University of Southern Queensland
Faculty of Health, Engineering and Sciences

Philosophy and Design of Reverse Osmosis Membrane Replacement

A dissertation submitted by

Jonathan McCluskey

In Fulfillment of the requirements of

ENG4111 and ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Honours) (Mechanical)

Abstract

Water treatment technologies constantly advance as the demand for access to clean water rises above supply. Veolia Water operates multiple water treatment facilities with daily production capacities exceeding 100 ML. Reverse osmosis is a major operation within these facilities and has the ability to remove dissolved salt content from feed water. This process requires consumable membranes which, as they approach their design life or begin to lower in their production capabilities, require replacement.

The current reverse osmosis membrane replacement process requires a high number of operators with a vast amount of manual handling. This project is focused upon reducing manual handling in the membrane replacement that is currently carried out, specifically at QGC Kenya, a water treatment facility operated by Veolia Water. In an industry, and within a company, that constantly strives towards increasing safety culture an engineering solution can reduce the need for manual handling in such operations.

The work produced within this dissertation focuses on the reduction of manual handling. Components which aided this were designed and analysed using finite element analysis methods. The membrane replacement process was redesigned with this focus in mind. Subsequent to the design of the components and the updated methodology, analysis was carried out to provide financial justification for this change in replacement philosophy.

The results of this project allow for future work to be carried out, in the manufacturing and physical testing of the components. Through physical testing, the theoretical values could be confirmed or altered.

University of Southern Queensland
Faculty of Health, Engineering and Sciences

ENG4111 and ENG4112 Research Project

Limitations of Use

Certification of Thesis

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Jonathan McCluskey

Student Number: [redacted]

Acknowledgements

I would like to express my thanks to my supervisor, A/ Prof. Andrew Wandel, for the assistance, support and consistently punctual feedback throughout the creation and completion of this project.

Furthermore, I would like to express my thanks to my colleagues for the assistance pertaining to on-site resources.

Finally, I would like to express thanks to both friends and family for the greatly appreciated support throughout the preparation and completion of this project.

Contents

List of Figures

List of Tables

Nomenclature

EPDM	Ethylene Propylene Diene Monomer
EPT	Ethylene Propylene Terypolymer
FEA	Finite Element Analysis
LTI	Lost Time Injury
LTIFR	Lost Time Injury Frequency Rate
RO	Reverse osmosis
TDS	Total Dissolved Solids
TSS	Total Suspended Solids

1. Introduction

1.1 Background

1.1.1 Water Treatment Processes

Water treatment is essentially the method used to recycle or desalinate water, ranging from by-product wastewater to sea water, in order to increase its useability. Membrane treatment is a form of treatment that varies in its ability to remove particles from the feed water, which could be suspended solids or dissolved solids. A few of the processes and their respective treatment abilities are as follows: microfiltration which is used to removed bacteria; ultrafiltration, which removes dissolved organic contaminants as small as 10 nm; nanofiltration, targeting heavy metals and heavy metals down to 1 nm; and reverse osmosis (RO) with the ability to remove dissolved solids, commonly referred to as ions (R Semiat, 2020). Most of the membrane processes are used in order to reduce the suspended solids from the water prior to the RO process, which allows for the process to be carried out efficiently without suffering from damage. These processes comprise the majority of membrane treatment, however, there are other processes that are utilised, dependent on the needs of the treatment facility.

The processes that utilise methods other than filtration include the use of an ultraviolet system. This system kills microorganisms using high intensity ultraviolet lamps, generally at a frequency of 254 nm. This is utilised in order to produce water that is free from contaminants, which could be harmful to the consumer. Removing the harmful contaminants at the point of contact, ultraviolet systems do not increase the protection against the microorganisms, so the water must be kept in certain conditions for it to remain beneficial and harmless to the consumer. Distillation can also be used, which involves the heating of water until it reaches a vapour state, followed by a cooling process and the collection of fluid that was once vaporised. The evaporation-condensation process is one of the most effective water treatment processes, when aiming for the minimum number of dissolved solids. The process is not the most efficient though, as a large amount of energy is required to sustain this process. The distillation process is carried out in Brine Concentrators, which can be used subsequent to RO. The purpose of this method is that the by-product of RO, a concentrated brine solution, can be treated to minimize waste and further increase the percentage of treated water.

1.1.2 Why Does Water Treatment Exist?

The water treatment industry becomes increasingly more important as the global standard of living tends to improve and the demands for water increase (S.E. Jorgensen, 2008). Providing the ability to recycle and reuse water, water treatment is necessary in a society that constantly attempts to improve sustainability. There are a number of historical events and statistics that provide further evidence on the importance of water treatment.

As the population continues to grow, it is predicted that, by 2050, at least a quarter of the population will suffer from water scarcity (Acciona, N.D). This problem affects all continents of the world and, as an integral resource, lack of water can result in detrimental health consequences, caused by poor sanitation and lack of drinking water. While serious water scarcity problems are predicted for the future, there are also significant issues in the current day, particularly in low and middle-income countries. The development of water treatment has the ability to reduce the 827,000 deaths in these countries, resulting from a combination of water shortage and poor sanitation (WHO, 2019). The logical solution to a lack of water is to create water, that is of adequate quality for sanitation and consumption. While the concept of creating water is enticing, in practise it is a difficult and dangerous feat (Clark, 2007). The next step in the logical thinking process would be to treat water that exists but is not suitable for human consumption in its original state. Water treatment is possible and is taking place on a large scale around the world.

A historical event that can be called upon to provide an example where water treatment has already provided benefit in society is The Great Stink of London. In 1858 the River Thames was a dumping ground for the city's sewer waste, causing the quality of water to decrease extremely to a foul-smelling brown fluid (ATI, 2017). The water, contaminated with waste, was proven to cause diseases that would commonly result in death, due to the lack of medicinal knowledge at the time. Although the diseases were caused by the contaminated water itself, the foul smell was the concern of the general population as the temperatures increased in the summer of 1858 (Daunton, 2004). In this case, a development of an advanced sewage system was the solution, however, this was a result of the advancement of water technologies, just as water treatment is.

Depending on the types of treatment water undergoes, and its final quality and mineral content, there are different classifications of water. The differing levels of water treatment applied indicate what the water can be used for.

1.1.3 Reverse Osmosis Process

Osmosis is defined as the movement of a solvent through a semipermeable membrane into a higher solute concentration that allows for the equalization of the solute. RO is the process where fresh water is separated, generally from the salt that resides within it. In RO, pressure is used in combination with the semipermeable membrane allowing the water to have salt removed, and the concentrated brine solution is left separated, this is portrayed in Figure 1. The brine solution is comprised of the salt that is removed, as well as a small amount of water that does not pass through the membrane. The resultant water is named permeate, which is the useful product of the process, while the brine is a by-product which can continue to further methods of water treatment or remain as a waste by-product.

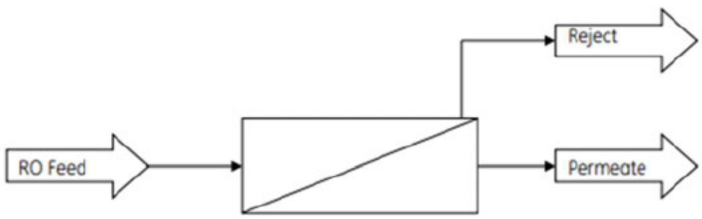

Figure 1. Systematic View: Reverse Osmosis

It is common for the further methods of water treatment to include advanced stages of RO. In the advanced stages, higher pressure is used for an increase the recovery rate of the feed water to, useful, permeate, as shown in Figure 2.

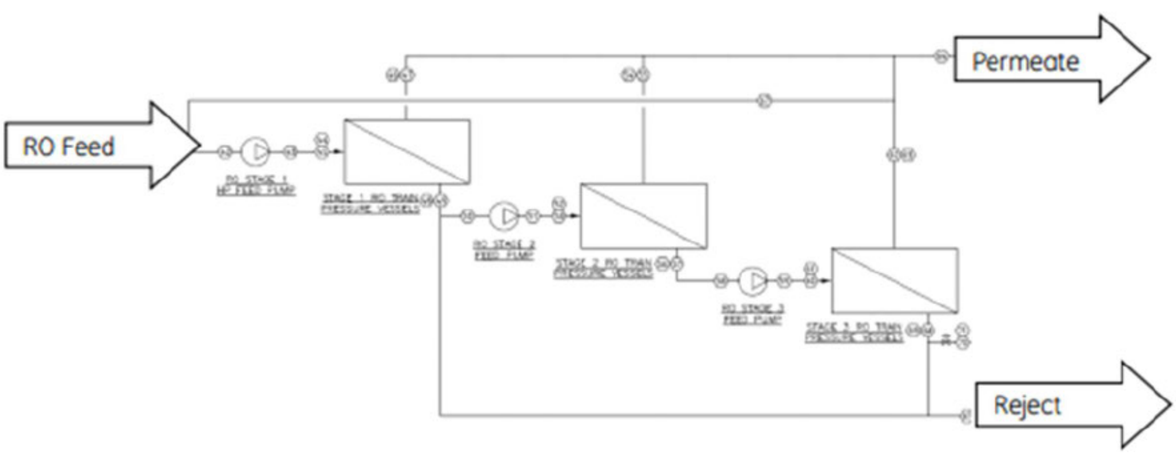

Figure 2. Detailed Systematic View: Reverse Osmosis

1.1.4 History of Reverse Osmosis

Reverse Osmosis originally began to be developed in the 1970s, in these stages the membranes were manufactured using cellulose acetate. The reaction rate of these membranes was of a similar ability to the modern-day membranes, at 98.5%. The constraints of these designs were the flow rates through the RO process. In this time period the maximum capacity of flow rate existed at approximately 250 L/hour, which has seen many advancements in recent times. With the development of thin film composite polyamide membranes, of sizes up to 16 inches diameter, the permeate can be produced at flow rates up to 8000 L/hour. The salt rejection has also increased by a further 1.2%, with a common rejection rate now being 99.7% (J. Johnson, 2010).

The increase in reverse osmosis productivity has also been increased by focusing on pre-treatment processes, as well as the advancement of the membranes themselves. By removing particles classified as total suspended solids (TSS) the amount of total dissolved solids (TDS) removed within the reverse osmosis vessels can be increased. There are a number of pre-treatment processes that exist commonly in water treatment plants (KL Stoughton, 2013). These pre-treatment methods are used in the water treatment plant at which this project is to be carried out.

- Simple mesh strainers are used to remove the largest TSS, which would be measured at approximately 5 microns.
- Disc filters, which consist of mesh elements, are a common tool used for solid-liquid separation, prior to the reverse osmosis process. This further decreases the TSS of the water that is fed to the reverse osmosis vessels (T Sparks, 2015).
- To further remove TSS, coagulation and flocculation tanks are used as a pre-treatment process, these processes are similar but have key differences. Coagulation is the process in which the stabilization of the TSS is disrupted through the addition of a chemical while flocculation aims to cause the TSS to form larger agglomerates, making the solids easier to filter.
- Ion exchange utilises resin in order to make a relationship between cations and anions, which removes some impurities from the water prior to the reverse osmosis process (S.S. Muthu, 2017).

- Within primary and secondary ultra-filtration processes, cartridge filters are utilised which can often be the final pre-treatment process prior to the reverse osmosis process, removing the final amounts of TSS.
- Following this process, reverse osmosis is used which, due to the removal of TSS can focus on the removal of the TDS within the feed water.

1.1.5 Membrane Replacement

The existing process for replacing membranes varies across Veolia Water sites, however the core of the process remains the same. As sourced from a Veolia Water Work Instruction document, the current RO membrane replacement strategy exists in four stages. These steps occur on a vessel by vessel basis, which minimizes the risk of contamination within the vessels from foreign entities. The stages are as follows:

- End Cap Removal (Upstream and Downstream)
- Membrane Removal and Replacement
- Downstream End Cap Installation
- Upstream End Cap Installation

Removing the end caps from each end of the vessel consists of cleaning the end cap and surrounding section of the vessel in order to further minimize the risk of contamination. Following the cleaning of the area, the permeate pipework is carefully disconnected and the end caps and thrust cones are removed from the vessel and stored in a dry, clean place. The end cap and thrust cone are shown in Figure 3.

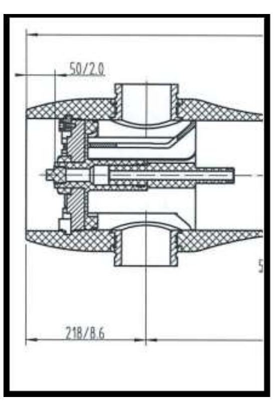

Figure 3 a. Sectional View: End Cap

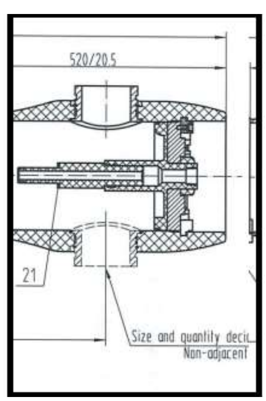

Figure 3 b. Sectional View: End Cap

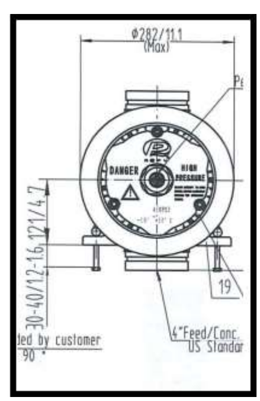

Figure 3 c. Front View: End Cap and Thrust Cone

Following the removal of the end caps, the membranes are removed and replaced from an individual vessel simultaneously. This section of the process entails the most manual handling through the amount of force required to remove the membranes. The new membranes are inserted and used as a pushing mechanism to remove the old membranes. As the previous membranes are forced out of the vessel, they are caught by operators and placed on their working platform to be manually transported by a fellow operator to a different area in the RO shed. The mass can vary due to the amount of water held in the discarded membranes, the newly acquired membranes are of approximately 15 kilograms. The membrane's dimensions are illustrated in Figure 4, these dimensions paired with the mass of the membranes can be used to understand the difficulty of the manual handling processes that exist.

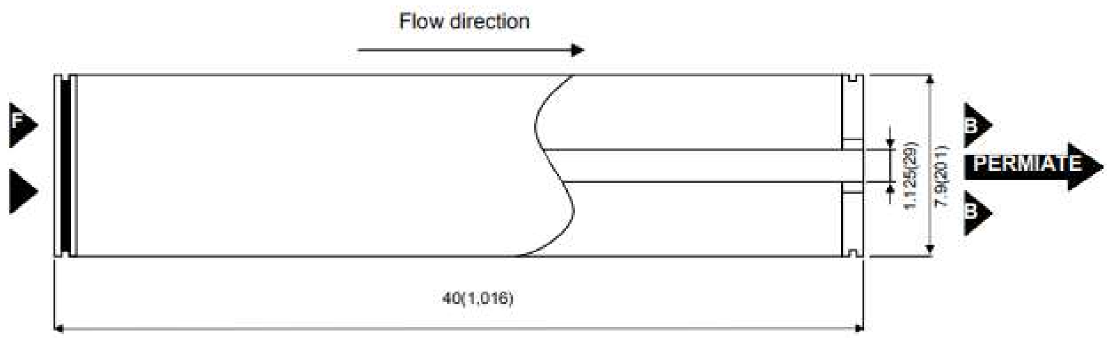

Figure 4. Membrane: Direction of Flow

Once the seven membranes that originally resided in the vessel are replaced with the new membranes, the downstream end cap is reinstalled. The end cap is inserted into the vessel to pass the retaining groove, which is used as a locking mechanism. The clamps are inserted into the retaining groove and are attached to the end cap by means of screwing bolts through the clamps into the appropriate spot on the end cap.

From here, the final step is to reinstall the end caps on the upstream end of the vessel, while shimming the end caps to ensure that there is no excessive space existent between the end cap and the RO membrane. The shimming process is simply carried out utilising 2 mm spacers, enough of these spacers are used so that the end cap can not pass the retaining groove. Once the correct number is reached to achieve this, one spacer is removed and any remaining movement is marginal and acceptable. Similarly, to the downstream section, the clamps are placed in the retaining groove and bolted into the end cap.

The overall result of this existing process is that the operators carrying out the work are expose to a large amount of repetitive, laborious work. The constant actions of lifting, pushing, catching and placing down the heavy membranes pose dangers which should not exist in a worksite. Avoiding these dangers through the manipulation of this process to remove these strenuous actions aligns with the safety culture held by the company. The decrease of time and the number of operators required for the process also allows for the process to be more financially efficient.

1.2 Project Aim

The aim of the project is to develop a process to replace the membranes used in the RO vessels, with the primary focus being removing the element of manual handling that currently exists. This will entail designing and testing relevant components, as well as a suitable schedule for carrying out the replacement process.

1.3 Project Objectives

The objectives of the project are outlined below:

1. Review existing methods and philosophies surrounding reverse osmosis membrane replacement.

2. Design components which assist in the reduction of manual handling during the process.

3. Carry out finite element analysis (FEA) of both designed and existing components using Creo Parametric, verify results using hand calculations.

4. Narrow down to most suitable components based on FEA and resource availability.

5. Analyse historical data and predictions of cost to carry out a financial break down of the current processes against the newly developed process.

6. Analyse data regarding quality of permeate to develop a suggested pattern of membrane replacement to efficiently minimize decrease of water quality.

2. Literature Review

2.1 Manual Handling

2.1.1 Definition of Manual Handling

A straight-forward definition of manual handling is the act of moving something using physical strength, rather than being aided by a machine (Cambridge Dictionary, n.d.). Safe Work Australia encompasses a task with the following actions as manual handling tasks; repetitive movement, repetitive or sustained force, high or sudden force, sustained or awkward postures and exposure to vibration (Safe Work Australia, n.d.).

2.1.2 Reducing Manual Handling in the Workplace

Good work design in the planning and conceptual phases of a process provides the highest level of reasonable protection from manual handling. Suitable, well designed processes are successful in preventing work-related deaths and injuries. This can result from decreasing physical or mental stress, which arise from manual handling. The mental aspects can arise where the manual handling is expected to be carried out at a certain pace, which is stressing both physically and mentally (Work Safe Australia, 2018). The process of reviewing measures of for hazard mitigation is accepted by Safe Work Australia in the Figure 5.

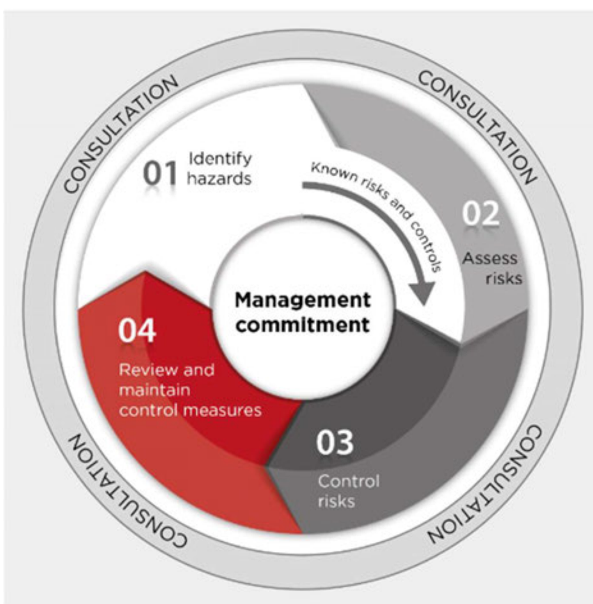

Figure 5. Management Commitment

2.1.3 Injuries resulting from Manual Handling

Manual Handling in the workplace accounted 24% of workplace injuries in Australia between 2017 and 2018, in the forms of lifting, pushing, pulling or bending even though a large portion of manual handling is avoidable (Ausmed Editorial Team, 2019). While an injury is not ideal regardless of severity, the most serious and highly monitored form of injury is a lost time injury (LTI). An LTI is an injury which leads to 'lost time,' meaning that productive work time is lost due to the injury. The severity of an LTI is an injury which removes an employee's ability to carry out their usual tasks or an employee has to be absent from the workplace during recovery (Baseline Training, 2017). The frequency of a company's employees suffering from LTIs reflects on their safety significantly, through a lost time injury frequency rate (LTIFR). The rate is calculated by dividing the number of lost time injuries in an accounting period by the total hours worked in that period. Due to the low number that is usually calculated through this, the equation multiplies that result by one million as to interpret the data more efficiently (Safework Australia, 2020). Due to the importance of the LTIFR, this will be a serious consideration while designing the concepts, components and processes within my project.

2.1.4 Push and Pull Strengths

Within a workplace, employees and operators have limitations to their physical abilities. When carrying out manual handling activities, it is important to consider that if the task requires force excessive to that of an operator's physical ability that components may be acquired. In a study, female workers could pull at a maximum force equal to 244 N and push at a maximum of 140 N. Males could pull at a maximum of roughly 400 N, while they could push at a maximum force of 251 N (Das, 2004).

2.2 Membrane Life expectancy

2.2.1 Measuring Performance of Reverse Osmosis

In reverse osmosis there are three basic metrics which are used to reference the process' performance. Salt rejection is the measurement of the efficiency of the membrane to reject salt passage. The salt rejection percentage is calculated using the following equation:

$$Salt\ Rejection\ \% = \frac{Conductivity\ of\ Feed\ water - Conductivity\ of\ Permeate}{Conductivity\ of\ Feed\ Water} \times 100$$

Similar to this measurement, salt passage is simply 100% minus this value, referring to the amount of salt that passes through the membrane rather than the salt that does not pass through with the permeate.

A further measure of performance exists through the recovery rate of water. The equation relating to this is as follows:

$$Recovery\ \% = \frac{Permeate\ Flow\ Rate}{Feed\ Water\ Flow\ Rate} \times 100$$

This process can be summarised as the amount of water that is processed and returns as permeate after reverse osmosis, in comparison to the amount of water that is fed into the process (PURETEC, n.d.).

2.2.2 Modes of Failure

The parameters that indicate that a replacement of the RO membranes is required can be a lowering of quality of the permeate produced in the process or pressure increasing, due to the degradation of the membranes. These performance parameters naturally alter due to the repeated process of reverse osmosis but can also change due to physical damage occurring due to fatigue failure of the membranes' mechanical integrity (Hydranautics, 2013). The decrease in water quality is generally the main cause for a membrane replacement. The increase in salt passage is compared to the financial costs of replacing membranes and hence the as-needed schedule of membrane replacement is created (Beaty, 2017).

Reverse osmosis exists in two different forms that depend on its use. Utilized in different situations, there are domestic and commercial RO systems (Micron, N.D). It is important to recognise this in the research of membrane fouling as the scale could differ greatly. The existence of fouling is generated from a growth of microorganisms occurring in the filtration elements of membranes. The level of fouling depends on certain system parameters and the surrounding environment, such as flow rate and temperature. The feed water's quality is a primary cause in fouling, and the existence of any biological or colloidal substances can have detrimental effects on the membrane's productivity (Marshall, 2018). Depending on the extent to which the membranes are affected by these external factors, the fouling that is caused can be reversible or irreversible. Reversible fouling is when the issue can be counteracted through flushing and forms of physical cleaning (Najafpour, 2015). Once the membrane pores are blocked and there is a strong adhesion between the membrane and the foulants, the failure is classified as irreversible fouling (Du, 2010). The physical appearance of fouling can be observed, as shown in Figure 6, however this proves difficult while the membranes are internal to the vessels. The ability to discover the need for membrane replacement will be discussed further in Section 2.2.3.

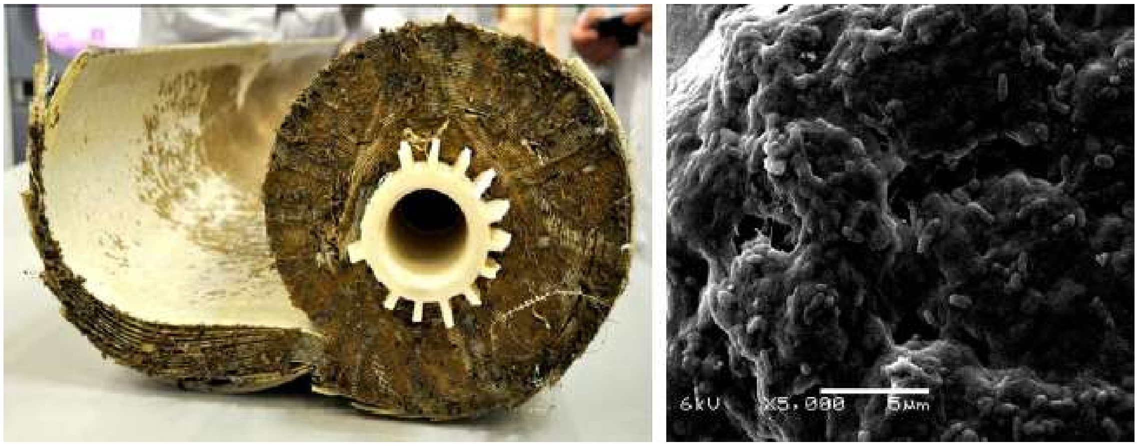

Figure 6. Extreme Case of Membrane Fouling Sourced From Wageningen University & Research

The membranes can also fail physically due to extreme deviation of the recommended system parameters. The membrane, a cylinder of wound elements, can become unravelled when pressure exceeds the membranes specifications at rapid pace. This failure is known as telescoping, due to the visual appearance that resemble a telescope's extension mechanism (Reverse Osmosis Chemicals, 2018). Similar effects occur under extreme temperatures, where the surrounding environment poses a threat to the membranes' integrity. Arising from similar causes, a physical cracking of the fibreglass casing of the membrane can occur (Koutchkov, 2017). In RO systems that suffer from these defects, the quality of water produced can be affected through the problematic factors that cause the failures as well as the failures themselves.

2.2.3 Need for Membrane Replacement

The need for membrane replacement arises, primarily, from a decrease in the quality of the water that is being produced. A reduction in quality of permeate can occur due to any of the modes of failure mentioned in section 2.2.2 (Natto, 2013). There are many methods that can be used to decide that a membrane replacement is necessary ranging from the age of the membranes to the data measured by a number of sensors.

The RO feed water can be, and is for the specific setup of this project, measured using turbidity and measuring silt density index (Baker, 2004). These sensors are used to indicate the amount of TSS, which can indicate what positive and negative outcomes of the RO process can be as well as the likelihood of fouling occurring. The silt density index focuses on a time measurement, rather than an amount of solids. This removes the discrepancies arising from the size or type of suspended solid. The time taken for the feed water through a standard pore size is measured and recorded for this value. In conjunction with measuring the rate of that fouling can occur, there are processes in place than decrease the effects of biofouling. A Clean-In-Place can be used to flush and chemically counteract the effect of fouling (Hoey, 2015). Studying the CIP processes that take place at the Kenya Water Treatment Facility, there are a number of chemicals that are used in combination. Sodium hydroxide, Ethylenediaminetetraacetic acid, ammonia and hydrochloric acid are used in conjunction in specific ratios to increase the life span of the membranes.

A measure of the TDS, used both prior and subsequent to the RO process, is conductivity. Using conductivity sensors on either side of the system allows for a measure in the decrease of suspended solids. The units of this measure are in Siemens per metre, with a lower value indicating a decrease in salt content which is ideal for permeate produced via reverse osmosis (Lenntech, N.D).

2.3 Conditions in Practise

The scale of the project can be conveyed through both the literal numbers, combined with the diagram that is Figure 7. The RO vessels, their train setups and the entire reverse osmosis process takes place within one building. Housing five trains, with three stages to each train, the RO setup takes place in a physically large area. Each vessel, regardless of the stage houses seven vessels, the total scale is conveyed through Table 1.

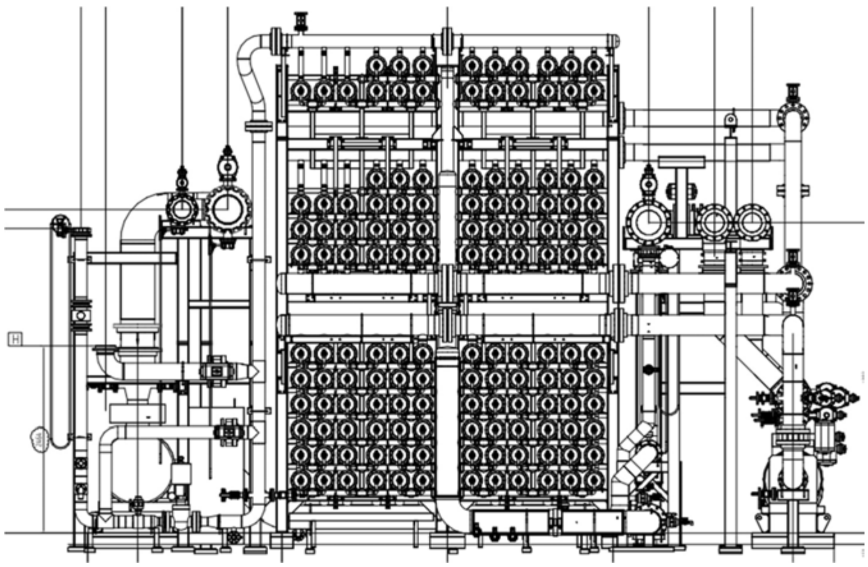

Figure 7. Reverse Osmosis Train Setup

	Stage 1	Stage 2	Stage 3	Train (All Stages)
Length of Vessels (mm)	7726	7630	7630	-
Diameter of Vessel (mm)	282	282	282	-
Number of Vessels	72	45	22	139
Number of Membranes	504	315	154	973

Table 1 Specifications of Trains, Stages and Vessels

The shed, in which the RO vessels and respective trains are housed is an important factor in the design of the components. The spatial constraints provide limitations to how large and mobile the components can be. The shed is shown in a front view, in Figure 8, however most of the constraints result from the spacing between trains. In order for the designs to be operable on all trains and vessels, the minimum space available will be used to design the components.

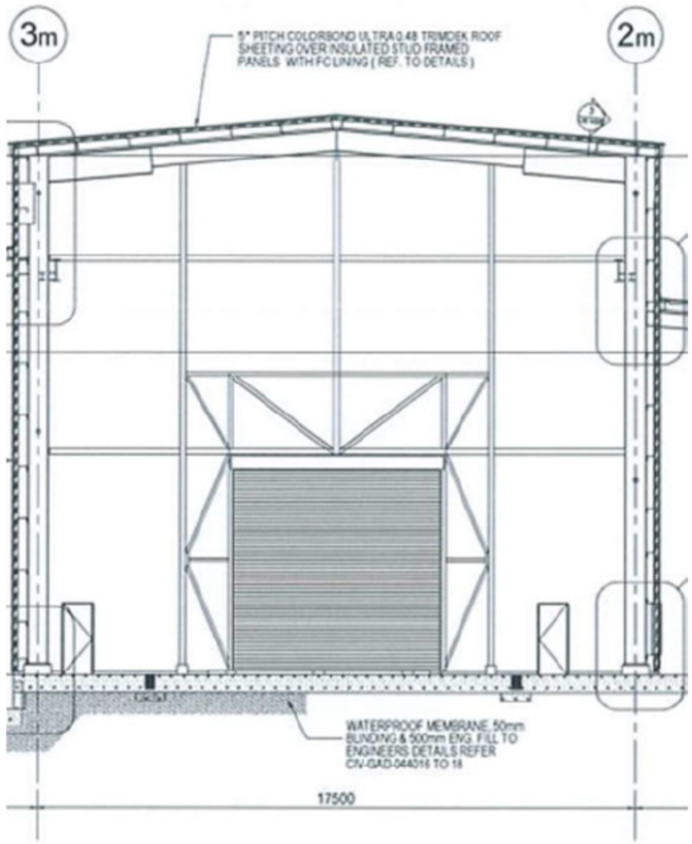

Figure 8. Reverse Osmosis Shed

The spacing between the walkways that run parallel to the trains has a minimum value of 1.5 m. This space would be required for operators to relocate between the sides of the vessels, dependant on whether the vessels are being inserted or removed. This area should be left clear and designs should not be made with intention to utilize this space. On the side feed and flow sides of the trains, on which the membranes are inserted or removed, there is a minimum spacing of 4 m between the walls of the shed or relevant operating panels that reside within the shed.

2.4 Materials, Forces and Friction

2.4.1 Membrane Materials

The materials to be researched and discussed regarding the membrane are that of the semi-permeable material and the brine seal's material. The semipermeable material is what makes up the majority of the membranes as a component. A brine seal is a plastic or rubber device that seals the outside of one end of the RO membrane, used to prevent feed water by passing the reverse osmosis process (ROchemicals, n.d.).

As per the specifications provided by Toray, the manufacturer of the membranes used at Kenya Water Treatment Facility, the material used for the brine seal is Ethylene Propylene Terypolymer (EPT) which is also commonly referred to as Ethylene Propylene Diene Monomer (EPDM) (Monroe, 2016). The brine seal is a V-ring and the combination of this shape and the material's properties are what prevent the feed water from being able to bypass the membranes. The design of the brine seal limits the freedom of inserting and removing membranes to one direction only. Trying to counteract the friction force generated while moving the membrane against the direction of flow far exceeds the friction force required while moving the membrane in the direction of flow.

The semi-permeable material that comprises the membrane is, from the manufacturer's specification sheet, a cross linked fully aromatic polyamide composite. Cross linked polymers have much different specifications than thermoplastic polymers in that they have are soft and flexible at room temperature. This is due to these materials having a low shear modulus when above the glass transition temperature (Cheremisnoff, 2001). Fully aromatic polyamide composite, when used as a membrane allows for a high percentage of salt rejection while also allowing for a high permeate production rate (Kurihara, 1994). The advancement of the efficiency resulted from the use of this material, in accordance with the development of membrane design.

2.4.2 Pressure Vessel Material

The pressure vessels that the membranes reside in and the reverse osmosis process takes place in are made of a fibre-reinforced plastic. The ROPV branded pressure vessels were not accompanied by a specification of material. The known, generalised properties of fibre-reinforced plastics as well as the provided specifications of strength can still provide context to the characteristics of the material.

The specification sheet provided indicates that stage 1, 2 and 3 vessels have strengths of 450, 1000 and 1200 PSI respectively. This is approximately to 3.103, 6.895, 8.274 MPa, respectively. While designing the components, the lowest value of 3.103 MPa will be the value considered, so that each vessel can use the same process without fear of failure.

2.4.3 Overcoming Friction

The essential idea of this project is to remove RO membranes from a vessel using water pressure, and within that idea the friction must be considered. This is often calculated using a known coefficient of friction. The coefficient of friction is the measure of friction existing between two bodies, where a low value indicates less force is required to move a body (J. O. Bird, 1993). Since the coefficient of friction is a ratio between the friction force and the normal force (B.K. Behera, 2010), these values can be used in tests in order to calculate the dimensionless value. The practical technique to solve this problem consists of using a body of mass and a pulley in order to calculate the net force, friction force and time taken to move the body, along with the known normal force to solve for the coefficient of friction (A Balter, 2018).

Static and Dynamic friction are two forms of friction, each with their own coefficients, that vary. Static friction is the force that resists the relative sliding motion between surfaces, while the surfaces are at rest. Static friction is caused by surface roughness, with ‘peaks and valleys’ existent to nano-scale dimensions (D.A. Hanaor, 2016). Once two objects have relative motion present, kinetic friction arises, which is also commonly referred to as dynamic friction. Dynamic friction is considered to be caused through chemical bonding of the surfaces, rather than the peaks and valleys causing the friction. The dimensionless value of kinetic friction is often lower than its static counterpart and due to this, the static friction coefficient can be used as an initial placeholder in calculations if required (S.D. Sheppard, 2006).

2.5 Component Design

2.5.1 Holding and Catching Apparatus

This component is designed to support the weight of new and discarded membranes, which have a mass of approximately 15 kilograms. The mass to be supported will not be dynamic in the sense that it will excessively move while supported. Movement does occur, however, when the membranes are discarded from the vessels the force will slowly dissipate from the vessel and supported by the holding and catching apparatus. The limits of which this apparatus must operate include adjustable heights and transporting side to side in order to align with the membranes being discarded. During operation, the structure will remain still, which removes the need for further support which is necessary in dynamic operations (Muskens, 2011).

The cradle section of the design would not require an exceedingly strong material, however the support section will. Considering safety in design, the goal of designing components safely is to minimize workplace hazards through the design process (ASI, N.D.). To follow a simple design, using structural steel, the necessary number of joints and cross members to have a support of sensible strength can be manipulated during the CAD process (Mishra, N.D.).

The environment in which the apparatus is operated requires caution, due to the possibility of corrosion from sodium chloride. Sodium chloride corrosion poses threat when the surface of a material is dampened by an electrolyte and this situation describes the possible effects on concentrated brine contacting stainless steel (Houska, 2007). This corrosion can have significant effects on the structural sturdiness through pitting corrosion and an increased likelihood of physical cracking (Mameng, 2014). To counteract this, a simple maintenance pattern of cleaning the surfaces of the apparatus could be implemented in intervals during the membrane removal procedure.

2.5.2 Pressure-Based Membrane Removal Tool

This component is designed to act as a vessel end cap that allows water to pass through to the vessel and create a pressurized volume between the membranes and itself. The exact required specifications of the material will be explored during the CAD process of these designs. The material of the existing end cap will be analysed and compared to new materials that can be switched and tested on the component (AutoDesk, 2018). If an existing end cap can be modified for this use the financial impacts would be lowered, as well as material waste (Rose, 2017). Given that the replacement operations would aim to not exceed the pressure during the reverse osmosis process, the existing end cap would have sufficient strength, aside from the created stress concentrations which would be analysed. Initially, the materials that seem to be suitable for a new design of this component are polymer and plastic composites. Of these materials there are a number of variations each with strengths and weaknesses (Engineering 360, N.D).

As with the holding and catching apparatus, there will be exposure to permeate and concentrated brine. Given that the internal face of the end cap will be in direct contact with water during operation, this will be a large factor in the material selection. The stated materials, polymer and plastic composites, are suitable for this operation (Kiss, 2013). Once a suitable material is selected the focus of ensuring the component's quality post-use would be through the maintenance schedules.

2.5.3 Maintenance of Components

Regardless of its operation, a consistent and efficient maintenance schedule can improve the life and competence of a component. Scheduled maintenance is a pattern of maintenance with specific intervals in which general maintenance tasks, such as repairs and upkeep of components is carried out (UpKeep, N.D). By acting on possible failures prior to the occurrence of them, there are improvements in both safety and financial situations. The number of components produced used for this operation can be minimized through ensuring the life of the components is maximized. At Veolia Water, a database named Veolia Asset Management System is used to record assets and link each asset to the necessary preventative maintenance schedules. A specific maintenance activity task plan could be produced for these components, which would focus on inspection and ensuring normal operation rather than an activity such as replacements of wearable components.

The maintenance of this component would focus on inspection, due to the nature of the components. The life of the components can be affected by a number of things such as operation time, the presence of vibration and unexpected sudden forces (Li, 2005). From a schedule in which inspections are carried out, any components that appear to be failing, such as an O-ring or corroded bolt can be reported. From this report a corrective work order, used in the Veolia Asset Management System, could be created for the components and the problem can be amended. This reduces the amount of wasted work hours and cost of replacing components that may not be suffering from wear in a certain time period, without removing the ability to ensure that the components are operating in normal conditions.

2.6 Finite Element Analysis Philosophy

In order to virtually analyse structures or mechanisms that are produced in computer aided drafting there are two different techniques. In order for mechanical structures to be assessed, FEA can be used which will provide values such as the strength of the structure and the deflection of the component. Fluids can be analysed using computational fluid dynamics, this method shows how a computer aided draft of a structure interacts with fluids such as air and water (CADTEK, N.D). Although the pressure that is applied to the vessels is induced through a fluid, water, the pressure created can be used and applied using FEA. This can provide the displacement of the membranes, as well as monitor the stress that is applied to vessel.

Von Mises stress analysis is a good option for analysing ductile materials, which present equal tensile and compressive strength qualities (Gonzalez, 2011). In the case of brittle materials, in which the tensile strength differs from the compressive strength, another method of stress analysis will yield more accurate results.

2.7 Improved Sustainability

2.7.1 Sustainable Design

Sustainability in design focuses on a set of principles that aim to reduce negative impacts on the surrounding environment and the people in the environment (GSA, 2020). The official definition of sustainability, as defined in 1987 is "Development that meets the needs of the present without compromising the needs of future generations." This can be described on a small scale, relevant to this project, as designing the components and processes to carry out the necessary work presently and has the ability to continue to be efficient in the future. This focus on designing sturdy components is an important principle in sustainable design which benefits the financial and safety aspects of the procedure. As the procedure will be designed to be suitable for the foreseeable future, the need for future-proof design in modern day engineering design is satisfied.

While these aspects are important, the environmental factors of the design are also an important factor of the design. (McLennan, 2004). The number of consumable components should be minimized in order to reduce the waste generated from the process. The components that may need replacing due to fatigue, such as O-rings, should be maintained correctly in order to increase their life expectancy and hence reduce the overall waste.

2.7.2 Recycling Resources

The designed components should not only be sustainable, but they should also utilize materials, such as water, in a sustainable manner. These resources can often be overlooked, however the environmental impacts of wasting a resource, such as water, can be significant (Vanegas, 2004). This could be carried out through designing the components to directly reuse the water that creates the pressure within the vessel or to feed the water effectively to existing waste re-use passages. Through utilizing existing service water systems and returning the water to this system, there would a minimum amount of wasted resources, occurring only to accidental spillage.

3. Methodology

3.1 Introduction to Methodology

In order to have produced a successful project and accompanying dissertation, the literature review carried out is thorough and well researched. The concepts are created in relation to the required mobility, reach and space constraints of the RO shed. As the designs of different components don't specifically correlate to each other, the processes of design were carried out individually. The final resulting components are:

1. A membrane removal tool, which uses water pressure to displace the membranes from the vessel
2. A membrane holding and catching apparatus which is held at the height of the relevant vessel to catch the membranes upon expulsion and assist in inserting membranes
3. A pump skid with necessary components for removing the membranes in unison with the membrane removal tool removing the physical pushing for the expulsion of the membranes

Along with these components a membrane replacement process was created with instructions for the operators in how to efficiently use the designed components. The process utilises the new components to massively reduce the manual handling. Calculations were carried out in order to accurately present instructions of the time taken for expulsion of membranes, draining of water and other such processes.

Research into data, with several indicators that point toward the life expectancy of membranes and the degradation of permeate provided the ability to create a membrane replacement pattern logic flow chart.

Relevant financial breakdowns were produced, regarding the previous and newly designed process. The financial analysis was used to prove that there were no further financial repercussions within the replacement process. This was not a priority, however it provided further proof of the sustainability of the process.

3.2 Methodology

3.2.1 Membrane Removal Tool

This component is designed to be attached to the insertion side of the vessel to allow for water to be inserted into the vessel. The water will ultimately create a pressurized volume that is utilized to displace the membranes from within the RO vessels, ejecting from the opposite side to where this tool is applied. The methodology is as follows:

1. Appropriate specification sheets and historical knowledge of the vessels, membranes and end caps were gathered. This information will be used to calculate limits and safety factors regarding pressure and volume of water.

2. A gathering of possible designs was discussed and hand sketched. Each design has its own unique features that each provided positives and negatives.

3. Each design required supplementary components, as discussed during the design of the components. These were modelled within Creo Parametric 6.0.

4. In order to narrow down the number of designs, each was judged using a series of criteria within a decision matrix. The five categories that each concept design was judged upon were reduction of manual handling, cost, feasibility, strength and durability.

5. A discussion took place in order to abandon the design which provided the least benefit and/ or had the most negative aspects.

6. As discussed in the literature review section, an initial estimate of the coefficient of friction was calculated. The method used in order to estimate this coefficient is based upon empirical data and situations, including pushing force statistics and historical replacements.

7. The two designs selected were modelled within Creo Parametric 6.0 using the appropriate dimensions as found in Step 1.

8. Both of the designs prepared in Creo Parametric 6.0 were analysed using Creo Simulate 6.0. Using FEA, the vessel, supplementary components and designed components were each analysed for the stresses applied. The stresses were as a result of the pressure and forces calculated in Step 6.

9. From here, a combination of the results from FEA and the original decision matrices results were used in order to select the final design.

3.2.2 Pump Skid

The pump skid is the component, designed to a certain set of specifications, that accompanies the membrane removal tool. These specifications are such that the pump can produce the pressure necessary to overcome the friction between the membranes and the RO vessel. Other points to consider for the pump skid are its size, weight and its ability to be moved to the required areas. The methodology is as follows:

1. Using knowledge of existing pump skids at QGC Kenya, multiple designs of pump skids were created. The three designs accompanied different forms of mobility and included a design without a portable pump, rather than any accompanying skid.

2. In order to narrow down the number of designs, each was judged using a series of criteria within a decision matrix. The five categories that each concept design was judged upon were reduction of manual handling, cost, feasibility, efficiency and durability.

3. The results yielded from the decision matrices allowed for amendments and abandonments to be made. The pump skid designs were narrowed down to one, rather than multiple.

4. Following this step, calculations were carried in order to estimate the dimensions required of the design. The calculations of the pressure required, and examples of existing pumps were used for this.

5. The pump skid was modelled within Creo Parametric 6.0 to suffice the dimension requirements found in Step 4.

6. FEA of this model was carried out to estimate the factor of safety of the design using Creo Simulate 6.0.

3.2.3 Holding/ Catching Apparatus

This component is responsible for both holding and catching membranes prior to insertion and subsequent to expulsion. The component must be able to be moved to different heights dependant on the stage or specific vessel. The main focus in this component is to remove as much manual handling of the membranes as possible while the membranes are not within the RO vessels. The methodology is as follows:

1. Specifications of the RO membranes, including physical size and mass will be collected. This information was used in order to approximate the physical requirements of the holding and catching apparatus design.

4. A number of possible designs were described and hand sketched. Each design has its own unique features in that some are designed to hold a vessel's worth of membranes while some are designed to hold a singular membrane.

5. In order to narrow down the number of designs, each was judged using a series of criteria within a decision matrix. The five categories that each concept design was judged upon were reduction of manual handling, cost, feasibility, strength and durability.

6. A discussion took place in order to abandon designs and make amendments to the design that would continue to be modelled. Incorporating the best aspects of each design into one allowed for an efficient final design.

7. The selected design was modelled within Creo Parametric 6.0 using the appropriate dimensions as found in Step 1.

8. The model prepared in Creo Parametric 6.0 was analysed using Creo Simulate 6.0. Using FEA, the data found in Step 1 was used to calculate the factor of safety of the component and ensure the component could fulfill its requirements.

3.2.4 Membrane Replacement Methodology

This section consists of a number of plans designed to instruct the operators on how to utilise the newly designed components. This incorporates direct instructions of the components as well as appropriate timings and pressures to use.

1. This process began by gathering data and carrying out calculations. The calculations included a pressure curve of which to operate the membrane removal tool at and the time required for expulsion and water drainage.

2. As well as the theoretical values of time and pressures, the number of operators required for each process was also decided.

3. From here, a replacement methodology was created with clear and concise instructions. Instructions were created for each individual stage of the reverse osmosis process.

3.2.5 Membrane Replacement Philosophy

The philosophy behind the membrane replacement is based around the requirement and timing of the replacement, rather than the physical process. Using key parameters as an indication allowed for a relevant workflow to be formulated.

1. This process began by searching through and collating the relevant information from a large spreadsheet. The spreadsheet had daily recordings of a number of parameters for all trains and stages of reverse osmosis.

2. From this data and communication with technical stakeholders, key parameters were selected that provided the most benefit to the indication of membrane and water quality.

3. Once the parameters were selected, a large amount of the data was viewed and analysed in order to recommend accurate values. These values act as indicators to the importance of a discussion regarding a membrane replacement being carried out.

4. Finally, from the indicators set, an automated workflow was created using Smartsheet. This workflow notifies the relevant stakeholders of the current state of the membranes if they reach a point of requiring attention.

3.2.6 Financial Analysis

This aspect of the project is used to provide further reasoning for the feasibility of implementing the designed components. By having a financial comparison, the benefits of the project can be scrutinized, and a final recommendation could be made with a combination of aspects from each process.

1. Historical data was gathered for both stage one and three replacements. These were the only two available but were able to provide data for each extreme of the RO process.

2. Through calculations and estimation, a general equation was formulated. This split up the total cost into the time taken, number of operators, hourly costs and cost of scaffolding.

3. For accurate comparison, the historical costs were estimated using this general equation. This allowed for the comparison of normalised values, rather than a historical recording and a calculated cost.

4. Using a number of specifications that had been calculated, the cost of the new strategies was calculated.

5. These values were compared and the percentage difference between the financial implications of both processes was recorded.

3.3 Possible Consequences

The common modes of failure in mechanical design are categorised as follows; Fracture, which is when a material begins to crack, this can be on a microscopic level or visible cracking. Yielding occurs when a component or body undergoes an amount of stress that exceeds the strength of the material or component design. Insufficient stiffness can cause a bending failure, named deflection which occurs when the ductility of the materials used do not meet the necessary standards for the process. Fatigue failure can appear as any of the previous mentioned failures but occurs due to a loss of strength from repetitive forces on the component. Creep is similar in that it occurs over a period of time and is due to the nature of some materials to plastically deform under stress (Cyprien, 2017).

In this project, it is important to consider the stresses which will be caused due to the water pressure. The nature of using pressure in order to move the membranes means that it is important to analyse the stresses in comparison to the strength of the materials. A serious injury could occur from a catastrophic failure of components surrounding a pressurised vessel. While considering these stresses, the possibility of fatigue also has to be explored and hence maintenance of the components would be pertinent, subsequent to the initial design and creation.

With the possible negative consequences considered and the relevant actions taken, the prosperity of the project can be discussed. The reduction in manual handling would be the main focus of the project's accomplishments. Within an industry that promotes and continually improves safety standards and culture, the removal of any unnecessary harm surrounding manual handling is pertinent. Following safety standards and ensuring the components operate correctly, there will be minimum risk compared to that of manual handling activities.

A secondary objective would be the increase in the financial efficiency of this process, through this project. This would be a consequence of the reduction of required operators for membrane replacement. The investment in producing the required components, along with the necessary maintenance schedules, could ultimately provide large financial benefits.

3.4 Project Constraints

The largest constraint that exists is COVID-19. The ongoing pandemic was declared an international concern to health on the 30th of January 2020 and since this date various quarantine and social distancing laws were implemented (WHO, 2020). These laws caused workplaces to shut down, because of this the scope of work regarding practical tests was affected. The design aspect of this project can account for a lot of the final output, which allows for the project to continue, with slight modifications to the focus.

3.5 Risk Assessment

The following risk assessment is sourced from the Queensland Government Enterprise Architecture. The consequence against likelihood table, shown in Figure 2 will be used in order to formulate the level of risk associated with each of the tasks identified. The identified tasks, associated risks and mitigation controls are compiled in Table 2. The actions and controls are tabulated in a concise manner to ensure the relevant information is clear and accessible.

	Consequence				
Likelihood	Insignificant	Minor	Moderate	Major	Critical
Rare	LOW Accept the risk Routine management	LOW Accept the risk Routine management	LOW Accept the risk Routine management	MEDIUM Specific responsibility and treatment	HIGH Quarterly senior management review
Unlikely	LOW Accept the risk Routine management	LOW Accept the risk Routine management	MEDIUM Specific responsibility and treatment	MEDIUM Specific responsibility and treatment	HIGH Quarterly senior management review
Possible	LOW Accept the risk Routine management	MEDIUM Specific responsibility and treatment	MEDIUM Specific responsibility and treatment	HIGH Quartely senior management review	HIGH Quarterly senior management review
Likely	MEDIUM Specific responsibility and treatment	MEDIUM Specific responsibility and treatment	HIGH Quarterly senior management review	HIGH Quarterly senior management review	EXTREME Monthly senior management review
Almost certain	MEDIUM Specific responsibility and treatment	MEDIUM Specific responsibility and treatment	HIGH Quarterly senior management review	EXTREME Monthly senior management review	EXTREME Monthly senior management review

Figure 9. Risk Assessment Matrix

Identified Risk	Original Level of Risk	Mitigation Controls
Pressurized Water: During operation of components, pressurized water is present.	**Medium**	Extensive research and analysis to ensure accurate safety factors. Ensure formal and concise instruction regarding operations of components
Suspended Load: Membranes are held at different heights by a mechanical component	**Low**	Ensure analysis of mechanical components prior to operation. Explain the risks to those operating the components.
Moving Bodies: As the membranes are expelled from the vessels, there is an object of 15 kg mass moving.	**Low**	Explain to operators the process so that they are aware of how the membranes are going to act during operations.
Excessive Noise: A pump operating indoors could cause levels of sound that could cause injury to operators.	**Medium**	Use components for the pump skid which minimize the risk of excessive noise. If not possible, identify and instruct operators to use adequate PPE.
Slips, Trips & Falls: With the presence of water and possible spillages, a hazard of slipping arises.	**Medium**	Include adequate times for draining of water in the operation manual. Design components in a manner which minimalizes possible spillages.
Display Screen Equipment: The existence of sensors and their relevant gauges would need to be monitored and could cause awkward postures.	**Low**	Design gauges to be visible from a multitude of angles to decrease sustained awkward poses while attempting to monitor parameters.

Table 2. Risk Assessment

4. Concepts & Designs

4.1 Initial Concepts

4.1.1 Membrane Removal Tool Concepts

Concept one utilizes an existing component, a vessel end cap. The existing component would be sourced from spare parts and would have small modifications made to it. The modification would include removing the cylinder that connects to the membrane, allowing for an area between the internal face of the modified end cap and the first membrane. A hole would be cut through the end cap, offset from the centre to not interfere with the endcap's waterproofing abilities. Offering a connection to a pipe, the hole cut would have attached a simple flange connection. This allows the pipe to be removed and attached as necessary. Due to the existing set up of the reverse osmosis vessels, the drain ports that are present would need to be plugged with a supplementary component. A further supplementary component needed is a membrane blank. This attachment is a blank face that connects to the membrane in order to ensure that there is no water leaking through possible gaps between the membrane and the vessel.

Concept two also utilizes an existing end cap, however further modification would take place in order to decrease the number of supplementary components required. Rather than vessel drain plugs, a barrel of equal diameter would be attached to the end cap to extend the length to cover the vessel drain ports. The barrel would be hollow, with holes that line up with the drain port. The internal face would have two holes, one of which for water insertion and one for water drainage. An external lever would be used in order to control a revolving wall which allows the operator to choose which hole is exposed. The vessel drain plug is not necessary with this design, however, the blank attachment is still necessary for this design to impede the water from entering the membrane.

Concept three is an original design being manufactured, rather than an existing component being modified. The general shape of the end cap would be mimicked to ensure that the component would fit effectively. In this design, the hole for the water entering the vessel would be centred. Surrounding the component would be an inflatable O-ring, which inflates upon the water entering the component. This would remove the need for the existing clamps to be used in the replacement process. A positive of this design is that there are no interfering components, that aren't specifically chosen to be there for the purpose of membrane removal. Rather than the locking system of clamps that exists on the end cap, a hollow O-ring would be used. This hollow O-ring would consist of channels, directly fed from the water supply in order to increase pressure between the tool and the vessel walls. A pressure actuated valve would be necessary in order to ensure the tool is secured, prior to water entering the vessel. The barrel design mentioned in Removal Tool Concept #2 could be utilized, otherwise the vessel drain plugs would need to be manufactured.

4.1.2 Holding/ Catching Apparatus

Concept one is designed to hold seven membranes at once. This removes the need for each individual membrane to be manually handled, while at uncomfortable positions. The apparatus in this concept is essentially a crate, with walls located around the rear and sides. The crate would have a patterned base, with hemicylinders of equal diameter to the membranes. This ensures the membranes stay in place and manual handling is not required in order to manipulate the membranes into adequate locations. For each holding/ catching apparatus design there is an option for the design and implementation of extending legs or for a forklift attachment. If legs were utilised for this design, the legs would need to be mobile or the apparatus would need to move separate to the legs to ensure each membrane can be held parallel. If a forklift attachment is used, the movement of the forklift could be used for this reason.

Concept two is designed as a means for the membrane to roll from the vessel to a waste bin. The design is specified to only the width of one membrane, as a membrane would never be permanently stored on the apparatus. Instead as each membrane is expelled from the vessel, it would eventually roll from the tilted apparatus. A slide would be designed and attached tangential to the length of the membrane, so that the membrane is able to freely roll. Similarly to the first concept, a number of attachments could be used for the movement and stability of the apparatus.

4.1.3 Holding/ Catching Apparatus Support

Concept one is designed as a form of telescoping legs, which provide support to the apparatus. This design would not be easily mobile, and hence most of the movement would occur once the membranes are removed from the apparatus. The legs could be manually lifted and lowered with a pin system to lock the legs at an appropriate height. The gaps between the holes for the pins would be designed at the appropriate distance between the heights of the vessels. An alternative to the manual changing of specified heights would be a manually operated worm drive. This would incur less rigorous manual handling than manually lifting the apparatus. In order to be able to support a maximum potential of seven membranes, the legs would be reinforced with necessary cross bars.

This concept would include forklift attachments, rather than a specific design of legs. This design is mobile, given the nature of the forklift being able to move freely. The lifting process in this design would rely on the forklift, rather than any form of manual handling. The heights to which the apparatus is raised is not limited to specific specifications, however there is a limit to the height of the forklift.

4.1.4 Pump Skid

Concept one allows for a relatively large pump. The larger pump would allow for a higher velocity of water and hence the pressurized volume can be created in a short amount of time. This would decrease the time taken to expel the membranes, however, the larger pump and motor would require a larger base with an attached control panel. The base would be mobile, so that the pump can be placed in appropriate positions for the process of the operation. Utilizing a forklift attachment at the base allows for the large, bulky pump skid to be relocated without manual handling.

Concept two also incorporates a relatively large pump. Other than the form of mobility, the pump follows the same design as Pump Skid Concept one. The pump would be housed on a large base and surrounded by a steel structure. This structure would include hooks, which could be attached to an overhead gantry crane, present at the site.

Concept Three utilizes a smaller pump and would not require a designed and manufactured base or support. The pump would be significantly lighter and would not require a form of transport other than being manually moved.

4.2 Supplementary Components

4.2.1 Vessel Drain Plug Concept

This concept, shown in Figure 12, would require the manufacturing of an original component, of which two are required per vessel. These two can be reused for each vessel. A cylinder, of equivalent diameter to the drain ports would be created, with a section of a cylinder acting as an internal face, matched to the diameter of the internal vessel. This face would provide a method of impeding the water from exiting the vessel. The cylinder would include 2 O-rings which would create friction between the drain port and the component. The pressure from the water would act on the face of the cylinder, further ensuring that it does not become free of the drain port.

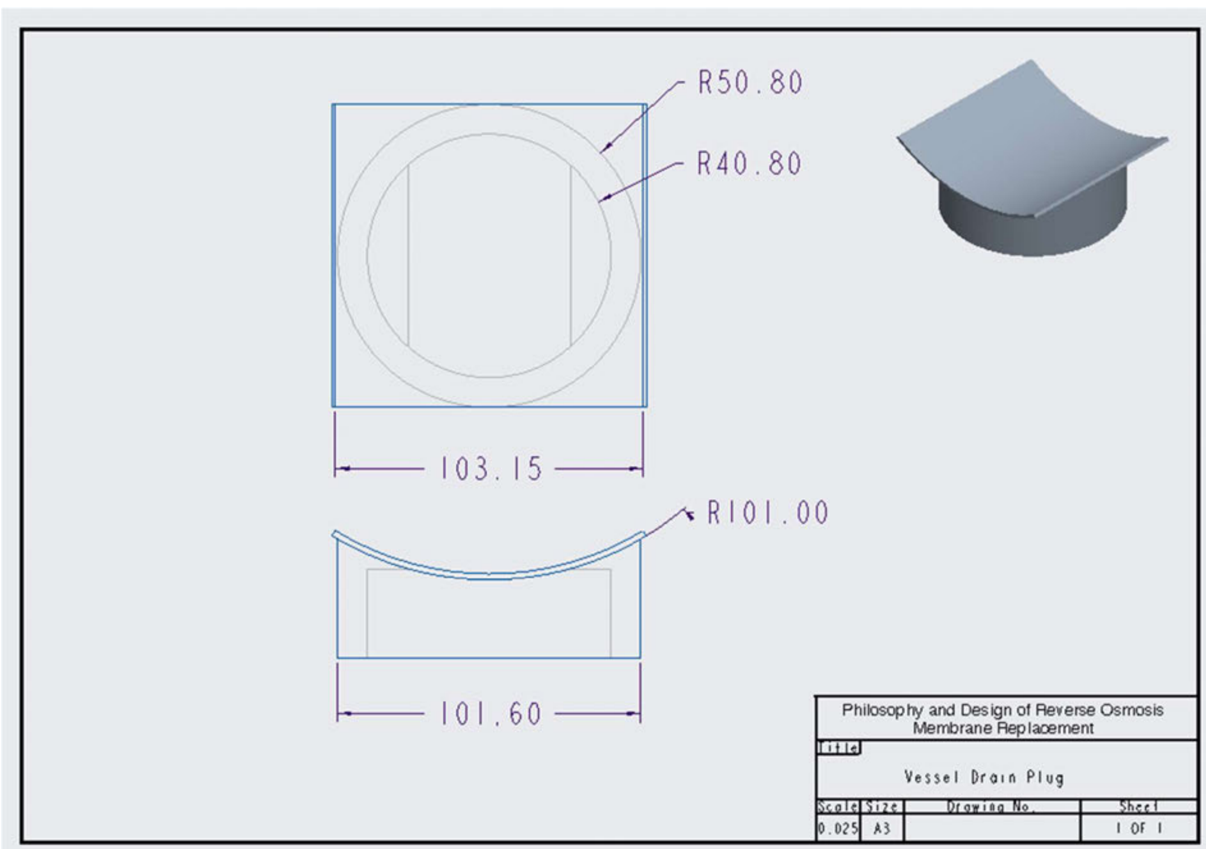

Figure 10. Engineering Drawing: Vessel Drain Plug

4.2.2 Membrane Blank

This concept would utilize the existing membrane links with modification, as shown in Figure 13. The membrane links are designed to be inserted into the membrane and hence using this existing design would ensure the membrane blank does not become removed. The membrane link would be cut in half and a large circular surface, of equal diameter to the membrane would be attached. This large, blank face allows for an equal amount of pressure to be applied to the membrane.

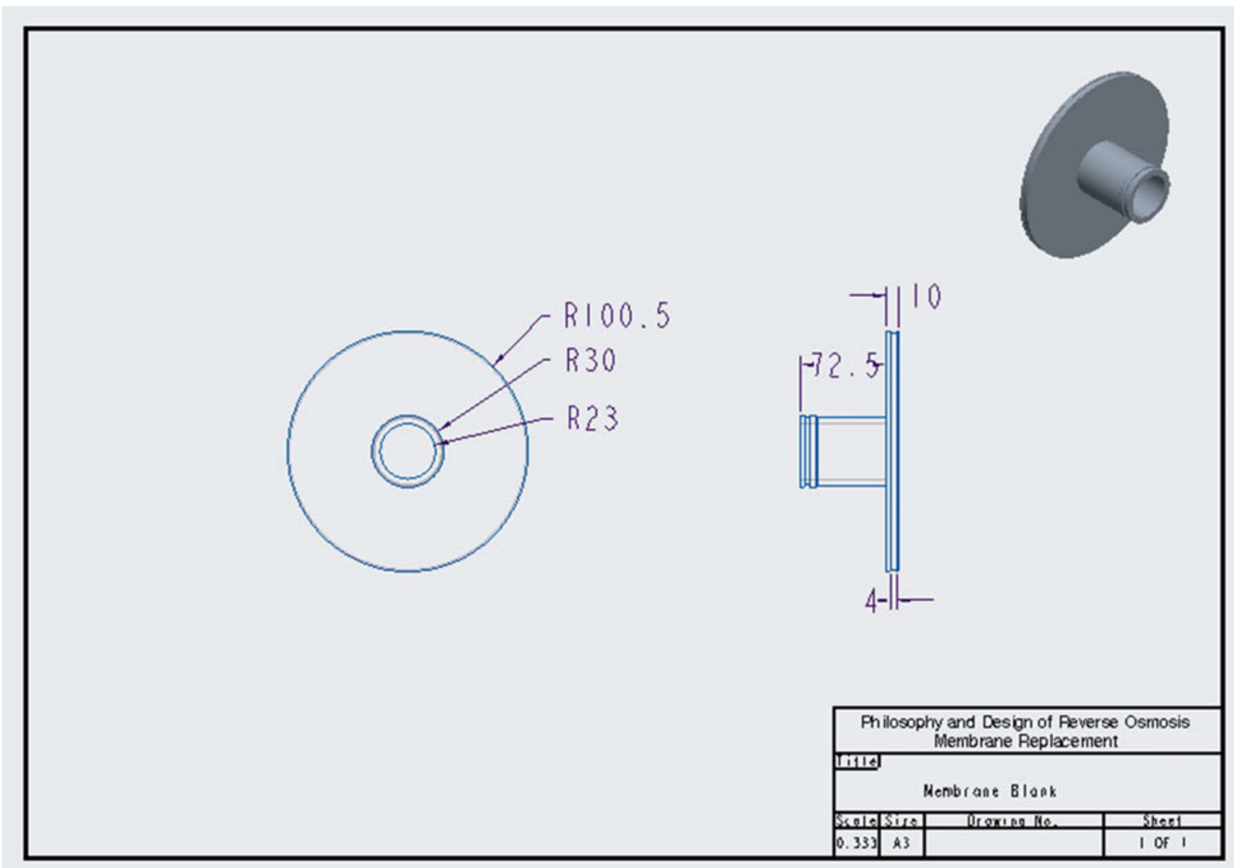

Figure 11. Engineering Drawing: Membrane Blank Attachment

4.3 Decision Matrices

4.3.1 Classifications and Weighting

This set of decision matrices will not aim to produce the final design for each set of components but rather eliminate any designs that are not appropriate. A generic set of deciding factors has been selected and appointed a specific weighting in relation to its importance in the design of the components. These assessments are based on initial perceptions from the concepts, rather than calculations. The weightings add to equal one, while the score each component receives is between one and five. The classifications their relevant weighting are as follows:

Reduction of Manual Handling (Weight = 0.25): This classification judges the component's ability to reduce the manual handling of its specific operation. Where a component completely removes manual handling, it will receive a score of five and a component which increases the amount of manual handling will receive a score of zero.

Cost (Weight = 0.25): This classification assesses the cost of the production and materials of the component. Where the component itself incurs no extra cost to its relevant section of the operation it will be appointed a five and a zero when it significantly increases the cost.

Feasibility (Weight = 0.2): This classification is similar to the assessment of cost, but rather than the dollar amount being assessed it is the ability to produce the component. Where the component can be sourced from existing component with minimal modification it will receive a five and when the component would be near impossible to produce with the materials on hand at site, it will receive a zero.

Strength/ Efficiency (Weight = 0.2): This classification judges the component's ability to either hold or move the membranes, depending on the component's requirements. Where the component can easily hold the weight or produce the pressure to remove the membranes it will be appointed a five and where the component would fail catastrophically it will receive a zero.

Durability (Weight = 0.1): This classification assesses the relevant amount of life cycles that the component would have. Where the component would easily last for a significant number of cycles with a minimal amount of preventative maintenance the component will receive a five and a zero for where the component would fail after one use.

4.3.2 Decision Matrices

Membrane Removal Tool

	Reduction of Manual Handling	Cost	Feasibility	Strength	Durability	**Overall**
Concept #1	4	4	4	3	4	3.8
Concept #2	4	3	5	4	4	3.95
Concept #3	4	2	3	4	4	3.3

Table 3. Decision Matrix: Membrane Removal Tool

Holding/ Catching Apparatus

	Reduction of Manual Handling	Cost	Feasibility	Strength	Durability	Overall
Concept #1	3	3	3	4	3	3.2
Concept #2	4	3	4	4	4	3.75

Table 4. Decision Matrix: Holding/ Catching Apparatus

Holding/ Catching Apparatus Support

	Reduction of Manual Handling	Cost	Feasibility	Strength	Durability	**Overall**
Concept #1	2	2	2	4	3	2.5
Concept #2	4	4	3	4	5	3.9

Table 5. Decision Matrix: Holding/ Catching Apparatus Support

Pump Skid

	Reduction of Manual Handling	Cost	Feasibility	Efficiency	Durability	**Overall**
Concept #1	3	4	4	2	3	3.25
Concept #2	5	3	3	4	4	3.8
Concept #3	4	3	3	4	4	3.55

Table6. Decision Matrix: Pump Skid

4.4 Amendments to Concepts

4.4.1 Membrane Removal Tool

When considering the design and manufacturing process of the membrane tool, the main considerations are both the cost and feasibility. In these sections, Concept #1 and #2 excel while Concept #3 receives much lower scores. Once the component is manufactured the deciding factors become the reduction of manual handling, strength and durability. There is no indication that Concept #3 provides exceptional capabilities in these categories to justify the increase in cost and decrease in feasibility. Prior to modelling and analysing the components, Concept #3 will be abandoned due to its lack of benefit.

4.4.2 Holding/ Catching Apparatus

The concepts described for the holding/ catching apparatus both have benefits in their design, however concept #2 receives a significantly better score from the decision matrix. In this case, it is important to consider the benefits of each rather than abandoning a design purely based upon its score. Moving forward the concepts will be combined in terms of Concept #1's ability to contain seven membranes at a time and Concept #2's constant tilt. This design will be created with interchangeable attachments of both a slide, for when the membranes are being removed and a wall for the storage and insertion of the membranes.

4.4.3 Holding/ Catching Apparatus Support

Concept #1 receives a significantly lower overall and reduction in manual handling score when compared to Concept #2. This data can be used in order to abandon Concept #1 as designing and manufacturing components that do not provide manual handling benefits to the operator is counterproductive. Possible improvements to Concept #2, with minimal added cost and no reduction in the other categories, include the ability to transport the apparatus by an overhead gantry crane. This component will no longer be separated from the Holding/ Catching Apparatus.

4.4.4 Pump Skid

The pump skid concept designs receive similar scores and there seems to be no apparent reason for the abandonment of any concepts at this stage. However, by combining Concept #2 and #3, there will be great increases in benefit, with very low increase in cost. Concept #2 and #3 will be combined as a combined component, with the ability to be transported via forklift and overhead gantry crane. The engineering drawings and analysis of this component can not be created until the dimensions have been approximated. This will occur subsequent to the initial calculations of the FEA.

5. Analysis of Ongoing Concepts

5.1 Initial Calculations

5.1.1 Coefficient of Friction

The coefficient of friction can be calculated used the empirical data of an ample pushing force of 400 N, as found in the literature review. This value is used as an estimate of the force applied by operators in previous membrane replacements, to calculate the static friction. In the following table the force due to static friction is represented by F_s, the coefficient of static friction is μ_s and the normal force of seven membranes is represented by N. The calculations for the values in Table 7 can be seen in Appendix B1.

F_s	400 N
N	1030.5 N
μ_s	0.3883

Table 7. Coefficient Of friction Key Values

5.1.2 Pressure Required to Overcome Static Friction

In order to displace the membranes, the pressure within the vessel will be required to overcome the force due to static friction. A combination of the pressure required, P; the coefficient of static friction, μ_s; the normal force of seven membranes, N; and the surface area of the membrane blank, A. The value calculated will be the minimum required value, P1; while a conservative maximum value will be estimated, P2. The calculations for the values in Table 8 can be seen in Appendix B2.

N	1030.5 N
μ_s	0.3883
A	3.173×10^{-2} m^2
P1	12.61 kPa
P2	25.00 kPa

Table 8. Pressure to Overcome Friction Key Values

For FEA, this pressure, P2, will be applied upon the internal wall of the vessel, the membrane blank and the membrane removal tool. The sectional surface area upon which this pressure is calculated using a number of lengths. These lengths include: Length between the membrane blank and removal tool, L; the length between the membrane face and end of the vessel, L_T; the width of the membrane blank face, L_{MB}; the width of the membrane removal tool, L_{MRT}; and the length between the external of the removal tool and the edge of the vessel, L_E; and the offset to which the pressure would be placed, L_{offset}. The relevant calculations for the values presented in Table 9 can be seen in Appendix B3.

L_T	407 mm
L_{MB}	10 mm
L_{MRT}	280.4 mm
L_E	83 mm
L	33.6 mm
L_{offset}	363.4 mm

Table 9. Pressure Applied Section Key Values

5.1.3 Pump Specifications

The pressure required to displace the membranes was found to be relatively low and hence the pump does not need industrial standard specifications. As a placeholder for estimations of size and mass for FEA, cost and life for financial analysis etc. will be the 5400 L/H *Certa Multistage High Pressure Water Pump*. The specifications of this pump can be seen in Table 10.

Cost	$260 AUD
Warranty Life	8760 Hours
Height	432 mm
Width	173 mm
Depth	445 mm
Mass	15.04 kg

Table 10. Pump Specifications

5.2 Engineering Drawings

5.2.1 Membrane Removal Tool

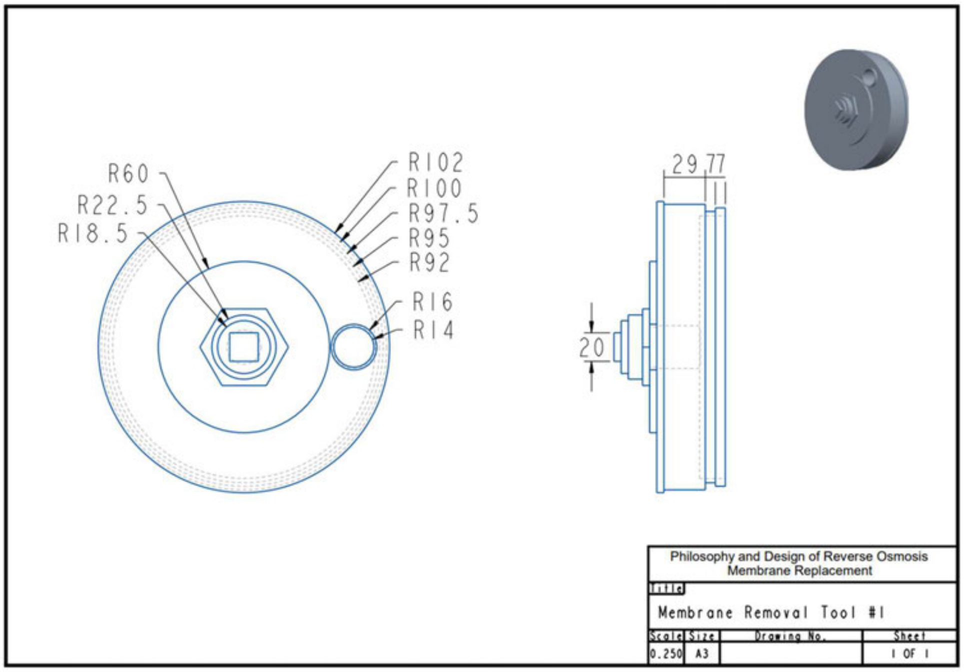

Figure 12. Engineering Drawing: Membrane Removal Tool #1

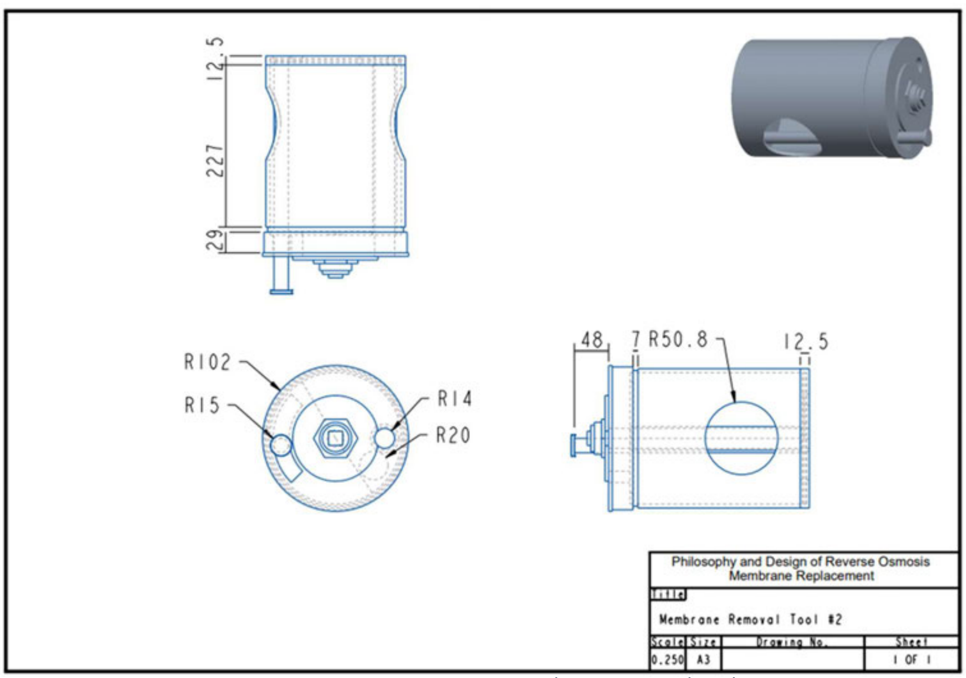

Figure 13. Engineering Drawing: Membrane Removal Tool #2

5.2.2 Holding/ Catching Apparatus

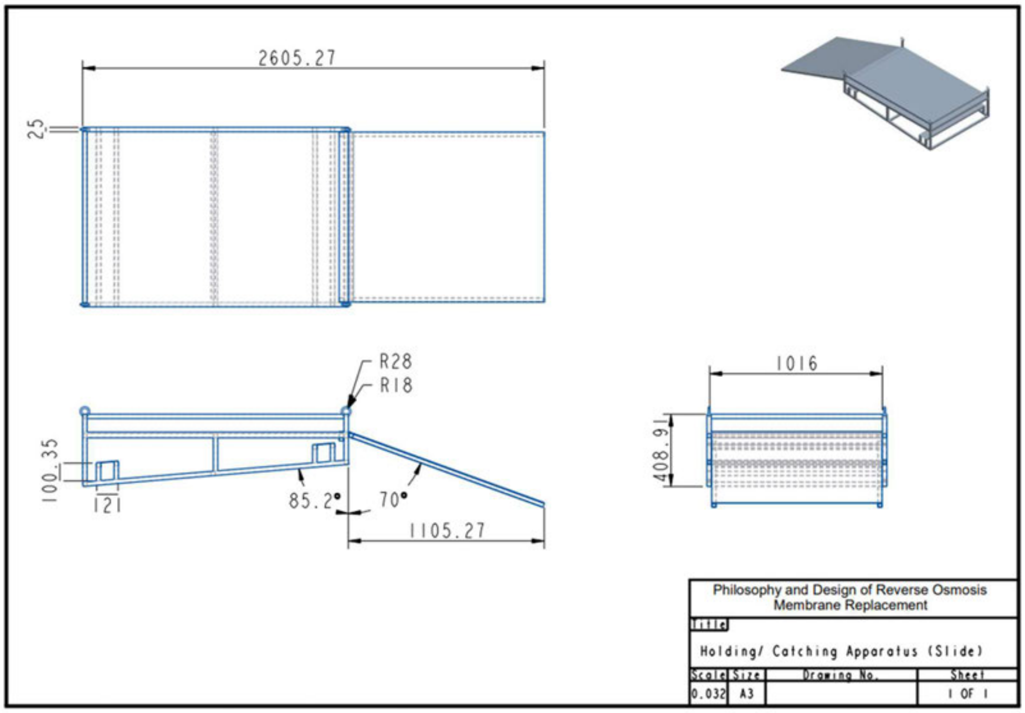

Figure 14. Engineering Drawing: Holding/ Catching Apparatus w/ Slide Attachment

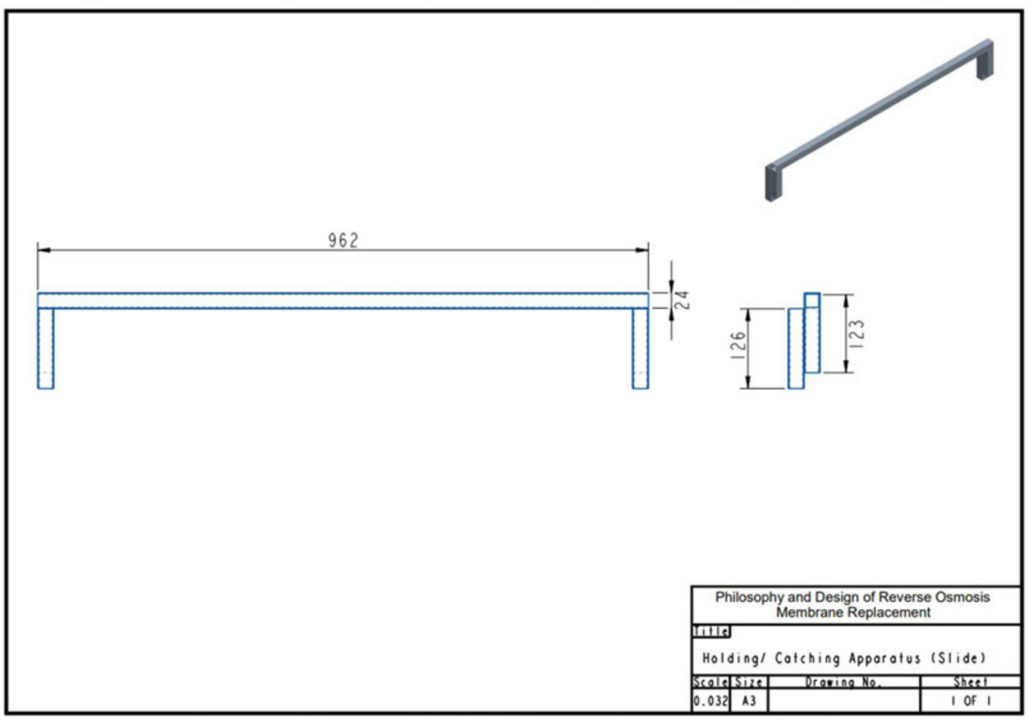

Figure 15. Engineering Drawing: Holding/ Catching Apparatus Wall (Interchangeable w/ Slide)

5.2.3 Pump Skid

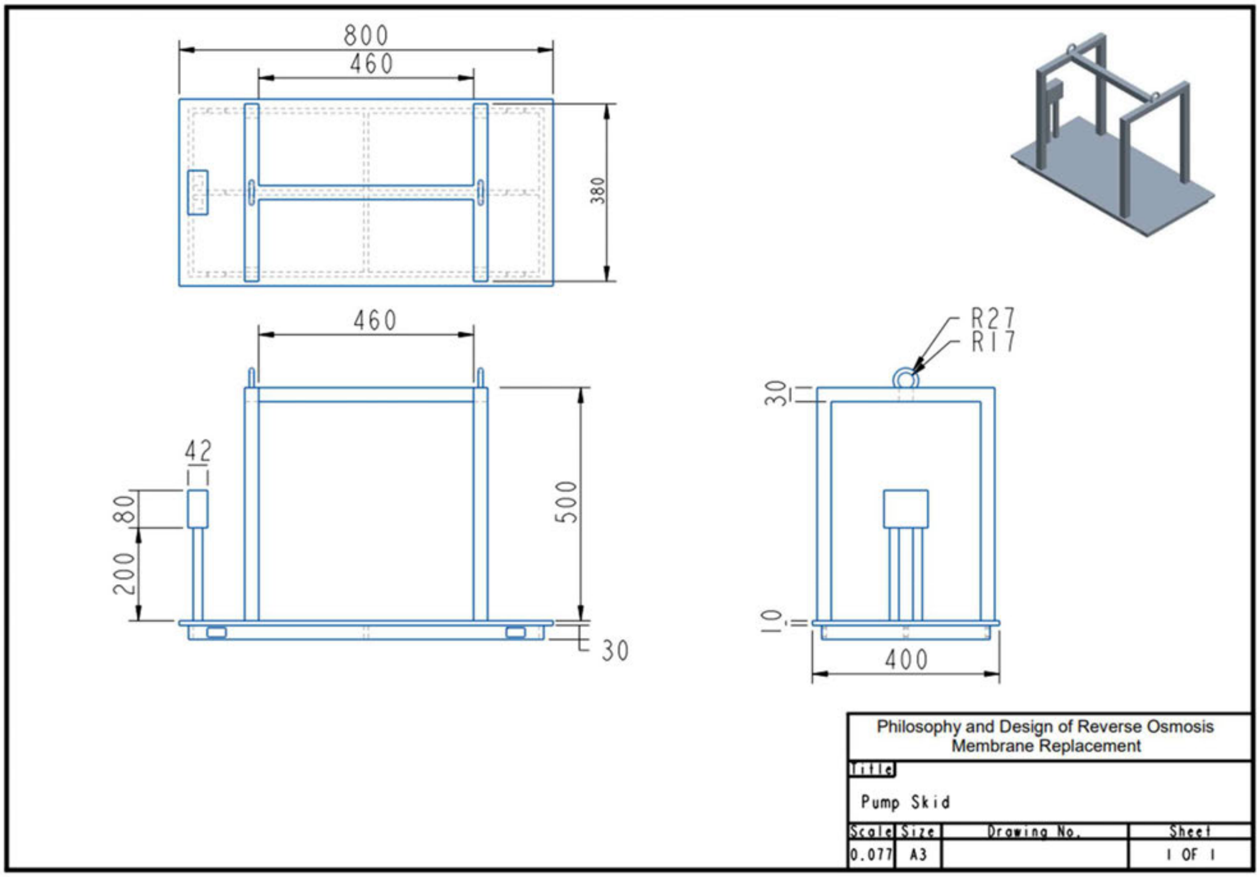

Figure 16. Engineering Drawing: Pump Skid

5.3 Finite Element Analysis of Supplementary Components

5.3.1 Reverse Osmosis Pressure Vessel

This vessel is analysed at the maximum afore mentioned pressure value, 25 kPa across three sections of differing lengths. The lowest strength of all stage vessel is 3.103 MPa. Given that this number is never exceeded, the process will be suitable for all three stages of vessel specifications. This component is the only one which can be considered as having a brittle material. Due to the information found in the literature review, max principal stress was used for this component.

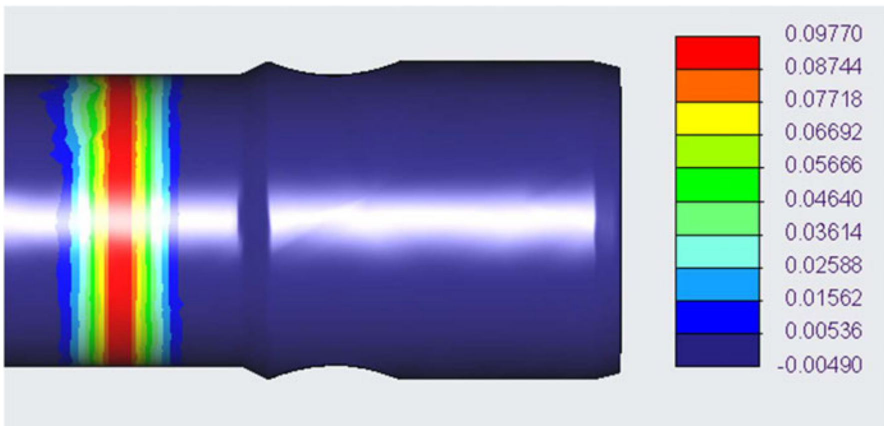

Figure 17. Vessel FEA: 25 kPa – Between End Cap and Seven Membranes (External) (Legend – MPa)

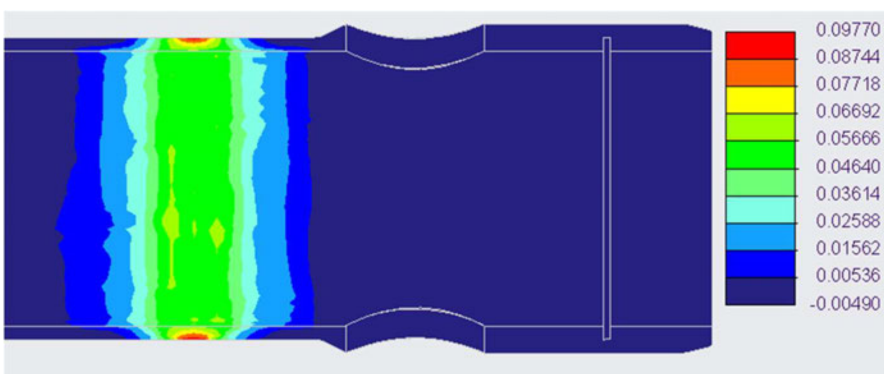

Figure 18. Vessel FEA: 25 kPa – Between End Cap and Seven Membranes (Internal) (Legend – MPa)

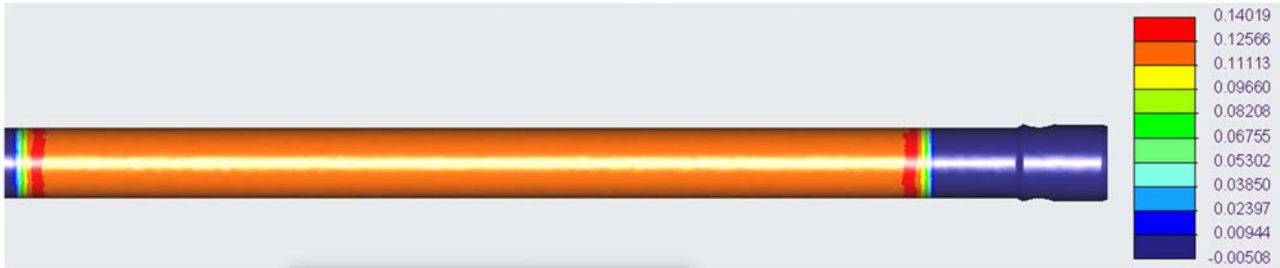

Figure 19. Vessel FEA: 25 kPa – Between End Cap and Four Membranes (External) (Legend – MPa)

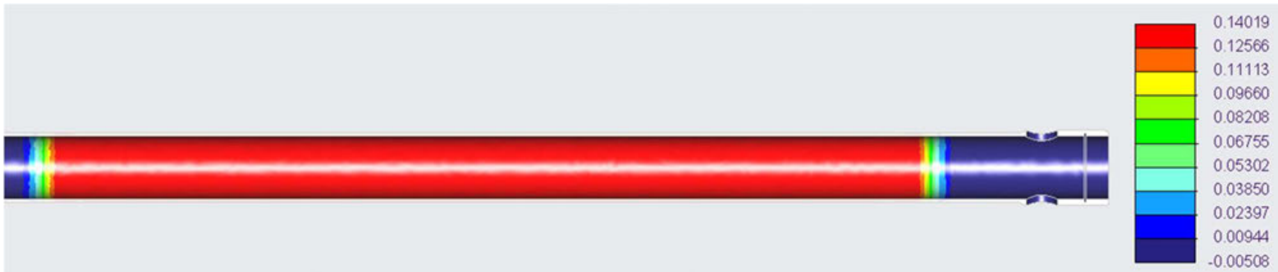

Figure 20. Vessel FEA: 25 kPa – Between End Cap and Four Membranes (Internal) (Legend – MPa)

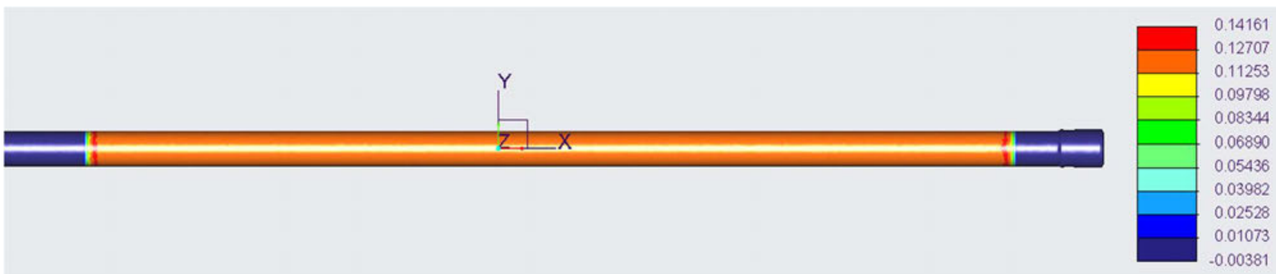

Figure 21. Vessel FEA: 25 kPa – Between End Cap and One Membrane (External) (Legend – MPa)

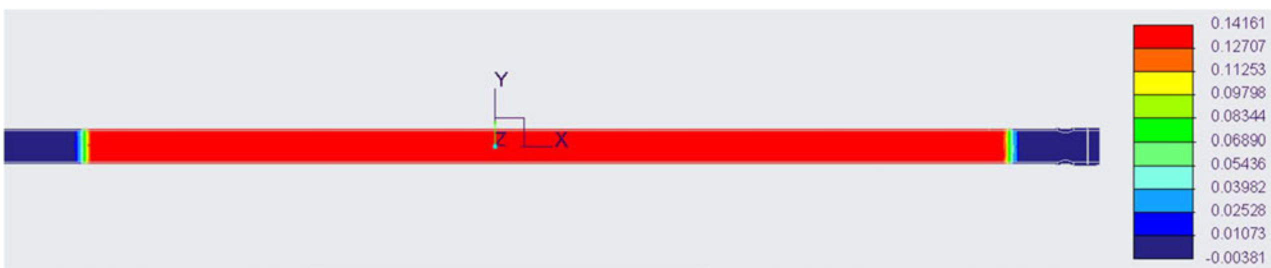

Figure 22. Vessel FEA: 25 kPa – Between End Cap and One Membranes (Internal) (Legend – MPa)

5.3.2 Membrane Blank

Using Von Mises stress analysis, the stress resulting from the 25 kPa acting upon the membrane's face can be visualized. The analysis was carried out with the legend representing stress in MPa.

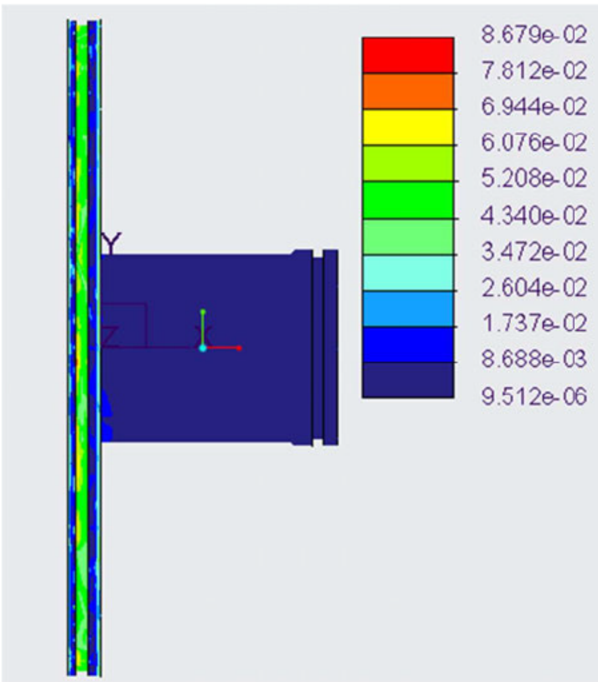

Figure 23. Membrane Blank FEA: 25 kPa – Side View (Legend – MPa)

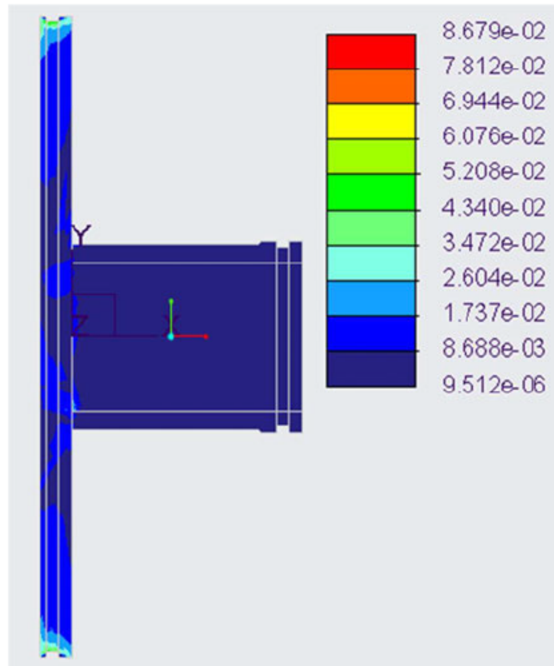

Figure 24. Membrane Blank FEA: 25 kPa – Side View (50% Cut) (Legend – MPa)

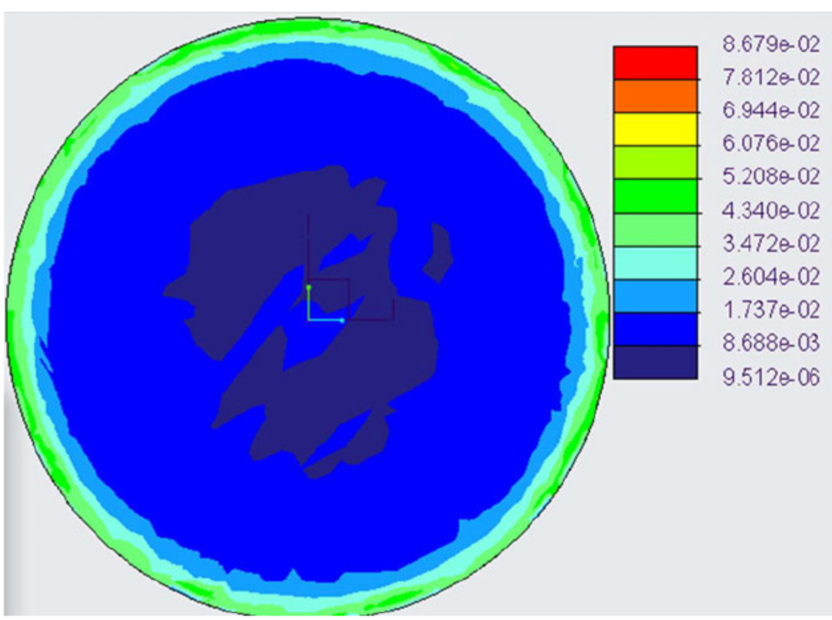

Figure 25. Membrane Blank FEA: 25 kPa – Front View (Legend – MPa)

5.3.3 Vessel Drain Plug

This component will have the defined 25 kPa pressure value placed upon its surface which is internal to the vessel. The form of analysis is Von Mises stress analysis.

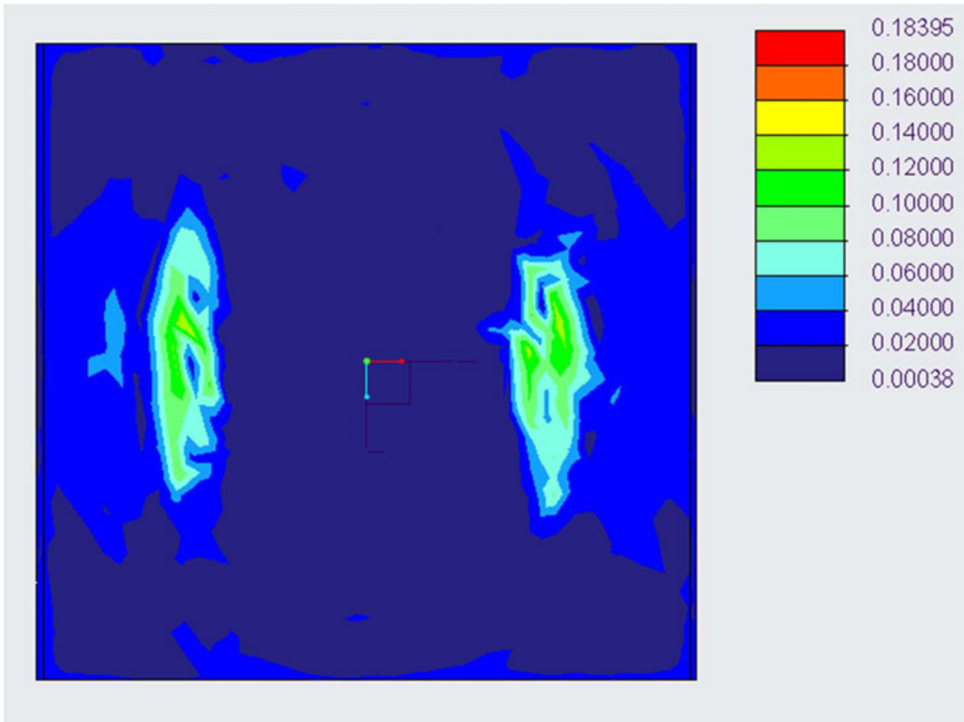

Figure 26. Drain Plug FEA: 25 kPa – Top View (Legend – MPa)

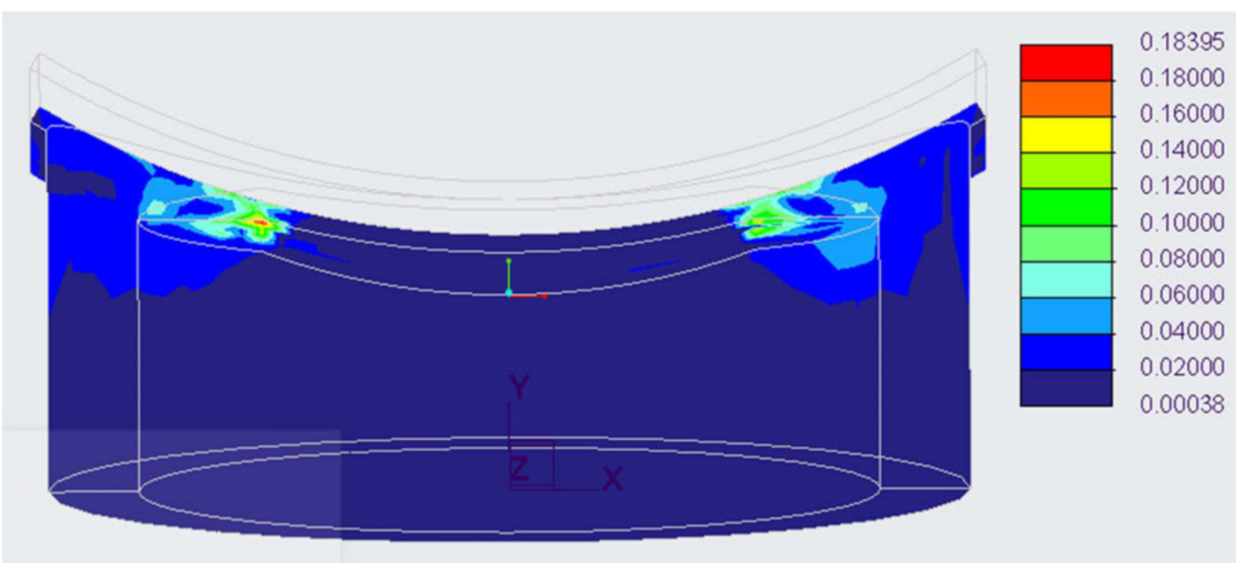

Figure 27. Drain Plug FEA: 25 kPa – Side View (50% Cut) (Legend – MPa)

5.4 Discussion of Analysis of Supplementary Components

5.4.1 Reverse Osmosis Pressure Vessel

Regardless of the positioning of the membranes, at the maximum pressure of 25 kPa the maximum stress induced was 0.1416 MPa. This is far lower than the specified maximum operating pressure that was used as the yield strength, 3.103 MPa. The vessels, therefore, have a minimum factor of safety of:

$$FoS = \frac{Max\ Allowable\ Stress}{Max\ \ Stress}$$

$$FoS = \frac{3.103}{0.1416}$$

$$FoS\ \approx 22$$

The pressure is, for the majority of the section under pressure, uniform with small fluctuations across the edges of the section. The initial section in which the pressure will be applied has the lowest stress acting upon it, however the length of the applied pressure does not have a significant affect on the maximum stress experienced by the vessel. The sections of pressure that represent one and four membranes remaining have very similar results which reinforces this claim. This outcome can be attributed to the fact that regardless of the length, as the membranes move, the pressure applied remains the same. As the operator is instructed to slowly allow water to enter the vessel and to control the pressure accordingly, there is no significant amount of impact loading that needs to be considered. The process does not need to be modified in order to be safely carried out when considering the limits of the pressure vessel, as shown through the calculation of the factor of safety.

5.4.2 Membrane Blank

The maximum stress, even at a point of concentration is significantly low for the membrane blank. Using PVC for this material, the maximum stress at any point was 86.78 kPa which presents another large safety factor when considering a tensile yield strength of 55.2 MPa (Engineering Toolbox, N.D). The factor of safety is then:

$$FoS = \frac{Tensile\ Yield\ Strength}{Max\ \ Stress}$$

$$FoS = \frac{55.2}{0.08678}$$

$$FoS\ \approx 630$$

With a factor of safety this large, it is apparent that the process does not require any modification to meet the limits of this component. The maximum stress recorded was apparent upon the cut-out to where a large O-ring would exist. This outcome is to be expected due to the possibility of stress concentration occurring at the corner of the ridge. The pressure applied directly to the internal face of the membrane blank reflects that the stress is largest at the edges and least at the centre. Once again this can be attributed the existence of the notch around the external radius of the membrane blank. The thinnest area is likely to experience the most stress as reflected through the FEA. The centre of the membrane blank is also supported and constrained in one direction by the membrane face, allowing for further support for the thicker section of the membrane blank. This design is proven through FEA to be safe with low amounts of stress, even at the thinnest and most concentrated points of the design.

5.4.3 Vessel Drain Plug

Under the same load set as the membrane blank, the vessel drain plug experiences larger stresses upon its curved face. The value, when compares to the tensile yield strength of PVC still does not pose any threat of instant failure. The factor of safety is:

$$FoS = \frac{Tensile\ Yield\ Strength}{Max\ \ Stress}$$

$$FoS = \frac{55.2}{0.18395}$$

$$FoS\ \approx 300$$

This factor of safety indicates that the process does not require any modification in order for it to be safely carried out. There are small stress concentrations existing at the external face of the vessel drain plug. The points of concentration are located at the edges where the curved surface meets a flat surface. This stress concentration is an expected phenomenon and hence this does not provide reason for concern. Furthermore, the exceptionally high factor of safety is calculated using the value of this stress concentration. Upon the internal face of the vessel drain plug, the highest amount of stress experienced lines up with the points of stress concentration. With these points of stress concentration and a curved surface, it is expected that the stress would not be uniform upon this surface.

5.5 Finite Element Analysis of Concept Designs

5.5.1 Membrane Removal Tool

5.5.1.1 Concept #1

Both concepts were analysed with the selected maximum pressure of 25 kPa applied to the internal surfaces. As the material is of a ductile nature, Von Mises stress analysis was used.

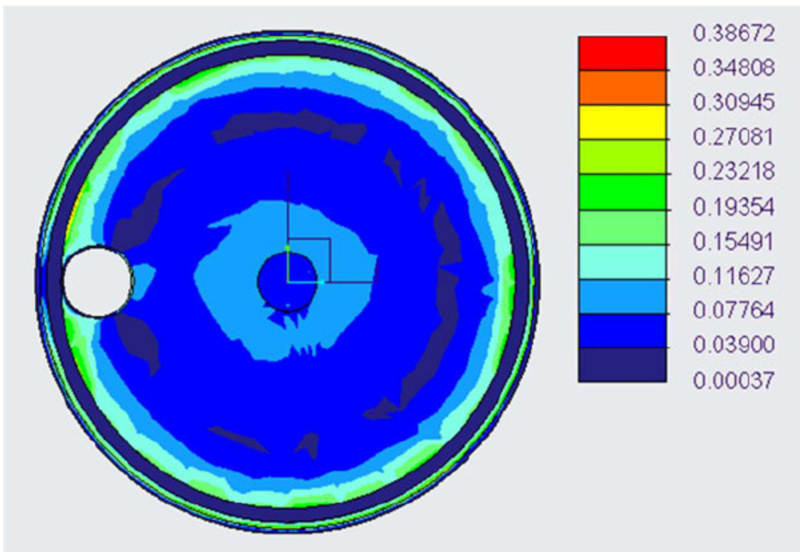

Figure 28. Membrane Removal Tool #1 FEA: 25 kPa – Internal Face (Legend – MPa)

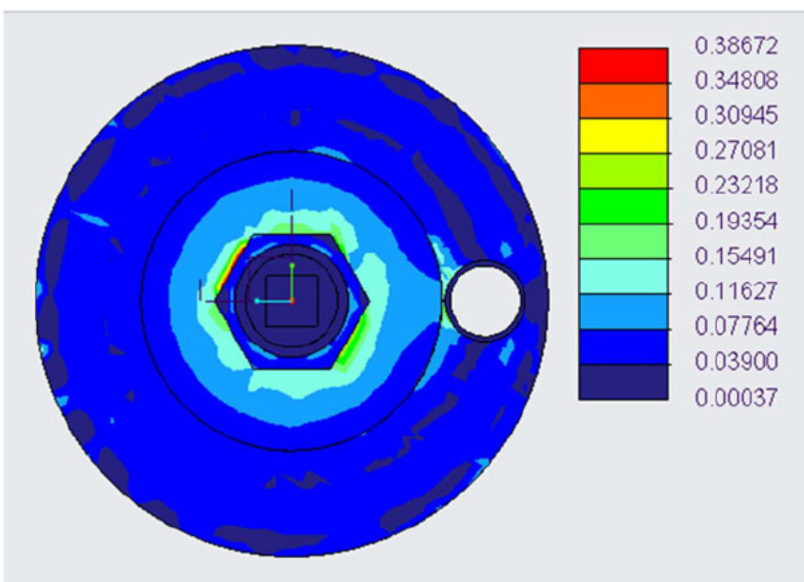

Figure 29. Membrane Removal Tool #1 FEA: 25 kPa – External Face (Legend – MPa)

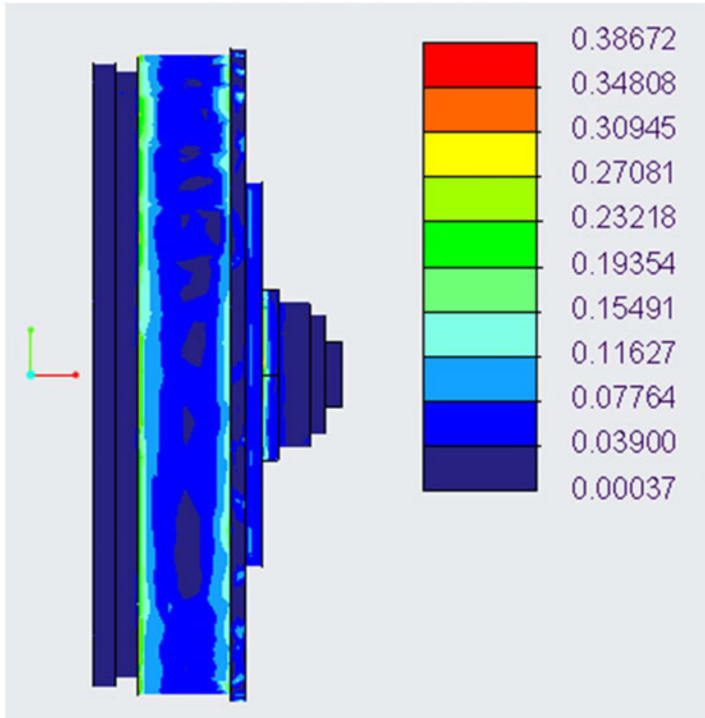

Figure 30. Membrane Removal Tool #1 FEA: 25 kPa – Side View (Legend – MPa)

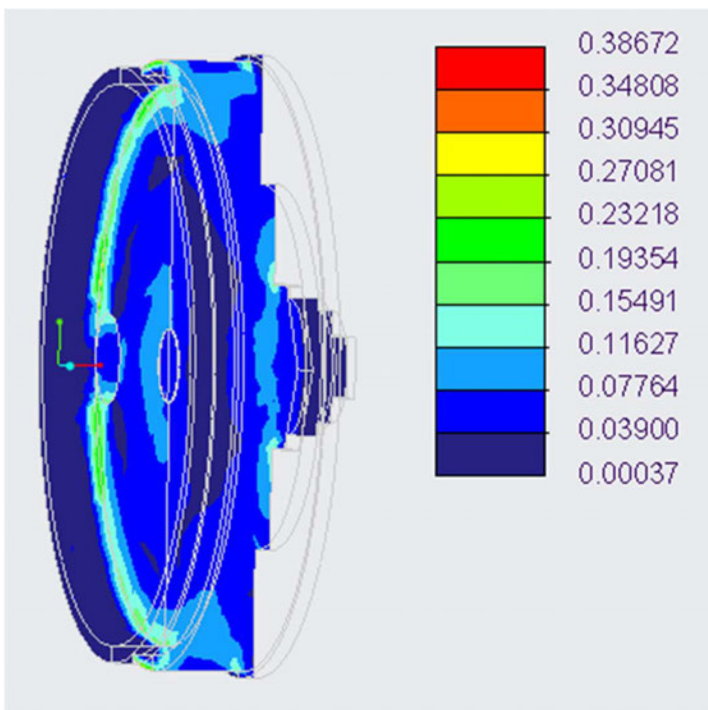

Figure 31. Membrane Removal Tool #1 FEA: 25 kPa – Side View (50% Cut) (Legend – MPa)

5.5.1.2 Concept #2

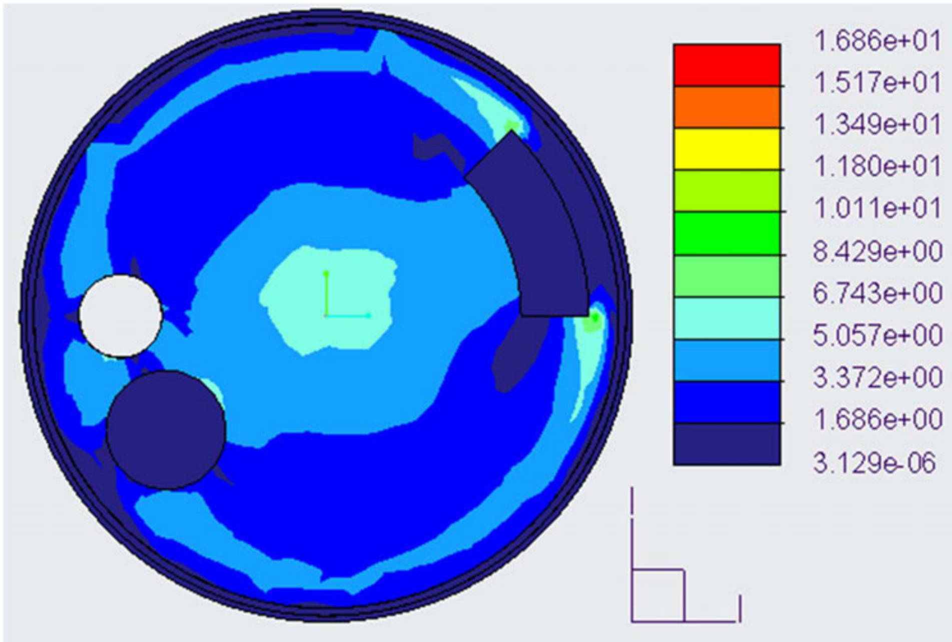

Figure 32. Membrane Removal Tool #2 FEA: 25 kPa – Internal Face (Legend – MPa)

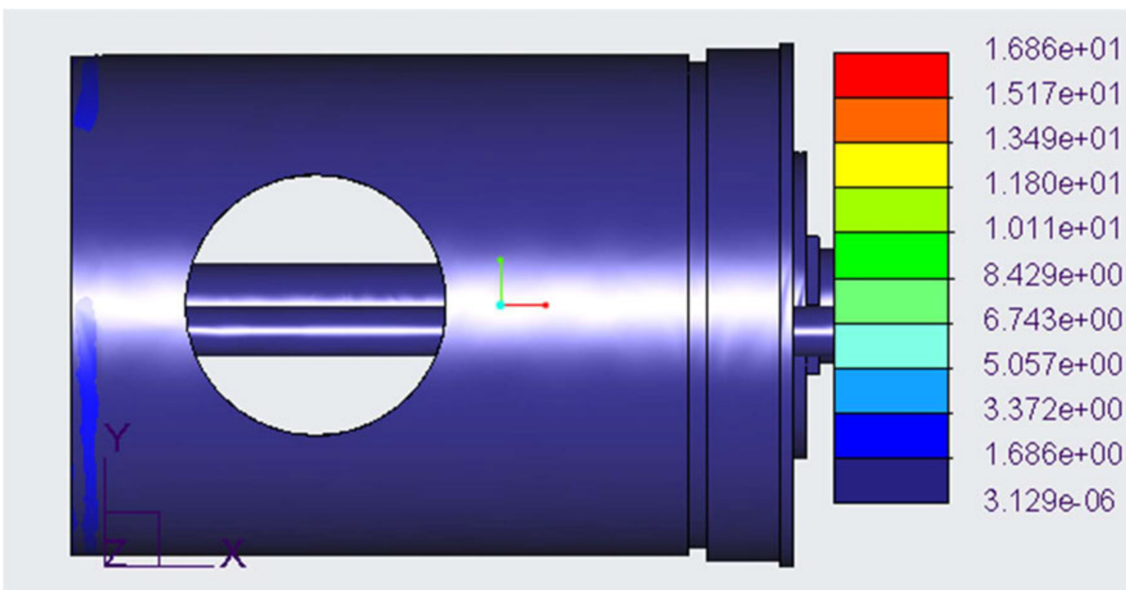

Figure 33. Membrane Removal Tool #2 FEA: 25 kPa – Side View (Legend – MPa)

5.5.2 Holding/ Catching Apparatus

5.5.2.1 Holding and Insertion of Membranes

The final concept design that resulted from the combination of original concept designs was analysed using Von Mises stress analysis. There were multiple cases and load sets used for analysis to analyse the apparatus under all steps of the process. In this case, the apparatus is analysed while being used to store seven membranes. The force acting upon the horizontal surface and the vertical wall was calculated using trigonometry:

$$F_{y-7\ Membranes} = m_{7\ Membranes} g cos(\theta_{tilt})$$

$$F_{y-7\ Membrane} = 105 \times 9.81\ cos(4.76°)$$

$$F_{y-7\ Membranes} = 1026.5\ N$$

$$F_{x-7\ Membranes} = m_{7\ Membranes} g sin(\theta_{tilt})$$

$$F_{x-7\ Membranes} = 105 \times 9.81\ sin(4.76°)$$

$$F_{x-7\ Membranes} = 85.475\ N$$

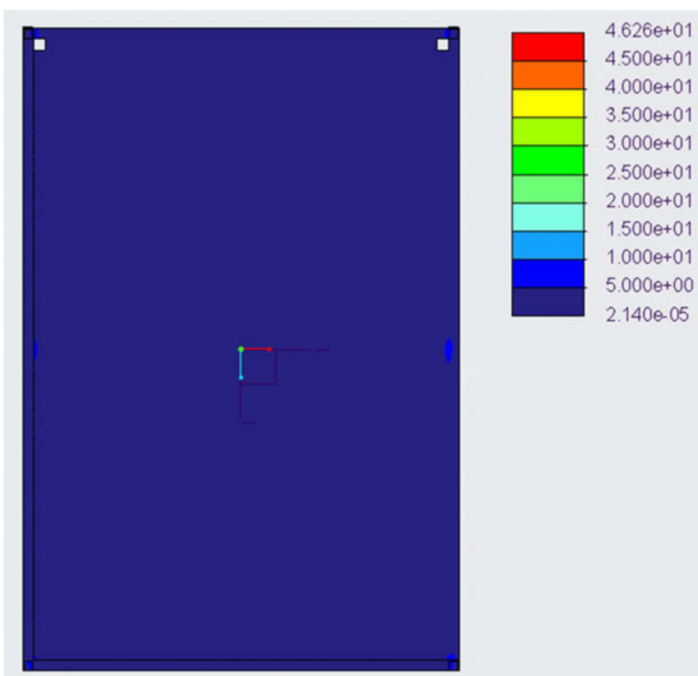

Figure 34. Apparatus FEA: 7 Membranes – Top View (Legend – MPa)

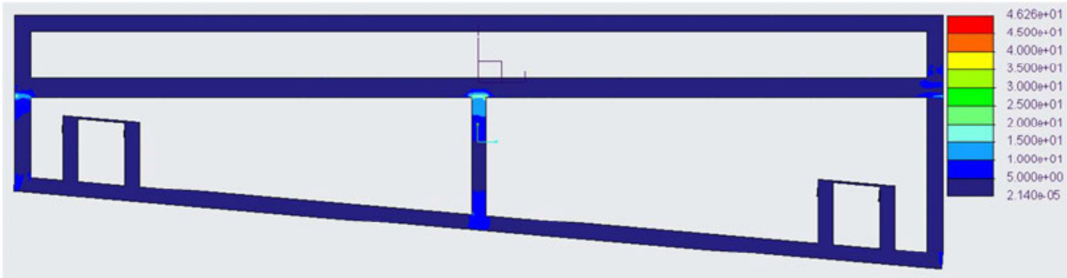

Figure 35. Apparatus FEA: 7 Membranes – Side View of Apparatus (Legend – MPa)

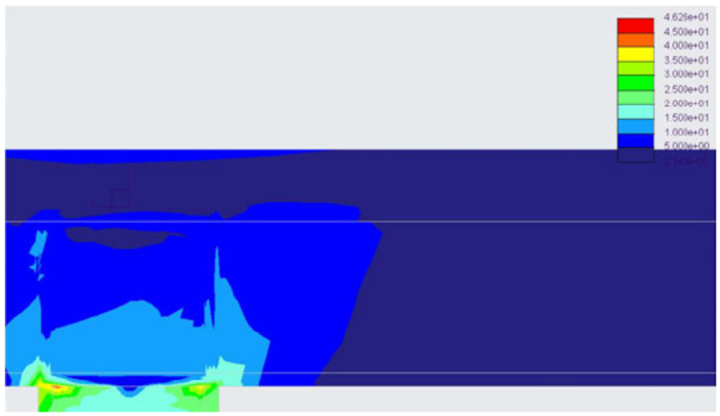

Figure 36. Apparatus FEA: 7 Membranes – Side View of Apparatus (Zoomed and Cut for Stress Concentration) (Legend – MPa)

Figure 37. Apparatus FEA: 7 Membranes – Front View of Wall Attachment (Legend – MPa)

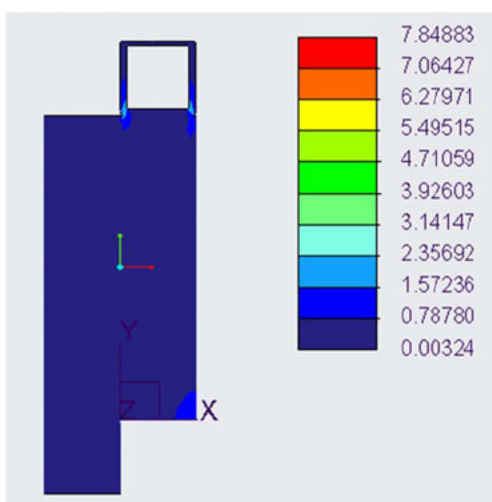

Figure 38. Apparatus FEA: 7 Membranes – Side View of Wall Attachment (Legend – MPa)

5.5.2.2 Removal of Membranes

The slide attachment of the holding/ catching apparatus was analysed under Von Mises stress analysis and the resultant stresses are presented in MPa. The slide had the equivalent force of one membrane placed upon it, which represents the process of removal as each membrane is individually expelled.

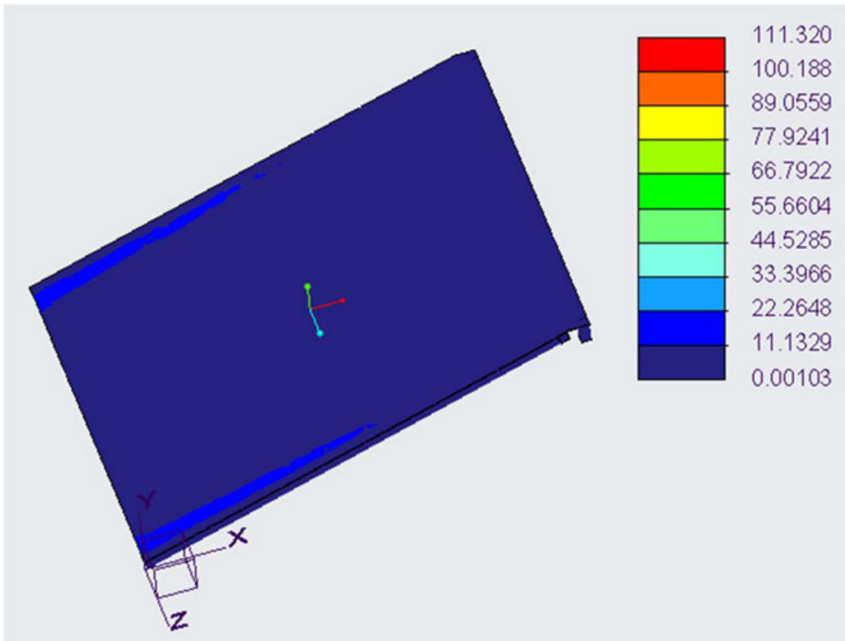

Figure 39. Apparatus FEA: 1 Membrane – Top View of Slide Attachment (Legend – MPa)

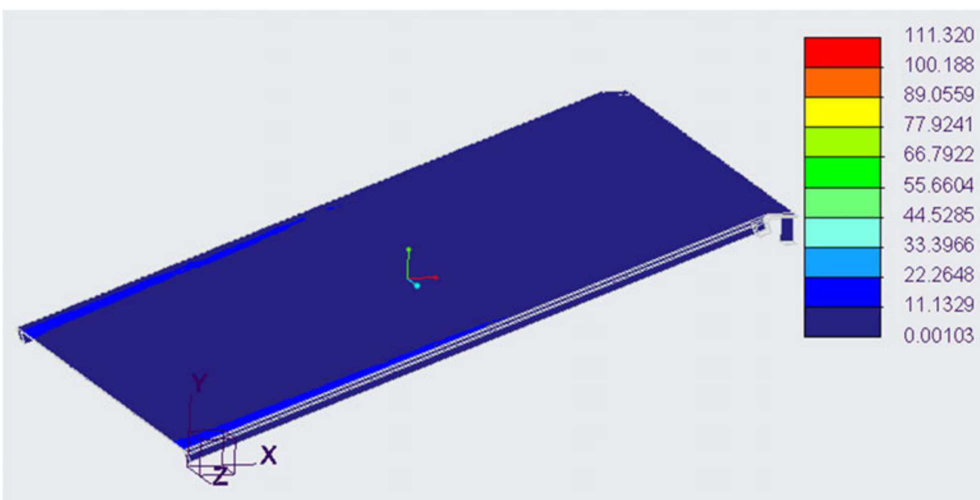

Figure 40. Apparatus FEA: 1 Membrane – Side View of Slide Attachment (Legend – MPa)

5.5.3 Pump Skid

The pump skid was analysed using a force applied upon the bottom surface equal to the weight of the pump, specified earlier. The force was spread upon a surface region of 445 mm by 173 mm, central to the skid. Von Mises stress analysis was used.

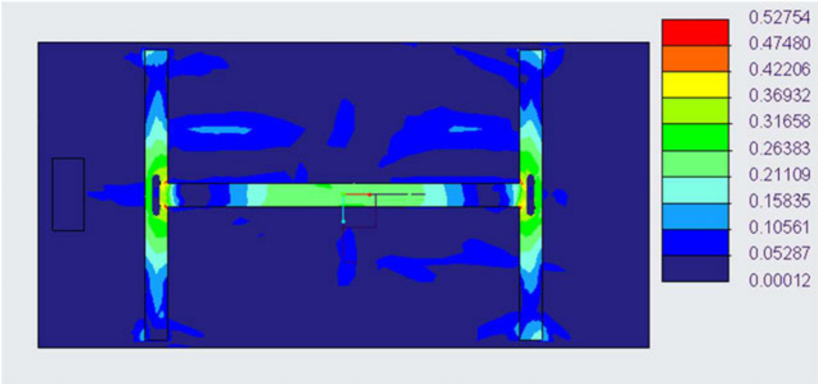

Figure 41. Pump Skid FEA: Weight of Pump – Top View (Legend – MPa)

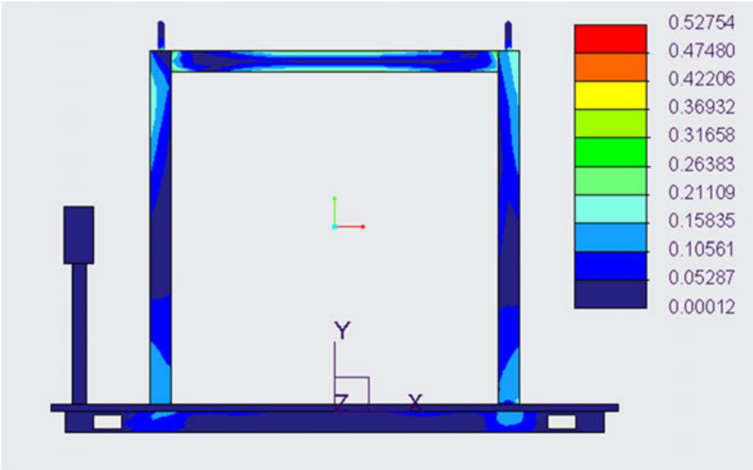

Figure 42. Pump Skid FEA: Weight of Pump – Side View (Legend – MPa)

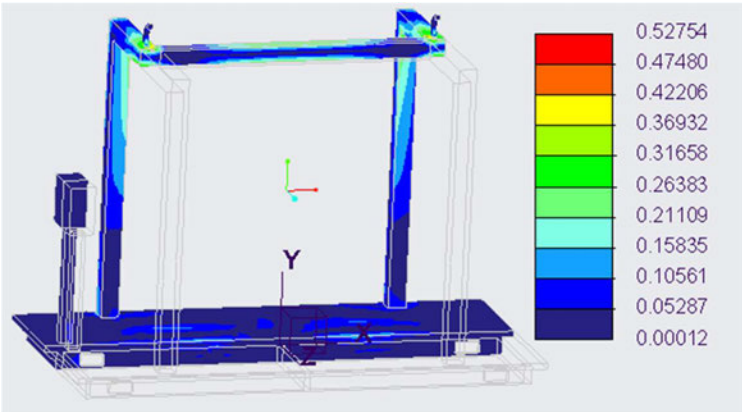

Figure 43. Pump Skid FEA: Weight of Pump – Side View (50% Cut) (Legend – MPa)

5.6 Selection, Feasibility and Discussion of Components

5.6.1 Membrane Removal Tool

The two concepts had differing maximum stress values experience by a factor of approximately ten. Concept #1 had a significantly lower maximum stress value than Concept #2. Where the two are made of the same material, the change in stress is purely due to the physical design of the concepts. In order to understand whether this change in stress values will play a significant role in the decision of the final components, the factor of safety for each is presented in below, while the relevant calculations can be seen in Appendix C1.

$$Factor\ of\ Safety_{Concept\ \#1} \approx 142$$

$$Factor\ of\ Safety_{Concept\ \#2} \approx 3$$

These factors are safety are significantly different, as would be expected from the difference in stress experienced. With a minimum safety factor of 3 though, there is no indication that the component needs to be chosen based purely on its reliability. The design for Concept #2, has an internal face that is much thinner and less supported than the internal face of the membrane removal tool. This face is the section with the pressure acting upon it and hence the change in stress is expected. Within Concept #1 there are two existing points of stress concentration, one of which is where the external face meets extruding components at the centre of the end cap. Another is at the edge of the end cap on the internal face. Concept #2 experiences stress upon the internal face distributed roughly as highest stress towards the centre, lowering towards the edges. This is expected as the centre of the internal face within this design is not supported, while thin walls surround the external radius. There are some fluctuations surrounding the holes which is to be expected. With both concepts being considered relatively safe, the benefits of Concept #2 start to become prominent. The increase in strength of Concept #1 is not reparation for its lack of ability to effectively drain the water from the vessel once the membranes are removed. Concept #2, with its ability to allow the water to both enter and expel the vessel is the most effective design.

5.6.2 Holding/ Catching Apparatus

Throughout each of the load sets applied to the holding/ catching apparatus, there is a large difference in maximum stress experienced by the component. While the stress values are low for the storage of seven membranes, one membrane rolling down the slide induced a significantly larger amount of stress. The recorded maximum stress is 111.3 MPa and the tensile yield strength of steel is 585 MPa (Engineering Toolbox, N.D). The factor of safety can be considered is displayed in below, the relevant calculations can be found in Appendix C2.

$$Factor\ of\ Safety\ \approx 5.2$$

When compared to each of the other analysed and discussed components this is a relatively low factor of safety. It can be seen that there is a stress concentration present within the FEA results. Using engineering judgement, it is possible that this concentration results from the constraint set of the component, rather than being an accurate representation of stress. Regardless of this issue, the slide could be further reinforced with the same steel bars used in the design and the plate steel could be increased in thickness with very minimal modification. The apparatus and the wall, used for holding up to seven membranes, experienced much lower stress values. This component is, hence, declared as viable for use in the process. The possible modifications carried out to the slide to increase the factor of safety are optional. Having a set of components of which the lowest factor of safety is 5.2 presents the positivity of the component's strength rather than the opposite.

5.6.3 Pump Skid

The maximum experienced stress within the pump skid resulted from the mass of the structure itself. This can be seen in the stress concentrations of the FEA figures. The factor of safety for this component is shown below, while the calculations are in Appendix C3.

$$Factor\ of\ Safety > 1000$$

The stress caused by the mass of the pump is minimal in comparison to the stress experienced by the beams. Attributed to self-weight, the stress could be decreased through using hollow bars. The stress concentration occurs at the joined beams that create the structure surrounding the pump. It should be noted that the points of stress concentration are relatively close to the hooks that assist in lifting with the overhead gantry crane. If the factor of safety wasn't as high as yielded through FEA this could be a cause of concern. However, this component is very obviously feasible in terms of its structural abilities. This combined with the efficiency of the forklift attachments and gantry hooks makes this component feasible overall.

6. Membrane Replacement Methodology

In order for the new components to have the benefits of the reduction in manual handling, the process of how they are used must be explained. During the operation, if the operators are not aware of the changes through a concise methodology, there may be no benefit from the design of the components.

6.1 Component Preparation

6.1.1 Membrane Removal Tool

To prepare this component after manufacture, there are minor components which need to be incorporated into the design. The hole used for water insertion must be fitted with an appropriately sized flange for connection to a pipe. This is required as the pipe would be permanently fixed to the pump skid and allowing disconnection from the pump skid and the membrane removal tool would be beneficial for both storage and maintenance purposes. Also attached to the membrane removal tool, a pressure indicator would prove beneficial in allowing the operator to monitor and adjust the pressure within the vessel. The adjustment would be carried out through an attached ball valve with a small rotating handle. This is necessary as within the replacement methodology the operator would be instructed to adjust the pressure within the vessel.

6.1.2 Pump Skid

To prepare this component, subsequent to manufacture, there are some key components which need to be included. Pipes from both, the source of the water and to the membrane removal tool are required. These will be permanent fixtures to the pump and stored within the pump skid. The water will be sourced from an existing pipe vent that is usually closed with a blank flange.

6.2 Replacement Methodology Calculations

Each component was tested using a maximum pressure of 25 kPa. However, this value can be significantly reduced once motion has begun and may never be reached to initiate motion. In order to calculate the pressure required once motion has begun an appropriate pressure will be decided for each number of membranes, except the final membrane, which will be manually removed. An ideal time to expel all but the last membrane would be 10 seconds. The ideal acceleration and corresponding pressures required are presented in Table 11. The calculations for each are presented in Appendix D1.

Ideal Acceleration	0.1402 m/s^2
Pressure to Move Seven Membranes	0.460 kPa
Pressure to Move Six Membranes	0.394 kPa
Pressure to Move Five Membranes	0.329 kPa
Pressure to Move Four Membranes	0.263 kPa
Pressure to Move Three Membranes	0.197 kPa
Pressure to Move Two Membranes	0.131 kPa

Table 11. Pressure Required for Replacement Key Values

The drainage of the water can be calculated through an equation which takes in to account the specifications of the vessel and the drainage holes (Hayward, N.D). The time taken is calculated to provide benefit for both the membrane replacement methodology as well as the financial analysis. The true time taken may differ slightly and within the membrane replacement strategy, operators will be instructed to use their discretion. This is also true for the pressure required to move the membranes, where physical testing could not be carried out. The advice given will include never exceeding the tested 25 kPa. Other advice will be to swiftly decrease the pressure once motion has begun and increase the pressure upon the membranes in the case of the expulsion exceeding 10 seconds. The time taken to drain the water from the vessel can be seen below, while the calculations are in Appendix D2.

$$Time\ to\ Drain = \ 4.52\ Minutes$$

6.3 Updated Membrane Removal Methodology

The updated process will be formatted in a similar format to the existing methodology produce by Veolia Water. Numbered steps will be listed with enough detail so as to not cause unnecessary confusion.

6.3.1 Stage One Removal

1. Using a forklift, relocate the pump skid from where it resides to the insertion side of the train of which the membranes are being replaced. Place the bin used for the discarding of the membranes on the removal side of the vessels. Use the forklift to collect the holding/ catching apparatus and accompanying attachments. Be sure to collect the apparatus so that the tilt goes down, away from the driver's seat of the forklift. Locate the forklift on the removal side of the train.

2. Collect the membrane removal tool and connect the pipe, attached to the pump, to the relevant connection on the membrane removal tool. Collect the membrane blank. Ensure the operating lever on the membrane removal tool is pushed to the "Water In" Position.

3. Remove end cap assemblies and thrust cones from all pressure vessels in the train, on both upstream and downstream ends. Carefully disconnect the permeate pipework at the downstream end of the vessels. Store the end cap assemblies in a clean and dry place.

4. Ensure one operator is on the removal end of the vessels, operating the forklift and one operator is on the insertion side to operate the membrane removal tool.

5. Starting from the bottom of the train and using the holding/ catching apparatus with the wall attachment, use the forklift to line up the apparatus with the first vessel. Line up the apparatus so that the elevated end of the apparatus is aligned with the edge of the vessel.

6. Attach the membrane blank to the membrane and membrane removal tool to the vessel as an end cap is attached, using the existing end cap clamps. Ensure communication is clear between the two operators when the process is going to start.

7. Turn on the pump and open the valve slowly, monitoring the attached pressure indicator, aiming for approximately 16 kPa and ensuring the pressure within the vessel does not exceed 25 kPa. Once motion has begun, begin to close the valve.

8. As motion begins close the valve to reduce the pressure to approximately 0.5 kPa. Continue to slowly close the valve as membranes are expelled. The operator of the forklift must indicate when the seventh membrane is half removed from the vessel.

9. If the membranes are taking significantly longer than ten seconds to expel from the vessel, increase the pressure accordingly.

10. At this point, turn off the pump and operate the membrane removal tool's lever to the "Water Out" position. Allow approximately 5 minutes for the water to drain from the vessel.

11. Once the water has drained from the vessel, manually move the final membrane so that it is completely on to the holding/ catching apparatus. Now use the forklift to locate the apparatus over the edge of the bin being used. Manually remove the wall attachment so that the membranes roll into the bin.

12. Once a vessel has its membranes expelled, loosely reattach the end caps to the vessel. This is to allow for the water to continue draining through the ports and not leak externally.

13. Repeat this process for each vessel until the vessel's height exceeds the height of the bin. At this point begin to use the slide attachment and locate the middle of the apparatus in line with the vessel and the slide attachment over the bin. Now as the membranes are expelled, they will automatically roll to the bin.

6.3.2 Stage One Replacement

1. Ensure that the forklift and the holding/ catching apparatus are located at the insertion end of the vessels. Elevate the apparatus, using the forklift, to the most comfortable height for loading the membranes.

2. Ensure the wall attachment is attached to the apparatus. Both operators can assist each other in loading seven membranes upon the apparatus.

3. Operate the forklift and lower the apparatus so that the membrane on the lower end of the tilt is lined up with the vessel.

4. Ensure that the technician is ready to begin recording the serial numbers as they are inserted. Also allow the technician to order the membranes if necessary, in order to get ahead and record each serial number in ample time.

5. Remove the loosely attached end caps from the vessels and store in a clean and dry place.

6. Begin to manually push each membrane in to the vessel. Insert the relevant membrane links between each membrane as they are inserted. At this point both operators can remain on the insertion side of the vessels and assist in the insertion.

7. Carry this process out for each vessel, until the four bottom rows all have new membranes replaced. At this point, contact the relevant contractors to install scaffolding at the relevant height for the final four rows of vessels.

8. Continue the process and once all membranes have been inserted begin to reinstall all end cap and thrust cone assemblies.

9. Once this process is complete, return the pump skid and components using the necessary forklift assistance to their standby residence.

6.3.3 Stage Two/ Three Removal

1. Contact the relevant contractors to install scaffolding at the relevant height for either stage two or three vessels. Scaffolding will be required on either side of the vessels for these stages.

2. Using a forklift, locate the pump skid to the insertion side of the train of which the membranes are being replaced. Place the bin used for the discarding of the membranes on the removal side of the vessels. Use the forklift to collect the holding/ catching apparatus and accompanying attachments.

3. Attach the holding/ catching apparatus to the gantry on the removal side of the vessels.

4. Collect the membrane removal tool and connect the pipe, attached to the pump, to the relevant connection on the membrane removal tool. Collect the membrane blank. Ensure the operating lever on the membrane removal tool is pushed to the "Water In" Position. Ensure the operating valve is closed prior to use.

5. With one operator on the scaffolding on each side of the vessels, remove end cap assemblies and thrust cones from all pressure vessels in the train, on both upstream and downstream ends. Carefully disconnect the permeate pipework at the downstream end of the vessels. Store the end cap assemblies in a clean and dry place.

6. Ensure the operator on the removal end of the vessels, is operating the overhead gantry and line up with the first vessel of which the membranes will be removed. Ensure the holding/ catching apparatus has the wall attachment connected.

7. Attach the membrane blank to the membrane and membrane removal tool to the vessel as an end cap is attached, using the existing end cap clamps. Ensure communication is clear between the two operators when the process is going to start.

8. Turn on the pump and open the valve slowly, monitoring the attached pressure indicator, aiming for approximately 16 kPa and ensuring the pressure within the vessel does not exceed 25 kPa. Once motion has begun, begin to close the valve.
9. As motion begins close the valve to reduce the pressure to approximately 0.5 kPa. Continue to slowly close the valve as membranes are expelled. The operator of the expulsion side must indicate when the seventh membrane is half removed from the vessel.

10. If the membranes are taking significantly longer than ten seconds to expel from the vessel, increase the pressure accordingly.

11. At this point, turn off the pump and operate the membrane removal tool's lever to the "Water Out" position. Allow approximately 5 minutes for the water to drain from the vessel.

12. Once the water has drained from the vessel, manually move the final membrane so that it is completely on to the holding/ catching apparatus. Now use the overhead gantry to locate the apparatus over the edge of the bin being used. Now an operator on the ground floor can manually remove the wall attachment so that the membranes roll into the bin.

13. Once a vessel has its membranes expelled, loosely reattach the end caps to the vessel. This is to allow for the water to continue draining through the ports and not leak.

14. Repeat this process for each vessel.

6.3.4 Stage Two/ Three Replacement

1. Ensure that the holding/ catching apparatus is located at the insertion end of the vessels, using the overhead gantry. Elevate the apparatus, to the most comfortable height for loading the membranes.

2. Ensure the wall attachment is attached to the apparatus. The operator on the ground floor can begin loading seven membranes upon the apparatus.

3. Using the overhead gantry crane, raise the membranes to the height of the first vessel.

4. Ensure that the technician is ready to begin recording the serial numbers as they are inserted. Also allow the technician to order the membranes if necessary, in order to get ahead and record each serial number in ample time.

5. Remove the loosely attached end caps from the vessels and store in a clean and dry place.

6. Begin to manually push each membrane in to the vessel. Insert the relevant membrane links between each membrane as they are inserted.

7. Carry this process out for each vessel, adjusting the positioning of the apparatus to the relevant height of the vessel of focus.

8. Continue the process and once all membranes have been inserted begin to reinstall all end cap and thrust cone assemblies.

9. Once this process is complete, return the pump skid and components using the necessary forklift assistance to their standby residence.

7. Membrane Replacement Philosophy

7.1 Key Parameters for Membrane Replacement

There are three key parameters for membrane replacement that are viewed by the technical experts at Veolia Water. These three parameters are normalised in order to interpret the data without anomalies occurring due to changes in external parameters such as temperature. They are average specific flux, average salt passage and average differential pressure across the vessel. As these key pieces of data change over time, the need for membrane replacement increases.

In order to analyse this data across different stages, a large amount of data for all stages and trains has been interpreted. Including all trains and stages, a number of parameters and recordings were sourced from the process engineer present at the site. This data spans from 01/07/2017 to 30/03/2020 and includes multiple membrane replacements. In order to analyse each stage a range of data will be selected that can accurately represent the life span of the membranes within that stage. The data is recorded daily, with some dates which lack any recordings.

7.2 Visualising Data

The data presented in Figures 44, 45 and 46 are based upon the daily recordings of the key parameters. The data used spans from July 2017 until April 2020 and provides typical representation of membrane's life cycle, where stage one and three are prior to a replacement and stage two represents conditions over time, since there are no recorded replacements. These data sets can be viewed in Appendix F1, F2 and F3.

7.2.1 Average Normalised Specific Flux

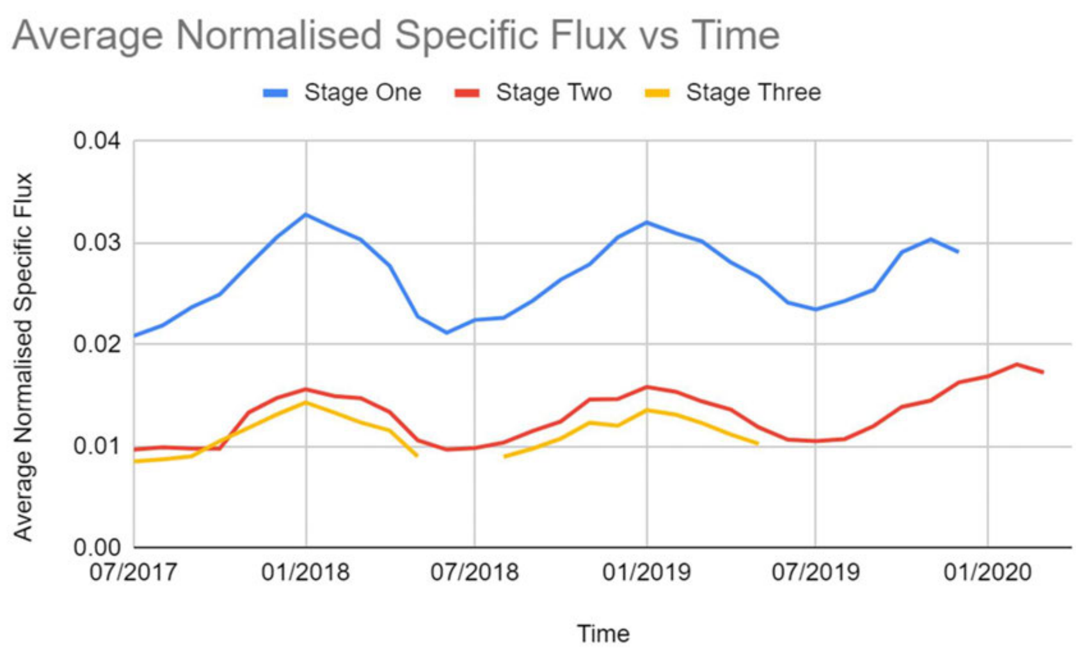

Figure 44. Average Normalised Specific Flux against Time

The specific flux both fluctuates over time and gradually increases as presented in Figure 44. Stage one has significantly larger values, as the flow rate and amount of water produced is significantly larger. It is important to note that where there was no data recorded for a whole month, the value is simply ignored and not displayed within the graph. Although the values are normalized for comparison, the fluctuation follows a seasonal pattern. It would be logical to assume that the change in environmental factors such as temperature and humidity may be causing this. Where temperatures are generally higher, the specific flux also increases. With this set of data, it is clear that the increase does not have to be of a significant scale for a membrane replacement to be carried out.

7.2.2 Average Normalised Salt Passage

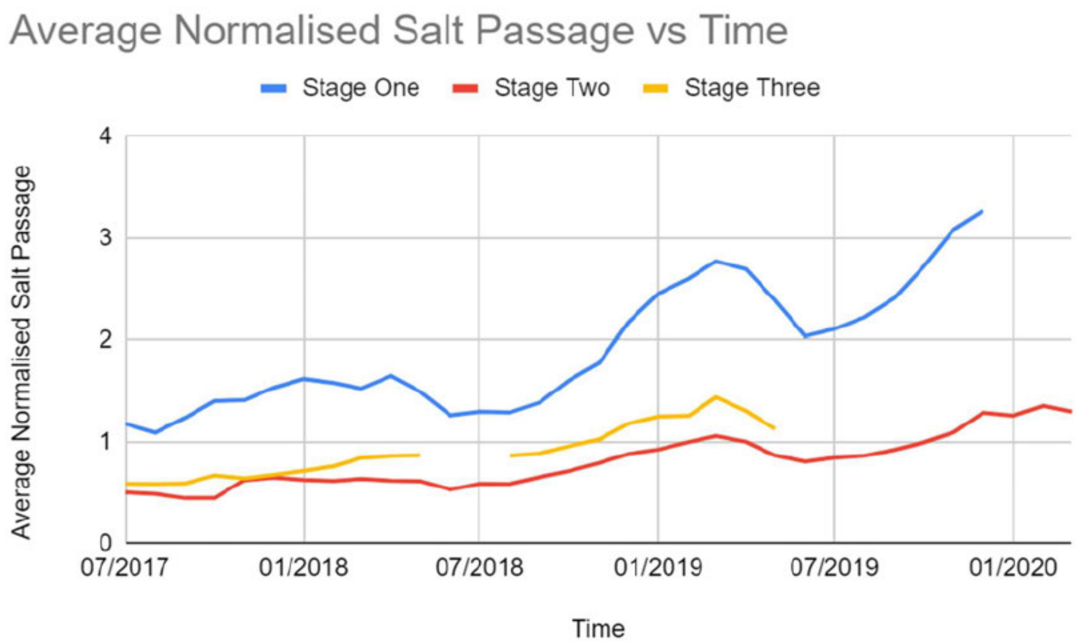

Figure 45. Average Normalised Salt Passage against Time

As compared to the specific flux, the difference between stage one and the other stages is not as significant but still exists as shown in Figure 45 The increase of salt passage can be seen clearly, although there are fluctuations within the data. The larger fluctuations can be attributed to seasonal environmental factors, however there are smaller fluctuations that occur out of pattern. These fluctuations can be attributed to the regained performance from the clean-in-place procedures. For this key parameter, there is a visible increase in salt passage. Hence a specific value of increase can be pinpointed, indicating a necessary membrane replacement.

7.2.3 Average Normalised Differential Pressure

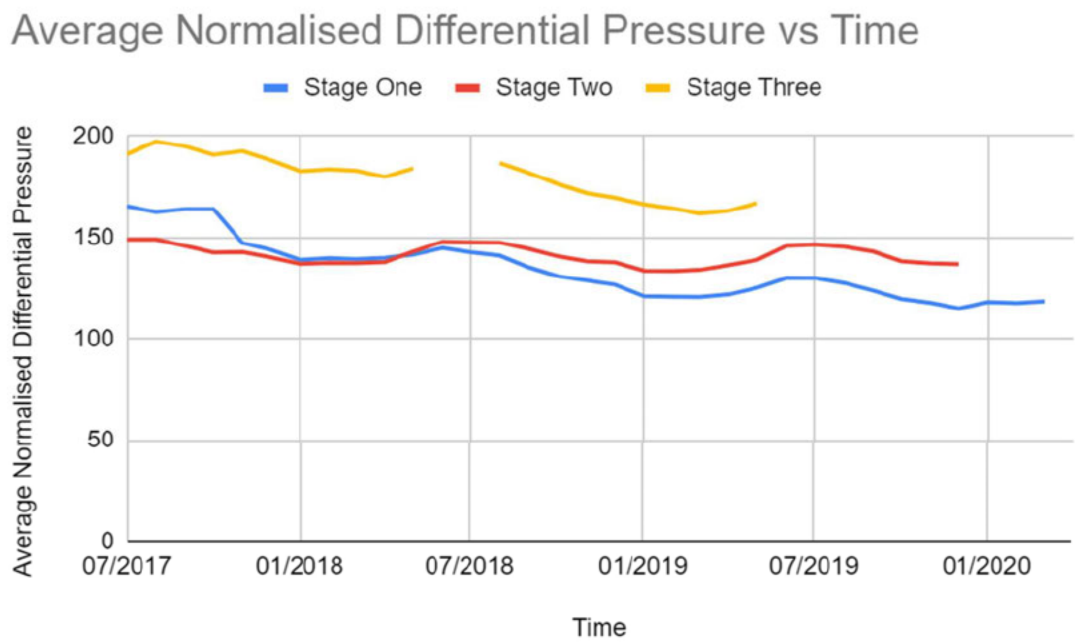

Figure 46. Average Normalised Differential Pressure against Time

Compared to the data presented for the other key parameter, the average normalised differential pressure is opposite in most ways. In this set of data stage three has the largest values, as this stage is operated under the highest pressure, as represented in Figure 46. Following this stage one and two are similar but stage two has larger values for the majority of the data. The fluctuations present within the other key parameters are not as apparent but still exist on a smaller scale. The values decrease over time, and since the fluctuations are not as significant, the indication for membrane replacement can be interpreted visually.

7.3 Replacement Indicators

7.3.1 Overview

The indicators for membrane replacement are based off of four main parameters: specific flux, salt passage, differential pressure and the design life of the membranes. With water quality being assessed and Veolia Water being held to Treated Water Compliance, salt passage will be the main factor as a replacement indicator, alongside membrane life. In order to formulate a strategy for membrane replacement, these parameters will be split in to three different categories of criticality. These categories will be labelled as: in working order, in need of attention and in need of urgent attention. Each parameter will have its own criteria to reach these categories. None of these categories necessarily indicate that a membrane replacement needs to be carried out as a matter of emergency but rather to indicate that a discussion is needed. With anomalies in usage and fluctuations in conditions it is unrealistic, in practise, to purely base the replacement on values without discussion and analysis. The relevant stakeholders, such as process engineers and managers can engage discussions based on these categories of criticality.

7.3.2 Selection of Indication Values

Through maximum and minimum values present for each stage, suitable values can be selected for salt passage criticality. An example of the data for each stage can be seen in Appendix F1, F2 and F3. At a suitable value, weighted towards the maximum recorded value, the parameter will indicate that attention is needed. As the data further approaches the minimum values recorded, the criticality for that parameter will be indicate that urgent attention is needed.

For stage 1, each of the parameters are shown with their relevant criticalities in Table 12.

Salt Passage: In Working Order	**<3%**	
Salt Passage: In Need of Attention	**>3%**	
Salt Passage: In Urgent Need of Attention	**>3.30%**	

Table 12. Salt Passage – Replacement Indication Values (Stage 1)

For stage 2, each of the parameters are shown with their relevant criticalities in Table 13.

Salt Passage: In Working Order	**<1.3%**	
Salt Passage: In Need of Attention	**>1.3%**	
Salt Passage: In Urgent Need of Attention	**>1.4%**	

Table 13. Salt Passage – Replacement Indication Values (Stage 2)

For stage 3, each of the parameters are shown with their relevant criticalities in Table 14.

Salt Passage: In Working Order	**<1.3%**	
Salt Passage: In Need of Attention	**>1.3%**	
Salt Passage: In Urgent Need of Attention	**>1.4%**	

Table 14. Salt Passage – Replacement Indication Values (Stage 3)

The membranes are designed to the same design life and hence the criticality across the stages does not differ. The criticality categories for membrane life is represented in Table 15.

Membrane Life: In Working Order	**>5 Years**	
Membrane Life: In Need of Attention	**>5 Years**	
Membrane Life: In Urgent Need of Attention	**>6 Years**	

Table 15. Membrane Life – Replacement Indication Values

7.4 Membrane Replacement Philosophy

The replacement of membranes should not follow a pattern based purely upon time. If the conditions were more consistent, the average time taken for key parameters to reach a certain point could be used as a replacement indicator. The conditions in practise fluctuate largely to the point which makes basing the replacement upon an average time impractical. Instead parameters are used, salt passage and membrane life. Incorporating membrane life into the considerations for membrane replacement allows for time to be a factor without impractically indicating unnecessary replacements. Salt passage is a key parameter that allows for the quality of the membrane itself to be measured, however, an inference can also be made into the quality of water from this parameter.

These two parameters are the main indicators that a membrane replacement needs to be discussed. Each has its own criteria that represents the level of importance of this discussion. As the conditions worsen, the relevant stakeholders can further prioritise the discussion. The three categories, dependent upon the criteria, are in working order, in need of attention and in urgent need of attention. Technical discussion can result in the overall importance of the parameters. For example, if the membranes of a certain stage approach their design life and become in need of attention but the conditions aren't worsening, the overall categorisation can be labelled as in working order until salt passage also indicates attention is needed.

7.5 Automation of Membrane Replacement Philosophy

Utilising a web and mobile resource, Smartsheet, the relevant stakeholders can be notified of the state of the relevant key parameters automatically. Within this application, currently used by Veolia Water, each train would have its own sheet that is stored in a cloud database. With a similar interface to excel the data could be set up in row and column form. With daily recordings of data, the first column would be the automatic recording of dates. A column for the salt passage would be set up for each stage within the relevant train. For membrane life, the date of last replacement would be manually recorded while a secondary column would formulate the number of days since replacement. From these columns, the relevant workflow can be generated in order to notify the relevant stakeholders. The automated workflow is presented in Figure 47 a and b, the workflow continues from the bottom of Figure 47 a to the top of Figure 47 b.

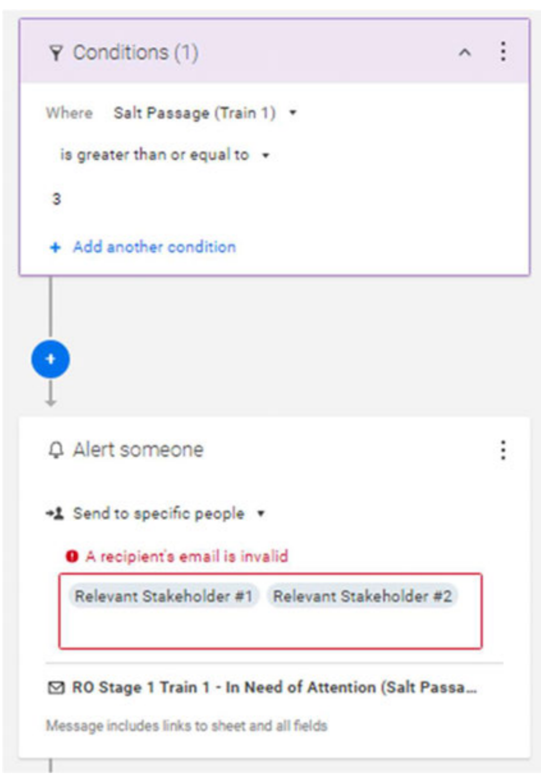

Figure 47 a. Automated Indication Workflow 1

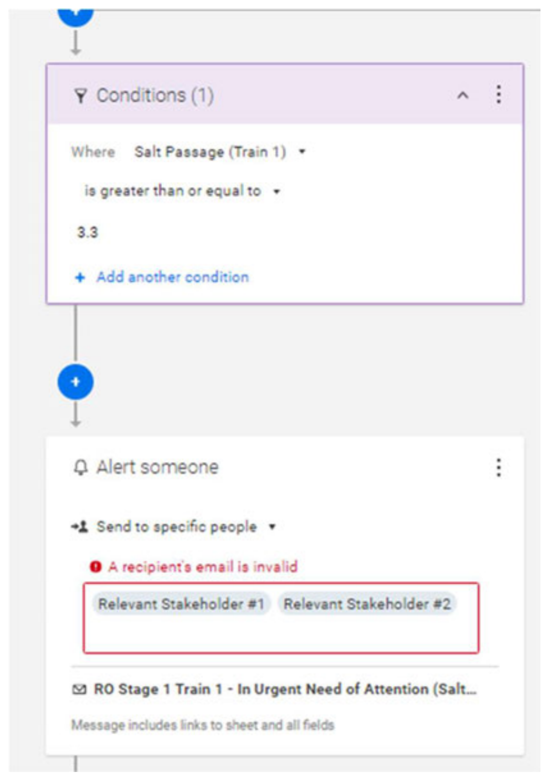

Figure 47 b. Automated Indication Workflow 2

The presented example is representative of the workflow set up for train one, stage one and specifically refers to salt passage. Within this workflow, the conditions can be seen to be set at greater than or equal to the values specified in Table 12. Utilising the same methodology, a similar workflow could be created for salt passage and membrane life for each stage. As can be seen, an initial email is sent specifying the category, in need of attention, when the relevant value is exceeded. Following this, a secondary email is sent representing that urgent attention is needed when the relevant value for this category is exceeded. This workflow would be applied to all five documents, used to represent each train.

This process well integrates with the existing process for the philosophy surrounding membrane replacement. Rather than basing the replacement purely on parameters and values, the deciding factor is discussion between the technical experts regarding reverse osmosis. This addition of specific parameters and automated workflows allows discussion to be initiated upon the basis of more structure than the existing philosophy. The automated workflow decreases the possibility that a concerning outcome goes unnoticed.

8. Financial Analysis

8.1 Historical Financial Data

For historical data of the financial repercussions of the membrane replacement process two complete stage one and two stage three complete membrane replacement procedures were sourced. Stage two membrane replacement data could not be sourced, however the largest number of vessels are present in stage one and the least in stage three. It is fortunate then, that these two stages had financial information available as they represent each extreme of a number of parameters including the number of vessels and height.

8.1.1 Stage One Replacement

The first set of financial data was recorded as a singular entry to the database of work orders, while the second was split between removing and inserting the membranes. The difference in the second was purely down to the bookkeeping method used, as the physical process was simultaneous. Within each set of data, the costs are split between two categories, the first of which is the cost of labour, which represents the amount of money spent on the hourly rates of the operators carrying out the process. The second is the cost of labour hire, which represents the amount spent on contractors to carry out tasks, such as scaffolding around the vessels.

Work Order Number/s:		*WO1005181566*	
Scheduled Start Date:		*29/11/2018*	
	Labour (Internal Employees)	**Labour Hire (External Employees)**	**Total**
Cost	$ 9,130.00	$ 3,366.00	$ 12,496.00

Table 16. Financial Data: WO1005181566 (Stage One Replacement)

Work Order Number/s:		*WO1005454475 / WO1005430563*	
Scheduled Start Date:		*04/01/2020*	
	Labour (Internal Employees)	**Labour Hire (External Employees)**	**Total**
Cost (Removal)	$ 495.00	$ 4,860.00	$ 5,355.00
Cost (Insertion)	$ 11,660.00	$ -	$ 11,660.00
Cost (Total)	$ 12,155.00	$4,860.00	$17,015.00

Table 17. Financial Data: WO1005454475 / WO1005430563 (Stage One Replacement)

8.1.2 Stage Three Replacement

The first set of financial data was recorded in two sections, the removal and insertion of the membranes. The removal of the membranes was used to document the cost of the internal labour while the insertion was used to record the external labour hire. As each work order has only cost assigned to it, these can be combined. The second replacement was recorded as a singular entry.

Work Order Number/s:		*WO1004902741/WO1004902739*	
Scheduled Start Date:		*15/11/2018*	
	Labour (Internal Employees)	**Labour Hire (External Employees)**	**Total**
Cost	$ 3,025.00	$ 3,870.50	$ 6,895.50

Table 18. Financial Data: WO1004902741/WO1004902739 (Stage Three Replacement)

Work Order Number/s:		*WO1005181566*	
Scheduled Start Date:		*24/04/19*	
	Labour (Internal Employees)	**Labour Hire (External Employees)**	**Total**
Cost	$ 3,795	$ 4,511.25	$ 8,306.25

Table 19. Financial Data: WO1005181566 (Stage Three Replacement)

8.2 Breakdown of Historical Data

The costs that are recorded in the database and presented in the previous section can be based upon estimates of cost and there is room for error. In order to produce values that can be used for a comparison between the costs of a newly designed process and the existing process a breakdown can be carried out. Using a combination of empirical data for the number of employees and time taken, as well as the recorded total costs, standard costs can be created. The base values that will be used for comparison are the number of operators for each stage, the cost of an internal operator, the hours of operation for each stage and the cost of scaffolding for each stage.

8.2.1 Cost per Hour for Internal Operators

From empirical data, it is known that six operators were used for the stage one membrane replacement (WO1005454475 / WO1005430563) over three, eight hour, days of operations. This can be used to find a cost per hour for internal operators.

$$Cost\ of\ Internal\ Labour = Cost_{Labour} = \$\,12{,}155$$

$$Number\ of\ Operators = N_{Operators} = 6$$

$$Hours\ of\ Operation = T_{Operation} = 24$$

Therefore:

$$\frac{Cost\ (\$)}{Hour} = \frac{Cost_{Labour}}{N_{Operators} \times T_{Operation}}$$

$$\frac{Cost\ (\$)}{Hour} \approx \$85/Hour$$

8.2.2 Hours of Operation

A combination of the empirical data known for the stage one membrane replacement (WO1005454475 / WO1005430563) and the number of vessels in each stage can be used to calculate the number of hours for stage two and three. A ratio of the time taken for each stage and the number of vessels will yield an approximation for this. The results are presented in Table 20 and the calculations can be seen in Appendix E1.

Number of Vessels: Stage 1	72
Number of Vessels: Stage 2	45
Number of Vessels: Stage 3	22
Hours of Operation: Stage 1	24
Hours of Operation: Stage 2	15
Hours of Operation: Stage 3	7.33

Table 20. Number of Vessels and Hours of Operation

Each stage will be approximated to take a decreasing number of hours in 8 hour intervals. Stage one requires 24 hours of operation, stage two requires 16 hours of operation and stage three requires eight hours of operation.

8.2.3 Number of Operators per Stage

The data estimated so far can be used in combination in order to calculate the number of operators for each stage. Stage one is a known number, six, and the total cost of labour for stage three replacements will be used in order to calculate the operators required for that process. With the limited data available for stage two, an assumption will be made that the same number of operators are required as stage two. This follows the logic that stage one can differ due to the availability of ground level work in unison with the work taking place upon the scaffolding. Meanwhile, stage two and three operations take place at heights not reachable from the ground level, indicating that the same number of operators will be required. The calculated number of operators is presented in Table 21, while the calculations can be found in Appendix E2.

Cost per Hour	$85
Hours of Operation: Stage 1	24
Hours of Operation: Stage 3	8
Number of Operators: Stage 1	6
Number of Operators: Stage 2	3
Number of Operators: Stage 3	3

Table 21. Hours of Operation and Number of Operators

In the case of the first stage membrane process, there were two operators on either side of the vessels handling the membranes in direct contact with the vessels. At the same time there was a third operator on each side handling the membranes from the ground to the operators for insertion or vice versa on the expulsion side. It can be assumed in the case of stage two and three there would be an operator elevated on scaffolding either side of the vessels while one operator was on the ground level handling the membranes for elevation or vice versa for expulsion.

8.2.4 Scaffolding Costs

From the work orders recorded as historical financial data, the averages of the scaffolding costs can be calculated. This will produce the estimated cost of scaffolding for both stage one and three. If these values are within 10% of each other, the average cost will be calculated and assumed to be equal for each stage. If the values differ significantly, then interpolation will be used to calculate a cost for the scaffolding required for stage two. The percentage difference and corresponding costs of scaffolding are listed in Table 22, the calculations are presented in Appendix E3.

Empirical Scaffolding Cost: Stage 1	$ 4113
Empirical Scaffolding Cost: Stage 3	$ 4190
Percentage Difference: Stage 1 & 3	1.87%
Theoretical Cost of Scaffolding	$ 4150.50

Table 22. Scaffolding Costs

8.2.5 Cost of Operation per Stage

These base values can now be combined into a general equation that can be used to calculate an estimated total cost of a replacement for each stage. Using a general equation will allow for more accurate comparison due to the same base values being used. This removes the need for completely relying on the recorded financial data. One factor missing from the general equation is the cost of a technician, whose duty is to record the serial numbers of each membrane. The membranes must be recorded in a spreadsheet matching the physical location in the vessels. Since the cost would be equally added to each stage, it can be ignored for the total cost calculations, which can be seen in Appendix E4. The results, as produced using the general equation, are shown in Table 23. It is important to note that the internal operators who are on site are paid regardless of the task that they are carrying out. Allocating the cost and time directly to the task, however, allows for analysis of the reduced number of hours that are spent on this process and can be used elsewhere on site.

$$Total\ Cost = \left(T \times N_{Operators} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

Historical Cost: Stage 1	\$ 16391.50
Historical Cost: Stage 2	\$ 8231.50
Historical Cost: Stage 3	\$ 6191.50

Table 23. Historical Cost per Stage

8.3 Breakdown of Updated Process

8.3.1 Updated Number of Operators per Stage

For the new replacement strategy, each stage requires less operators, however the number still differs per stage. For stage one, an operator is required for each side of the vessels. For stage two and three, there is one more operator required. This ensures that there is one operator present on the scaffolding, either side of the vessels and an operator on the ground floor. The operator on the ground floor handles the membranes and controls the overhead gantry. The final numbers incorporated in to the updated strategy are shown in Table 24.

Number of Operators: Stage 1	2
Number of Operators: Stage 2	3
Number of Operators: Stage 3	3

Table 24. Updated Number of Operators

8.3.2 Updated Hours of Operation

The number of hours spent on each stage for the membrane replacement operation can be calculated using a general equation. First, the calculation of the time per vessel is calculated using a combination of estimations and prior calculations. The results for each vessel are in Table 25, while Appendix E5 contains the calculations.

Time to Attach/ Remove End Caps	1 Minute
Time to Attach/ Remove Membrane Removal Tool	1 Minute
Number of Operators: Stage 3	1 Minute
Time to Expel Membranes	0.333 Minutes
Time to Drain Water	5 Minutes
Time to Dispose of Membranes – Slide Attachment	0 Minutes
Time to Dispose of Membranes – Wall Attachment	0.5 Minutes
Time for Gantry Crane Travel	5 Minutes
Time per Vessel: Stage 1	7.583 Minutes
Time per Vessel: Stage 2 & 3	12.83 Minutes

Table 25. Time for Individual Processes

From these values, the number of hours per stage can be calculated. There must also be considerations of both preparation before the operation and the clean up afterwards. The time allotted for these processes as well as the total times per stage are displayed in Table 26. The calculations can be found in Appendix E6.

Time for Preparation	0.5 Hours
Time for Clean-Up	0.5 Hours
Total Time of Process: Stage 1	10.1 Hours
Total Time of Process: Stage 2	10.63 Hours
Total Time of Process: Stage 3	5.71 Hours

Table 26. Updated Hours of Operation

8.3.3 Updated Cost of Operation per Stage

The financial implications per stage is calculated using the same general equation that was used to estimate the historical costs. The calculations for this can be found in Appendix E7, while the values are presented in Table 27.

Updated Strategy Cost: Stage 1	$ 5868.50
Updated Strategy Cost: Stage 2	$ 6862.15
Updated Strategy Cost: Stage 3	$ 5607.55

Table 27. Updated Cost of Operation

8.4 Comparison of Financial Implications

The financial implications do not need to be significantly lowered for the project to be feasible in practical applications. Where the financial implications of the updated strategy is roughly the same as historical implications, the benefit of the reduction of manual handling is amplified. If there is a lower cost for the updated process, there is only further benefit for the company, the historical and updated costs can be seen in Table 28.

Historical Cost: Stage 1	$ 16391.50
Historical Cost: Stage 2	$ 8231.50
Historical Cost: Stage 3	$ 6191.50
Updated Strategy Cost: Stage 1	$ 5868.50
Updated Strategy Cost: Stage 2	$ 6862.15
Updated Strategy Cost: Stage 3	$ 5607.55

Table 28. All Costs of Operation

The percentage differences for each stage can be calculated using a general equation. The percentage of money saved is presented in Table 29.

$$Savings_{\%} = \frac{Total\ Cost_{Updated} - Total\ Cost_{Historical}}{Total\ Cost_{Historical}} \times 100$$

	Stage 1	Stage 2	Stage 3	Train (Total)
Historical Financial Implication	$ 16391.50	$ 8231.50	$ 6191.50	$ 30,814.50
Updated Financial Implication	$ 5868.50	$ 6862.15	$ 5607.55	$ 18,338.20
Percentage Saved	**64.20%**	**16.64%**	**9.43%**	**40.48%**

Table 29. Compared Costs of Operation

Each stage has less financial implication than the historical strategies of membrane replacement. Stage one has the most significant savings, with less than half of the financial implications of the average existing process for this stage. The large savings from in this stage can be attributed to both half the amount of scaffolding being used and a lower number of operators. With the preparation of scaffolding being a significant constant amount, halving this provides large benefit. Secondarily, lowering the number of operators and the number of hours those operators are working on the replacement process was bound to produce large savings.

Stage two and three have lesser savings, however this is not a negative outcome. Where the manual handling is reduced without larger financial implications there is no concern. The reason the savings within stage one and two are not lowered by as much is attributed to the cost of scaffolding. With these stages residing at much more significant heights than stage one, scaffolding is required for each side for safety purposes. The time taken is reduced, but not as significantly as stage one. The cause of this is the time it may take to safely operate the overhead gantry crane and the travel time for raising and lowering the membranes as necessary.

The overall savings for a full train of membrane replacement results in approximately 40% savings. This is attributed mostly to the significant savings mentioned in stage one. Had stage two and three suffered from impacting the financial aspect of the process negatively, this percentage of savings would not have been as impressive. From all perspectives pertaining to the financial analysis, this process is feasible and worth implementing in to practise.

9. Conclusion and Further Works

9.1 Conclusion

The works of this project have proven that the reverse osmosis membrane replacement progress can be improved greatly to reduce manual handling. The outcomes of the project have been able to successfully reduce the manual handling. The designed components decrease the manual handling in every aspect of the membrane replacement process. Furthermore, with an updated membrane replacement methodology curated specifically to the newly designed components, the operators can carry out the process with improved safety standards.

Through multiple forms of analyses, the feasibility of both the process and component design has been proven. FEA allowed for the yield strength of all components to be assessed against the relevant forces and pressure applied. Given that the lowest factor of safety involved was three, there are no detrimental safety implications accompanying the newly designed components. With safe components that aid in the reduction of manual handling, there has been an obvious increase in the overall safety of the process.

Supplementary to the updated physical replacement process, a solution to the long-term replacement philosophy was theorised. Through the categorisation of key parameter values, criteria were set to classify the need for discussion regarding a membrane replacement. The categories are classified as in working order, in need of attention and in urgent need of attention. This improved the current replacement philosophy by adding structure to the indication process. The philosophy is based upon discussions between relevant stakeholders. When the membranes decrease in quality to a point of concern an automated system now informs all parties that this discussion should take place.

With the increase of safety and reduction of manual handling proven, the feasibility of switching the processes was further shown through financial analysis. There were savings in every stage of the membrane replacement process and hence utilising the components and updated methodology provides further benefit to Veolia Water. While the project could be considered successful without reducing financial implications, lowering the cost of the process has further increased the success of the project.

9.2 Further Works

Further work for this project generally surrounds the physical aspects. In a practical engineering project, physical testing is important in order to confirm the or find possible errors in the theoretical work. This physical testing would be used to confirm values such as the coefficient of friction through practical tests, rather than through calculation. This kind of testing was hindered during the timeframe of this project by COVID-19.

In terms of the components, the physical testing would allow for the confirmation of the safety and viability of the components. As work on this project continues, the next step would be the manufacturing of the components. Spare RO vessels would be utilised to ensure the components designed are functional and safe as theorized.

The updated process, including the implementation of the designed components, can be discussed with operators. From these discussions the operators can gain understanding of the new components. Simultaneously, their practical knowledge may be of benefit.

The automated workflow, that is the membrane replacement philosophy, can be discussed with relevant stakeholders and engineers. This may allow for the use of more key parameters that are of interest. The workflows can also be specified to act as an individual would prefer. Where some key parameters may be of more importance to that individual, the workflow could be set to notify them specifically at different points of data.

Overall, the further works for this project are based heavily around the implementation of the process into Veolia Water. Certain processes must be carried out prior to this, such as a *Management of Change* form. This form allows all technical experts and engineers to approve, question and suggest modifications to any change taking place on site.

References

Acciona, n.d. The Importance Of Water Treatment | ACCIONA | Business As Unusual. [online] Acciona.com. Available at: <https://www.acciona.com/water-treatment> [Accessed 14 April 2020].

ASI, n.d. ASI - Design For Construction. [online] Steel.org.au. Available at: <https://www.steel.org.au/focus-areas/steel-and-design/design-for-construction/> [Accessed 14 August 2020].

ATI, 2017. Re-Smelling London's Great Stink Of 1858. [online] All That's Interesting. Available at: <https://allthatsinteresting.com/great-stink-london> [Accessed 28 August 2020].

Ausmed Editorial Team, 2019. *Manual Handling | Ausmed*. [online] Ausmed.com.au. Available at: <https://www.ausmed.com.au/cpd/articles/manual-handling-an-overview> [Accessed 6 May 2020].

AutoDesk, 2018. Polymer And Plastic Composites Selection Guide | Engineering360. [online] Globalspec.com. Available at: <https://www.globalspec.com/learnmore/materials_chemicals_adhesives/composites_textiles_reinforcements/fiber_reinforced_plastics_frp_smc_prepregs> [Accessed 15 July 2020].

Baker, R., 2004. Membrane Technology And Applications. Oxford: Wiley-Blackwell.

Baseline Training, 2017. 10 Years In Safety - What Are Ltis & Do They Matter?. [online] Baseline Training. Available at: <https://www.baselinetraining.com/10-years-safety-ltifrs-workplace-safety/> [Accessed 10 April 2020].

Beaty, J., 2017. Use Of Membrane Performance Metrics To Characterize Membrane Replacement Requirements.

Beyer, F., 2020. Isolation And Characterization Of Microorganism Involved In Membrane Biofouling. [online] WUR. Available at: <https://www.wur.nl/en/show/Isolation-and-characterization-of-microorganism-involved-in-membrane-biofouling-1 htm> [Accessed 14 October 2020].

Bratby, J., 2016. Coagulation And Flocculation In Water And Wastewater Treatment. London: IWA Pub.

Cadtek, 2017. FEA And CFD, What's The Difference? When To Use One Or Both?. [online] CAD Design Technologies | CADTEK. Available at: <https://www.cadtek.com/fea-cfd-whats-the-difference/> [Accessed 2 July 2020].

Cambridge Dictionary, n.d. MANUAL HANDLING | Meaning In The Cambridge English Dictionary. [online] Dictionary.cambridge.org. Available at: <https://dictionary.cambridge.org/dictionary/english/manual-handling> [Accessed 9 May 2020].

Cheremisinoff, N., 2001. Condensed Encyclopedia Of Polymer Engineering Terms. Boston: Butterworth-Heinemann.

Clark, J., 2007. Why Can't We Manufacture Water?. [online] HowStuffWorks. Available at: <https://science howstuffworks.com/environmental/earth/geophysics/manufacture-water.htm> [Accessed 6 July 2020].

Cyprien, 2017. Failure Modes. FEA For All, [online] Available at: <https://feaforall.com/failure-modes/> [Accessed 11 May 2020].

Das, B. and Wang, Y., 2004. Isometric Pull-Push Strengths in Workspace: 1. Strength Profiles. International Journal of Occupational Safety and Ergonomics, 10(1), pp.43-58.

Daunton, M., 2004. BBC - History - London's 'Great Stink' And Victorian Urban Planning. [online] Bbc.co.uk. Available at: <http://www.bbc.co.uk/history/trail/victorian_britain/social_conditions/victorian_urban_planning_04.shtml> [Accessed 27 May 2020].

Du, X., Shi, Y., Jegatheesan, V. and Haq, I., 2020. A Review on the Mechanism, Impacts and Control Methods of Membrane Fouling in MBR System. Membranes, 10(2), p.24.

Engineering 360, n.d. Polymer And Plastic Composites Selection Guide | Engineering360. [online] Globalspec.com. Available at: <https://www.globalspec.com/learnmore/materials_chemicals_adhesives/composites_textiles_reinforcements/fiber_reinforced_plastics_frp_smc_prepregs> [Accessed 7 August 2020].

Engineering Toolbox, n.d. Thermoplastics - Physical Properties. [online] Engineeringtoolbox.com. Available at: <https://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808 html> [Accessed 28 June 2020].

Engineers Australia, 2019. Code Of Ethics And Guidelines On Professional Conduct. [ebook] Available at: <http://Code of Ethics and Guidelines on Professional Conduct>.

GSA, 2020. Sustainable Design. [online] Gsa.gov. Available at: <https://www.gsa.gov/real-estate/design-construction/design-excellence/sustainability/sustainable-design#:~:text=Sustainable%20design%20seeks%20to%20reduce,and%20create%20healthy%2C%20productive%20environments> [Accessed 18 June 2020].

Hanaor, D., Gan, Y. and Einav, I., 2016. Static Friction At Fractal Interfaces. Tribology International

Hayward Flow Control, n.d. [online] Haywardflowcontrol.com. Available at: <https://www.haywardflowcontrol.com/assets/documents/flowcontrol/pdf/VessTime.pdf> [Accessed 3 July 2020].

Hoey, C., 2015. What Is 'Cleaning In Place,' Or CIP?. [online] Burkert.com.au. Available at: <https://www.burkert.com.au/en/Company-Career/What-s-New/News/What-is-Cleaning-in-Place-or-CIP> [Accessed 14 July 2020].

Houska, C., 2007. Deicing Salt - Recognizing The Corrosion Threat. [online] Imoa.info. Available at: <https://www.imoa.info/download_files/stainless-steel/DeicingSalt.pdf> [Accessed 14 May 2020].

Hydranautics, 2013. [online] Membranes.com. Available at: <https://membranes.com/docs/tsb/TSB126.pdf>.

Johnson, J., 2010. Engineering Aspect Of Reverse Osmosis Module Design. [online] Lenntech.com. Available at: <https://www.lenntech.com/Data-sheets/Engineering-Aspects-of-Reverse-Osmosis-Module-Design-L.pdf>.

Kiss, D., 2013. Materials Corrosion - Basic Types Of Corrosion That Designers And Engineers Must Be Able To Competently Address.. [online] Mission Viejo, CA Patch. Available at: <https://patch.com/california/missionviejo/materials-corrosion--basic-types-of-corrosion-that-designers-and-engineeers-must-be-able-to-competently-address> [Accessed 1 July 2020].

Kurihara, 1994. Desalination. 96(1-3).

Lenntech, n.d. Water Conductivity - Lenntech. [online] Lenntech.com. Available at: <https://www.lenntech.com/applications/ultrapure/conductivity/water-conductivity htm> [Accessed 3 April 2020].

Li, W., 2015. An inspection-maintenance model for systems with multiple competing processes. Transactions on Reliability, [online] 54(2). Available at: <https://ieeexplore.ieee.org/abstract/document/1435726> [Accessed 29 June 2020].

Mameng, H., 2014. Corrosion Of Stainless Steel In Sodium Chloride Brine Solutions.

Marshall, K., 2018. What Is Membrane Fouling And How Can You Avoid It?. [online] Samco Tech. Available at: <https://www.samcotech.com/what-is-membrane-fouling-and-how-can-you-avoid-it/> [Accessed 25 May 2020].

McLennan, J., 2004. The Philosophy Of Sustainable Design.

McMordie Stoughton, K., 2013. Reverse Osmosis Optimization. [ebook] Pacific Northwest National Laboratory. Available at: <https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22682.pdf>.

Micron, n.d. Domestic & Commercial Reverse Osmosis And Ultra Filtration. [online] Micron - Domestic & Industrial Water Treatment. Available at: <https://www.micron.be/domestic--commercial-reverse-osmosis-and-ultra-filtration html> [Accessed 14 October 2020].

Mirriam-Webster, 2020. Definition Of OSMOSIS. [online] Merriam-webster.com. Available at: <https://www.merriam-webster.com/dictionary/osmosis> [Accessed 12 April 2020].

Mishra, G., 2020. What Are Methods Of Steel Structure Design?. [online] The Constructor. Available at: <https://theconstructor.org/structural-engg/methods-of-steel-structure-design/6876/> [Accessed 29 April 2020].

Muskins, R., 2011. Handbook Of Logic And Language. 2nd ed. Elsevier.

Muthu, S., 2010. Sustainable Fibres And Textiles. Woodhead Publishing.

Najafpour, G., 2015. Biochemical Engineering And Biotechnology. 2nd ed. Elsevier.

Pérez-González, A., Iserte-Vilar, J. and González-Lluch, C., 2011. Interpreting finite element results for brittle materials in endodontic restorations. BioMedical Engineering OnLine, 10(1), p.44.

Puretec, n.d. Puretec Industrial Water | What Is Reverse Osmosis?. [online] Puretecwater.com. Available at: <https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis#salt-rejection> [Accessed 14 April 2020].

Queensland Government Chief Information Office, 2020. ICT Risk Matrix. [online] Queensland Government Enterprise Architecture. Available at: <https://www.qgcio.qld.gov.au/information-on/ict-risk-management/ict-risk-matrix> [Accessed 14 May 2020]

Reverse Osmosis Chemicals, 2020. Telescoping - Reverse Osmosis Systems. [online] Reverseosmosischemicals.com. Available at: <http://reverseosmosischemicals.com/reverse-osmosis-guides/reverse-osmosis-glossary-terms/telescoping-reverse-osmosis-systems> [Accessed 3 August 2020].

Rose, 2017. How To Decide Between Modifying Existing Or Buying New Packaging Equipment. [online] https://www.edlpackaging.com/blog/how-to-decide-between-modify-existing-or-buy-new-packaging-equipment. Available at: <https://www.edlpackaging.com/blog/how-to-decide-between-modify-existing-or-buy-new-packaging-equipment> [Accessed 13 May 2020].

SafeWork Australia, 2018. Good Work Design Handbook. [online] Safeworkaustralia.gov.au. Available at: <https://www.safeworkaustralia.gov.au/system/files/documents/1702/good-work-design-handbook.pdf> [Accessed 9 May 2020].

SafeWork Australia, 2020. Lost Time Injury Frequency Rates (LTIFR) | Safe Work Australia. [online] Safeworkaustralia.gov.au. Available at: <https://www.safeworkaustralia.gov.au/statistics-and-research/lost-time-injury-frequency-rates-ltifr> [Accessed 12 May 2020].

Sparks, T., Chase, G. and Sutherland, K., 2015. Filters And Filtration Handbook. 6th ed. Butterworth-Heinemann.

UpKeep, n.d. [online] Onupkeep.com. Available at: <https://www.onupkeep.com/learning/maintenance-types/scheduled-maintenance#:~:text=Scheduled%20maintenance%20is%20any%20repair,are%20performed%20and%20by%20whom.> [Accessed 14 April 2020].

Vanegas, J., 2004. Sustainable Engineering Practice. Reston, VA: American Society of Civil Engineers.

Voutchkov, N., 2017. Pretreatment For Reverse Osmosis Desalination. San Diego: Elsevier Science & Technology Books.

WHO, 2019. Sanitation. [online] Who.int. Available at: <https://www.who.int/news-room/fact-sheets/detail/sanitation> [Accessed 18 March 2020].

Appendices

Appendix A Project Specification

ENG4111/4112 Research Project

Project Specification

For: Jonathan McCluskey

Title: NAME CHANGE: Philosophy and Design of Reverse Osmosis Membrane Replacement

Major: Mechanical Engineering

Supervisor: Andrew Wandel

Enrolment: ENG4111 - S1, 2020
ENG4112 - S2, 2020

Project Aim: To develop a process and the necessary components to remove and replace membranes used in the reverse osmosis process.

Programme: Version 2, 2nd April 2020

1. Review existing methods and philosophies surrounding reverse osmosis membrane replacement.

2. Design components which assist in the reduction of manual handling during the process.

3. Carry out finite element analysis (FEA) of both designed and existing components for material selection and stress analysis using Creo Parametric, verify results using hand calculations.

4. Narrow down to most suitable components based on FEA and resource availability.

5. Analyse data regarding quality of permeate to develop a suggested pattern of membrane replacement to efficiently minimize decrease of water quality.

6. Analyse historical data and predictions of cost to carry out a financial break down of the current processes against the newly developed process.

If time and resources permit:

7. Field testing of all components

8. Analyse and compare results from theoretical calculations against results from field testing.

9. Use data from field testing to suggest changes or comment on efficiency of process

Appendix B1 Design Calculations: Coefficient of Friction

$$F_s = \mu_s N$$

Where:

$$F_s = 400\ N$$

And:

$$N = mg$$

$$N = 7(15) \times 9.81$$

$$N = 1030.05\ N$$

Therefore:

$$\mu_s = \frac{F_s}{N}$$

$$\mu_s = \frac{400}{1030.05}$$

$$\mu_s = 0.3883$$

Appendix B2 Analysis Calculations: Pressure Required

$$P = \frac{\mu_s N}{A}$$

Where:

$$\mu_s = 0.3883$$

$$N = 1030.05\ N$$

And:

$$A = \pi * 0.1005^2$$

$$A = 3.173 \times 10^{-2}\ m^2$$

Therefore:

$$P = \frac{\mu_s N}{A}$$

$$P = \frac{0.3883 \times 1030.05}{0.03173}$$

$$P = 12605.37\ Pa$$

Appendix B3 Analysis Calculations: Pressure Placement

$$L = L_T - (L_{MB} + L_{MRT} + L_E)$$

$$L_{Offset} = L_{MRT} + L_E$$

Where:

$$L_T = 407\ mm$$

$$L_{MB} = 10\ mm$$

$$L_{MRT} = 280.4\ mm$$

$$L_E = 83\ mm$$

Therefore:

$$L = L_T - (L_{MB} + L_{MRT} + L_E)$$

$$L = 407 - (10 + 280.4 + 83)$$

$$L = 33.6\ mm$$

And:

$$L_{Offset} = L_{MRT} + L_E$$

$$L_{Offset} = 280.4 + 83$$

$$L_{Offset} = 363.4\ mm$$

Appendix C1 Factor of Safety: Membrane Removal Tool Calculations

$$FoS_{Concept\ \#1} = \frac{Tensile\ Yield\ Strength}{Max\ Stress}$$

Therefore:

$$FoS_{Concept\ \#1} = \frac{55.2}{0.3867}$$

$$FoS_{Concept\ \#1} \approx 142$$

And:

$$FoS_{Concept\ \#2} = \frac{55.2}{16.86}$$

$$FoS_{Concept\ \#2} \approx 3$$

Appendix C2 Factor of Safety: Holding/ Catching Apparatus Calculations

$$FoS = \frac{Tensile\ Yield\ Strength}{Max\ Stress}$$

$$FoS = \frac{585}{111.3}$$

$$FoS \approx 5.2$$

Appendix C3 Factor of Safety: Pump Skid Calculations

$$FoS = \frac{Tensile\ Yield\ Strength}{Max\ Stress}$$

$$FoS = \frac{585}{0.5275}$$

$$FoS > 1000$$

Appendix D1 Updated Replacement Strategy Calculations: Ideal Acceleration and Pressure

$$a = \frac{2d}{t^2}$$

Where:

$$Distance\ to\ expel\ all\ but\ the\ last\ membrane = d = \ 7011\ mm$$

Therefore:

$$a = \frac{2 \times 7.011}{10^2}$$

$$a = 0.14022\ m/s^2$$

And:

$$P_N = \frac{m_M a}{A}$$

Where:

$$Pressure\ at\ number\ of\ membranes\ present = \ P_N$$

$$No.of\ Membranes\ present = N$$

$$Mass\ of\ singular\ membrane = m_{Membrane} = 15.04\ kg$$

$$Mass\ of\ membranes\ at\ N\ present = \ m_N = m_{Membrane}N$$

$$Area\ of\ membrane = A = 0.032\ m^2$$

Therefore:

$$P_7 = 0.460\ kPa$$

$$P_6 = 0.394\ kPa$$

$$P_5 = 0.329\ kPa$$

$$P_4 = 0.263\ kPa$$

$$P_3 = 0.197\ kPa$$

$$P_2 = 0.131\ kPa$$

Appendix D2 Updated Replacement Strategy Calculations: Time to Drain Vessels

$$T_{Drain} = \frac{L(D^{\frac{3}{2}} - (D-h)^{\frac{3}{2}}}{3C_d A}\sqrt{\frac{8}{g}}$$

Where:

$$Time\ Taken\ to\ Drain\ Water = T_{Drain}$$

$$Length\ of\ Vessel = L = 7.61\ m$$

$$Diameter\ of\ Vessel = D = 0.202\ m$$

$$Height\ of\ Water = h = 0.202\ m$$

$$Discharge\ Coefficient_{Sharp\ Edged} = C_d = 0.61$$

$$Area\ of\ Orifice = A = 0.001257\ m^2$$

$$Gravitational\ Acceleration = g = 9.81\ m/s^2$$

Therefore:

$$T_{Drain} = \frac{7.61(0.202^{\frac{3}{2}} - (0.202 - 0.202)^{\frac{3}{2}}}{3 \times 0.61\ \times 0.001257}\sqrt{\frac{8}{9.81}}$$

$$T_{Drain} = \ 271.2\ Seconds$$

$$T_{Drain} = \ 4.52\ Minutes$$

Appendix E1 Financial Analysis Calculations: Hours of Operation

$$Hours\ of\ Operation_{Stage\ 1} = T_{Stage\ 1} = 24$$

$$Number\ of\ Vessels_{Stage\ 1} = N_{V-Sta\quad 1} = 72$$

$$Hours\ of\ Operation_{Stage\ 2} = T_{Stage\ 2}$$

$$Number\ of\ Vessels_{Stage\ 2} = N_{V-Stage\ 2} = 45$$

$$Hours\ of\ Operation_{Stage\ 3} = T_{Stage\ 3}$$

$$Number\ of\ Vessels_{Stage\ 3} = N_{V-Sta\quad 3} = 22$$

Therefore:

$$\frac{T_{Stage\ 1}}{N_{V-Sta\quad 1}} = \frac{T_{Stage\ 2}}{N_{V-Stage\ 2}}$$

$$\frac{T_{Stage\ 1} \times N_{V-Sta\quad 2}}{N_{V-Sta\quad 1}} = T_{Stage\ 2}$$

$$T_{Stage\ 2} = 15\ Hours$$

And:

$$\frac{T_{Stage\ 1} \times N_{V-Stage\ 3}}{N_{V-Stage\ 1}} = T_{Stage\ 3}$$

$$T_{Stage\ 3} = 7.333\ Hours$$

Appendix E2 Financial Analysis Strategy Calculations: Number of Operators

$$\frac{Cost\ (\$)}{Hour} \approx \$85/Hour$$

$$Hours\ of\ Operation_{Stage\ 3} = T_{Stage\ 3} = 16$$

$$Number\ of\ Operators_{Stage\ 3} = N_{Operators-Sta\quad 3}$$

$$Average\ Total\ Cost\ of\ Internal\ Labour_{Stage\ 3} = Cost_{Labour-Stag\quad 3}$$

Therefore:

$$Cost_{Labour-Stag\quad 3} = \frac{Cost_{Labour-Sta\quad 3-1} + Cost_{Labour-Stag\quad 3-2}}{2}$$

$$Cost_{Labour-Stage\ 3} = \$\ 3410$$

And:

$$N_{Operators-S\qquad 3} = \frac{Cost_{Labour-Stage\ 3}}{\frac{Cost\ (\$)}{Hour} \times T_{Stage\ 3}}$$

$$N_{Operators-St\qquad 3} = \frac{3410}{85 \times 16}$$

$$N_{Operators-Stage\ 3} \approx\ 3$$

And:

$$N_{Operators-St\qquad 2} = N_{Operators-St\qquad 3} =\ 3$$

Appendix E3 Financial Analysis Strategy Calculations: Scaffolding Costs

$$Percentage\ Difference = \Delta_{\%} = \frac{Cost_{Hire-Stage\ 3} - Cost_{Hire-Stage\ 1}}{Cost_{Hire-Stage\ 1}} \times 100$$

Therefore:

$$Cost_{Hire-Stage\ 3} = \frac{Cost_{Hire-Stag\ \ 3-1} + Cost_{Hire-Stag\ \ 3-2}}{2}$$

$$Cost_{Hire-Stag\ \ 1} = \frac{3366 + 4860}{2}$$

$$Cost_{Hire-Stage\ 1} = \$\ 4113$$

And:

$$Cost_{Hire-Stage\ 3} = \frac{3870.5 + 4511.25}{2}$$

$$Cost_{Hire-Stag\ \ 3} = \$\ 4190$$

And

$$\Delta_{\%} = \frac{4190 - 4113}{4113} \times 100$$

$$\Delta_{\%} = 1.872\%$$

$$\Delta_{\%} < 10\%$$

Therefore:

$$Average\ Cost\ of\ Labour\ Hire = Cost_{Hire}$$

$$Cost_{Hire} = \frac{Cost_{Hire-Stag\ \ 1} + Cost_{Hire-Stage\ 3}}{2}$$

$$Cost_{Hire} = \$\ 4151.50$$

Appendix E4 Financial Analysis Strategy Calculations: Cost of Historical Operations

$$Total\ Cost = \left(T \times N_{Operators} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

Therefore:

$$Total\ Cost_{Stage\ 1-Historical} = \left(T_{Stage\ 1} \times N_{Operators-Stag\ \ 1} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

$$Total\ Cost_{Stage\ 1-Historica} = (24 \times 6 \times 85) + 4151.5$$

$$Total\ Cost_{Stag\ \ 1-Historical} = \$\ 16391.50$$

And:

$$Total\ Cost_{Stage\ 2-Historical} = \left(T_{Stage\ 2} \times N_{Operators-Sta\ \ 2} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

$$Total\ Cost_{Stage\ 2-Historical} = (16 \times 3 \times 85) + 4151.5$$

$$Total\ Cost_{Stage\ 2-Historical} = \$\ 8231.50$$

And:

$$Total\ Cost_{Stage\ 3-Historical} = \left(T_{Stage\ 3} \times N_{Operators-S\ \ 3} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

$$Total\ Cost_{Stage\ 3-Historical} = (8 \times 3 \times 85) + 4151.5$$

$$Total\ Cost_{Stage\ 3-Historical} = \$\ 6191.50$$

Appendix E5 Financial Analysis Strategy Calculations: Time per Vessel

$$Time\ per\ vessel = T_{Vessel}$$

$$Time\ to\ attach\ and\ remove\ end\ caps = T_{End\ Caps} = 1\ minute$$

$$Time\ to\ attach\ and\ remove\ membrane\ removal\ tool = T_{MRT} = 1\ minute$$

$$Time\ to\ expel\ membranes = T_{expel} = 0.333\ minutes$$

$$Time\ to\ drain\ water\ from\ vessel = T_{Drain} = 5\ minutes$$

$$Time\ to\ dispose\ of\ membranes - Slide\ Attachment = T_{Dispose-S} = 0\ minutes$$

$$Time\ of\ gantry\ crane\ travel = T_{gantry} = 5\ minutes$$

$$Time\ to\ dispose\ of\ membranes - Wall\ Attachment = T_{Dispose-W} = 0.5\ minutes$$

Therefore:

$$T_{Vessel-Stag\ \ 1} = T_{End\ Caps} + T_{MRT} + T_{expel} + T_{Drain} + 0.5T_{Dispose-S} + 0.5T_{Dispose-W}$$

$$T_{Vessel-Stage\ 1} = 7.583\ minutes = 0.1264\ hours$$

And:

$$T_{Vessel-Stage\ 2,3} = T_{End\ Caps} + T_{MRT} + T_{expel} + T_{Drain} + T_{Dispose-W} + T_{gantry}$$

$$T_{Vessel-Stage\ 2} = 12.833\ minutes = 0.2139\ hours$$

Appendix E6 Financial Analysis Strategy Calculations: Time per Stage

$$Time\ per\ stage = T_{stage} = T_{Prep} + T_{Clean} + N_{Vessel}T_{Vessel}$$

Therefore:

$$T_{stage\ 1-Update} = 0.5 + 0.5 + 72 \times 0.1264$$

$$T_{stage\ 1-Updated} = 10.1\ Hours$$

And:

$$T_{stage\ 1-Update} = 0.5 + 0.5 + 45 \times 0.2138$$

$$T_{stage\ 2-Updated} = 10.63\ Hours$$

And:

$$T_{stage\ 1-Updated} = 0.5 + 0.5 + 72 \times 0.2138$$

$$T_{stage\ 3-Updated} = 5.71\ Hours$$

Appendix E7 Financial Analysis Strategy Calculations: Cost per Stage

$$Total\ Cost = \left(T \times N_{Operators} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

Therefore:

$$Total\ Cost_{Stage\ 1-Updated} = \left(T_{Stage\ 1} \times N_{Operators-Stage\ 1} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

$$Total\ Cost_{Stage\ 1-Updated} = (10.1 \times 2 \times 85) + 4151.5$$

$$Total\ Cost_{Stage\ 1-Updated} = \$\ 5868.50$$

And:

$$Total\ Cost_{Stage\ 2-Updated} = \left(T_{Stage\ 2} \times N_{Operators-Sta\quad 2} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

$$Total\ Cost_{Stage\ 2-Updated} = (10.63 \times 3 \times 85) + 4151.5$$

$$Total\ Cost_{Stage\ 2-Updated} = \$\ 6862.15$$

And:

$$Total\ Cost_{Stage\ 3-Updated} = \left(T_{Stage\ 3} \times N_{Operators-S\qquad 3} \times \frac{Cost\ (\$)}{Hour}\right) + Cost_{Hire}$$

$$Total\ Cost_{Stage\ 3-Updated} = (5.71 \times 3 \times 85) + 4151.5$$

$$Total\ Cost_{Stage\ 3-Updated} = \$\ 5607\ .55$$

Appendix F1 Replacement Strategy: Typical Stage 1 Data

Date (Month/Year)	Average Normalised Specific Flux	Average Normalised Salt Passage	Average Normalised Differential Pressure
07/2017	0.0209	1.1790	149.11
08/2017	0.0219	1.0911	149.07
09/2017	0.0237	1.2389	145.89
10/2017	0.0249	1.4015	142.63
11/2017	0.0278	1.4108	142.87
12/2017	0.0305	1.5335	140.21
01/2018	0.0328	1.6199	137.08
02/2018	0.0315	1.5801	137.55
03/2018	0.0303	1.5254	137.50
04/2018	0.0278	1.6489	137.97
05/2018	0.0228	1.4942	143.02
06/2018	0.0212	1.2627	147.98
07/2018	0.0224	1.2993	147.73
08/2018	0.0227	1.2906	147.57
09/2018	0.0243	1.3885	144.43
10/2018	0.0264	1.6063	140.83
11/2018	0.0279	1.7791	138.37
12/2018	0.0306	2.1742	137.83
01/2019	0.0320	2.4538	133.67
02/2019	0.0310	2.6008	133.50
03/2019	0.0302	2.7712	134.12
04/2019	0.0281	2.6936	136.50
05/2019	0.0266	2.3862	139.03
06/2019	0.0241	2.0368	145.96
07/2019	0.0235	2.1054	146.51
08/2019	0.0243	2.2218	145.53
09/2019	0.0254	2.4091	143.12
10/2019	0.0291	2.7185	138.37
11/2019	0.0304	3.0849	137.38
12/2019	0.0291	3.2680	137.02

Appendix F2 Replacement Strategy: Typical Stage 2 Data

Date (Month/Year)	Average Normalised Specific Flux	Average Normalised Salt Passage	Average Normalised Differential Pressure
07/2017	0.0097	0.5024	165.51
08/2017	0.0099	0.4880	162.53
09/2017	0.0098	0.4469	164.08
10/2017	0.0098	0.4469	164.08
11/2017	0.0133	0.6258	147.30
12/2017	0.0148	0.6491	143.99
01/2018	0.0156	0.6264	138.96
02/2018	0.0150	0.6165	139.85
03/2018	0.0147	0.6371	139.29
04/2018	0.0134	0.6193	139.96
05/2018	0.0106	0.6155	141.57
06/2018	0.0097	0.5326	144.89
07/2018	0.0099	0.5891	142.74
08/2018	0.0104	0.5871	141.09
09/2018	0.0115	0.6548	135.31
10/2018	0.0125	0.7142	131.05
11/2018	0.0146	0.7918	128.88
12/2018	0.0147	0.8819	126.80
01/2019	0.0159	0.9259	121.13
02/2019	0.0154	0.9994	120.97
03/2019	0.0144	1.0581	120.82
04/2019	0.0136	1.0020	122.01
05/2019	0.0119	0.8661	125.27
06/2019	0.0107	0.8069	130.13
07/2019	0.0105	0.8449	130.07
08/2019	0.0107	0.8649	127.66
09/2019	0.0120	0.9223	123.90
10/2019	0.0139	0.9957	119.79
11/2019	0.0145	1.0943	117.89
12/2019	0.0163	1.2886	115.13
1/2020	0.0169	1.2587	118.25
2/2020	0.0181	1.3567	117.79
3/2020	0.0173	1.2970	118.61
4/2020	0.0153	1.3027	121.68

Appendix F3 Replacement Strategy: Typical Stage 3 Data

Date (Month/Year)	Average Normalised Specific Flux	Average Normalised Salt Passage	Average Normalised Differential Pressure
07/2017	0.0085	0.5896	191.02
08/2017	0.0087	0.5880	197.32
09/2017	0.0091	0.5915	194.93
10/2017	0.0105	0.6709	190.84
11/2017	0.0119	0.6432	192.58
12/2017	0.0132	0.6764	188.10
01/2018	0.0143	0.7150	182.76
02/2018	0.0133	0.7606	183.67
03/2018	0.0124	0.8426	182.96
04/2018	0.0116	0.8620	180.05
05/2018	0.0090	0.8686	184.06
06/2018	0.0000	0.0000	0.00
07/2018	0.0000	0.0000	0.00
08/2018	0.0090	0.8643	186.76
09/2018	0.0098	0.8879	181.75
10/2018	0.0108	0.9593	176.45
11/2018	0.0123	1.0259	171.91
12/2018	0.0121	1.1821	169.59
01/2019	0.0136	1.2504	166.33
02/2019	0.0131	1.2571	164.29
03/2019	0.0123	1.4397	161.88
04/2019	0.0112	1.3065	163.24
05/2019	0.0103	1.1279	166.98