Report to:
Jacobs Group (Australia) Pty Ltd

AGL Gas Import Jetty Project
Crib Point, Western Port

Plume Modelling of
Discharge from LNG Facility

FINAL

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Contents

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Plume Modelling of Discharge from LNG Facility

EXECUTIVE SUMMARY

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

- Continuous mooring of a FSRU at the existing Crib Point Jetty, which will receive LNG carriers of approximately 300 m 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.

The Crib Point Jetty in Western Port has been selected by AGL as the preferred location for the Project as it is an established, operating port. The proposal involves a continuously moored FSRU – essentially an LNG ship with equipment on board that circulates seawater to warm and regasify LNG. Gas from the FSRU will flow to the shore via the gas flowline.

During the heat-exchange process to warm LNG, up to 450,000 kL/d of seawater will be taken from Western Port by the FSRU, passed through a heat exchanger and discharged back to Western Port. The circulated seawater discharged from the heat exchanger will be approximately 7°C cooler than ambient seawater.

This report examines the dilution of the discharge of cooler seawater from the re-gasification facility. Several options to discharge the cooler seawater are considered. This information was prepared as an input to reports evaluating the ecological effects of the Project to be used in support of:

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

The assessment concludes that discharged seawater would dilute rapidly after discharge, with the initial dilution at the seabed depending on the depth and number of discharge ports and the velocity of discharge.

AGL's preferred design is a 6-port discharge. With discharge from six ports, (one on each side of the FSRU for each of the three regasification trains), the modelling shows that the discharged plumes will sink to the seabed within the berth area and produce a diluted field on the seabed that would be 0.3°C cooler than ambient seawater. This field will mix fully with tidal currents.

When an LNG vessel is moored beside the FSRU, it may restrict the path of the plumes on the starboard side of the FSRU and the dilution could be temporarily reduced. This could occur about once a week over a 24-hour period.

During the period of weaker currents near slack water, the diluted field could form a stable layer on the seabed about 2 m thick, extending for a maximum of 200 m distance. The layer formed at slack water will become mixed into the ambient seawater when currents increase an hour later in the tide cycle.

In summary, the preferred 6-port design will always achieve the dilution required to mix the diluted cold-water field into ambient seawater in the passing tidal flow at Crib Point.

1. INTRODUCTION

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

CEE has prepared this report to assess the discharge arrangements for seawater used in the heat exchanger that could be part of the proposed LNG Floating Storage and Regasification Unit (FSRU) while moored in Western Port at the Crib Point Jetty. Western Port has a surface area of 680 km^2 at high tide but only 410 km^2 at low tide, when 40 per cent of the surface is intertidal mudflats. Water movement is principally driven by the tides, although winds of more than 35 km/hr can also affect circulation (Hinwood and Jones, 1979). Most water enters and leaves Western Port through the western entrance, and there is a net clockwise circulation around French Island (Lee, 2000).

This report examines the local effects of the discharge of colder seawater from a potential regasification facility moored at Crib Point Jetty including the dilution of the discharge plume for various discharge options, as an input to the ecological assessment of the effects of this discharge.

2. PURPOSE OF THIS REPORT

The purpose of this report is to:

- Predict the dilution of the discharged plume or plumes for single port, 2-port, 4-port and 6-port discharge options; and
- Assess the extent of the diluted field of cooler seawater formed at slack water.

This information is prepared as an input to assessments of the ecological effects the Project on the marine environment to be used 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.*

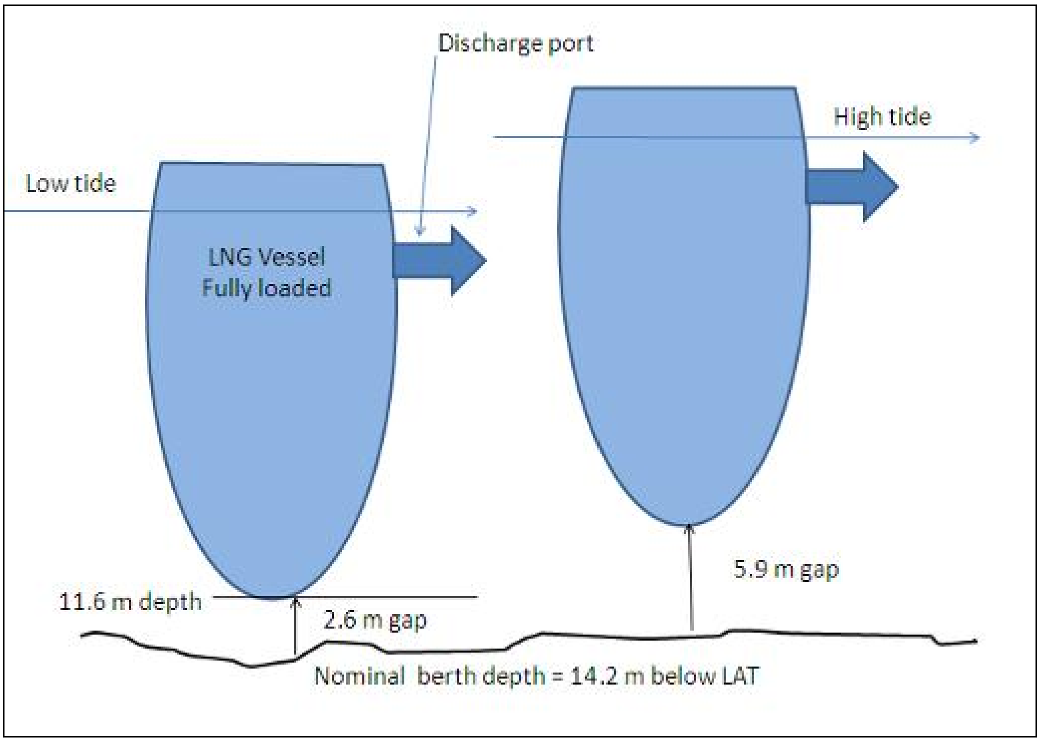
3. BASIS FOR DESIGN OF SEAWATER DISCHARGE

AGL provided a table of design parameters as the basis for design of the seawater discharge arrangements (see Appendix A). The key parameters are as follows:

- FSRU vessel is moored continuously at Crib Point Jetty;
- FSRU vessel is approximately 294 m long and 45 m across;
- Depth of vessel is 11.6 m fully loaded and 9.3 m when empty;
- Seawater discharge rate is 450,000 kL/d at full production;
- Discharge rates of 300,000 kL/d and 150,000 kL/d also were considered.

Several discharge options were assessed based on old and new FSRU designs, including a single port of 1.1 m diameter on the starboard side; dual ports of 0.9 m diameter (one on each side); four ports of 0.5 m diameter (two on each side); and six ports of 0.45 m diameter (two on each side for each of the three regasification units on the FSRU). From the assessment of these options, the 6-port option was selected by AGL as the preferred discharge configuration.

Figure 1. Discharge Port Located Below Sea Level



The discharged plumes of cooler seawater are more dense that the adjacent seawater and therefore descend to the seabed. The shear between the descending plume and the ambient seawater causes mixing and dilution. The dilution of a descending plume increases with the depth of water from the discharge port to the seabed. There are three factors that influence the depth of discharge water below the port to the seabed:

1 The discharge port (or ports) must be located below sea level so that the discharge does not form a visible "waterfall". Thus the discharge port (or ports) are located a nominal two times the port diameter below sea level.

2 As shown in Figure 1, the vessel floats up and down with the tide, but the discharge ports remain the same distance below the water surface at low tide and high tide, so the depth of water below the ports is greater at high tide.

3 A fully loaded vessel has a draft of 11.6 m while an empty vessel has a draft of 9.3 m (2.3 m less depth into the water). Thus, as illustrated in Figure 2, the ports will be deeper below the water surface for a full vessel than for an empty vessel.

Figure 2. Depth of Discharge Port Varies with Vessel Loading

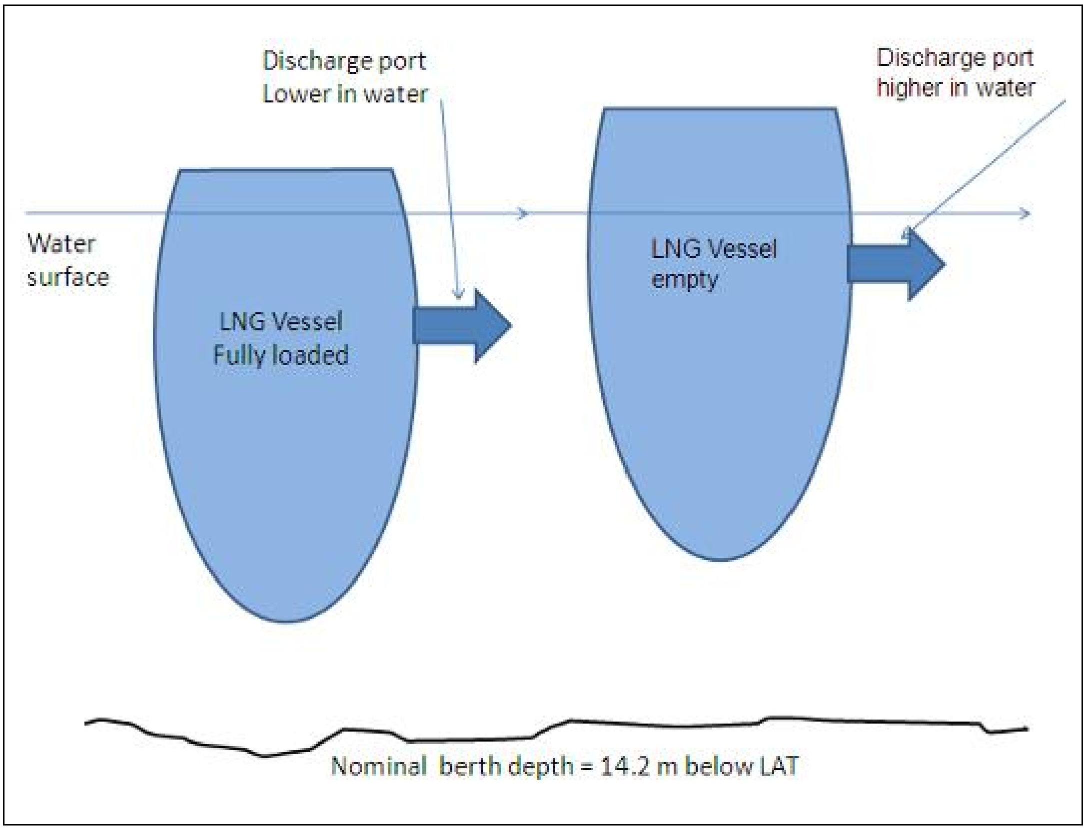


Table 1 summarises the calculations for the depth between the discharge port or ports and the seabed for the various conditions. As would be expected, the minimum water depth of 8.6 m occurs with a single port in a fully laden vessel at low tide, whereas the greatest water depth of 15.5 m occurs with 6-ports on an almost-empty vessel at high tide. There is large range in water depth for the discharge ports and the implications on initial dilution are assessed below.

Table 1. Depth of Water Below Discharge Ports for LNG Vessel

Parameter	One port of 1.1 m diam		Two ports of 0.9 m diam		Four or Six Ports	
Water above port	2.2 m		1.8 m		1.0 m	
Diameter of port	1.1 m		0.9 m		0.5 m	
Tide	**Low**	**High**	**Low**	**High**	**Low**	**High**
Empty vessel	10.9 m	13.9 m	11.5 m	14.5 m	12.5 m	15.5 m
Full vessel	8.6 m	11.6 m	9.2 m	12.2 m	10.2 m	13.2 m

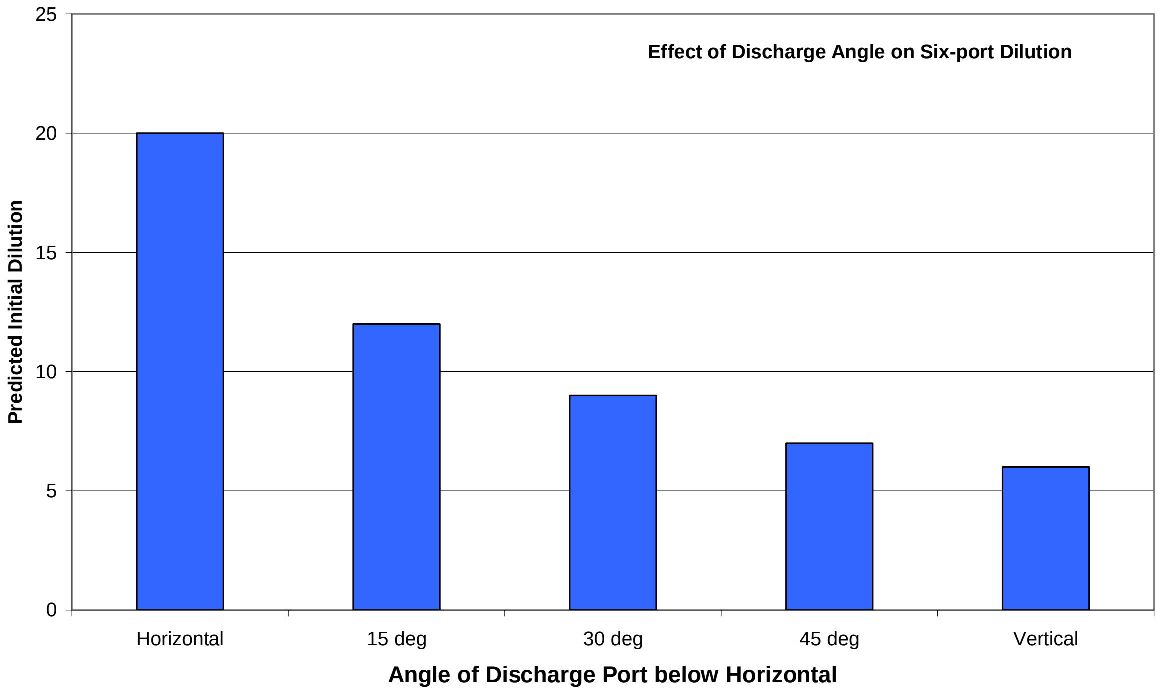
4. ANGLE OF DISCHARGE FROM PORT

The dilution depends on the length of the discharge plumes before they reach the seabed, which depends on the depth of water and the angle of discharge. The design data provided by AGL (see Appendix A) indicated that with 1 or 2 ports the discharge would be at 15 degrees below the horizontal. Thus, initial dilution simulations explored the effect of the discharge angle on initial dilution. These simulations were made for discharge from a fully laden vessel at low tide. This case has the smallest depth of water below the port ("worst-case"). Five discharge angles were examined: horizontal, 15 degrees below horizontal; 30 degrees below horizontal; 45 degrees below horizontal and vertical.

Initial dilution was calculated using the CEE computer model *INITDIL*. This model has been published in peer reviewed publication in the open literature (Wallis, 1985), verified against the performance of existing outfalls around the world (Wallis, 1981; Wallis 2016) and found to successfully predict the initial dilution of actual outfalls. The model calculated the initial dilution of buoyant and dense plumes, and estimates the thickness of the diluted cold-water field. The initial dilution can be predicted for the case of slack water (worst case) and for various current speeds.

Figure 3 shows the predicted initial dilution for the case of discharge from six ports of 0.45 m diameter with a total discharge of 450,000 kL/d from a fully loaded vessel at low tide. With horizontal discharge, the dilution is predicted to be 20:1. For comparison, an alternative plume model published by Cederwall (1968) predicts a similar initial dilution of 21:1.

Figure 3. Effect of Discharge Angle on Initial Dilution



As can be seen in Figure 3, the dilution decreases from 20:1 with horizontal discharge to 12:1 at a discharge angle of 15 degrees and to 6:1 with discharge vertically downwards. The discharge decreases as the port angle declines below horizontal (tilted down) because the length of the plume between the port and the seabed shortens as the downward angle increases, so there is less interfacial mixing and thus lower dilution. The conclusion drawn from these predictions is that the ports should discharge horizontally to maximise dilution.

5. EFFECT OF WATER DEPTH ON DILUTION

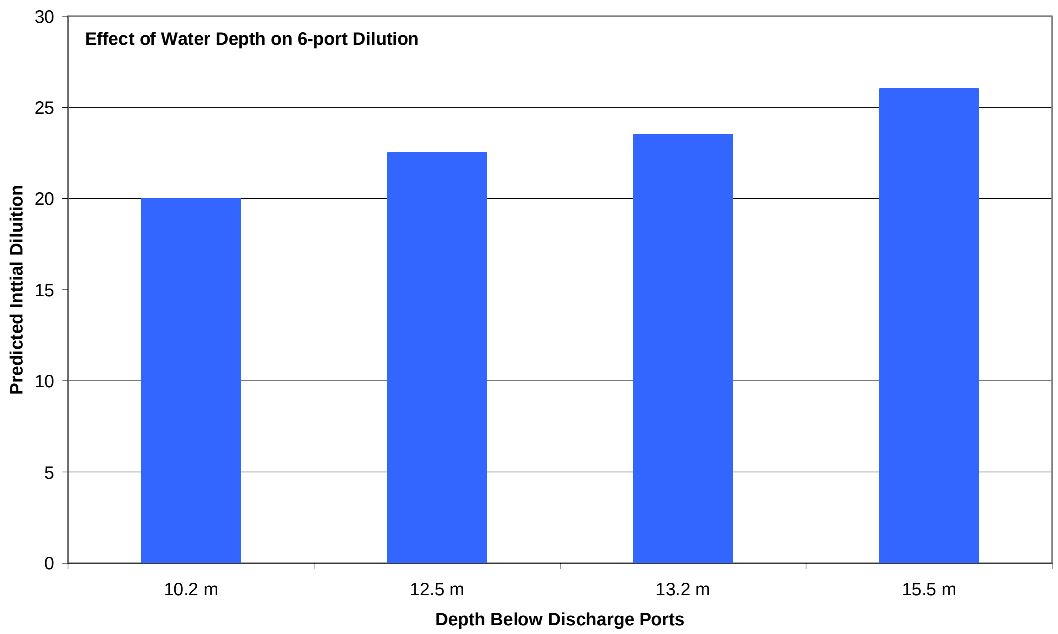
The dilution increases with the length of the plume (or, for a horizontal discharge, the depth of water between the discharge port and the seabed). Thus, the second set of dilution simulations explored the effect of water depth on initial dilution. These simulations were made for the "worst-case" of slack water, and for various stages of the tide. Four cases were examined using the 6-port configuration:

- 10.2 m - Low tide and fully laden vessel;
- 12.5 m - Low tide and empty vessel;
- 13.2 m - High tide and fully laden vessel;
- 15.5 m - High tide and empty vessel.

Figure 4 shows the predicted initial dilution for these depth cases with a discharge of 450,000kL/d. At low tide and with fully laden vessel, the initial dilution is 20:1, as shown in Figure 4 (corresponding to the dilution for the same case in Figure 3). This is the lowest dilution for the 6-port configuration.

At high tide, or with a part or fully empty vessel, the depth below the water is greater and the predicted initial dilution also is greater. Thus over a tide cycle, and during the period when the LNG vessel is being unloaded, the dilution will vary from 20:1 to 26:1. It is apparent that depth of water is a significant parameter, and consideration of the stage of the tide is required to assess the environmental effects of the proposed discharge.

Figure 4. Effect of Water Depth on Initial Dilution



6. EFFECT OF DISCHARGE RATE ON DILUTION

For flow situations where the dilution is mostly due to gravity (i.e., dense plume with a long path or buoyant plume), the dilution increases in proportion to the depth of water but decreases in proportion to the discharge rate. In simple terms, a higher rate of discharge results in lower dilution, while a lower rate of discharge results in higher dilution.

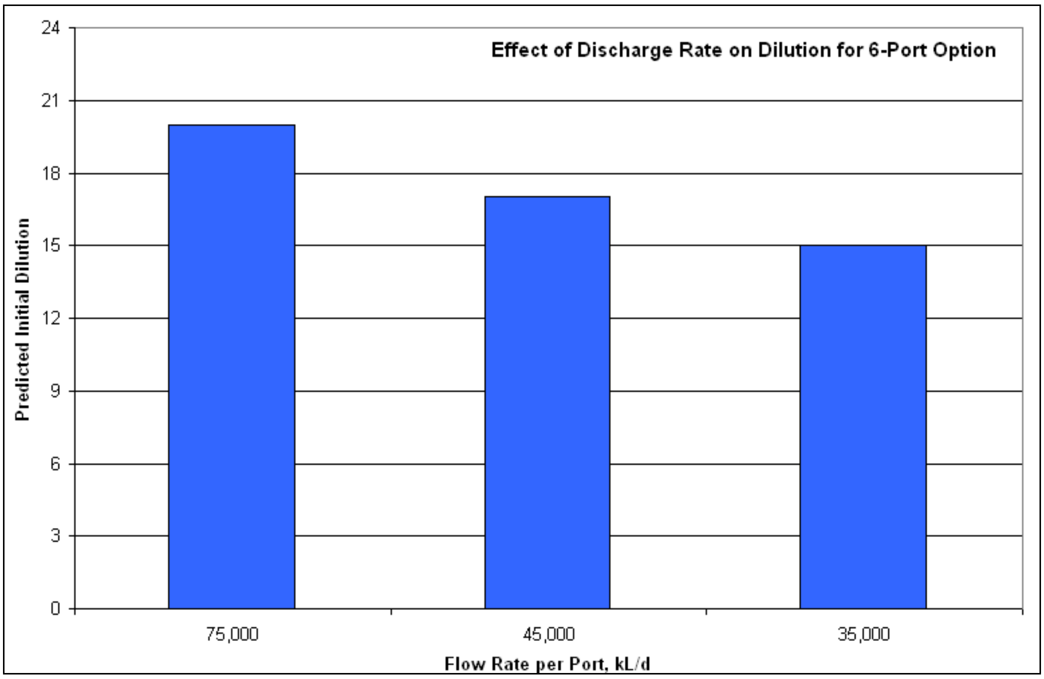
For the Crib Point situation, the density difference between the plume and the ambient seawater is small (only 0.8 kg/m^3 for a 7°C temperature difference), and the dilution is more strongly influenced by momentum-induced mixing than by the effects of gravity. For a fixed port diameter, the velocity decreases with the discharge rate, and hence the momentum-induced mixing decreases with the discharge rate. Thus, there are two processes to be considered, which tend to counter-balance each other. The dilution increases as the discharge decreases, but also decreases as the velocity decreases.

To establish the outcome in the Crib Point situation, a series of runs were made for the 6-port case with three different flow rates:

- 75,000 kL/d per port (full production of 450,000 kL/d via six ports),
- 50,000 kL/d per port; and
- 35,000 kL/d.

Figure 5 shows the predicted initial dilution for these discharge cases (assuming the diameter of the discharge ports remains fixed). Overall, the dilution decreases as the flow rate decreases, from a maximum of 20:1 at full flow (450,000 kL/d or 75 kL/d per port) to a minimum of 15:1 at 35,000 kL/d/port. The dilution would become even smaller at discharge rates below 35,000 kL/d/port.

Figure 5. Effect of Discharge Rate on Dilution for 6-port Option

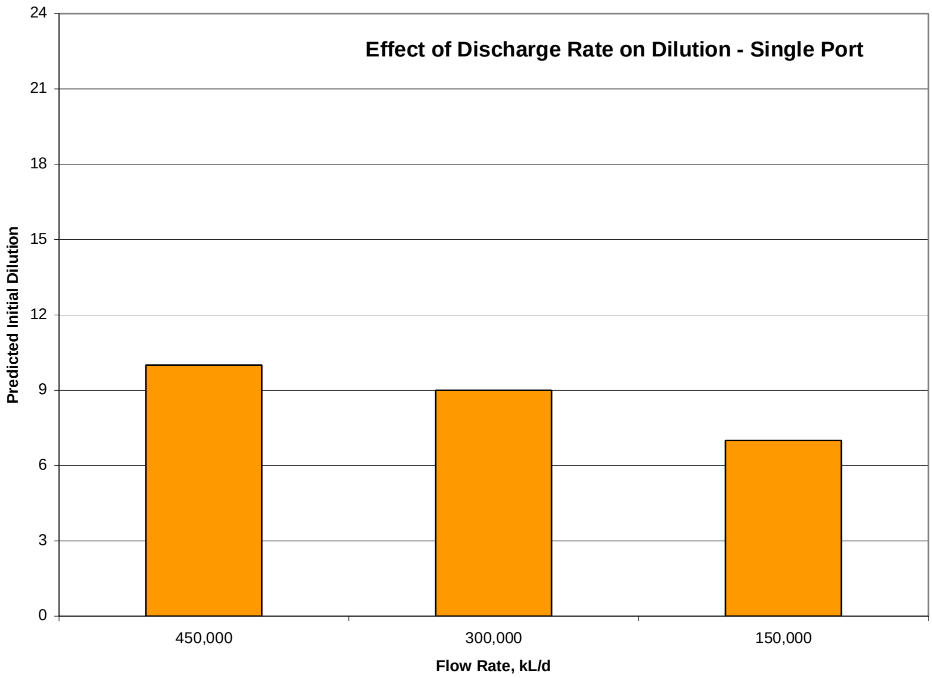


To further illustrate the effect of discharge rate (or discharge velocity, as the port diameters are fixed), a series of runs also were made for the single-port case with three different flow rates:

- 450,000 kL/d (full production),
- 300,000 kL/d (2-skid production), and
- 150,000 kL/d (1-skid production),

Figure 6 shows the predicted initial dilution for these discharge cases. Overall, the dilution decreases as the flow rate decreases, from a maximum of 10:1 at 450,000 kL/d to a minimum of 7:1 at 150,000 kL/d.

Figure 6. Effect of Discharge Rate on Initial Dilution



It is apparent from Figure 6 that the momentum-induced mixing is decreasing faster than the flow rate, so that initial dilution declines faster than the discharge rate does.

7. EFFECT OF NUMBER OF PORTS ON DILUTION

In this section, the discharge options evaluated are:

- Single port of 1.1 m diameter on starboard side;
- Dual ports of 0.9 m diameter (one on each side);
- Four ports of 0.5 m diameter (two on each side); and
- Six ports of 0.45 m diameter (three on each side).

AGL advised that a diffuser with a larger number of ports (i.e. greater than six ports) was not conventional practice for a FSRU and so that option is not analysed in this report.

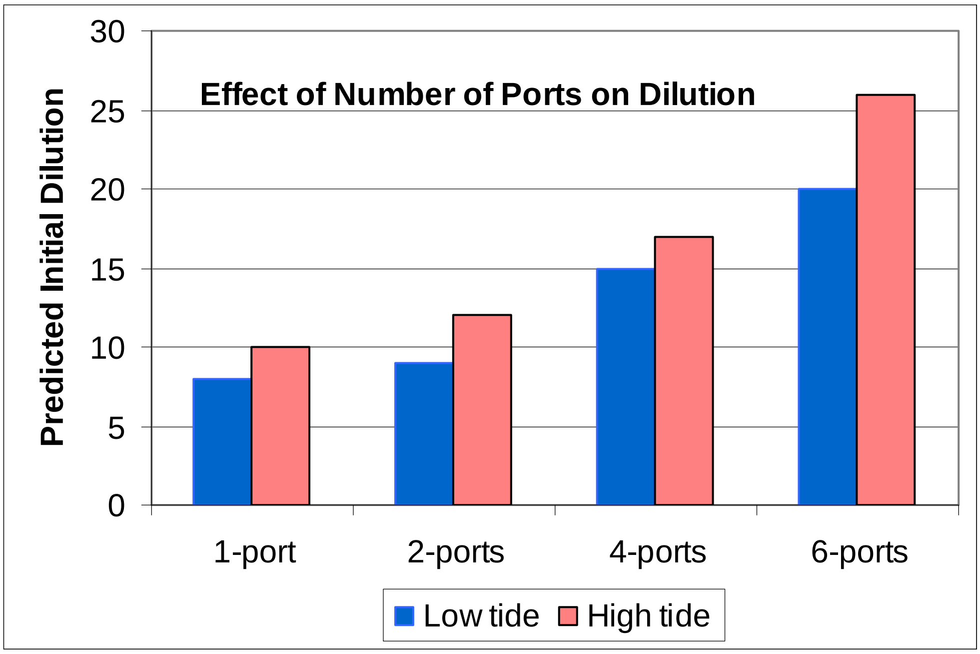
To examine the effect of the number of discharge ports on dilution, the minimum initial dilution for each of the four options has been calculated for the case of a fully loaded vessel at low tide with the maximum discharge rate of 450,000 kL/d.

As would be appreciated from the discussions of cases above, higher dilutions will be achieved when:

- It is high tide (compared to low tide);
- The vessel is nearly empty (as ports are higher above the seabed);
- The tidal velocity is higher than at slack water (see later discussion).

Figure 7 shows the predicted initial dilution for the four options concerning the number of ports. The single port option provides a dilution of 8:1 to 10:1 (from low tide to high tide); the 2-port option provides a dilution of 9:1 to 12:1, the 4-port option provides a dilution of 15:1 to 17:1; and the 6-port option provides a dilution of 20:1 to 26:1.

Figure 7. Effect of Number of Ports on Dilution – Constant Discharge



In terms of the temperature of the resulting diluted field on the seabed:

- A single port would produce a diluted cold-water field about 0.8°C cooler than ambient;
- A 2-port option would produce a diluted cold-water field about 0.7°C cooler than ambient;
- A 4-port option would produce a diluted cold-water field about 0.45°C cooler than ambient; and
- A 6-port option would produce a diluted cold-water field about 0.33°C cooler than ambient.

More ports produce a higher dilution, as would be expected. Therefore, the question arises as to how many ports are necessary to avoid adverse environmental effects – and that question is answered in the following sections of this report.

8. WHAT DILUTION IS REQUIRED?

The dilution required to achieve good mixing between the diluted field and the adjacent seawater is calculated from the minimum density difference that allows shear caused by tidal currents to erode and mix the cold-water field with the adjacent seawater.

This threshold condition is calculated from the Richardson Number (R), which is a dimensionless ratio that expresses the ratio of buoyancy forces to shear forces. The Richardson Number is widely used in investigating density flows in oceans, lakes and the atmosphere, and for the Crib Point situation is calculated as:

$$R = buoyancy / shear = g \, \mathrm{p} \, D / P \, U^2$$

where g is gravity, p is density difference, D is the depth of the stratified layer experiencing shear, P is ambient density and U is the tidal current speed.

The critical Richardson Number, below which fluids are dynamically unstable and turbulent, is widely accepted to be 0.25, based on extensive research. It has been demonstrated that $R < 0.25$ is a necessary condition for velocity shear to overcome the tendency of a stratified fluid to remain stratified (*J S Turner, Buoyancy Effects in Fluids, Cambridge Univ Press, 1973*).

The values for several of the parameters in the equation above are known, and the parameter that is to be established is p (density difference). Substituting the known parameters,

$$R = g \, \mathrm{p} \, D / P \, U^2 = 9.8 \, x \, \mathrm{p} \, x \, D /1025 \, U^2 = \mathrm{p} \, x \, D / 105 \, U^2 = 0.25$$

Predicted values of the field depth (D) and the tidal current (U) are presented in subsequent sections of this report. For a preliminary estimate of p, we can adopt the following values: D = 3 m; U = 0.1 m/s. Substituting these values:

$R = 0.25 = \mathrm{p} \times 3 / 105 \times 0.01 = 2.8 \, \mathrm{p}$

Hence p = 0.088 kg/m^3.

This density difference of 0.088 kg/m^3 corresponds to a temperature difference of 0.4°C. Thus the required minimum dilution is 7°C / 0.4°C = 17:1.

From these preliminary calculations, it is apparent that the single port and 2-port discharges will produce a field of cold water that is dynamically stable and will persist on the seabed until higher tidal velocities (than 0.1 m/s) occur.

A 4-port discharge option will be marginal – satisfactory at high tide but marginal at low tide with cold water pooling forming on the seabed.

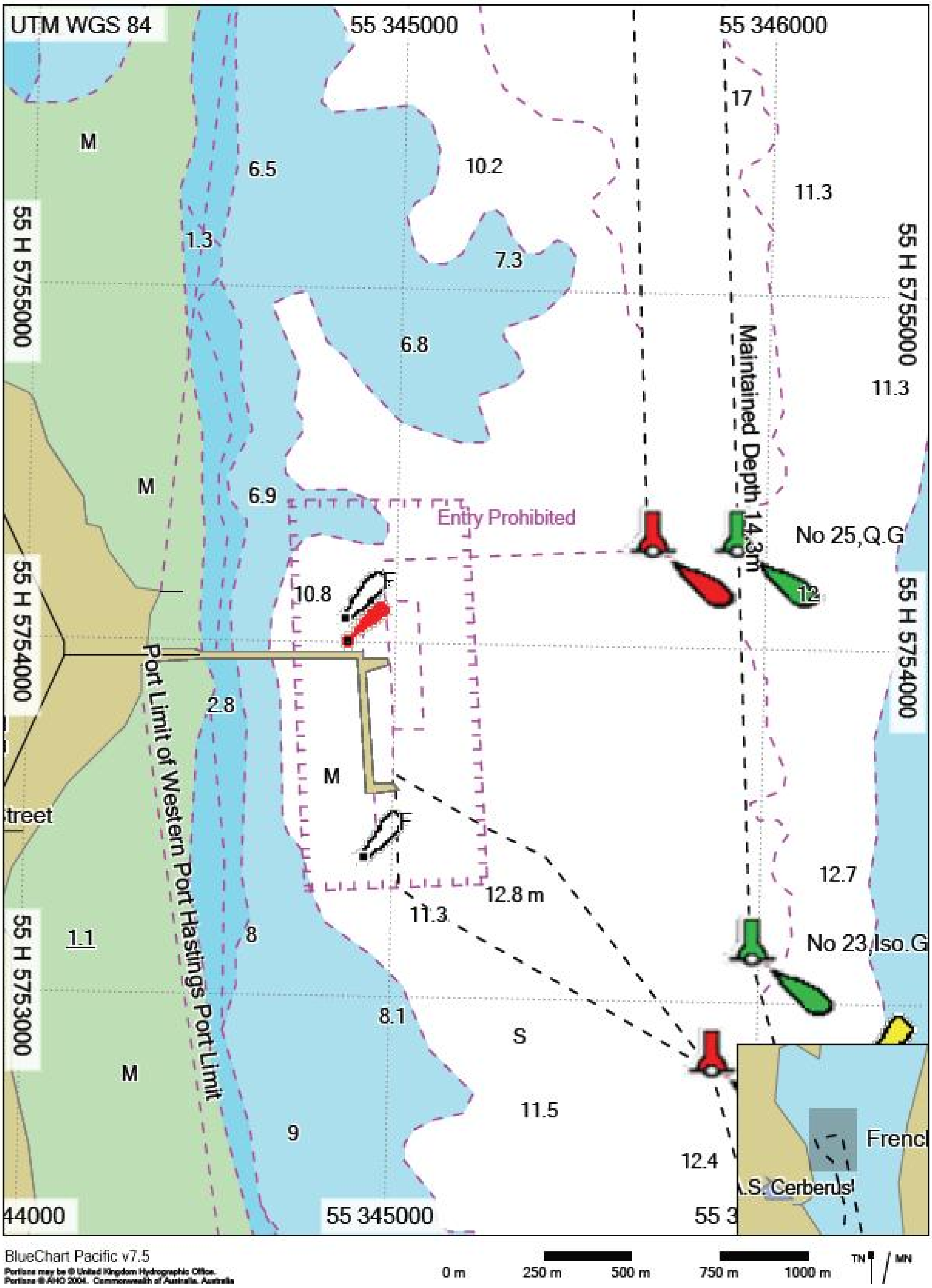
On the other hand, the 6-port option proposed by AGL will produce a dilution that always exceeds 20:1 and thus the resulting diluted field will mix rapidly with ambient tidal currents.

In summary, the 6-port option will always achieve the dilution required to mix the diluted cold-water field into ambient seawater in the passing tidal flow at Crib Point.

9. BATHYMETRY AT CRIB POINT

Figure 8 shows the bathymetry in the area of the Crib Point Jetty. The depth of the access channel, the turning basin and the berths are maintained at a minimum depth of 14.3 m below LAT (Lowest Astronomical Tide which is the lowest tide level which can be predicted to occur under any combination of astronomical conditions. There is a shallow bank to the north of Crib Point.

Figure 8. Bathymetry in Area of Crib Point Jetty

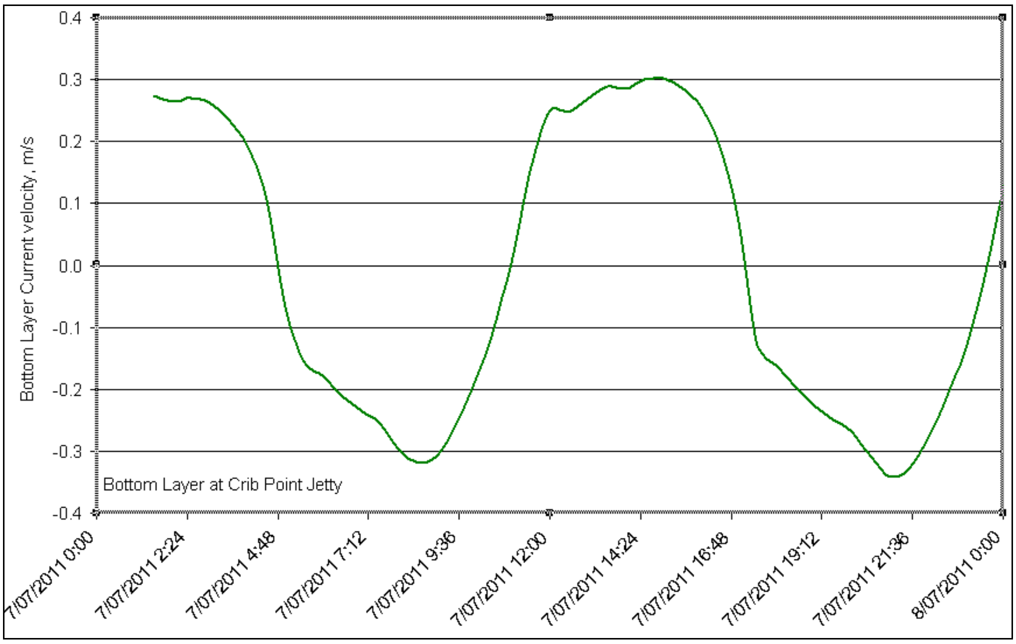


10. CURRENTS AT CRIB POINT

Currents at Crib Point are driven by many factors but principally by the diurnal tidal cycle. Typically, the flood tide currents (in the main channel, averaged over the depth) are in the range of 0.05 to 0.55 m/s while the ebb tide currents are slightly stronger at 0.05 to 0.65 m/s, but over a shorter period (Ref RH-DNV, 2015). The current patterns in the main channels are elliptical, with lateral currents at high and low tide, generated by the bathymetry of Western Port. Thus, there is seldom zero current speed, even at high or low tide.

Figure 9 shows the pattern of tidal currents in the bottom layer (seabed to 2 m above seabed) at Crib Point Jetty as derived from a hydrodynamic model run by Water Technology (2017). The peak flood tide current is 0.3 m/s while the peak ebb tide current averages about -0.33 m/s (negative current velocity is to the south).

Figure 9. Bottom Layer Currents at Crib Point Jetty



The tidal excursion, which is the distance a particle of seawater travels from low tide to high tide, is 4.3 km for the bottom layer currents. For the upper layers in the water column, the currents and therefore the tidal excursion is greater (at 6 km).

At low tide, the currents are weak (around 0.05 m/s) for a period of 30 minutes or so. If there was insufficient initial dilution in the descending plume, a pool of cold water could form under the vessel over this period when the diluted plume reaches the seabed and slowly spreads.

The currents are much stronger for most of the tide cycle. While the stronger currents increase the rate of initial dilution marginally, they increase the shear at the interface of the cool layer considerably, eroding and mixing any cold-water layer that forms at slack water.

11. DEPTH OF COLD WATER LAYER

Figure 10 shows a schematic diagram of the hydrodynamic processes that influence dilution. The plumes of water start from the discharge ports at 7°C cooler than the adjacent seawater and is therefore 0.8 kg/m^3 more dense than ambient seawater. Each plume descends to the seabed, diluting on the way due to shear between the descending plume and the adjacent seawater. The initial dilution is marginally greater at times of stronger currents. The subsequent calculations are for a single port discharge (as a conservative case scenario) as well as for the preferred design option of a 6-port discharge at times of low current speeds.

Figure 10. Diagram of Descending Dense Plume and Bottom Cold Pool

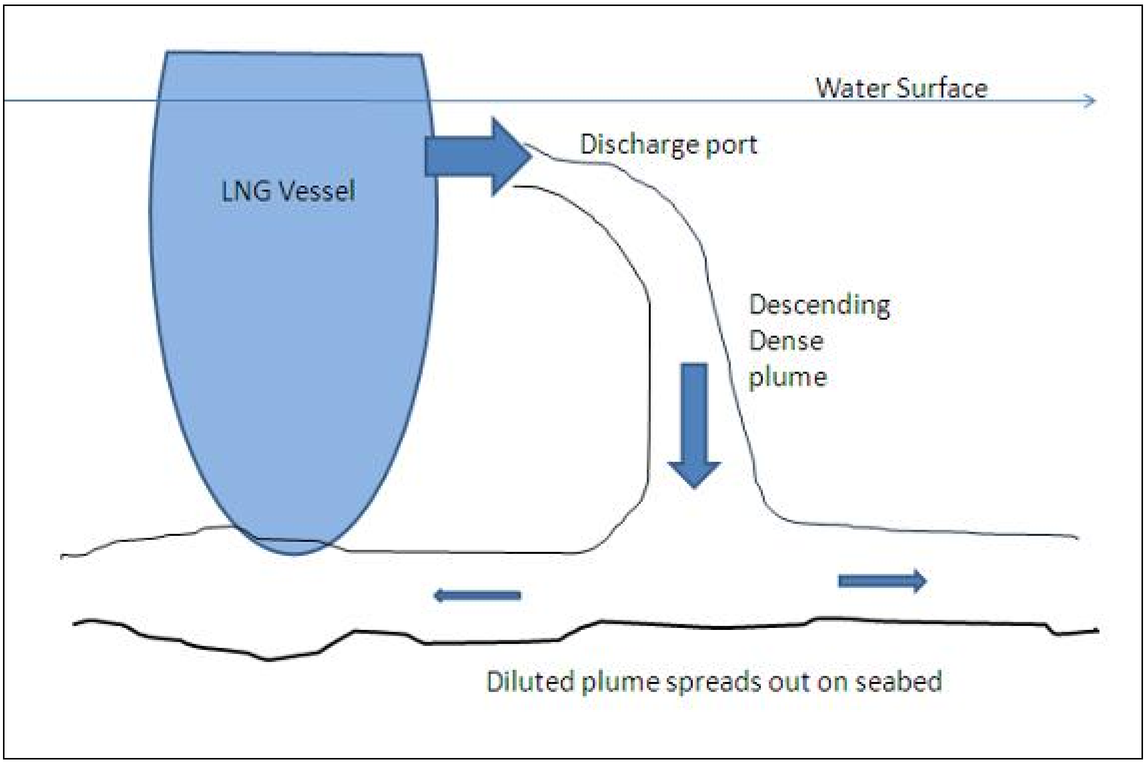


Figure 11 shows the behaviour of the cold-water field over the period of the 6-hour flood tide. The upper plot in Figure 11 shows the tidal current (smoothed by averaging several flood tides). The current speed rises from 0.05 m/s at low tide to a peak of 0.3 m/s and then falls back to 0.05 m/s at high tide (Water Technology, 2017).

The central plot in Figure 11 shows the excursion of particles each half-hour of the flood tide. In this conservative single-port case, the excursion is only 90 m at slack water but increases to 540 m over the half hour at times of peak currents.

The lower plot in Figure 11 shows the thickness of the cold-water pool formed on the seabed at the base of the plume for the single port option. At slack water, the layer is predicted to be 2.5 m thick. As the current speed increases, the layer thickness is less, as the shear due to the passing current pulls the diluted plume along the seabed. At the peak current speed, the layer is just under 1 m thick.

Figure 11. Behaviour of Cold Plume in Flood Tide Period – Single Port

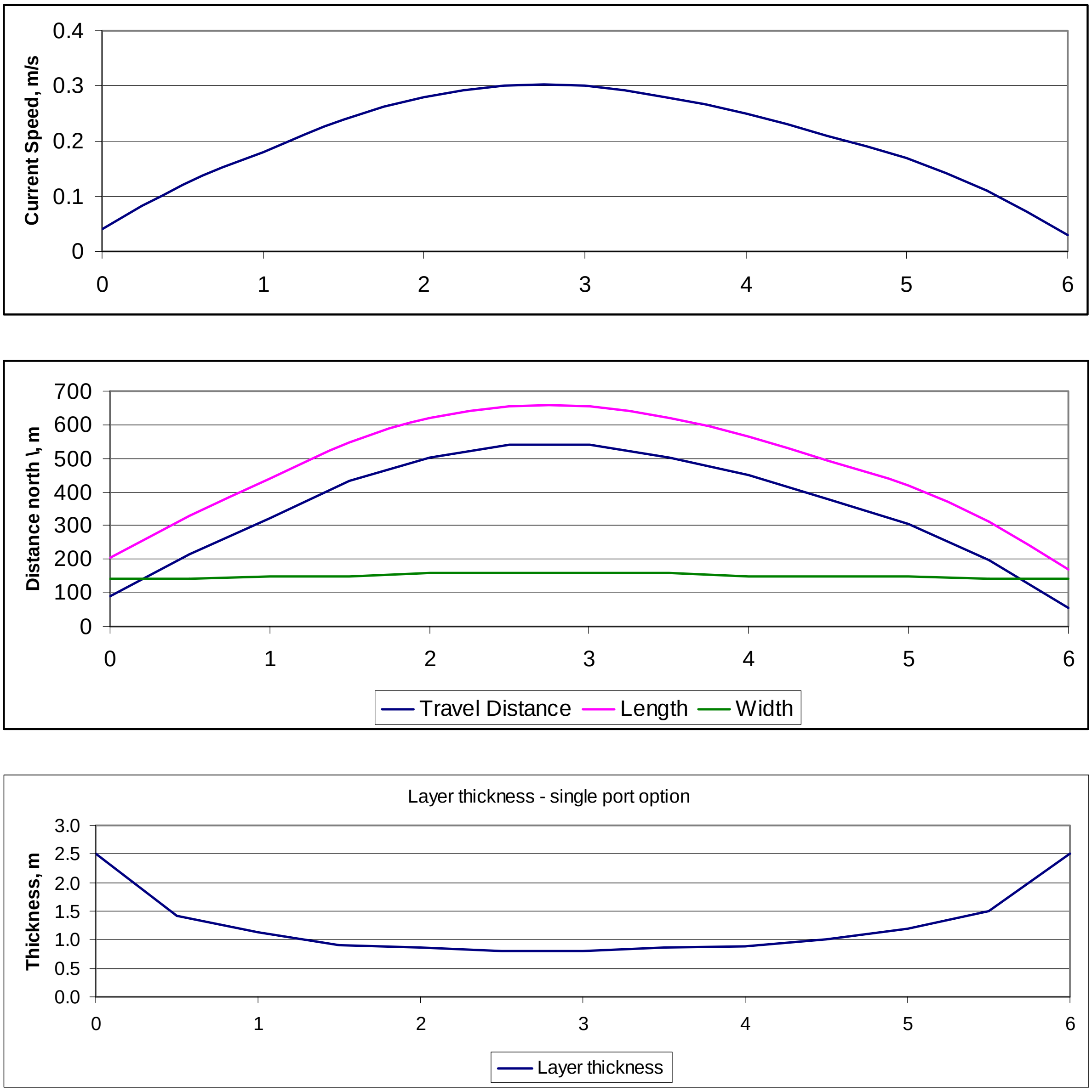
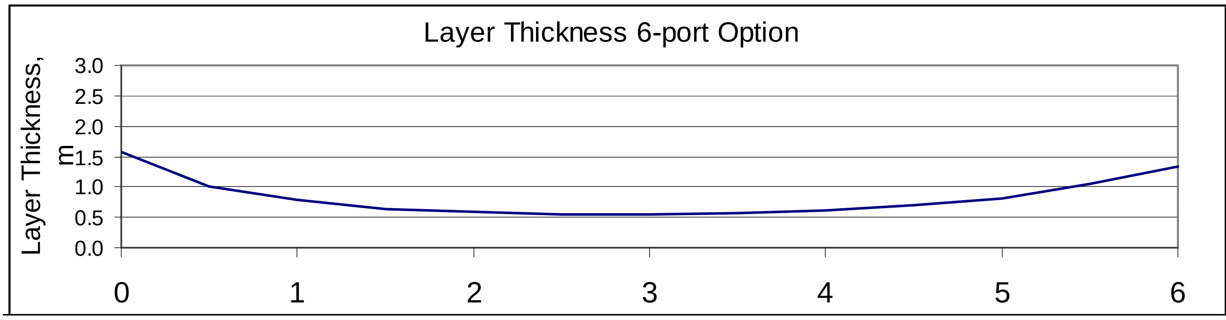


Figure 12 shows the thickness of the cold-water pool that could form on the seabed for the proposed 6-port option. The field is thin and rapidly eroded by the passing currents, as described in the next section.

Figure 12. Layer Thickness - Six Port Option



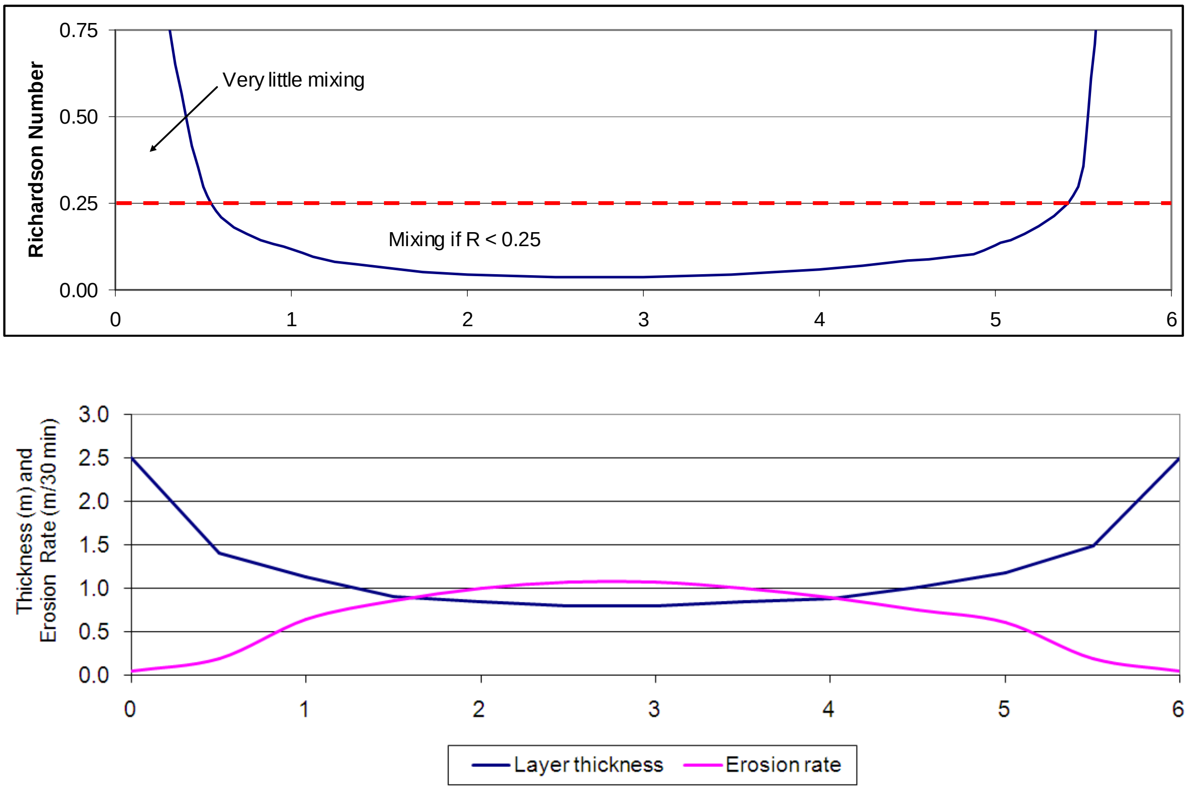
12. CALCULATED DYNAMIC RICHARDSON NUMBER

From the geometry of the diluted field on the seabed, the density difference and the current speed, the Richardson Number can be calculated for each half hour of the flood tide. The result is shown in Figure 13 for the single port option.

At and near low and high water – the times with weak currents - the Richardson Number exceeds 0.25 (indeed, it exceeds 1.0) and there is very little mixing. Thus, the stratified dense field formed at these times is not quickly mixed into the ambient seawater current.

However, for most of the flood tide, the currents are sufficiently strong to produce a Richardson Number below the critical value of 0.25 and there is a moderate to high rate of vertical mixing.

Figure 13. Richardson Number and Mixing of Dense Field - Single Port

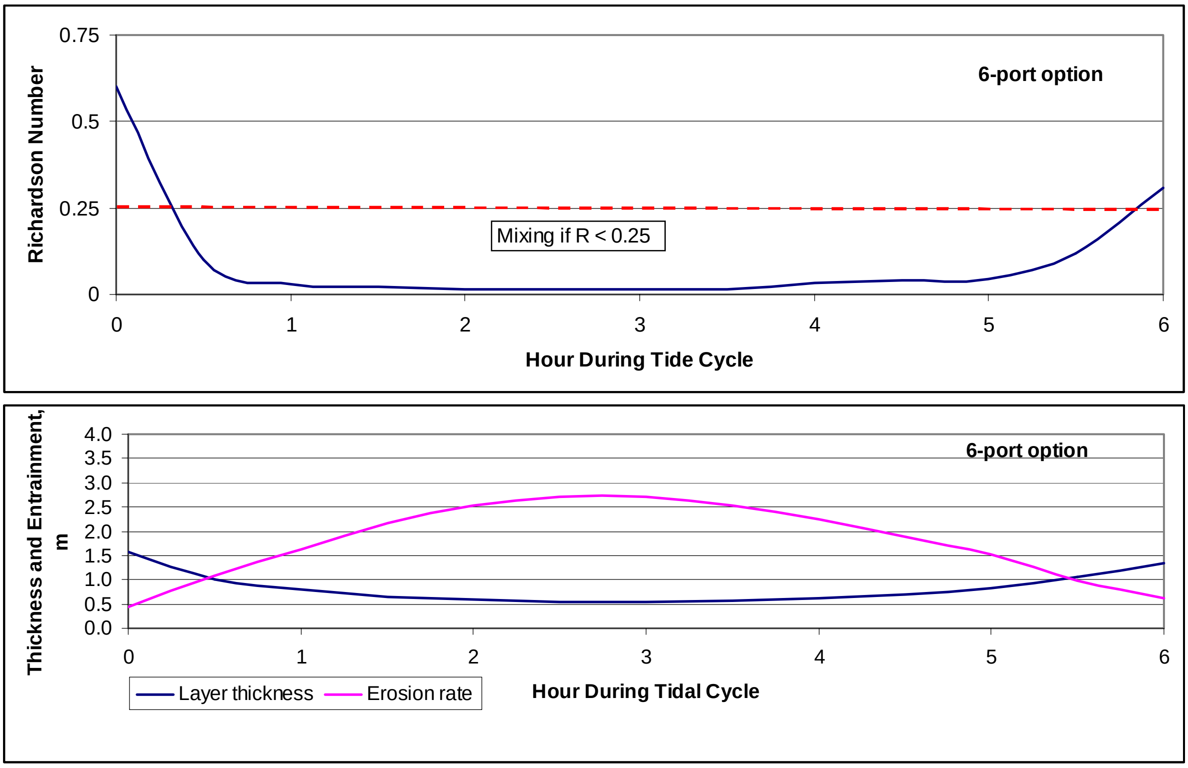


The lower figure in Figure 13 shows, for each half-hour time step, the thickness of the layer of cooler water on the seabed (blue line) and the rate of erosion or mixing of the more dense layer (pink line). When the blue line is above the pink line, the field is thicker than the rate of mixing, and so most or a remnant of the cooler layer persists to the next time step.

On the other hand, when the pink line is above the blue line, the rate of vertical mixing field is greater than the depth of the cooler layer and so the cooler layer is entirely mixed into ambient seawater in that time step.

For the proposed 6-port option, the rate of vertical mixing is greater than the depth of the cooler layer except for a brief period at slack water. Thus, with the 6-port option, the cooler layer is entirely mixed into ambient seawater and into the passing seawater for almost all the tide cycle, expect (perhaps) for a short period at slack water.

Figure 14. Richardson Number and Mixing of Dense Field - 6-port Option



The Water Technology computer model of currents predicts zero longitudinal current speed at slack water (averaged over the depth). In practice, based on field measurements of currents in Western Port, when longitudinal currents are close to zero at slack water there is a small lateral current caused by draining (or filling) of the mudflats and bays on the sides of the main channel. This is shown by the elliptical current vector formed over a full tidal cycle.

As a result, it is considered that the time for formation of a cooler layer on the seabed with the 6-port discharge option is probably 30 minutes or less, at times of slack water. In that case, the field will spread less than 200 m from the discharge ports, and thus be contained within a field of 200 m radius that is well within the defined port waters of the Port of Hastings (as defined by the Victorian Regional Channels Authority, 2018).

In contrast, with a single port discharge, the time for formation of a cooler layer on the seabed is probably 1 hour or more, over the period of slack water and weaker tidal currents. In that case, the field will spread about 600 m from the discharge ports, although it will still be contained within the defined port waters of the Port of Hastings. As stated above, this single port discharge option is presented for comparison purposes only.

13. DYNAMIC BEHAVIOUR OF DILUTED COLD-WATER FIELD

The rate of vertical mixing has been assessed from the experimental data published by Keulegan (1949) and Kato and Phillips (1969). These experiments show that the vertical mixing rate is proportional to the shear velocity (effectively higher shear creates internal waves which create upward mixing) and inversely proportional to the density difference between the fluids.

The resulting mixing rate varies from 0.0002 m/s at a current speed of 0.1 m/s to 0.0010 m/s at a current speed of 0.5 m/s. These may appear to be small, but they correspond to mixing rates of 0.72 m/hour to 3.6 m/hr, which are significant rates of mixing in comparison to a field thickness of 1.0 to 2.5 m.

The lower plots in Figures 13 and 14 show the thickness of the cold-water pool formed on the seabed at the base of the plume (blue line) and the mixing or erosion rate (pink line) expressed in metres/half hour. Figure 13 shows that, at slack water, the layer is 2.5 m thick and erosion is weak. However, as the current speed increases, the layer thickness decreases and the erosion rate increases. For the 2.5 hours with strong currents, the erosion rate in 30 minutes equals or exceeds the layer thickness. Thus at or near peak currents, the field is mixed into the ambient seawater current in 30 minutes or less. Figure 14 shows, for the 6-port option, a thinner layer only 0.5 to 1.5 m thick and erosion is generally greater than the depth of the field, so the diluted discharge is quickly mixed into the passing seawater.

As a check, it is noted that field measurements at the discharge from a desalination plant with a discharge rate of 5 m^3/s (very similar to the proposed Crib Point FSRU) identified a stable dense field on the seabed that extended over a diameter of 800 m with a density difference 0.2 to 0.85 kg/m^3 (due to slightly higher salinity). The vertical mixing rate for this dense field in the ocean (based on the measured initial dilution of 30:1) was 0.0003 m/s (corresponding to 1.1 m/hr). This measured mixing rate falls within the published range, and corresponds to a typical ocean current speed of 0.2 m/s (for the measured density difference).

The time scale for the data in Figures 13 and 14 is 30 minutes. A negligible cold-water layer will occur when the erosion in 30 minutes equals or exceeds the thickness of the cold-water layer on the seabed. The cold-water layer can only form when the erosion rate is small and insufficient to remove the layer in the 30-minute time interval.

For the period at and just after slack water, vertical mixing is slower and thus there is a potential for the formation of a cold-water layer if the current speed is less than 0.13 m/s, and the Richardson Number is above 0.25. In the next hour, however, that patch will be progressively eroded and mixed with the ambient seawater.

The results of calculations, on a 30-minute time step, show that the extent of the cold-water layer depends on the initial dilution (and thus the number of ports):

- For a 6-port discharge, the field may form briefly at slack water and would extend for less than 200 m radius;
- For a single-port discharge, the field would extend for 600 m north and 240 m wide.

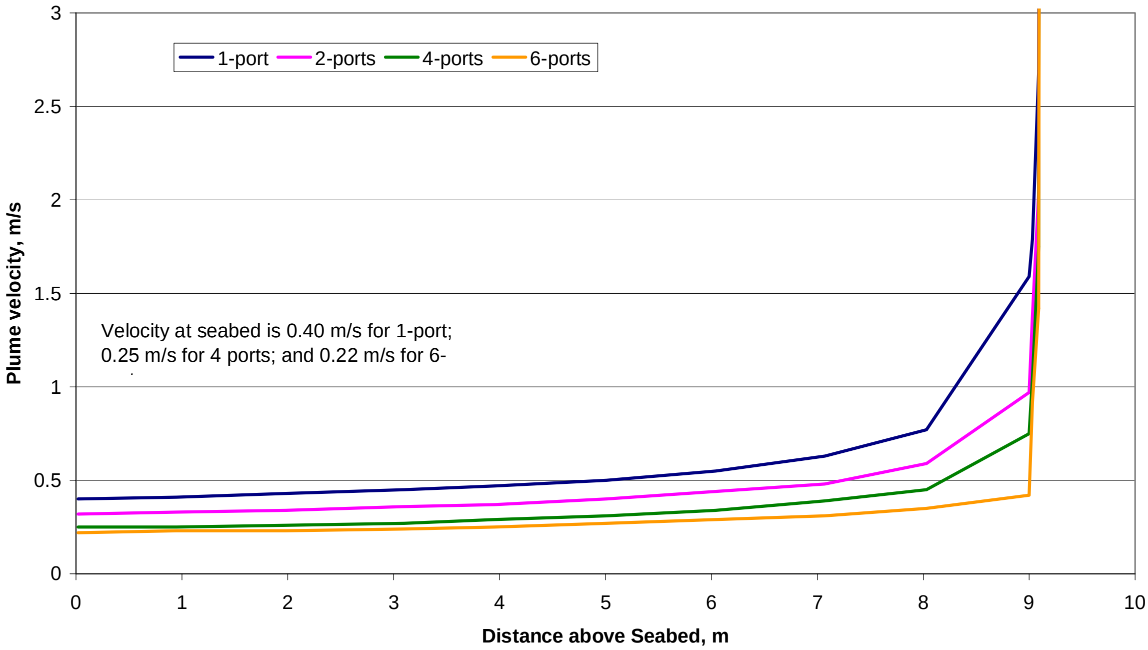
14. VELOCITY AND TRANSLATION OF PLUMES

At the proposed rate of discharge of 450,000 kL/d (equal to 5.2 m^3/s) and a 7°C initial temperature difference, the discharge has a net excess density of 15 t/hr relative to ambient seawater. The discharge plume descends rapidly through the water column, slowing as it mixes with ambient seawater.

Figure 15 shows the predicted velocity of the plume during descent. Initially the velocity is high (over 5 m/s) but the velocity decreases rapidly in the first metre vertically of the decent (although, as shown in the next figure, this represents a considerable distance transversely). When the plume reaches the seabed, the plume velocity will be:

- 0.40 m/s for a single port discharge;
- 0.32 m/s for a 2-port discharge;
- 0.25 m/s for a 4-port discharge; and
- 0.22 m/s for a 6-port discharge.

Figure 15. Velocity of Plume at Various Distances (Seabed is zero depth)

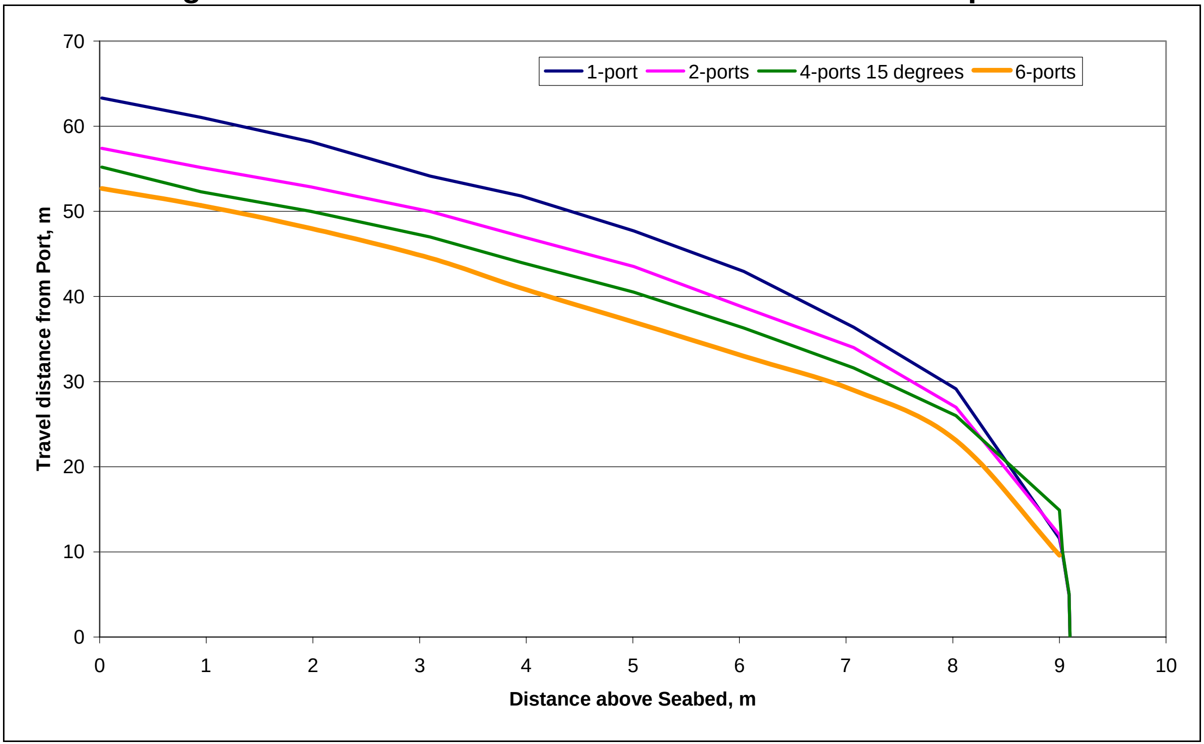


The plume will have a mass flux of about 19 t/s for the single port discharge and 18 t/s for each plume in the 6-port discharge. This large mass of seawater moving at a moderate velocity will erode a pit where the plume reaches the seabed.

Another aspect of interest in the behaviour of the discharge plume is the extent of travel away from the FSRU. The discharge plume has a large mass flux (5.2 m^3/s as noted above) and is discharged horizontally at a high velocity (around 5.4 m/s). Thus, the plume has a large horizontal momentum that conveys the plume a considerable distance from the discharge port.

Figure 16 shows the predicted translation of the plume during descent for various port options. The single port option will travel 63 m laterally from the port before it reaches the seabed at low tide, and around 70 m at high tide.

Figure 16. Translation of Plumes for Various Port Options



The 6-port option will travel 52 m laterally from the port before it reaches the seabed at low tide, and around 58 m at high tide.

Note that the predictions of initial dilution assume that the path of the plume is not impeded by the jetty or other structures or vessels. In our view, it is likely that the plumes will interact with the adjacent LNG vessel during LNG unloading operations, and this will reduce the travel distance of the plume and hence the initial dilution (although only when a LNG vessel is moored alongside the FSRU). The resulting dilution is then likely to match the 2-port option for the three ports on the offshore side, and match the 6-port option for the three ports on the inshore side.

For this reason, this report has presented the dilutions and cold-water field implications for a range of discharge options.

When a LNG vessel is moored beside the FSRU, it may restrict the path of the plume on the starboard side of the FSRU and the dilution could be temporarily reduced. This could occur about once a week over a 24-hour period. During the period of weaker currents near slack water, the diluted field could form a stable layer on the seabed about 2 m thick, extending for a maximum of 200 m distance. The layer formed at slack water will become mixed into the ambient seawater when currents increase an hour later in the tide cycle.

15. CONCLUSION

This assessment concludes that discharged seawater would dilute rapidly after discharge, with the initial dilution at the seabed depending on the number and depth of discharge ports and the velocity of discharge. AGL's preferred design is a 6-port discharge. Fewer discharge ports have been considered in this assessment for comparison purposes only.

Modelling shows that the initial dilution depends on the number of discharge ports. For the 6-port discharge option proposed by AGL, the lowest dilution would be 20:1 (at low tide and a vessel with a full LNG load) and the highest dilution would be 26:1 (achieved at high tide and a near-empty vessel).

For the period at and just after slack water, vertical mixing is slower and thus there is a potential for the formation of a cold-water layer on the seabed over that period.

A single port discharge was examined as a worst-case option and showed that a layer of cooler water at 0.8°C below ambient will form for a period of just under an hour at each slack water. The maximum extent of the layer for the single port discharge has been calculated from the balance between initial field thickness, shear due to ambient currents and vertical mixing. The layer will extend about 600 m north in the flood tide, and a similar distance to the south in the ebb tide. The layer will be a maximum of 240 m wide and thus be contained within the defined port waters of the Port of Hastings.

AGL's preferred discharge configuration is for a 6-port discharge. For a 6-port discharge, the cold-water field may not form at slack water but if it does, it will extend for less than 200 m north and 120 m wide and have a temperature difference of only 0.3°C from ambient seawater. The layer will be contained within the defined port waters of the Port of Hastings. The cold-water layer may not form with the 6-port option if there are sufficient lateral currents over slack water at the discharge site.

When an adjacent LNG vessel restricts the path of the plume, the dilution could be reduced. This could occur about once a week over a 24-hour period. In the weaker currents near slack water during this period, the diluted field could form a stable layer on the seabed about 2 m thick. The layer formed at slack water will become mixed into the ambient seawater when currents increase later in the tide cycle.

To achieve effective dilution, the discharge ports should be horizontal, near the water surface and have a high discharge velocity (> 5 m/s).

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APPENDIX A: NEAR-FIELD MODELLING PARAMETERS

Parameter	**Unit**	**Response**
Discharge rate	m3/d	450,000
Temperature difference	°C	7°C on exit from FSRU
Depth of Water	m	Stern Min 12.8 Bow Min 14.7 Tide can add 3.3 m to these depths
Depth of Ship	m	Fully Loaded 11.6 m Ballast only 9.3 m
Vessel length	m	294 m (285 m parallel length next to hull)
Discharge from Single Side Port		
Depth of port below sea level	m	10.3 m above vessel base line, 100 m forward of stern, starboard side
Diameter of port	m	1.1
Angle below vertical	deg	15
Discharge from Side Dual Ports		
Depth of ports below sea level	m	8.5 m above vessel base line, close to bow of vessel
Diameter of port	m	0.9 each port
Angle below vertical	deg	15
Discharge from Multiple Ports		
Depth of ports below sea level	m	At CEE discretion
Angle below vertical	deg	0 (horizontal discharge)

Seawater inlets
Depending on design, inlet may be through existing vessel sea chests
High sea chest: Distance from stern: 55.2m, Height: 4.6m above Base Line (B.L.) Sea chest gratings follow hull shape

Low sea chest: Distance from stern: 54.0m, Height: 3.4m above Base Line (B.L.) Sea chest gratings follow hull shape

If the regas system is mounted in the bow, two options are under consideration:
Caisson type pumps (internal) with the inlet strainers (retractable during sailing conditions) underneath the fore ship (ie at the base of vessel)

Sea chests on port and starboard side, at similar elevation to main sea chests, feeding into the same crossover line.