Watts The power requirements for the EC treatment was not specified
Utility requirements (natural gas, de-ionized water line etc.)	There are no special utility requirements indicated in the report. CO ₂ gas was used using a gas cylinder at a flow rate of 20 ml/min
Energy consumption	Under experimental conditions the energy consumption for the electro-coagulation with the ultrasonic treatment process was ~0.75 kWh/m ³
Venting requirements- fume hood, etc...	Experiments were conducted in the laboratory with standard fume hoods. The off gases were vented
Chemical requirements MSDS and HS&E requirements Handling of chemical by-products	Not specified. MSDS/HS&E are not provided Coagulated sludge will require disposal as per applicable regulations. Details of the volume and analysis of the sludge has yet to be determined.
Type of system tested	A bench-top EC and US System
Technology readiness level	Level -1
Feed Volume: Product Volume: Waste Volume: Flow rate: Flow rate:	The feed volume was 10 litres The product volume was not specified The waste volume was not specified Flow rate of water during EC process was 0.5 L/minute Flow rate: Flow rate of CO ₂ gas supply was 20 ml/minute
Overall costs (capital cost, operational cost, and equipment maintenance costs)	Easwara anticipates a 10 to 15% cost reduction of current industrial application of EC process. A higher technology readiness level (TRL) is required to confirm the capital expenditures and the operational and maintenance expenditures associated with the EC and the US system.
Pre-Treatment Requirements: Mid-Treatment Requirements: Post-Treatment Requirements:	Pre-Treatment: Not required Mid-Treatment: Unlikely but is not ruled out based on the type of feed water Post-Treatment: The coagulated sludge and the scale removed from the electrode after ultrasonic treatment must be separated and disposed of. Regular maintenance operations are required to collect precipitated waste and to replace spent EC electrodes
Concentrated Waste/Disposal	Wastes must be handled/disposed as per applicable regulations

Further investigations of the US system with EC treatment will be required at a higher technology readiness level in order to provide the design basis for the pilot scale up. The piloting of a mobile treatment system on-site would provide valuable design and cost data of this novel technology and proof of field performance before large investments are made for the treatment and recycle of frac flow-back water in hydraulic fracturing operations

1.0 Technology Review

Background and Introduction: The background to this research investigation started in 2013 when a project titled the “Separation of silica from wastewater”, sponsored by Easwara, demonstrated the application of ultrasonic technology for the successful cleaning of heavily contaminated electrodes. Through Easwara’s sponsorship two NSERC Engage grants were awarded to the University of Calgary which supported further research as follows: (i) “Electrocoagulation for the treatment of flow-back water from hydraulic fracturing” and (ii) “Evaluation of electrocoagulation to remove heavy metals and break down emulsion from flow back water”. These projects were followed by the ECO II project funded by PTAC/NRCAN titled the Novel Water Treatment Technology for Applications in Hydraulic Fracturing. The ECO II project combines an ultrasonic process with electrocoagulation for reducing the fouling of electrodes during the treatment of frac flow-back water. The results of the ECO II project have been reported in Easwara’s Final draft report. This preliminary technology assessment is based on the Easwara’s Final draft report dated February 29th and specific clarifications provided by Easwara via email correspondence in March 2016.

EC is an electrochemical process used for the purification of various types of water such as oily wastewater; pulp and paper wastewater; food and beverage, tannery, textile and dye based wastewater; surface water as well as model water and wastewater containing suspended solids, heavy metals, nutrients, cyanide and other elements and ionsⁱⁱⁱ, ^{iv}. EC effectively removes colloidal and emulsified pollutants by applying a direct electrical current through the contaminated water using metal (generally iron or aluminum) electrodes that results in the release of metal cations from a sacrificial electrode (anode). Through a range of complex mechanisms these metal cations destabilize the colloids and emulsions by charge neutralization, break oily emulsions leading to droplet coalescence, and cause the coagulation and agglomeration of particles, while enhancing their separation from the solution by precipitation and floatation. However, the EC treatment process also leads to the deposition of impurities on the electrodes and causing fouling and associated challenges. Fouled electrodes retard the EC performance efficiency and therefore they need to be cleaned regularly. The regular clean-up requires intermittent stopping and restarting of the EC treatment process for a few hours in order to extract, clean and re-install the electrode back into the EC cell. The ECO II project was aimed at addressing these challenge during the EC treatment process.

An ultrasonic process was tested and optimized by Easwara to clean the electrodes rapidly and effectively during the EC treatment of frac flow-back water. Ultrasound is a longitudinal wave which has frequencies greater than 20 kHz. These waves are formed by the rapid growth and collapse of oscillating bubbles in milliseconds and their mechanisms are drawn together from principles based on acoustics, cavitation, nucleation and associated fluid dynamics^v. The collapse of the oscillating bubbles create intense pressures and temperatures, and while, at the electrode, the high pressure micro-jets from the ultrasound is thought to impact the electrode surface by removing the scale layer. The electrocoagulation combined with ultrasound is expected to improve the kinetics and the effectiveness of the electrode processes for the treatment of water^{vi}.

Objectives and Scope: The overall objective was to determine the efficacy of the Ultrasound (US) in reducing electrode fouling during the EC treatment process. The specific objectives were as follows: (i) to optimize an US system for the effective cleanup of the fouled electrode; and (ii) to test EC for the removal of target contaminants such as total suspended solids, total hardness, heavy metals and total petroleum hydrocarbons from frac flow-back water. The project scope involved the combination of two processes that was incorporated in the same EC treatment device namely the artificial fouling of the electrodes during EC treatment of frac flow-back water, and the use of a US transducer to optimize the clean-up of the fouled electrodes.

Experimental Approach and Methodology: The experimental approach involved investigations in two major steps namely; (i) electrode fouling and (ii) electrode de-fouling in order to meet the objectives. Electrode fouling involved investigations of the efficiency of the EC in removing target contaminants. Electrode de-fouling involved investigations of the US parameters such as the frequency, exposure time, power output, distance between electrode and the transducer and the power requirements. The experimental unit consisted of an EC cell combined

with an US system mounted parallel to the electrode. Figures 1a and 1b show the configuration of the apparatus that combines the US process with the EC treatment device used for testing the frac flow-back water.

Electrode Fouling: In the first step the frac flow-back water for the bulk experiments was obtained from the Progress Energy's pond. This water was pumped into EC cell at a rate of 0.5 L/minute and treated with a current density of 40 mA/cm² at 2.0 to 2.5 Volts for a duration of 20 to 30 minutes and lead to the coagulation of water contaminants and fouling of the electrode. At the end of the EC treatment, the deposition of precipitates on the electrode was tested for its chemical composition, and the same electrode was exposed to the US process for de-fouling. About 20 litres of water was treated and collected at the outlet of the EC cell.

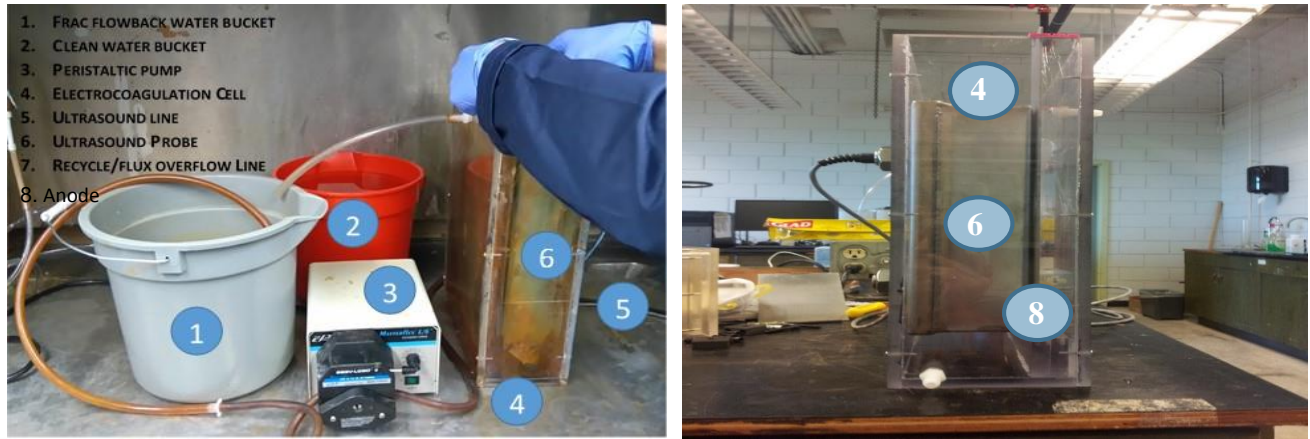


Figure 1a. EC-US configuration of the apparatus (Left) **Figure 2b.** EC-US Cell Vertical View (Right)

A focused total hardness experiment was conducted in a bench top EC unit with a set of 18 iron electrodes from Powell Water Systems Inc., USA, as shown on Figure 2. De-oiled flow-back water with elevated total hardness was pumped through the chamber at a flow rate of 300 ml/minute and at 10 to 25 Volts (0.5 to 1.5 amperes) for a duration of 1 to 3 minutes. To facilitate the removal of total hardness, carbon dioxide (CO₂) gas was bubbled at a rate of 20 ml/minute into the frac flow-back water during EC treatment process.



Figure 2a. EC unit for Total hardness Analysis (Left) **Figure 2b.** Electrodes inside test chamber (Right)

The Powell Water System with 18 electrodes was also used for the testing of total suspended solids (TSS) and total petroleum hydrocarbons (TPH) from the flow-back water. The test water sample containing the elevated TSS and TPH was exposed to an EC treatment of 20 Volts (approximately 4 amps) over a time duration of 12 minutes. This treatment led to the separation of water from impurities due to the formation of coagulated sludge which settled to the bottom of the cell. The water before and after this treatment was sampled for analysis. In total, 2 litres of water were treated in each experiment for the analysis of target contaminants. The experiments performed

in the Powell Water System were aimed at the evaluation of feasibility of EC treatment for removal of TSS and TPH from frac flow-back water as well as for the testing of the effect of CO₂ gas for the removal of total hardness.

Electrode De-Fouling: In the second step, fouled electrode was placed at a distance of about 5 to 20 mm away from US transducer and the frac flow-back water was treated with various US regimens at wattages ranging from 125W to 500W, and at frequencies of 25 kHz or 40 kHz for a duration of 1 to 3 minutes. The visual results of the removal of the scale from the electrode surface and reliability of cleaning was recorded. Based on the results of iterative experiments, the optimization of the key parameters for a rapid and effective electrode (anode) de-fouling during the application of US process in the EC treatment was determined.

The feed water and the treated water were analyzed for total hardness, TSS and TPH before and after EC treatment. The test methods were as follows. Total Hardness as analyzed by EDTA titration using Eriochrome BlackT as the indicator and the ammonia and ammonium chloride (NH₃-NH₄Cl) as the buffer, and reported in parts per million (ppm) of CaCO₃. TPH was analyzed using gas chromatograph coupled a flame ionization detector and mass spectrometry. TSS were determined by analyzing the turbidity of water. Turbidity is a measurement of how light scatters when it is aimed at water and bounces off the suspended particles. It is not a measurement of the particles themselves. The turbidity and TSS relationship is interpreted by a linear regression analysis where the turbidity is used as a predictor of TSS. Samples of the scale were collected and analysed by powder X-Ray diffraction (XRD).

Results and Discussion

Feed Water Results: Prior to the start of the experiments, frac flow-back water obtained from the Progress Energy's pond and used in this project was analysed for the chemical composition of the target contaminants. The results of this analysis showed that the frac flow-back water contained 82,260 ppm sodium chloride (NaCl), 17,560 ppm calcium chloride (CaCl₂) and 3,440 ppm magnesium chloride (MgCl₂). The total hardness was 1130 mg/L as CaCO₃. The total suspended solids derived from the corresponding turbidity result was 860 NTU and the total petroleum hydrocarbon concentration was 2860 ppm.

Electrode Fouling: The EC treatment applied a direct electric current through the frac flow-back water using either an iron or aluminum electrode. The iron anode oxidises to form dissolved ferrous and ferric ions (Fe²⁺ and Fe³⁺) in solution, and similarly the aluminum anode oxidizes to form dissolved aluminum ions (Al³⁺). At the cathode water is electrolysed to form hydrogen and generate spontaneous hydroxide and poly-hydroxides. These ions can destabilise colloidal contaminants by charge neutralisation, while the precipitation of ferric hydroxide for instance can lead to sweep coagulation of inorganic and organic contaminants in the water and assist in settling the solids.

The mechanism of the destabilization of oil-in-water emulsions is complex. Under an electric field water droplets become polarized and tend to align themselves in the direction of the electric forces thus bringing the droplets together, breaking their film and causing them to coalesce. In the case of the emulsions in frac flow-back water, where the emulsions are stabilized by fine solids, the metal iron or aluminum cations released neutralize the negatively charged particles associated with emulsion droplets causing their agglomeration and the coalescence of the droplets. This event also causes the precipitation of solid aggregates and floatation of oil droplets leading to an effective separation of oil and solids from water.

This electro-chemical mechanisms above explain as to how the frac flow-back contaminants lead to the formation of a coagulated sludge, solid aggregates and flotation of contaminants. The end result of this mechanism is similar to conventional chemical coagulation which apply iron or aluminum salts to cause the complexation and precipitation of scale causing ions. However, during EC treatment no chemical additives are used. Instead it is the iron or aluminum ions generated from sacrificial electrode (anode) that provide the metal ions to achieve coagulation. At the anode, an electrode erosion occurs because oxidation takes place. At the cathode, a metal ion reduction takes place. Electrode fouling happens when there is deposition of contaminants on the electrode surface.

The Easwara report showed a reduction of hardness associated with calcium and magnesium cations in the flow-back water after EC treatment. The insoluble products of the oxidation of these and other metals settle at the bottom of the EC treatment device and also accumulate on the electrode surface thus fouling the electrode. The

precipitation of metal that settled to the bottom of the EC treatment device was not determined in the present experiments; while the accumulation and deposition of metal oxides and hydroxides that was seen on the anode surface after EC treatment as shown in Figure 3A was analyzed. The result of this deposition by XRD analysis revealed that the electrode fouling comprised 90% iron, 8% magnesium, 2% calcium and approximately 0.1% barium and silica respectively as shown in Table 1.

Electrode De-fouling: In the second step of the experimental treatment, the parameters for electrode de-fouling of the scale deposited during EC treatment of flow-back water having elevated concentrations of NaCl, CaCl₂ and MgCl₂ were tested. De-fouling was performed with the US transducer mounted parallel to the fouled electrode as shown in Figure 3a on the right side. The electrode in Figure 3a on the left side represents the cathode. The US frequency and power applied to the electrodes, the exposure time and distance between electrode and US transducer were tested for their effectiveness in the removal of scale. The elimination of the scale layer under different US regimens demonstrated that the scale removal increased as the applied frequency was decreased from 40 kHz to 25 kHz and the applied power was increased from 125W to 480W. The reduction of the distance between electrode and US transducer from 20 mm to 5 mm also greatly improved the scale removal efficiency.



Figure 3a Fouled cathode (left) and anode (right) **Figure 3b** Defouled anode 2 minutes (left) and 4 minutes (right)

Ultrasound leads to cavitation bubbles in the water, which collapse creating intense pressure and temperature at the electrode surface, scouring the scale off the electrode. The ultrasound energy dissipates with distance from the transducer, and it was found that the removal of the fouling took longer when the electrode was placed at larger distances from the transducer. Of the conditions tested, the most rapid removal of fouling of 2 minutes was found to occur at a power of 480 W and 25 kHz (for a transducer of 25.4 x 30.48 cm in dimension), with a spacing between the electrode and the transducer of 5 mm. The electrode in Figure 3b on the left side shows the result of the electrode de-fouling under these conditions. A longer exposure to the US did not improve the electrode de-fouling any further as seen in Figure 3 b, on the right side. Cleaning was achieved due to shear forces created by ultrasonic waves on the electrode surface.

Electrocoagulation Efficiency: EC is an effective technology for the rapid removal of total suspended solids, oily sludge and total hardness from waste water in a variety of industries ⁱⁱⁱ. According to the results of the experiments, the EC treatment efficiency in removing the total hardness, TPH and TSS from frac flow-back water was significantly high at over 90% overall as shown in Table 1.

During the EC treatment the precipitation of some of the divalent metals such as calcium and magnesium was enhanced by the bubbling of CO₂ gas into the flow-back which resulted in the formation of their carbonates. These carbonates of calcium and magnesium precipitate out of the frac flow-back water due to their low solubility. In particular, increasing the voltage up to 25 V (approximately 1.5 amperes) during the EC treatment of flow-back water reduced the initial total hardness of 1130 mg/L as calcium carbonate (CaCO₃), by about 50% to a total hardness concentration of 570 mg/L as CaCO₃. Further improvements in the removal of total hardness was achieved by bubbling CO₂ gas through the frac flow-back water during EC process. As a result, a significant reduction in the total hardness of 100 mg/L as CaCO₃ was successfully achieved which was equivalent to approximately a 91% removal after a 20 minute treatment. The EC treatment with CO₂ gas bubbling is an attractive novel technology, which provides a potential alternative to replacing the conventional lime softening processes.

The concentrations of the chloride salts of sodium, calcium and magnesium (NaCl, CaCl₂ and MgCl₂) were reported before the EC treatment but were not reported after the EC treatment. The total hardness includes the concentration of calcium, magnesium, barium, silica and similar scale causing divalent and polyvalent cations and anions. Given the fact that a significant reduction in the concentration of the total hardness was achieved it would have been useful to measure the reduction of the CaCl₂ and MgCl₂ and determine their correlation to the reduction of total hardness in water. Salinity is an important water parameter in hydraulic fracturing. Although the initial NaCl concentration of the frac flow-back was reported before the experiment, the concentration after the experiment was not reported. The alteration in the electro-chemistry that occurred during the EC treatment and the impact to the concentration of electrical conductivity (salinity) and the total dissolved solids (TDS) of the water after the EC treatment would have been useful because water with elevated salinity concentrations need to be measured to assess their use in recycling or disposal in hydraulic fracturing.

Table 1. Results of EC-US treatment of frac flow-back water

Parameters associated with Objectives	Before EC-US process	After the EC process	After the US process	Removal after EC-US treatment
(i) Optimization of the Ultrasonic Process				
XRD Results for Scale Components:				
- Iron	NA	~ 90%	NR	NR
- Calcium	NA	~ 2%	NR	NR
- Magnesium	NA	~ 8%	NR	NR
- Barium	NA	~ 0.1%	NR	NR
- Silica	NA	~ 0.1%		
Visual Results	No Scale Deposits	Scale Deposits	No Scale Deposits	Scale removal
(ii) Electrocoagulation Treatment				
NaCl, ppm	82,260	NR	NA	NR
CaCl ₂ , ppm	17,560	NR	NA	NR
MgCl ₂ , ppm	3,440	NR	NA	NR
Total Hardness, as ppm of CaCO ₃				
- without CO ₂	1130	570	NA	50%
- with CO ₂	1130	100	NA	91%
TPH, ppm	2860	100	NA	97%
Turbidity, NTU As a predictor of TSS	860	26	NA	97%
Heavy metals, ppm (Iron and Barium)	NR	NR	NA	NR

* NA denotes not applicable; NR denotes not reported

The removal of suspended colloids from frac flow-back water was determined by the reduction of turbidity of water, which is used as an indicator of total suspended solids. The EC treatment at the operating conditions of 20 Volts (approximately 4 amperes) over a time duration of 12 minutes resulted in the reduction of water turbidity from 860 NTU to 26 NTU which was equivalent to a 97% removal. The TSS removal by EC correlates well with the efficiency of chemical coagulation^v. However, the advantage of the EC treatment over conventional coagulation includes lowered energy consumption, cost, and maintenance, rapid treatment, lowered volumes of coagulated sludge, and the avoidance of chemical additives. The EC treatment at the same operating conditions revealed a reduction of 97% TPH concentration. Thus, the EC treatment is an effective and rapid de-oiling method

that can potentially replace conventional de-oiling treatment sequences such as the use of activated carbon adsorption, and other physio-mechanical separation processes which yield a comparatively lower TPH removal of approximately 60 to 80% depending on the feed water conditions^{vi}.

In the Easwara report the removal of heavy metals is confirmed from the concentration of barium and iron concentration deposited on the electrode. However, the concentration of iron and barium in flow-back water before the start of the EC treatment and after the end of the EC treatment was not reported. Without a comparative evaluation of the concentration of iron and barium before and after treatment the conclusion made on the removal of heavy metals is not reliable. As shown in Table 1 the results of the EC treatment combined with the US process was successful in removing most target contaminants from frac flow-back water and showed a high efficiency of over 90% in the reduction of total hardness, TSS, and TPH.

2.0 Conclusions

The assessment of the results associated with the specific objective (i) showed that optimization of the US process for the rapid clean-up of the anode during the EC treatment of the frac flow-back water tested was highly effective. The assessment of the results associated with specific objective (ii) showed that the EC treatment for removal of total suspended solids, total hardness, and total petroleum hydrocarbons from frac flow-back water was successful. The removal of heavy metals such as iron and barium could not be verified because it not supported by comparative results before and after the treatment.

An assessment of the overall results showed that when Easwara's US process was combined with the EC treatment, a major drawback associated with electrode fouling could be overcome successfully without the extraction of electrodes as opposed to the current practice which requires the intermittent stopping of the EC treatment process for the extraction, clean-up and re-installation of the electrodes. Relevant details of pertinent parameters have been outlined in the Technology Assessment Summary in page 7.

3.0 Recommendations

Currently Easwara's novel water treatment is a bench scale technology at a technology readiness level of 1. At this scale, the bench scale process provides uniform cavitation and reliable electrode cleaning. The next step is to conduct tests focused on anticipated process and design challenges in order to obtain a sound design basis for a pilot scale up. This would include the consideration of multiple electrodes associated with appropriate US systems that will be required to effectively coagulate contaminants from large volumes of frac flow-back water in the field. Simultaneous de-fouling of the electrodes would be required through the direct integration of US transducers with each electrode since the efficiency of the US cleaning depends on current density and distance between transducer and electrode surface.

Other factors, which could affect the electrocoagulation, is the variance in the complexity, type and concentration of contaminants in frac-flow back water. Chemical contaminants not found or tested in the current project could be deposited on the electrode during EC process, and could change the chemical and physical properties of this deposit, and thereby, change the effectiveness of its de-fouling with the US process. A comprehensive analysis of the physical and chemical properties of the target contaminants from frac flow-back before, during and after the EC-US process is critical. The analytical results in conjunction with the optimum process conditions and a consideration of the parameters outlined in the technology assessment summary in Page 7 of this report should be able to provide a design basis for a pilot scale up.

Another anticipated issue is the waste precipitated at the bottom of the EC cell. If this waste is not removed it will affect the efficiency EC cell operation and could lead to its resuspension and re-emulsification into the treated

flow-back water. Therefore, the EC cell combined with the US system will require regular cell maintenance to remove waste. These design challenges should be addressed in the next phase of this project.

In summary future investigations must consider the following;

- Combining the EC-US treatment process with the application of carbon dioxide bubbling in a continuous batch process
- Determining the effect of chemical composition of target contaminants from different sources of frac flow-back water, including their pH, flow rate and shear stress on electrode fouling and de-fouling
- Testing the EC cell with multiple-electrodes combined with the US treatment of each electrode for handling varying frac flow-back chemistries
- Testing a containment system for the continuous waste removal of the debris from the electrode
- Tying together the acquisition of results from the chemical characterization, process conditions and relevant technology parameters (refer to page 7) in order to assess efficacy of the EC-US, after EC-CO₂, after US and post treatment

The results from the proposed investigations is expected to assist in providing the preliminary design basis for the pilot scale up of the combined EC and US the pilot system.

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