

DEOXYGENATION OF COAL SEAM GAS PRODUCED ASSOCIATED WATER FOR MANAGED AQUIFER RECHARGE UTILISING MEMBRANE TECHNOLOGY

A Practical Application of Gas-Transfer Membranes

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ABSTRACT

During coal seam gas (CSG) production water is separated from gas. This associated water (AW) can then be re-injected into a suitable aquifer. This process is called managed aquifer recharge (MAR).

Prior to reinjection deoxygenation can be required to reduce dissolved oxygen (DO) in the water. This project was concerned with the design, build, and commission of a de-oxygenation plant to reduce the DO content to below a concentration of 0.5 mg.L⁻¹ in nine mega-litres per day (MLD) and a pressure of 2500 kPa.

The plant pumping system incorporated eight multistage centrifugal 90 kW variable speed drive (VSD) pumps operating in both series and parallel bringing the flow from a low pressure 30 kPa onto a higher pressure of above 2500 kPa.

At the heart of the de-oxygenation plant are gas transfer membranes. The membranes consist of hydrophobic hollow fibres that allow the water to flow around them and a gas stream to flow inside them.

Plant operating analysis showed the importance of

vacuum line integrity to the process and that the purity of the N₂ sweep gas and vacuum pressure were vital to high-end performance.

Results on site showed the plant could reach below the target DO level of less than 0.5 mg.L⁻¹ to as low as 0.1 mg.L⁻¹ and that flows could range from 35 kL/hr to 400 kL/hr at pressures ranging from 2000 – 2500 kPa.

INTRODUCTION

Coal Seam Gas (CSG) is a naturally occurring gas that is sometimes termed an unconventional gas due to its geological location and extraction requirements. Whereas natural gas can be sourced from a pocket of gas taken by simple conventional methods such as drilling from the earth's surface into a rock strata. CSG is located between coal seams beneath the earth's surface and requires an advanced extraction methodology, (Williams J. et. al. 2012).

Figures 1, 2 and 3 show diagrammatically the conventional and unconventional geological gas locations.

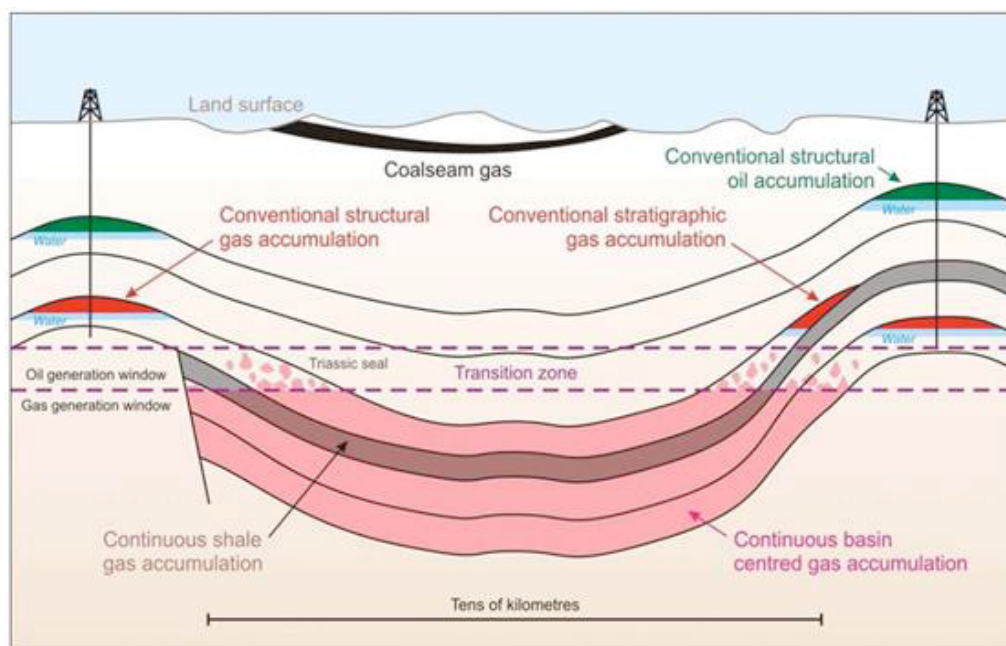


Figure 1: Schematic diagram showing conventional and unconventional oil and gas accumulation types (Source: Beach Energy Limited, AGM Presentation, 2011. Amended from Schenk and Pallastro, 2002).

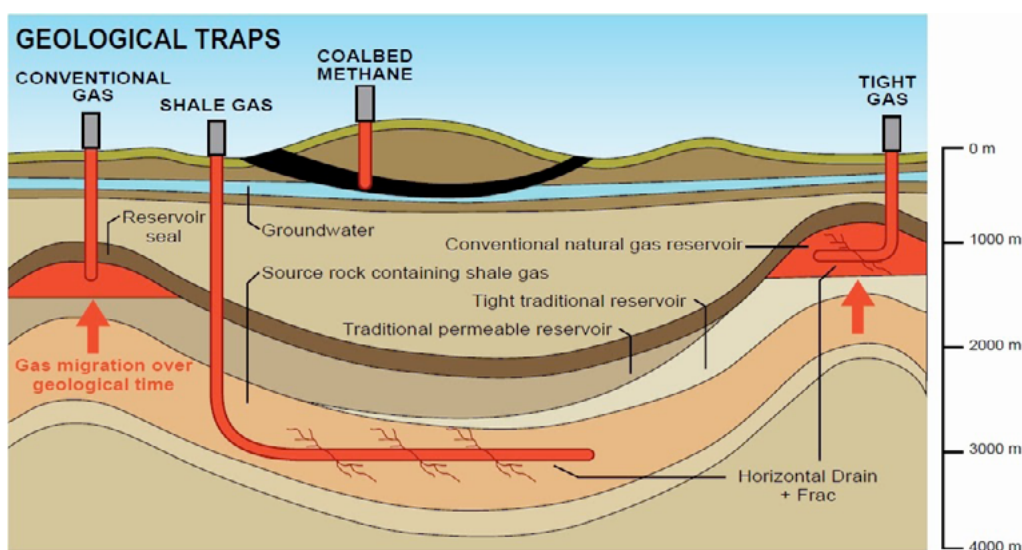


Figure 2: Schematic diagram showing shale gas extraction. (Source: Government of WA Gas Fact Sheet - Gas Resource Types, 2015)

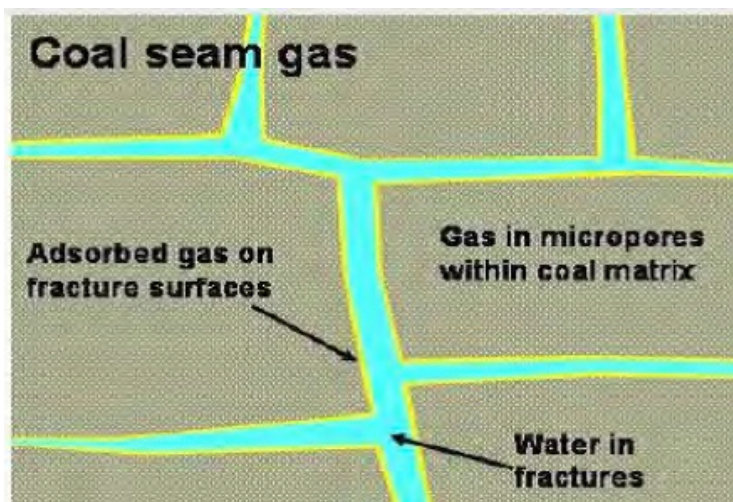


Figure 3. Schematic of the formation of coal seam natural gas (Source: Geoscience Australia, 2015).

CSG is formed nearly entirely of methane (CH_4) and can be gas and in a near-liquid state in the pores of coal and adsorbed onto the coal surface.

The gas is secured in its location via the surrounding pressure of the reservoir and water.

To capture the gas the water pressure within the coal seams must be released. Hydraulic fracturing is carried out to accommodate this. This is a process whereby water, sand, and some chemical aids are pumped under high pressure into the coal shale. This fractures the shale and allows the sand particles to keep the areas open while the gas escapes back up the riser to the earth's surface.

The volume of water involved in CSG unconventional extraction varies over time and is dependant on the hydrogeology in the area but recent estimates are in the order of 300 GL/Yr, according to the National Water Commission estimate, (NWC 2011). The Queensland Water Commission estimates 126 – 281 GL/Yr, (QWC, 2011). The Queensland Government requires all gas operators to deal with associated water in a sustainable way. This requires treatment of the water so it can be used in environmental flows, town water supplies, irrigation, and aquifer recharging.

This has been enshrined in Queensland's Waste Reduction and Recycling Act of 2011 (Gas Fields Commission Queensland, 2016). Queensland's CSG water managements preferred option is aquifer recharge. For deeper aquifer targets the receiving

hydrogeological properties of the aquifer are very important. The compatibility of the injectate must be in-line with the receiving water so as to mitigate the risk of encrustation, precipitation, scaling and bio-fouling (Klohn Krippen Berger, 2011).

Injection water properties that can limit through clogging or stop aquifer recharge would include excess metals and suspended solids; hazardous properties such as pathogens and radionuclides; and nutrients for clogging or biofilms such as organic carbon, nitrate, and dissolved oxygen, (Ibid). Pre-injection pre-treatment is a must to ensure limiting associated water properties are reduced to non-impact levels.

This also includes treatment to ensure hydrogeochemical interactions do not become a concern after injection. Matching of the chemical characteristics of the aquifer water and associated water may require not only pre-treatment such as reverse-osmosis but also blending with raw water to ensure an acceptable water match. Redox or the state of reduction – oxidation can require an amendment to the dissolved oxygen content of the associated water. One such method to reduce the dissolved oxygen content in the CSGAW is to apply scientific gas laws and practically achieve deoxygenation utilising membrane technology.



DEOXYGENATION

The amount of oxygen (O_2) dissolved in liquid can be derived from Henry's Law. This states that "at a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid". The following equation is generally valid at low dissolved gas concentrations:

$$1. P_1 = H \cdot x$$

Where

P_1 = Partial pressure of gas
 H = Henry's constant for gas
 x = Concentration of dissolved gas

To define the partial pressure of a gas we look to Dalton's Law, which states that "the total pressure of a mixture of gases is equal to the sum of the partial pressures of the component gases":

$$2. P_{total} = P_{gas1} + P_{gas2} + P_{gas\ n}$$

This can also be expressed using the mole fraction of a gas, x , as follows:

$$3. P_{gas1} = y_1 P_{total}$$

Where

y_1 is the mole fraction of the component.

Therefore, for an isochoric and isothermal process the pressure that a gas will exert is dependent on the individual concentration of the gas in a mixture. Knowing this allows the driving force to be created to remove a gas such as dissolved oxygen from a liquid such as associated water, (Membrana, 1997).

Applying both Dalton's and Henry's Laws to water in contact with air will allow for the dissolved oxygen content to be calculated under optimum conditions. Air is approximately made up of 21% oxygen and 79% nitrogen, so that the partial pressure of oxygen is equal to the total pressure of the air multiplied by oxygen's mole fraction. The pressure of air is equal to one atmosphere. Using equation {3}:

$P_{gas1} = y_1 P_{total}$
 P_p of oxygen = $0.21 \cdot 1 \text{ atm}$
 P_p of oxygen = 0.21 atm

Knowing the partial pressure of oxygen enables the calculation of dissolved oxygen in water at a certain temperature. Rearranging equation {1} gives the following expression:

$$4. x = P_1 / H$$

Where

P_1 equals 0.21 atmospheres and, from standard engineering tables, Henry's Constant (H) at a nominal 25 degrees celcius equals $2.465 \cdot 10^4$ atmospheres per gram of oxygen per gram of water. Thus:

$x = 0.21 / 2.465 \cdot 10^4$
 $x = 8.519 \cdot 10^{-6}$
 $x = 8.52$ parts oxygen per million parts water

This 8.52 mg.L-1 is directly related to the partial pressure of oxygen, therefore, reducing this partial pressure of oxygen will have a direct effect on the solubility of oxygen in water.

Dalton's Law shows that reducing the overall pressure of the total gas will reduce the partial pressure of the constituent gases, i.e. oxygen in this case. Furthermore increasing the volume of one gas and decreasing the volume of another constituent gas will change the concentrate in the mixture, i.e. increasing nitrogen to decrease oxygen in this case (Ibid).

MEMBRANE GAS TRANSFER

Gas transfer membranes differ from standard liquid-solid separation membranes such as micro-filtration and reverse osmosis membranes in that they do not operate at high differential pressures in the liquid phase. The driving force is instead instigated at the boundary wall of the membrane, which consist of hollow hydrophobic polypropylene fibres. This allows for mass transfer between the phases without one phase infiltrating another.

Figure 4 shows a hollow fibre with gas internally (lumen side) and water externally (shell side) and liquid/gas contact at the fibre pores, (Courtesy, Membrana). In this case for dissolved oxygen removal from CSG associated water nitrogen is used as the effective sweep gas applied internally to the hollow fibre aided with the application of a vacuum draw to this gas phase to reduce its pressure.

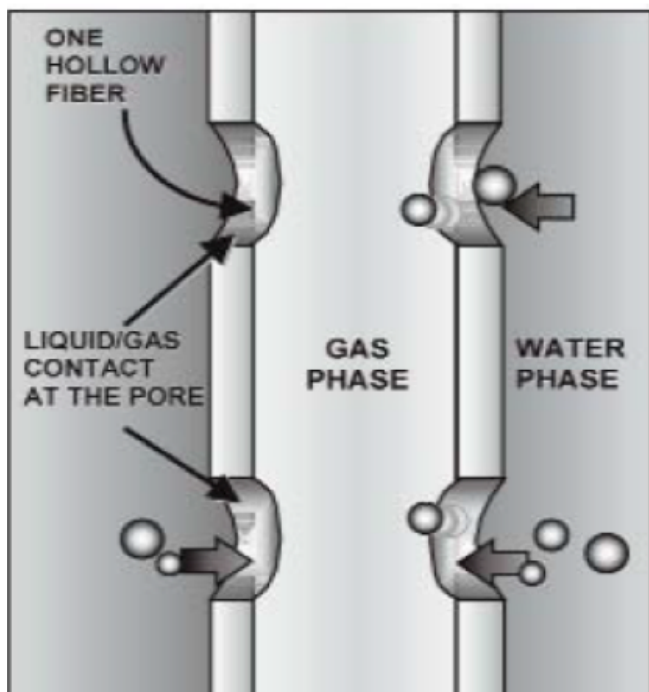


Figure 4. Gas transfer in a hollow fibre (Membrana, 1997).

For the water to pass through the hollow fibre into the gas phase on the lumenside, a break-through pressure would have to be achieved. This is normally far in excess of any operating pressure the fibre will see during its life and can be calculated from a modified Young-Laplace equation as follows (Wiesler, 1996):

$$5. \quad P = -2\sigma \cos \theta / r$$

Where

P = Breakthrough pressure
 θ = Contact angle
 σ = Surface tension of the water
 R = Radius of pore in microporous membrane

The hydrophobic polypropylene hollow fibres have a pore size of 0.05 microns and a break-through pressure capacity of over 10 barg (1000 kPag).

Measuring the ratio of inlet dissolved gas concentration to outlet dissolved gas concentration allows a simple model to be developed using multi-stage column equations (Ibid).

$$6. \quad C_i / C_o = e^{(-kaL / v_o)}$$

Where

C_i = Inlet dissolved gas concentration
 C_o = Outlet dissolved gas concentration
 k = Mass transfer coefficient
 a = Surface area
 L = Length
 v_o = Velocity of fluid

The rate at which a mass can transfer through a medium is termed the mass transfer coefficient (k). The reciprocal to this is the resistance to transfer through a medium, which when individual reciprocal mass transfer coefficients are added equates to the overall mass transfer coefficient reciprocal.

$$7. \quad 1 / K_{ov} = 1 / K_i + 1 / K_m + 1 / K_v$$

Where

K_{ov} = Overall mass transfer coefficient
 K_i = Liquid phase mass transfer coefficient
 K_m = Membrane mass transfer coefficient
 K_v = Vapour phase mass transfer coefficient

For gas molecules to migrate from the liquid side of the fibre to the gas side of the fibre, the molecules must move through water molecules and diffuse through the gas molecules inside the pore to make the transfer complete. It is the water phase that forms the majority of the resistance to mass transfer for the oxygen and indeed to such an extent as to make both the gas and membrane fibre resistance negligible (Yang et. al., 1992).

Inside and outside hollow fibre flows have mass-transfer coefficients that can be correlated. Noting that the resistance comes predominantly from the water phase, the correlation can be expressed in terms of the membrane and the water velocity in contact with it (Reid et. al., (1993). A hollow fibre with an internal water flow correlates as:

$$8. \quad K_d / D = 1.62 (d^2 / v / LD)^{1/3}$$

Where

A hollow fibre with water flowing externally and perpendicular correlates as:

9. $K_d/D = 1.4(dv_o/D)^{1/3}$

Where for both correlations (No 8)

k = Mass transfer coefficient
d = Fibre diameter (Inside for Eqn 8 and outside for Eqn 9)
D = Diffusion coefficient of oxygen in water
v = Actual water velocity
L = Length of the contactor
Vo = Superficial water velocity

In terms of overall performance of a membrane fibre to deliver gas transfer effectively, a simple and good operating measure is the percentage removal of a gas from a liquid. The gas concentration at inlet versus the gas concentration at outlet, (Wiesler, 1996).

10. $[(C_i - C_o)/C_i] \times 100$

Where

Ci = Inlet concentration
Co = Outlet concentration

PLANT DESCRIPTION

The MAR deoxygenation package forms part of the pre-treatment process, and is designed to reduce dissolved oxygen (DO) in the water prior to re-injection. The required reduction in DO is to achieve discharge level of less than 0.5 mg.L⁻¹ (500 ppb).

The deoxygenation plant consists of several major components, and some ancillary equipment. The major components are mounted on 4 interconnected transportable skids. The key components installed are as follows:

- ▶ 4 x Low pressure centrifugal feed pumps
- ▶ 2 x Micron cartridge filters (19 filters per unit)
- ▶ 2 x Centrifugal service water pumps
- ▶ HMI/PLC
- ▶ Analysis board - Wet racks
- ▶ 3 x Liquid-ring vacuum pumps
- ▶ 18 x Gas transfer membrane contactors
- ▶ 2 x air compressor units
- ▶ 2 x refrigerant type air dryers
- ▶ Air accumulator
- ▶ PSA nitrogen generator

- ▶ Nitrogen storage unit
- ▶ 4 x High pressure centrifugal discharge pumps
- ▶ Clean-in-place system
- ▶ CIP air operated double acting diaphragm pump
- ▶ Plant gauges and sensors
- ▶ Plant instruments and meters
- ▶ Pipe work and valves
- ▶ Electrical power supply & VSD's
- ▶ Glass lined balance tank

Coal seam gas associated water (CSGAW) is desalinated using reverse osmosis (RO). Desalinated Water (DW) is stored in a balance tank. This water is then transferred 20 metres through a DN400 mm HDPE pipe to four (3 duty + 1 standby arrangement) KSB Multitec low pressure pumps on the inlet of the de-oxygenation package and also to feed two service water pumps, which operate in a duty/standby configuration. The pumps operate under positive suction pressure from the balance tank.

The DW water is pumped to two duty cartridge filters using the Multitec pumps, for removal of particles above five micron that may have come through or have been picked up post RO. These pumps are designed to run under maximum conditions of 375 kL/hr and 1500 kPa. The turn down rate is to 10% or 37.5 kL/hr at 1500 kPa.

The quality of the water entering the plant is measured through a wet rack that takes a side stream of the forward flow from the service water pumps and measures the conductivity, temperature, pH, flow, and dissolved oxygen of the water. Mechanical pressure protection of downstream membrane contactors is achieved through the use of a pressure relief valve that can free flow to a site drain. The other two pumps that operate in duty/standby configuration are centrifugal type and operate at 3.3 kL/hr and 200 kPa. These pumps feed water to service liquid ring vacuum pumps in the downstream process.

The system designed allows for the potential of blending the desalinated water pre-deoxygenation to the package plant and as such the plant utilises two horizontal PALL Ultipleat® high flow filters. Each filter housing contains 19 filter elements that filter the incoming water down to five micron. Each filter unit can accommodate 100% of the maximum flow but operate under normal conditions on 50% to each unit.

The Ultipleat® High Flow XL filter is a large diameter, coreless, single open ended, pleated cartridge with an inside to outside flow pattern. The spacing between the pleats within the filter has been optimized to deal with applications with moderate solids loadings. The filter's unique crescent-shaped pleat geometry, combined with its large six inch (15.24 mm) diameter allows significantly fewer filters and smaller housings for high flow rate applications, (PALL Filtration, 2012).

The membranes are the main plant unit process consisting of 18 gas-transfer membrane contactors. The heart of the de-aeration plant is the Membrana "Liqui-Cel®" membranes. This is where the DO in the feed water is removed, and ultimately wasted to the atmosphere. The gas-transfer membranes are a semi-permeable membrane that allow oxygen to pass through, whilst minimising the pass through of water. Highly pure nitrogen is the sweep gas used on the gas side of the membrane to deplete the DO on the liquid side. The nitrogen is generated on site from compressed air, as air contains approximately 78% nitrogen.

A liquid ring vacuum pump draws the nitrogen across the membrane on the gas side, and oxygen passes across the membrane into the nitrogen stream, and is ultimately wasted to atmosphere.

The membrane is contained in a pressure vessel creating a single contactor. The plant is designed for a total of 18 membrane contactors, arranged in six banks of three contactors each. The process design performance is based on five banks and 15 membrane contactors. This allows for clean in place (CIP) and routine maintenance on the membranes without a loss in productivity and downtime.

Figure 5 is a schematic diagram of a typical Liqui-Cel® contactor for process description purposes as the deoxygenation membranes herein used standard RO vessel housings. Each vessel has four ports, namely sweep gas in, sweep gas out, process water in and process water out. The contactors used in this description are Liquicel's "Extra-Flow" design, which uses a radial liquid flow path for the process water, around a central baffle, (Membrana, 2012).

Inside the Liqui-Cel contactors are a very large number of micro-porous

polypropylene hollow fibres, arranged around a central distribution tube. Each fibre has an outside diameter of typically 300 microns, and a bore of typically 200 microns. The fibre material is hydrophobic, and therefore resists the passage of water through the pores. The passage of gas through the pores is resisted by ensuring that the pressure on the RO permeate side is higher than the pressure on the sweep gas side.

In normal operation, liquid (the RO permeate being de-gassed) passes on the outside (shell side) of each fibre, while the sweep gas (nitrogen) passes through the inside (lumen side) of each fibre. The contactor operates in counter-flow mode, which means that the sweep gas flows in the opposite direction to the water, (Ibid).

When nitrogen sweep gas comes into contact with the process water at the pores, the DO in the process water attempts to equilibrate with DO in the sweep gas (which is near zero). As a result, oxygen passes through the pores from the process water to the nitrogen sweep gas stream. Using multiple banks, and a counter flow arrangement, ensures that the DO concentration in the sweep gas stream is as low as possible, maximising the amount of DO that can be removed, (Ibid).

The contactors are operated in sweep/assisted vacuum (combo) mode to provide the most efficient operating methodology for achieving low DO concentrations in the product water.

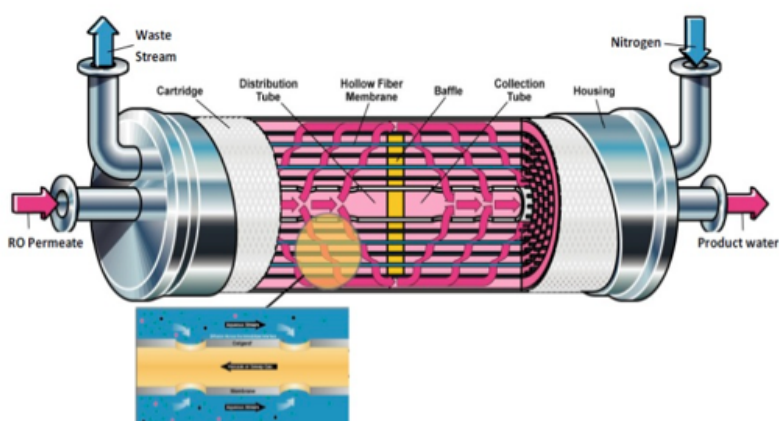


Figure 5. Gas transfer membrane contactor (Membrana, 2012).

The operating method simply means that the nitrogen is applied under low pressure to the contactor sweep gas inlet port, and a vacuum is applied at the sweep gas outlet port. This ensures optimum flow of the sweep gas through the contactor, and maximises extraction of the waste gas (oxygen). Also, lowering the gas pressure on the lumen side of the membrane increases the partial pressure differential for oxygen compared to the RO permeate, which increases the transfer rate of oxygen through the pores, (Ibid).

Treated Desalinated Water (DW) below the maximum value of 0.5 mg.L^{-1} DO is fed through a DN250 mm stainless steel pipe to four (3 duty + 1 standby arrangement) KSB Multitec high pressure pumps on the discharge of the de-oxygenation package. The pumps operate under positive suction pressure of 1000 kPa. The DW Water is pumped to the MAR injection point using the discharge Multitec pumps as an 'in-series' pump system to generate the required discharge pressure. These three pumps together are designed to run under maximum conditions of 375 kL/hr and 2500 kPa. The turn down rate is to 10% or 37.5 kL/hr at 2500 kPa.

The quality of the water leaving the plant is measured through a wet rack that takes a side stream of the forward flow and measures the conductivity, temperature, pH, flow, and dissolved oxygen of the water. The clean-in-place (CIP) system operates on a return loop between the membrane contactor banks and the CIP make-up system.

The compressed air for the plant is generated by two Atlas Copco duty/standby oil free reciprocating compressors. The air is treated for moisture via a refrigerated air dryer designed to maintain a pressure dew point (PDP) of less than five degrees Celsius as required by the pressure swing adsorption (PSA) nitrogen system. The compressed and dried air flows to and is treated via a 1 micron and then 0.01 micron filter train to remove particulate, water and oil from the stream before entry to the PSA unit to protect the sieve material inside the PSA. The compressed air flows into the bottom of one of two sieve beds. The sieve beds are packed with a molecular sieve. As the air flows up through a sieve bed, the molecular sieve physically captures the oxygen molecules, while allowing the nitrogen molecules to pass. The nitrogen molecules flow through the sieve and out of the top of the sieve bed. As the nitrogen exits the sieve bed, it flows into a tank for storage and use, (OSGS, 2012).

Instruments monitor the purity and pressure of the nitrogen in the receiving tank. The control system uses the pressure information to start and stop the nitrogen generator, maintaining the desired pressure (amount of nitrogen) in the tank.

After a short time, the molecular sieve in the sieve bed becomes saturated with oxygen, and it can no longer remove a sufficient amount of oxygen from the air. At this point (after a pre-determined time), the control system directs the flow of incoming air to the second sieve bed via a series of internal valves inside the PSA cabinet so that nitrogen generation can continue. While the second sieve bed generates nitrogen, the system purges the oxygen from the first sieve bed by opening a series of exhaust valves. The opening of these valves allows the air in the saturated sieve bed to exhaust and effectively regenerate ready for the next cycle. The system swings back and forward on this cycle to allow for a constant production of nitrogen, (Ibid).

The nitrogen feed to the membrane contactor banks is pulled through the system at a rate of 17 NkL/hr and 10 kPa (absolute) via two duty and one standby vacuum pumps. The vacuum line containing nitrogen and air is then vented to atmosphere above the roof of the plant. As the nitrogen and air is vented it moves through a condensate trap to remove liquid vapour to the skid drain that subsequently discharges to a common plant drain.

The pumps used are liquid ring vacuum pumps. The water for these pumps is delivered from the service water pumps in the plant.

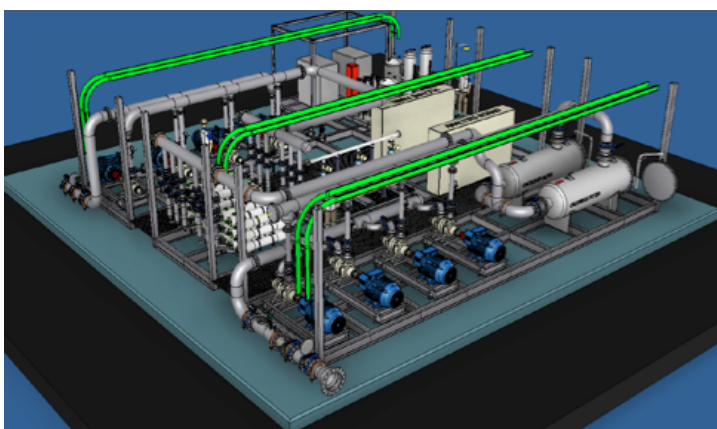


Figure 6a. MAR Deoxygenation Package 3D Design Development, (Waternish Engineering)

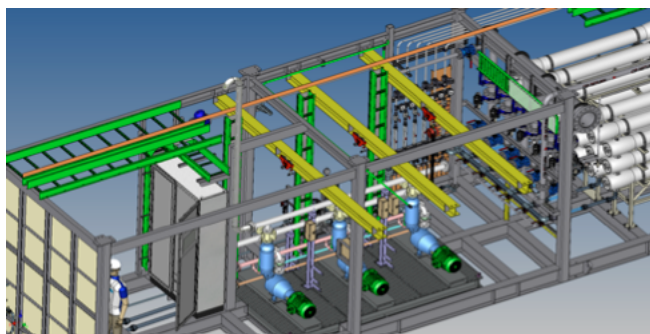


Figure 6b. MAR Deoxygenation Package 3D Design Development, (Waternish Engineering)

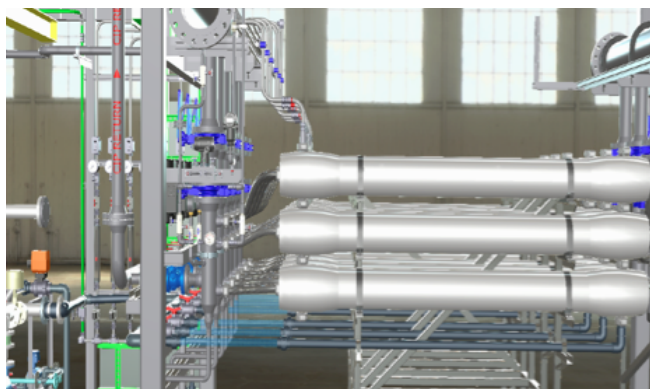


Figure 6c. MAR Deoxygenation Package 3D Design Development, (Waternish Engineering)



Figure 6d. MAR Deoxygenation Site Photo, (Waternish Engineering)

Figure 6a, 6b, 6c show design development for the MAR deoxygenation package and 6d shows a site photo.

The pumps used are liquid ring vacuum pumps. The water for these pumps is delivered from the service water pumps in the plant.

RESULTS AND DISCUSSION

The overall solution was driven by the deoxygenation process. The selection of the type and amount of gas transfer membranes was critical not only to deoxygenation in itself but also to the plant as a whole. The plant had stringent availability and reliability requirements that required back-up and standby systems to be in place for instruments, pumps and equipment while allowing for both cleaning and soft maintenance in-place to be carried out.

Initial theoretical calculations were carried out to narrow the search requirements around deoxygenation and plant requirements and this was then followed up with detailed numerical analysis using a proprietary software from Liqui-cel called GasCAD. Using GasCAD software allowed the author to iterate several solutions during the initial design phase so as to optimise for both deoxygenation and overall plant equipment effectiveness.

Based on applying maximum and average inlet conditions the expected outlet conditions were predicted. This included inlet to outlet oxygen concentrations and gas removal efficiency, nitrogen sweep gas flowrates required, nitrogen purity, vacuum pressure requirements, pressure drops across the membranes, heat loads, and of course type, number and configuration of gas transfer membrane contactors. Table 1 identifies final options selected for the MAR package.

From the GasCAD derived data it was decided to adopt 18 membrane contactors consisting of six, three contactor, banks. Five banks would operate in parallel to achieve a required flowrate of 375 kL/hr against a discharge pressure to the aquifers in the range of 2000 - 2500 kPa.

This then allowed for one bank to be off-line for a clean-in-place activity when necessary. The prevention of fouling of the membranes is controlled upstream of the process in the pre-treatment system, which can include standard physico-chemico process operations and reverse-osmosis filtration, but when fouling does occur this is detected through the reduction in efficiency of dissolved oxygen removal and an increase in differential pressure across the membranes. Service life of membranes can be over ten years under ideal operating conditions (Membrana, 2012) and replacement costs are low relative to the overall plant.

Table 1. GasCAD Software Results for Deoxygenation

Design Criteria	Unit	Option 1	Option 2	Option 3	Option 4
Membrane Contactor		8x80	8x80	8x80	8x80
Membrane Fibre		X-40	X-40	X-40	X-40
Feed Flow	m ³ /hr	375	375	375	375
Temperature	°C	10 (max of 35)	10 (max of 35)	10 (max of 35)	10 (max of 35)
pH	pH	7.2	7.2	7.2	7.2
Inlet O ₂	ppb	10,000	10,000	10,000	10,000
N ₂	ppb	18,150	18,150	18,150	18,150
Average Outlet O ₂	ppb	187	97	233	125
Maximum Outlet O ₂	ppb	319	164	400	125
Minimum Gas Removal O ₂	%	96.81%	98.36%	96.00%	98.75%
No. of Contactors Required	No.	15	18	15	18
No. Parallel Trains	No.	1	1	1	1
No. in Series	No.	1	1	1	1
Approximate Pressure Drop: less pipe loss	K/cm ²	3.78	2.69	3.78	2.69
Operating Mode		Combo w/ N ₂	Combo w/ N ₂	Combo w/ N ₂	Combo w/ N ₂
Total sweep rate	Nm ³ /hr	17	17	17	17
N ₂ concentration	%	99	99	99	99
Vacuum Volume Flow	m ³ /hr	280.2 @ 10 C / 446 at 35 C	281 @ 10 C / 446 @ 35 C	230 @ 10 C / 331 at 35 C	230 @ 10 C / 331 @ 35 C
Vacuum Pump Type		Liquid Ring	Liquid Ring	Liquid Ring	Liquid Ring
Vacuum Level	torr	75	75	90	90

During site testing the overall back pressure on the system was controlled by the actuated control valves at the well heads. Discharge from the MAR package was up to three wells simultaneously.

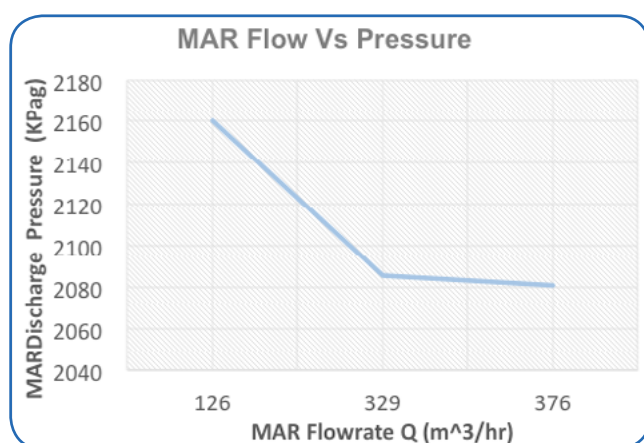

Figure 7. Flow Vs Pressure for MAR Package.

Figure 7 shows the pressure for three flow ranges on the MAR package from the well heads. Note that as the back pressure was artificially controlled at the well heads with control valves the flow-pressure relationship is not shown as linear as would be expected. This does show that the overall plant hydraulics reached nameplate status, i.e. 375 kL/hr at 2000 – 2500 kPa.

The flow to each membrane contactor at maximum design flow was 25 kL/hr. The numerical analysis from table 1 calculated a pressure drop of 378 kPa across the membrane contactor. Figures 8 and 9 show an expected theoretical pressure drop curve for the same membrane contactor and the actual pressure drop measured on site respectively. It shows 390 kPa for theory versus 400 kPa under site conditions. This shows the the pressure drop theory for the membranes held true under initial conditions for this site.

The vacuum pressure and nitrogen flowrate derived from GasCAD was 10 kPa (absolute) with 99% pure nitrogen flowing at a sweep rate of 17 NkL/hr. Figure 10 shows the the vacuum pressures and nitrogen flowrates on site. Under package nameplate conditions the vacuum pressure at the liquid-ring vacuum pumps and on inlet to the membrane contactors held steady at -91 (9 kPaa) and -80 (20 kPaa) kPa respectively. This was in-line with the requirements from the design analysis. The nitrogen levels from the numerical analysis were based on 17 NkL/hr or 18 NL/min/contactor. The recorded values on-site were lower with a flowrate recorded of 14 NL/min/contactor. It must be noted here that site findings observed by the author found that air infiltration through loose fittings in the supply pipework and the quality and pressure of the nitrogen supply contributed greatly to how the system performed.

The dissolved oxygen levels recorded on site ranged from 6 – 7 mg.L⁻¹ on the inlet to the plant. The target DO outlet concentration was below 0.5 mg.L⁻¹ and this was achieved on site. Figure 11 shows a graph of the values recorded for DO in versus DO out on site. The DO levels ranged from 0.4 mg.L⁻¹ to less than 0.01 mg.L⁻¹. Due to the nature of site testing and commissioning activities the results were taken at different times and days.

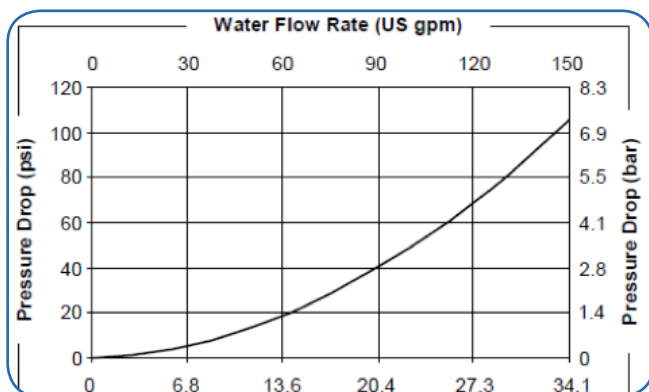


Figure 8. Membrane Contactor Pressure Drop (Membrana, 2012)

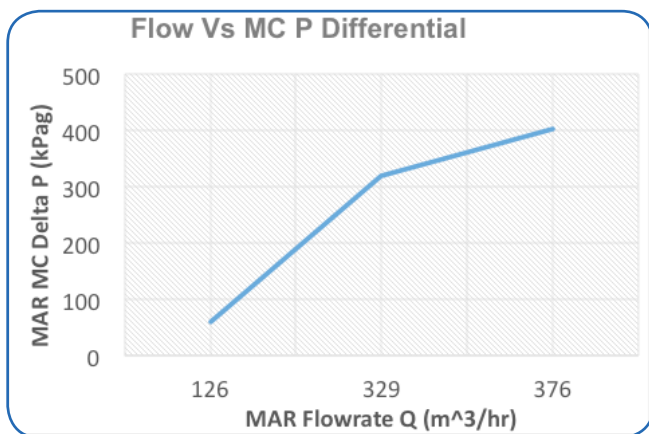


Figure 9. Membrane Contactor Pressure Drop under Site Conditions

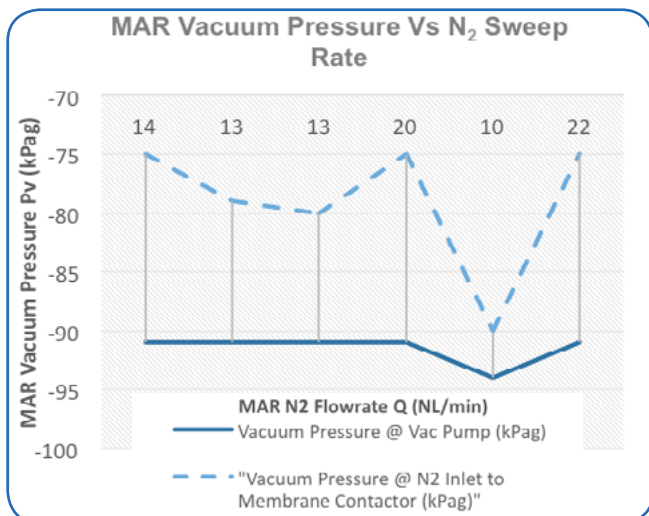


Figure 10. Membrane Contactor Vacuum Pressure and Nitrogen Sweep Rate under Site Conditions.

Issues around instrumentation sample lag times and general plant and site activities did affect the DO instrument readouts. Under steady-state conditions the DO on the outlet was below the target of 0.5 mg.L⁻¹ but the graphed data in figure 11 does not show the expected linearity.

Figure 12 shows the theoretical curve of maximum dissolved oxygen removal. At a flowrate of 25 kL/hr, equating to 375 kL/hr for the total plant, the DO removal rate is up to 99.2 %. Numerical analysis results from table 1 shows a minimum DO removal of 96.81 %.

Figure 13 shows theoretical, numerical and actual site DO removal efficiencies. The site value of 98.4% was in-line with design expectations. The final value recorded for dissolved oxygen on discharge from the MAR package was 0.098 mg.L⁻¹.

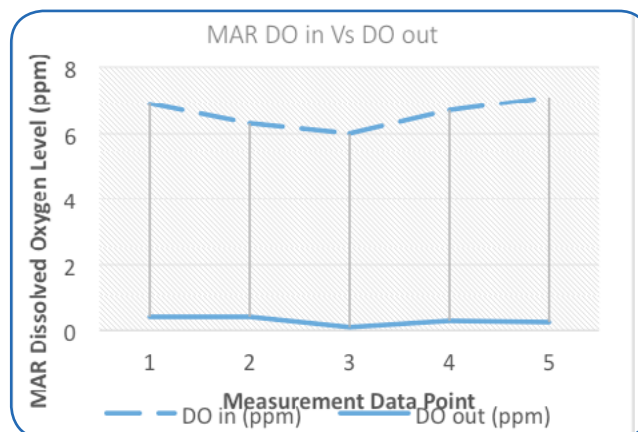


Figure 11. MAR Dissolved Oxygen Inputs Vs Outputs under Site Conditions.

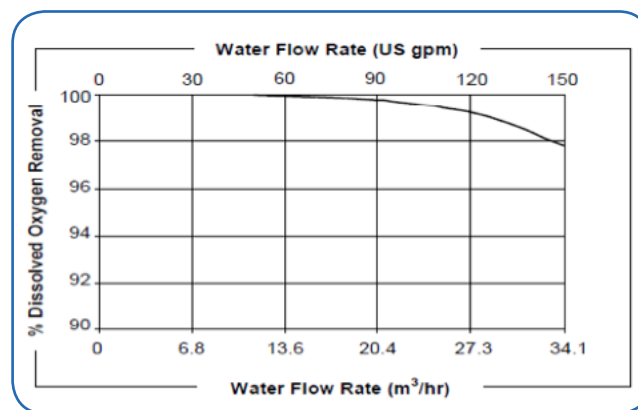


Figure 12. MAR Dissolved Oxygen Removal Percentage, (Membrana, 2012).

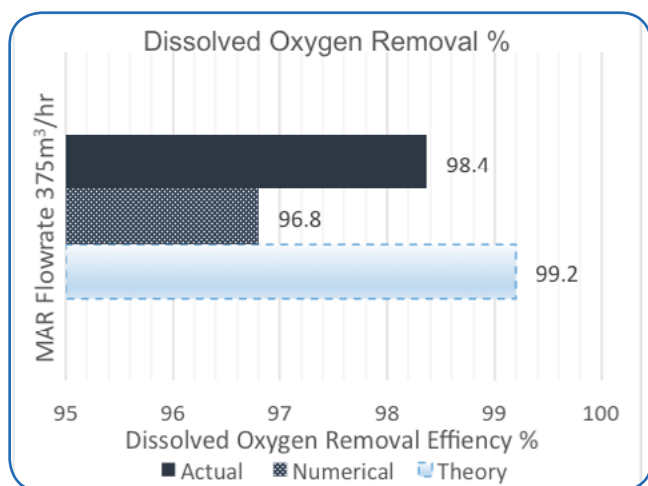


Figure 13. MAR Dissolved Oxygen Removal Percentage - Actual Site Conditions.

CONCLUSION

The efficacy of utilising membrane contactors for dissolved oxygen removal was established during the course of this project. Overall the MAR deoxygenation package operated to design levels at a flowrate of 375 kL/hr against a pressure of 2100 kPa and a reduction in dissolved oxygen of 98.4 % to a value of 0.098 mg.L⁻¹ of DO in the treated CSG associated water. Plant operating analysis elucidated on the importance of vacuum line integrity to the process and that the purity of the nitrogen sweep gas and vacuum pressure were vital to high-end performance.

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