

ELECTRO-COAGULATION OF MEAT PROCESSING WASTEWATER

Logan Yan^{1}, Mark Lay¹, Graeme D.E. Glasgow¹, Aaron Low² and Gordon Henderson³*

1 School of Engineering, Faculty of Science and Engineering, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand.

2 Ligar Polymers, Hamilton, New Zealand

3 Wallace Corporation, Waitoa, New Zealand.

ABSTRACT

Blood wastewater is a significant by-product of the meat processing industry with a solids concentration of 7% and 13% by weight. The blood is typically collected and steam coagulated at rendering facilities before dewatering. It is then either dried separately to produce bloodmeal or rendered with meat and bone to produce meat and bone meal. However, steam coagulation typically requires 200-250 kg of steam per tonne of blood, which can represent a problem if the rendering facility has insufficient steam capacity. A potential alternative is electro-coagulation. Electro-coagulation uses metal electrodes submerged in the wastewater to pass a current through the water, which results in the dissolution of metal at the anode. The metal ions that are liberated then coagulate the dissolved solids. A laboratory scale study was undertaken to examine the treatment performance, electrode requirements and configuration and costs associated with this treatment option for comparison with steam coagulation. Bench top prototype units were built consisting of up to nine pairs of aluminium electrodes submerged in a vessel operated in batch and continuous modes. These units were trialled examining the effect of voltage, electrode type and area, blood concentration, pH and flowrate on solids removal, foaming, amount of electrode consumed, and power consumption. Foaming was significant resulting in a foam with the similar water content to the blood wastewater, and needed dewatering. The electro-coagulation prototype combined with dewatering achieved solids removal rates up to 58% after 2 hours of treatment. The aluminium electrode consumption rate was 0.01 g/amp.min and was independent of the starting concentration of the blood wastewater. The mass of aluminium required to remove the solids varied from 0.5 g/g solids removed with a starting concentration of 0.2% solids, to 0.04 g/g solids at 11.5% starting concentration. Aluminium in the solids was estimated to be between 8-9% and the operating cost of the plant (aluminium electrodes and power) was calculated to be between 2.5 to 5 times that of steam coagulation.

KEYWORDS

Electrocoagulation, blood, wastewater

PRESENTER PROFILE

Logan Yan has a Bachelor of Engineering in mechanical engineering from China, a Postgraduate Diploma and a Masters of Engineering in material and process engineering in advanced oxidation for geosmin and methylisobourneol removal in water and wastewater treatment. Logan currently is employed by New-A-Innovation in Hamilton.

1 INTRODUCTION

The Wallace Corporation South Island rendering plant processes 8,000 litres of blood from nearby meat processing facilities every day. The blood (10-12% dry solids) is currently steam coagulated using direct steam injection to produce a precipitate before dewatering and rendering along with waste bone and meat to produce meat and bone meal. The boilers at the site currently cannot generate sufficient steam for steam coagulation (200-250 kg steam per tonne of blood). The aim of this project was to investigate electrocoagulation as an alternative to steam coagulation.

Electrocoagulation has proven to be an effective method to remove contaminants from water, it is used in waste water treatment to remove heavy metals, suspended and colloidal solids, fats, oil and complex organics, and also bacteria, viruses and cysts [1]. Electrocoagulation was first developed around 1910, and based on previous studies, the process can achieve over 99% removal of heavy metals as well as cell wall or cell membranes of microorganisms in water. The costs including electrodes, power, and system maintenance for waste water treatment operation are quite low [2].

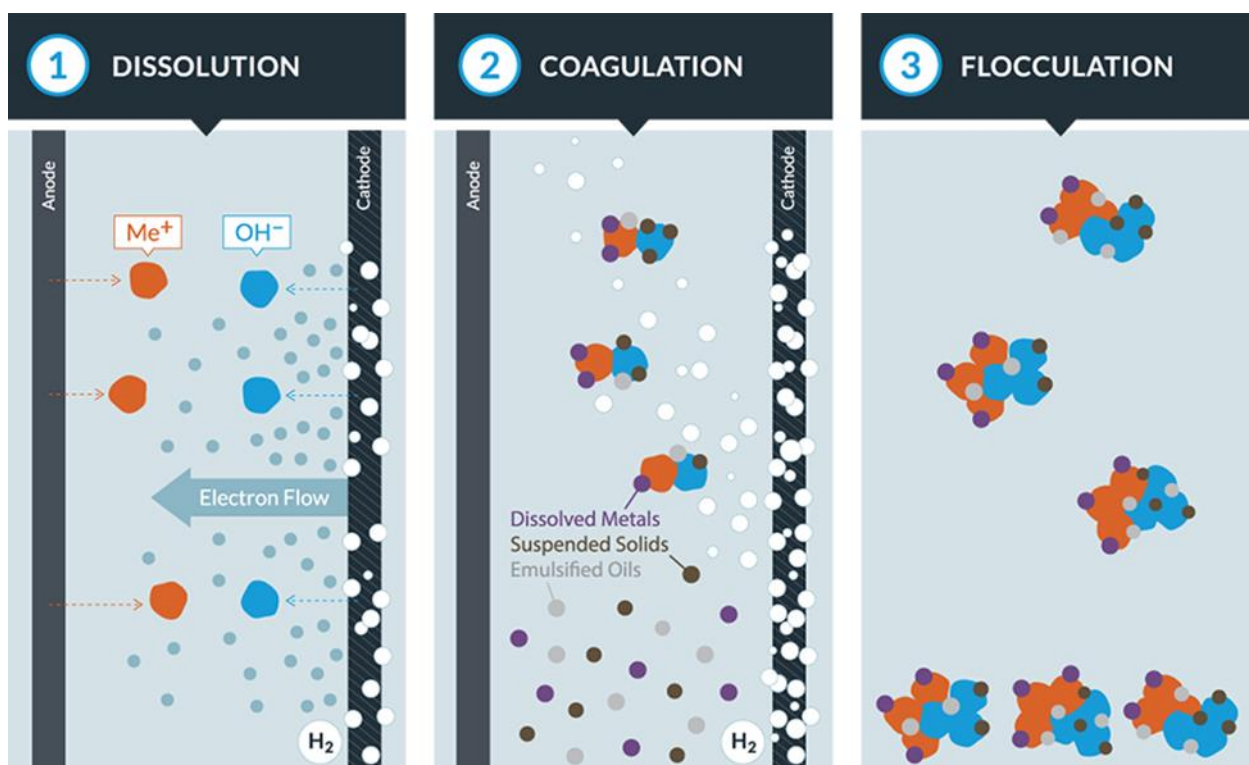


Figure 1: Electrocoagulation process [3].

In the electrocoagulation process, when an electric current is passed between two electrodes in water, water molecules are hydrolyzed into hydrogen gas and hydroxyl groups (Figure 1). Metal from the anode dissolves, releasing metal ions into solution, which act to coagulate dissolved and suspended solids by neutralizing the overall negative charge of the solids, enabling them to coagulate. Some of the coagulated and dissolved solids is floated by the hydrogen gas bubbles to form a foam, while the remaining coagulated solids settles and forms a sludge [3]. The sludge and foam then need to be dewatered.

In previous studies, aluminum and iron are widely used as electrodes in electrocoagulation. For the removal of sulfides, iron electrodes can remove above 90% while aluminum has removals less than 12%. However, in tannery wastewater treatment,

chromium removal can be greater than 97% with aluminum electrodes compared to 69% with copper and 90% with iron [4].

2 ELECTROCOAGULATION METHODS AND RESULTS

2.1 EFFECT OF ELECTRODE TYPE

The effect of aluminum and iron electrodes were investigated for electrocoagulating red blood cell concentrate that had been diluted to 0.2% solids (2 g/L). Aluminium and iron sheet was cut into plates 63 mm by 89 mm. The aluminium plates were 1 mm thick and the iron plates were 1.5 mm thick. Plastic with slots set at 1 cm apart were used on either side and top and bottom of the plates to space the plates apart and prevent short circuiting. The assembly was then placed in a 1.2 L container, the power supply attached using alligator clips, and the electrodes set up in alternating positive/negative arrangement across the assembly (Figure 2). This was placed on a magnetic stirrer and a magnetic flea used to agitate the solution. 1 L of dilute blood was added, resulting in a submerged electrode area of about 200 cm², and the power supply switched on. Foaming, solution clarity and sludge generation were noted.

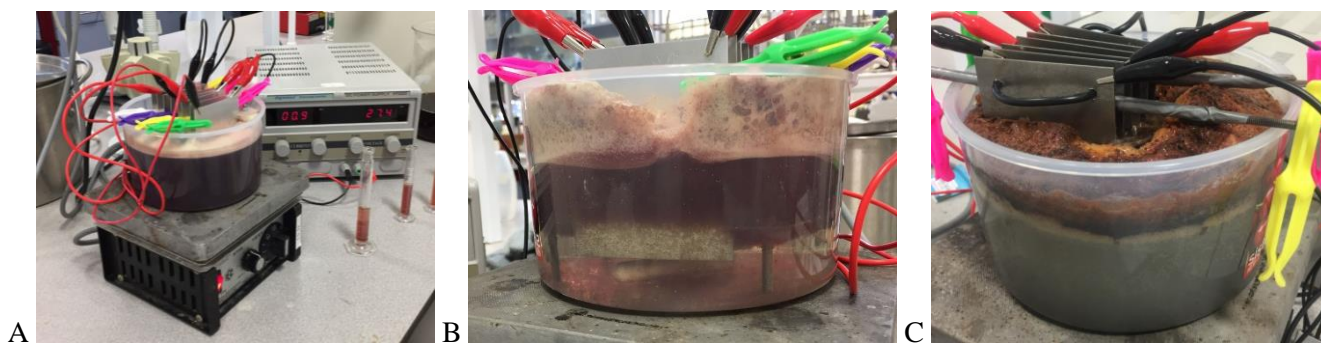


Figure 2: A. Original electrocoagulation system with B. aluminium electrodes and C. iron electrodes in a 0.2% solids blood solution.

For the aluminium plates, 27.4 V generated a current of 0.9 A. Foam started to appear after 30 minutes and the solution separated into a foam, clear liquid and a precipitate (Figure 2 B). No increase in temperature was noted, but as the solution cleared, the current dropped from 0.9 A to 0.3 A. This would be expected as the protein precipitates, there is a lower concentration of conducting ionic molecules in the solution, therefore resistance of the solution to flow of electrons would increase. No filtration was needed. Starting and final weight of the aluminium electrode was noted, and 1.04 g of aluminium was lost into the solution.

For the iron electrodes, 27.4 V was applied and foam appeared immediately. The foam was a red brown colour, due to oxidation of the iron electrodes, while the solution color was a dark gray (Figure 2 C). Temperature increased to 30°C. The foam was stable and could be easily separated from solution. Starting and final weight of the iron electrodes was noted, and a mass loss of 4.46 g of iron was recorded. Current during the experiment increased from 0.9 to 1.4 A, likely due to the increased concentration of iron in solution increasing the conductivity of the solution. The whole solution was filtered, and sludge showed a red brown colour, due to the amount of iron lost from the electrodes (Figure 6).

Aluminium was selected for the electrodes because it lost the least amount of electrode and resulted in a clear solution. In comparison, iron electrodes lost a far greater mass,

resulting in a red brown coloured sludge and gray coloured water. Furthermore, ash content from the coagulate using iron electrodes would be much greater due to the greater loss of electrode.

2.2 EFFECT OF BLOOD CONCENTRATION AND VOLTAGE ON CURRENT

To investigate the effect of blood concentration and voltage on current in electrocoagulation, blood was diluted 1.4, 7, 35 and 70 g/L (or 0.14, 0.7, 3.5 and 7% solids). This was placed in the same apparatus used for the initial experiments with four aluminium electrodes, spaced 2 cm apart, with a total electrode area of 146 cm² and the voltage gradually increased from 0 to 26.5 V, and current was recorded.

Current increased linearly with voltage (Figure 3) and the extent of increase (gradient) was dependent on the solution concentration.

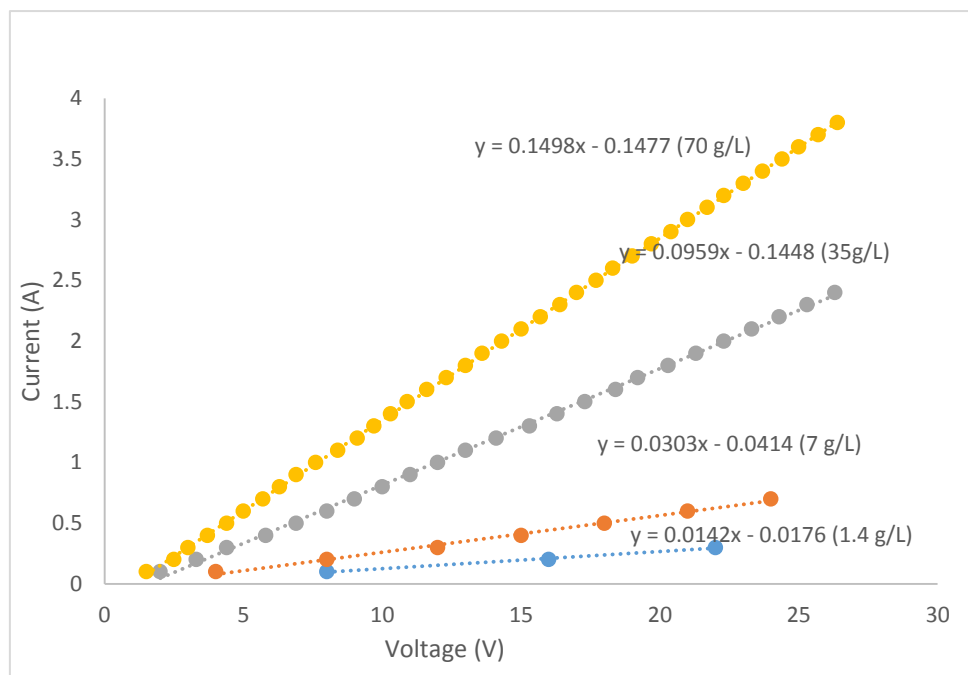


Figure 3: Current vs voltage for different concentrations of blood.

Current (I) in amps is given by the following:

$$I = \frac{V}{R} \quad (1)$$

Where V is voltage and R is resistance in ohms. As electrode area (A - cm²) increases, current will also increase, while as distance (l - cm) between electrodes increases, current will decrease, giving the following relationship.

$$I = \frac{VA}{Rl} \quad (2)$$

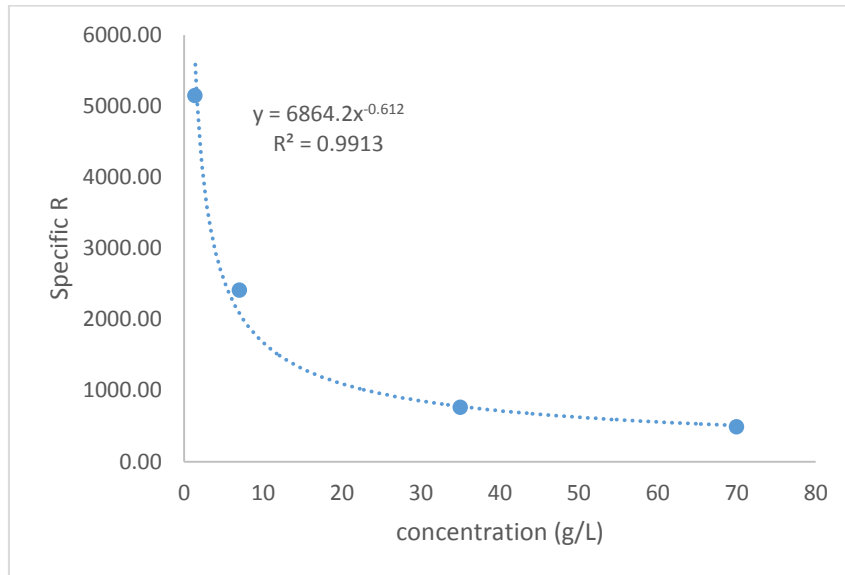


Figure 4: Current vs voltage for different concentrations of blood.

The gradient of the lines in figure 11 is equal to $1/R$, therefore by inverting the gradient, R of each solution was calculated to give a specific resistance of the solution vs solution concentration which accounted for electrode area and distance (Figure 4). Fitting a power law relationship to the curve in Figure 4 gives the following:

$$R = aC^{-b} \quad (3)$$

Where C is concentration in g/L and a and b are fitted parameters. Therefore the final equation for calculating current is:

$$I = \frac{VA}{aC^{-b}l} \quad (4)$$

2.3 EFFECT OF STARTING CONCENTRATION AND PH ON BLOOD ELECTROCOAGULATION

A new system was designed to give sufficient space for foam using a 5 L beaker. Electrodes were 300 mm by 50 mm and volume of solution typically used was 2 L, so immersed electrode area was 200 cm². In addition, due to potential short-circuiting, a 5-amp fuse was installed in the line between the electrodes and power supply to protect the power supply and prevent the cables from overheating. Foam was well controlled over 2 hours running time (Figure 13) and gradually dewatered after power was switched off (Figure 14), leaving a precipitate on the electrode surface (Figure 15).

This system was used to explore the effect of starting solution concentration (1.75%, 3.5% and 7% solids) and pH (adjusted using CaOH and NaOH 1M solution or 1M HCl) on percentage removal of solids, electrode consumption, % solids in the foam and sludge. In all experiments, 2 L of solution was used, voltage was 10 volts and running time was 2 hours. Samples were taken every 30 minutes, protein concentration was measured using UV absorbance, and power supply current was noted. Solution and foam was collected afterwards and centrifuged at 3000 rpm for 10 minutes and the foam, liquid and pellet oven-dried overnight at 70°C to determine solids content.

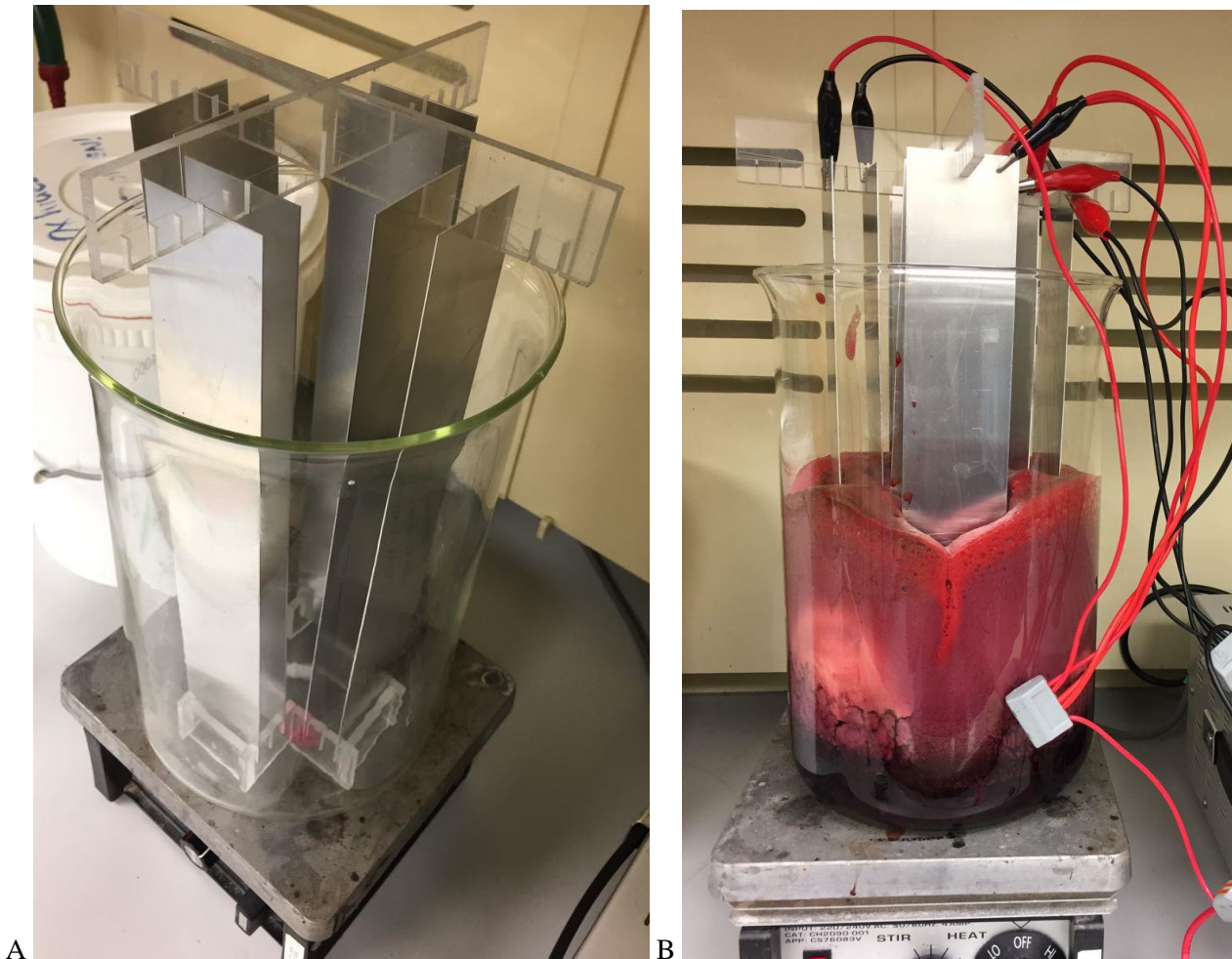


Figure 5: New batch electrocoagulation system: A. Empty, B. in operation.

Electrode mass loss was calculated using:

$$\text{Aluminum mass loss (g/amp.min)} = \frac{\text{plates weight before} - \text{plates weight after}}{\text{Average Amps} * \text{time}} \quad (5)$$

Electrode consumption per gram dry solids removed was calculated using:

$$\text{g aluminum/g dry solids removed} = \frac{\text{plates weight before} - \text{plates weight after}}{(\text{initial solid \%} * \text{Volume}) - (\text{final solid \%} * \text{Volume})} \quad (6)$$

Percentage removal of solids was calculated using:

$$\% \text{ removal} = \left(1 - \frac{\text{final solid \%}}{\text{initial solid \%}}\right) \times 100\% \quad (7)$$

Aluminium electrode mass loss was reasonably consistent across all starting % solids at 0.0105 to 0.011 g of electrode per amp per min, while there was some variation in mass loss for different pH ranging between 0.0079 to 0.0105 g/amp.min (Figure 6).

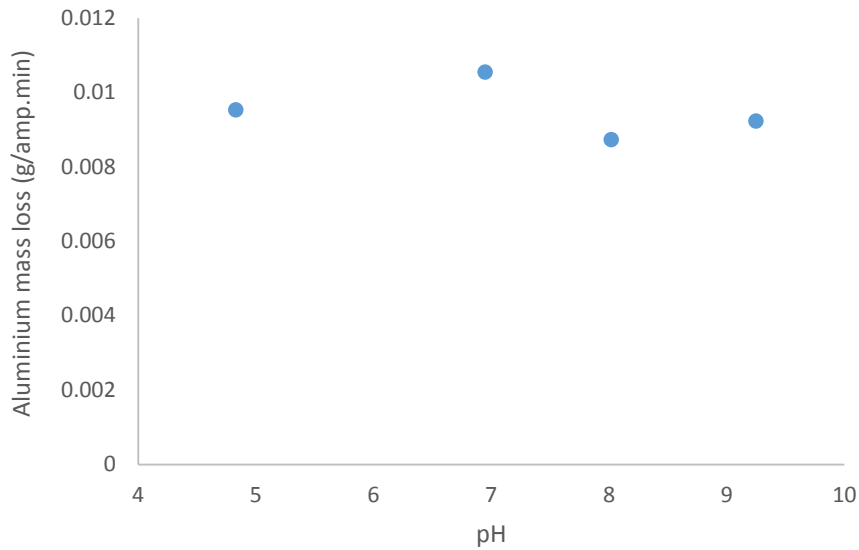


Figure 6: Aluminium mass loss with different starting pH at 3.5% solids.

Aluminium consumption per g dry solids removed started at 0.2 g/g dry solids at 1.75% starting solids, down to 0.078 g/g dry solids removed at 7% starting solids (Figure 7). This was expected as this is a common result found in coagulation where higher doses of coagulant are needed to remove lower concentrations of suspended solids. % removal increased with starting % solids (Figure 8), due to an increase in solution conductivity, meaning that more current passed through the solution at the same voltage (Figure 29), resulting in more gas bubbles being produced and more aluminium electrode being dissolved into solution, therefore a greater removal was achieved (Figure 26).

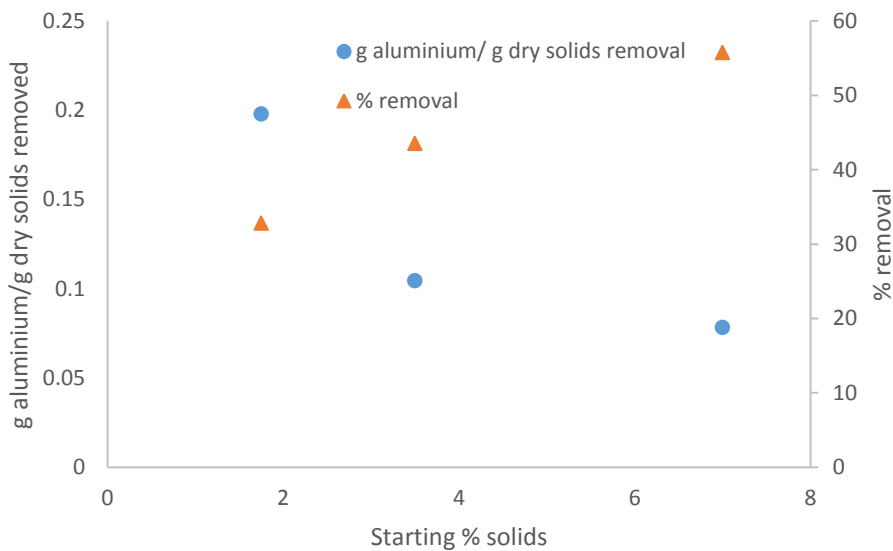


Figure 7: Aluminium used and % solids removal with different starting % solids.

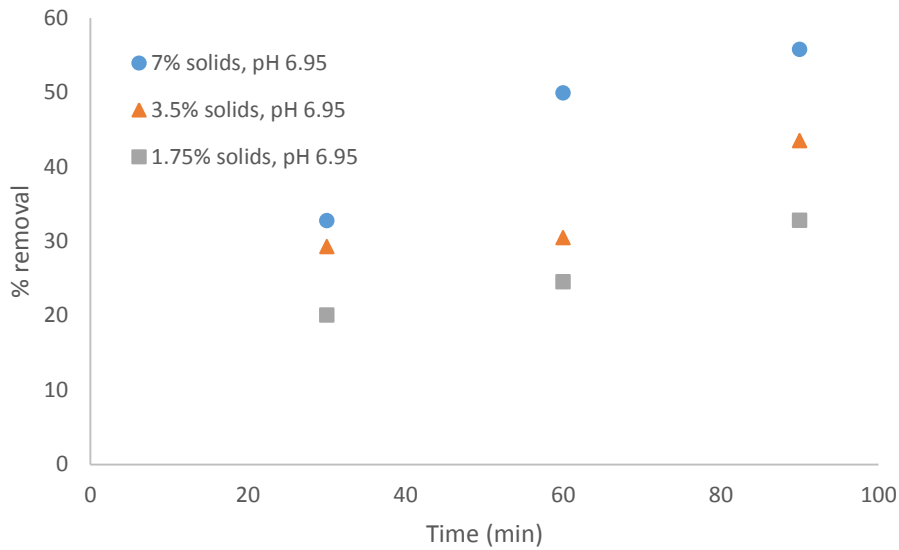


Figure 8: % removal vs time at different starting % solids.

Percentage removal increased when pH was changed either side of pH 7 (Figure 9 and 10) due to the increased ionic content from adding the acid or base increasing the conductivity of the solution, resulting in increased current flow (Figure 11). The amount of aluminium consumed per g dry solids decreased when pH was increased higher than 7 possibly due to calcium ions from the calcium hydroxide participating in coagulating the blood. In addition, the isoelectric point of haemoglobin is 6.9, therefore at higher pH it should have a higher overall negative charge which may possibly contribute to it denaturing and precipitating easier (adult haemoglobin is susceptible to alkali denaturation). At low pH, foaming was much greater than the high pH, possibly due to electrolysis of the HCl into gas, while foaming was more easily controlled when $\text{Ca}(\text{OH})_2$ was used.

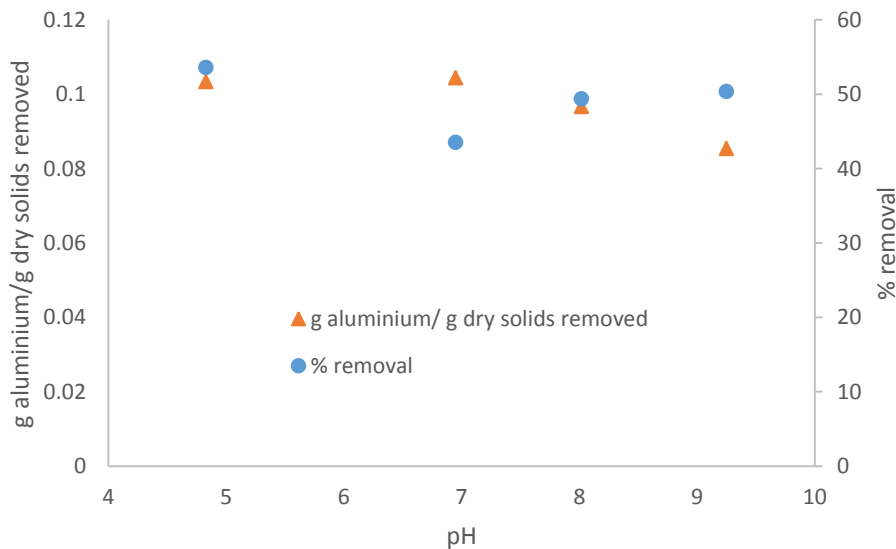


Figure 9: Aluminium used and % solids removal with different starting % solids.

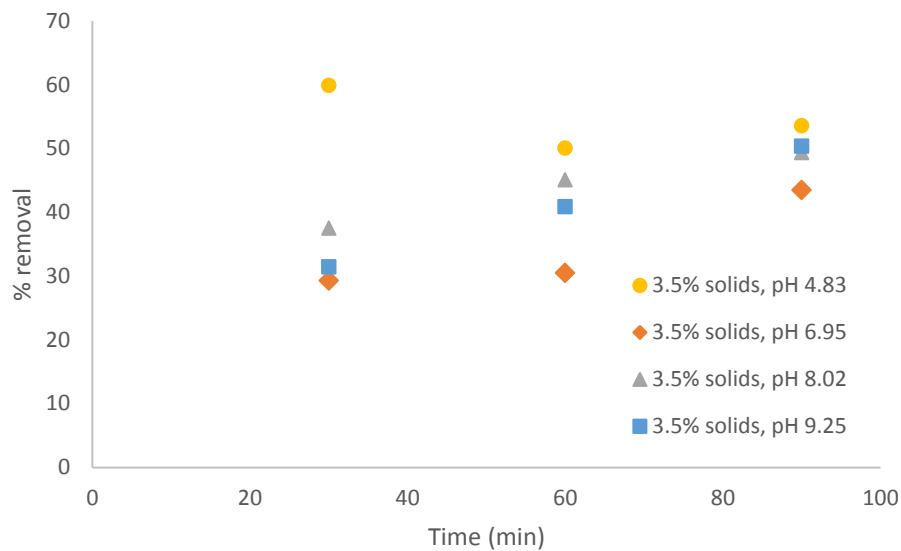


Figure 10: % solids removal over time with different starting % solids.

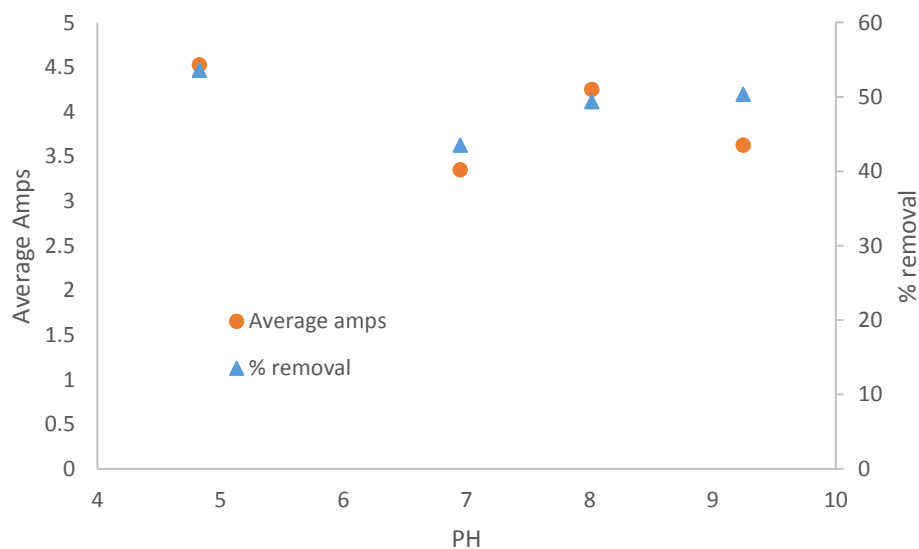


Figure 11: Average amps and % solids removal with different starting pH.

While the system was designed to control foaming during the blood coagulation process, over the 2 hours, foam remained under the level of beaker, but due to liquid being entrained in the foam, the liquid level decreased, so that contact area of electrodes and solution was not constant, resulting in reduced current flow. The liquid, sediment and foam after coagulation was hard to recover. Upon centrifugation, the foam formed a layer on top of the liquid and was consistently 12-15% solids, while the pellet formed was like a gel and was 10-13% solids, therefore while electrocoagulation had taken place, the removal of water was not sufficiently high given that typical starting solids of collected blood range between 7 to 11% solids. Furthermore, removal of solids as measured by UV did not exceed 56% over the two hours operating time. Therefore for successful operation, liquid level would need to remain constant, electrode area would need to be much greater, and the foam and sludge continuously dewatered so that the

remaining solids and liquid could be recycled back through the system. This led to the design of System 3 (Figure 12).

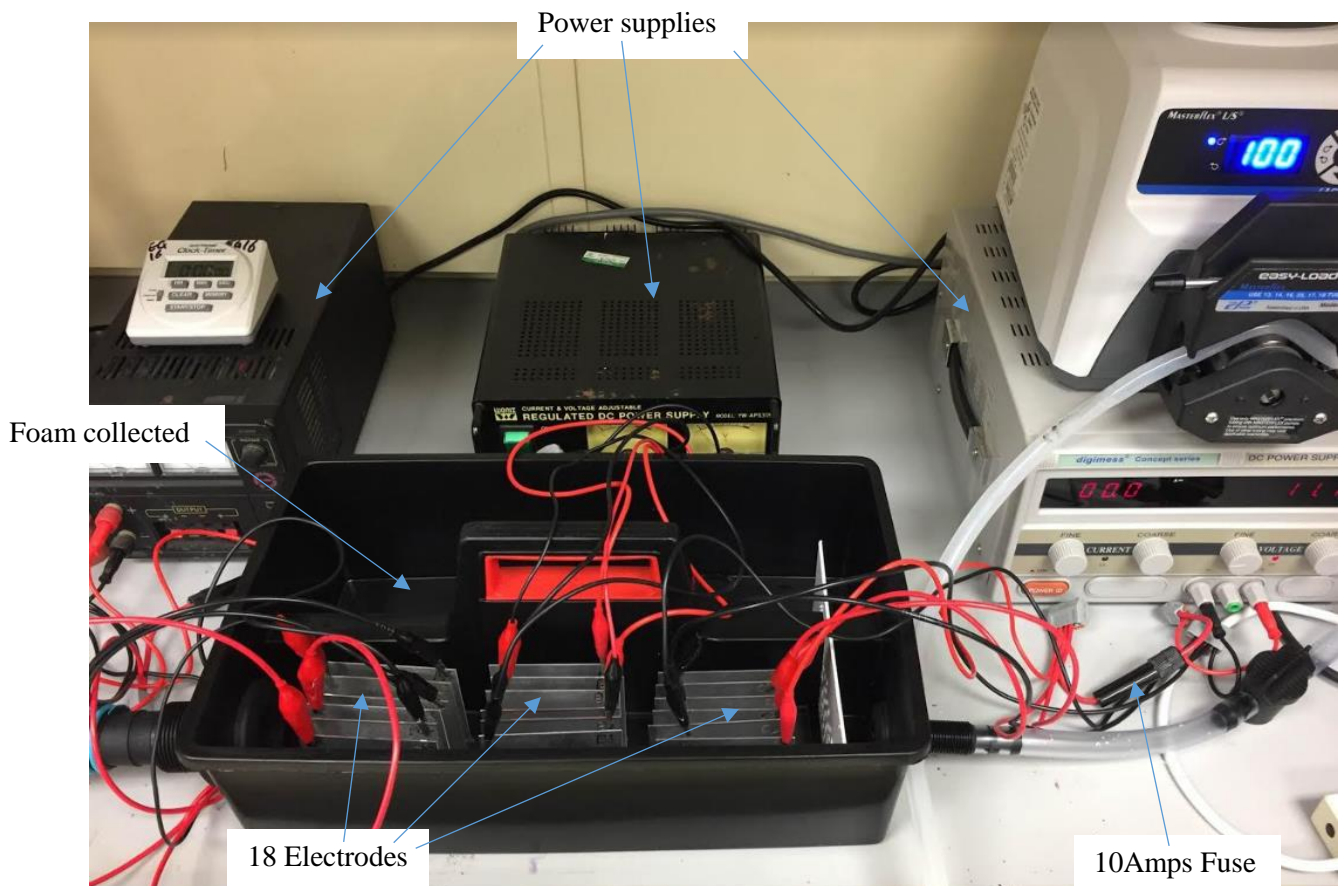


Figure 12: Continuous blood electrocoagulation system.

To achieve better foam control and extract samples easier, and also to mimic a process that might work on an industrial scale, a recycle system was used to keep the electrocoagulation running continually (Figure 12). 18 electrodes in 3 banks of six, each bank with its own power supply and fuse, was set up in one compartment which also had a bulkhead fitting for pumping blood from a five litre reservoir into the compartment, and an outlet which recycled the blood back to the reservoir. Foam overflowed into the second compartment where it was allowed to dewater and the liquid recycled back to the reservoir (Figure 13). Each run used 4 L of blood, which was pumped using a peristaltic pump at 186 ml/min, power was supplied to each bank of electrodes at 5 V and each electrode had an area of 50 cm². Due to some foam being carried over into the reservoir with the recycle liquid, a barrier was installed to prevent the foam escaping, but this prevented the liquid from being recycled. The liquid level in the foam compartment was raised by raising the level of the recycle tube and this helped prevent the majority of foam from going into the reservoir.

Three runs were carried out using blood at 11% solids which had been diluted to 2.75% solids. Samples collected for UV measurement were filtered using a 0.45 µm filter and diluted 1/200. 57% removal was achieved over a two hour run time (Figure 14) and average mass loss of aluminium per run was 5.8 g, which equates to 10.8 grams of solids removed per g of aluminium or 0.093 g aluminum per g solids. The anode dissolved during electro-coagulation (figure 37, 38), and every aluminum plate could be used up to five times, at 2 hours per run. Current was 2.5-1 amps for the first bank, 2.5-2 amps for the second bank, and 3.9-2.9 for the third bank of electrodes at 5 volts for each bank.

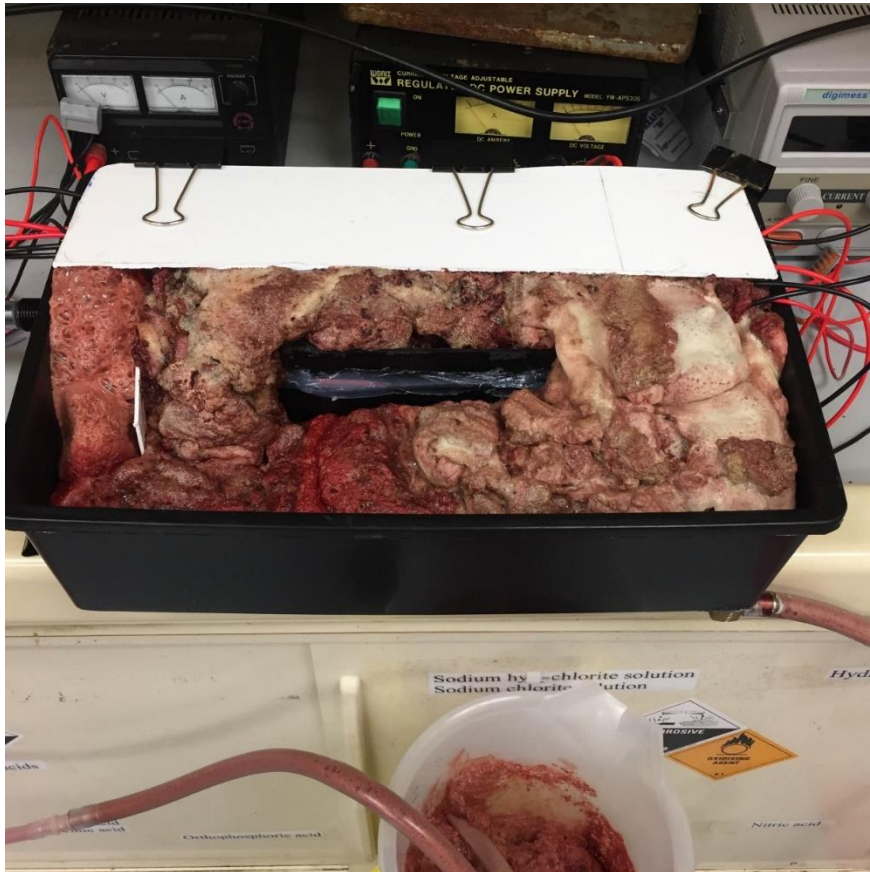


Figure 13: Continuous blood electrocoagulation system in operation with foam overflowing into the front compartment and liquid recycled through the bottom back to the reservoir.

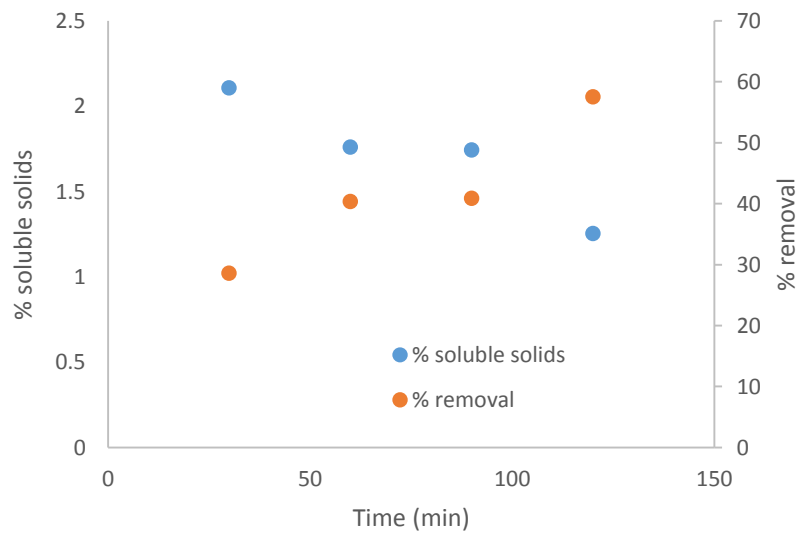


Figure 14: % removal and % soluble solids over time for continuous electrocoagulation.

Another three runs were carried out using blood at 13% solids with the pH adjusted to 9 using 500 ml 1M Ca(OH)₂ into 4 L of blood, giving a starting concentration of 11.5% solids. Power was supplied at 10 volts giving a current of 3.5 to 1 amps over the run for each bank. The lower current is likely due to the cathodes passivating (an oxide layer forming on the surface) which would increase resistance to current flow. Over two hours 7-8 g of aluminium electrode was consumed, and 42-51% removal was achieved. In a large-scale system, direction of current would need to be changed periodically, i.e. switch the cathode to anode, to prevent/reduce passivation.

Foams and sludge were centrifuged at 3000 rpm for 10 minutes. As the pellet and foams were not sufficiently dewatered, small samples of each were placed in 1.5 ml centrifuge tubes with filters and centrifuged at 17,000 rpm for 10 minutes, the liquid removed and the solids centrifuged again. This was repeated three times per sample. The foams dewatered better than the pellet, increasing the solids from 13% up to 30-58% solids for the foam compared to 26-40% for the pellet. The pellet was gel like with a very low hydraulic conductivity, i.e. the water would not pass through the solids and through the filter, but pool on the top, while the foam more readily allowed liquid through. Success of a large-scale process would depend on the ability of the centrifuges to dewater the solids, but potentially up to 40% solids for the sludge and up to 58% solids for the foam could be achieved, compared to current practice for steam coagulated blood where 55% solids can be achieved. Extent of dewatering would need to be confirmed on a large scale system.

3 ECONOMIC ANALYSIS

Based on data obtained from experiments carried out, in particular the amount of aluminium needed per g solids removed (Figure 15), current produced given concentration of blood, distance of the electrodes, electrode area and voltage (Equation 4); and aluminium consumption per amp per minute, a model was set up that predicted processing time given the operating conditions shown in Table 1 and electrode set up in Table 2, and estimated operating costs in Table 3.

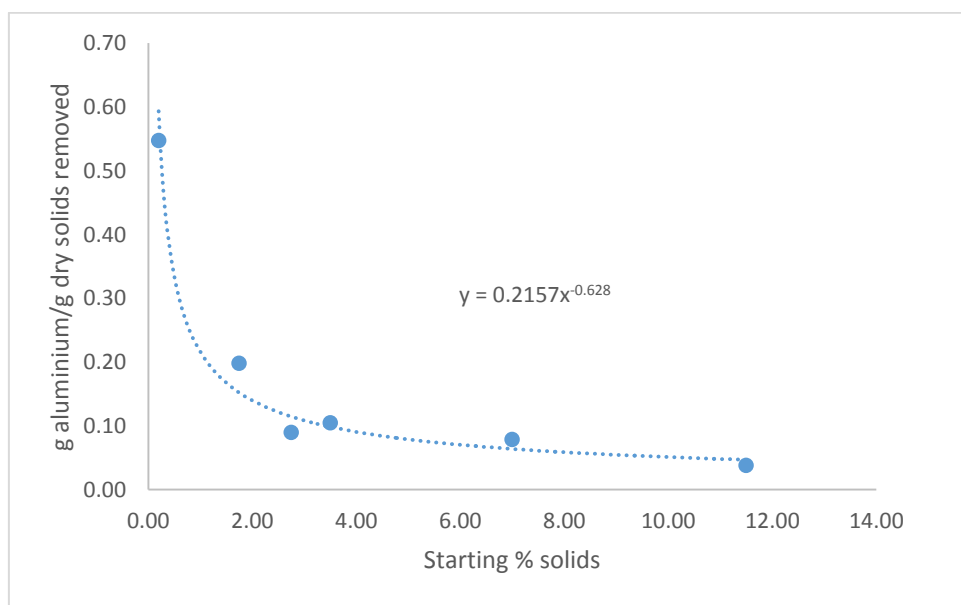


Figure 15: Aluminium needed per g solids removed

Table 1: Electrocoagulation operating conditions.

Electrocoagulation parameters

| | |
|---------------------------------------|-------|
| Volume blood processed per day (L) | 8000 |
| Starting concentration (g/L) | 110 |
| Solids (kg/day) | 880 |
| % removal | 98.0 |
| Mass of aluminium used (kg) | 83.6 |
| Fraction of aluminium in solids (g/g) | 0.088 |
| Aluminium consumption (g/amp.min) | 0.011 |
| Processing time (hr) | 7.71 |

Table 2: Electrode set up.

Electrode set up

| | |
|--|------|
| Density aluminium (g/cm ³) | 2.7 |
| Electrode area (m ²) | 96 |
| Electrode thickness (cm) | 2 |
| Electrode weight (kg) | 5184 |
| Distance between electrodes (cm) | 0.5 |
| Voltage (volts) | 10 |
| Electrode life time (days) | 62 |

Table 3: Electrocoagulation operating costs. Aluminium cost was based on the US spot price [5]. Centrifuge costs were based on an 11 kW centrifuge and electricity was assumed to be \$0.15 per kWhr.

Electrocoagulation Operating Costs

| | |
|-------------------------------|-------|
| Aluminium price (US\$/lb) | 0.79 |
| Aluminium price (NZ\$/kg) | 2.45 |
| Mass of aluminium used (kg) | 83.6 |
| Aluminium cost per day (\$) | 204.7 |
| Electrode power (kWhr) | 1327 |
| Centrifuge power (kWhr) | 85 |
| Cost of electricity (\$/kWhr) | 0.15 |
| Electricity cost per day (\$) | 211.8 |
| Total cost per day (\$) | 416.5 |
| Cost per kg/dry blood (\$/kg) | 0.49 |

The model assumed batch operation where all the foam and sludge from the electrocoagulator was continuously dewatered in a 2-10 m³/hr, 11 kW decanting centrifuge and the water recycled back to the electrocoagulator until a set percentage of solids had been removed (the same could also be achieved by using a holding tank to store the blood prior to passing through the electrocoagulator and recycling the water back to the holding tank).

Change in blood concentration due to loss of water to the dewatered coagulate was neglected (for 8 m³ at 110 g/L or 11% starting solids, approximately 800 L of water would be lost assuming the coagulate could be dewatered to 55% solids), although the increased concentration would be beneficial in increasing the current through the liquid.

Electrode area and spacing was adjusted to obtain a processing time of less than 8 hours. For example for 10 volt power supply, an electrode area of 96 m², or 48 1 m x 1

m x 2 cm thick electrodes spaced 0.5 cm apart, with an initial current draw of about 50,000 amps would be needed, or about 2100 amps per pair of electrodes. Over the processing time, as the solids decreased, the amps would drop to 5000 amps, or 210 amps per pair of electrodes (Figure 16), and power required would drop from 500 kW to 50 kW (Figure 17). Initially there is a high rate of removal (Figure 18) and aluminium consumption (Figure 19), but as the solids concentration and current drops, the rate of removal and aluminium consumption also drops. Assuming 98% removal, 83.6 kg of aluminium per batch would be used (Table 1), resulting in an electrode life time of 62 days (Table 2) and the resulting coagulate would contain 8.8% aluminium by weight on a dry basis, which would increase the ash content of the final rendered product.

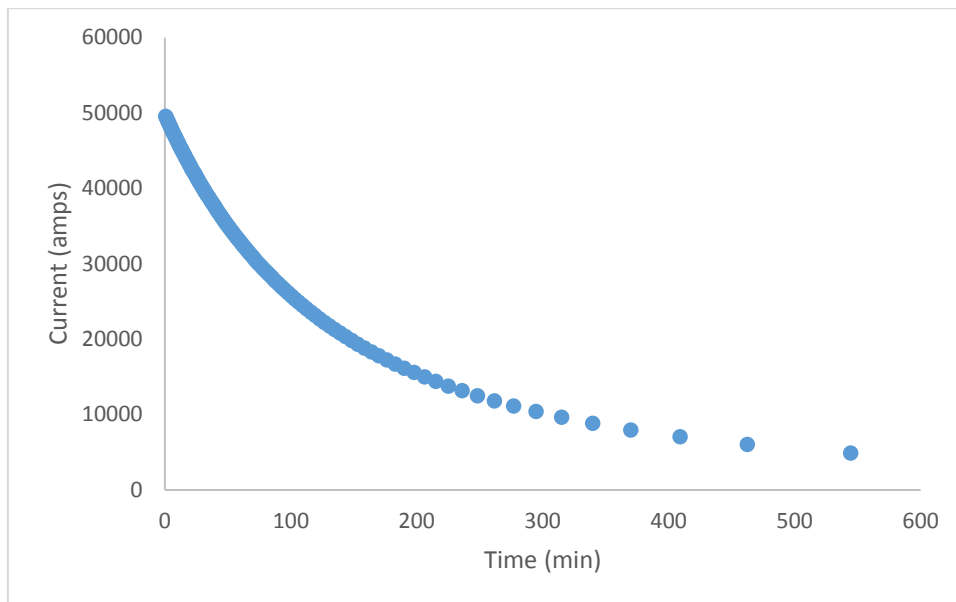


Figure 16: Current drawn by the electrocoagulator vs time using the conditions given in Table 1 and 2.

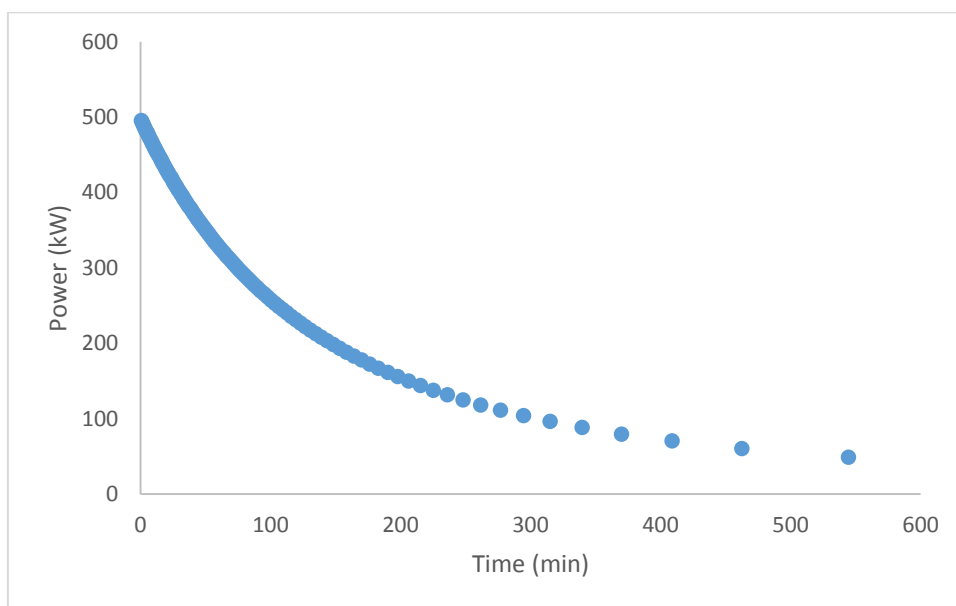


Figure 17: Power requirements of the electrocoagulator vs time using the conditions given in Table 1 and 2.

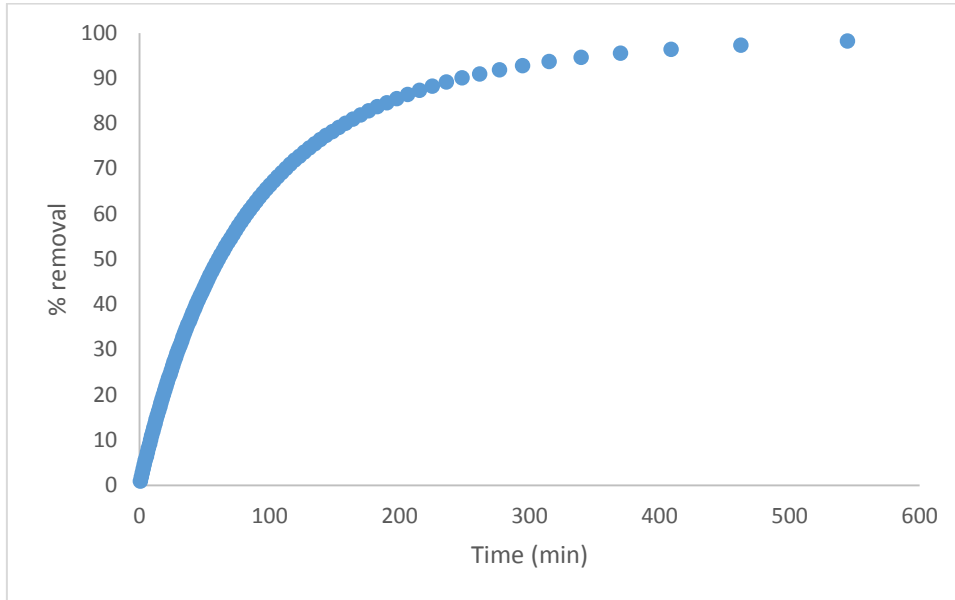


Figure 18: Percentage removal of blood solids vs time by the electrocoagulator using the conditions given in Table 1 and 2.

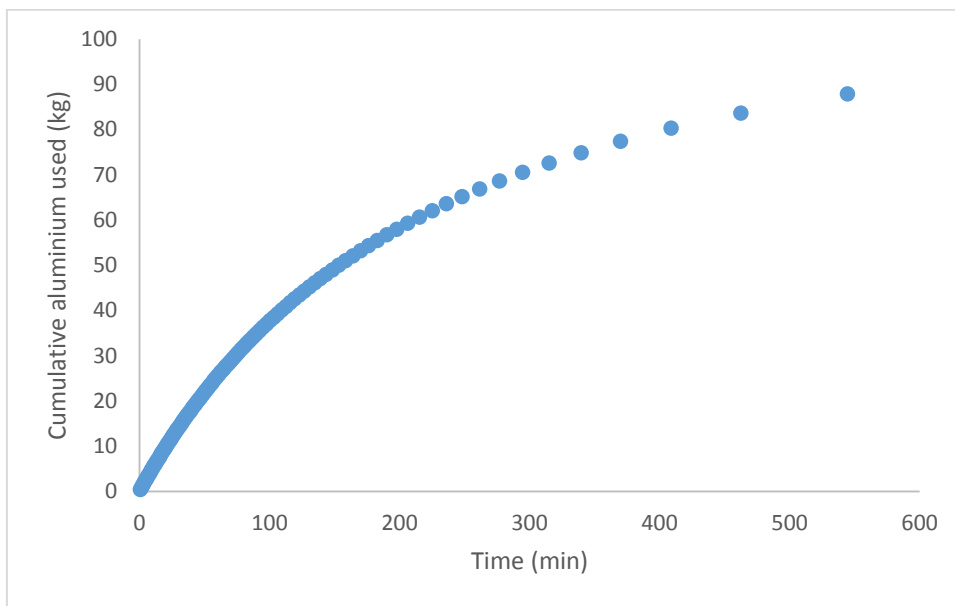


Figure 19: Cumulative aluminium used vs time by the electrocoagulator using the conditions given in Table 1 and 2.

For an electrocoagulator operating at 10 volts, power requirements would be 1327 kWhr resulting in an electricity cost of \$212 (excluding pumps) per day, and aluminium cost of \$205 per day, a cost of \$0.49 per kg dry blood. In comparison, steam coagulation, based on data supplied by Wallace, has a cost of \$0.1 per kg dry blood (Table 4).

Table 4: Steam coagulation operating costs. Boiler costs, steam requirements and coagulator throughput were based on internal communication with Wallace. Centrifuge costs were based on a 11 kW centrifuge and electricity cost given in Table 3.

Steam coagulation

| | |
|--|--------|
| Boiler (kg steam/hr) | 1814.4 |
| Diesel consumption per boiler (L/hr) | 100 |
| Diesel price (\$/L) | 0.71 |
| Cost per kg steam (\$/kg) | 0.04 |
| Steam coagulator throughput (m ³ /hr) | 2 |
| Coagulation steam consumption (kg/hr) | 550 |
| Process time (hr) | 4 |
| Steam cost (\$) | 86.1 |
| Centrifuge operating costs (\$) | 6.60 |
| Cost per kg dry solids (\$/kg) | 0.11 |

Various configurations of the electrocoagulator were trialed in the model (Table 5) and it was found that by reducing the voltage to 2 volts, increasing the electrode area to 480 m² (neglecting the practical aspects of trying to fit in that amount of electrode area) and settling for 90% recovery, power requirements could be dropped to 207 kWhr, giving a cost of \$0.25 per kg dry blood.

Table 5: Possible operating configurations of the electrocoagulator and the effect on cost per kg dry blood, power and aluminium content in the coagulate on a dry basis.

| Voltage | % removal | Process time (hr) | Electrode area m ² | Cost per kg/dry blood (\$/kg) | Power (kWhr) | Fraction aluminium in solids (g/g) |
|---------|-----------|-------------------|-------------------------------|-------------------------------|--------------|------------------------------------|
| 2 | 98% | 7.71 | 480 | 0.30 | 265 | 0.088 |
| 2 | 95% | 5.66 | 480 | 0.27 | 238 | 0.082 |
| 2 | 90% | 4.14 | 480 | 0.25 | 207 | 0.076 |
| 4 | 98% | 7.71 | 240 | 0.35 | 531 | 0.088 |
| 4 | 95% | 5.66 | 240 | 0.32 | 475 | 0.082 |
| 4 | 90% | 4.14 | 240 | 0.29 | 414 | 0.076 |
| 6 | 98% | 7.71 | 160 | 0.39 | 796 | 0.088 |
| 6 | 95% | 5.66 | 160 | 0.36 | 713 | 0.082 |
| 6 | 90% | 4.14 | 160 | 0.33 | 620 | 0.076 |
| 8 | 98% | 7.71 | 120 | 0.44 | 1062 | 0.088 |
| 8 | 95% | 5.66 | 120 | 0.40 | 950 | 0.082 |
| 8 | 90% | 4.14 | 120 | 0.37 | 827 | 0.076 |
| 10 | 98% | 7.71 | 96 | 0.49 | 1327 | 0.088 |
| 10 | 95% | 5.66 | 96 | 0.45 | 1188 | 0.082 |
| 10 | 90% | 4.14 | 96 | 0.41 | 1034 | 0.076 |

4 CONCLUSIONS

Blood can be electrocoagulated resulting in solids removal due to coagulation, foaming and settling. On lab scale using 1, 2 and 4 L volumes at various percentage solids, and batch and continuous operation, solids removals of up to 58% could be achieved in 2 hours of operation. Iron electrodes resulted in grey water and a red brown sludge and excessive electrode consumption, while aluminium electrodes gave lower electrode consumption and a clear liquid using dilute blood. Typical aluminium electrode consumption was 0.01 g/amp.min which was independent of starting concentration, and

amount of aluminium required to remove the solids varied from 0.5 g/g solids with a starting concentration of 0.2% solids, to 0.04 g/g solids at 11.5% starting concentration. Resistance of blood to current flow at varying concentrations and voltages was modelled using a power law relationship, and was used to model a large scale system.

Foaming was due to hydrogen gas production during electrocoagulation, the foam had a density of 200 kg/m³ and generally contained 10-15% solids by weight, while the sludge contained 10-13% solids, compared to starting blood solids of 11% , therefore both need to be dewatered and water recycled back to the electrocoagulator, otherwise there would not be sufficient liquid flow. Dewatering in the lab was problematic, but using small centrifuge tube with filters, the foam could be dewatered up to 58% solids, and the sludge up to 40% solids.

Models of a large scale system processing 8 m³ of blood at 11% solids over an 8 hour period with 98% removal of solids for a 10 volt system required an electrode area of 96 m², power requirements of 1327 kWhr, and 86 kg of aluminium electrode consumed, resulting in a coagulate with 8.8% by weight aluminium, and an operating cost of \$0.49 per kg blood on a dry basis, compared to steam coagulation which has an operating cost of \$0.1 per kg dry blood (this does not include drying costs). Operating cost of the electrocoagulator could be reduced to \$0.25 per kg dry blood by reducing operating voltage to 2 volts, increasing electrode area to 480 m² and reducing solids removal to 90%.

It should be noted that the values given by the model are optimistic, the model does not account for reduced electrocoagulator performance due to electrode corrosion, passivation and fouling. In addition practical aspects such as collecting and dewatering the foam, changing the electrodes periodically, and the general and safety aspects of delivering high currents were not considered.

ACKNOWLEDGEMENTS

Wallace Corporation for funding the project.

REFERENCES

- [1] F&T Water Solutions (2017). "Electrocoagulation overview." Retrieved from: <http://www.ftwatersolutions.com/electrocoagulation/>
- [2] World of Chemicals (2017). "Electrocoagulation - new technology for the wastewater treatment." Retrieved from: <http://www.worldofchemicals.com/18/chemistry-articles/electrocoagulation-new-technology-for-the-wastewater-treatment.html>
- [3] Water Tectonics (2017). "What is Electrocoagulation." Retrieved from: <http://www.watertectonics.com/electrocoagulation/>
- [4] Kadirvelu, K., et al. (2001). "Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste." *Bioresource Technology* **76**(1): 63-65.
- [5] Investment Mine (2017). "Aluminium Prices and Aluminium Price Charts." <http://www.infomine.com/investment/metal-prices/aluminum/>