AGL Gas Import Jetty Project Crib Point, Western Port

Chlorine in seawater heat exchange process at Crib Point

FINAL

30 August 2018

Environmental Scientists and Engineers
www.cee.com.au

AGL Gas Import Jetty Project
Crib Point, Western Port

Chlorine in seawater heat exchange process at Crib Point

Contents

Tables

Figures

Report to	Report prepared by
	Scott Chidgey
	CEE Pty Ltd
	Unit 4, 150 Chesterville Rd
	Cheltenham, VIC, 3192
	Ph. 03 9553 4787
	Email. chidgey@cee.com.au

CEE (2018)

Cover photo: Cribb Point Jetty (S Chidgey)

Document History

Document Details			
Job Name	AGL Gas Import Jetty Project	**Job No.**	IS210700
Document	Chlorine in seawater heat exchange process at Crib Point		

Revision History					
Revision	**Date**		**Prepared By**	**Checked By**	**Approved by**
Final (Ver 01)	27/07/18	Name	S. Chidgey	S Ada	S Ada
Final (Ver 02)	30/08/18	Name	S. Chidgey	S Ada	S Ada

Chlorine in seawater heat exchange process at Crib Point

EXECUTIVE SUMMARY

AGL Wholesale Gas Limited (AGL) is proposing to develop a Liquefied Natural Gas (LNG) import facility, utilising a Floating Storage and Regasification Unit (FSRU) to be located at Crib Point on Victoria's Mornington Peninsula. The project, known as the "AGL Gas Import Jetty Project" (the Project), comprises:

- The continuous mooring of the FSRU at the existing Crib Point Jetty, which will receive LNG carriers of approximately 300m in length
- The construction of ancillary topside jetty infrastructure (Jetty Infrastructure), including high pressure gas unloading arms and a high pressure gas flowline mounted to the jetty and connecting to a flange on the landside component to allow connection to the Crib Point Pakenham Pipeline Project.

AGL has selected Crib Point Jetty in Western Port as the preferred location for the Project as it is an established, operating port. Western Port has an area of approximately 680km^2 and estimated volume of 0.8km^3.

The FSRU will be continuously moored to receive LNG cargos from visiting LNG carriers, store the LNG and re-gasify it as required to meet demand for high pressure pipeline gas.

Regasification involves the heating of LNG using the ambient heat of seawater in Western Port. A daily volume up to 450,000 kL (450 ML/day) of seawater from Western Port will be pumped at a rate of 5.2 m^3/s through heat exchangers in the FSRU. Seawater contains a range of marine biota and propagules that can attach to the pipes and grow into larger individuals that can block the heat exchanger pipes. This biological process can be prevented by the addition of a biofouling inhibitor at the intake to prevent 'biofouling'. In this case, the biofouling inhibitor is produced by electrolysis of seawater at the intake to produce chlorine and hypochlorite.

AGL engaged Jacobs Group (Australia) Pty Ltd and their specialist subconsultants to investigate the potential impacts of the seawater intake/discharge arrangements on environmental conditions in Western Port. Desktop studies were undertaken to investigate the hydrodynamics of Western Port and the ecological effects of the seawater intake and discharge.

The scope of this assessment was to review potential implications to the marine ecosystem of any residual chlorine in the discharge from the FSRU heat exchange discharge. This report was prepared in support of:

- A referral under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act),
- A referral under the Victorian *Environment Effects Act 1978*, and
  Identification of requirements under the Victorian *Flora and Fauna Guarantee Act 1988* (FFG Act).

Section 3 of ANZECC National Water Quality Guidelines provide trigger values for "Chlorine" (free chlorine) to protect freshwater aquatic environments. The guidelines provide a trigger value of 3 µg Cl/ L (0.003 mg/L) for 95 % ecosystem protection and 1 µg Cl/L (0.001 mg/L) for 99 % ecosystem protection in freshwater aquatic environments. ANZECC does not list a

trigger for chlorine in marine (seawater) environments, but recommends use of the 3 µg Cl/ L (0.003 mg/L) trigger as "an indicative interim working value" in marine environments.

Modelling of the seawater discharge via six discharge ports, as proposed by AGL, and desktop and laboratory studies of chlorine behaviour and toxicity in seawater showed that a combination of dilution and time to react with seawater constituents in the marine environment would result in environmentally safe concentrations of chlorine that will protect beneficial uses of the seawater returned to Western Port. Chlorine concentrations in the water discharge will decrease along a gradient from the points of discharge, reaching ANZECC (2000) and USEPA (1985) guideline objectives within an area extending 200 m downstream (north and south) and 60 m east and west of the discharge.

1   INTRODUCTION

1.1   Project overview

AGL Wholesale Gas Limited (AGL) is proposing to develop a Liquefied Natural Gas (LNG) import facility, utilising a Floating Storage and Regasification Unit (FSRU) to be located at Crib Point on Victoria's Mornington Peninsula. The project, known as the "AGL Gas Import Jetty Project" (the Project), comprises:

·   The continuous mooring of the FSRU at the existing Crib Point Jetty, which will receive LNG carriers of approximately 300m in length

·   The construction of ancillary topside jetty infrastructure (Jetty Infrastructure), including high pressure gas unloading arms and a high pressure gas flowline mounted to the jetty and connecting to a flange on the landside component to allow connection to the Crib Point Pakenham Pipeline Project.

Jacobs Group (Australia) Pty Ltd (Jacobs) was engaged by AGL to undertake planning and environmental assessments for the AGL Gas Import Jetty Project. Jacobs engaged CEE Environmental Scientists and Engineers to define the marine environmental characteristics and identify key potential risks to the marine environment from the development and operation of the Project.

1.2   Background

The regasification of LNG at Crib Point will involve the use of ambient seawater to transfer heat for increasing the temperature of the LNG into a gaseous form. The LNG and ambient seawater will pass through a heat exchanger system which includes small metal pipes with high surface area to optimise heat exchange.

Seawater contains a range of marine biota and propagules that can attach to the pipes and grow into larger individuals that can block the heat exchanger pipes. This biological process can be prevented by the addition of a biofouling inhibitor at the intake to prevent 'biofouling' in heat exchanger pipes. In this case, the biofouling inhibitor is produced by electrolysis of seawater at the intake to produce chlorine and hypochlorite (similar to saltwater swimming pool chlorinators).

The seawater discharged from the FSRU heat exchanger will contain residual chlorine from electrolysis of seawater at the intake – the residual chlorine will be managed at less than 0.1 mg Cl_2/L. Electrolysis of seawater creates chlorine, which rapidly reacts in seawater to form a range of short-lived toxicants including hypochlorite and various bromine oxidants. Residual chlorine chemicals in the seawater discharge at Crib Point is recognised as a potential risk to marine environmental values in the vicinity of Crib Point.

The reduction of chlorine in the environment after discharge from the FSRU at a concentration of 0.1 mg Cl_2/L was indicatively modelled by Water Technology (2017) using reduction rate formulae and coefficients from the literature and Water Technology's validated hydrodynamic model for Western Port.

It was recognised that chlorine reduction rates in seawater were dependent on a range of factors including water temperature, local seawater quality, discharge arrangements and initial chlorine concentration. CEE were engaged to review literature, measure chlorine reduction rates in Western Port seawater (in the laboratory) at temperatures representing low, median and upper seawater at Crib Point and to test the toxicity of chlorine in Western Port seawater on a local species.

1.3   Purpose of this report

The purpose of this report was to assess potential implications to the marine ecosystem of any residual chlorine in the discharge from the seawater heat exchange discharge. The objectives are to:

·   Provide information on chlorine chemistry and behaviour in seawater,
·   Model chlorine reduction in the heat exchange discharge,
·   Undertake marine ecosystem toxicity testing of residual chlorine,
·   Determine chlorine guidance values for protection of marine ecosystem values,
·   Assess the extent of effects of the chlorine content in the seawater discharge on the marine ecosystem in Western Port, and
·   Inform the definition of the extent of a regulatory mixing zone for the seawater discharge.

This report was prepared in support of:

·   A referral under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act),
·   A referral under the Victorian *Environment Effects Act 1978*, and
·   Identification of requirements under the Victorian *Flora and Fauna Guarantee Act 1988* (FFG Act).
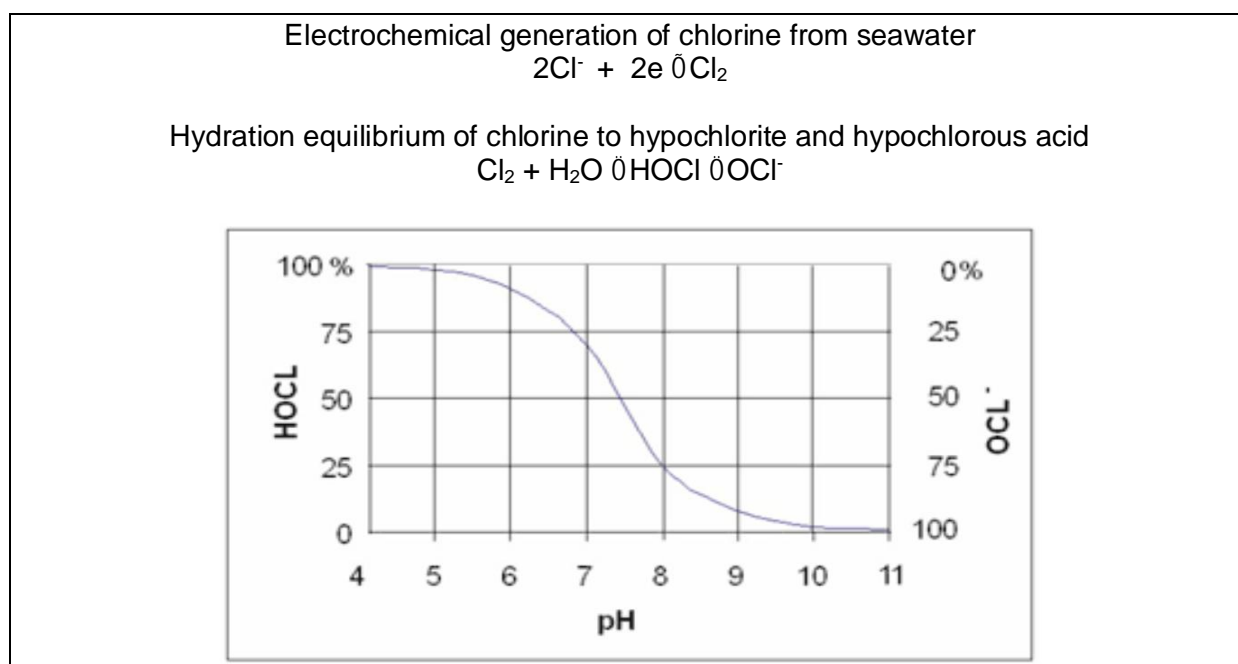
2   FREE RESIDUAL CHLORINE

Chlorine produced by electrolysis of seawater rapidly converts to hypochlorite as well as hypochlorous acid (HOCL). The equilibrium between the three chemicals is pH dependent and the group of all three chemicals is termed Free Residual Chlorine (FRC) or just Chlorine (Cl or Cl_2) for analytical reporting purposes. FRC is used in a variety of applications, including drinking water sterilisation, domestic bacterial disinfection, swimming pool disinfection and algal control, sewage disinfection and biofouling inhibitor controlling biological growth in seawater heat exchangers.

FRC can be conveniently produced by electrolysis of chloride ions in seawater (Figure 1) for disinfection and control of biological growth in industrial heat exchange systems. This is the process proposed to control biological fouling in the FSRU facility at Crib Point.

Figure 1 shows:
- The production of free chlorine from chloride ions in seawater by electrolysis,
- The equilibrium in water between the oxidants chlorine (Cl_2), hypochlorite (HOCl) and hypochlorous acid (OCl⁻), and
- The effect of pH on the equilibrium between hypochlorite and hypochlorous acid.

The pH of seawater is approximately 8.1, so most of the FRC is hypochlorous acid (OCl⁻).

Electrochemical generation of chlorine from seawater
$$2Cl^- + 2e \rightleftharpoons Cl_2$$

Hydration equilibrium of chlorine to hypochlorite and hypochlorous acid
$$Cl_2 + H_2O \rightleftharpoons HOCl \rightleftharpoons OCl^-$$

Figure 1. Hypochlorite – hypochlorous acid equilibrium (Wahab 2012)

Concerns over the effects of FRC in aquatic environments often relate to the formation chloramines, which occur when chlorine components combine with ammonia or other nitrogenous compounds. Chloramines are commonly formed during the disinfection of domestic wastewater effluent due to the relatively high concentration of ammonia and organic material. "Total Residual Chlorine" (TRCs) is usually measured as the toxic residual in chlorinated wastewater and is the sum of free chlorine (Cl_2, OHCl and OCl⁻) and combined chlorine (chloramines).

Ammonia concentration is considerably lower in Western Port seawater (typically <0.01 mg/L, EPA database) than municipal effluent (0.5 mg/L to 5 mg/L in secondary effluent), and so there is negligible potential for formation of significant quantities of chloramines (or bromamines as discussed below) from chlorination of Western Port seawater. Hence, in seawater with relatively low ammonia and organic matter, TRC is the same as FRC.

FRC decomposes through a number of reduction/oxidation processes resulting in off-gassing of chlorine, formation of salt (chloride), acid (HCL) and reaction with organic matter including bacteria and other biota.

Seawater also contains bromide (Br^-), which is another halogen chemical. FRC components react rapidly with the bromide in seawater to form bromine equivalents of the free chlorine chemicals. This process and its implications are discussed below.

2.1 Bromine compounds from free chlorine in seawater

Chlorine, hypochlorite and hypochlorous acid react rapidly (gain electrons) when added to seawater due to the presence of bromine and other constituents in seawater. Bromine is present in seawater as the salt Br^- at a concentration of approximately 70 mg/L (approximately 0.9 mM). Bromine and chlorine are both halides and have similar oxidative characteristics, although chlorine is the strongest oxidant and forms first when an electrical current is passed through seawater.

Following the addition of free chlorine to seawater, there is a rapid chain of reactions with the formation of a series of oxidant products including Cl_2, HClO, ClO^-, HBRO, BrO^- and other halide derivatives. The redox reaction between free chlorine and bromide in seawater (Equation 1) is rapid.

$$HClO + Br^- \ D \ HBrO + Cl^-$$
$$CLO^- + Br^- \ D \ BrO^- + Cl^-$$
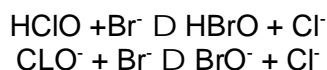
Equation 1. Free chlorine to free bromine in seawater
(Equilibrium in seawater is complete to right hand side)

The free, chlorine-based oxidants (Cl_2, HClO, ClO^-) are very short-lived ($t_{1/2} \sim 0.2$ s) in seawater and are mostly converted to back chloride ions in the marine environment (ANZECC 2000, Saeed *et al* 2015, Wahab 2012).

As a result, most of the chlorine-based oxidants convert the bromide (Br^-) in the seawater to the equivalent bromine oxidants HBrO and BrO^-. Hence the residual "FRC" is mostly bromine rather than chlorine based. (Common terminology continues to refer to the total amount of halogens (chlorine and bromine) in seawater as FRC as discussed below).

Bromine is also an effective disinfectant and biofouling inhibitor. Hence the conversion of chlorine oxidants to bromine oxidants in seawater does not result in a significant reduction in toxicity. In fact, the resulting toxicity from bromine products may be greater than chlorine in the pH range of the seawater. The relationship between free chlorine and bromine in seawater is discussed in a range of industry and regulatory documents on the discharge of disinfected municipal wastewater to marine environments, discharge of chlorinated cooling water to the marine environment and ballast water disinfection (Saeed *et al* 2015, USEPA 1985, USEPA 1991, USEPA 2017, Wang 2008, Wahab 2012). Chlorine and bromine are both halogens and behave in a similar way: chlorine (hypochlorite) is widely used as a domestic and industrial disinfectant and biofouling inhibitor; bromine (as hypobromite) is used as a disinfectant and algal growth inhibitor in swimming pools and spas.

Bromine has advantages and disadvantages compared to chlorine (hypochlorite). Bromine is more effective as an oxidant at pH >7.6, and is less odorous than chlorine. Bromine is more expensive and less commonly available as a domestic or industrial chemical than chlorine and therefore is not used to the extent of chlorine in domestic or industrial applications. However, bromine oxidants are formed incidentally in seawater following chlorination and are therefore a key halogen biofouling inhibitor in chlorinated seawater systems. It is the bromine products of seawater chlorination, particularly hypobromic acid, that is the key growth inhibitor in biofouling prevention systems in seawater heat exchange systems such power station cooling systems and LNG regasification projects.

The other active products of chlorination are longer-lived and reduce in concentration as oxidation continues over periods of hours (see Section 2.3). In seawater with low natural ammonia concentration and a pH of approximately 8.0, hypobromic acid may represent 80 to 99 percent of the oxidants (Figure 2, Wang 2008, Wahab 2012). There are various decomposition (reduction) models of first-order and second-order reduction of chlorine in seawater (Saeed *et al* 2015).

Reduction rates are dependent on numerous factors including initial concentration, temperature, pH, UV light and the presence of other organic, inorganic and metallic constituents.
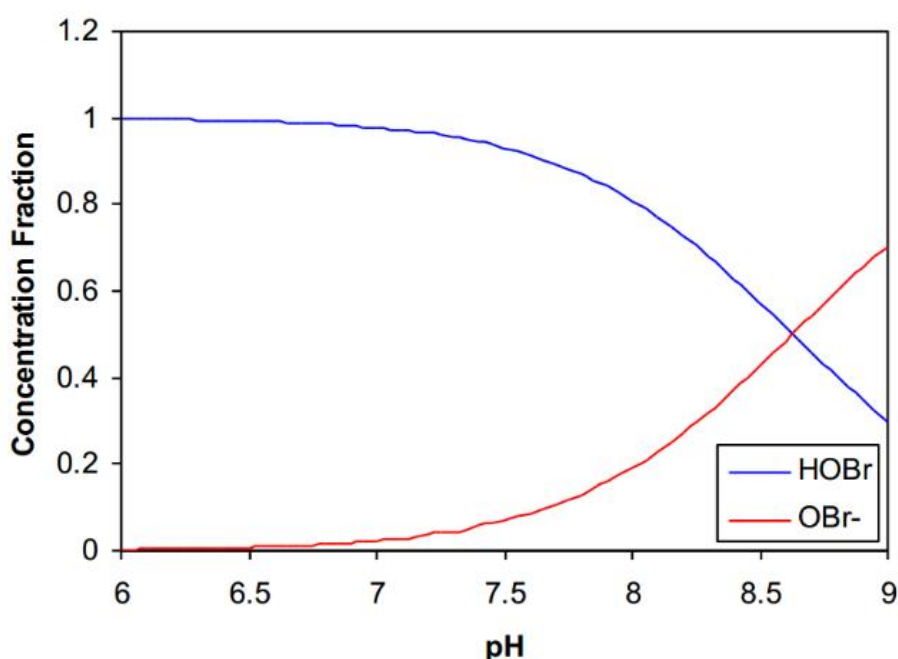
Figure 2. Hypobromite – hypobromic acid equilibrium (Wahab 2012)

Industry and regulatory agencies recognise that the impact assessment of chlorinated oxidants in seawater should include the total pool of halide derivative oxidants present. The pool of chemicals is sometimes termed total residual oxidants (TRO) (USEPA 1991, Wang 2008) or chlorine-produced oxidants (Burton 1977). Analytical methods used to determine total residual chlorine in freshwater and seawater also measure all halogenated oxidants, including bromine. USEPA uses the term Total Residual Chlorine or TRC as the measure of all chlorine-produced oxidants in freshwater or seawater. TRC and TRO is usually as expressed as mg Cl_2 L^{-1} or mg Cl L^{-1} for regulatory purposes (ANZECC 2000, USEPA 1985, 1991). For consistency with results reported in the literature, this report will use TRC.

2.2   Analytical methods for Free Residual Chlorine and Bromine

There are three generally-used methods for measuring free and total residual chlorine in freshwater and seawater samples: amperometric titration, DPD titration method and DPD colorimetric method (USEPA 2017, SOEQ 2014), which is relevant to Sections 2.3, 5 and 6 of this report.

Commercially available portable free chlorine measurement devices have detection limits of approximately 0.02 to 0.05 mg/L (Hach, Merck). These are fundamentally titration devices and measure concentration reasonably quickly (within minutes), although not instantly. As discussed above, the method for quantifying free chlorine or free bromine is the same. Most results are express the result for Total Residual Chlorine (TRC) as mg/L of chlorine. Hence, measurement of TRC in seawater is expressed as mg/L Cl or Cl$_2$, even though most of the TRC is bromine and the proportion of chloramines or bromamines is negligible.

2.3   Factors influencing TRC reduction rate

TRC concentration, and consequently TRC ecotoxicity, reduce in the marine environment in proportion to salinity, temperature, UV light and organic content of the ambient water. ANZECC and USEPA comment that the speed of reduction of TRC in the environment results in uncertainty of interpretation of ecotoxicity results from bioassays, which are usually longer in duration than 24 hours.

USEPA field procedures advise that TRC measurement "must be conducted within 15 minutes of sample collection" (USEPA 2017). TRC reduction rate needs to be determined over periods of hours to determine reduction rates that are relevant to dispersing and diluting chlorinated effluents. Similarly, toxicity bioassays need to reflect short term exposure effects (acute) over temporal scales relevant to discharge dispersion (hours), rather than chronic long-term exposure (days) which is unlikely in the broad environment, but may occur within approximately 20 m of a discharge port).

Laboratory based measurement of free or residual chlorine mass in clear seawater (Wahab 2012, Zeng *et al* 2009) demonstrate that TRC mass reduction rates depend strongly on salinity and temperature (Figure 3 and Figure 4). The reduction rate starting concentrations for these tests was calculated from the amount of chlorine (as hypochlorite) added to a volume of seawater.
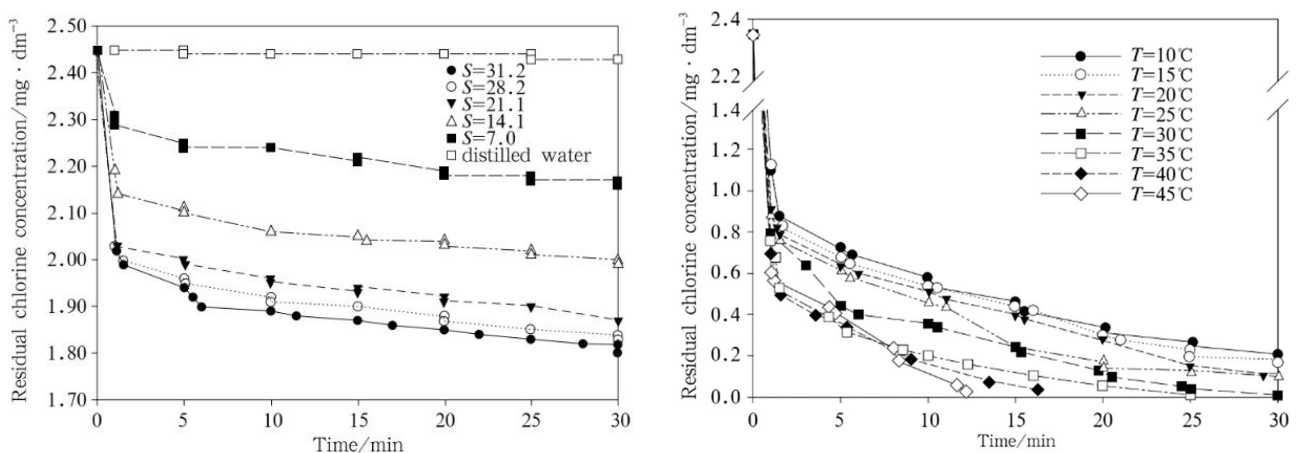

Figure 3. Residual chlorine concentration reduction with salinity and temperature (Zeng *et al* 2009)

Figure 3 shows the reduction in the mass concentration of chlorine measured intensively over 30 minutes. The figure shows a rapid reduction in mass concentration of chlorine in less than two minutes from addition of hypochlorite to seawater. By contrast there is negligible reduction in chlorine distilled water. The initial reduction in chlorine is salinity and temperature dependent.

The subsequent reduction in chlorine from 5 minutes to 30 minutes is relatively linear for different salinities at the same temperature, but appears to be logarithmic or exponential for the variation in temperature. Figure 4 shows the reduction in mass concentration of chlorine in seawater at different temperatures over 96 hours. Note that the fitted curves in some graphs asymptote above zero, whereas concentration at the limit of detection or zero is actually recorded.

Figure 5 shows the reduction in mass concentration of chlorine and the corresponding increase in bromoform mass concentration over more than 240 hours. Both figures include exponential curves to fit the data. The figures show the initial rapid reduction in free chlorine concentration followed by the slower reduction to zero over subsequent days.
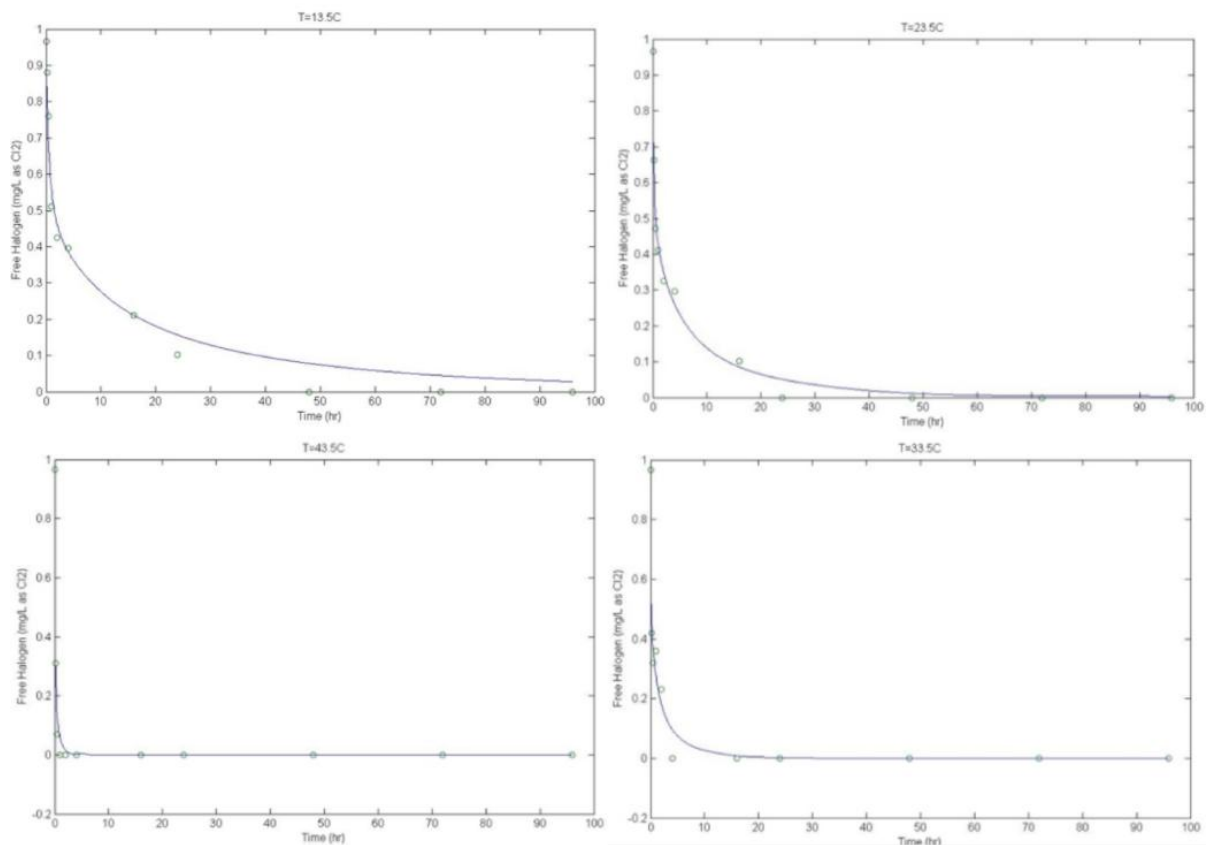
Figure 4 TRC reduction at 13.5°C, 23.5°C, 33.5°C and 43.5°C
(Wahab 2012)
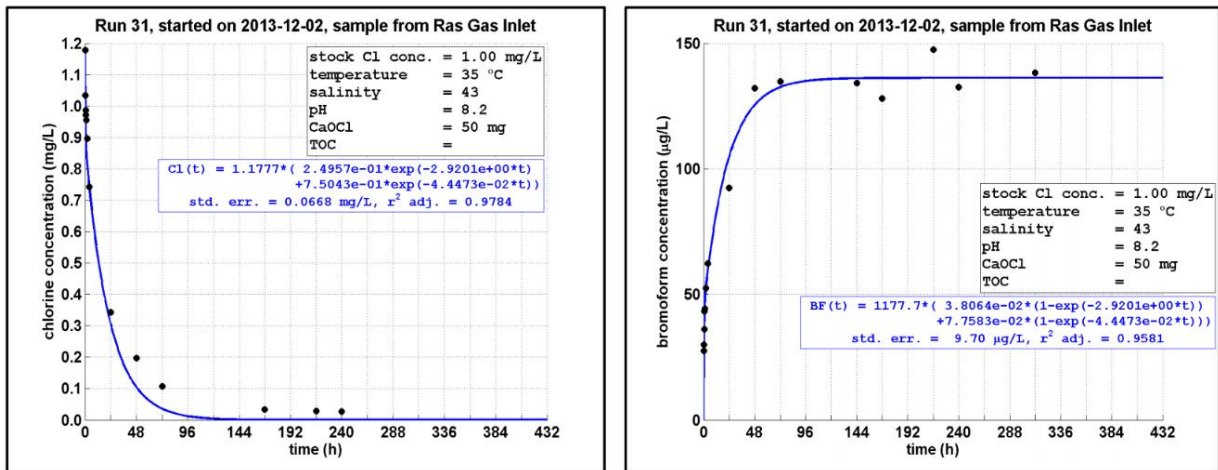
Figure 5. Residual chlorine and corresponding bromoform over >240 hours
(Saeed *et al* 2015)

Models of chlorine reduction in seawater have been described in terms of a first order reduction model for a curve fitted to the data from the beginning of the test to completion (Equation 2):

$$C(t) = C_0 e^{-kt}$$

Equation 2. First order chlorine concentration reduction model

Two-component exponential reduction models also are used in recognition of the different rates in chemical reactions that occur between the initial rapid phase and subsequent slower phase of the chlorine reduction process:

$$C(t) = C_0 (Ae^{-k_1 t} + (1-A) e^{-k_2 t})$$

Equation 3. Two component chlorine reduction rate model
(Saeed *et al* 2015)
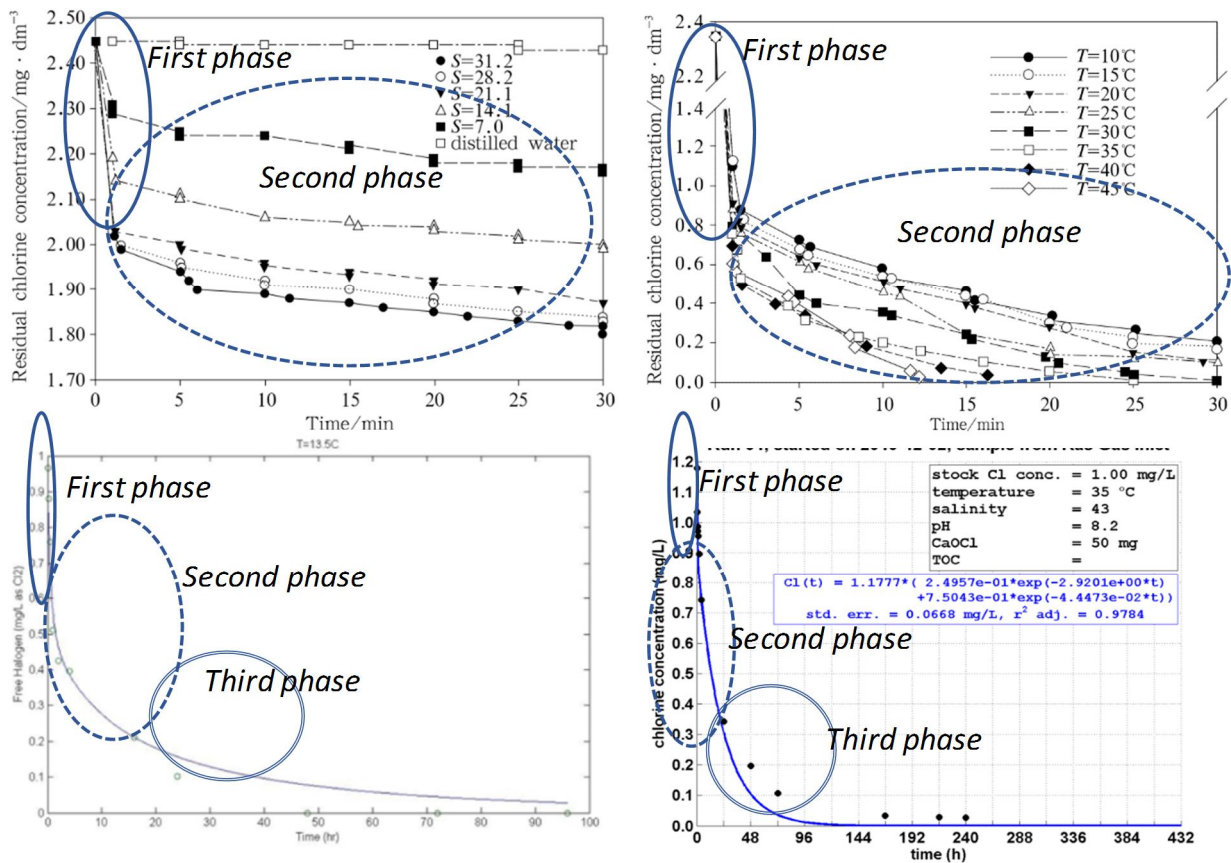
Figure 6. Examples of first, second and third phase chlorine reduction in seawater

The initial reduction rates are too rapid for conventional analytical methods to measure the starting concentrations. Hence starting concentrations must be estimated. For the same reason, there is likely to be variation in measured concentrations in the first minutes of experiments due to rapid reduction in concentrations and the time required for analysis.

Each of these phases will be associated with different stages of the heat exchange and dispersion in the marine environment at Crib Point.

2.4   Need for second and third stage chlorine reduction rate trials at Crib Point

It is proposed that chlorine will be generated at the inlet to the heat exchanger system of the FSRU at Crib Point. The free chlorine will rapidly proceed through the first phase of reduction in minutes, while it passes through the front end of the heat exchange system. The first rapid reduction phase should be complete by the time the seawater has reached the discharge point, so that all free chlorine will have already been converted to free bromine equivalents, and the disinfectant reduction will be proceeding at the slower, second phase rate.

Initial modelling of the FSRU discharge at Crib Point (Water Technology 2017) reduction model using the chlorine concentration of 0.1 mg Cl_2/L predicted by AGL at the discharge point. This approach to estimating chlorine concentration at a point in time includes use of a first or second order decay formula to fit the first, second and third phases of chlorine reduction with a (decay) coefficient that is specific to a particular water temperature.

This method is satisfactory for estimating chlorine concentrations over the far-field (> 500 m) but may over-estimate the loss rate of TRC in the FSRU discharge at distances less than 500 m (near-field) because it includes the rapid first stage of loss chlorine, which occurs within the heat exchanger. By the time the seawater reaches the discharge point, where environmental modelling commences and the initial concentration has dropped from 0.5 to 0.1 mg Cl_2/L, chlorine reduction processes will be in their slower, second or third phases.

Incorporation of chlorine reduction rates into hydrodynamic mixing models of dispersion should include only the slower, post-first phase rate applied to the chlorine concentration at the point of discharge. Hence trials of reduction rate in Crib Point seawater were designed for and implemented for this study as reported in Section 4. The reduction rates were then applied to near-field dilution process models reported in CEE 2018a.

3   REGULATORY GUIDANCE FOR CHLORINE IN MARINE ECOSYSTEM PROTECTION

ANZECC and USEPA discuss the determination of safe levels for TRC in the aquatic and seawater environments. TRC is determined to be an appropriate measure of chlorine-produced oxidants in both environments. Safe environmental concentrations for chemicals are determined by ANZECC and USEPA from statistical analysis of species sensitivity distribution resulting from numerous rigorously performed bioassays on suitable aquatic plants and animals. These bioassays may expose biota (mostly invertebrates and waterweeds) or developing biota (seeds, gametes, fertilisation processes or propagules) to a toxicant for hours, but are most often exposure is for days, typically 2 to 4 days.

Section 3 of ANZECC National Water Quality Guidelines provide trigger values for "Chlorine" (free chlorine) to protect freshwater aquatic environments. The guidelines provide a trigger value of 3 µg Cl/ L (0.003 mg/L) for 95 % ecosystem protection and 1 µg Cl/L (0.001 mg/L) for 99 % ecosystem protection in freshwater aquatic environments. However, there is not a trigger for chlorine in marine (seawater) environments. ANZECC explains that: *"In seawater, reaction with bromine results in formation of chloride ion and HOBr"*, but does not provide a marine ecosystem protection level.

The ANZECC guidelines recognise three levels of ecosystem protection described below with the corresponding ecosystem protection level.
1. 99 percent protection: High conservation/ecological value systems – including reserves such as Ramsar wetlands.
2. 95 percent protection: Slightly to moderately disturbed systems
3. 95 percent protection: Highly disturbed systems, although "lower protection levels…may be accepted by stakeholders"

Further detailed discussion of chlorine as a toxicant in Section 8.3 of ANZECC, states that *"Chlorine does not persist for extended periods in water but is very reactive and its by-products persist longer".* Hence, toxicity limits in ANZECC were derived from measurement of total residual chlorine as µg Cl/ L, and that, in marine water containing iodide and bromide, total residual oxidants were measured as µg Cl per L. The ANZECC trigger values for chlorine include chloramines and bromine oxidants as total chlorine produced oxidants. ANZECC further states that the 3 µg Cl/ L for 95 % ecosystem protection trigger for freshwater was considered of low reliability but was "*adopted as a marine low reliability trigger value, to be used only as an indicative interim working value.*" (No value was discussed for 99 % marine species protection, and no total residual chlorine values are listed for marine waters in ANZECC Table 3.4.1 Trigger Values for Toxicants.)

USEPA 1985 notes that the bioassays used to determine USEPA environment protection concentrations for TRC required flow-through systems to maintain the concentration of TRC at constant levels throughout the period of longer term tests and rejected the results of short term tests (3 hours). USEPA considered, however, that the results of the short-term tests were "useful for modelling purposes and for making decisions concerning this particular application", in this case "to simulate discharges from specially controlled chlorination of cooling systems". Hence, USEPA long term TRC criteria for ecosystem protection are conservative with respect to planktonic or mobile biota and are most relevant to biota constantly exposed to elevated chlorine concentrations such as those within the heat exchangers or attached to substrates that are constantly exposed to the discharge stream such as those attached to the jetty or in the seabed in the shipping basin.

A summary of the ANZECC and USEPA ecosystem protection guidance values for TRC is provided in Table 1.

Table 1. Chlorine ecosystem protection guidance values

Agency	Protection level	Value, mg/L
ANZECC 2000	95% species protection, freshwater and marine*	0.003
USEPA 1985, 1991	Four day mean (chronic), marine	0.0075
USEPA 1985, 1991	One hour mean (acute), marine	0.013

*Value for marine ecosystem "indicative interim working value".

These concentrations are close to or below the limits of practical detection (0.01 mg/L).

A key difficulty in establishing National trigger values is related to the rapid reduction of these oxidants in toxicity tests, particularly in relation to temperature. In one example, "Higher temperatures around 25°C resulted in complete loss of measurable residual chlorine and chloramines from the test vessels within 24 hours".

This is consistent with our review of chlorine chemistry and the chlorine reduction experiments for the Project described in this report. We conclude that the toxicity of discharges containing TRCs will vary between seasons according to water temperature and the sensitivity of regional and seasonal biota.

Temperatures in Western Port range from approximately 11°C up to 22°C over the year and the discharge from the FSRU heat exchanger is a further 7°C below ambient. Hence loss rates are lower at these temperatures as the trials in Section 5 demonstrate, and chlorine loss in the Western Port ecosystem will be substantially lower than those demonstrated in the warmer environments reviewed in Section 2.3.

Trials to determine chlorine reduction in Crib Point seawater at temperatures that occur at Crib Point were designed and implemented as documented in Section 4.

4   MODELLING CHLORINE REDUCTION AT CRIB POINT

The chlorine reduction rate in Crib Point seawater was determined in trial laboratory tests specifically for the initial assessment program. The trial focused on the reduction of chlorine after the first rapid initial phase that occurs over the first four minutes of chlorine addition. Hence, the trials focused on the hours of chlorine reduction after the first initial phase (taken as four minutes in this case).

4.1   Method

Seawater was collected from Stony Point Jetty near Crib Point in Western Port and transported to Ecotox Services environmental laboratory in Sydney. Hypochlorite was added in two volumes to represent 0.5 mg/L and 1.0 mg/L in unfiltered seawater at the commencement of second-phase chlorine reduction at three controlled temperatures representing the seasonal low (12°C), median (16°C) and high (20°C) seawater temperatures typical at Crib Point. Second-phase chlorine reduction was also measured in filtered seawater and artificial seawater at 16°C.

4.1.1   First phase

The first measurement was taken four minutes after initial mixing of chlorine and seawater. This was recognized as the period when fastest chlorine reduction would occur within the exchange unit. This rate has low relevance to loss rates in the marine environment after discharge. The experiment focused on the second and third phase reduction rates.

4.1.2   Second and third phase

Free and total chlorine was measured from four minutes after addition of the hypochlorite to coincide with the commencement of second-phase chlorine reduction. Chlorine was measured using a Merck Spectroquant Test Kit, which follows chlorine test procedures and QA/QC recommended by USEPA. There was less than 5 percent difference between free and total chlorine for all measurements.

The total chlorine measurements for all tests are shown in Table 2. Figure 7 shows the results for the unfiltered seawater tests. The table and figure show relatively rapid reduction in chlorine concentration from 4 minutes to three hours and a slower rate from four to 24 hours (240 to 1,440 minutes). The rate of reduction was slower for the lowest temperature (12°C) for both starting concentrations relative to the higher temperatures.

Table 2. Total chlorine in seawater trials using Crib Point seawater, November 2017

Seawater	TRC in Unfiltered samples						Filtered	Artificial
4 minute C_0	0.5 mg/L			1 mg/L			1 mg/L	0.5 mg/L
Temperature	12°	16°	20°	12°	16°	20°	16°	16°
Time, min								
4	0.44	0.39	0.48	1.02	0.94	0.98	1.03	0.48
9	0.47	0.33	0.41	0.99	0.88	0.93	0.99	0.40
14	0.42	0.32	0.40	0.97	0.87	0.90	0.95	0.32
20	0.41	0.28	0.36	0.95	0.85	0.87	0.92	0.27
35	0.40	0.29	0.35	0.93	0.83	0.87	0.90	0.24
45	0.39	0.28	0.33	0.92	0.83	0.83	0.89	0.23
60	0.38	0.23	0.33	0.90	0.82	0.83	0.86	0.19
90	0.35	0.20	0.29	0.91	0.77	0.79	0.83	0.16
120	0.33	0.17	0.24	0.86	0.74	0.76	0.75	0.14
150	0.32		0.23	0.85	0.72	0.74	0.74	0.13
180	0.31	0.15	0.22	0.81	0.71	0.70	0.73	0.11
240	0.30	0.14	0.22	0.81	0.67	0.71	0.70	0.12
540	0.24	0.11	0.20	0.77	0.52	0.62	0.54	0.10
1440	0.16	0.05	0.11	0.58	0.41	0.46	0.46	0.18
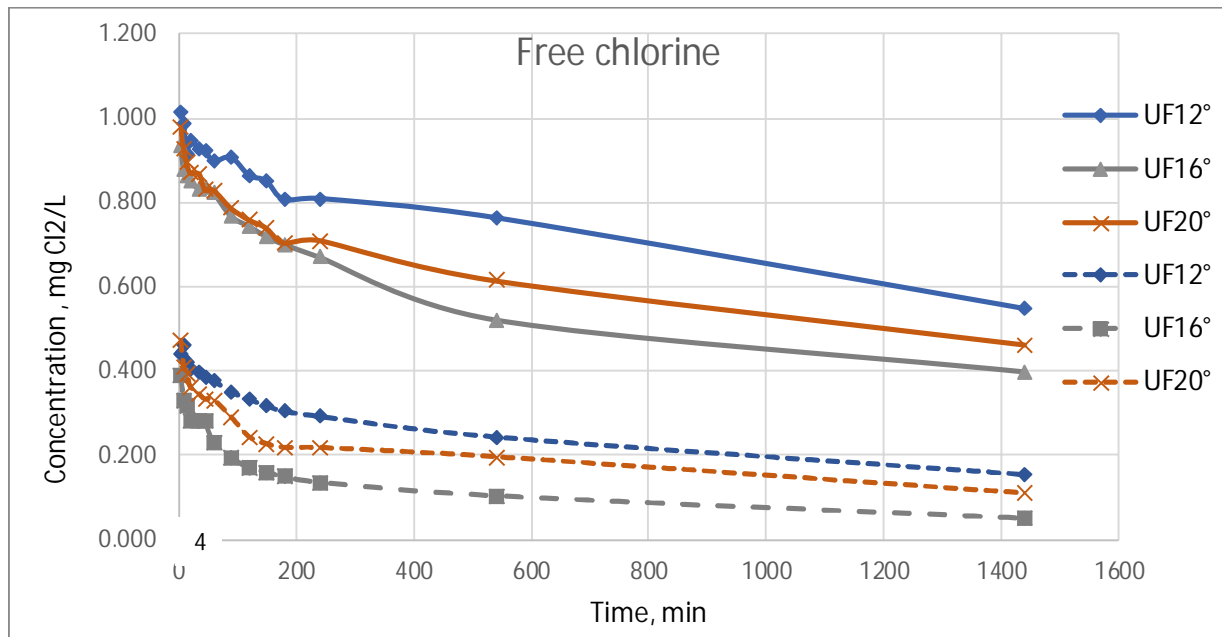
Figure 7. Total chlorine in unfiltered seawater, November 2017

The results were normalised to the starting concentration of each treatment to allow direct comparison of the reduction rates at different temperatures and treatment. The normalised results for unfiltered seawater at different temperatures and starting concentrations are shown in Figure 8.
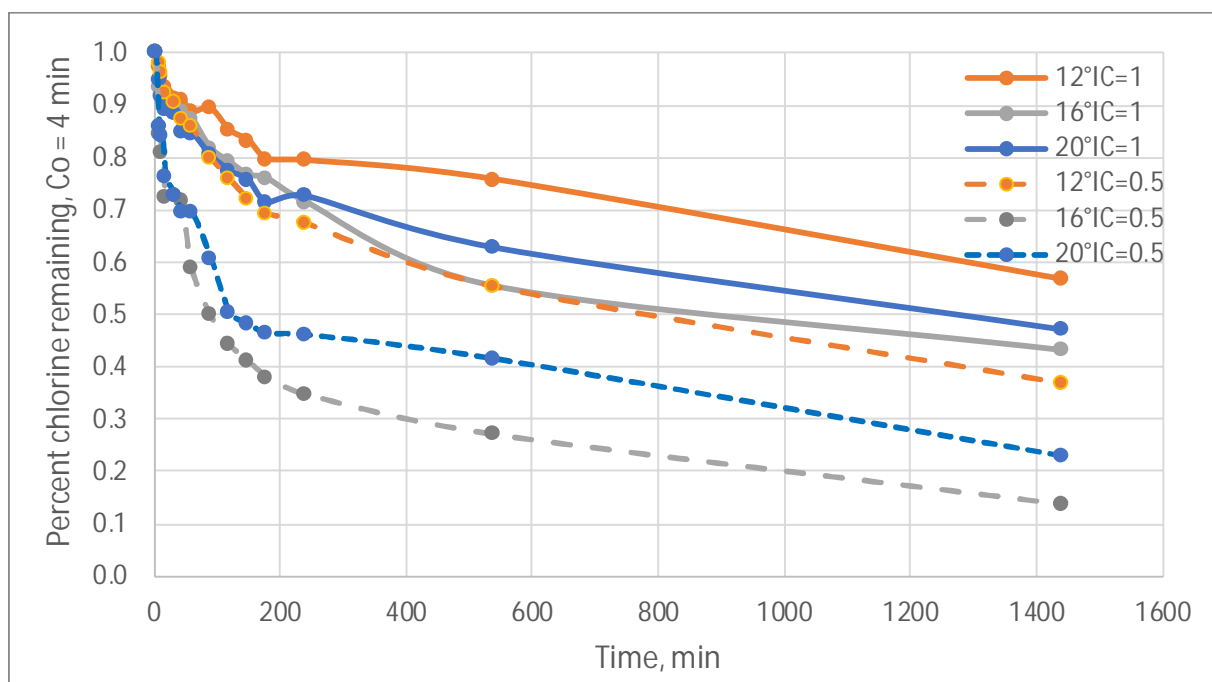
Figure 8. Normalised chlorine in unfiltered seawater, November 2017

The figure of normalised concentrations after the first phase shows:
- Fastest second phase chlorine reduction rates occurred over the initial two hours at higher temperatures (16°C and 20°C) compared to lower temperature (12°C) at the lower starting concentration (0.5 mg/L).
- Fast second phase chlorine reduction rates over the initial two hours at higher temperatures (16°C and 20°C) compared to lower temperature (12°C) at the same higher starting concentration (1.0 mg/L), although these were slower than the reduction rates for the same temperatures at the lower 0.5 mg/L starting concentration.
- Reduction rates were substantially lower three hours after initial dosing than in the first two hours. Third phase would appear to occur approximately 3 hours after initial addition of chlorine.

4.2   Three phases of chlorine reduction in seawater

The published and CEE results indicate three phases of chlorine reduction:
- A first initial phase of reduction over the first minutes of addition of chlorine to seawater that is the result of redox reaction of free chlorine (oxidant) with readily available inorganic seawater constituents including bromine.
- A second slower phase of redox reaction of free chlorine and bromine with relatively reactive organic seawater constituents.
- A third slow phase of redox reaction of free bromine and any remaining chlorine with refractory (stable, relatively unreactive) organic seawater constituents.

These phases of chlorine reduction are consistent with process concepts of 'chlorine demand' in treated wastewater disinfections systems, with the addition of an initial rapid reduction due to the high concentration of inorganic salts in seawater compared to freshwater sewage.
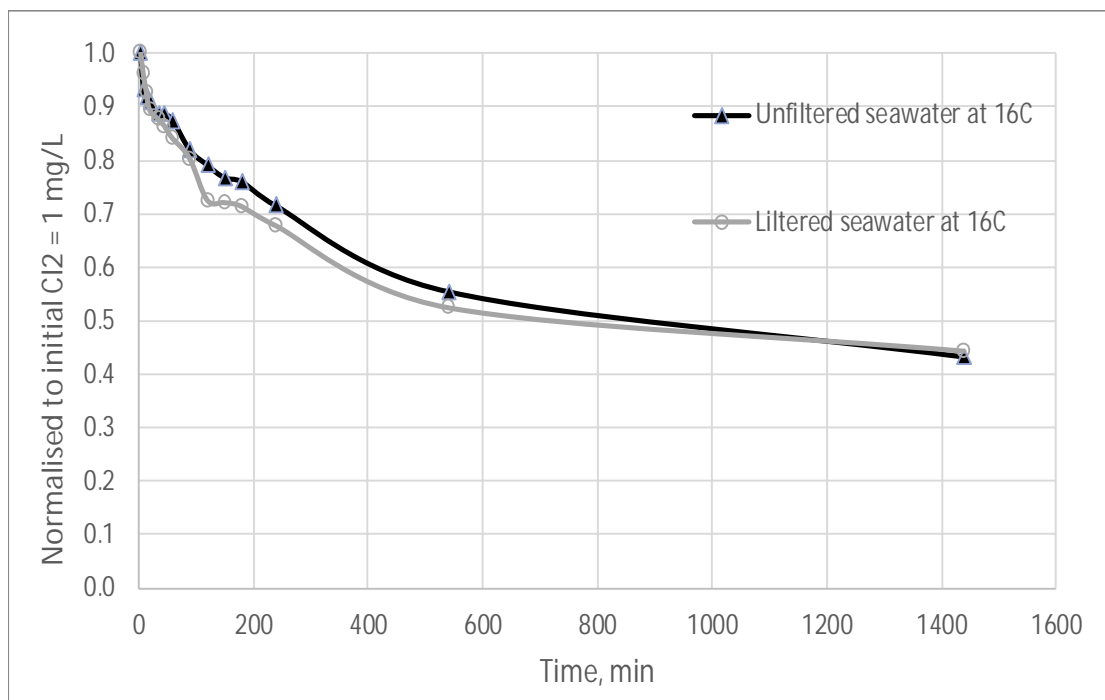
Figure 9. Chlorine reduction rates in unfiltered and filtered seawater

Figure 9 shows negligible difference between the filtered and unfiltered seawater results. This demonstrates that soluble constituents are the key to chlorine demand at the low suspended solids levels found in seawater and that the production of chlorinated organic compounds is expected to be low – especially compared to municipal wastewater discharges.

5 CHLORINE REDUCTION, FSRU SEAWATER PROCESSES AND DISPERSION MODELLING

The three phases of chlorine reduction in seawater identified in the previous section can be compared with the sequence of seawater in the regasification process:

· Chlorine addition: passage of seawater past the chlorinator at the intake to the heat exchanger pipes prior to pump manifolds and pumps

· Initial phase of rapid reduction (first five minutes): seawater passage from chlorinator, through pumps and front-end manifolds.

· Second phase of reduction (five minutes to two hours): middle and latter parts of heat exchange pipework, through the discharge outlets and during initial dilution stage of mixing

· Third phase of reduction (three hours to days): dispersing of already dilute chorine residuals with tidal currents.
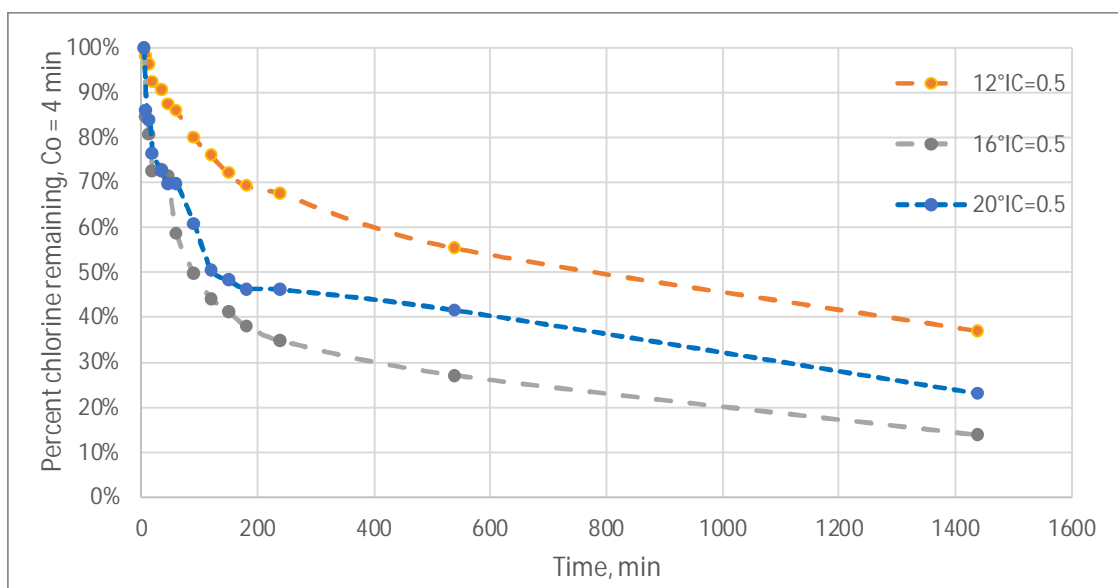
5.1 Chlorine concentration in discharge

The initial and residual chlorine concentration profile within the heat exchange system has been determined based on industry practise and experience. AGL advises that the chlorine concentration at the discharge outlet will be monitored and maintained at a concentration of 100 ppb or 0.1 mg/L. This will allow higher concentrations of chlorine at the intake and through the heat exchanger that will be sufficient to ensure that larvae and propagules do not survive to settle, grow and clog the pipes as they pass through the heat exchanger system.

The chlorine concentration at the outlet (0.1 mg/L) will be the result of the rapid phase chlorine concentration reduction processes due to first contact, mixing and reaction with seawater components within the heat exchanger. The chlorine compounds in the seawater at the discharge after passage through the heat exchanger may be, therefore, in the second phase of concentration reduction.

The previous sections of this report show that the rate of reduction of chlorine in seawater in the second phase of reduction is proportional to the concentration of chlorine at the start of the phase. Hence, rate of reduction is faster at a starting concentration 0.5 mg/L than starting at 1 mg/L as shown in the trial experiments.

The results of the percentage of chlorine remaining from a concentration of 0.5 mg/L at the start of the second phase is shown in Figure 10. It is expected that the rate of reduction of chlorine concentration in seawater at a concentration of 0.1 mg/L at the start of the second phase of reduction would be faster than those shown in the figure.

**Figure 10. Percent chlorine reduction in seawater
from starting concentration 0.5 mg/L**

5.2   Initial physical dilution phase

The initial dilutions were modelled under conservative one and two discharge port options and the preferred FSRU design, incorporating a six port discharge. These scenarios are modelled and discussed in CEE's initial dilution and nearfield modelling report (CEE 2018a) and associated cold-water discharge ecosystem assessment report (CEE 2018b).

Initial dilution is achieved during the stage of discharge when the cold-water containing chlorine is discharged as a jet or jets of seawater at a temperature that is initially 7°C below the ambient surrounding seawater. The jet is therefore more than 1 kg/m^3 more dense than ambient seawater and descends towards the seabed due to gravity and momentum. The jet entrains seawater and descends to the seabed, diluting on the way due to shear between the descending plume and the adjacent seawater. The initial dilution during the descent is higher at high tide compared to low tide and increases marginally at times of stronger tidal current. During periods of relatively low tidal currents and when modelled in the conservative case, the cold-water plume reaches the seabed and may spread to form a cold-water layer over the seabed in the shipping basin as shown in CEE 2018a and 2018b.

The minimum initial dilutions at the point of reaching the seabed layer for three discharge options are summarised in Table 3.

**Table 3. Initial physical dilution of heat exchange cold-water discharge**

Water depth below discharge point	Single port discharge	Double port discharge	Six-port discharge (AGL Preferred design)
High tide depth 12.2 m	10:1	12:1	23:1
Low tide depth 9.2 m	8:1	10:1	20:1

Discharge rate = 450,000 kL/d /d; FSRU fully loaded

The time for the cold-water plume to leave the discharge point and reach the seabed at low tidal current speeds is less than one minute (approximately 20 seconds) as shown in CEE 2018a and 2018b.

The results from the chlorine chemical reduction experiments for the second phase (start is 4 minutes after initial mixing) with second phase starting concentration 0.5 mg/L are shown in Figure 11.
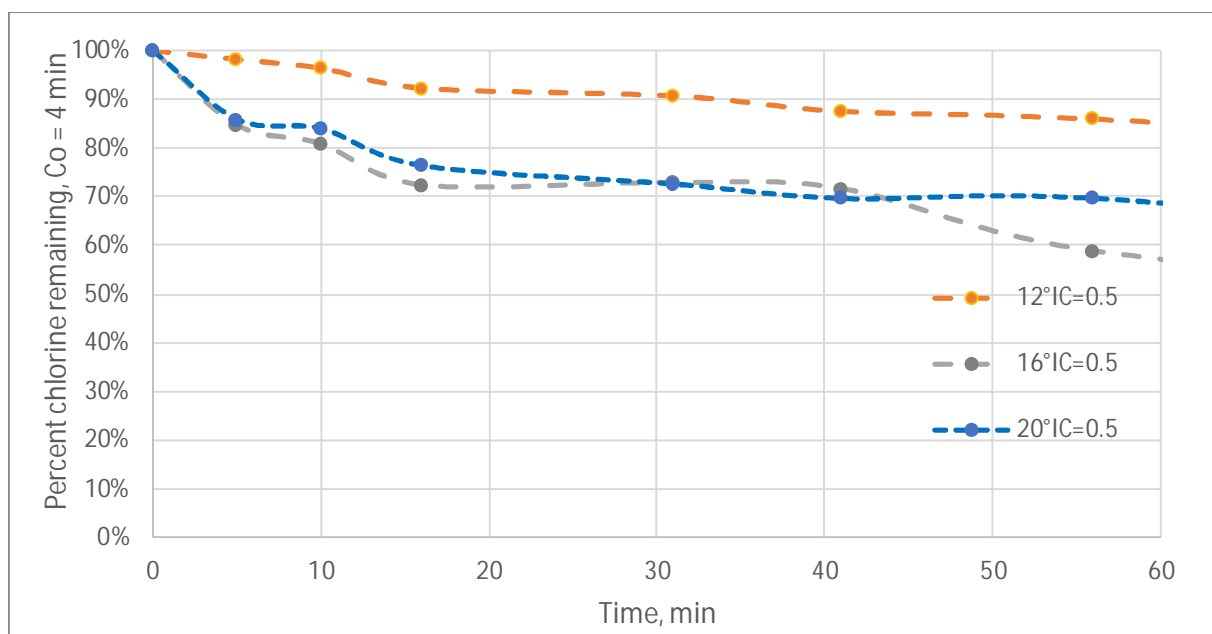
**Figure 11. Percent chlorine reduction in second phase
from starting concentration 0.5 mg/L**

The figure shows that the chemical reduction rate of free chlorine concentration over the first **five** minutes is very slow at 12°C (<2%) compared to 16°C (15%) and 20°C (16%). Hence the total physical dilution and chemical reaction in chlorine concentration over the initial dilution stage of discharge dispersion is:

· Entirely (>99.9%) due to the physical process of initial dilution alone at 12°C with no reduction from chemical reaction;
· 99% due to the physical process of initial dilution at 16°C and 20°C, with only about another 1% reduction due to chemical reaction.

The net concentration of chlorine in the cold-water discharge over the initial dilution stage due to initial dilution and chemical reduction for the discharge close to the seabed is shown in Table 4. At this stage, chlorine concentrations may be above the ANZECC Guideline value (Table 1), and further reduction of chlorine concentration by physical and chemical processes is required to ensure environmentally safe levels of chlorine are maintained in North Arm (see Sections 5.3, 5.4 and 7.2 below).

Table 4. Chlorine concentration after initial dilution and 20 second chemical reaction

Discharge arrangement	Water temperature		
	12°C	16°C	20°C
One outlets	0.011 mg Cl_2/L	0.011 mg Cl_2/L	0.011 mg Cl_2/L
Two outlets	0.009 mg Cl_2/	0.009 mg Cl_2/	0.009 mg Cl_2/
Six-port discharge (AGL preferred design)	0.005 mg Cl_2/L	0.005 mg Cl_2/L	0.005 mg Cl_2/L

5.3 Nearfield phase (6 hours)

The nearfield phase of the dispersion in this example may be considered to be one ebb or one flood tidal excursion over a period of approximately 6 hours. The results from the chlorine experiments for the second and third phase (start is 4 minutes after initial mixing and showing results for first 6 hours) with second phase starting concentration 0.5 mg/L are shown in Figure 12.
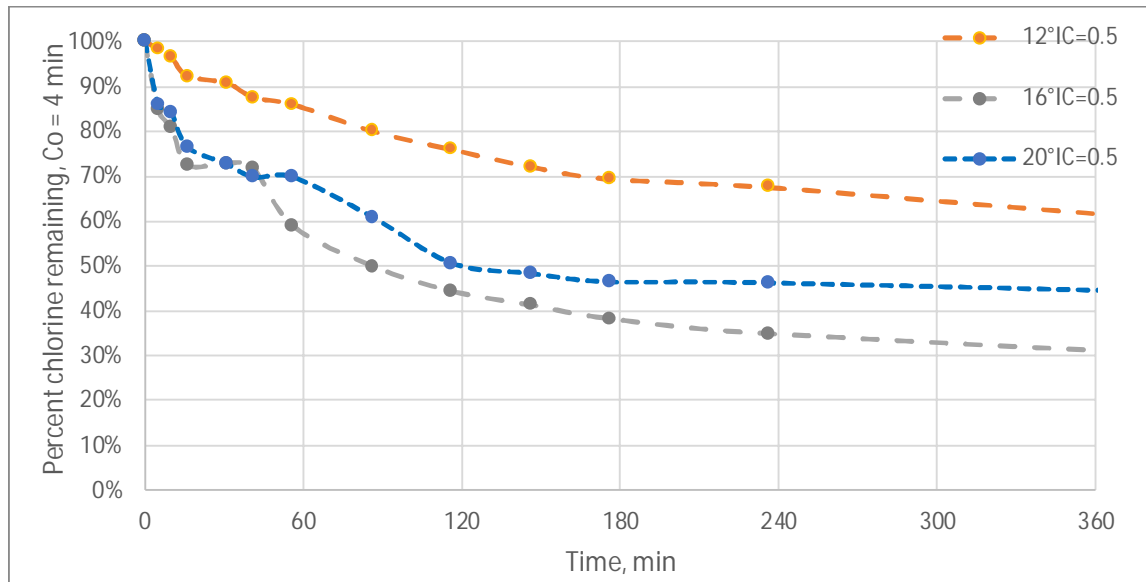
Figure 12. Percent chlorine reduction in second and third phase
Starting concentration 0.5 mg/L

The figure shows that the reduction rate due to chemical reaction in seawater over the first **6 hours** ranges from almost 40 percent for 12°C seawater to almost 70 percent in 16°C and 20°C seawater. The variation in chlorine concentration measurement at 16°C and 20°C in the first hour demonstrates the difficulties associated with the rapid speed of the chemical reactions versus the relatively slow speed of the analytical methods. However, the results are generally consistent with the published data discussed previously and are suitable for the purposes of this assessment.

5.4   Net outcome of chemical reduction and physical dilution

The net reduction in percent chlorine over a six-hour period due to initial dilution and chemical reaction and not allowing for nearfield mixing is shown in Table 5 and the corresponding chlorine concentrations are shown in Table 6.

Table 5. Net remaining chlorine after initial dilution and 6 hours chemical reaction

Discharge arrangement	Water temperature	
	12°C	16 to 18°C
One outlet	7.8 %	3.3 %
Two outlets	6.4%	2.2
Six-port discharge (AGL preferred design)	3.3%	1.4 %

Table 6. Chlorine concentration after initial dilution and 6 hours chemical reaction

Discharge arrangement	Water temperature	
	12°C	16 to 18°C
One outlet	0.008 mg Cl_2/L	0.003 mg Cl_2/L
Two outlets	0.006 mg Cl_2/L	0.003 mg Cl_2/L
Six-port discharge (AGL preferred design)	**0.003 mg Cl_2/L**	**0.001 mg Cl_2/L**

The estimates at this stage are relatively conservative due to the likelihood of increased chemical reduction rates of chlorine at the lower concentrations resulting from physical dilution. A permanent cold-water layer is not expected to form from the preferred six-port discharge design with relatively high subsequent mixing and dilution, and chlorine concentrations less than 0.001 mg/L 200 m downstream of the discharge outlets at mean seawater temperature.

6   ECOTOXICITY TEST OF CHLORINE IN CRIB POINT SEAWATER

As discussed in previous sections of this report, the concentration of chlorine reduces over three time phases starting immediately after its mixing with seawater. Regulators recognise this characteristic in setting indicative chlorine concentration protection levels and procedures for monitoring chlorine in the environment.

The rate of chlorine reduction in seawater depends on local seawater characteristics: the concentration of inorganic constituents that react rapidly with chlorine; the concentration of organic constituents that react rapidly with chlorine; the concentration of inorganic and organic constituents that react at slower rates with chlorine and bromine, and; ambient temperature.

The toxicity of residual reactive chlorine constituents to the plants and animals in the marine ecosystem also depends on the sensitivity of the local marine pants and animals to chlorine concentration. The difficulty in establishing safe ecosystem levels for chlorine in seawater ecosystems is discussed in Section 3 above.

Toxicity tests on at least five and up to 12 species are needed to establish environmentally safe dilutions for chemicals (Warne et al 2015), and it is likely that the USEPA and ANZEECC ecosystem protection guidance values presented in Section 3 are based on a sufficient range of quality assured data. However, the data are likely to have included overseas species and these limitations are recognised in the USEPA and ANZECC documents. It was considered useful, therefore, to test the sub-acute toxicity of chlorine in Crib Point seawater using a relevant southeastern Australia species and recognised test procedure to inform discussion of potential toxicity issues associated with the residual chlorine concentration in the seawater discharge at Crib Point and comparison with the USEPA and ANZECC guidance values.

6.1   Sub-acute sea urchin fertilisation 1-hour ecotoxicity test

A short term ecotoxicity test was chosen to inform assessment of the potential toxicity of the seawater heat exchanger discharge over the initial stage of dispersion in the marine environment at Crib Point. Ecotoxicity Services Australasia Pty Ltd is NATA accredited for a range of marine ecotoxicity tests including the sub-acute sea urchin fertilisation 1-hour ecotoxicity test (Figure 14).

The test followed a standard, nationally accredited procedure that involves exposing sea urchin sperm and eggs to a range concentrations of test material (chlorine-in-seawater) for one hour and twenty minutes. At the end of the exposure the percentage of fertilised eggs is determined. Statistical analyses are then applied to the results including the control exposure data to estimate the concentrations of chlorine causing chronic toxicity to a representative sensitive species reproductive stage.

The test gametes used were from the sea urchin *Heliocidaris tuberculata*, which is closely related to *Heliocidaris erythrogramma* (Figure 13) that is found together with *Goniocidaris tubaria* under Crib Point jetty.
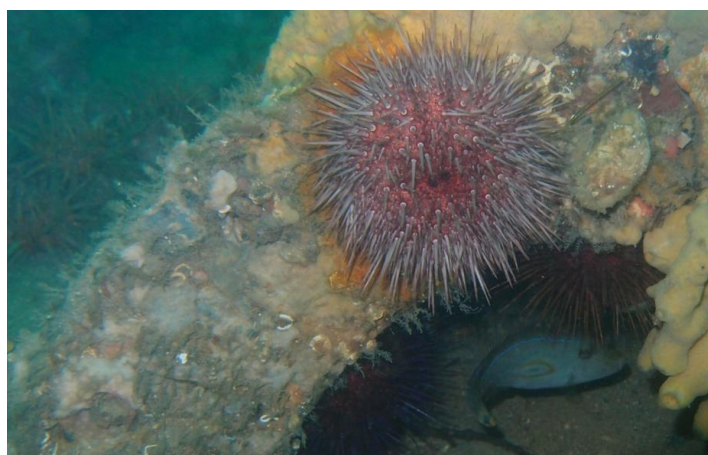
Figure 13. Sea urchin *Heliocidaris erythrogramma* under Crib Point jetty

Figure 14. Fact sheet for sea urchin fertilisation toxicity test

6.2 Sea urchin fertilisation test conditions

The standard test conditions for the sea urchin fertilisation test are described in Ecotox Services Test Report TR1518/2. Modifications for the chlorine toxicity test are discussed below.

6.2.1 Test temperature

It was recognised:
1. that average winter seawater temperature at Crib Point is approximately 12°C and chlorine concentrations are expected to remain higher in the mixing area at lower temperature
2. but that the test organism does not reliably produce gametes at temperature lower than 16°C. Many species do not reproduce in winter and gametes are expected to be low in abundance at lower water winter temperatures compared to warmer spring and summer water temperatures.

Therefore, toxicity was tested at 16°C as the average water temperature at Crib Point rather than the standard 20°C test temperature or at colder temperatures that may occur at Crib Point.

6.2.2 Test concentration range

The results of the chlorine reduction trials, the regulatory safe limits, the concentration of chlorine in the FSRU discharge and the statistical basis for were considered in setting the six nominal concentrations (as 'mg free Cl_2/L') to be used in the tests.

It was recognised that most of these concentrations would be estimated by serial dilution of the initial stock concentration and that actual commencement concentrations may vary due to the reduction processes described above. Hence, Ecotox Services reports results in three forms:
1. Percentage dilution – the dilution factor of the stock concentration
2. Nominal concentration – the concentration estimated from the dilution of the initial stock chemical concentration
3. Measured concentration – the concentration measured at the commencement of the test

The nominal concentrations and corresponding percentage dilution factor based on a stock concentration of 2 mg freeCl_2/L used in the tests and resulting measured concentration are shown in Table 7.

Table 7. Chlorine concentrations used in toxicity test

Nominal mg freeCl_2/L	Dilution percentage 2 mg freeCl_2/L stock	Measured mg freeCl_2/L
2.0	100	2.021
1.0	50	0.954
0.5	25	0.456
0.1	5	0.081
0.05	2.5	0.038
0.01	0.5	0.021

6.3   Toxicity test results

The concentration at which responses occur after the test duration are recorded relative to control waters. The responses are:

1. the lowest concentration at which a response occurred that was statistically significantly different from the control preparation is referred to as the **LOEC**; and
2. the concentration at which no response occurred is referred to as the **NOEC**.

If the NOEC is less than 100% effluent, then a statistical interpolation is used to determine the effluent concentration at which 50 percent of the test organisms were affected. This concentration is known as the **EC50** (effect concentration at which 50% of organisms responded). The EC50 allows a comparison of the results on a continuous concentration scale of, rather than the incremental results of NOEC and LOEC that can only be expressed in terms of the concentrations using in the test, which in this case were 2 mg/L; 1 mg/L; 0.5 mg/L; 0.1 mg/L; 0.05 mg/L; 0.01 mg/L. Hence, higher EC50s represent lower effluent toxicity.

An IC10 can also be statistically determined, which represents the calculated concentration at which 10 percent of the test biota are affected by the test exposure.

The EC50 or IC50 can be converted to Toxicity Units (TU) by simply calculating the reciprocal of the EC50. Hence, higher values on the TU scale represent higher toxicity of effluent, with 1 TU representing the lowest toxicity.

The toxicity test outcomes are shown graphically in Figure 15. Statistical analysis outcomes are summarised in Table 8.
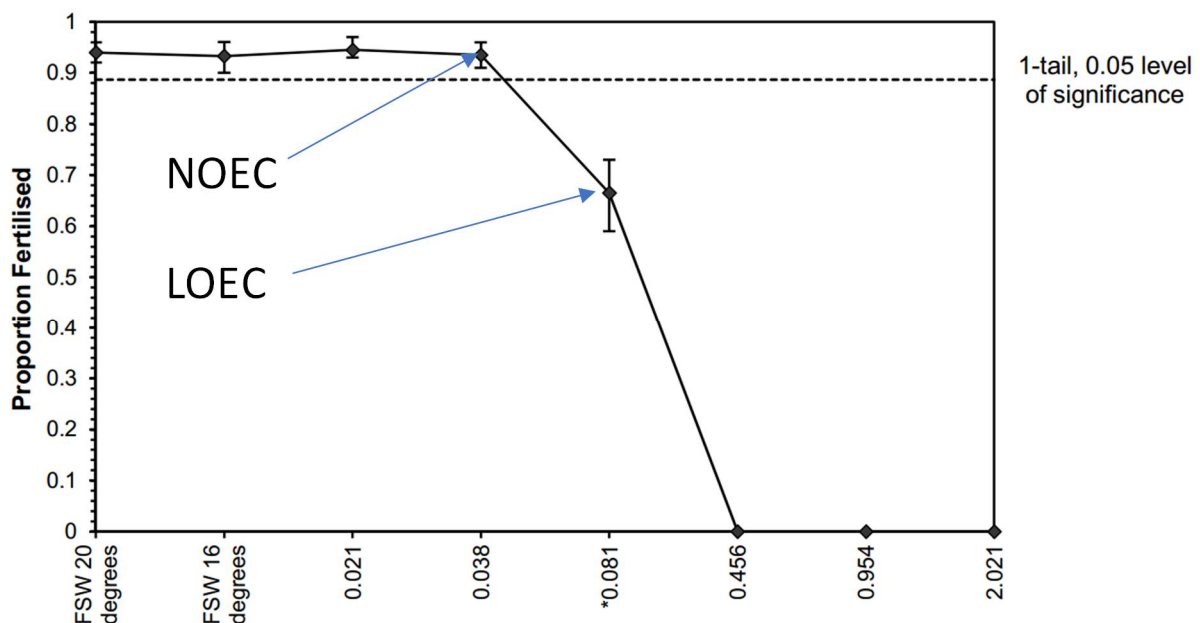

Figure 15. Graphical results of ecotoxicity test
(Measured concentration)

Table 8. Statistically calculated outcomes of toxicity test
(Measured concentration)

Outcome	Chlorine concentration, mg freeCl$_2$ /L
IC10	0.059
EC50	0.133
NOEC	0.038
LOEC	0.081

6.4   Interpretation of ecotoxicity test results

Figure 15 and Table 8 show that:
·   There was no fertilisation success at a concentration of 0.465 mg/L free chlorine in Crib Point seawater relative to the control treatment (plain filtered seawater)
·   Fertilisation of 50 percent of eggs in a concentration of 0.133 mg/L free chlorine was unsuccessful relative to the control treatment (plain filtered seawater)
·   Fertilisation of 10 percent of eggs in a concentration of 0.059 mg/L free chlorine was unsuccessful relative to the control treatment (plain filtered seawater)
·   Fertilisation of sea urchin eggs was unaffected by a concentration of 0.038 mg/L free chlorine in seawater.

6.5   Comparison with Guidance values

As discussed above, the result of a single toxicity test is insufficient to determine the environmentally safe concentration for a chemical, but the test using a southeastern Australian sea urchin species provides regional context to the guidance values established using data from national and international sources. The NOEC of 0.038 mg Cl$_2$/L and IC10 value of 0.059 Cl$_2$ mg/L are higher than the ANZECC 2000 indicative interim working value of 0.003 Cl$_2$ mg/L. This indicates that ANZECC 2000 indicative interim working value is greater than a factor of 10 to 20 below the NOEC and IC10 and is an appropriate conservative and useful value:
·   "*for modelling purposes and for making decisions concerning this particular application… (heat exchangers)*" (USEPA), and
·   "*as an indicative interim working value*" (ANZECC 2000) for this stage of the Project.

It is likely that the results of additional chlorine bioassays have been published since the database used to establish the USEPA and ANZECC 2000 guidance values, and that different regulatory toxicity values may become available in the future.

7 CONCLUSION

7.1 Implication of chlorine reduction and toxicity tests for Crib Point results

Chlorine concentration modelling in the feasibility stage of the Project included the first rapid stage of chlorine reduction in modelling the discharge and subsequent dispersion in the environment. This may have overestimated chlorine reduction in the environment and underestimated chlorine concentration in the environment.

The implications of subsequent chlorine reduction trials and the toxicity tests using (1) Crib Point seawater (2) a sub-acute (chronic) test sensitive (3) a representative marine species and (4) a test temperature relevant to the Crib Point environment and ecosystem are:

· The concentration of 0.5 mg/L of free chlorine generated at the entrance to the seawater heat exchange system will be toxic to a range of marine organisms passing through the heat exchange system. This is the desired outcome for the operation of the heat exchange system.

· The concentration of 0.1 mg/L of free chlorine remaining in the seawater as it leaves the heat exchange system will be toxic to some marine organisms that are very close to the discharge point and that are exposed for long enough for a toxic effect to occur. This is a generally accepted localised outcome for the operation of the heat exchange system provided that the effect is localised.

· The toxicity test NOEC of 0.038 mg/L of free chlorine is higher than the USEPA and ANZECC safe concentrations (Table 1) for free chlorine.
  o This is expected for a single species test, and demonstrates that the USEPA and ANZECC safe concentrations (Table 9) are appropriately conservative and useful:
    § *"for modelling purposes and for making decisions concerning this particular application…* (heat exchangers)*" (USEPA)*
    § *"as an indicative interim working value" (ANZECC)* for this Project.

· It is likely that the results of additional chlorine bioassays have been published since the database used to establish the USEPA and ANZECC 2000 guidance values, and that different regulatory toxicity values may become available in the future.

7.2 Synthesis of factors affecting chlorine concentration targets for Project

Table 9 presents the regulatory guidance safe concentrations of free chlorine (from Table 1), together with the calculated free chlorine concentrations calculated at 16°C (representing median ambient seawater temperature at Crib Point) after the period of initial dilution (from Table 4) and chemical reduction after 6 hours (from Table 6).

Table 9. Compiled environmental guidance and project chlorine concentrations

Condition	Free chlorine, mg Cl_2/L
ANZECC 2000 (95% SP)	0.003
USEPA (4 day)	0.0075
USEPA (1 hour)	0.013
At Discharge	0.1
After initial dilution and 20 sec chemical reduction:	
One and two port discharge	0.011
Six-port discharge	**0.005**
After initial dilution and 6 hours chemical reduction:	
One and two port discharge	0.003
Six-port discharge	**0.001**

The evidence concludes that:

· The process of initial dilution from the six-port discharge port/s will reduce the concentration of free chlorine residual from 0.1 mg Cl_2/L at the outlet to 0.005 Cl_2/L at the seabed. Further mixing with tidal currents within 200 m of the discharge point will reduce the chlorine concentration in seawater at ambient temperature of 12°C is to 0.003 Cl_2/L within 200 m downstream of the discharge point, while in warmer seawater (16°C to 18°C) the chlorine concentration is estimated to reduce to 0.001 mg Cl_2/L within the same distance.

· Discharge of the seawater via a six-port discharge, in accordance with AGL's preferred design, is expected to reach environmentally safe concentrations within an area extending approximately 200 m downstream of the discharge (north during rising tide and south during lowering tide) and 60 m east and west, based on the existing model outputs and regulatory guidance values for chlorine toxicity.

8 REFERENCES

ANZECC 2000. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.*

Burton 1977. *General test conditions and procedures for chlorine toxicity tests with estuarine and marine macroinvertebrates and fish.* Chesapeake Science March 1977, Volume 18, Issue 1, pp 130–136.

CEE 2018a. *Plume Modelling of Discharge from LNG Facility at Crib Point, Western Port – AGL Gas Import Jetty Project.* Report for AGL. Report for AGL.

CEE 2018b. *Assessment of effects of cold-water discharge on marine ecosystem at Crib Point – AGL Gas Import Jetty Project.* Report for AGL.

Saeed Suhur, Shwet Prakash, Nandita Deb, Ross Campbell, Venkat Kolluru, Eric Febbo and Jennifer Dupont 2015. *Development of a Site-Specific Kinetic Model for Chlorine Decayand the Formation of Chlorination By-Products in Seawater.* Journal of Marine Science and Engineering 2015 3:772-792

SOEQ (State of Oregon Environmental Quality) 2014. *Implementation instructions for the Water Quality Criterion Chlorine (CAS#7782-50-5).* Memorandum 28 November 2014.

USEPA 1985. *Ambient Water Quality Criteria for Chlorine -1984.* EPA 440/5-84-030 January 1985. US Environmental Protection Agency.

USEPA 1991. *Aquatic Life Fact Sheet – Ambient Water Quality Value- Substance: CHLORINE (Total Residual).* Fact Sheet Date: Sep 1 1991"

USEPA 2017. *Operating Procedure. Field Screening of Total Residual Chlorine.* Region 4. U S Environmental Protection Agency. Science and Ecosystem Division. Athens, Georgia.

Wahab 2012: *Environmental Impact Assessment of Residual Chlorine Discharge into Seawater.* Presentation Chemical Engineering Program, Texas A&M University at Qatar, May 2012.

Wang Jih-Terng, Ming-Hui Chen, Hung-Jen Lee, Wen-Been Chang, Chung-Chi Chen, Su-Cheng Pai and Pei-Jie Meng. 2008. *A model to predict Total Chlorine Residue in Cooliong Seawater of a Power Plant Using Iodine Colorimetric Method.* International Journal of Molecular Sciences 2008 (9): 542 – 553.

Warne MStJ, Batley GE, van Dam RA, Chapman JC, Fox DR, Hickey CW and Stauber JL. 2015. Revised Method for Deriving Australian and New Zealand Water Quality Guideline Values for Toxicants. Prepared for the Council of Australian Government's Standing Council on Environment and Water (SCEW). Department of Science, Information Technology and Innovation, Brisbane, Queensland. 43 pp.

Water Technology 2017. Hydrodynamic & Water Quality Modelling, Western Port Bay. Report to AGL Wholesale Gas Ltd.

Zeng Jiangning, Jiang Zhibing, Chen Quanzhen, Zheng Ping, Huang Yij 2009. *The decay kinetics of residual chlorine in cooling seawater simulation experiments.* Acta Oceanologica Sinica 2009, Vol.28, No.2, p.54- 59.