The Safety Assessment of LNG Marine Bunkering

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The marine bunkering of ships with LNG as an industry is in its infancy. There are no accepted and well defined industry rules and practices for defining safety zones around LNG bunkering operations. In this vacuum, many have been trying to adapt existing procedures and methodologies from similar industries. Are these appropriate? Are they correct? Are they conservative? The Society for Gas as a Marine Fuel (SGMF) formed a working group from within its membership in 2015 to consider these issues. This paper summarises the work carried out by DNV GL for SGMF to define safety zones that are applicable to a wide range of gas receiving ships and bunkering systems operating worldwide.

The aim of the research was firstly to determine which parameters were most important to the size of the safety zone and then secondly to provide simple methods of estimating safety zones based on a few, easily determined, parameters. The parameters considered include:

- LNG transfer flowrate, temperature and pressure,
- hose/hole sizes,
- orientations of leaks - vertical, horizontal and downwards
- climatic conditions - wind speed, atmospheric stability, ambient temperature and humidity
- LNG compositions (and physical properties)
- geometries/topographies for releases over land and sea and at different elevations
- durations of release (type of ESD system)

As anticipated and evidenced by the different safety distances for refuelling LNG fuelled trucks compared to bulk LNG transport and unloading, size matters. The larger the transfer rate, the larger the transfer equipment, the larger the potential leak and therefore the larger the safety distance. One safety distance will not fit all ships; if it works for a larger container-ship it would be hugely conservative for a small Roll-on/Roll-off ferry.

The results of the analysis have been incorporated into the BASiL (Bunkering Area Safety Information for LNG) tool. This is a database of 1.4 million combinations of the input parameters important to gas dispersion which allows multiple parameters to be considered simultaneously as they all interact and in different combinations lead to different safety distances. The BASiL tool is robust and can quickly calculate a range of safety distances for different ships over a variety of climatic conditions worldwide. It should allow safety zones to be consistently calculated by the industry.

Keywords LNG, Bunkering

Introduction

The marine bunkering of ships with Liquefied Natural Gas (LNG) as an industry is in its infancy. There are no accepted and well defined industry rules and practices for defining safety zones around LNG bunkering operations. In this vacuum, many have been trying to adapt existing procedures and methodologies from similar industries. Are these appropriate? Are they correct? Are they conservative?

The Society for Gas as a Marine Fuel (SGMF) formed a working group from within its membership in 2015 to consider these issues and the output from the group has been summarised in a previous paper (Haynes 2018) and an SGMF publication (SGMF 2018). This paper gives more technical details of the dispersion modelling that was carried out and the methods used to produce the BASiL (Bunkering Area Safety Information for LNG) tool which enables SGMF members to calculate Safety Zones that are appropriate for their operations. To explain the context for this, an overview of the work of the SGMF working group is given in the next section.

Defining Concepts

In setting hazard management areas, the concepts used are familiar based on existing methods for hazardous cargoes. SGMF has just refined these so that all stakeholders can identify what needs to be done and who the appropriate regulator needs to be. This is important. SGMF is not a purely shipping organisation, its remit is to cover the whole of the bunkering process and so includes non-ship elements such as road tankers, port facilities, LNG terminals and the public surrounding the area as well as the gas receiving ship and bunker vessels. SGMF’s aims for this guidance is that it can be used consistently across the bunkering chain worldwide.

On this basis five zones were defined (Figure 1):

- Hazardous zone
- Safety zone

- Monitoring and security area
- Marine exclusion zone
- External zone

The hazardous zone is well defined by existing standards and rules. It is the three-dimensional area where a flammable atmosphere could be present at any time (not just during bunkering) through leaking flanges, valves, etc. Calculations and terminology are largely consistent worldwide and both the IGC code (International Maritime Organisation's International Code for the construction and equipment for ships carrying liquefied gases in bulk) and IGF code (International Maritime Organisation's International Code of Safety for Ships using Gases or other low-flashpoint fuels) provide distances based on anticipated scenarios. SGMF has accepted these rules as written.

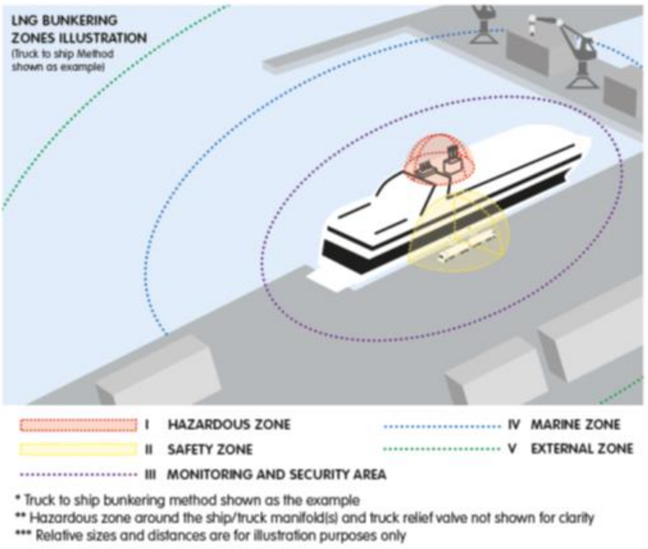


Figure 1 Safety management zones for LNG bunkering

The primary work was to define the Safety Zone, a three-dimensional shape around the LNG transfer system that could be impacted if a representative release of LNG or vapour were to occur during bunkering. Calculating the size of this zone has been challenging and is addressed in detail in this paper.

The Monitoring and Security Area is deliberately more loosely defined as SGMF does not believe that generic distances are firstly appropriate and secondly calculable. The Monitoring & Security Area is an area around the LNG transfer equipment that needs to be monitored as a precautionary measure to prevent interference with the LNG transfer operation and the Safety Zone. Local topography such as walls, buildings, stacks of containers, etc. reduce or prevent visibility and port/terminal control measures may affect what happens where.

The Marine Exclusion zone is familiar from standard port rules and procedures and, as normal, needs to be of sufficient size to prevent passing shipping from impacting the LNG transfer operation.

The External Zone is the distance to a defined risk level, generally in places where the public may be present, required by some regulatory regimes, particularly in Europe, and is the most obvious example of terrestrial and maritime rules needing to come together.

The Safety Zone is defined as a three-dimensional shape around the LNG transfer system that

- could be impacted if a representative release of LNG or vapour were to occur during bunkering.
- is controlled by the Person In Charge (PIC)
- contains only a few essential personnel, the PIC(s) and staff monitoring the manifold and hoses
- is used only for authorized activities, anything other than bunkering is a SIMOP and must be risk assessed for its compatibility with bunkering

In its simplest form the representative leak is easy to define as a hole (small compared to a complete rupture) in the bunkering transfer system (normally a hose) or the vapour return system. This leak may subsequently disperse into the atmosphere or ignite.

SGMF took the view that whilst a Quantitative Risk Assessment (QRA) may be required or carried out by some regulators, port authorities and operators, this would not form the basis of the guidance and a deterministic approach, similar to ISO 205191, would be followed. SGMF consulted on a confidential basis throughout the LNG road tanker industry and to a lesser extent with the cryogenic gases associations (liquid oxygen, nitrogen and argon) to determine good practice. The result of this work was that this no evidence that cryogenic transfer hoses have ruptured in service. They fail through the creation of small holes, which can be seen during inspection and operation, allowing removal from service before the hole size grows appreciably. Overstressing during bending is the primary cause of failure. For marine bunkering where movement is continuous, and not just during connection and disconnection, failure will be more frequent but the same mechanism is anticipated.

Three sets of data (UK HSE for metal hoses in chlorine service, Dutch regulations for rubber oil/LPG hoses and German scientific research) were analysed and although limited, appear to suggest that the hole size is a function of hose diameter. This is not unexpected as analysis of fixed pipework in oil and gas service offshore in the UK and Norwegian sectors of the North Sea produces a similar conclusion concerning hole size and pipe diameter. SGMF has therefore adopted a similar approach and also considers a flange/valve based failure.

BASiL looks at flash fires, not that these are more damaging or harmful than an explosion or jet/pool fire but that their initial extent is larger and could therefore incorporate more individuals and property.

Parameters Affecting the Safety Zone

The size of the Safety Zone will vary considerably depending on the nature of the transfer operation. One safety distance will not fit all ships. For example, it would be hugely conservative to calculate a Safety Zone that is applicable to a large container ship and then use this for a small Roll On-Roll Off ferry. Therefore, it was necessary to consider sufficient parameters in the modelling to distinguish between different types of bunkering operations and the conditions in which an accidental release might occur. The parameters affecting the Safety Zone that were modelled are shown and discussed in Table 1.

Table 1 Parameters Affecting the Safety Zone

Parameter Group	Parameter	Discussion
LNG transfer operation	LNG composition	Influences a number of other parameters such as the LFL, LNG density and vapour quality all of which effect the dispersion distances.
	Transfer flowrate	Used to check that pressure in hose can be maintained before ESD, i.e. the calculated release rate is less than transfer rate. This can be important for relatively large release sizes in smaller hoses.
	Hose diameter	Affects the release hole size.
	Pressure	Affects the mass flowrate of the release.
	Temperature	Together with the pressure this determines the vapour quality of the LNG which in turn will affect parameters such as the mass flow rate and the density of the dispersing jet.
Ambient conditions	Wind speed	Affects the mixing or air with the LNG vapour. Higher wind speeds generally cause more rapid dilution of the LNG vapour. However, very close to the source of high momentum jets higher wind speeds can give slower dilution, as the velocity difference between the jet and the wind is smaller.
	Wind direction	Affects how the air will mix with a jetted release. For horizontal jets the maximum dispersion distances occur for co-flowing winds.
	Atmospheric stability	Affects the turbulence in the atmosphere and hence the mixing of air and LNG vapour. Stable atmospheres result in less mixing than unstable atmospheres.
	Ambient temperature and humidity	Affects the energy in the atmosphere available to vaporise the LNG liquid.
Accidental release	Hole size	Affects the mass flow rate of the release.
	Orientation	Could be in any direction. Upwards and horizontal releases are likely to be free jet type releases. Downwards releases are likely to impact on the ground and result in LNG pools.

	Elevation	Is particularly important for horizontal releases as it effects the amount of air that can be entrained into the lower side of the jet. This will be smaller for lower elevations.
	Ground type	Affects the heat transfer to an LNG pool. Land will give a high initial heat flux but will then gradually cool when in contact with an LNG pool whereas deep water will remain at a constant temperature due to convective currents in the water.
	Surface roughness	Affects the atmospheric turbulence and the mixing of air with a release and hence the dilution of the LNG vapour.
	Ground temperature	Affects the heat transfer into an LNG pool.
Emergency response	Duration of the accidental release (type of ESD system)	If the release is isolated before the dispersing vapour reaches its maximum extent then it can reduce the dispersion distance. In many cases the duration of the release tends to be greater than the timescale for the dispersion.

Dispersion Modelling of Accidental Releases

The orientation of the release would be expected to have a very important effect on the dispersion, for example, vertically upwards free jets and vertically downwards jets which impact on the ground are likely to behave in significantly different ways. Hence, the study considered the three idealised cases of horizontal, vertically upward and vertically downward releases separately. These cases are discussed below.

The project considered the effect of all of the parameters on each release orientation. This generated a large amount of information, a small sample of which is discussed in this paper.

Varying one parameter at a time would have required the smallest number of calculations. However, there was a possibility that some of the parameter variations could interact to give a greater effect on the dispersion. For example, the upstream temperature affects the vapour quality of the release and hence its density. These density differences would be expected to have a greater effect on larger releases and at lower wind speeds. Therefore, where it was considered appropriate, the study considered the effect of varying multiple parameters simultaneously.

Horizontally Directed Releases

Dispersion predictions were made for free jets resulting from leaks with diameters of 5, 10 and 20 mm. This covered the range of leak sizes that could be considered representative, for defining the safety zone. That is, they are larger than the leaks used to define hazardous areas but smaller than catastrophic releases such as ruptures of the transfer hose. For these investigations it was assumed that the pressure inside the transfer hose did not drop when the leak started. This is a reasonable assumption for cases where the transfer rate exceeds the outflow rate through the leak, which is typically the case when the area of the leak is less than 10% of the cross-sectional area of the hose.

The first parameter variation that was considered was the wind speed. Although extremely high wind speeds could cause rough water and prevent bunkering from taking place, LNG transfers could occur at any reasonable wind speed.

Figure 2 shows the variation of the distance to the LFL with the wind speed for a range of atmospheric stabilities.

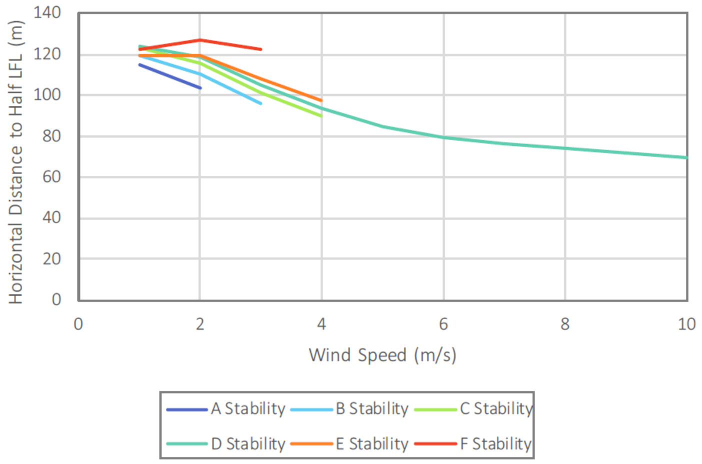


Figure 2 Variation of dispersion distance to the LFL with wind speed for an LNG release with a diameter of 20 mm

This figure shows that dispersion distances tend to be greater in lower wind speeds. However, for some stabilities the dispersion distances are greater in a wind speed of 2 m/s than in a wind speed of 1 m/s.

The initial part of a dispersing jet is dominated by the momentum of the jet, with greater entrainment occurring when there is a greater difference between the velocity of the jet and the velocity of the wind, hence, there would be less entrainment in higher wind speeds. As the jet entrains air and slows, the effect of the density of the jet becomes more important, and as the jet dilutes further and the density approaches that of the surrounding air, the effects of atmospheric turbulence become important. In these stages there would be less entrainment at low wind speeds. Since

Figure 2 shows that the maximum dispersion distance does not always occur for the lowest wind speed, and theoretical considerations also suggest that the wind speed can have complicated effects on the dispersion, all subsequent analysis calculated dispersion in 10 evenly spaced wind speeds between 1 and 10 m/s, for appropriate atmospheric stabilities. The variation of the maximum distance over these ten wind speeds with other parameters was then examined.

Predictions were also made for a range of temperatures and pressures of the LNG being transferred in the hose. Transfer pressures are typically between 4 barg and 10 barg, with pressures up to 20 barg possible. The temperature of the LNG is normally between its boiling point at atmospheric pressure and about 40°C warmer. Predictions were only made for combinations of pressure and temperature where the LNG inside the hose was in the liquid phase. These predictions are shown in Figure 3 for a steady state release with a diameter of 20 mm. As noted above, the distances plotted are the maximum dispersion distance predicted for a range of 10 wind speeds between 1 and 10 m/s.

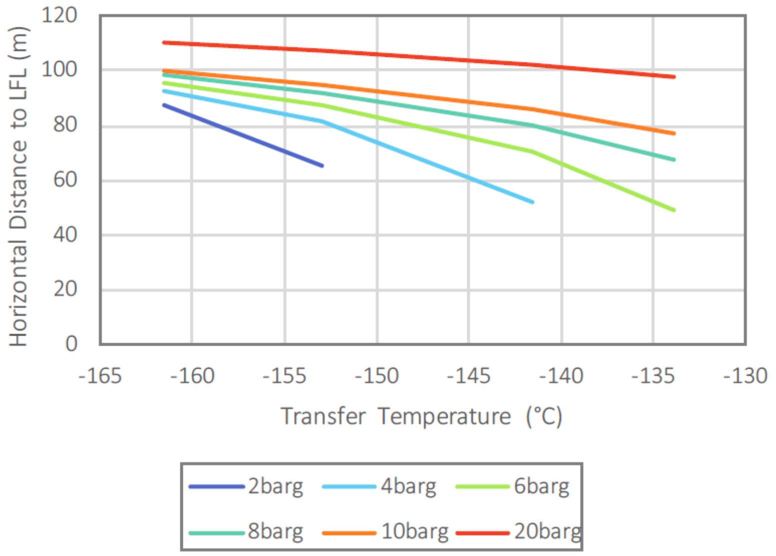


Figure 3 Variation of dispersion distance to the LFL with transfer pressure and temperature for an LNG release with a diameter of 20 mm

The predictions for releases from steady state 10 and 5 mm diameter holes showed similar trends. These predictions show that the dispersion is sensitive to the temperature and pressure of the LNG being transferred.

There is significant variation in the composition of LNG produced around the world. GIIGNL (International Group of Liquefied Natural Gas Importers) (GIIGNL 2017) give information about the composition of LNG from 23 export terminals. These LNG have molecular weights of between 16.2 and 19.2 g/mol. Figure 4 shows the phase envelopes of the different compositions. The bubble lines of the different compositions are quite similar, but there is a large variation in the location of the dew line.

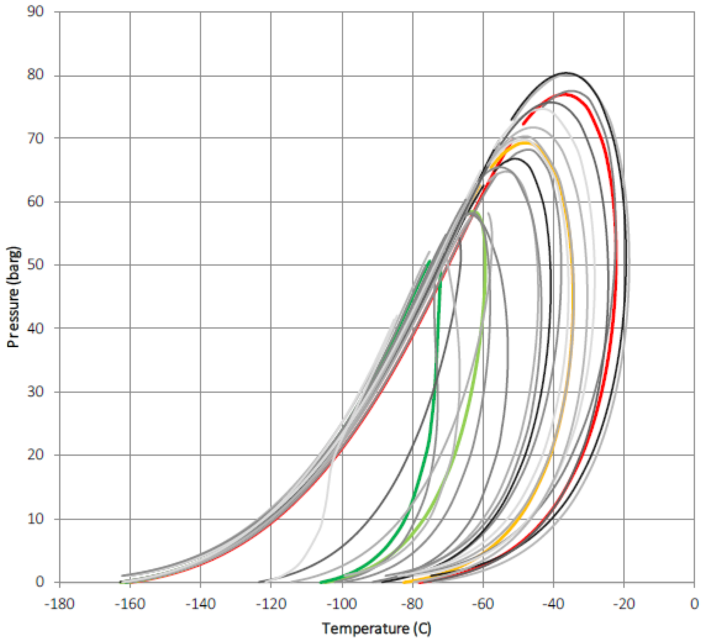


Figure 4 Phase envelopes for different LNG compositions

There are significant differences in the predicted dispersion distance for different LNG compositions as shown in Table 2.

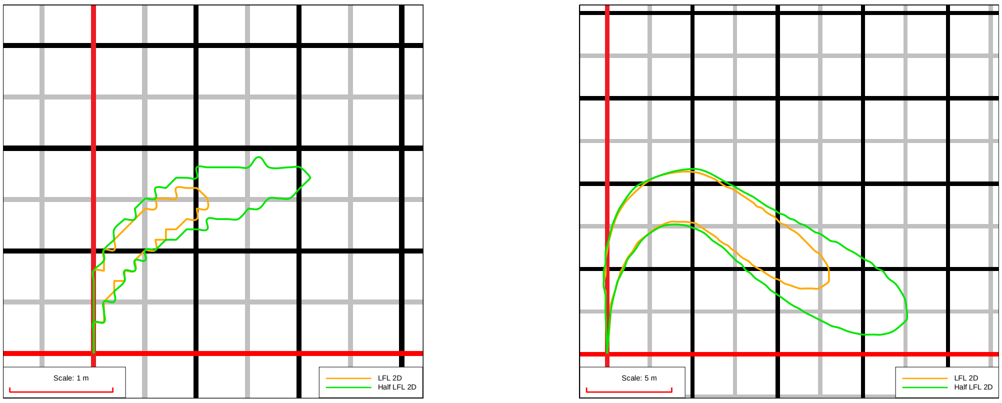
Table 2 Variation of dispersion distance with composition

Diameter of Release (mm)	Range of Dispersion Distances (m)
5	14 – 17
10	30 – 35
20	65 - 76

The predictions for horizontal jets assume that the jet forms a free jet which does not interact with any obstacles, although the effect of the interaction of the jet with the ground is accounted for. Depending on the configuration of the jet and obstacles, the interaction could make the dispersion distance larger or smaller than that for a free jet. The safety zone is intended to cover ‘representative’ releases rather than to encompass worst case catastrophic releases with low frequencies, and it was considered reasonable to use a free jet as a representative release.

Vertically Upward Directed Releases

LNG releases are significantly denser than air. For typical transfer pressures of up to about 9 barg, the velocity of the LNG release tends to be less than 100 m/s. This means that upward directed releases stall and fall back towards ground level, and for very many cases this occurs before the centreline concentration drops below the LFL. This is illustrated in Figure 5, which shows a vertical two-phase jet from a small leak with a diameter of 1 mm which is still flowing upwards when the concentration drops below the LFL, and a jet with a larger diameter of 10 mm which stalls and starts to flow downwards while the concentration is above the LFL.



a) Release with a diameter of 1mm

b) Release with a diameter of 10 mm

Figure 5 Two vertically upward jets, a jet from a leak with a larger diameter which stalls before the concentration falls below the LFL, and a smaller diameter leak which does not

At lower wind speeds, the stalling plume will tend to fall back on the upward flowing part of the jet, like a fountain. It would be expected that the interaction between the upward and downward flowing parts of the jet would result in the upward flowing jet re-entraining some of the downward flowing dense plume, rather than entraining less dense air. This is likely to reduce the height of the jet below that predicted by the integral model which does not account for these effects. Observations of experimental releases of dense phase CO_2 where the plume falls back on itself sometimes show fluctuations in the height at which the plume stalls. These may be due to fluctuations in the wind speed, which change the amount of the downward flowing plume that is re-entrained in the upward jet. These observations also suggest that the height at which the jet initially stalls, before any re-entrainment has occurred, is larger than the stalling height at later times. The integral model, which does not account for this re-entrainment, is likely to give a reasonable estimate of the initial height at which the plume stalls, and hence it is likely to give a reasonable prediction of the maximum height at which flammable gas is present.

Predictions for the vertical extent of the flammable cloud were carried out for a range of wind speeds. The greatest height occurred for the lowest wind speeds. This is because at higher wind speeds the velocity difference between the jet and the surrounding air is greater, resulting in more air being entrained into the jet, causing the velocity to reduce more rapidly, and the jet to stall closer to the leak. Although this was a consistent result across many parameter variations, the predictions for vertical jets used the same methodology as the horizontal jets, carrying out predictions for a range of wind speeds and using the maximum distance to the LFL.

Figure 6 shows the variation of the maximum vertical distance to the LFL with the pressure and temperature of the LNG in the transfer hose.

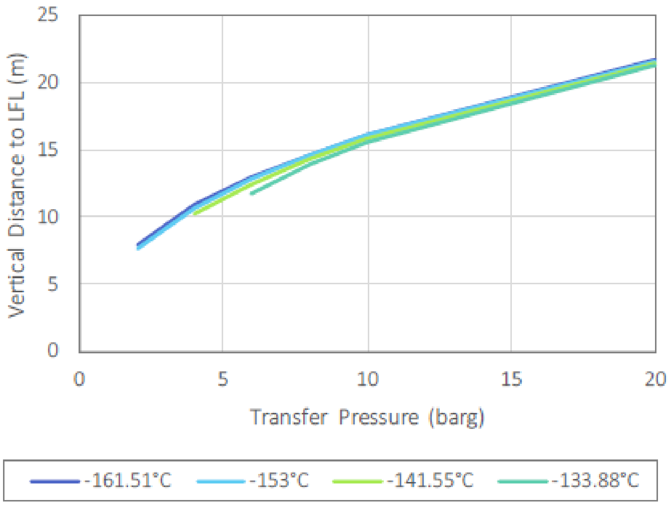


Figure 6 Variation of dispersion distance to the LFL with transfer pressure and temperature for a vertically upward LNG release with a diameter of 20 mm

Compared to the horizontal jets considered in the previous section, the vertical jets are more sensitive to the transfer pressure but less sensitive to the temperature.

Vertically Downward Directed Releases

Vertically downward releases have been modelled assuming that all of the LNG liquid after the release has flashed to atmospheric pressure rains out to form a pool on the ground or water surface. A dispersing dense gas cloud forms from a combination of the vapour boiling off this pool and any LNG vapour after the release has flashed to atmospheric pressure.

Figure 7 shows the variation of the predicted horizontal distance to the LFL with wind speed. Figure 8 shows similar information for the vertical distance.

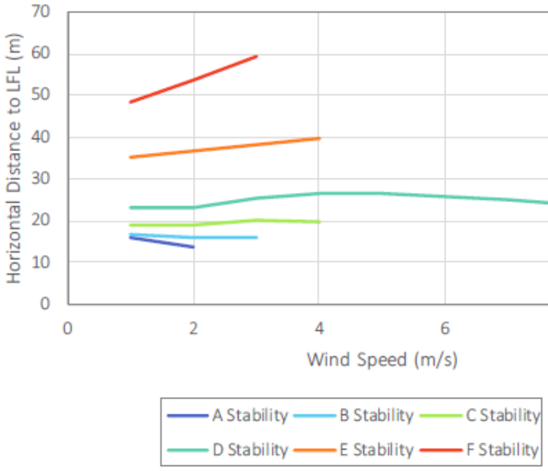


Figure 7 Variation of the horizontal dispersion distance to the LFL with wind speed and stability for a vertically downward LNG release with a diameter of 10 mm

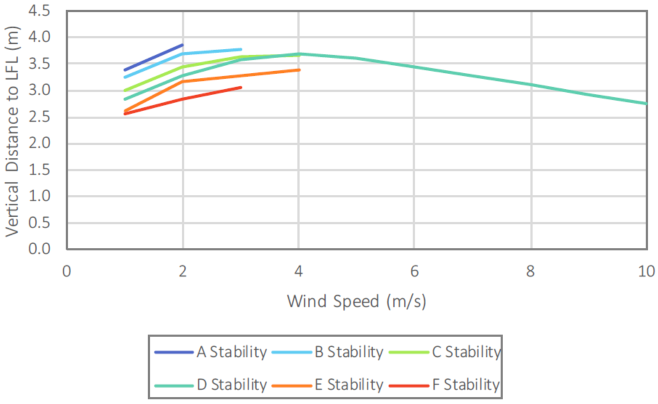


Figure 8 Variation of the vertical dispersion distance to the LFL with wind speed and stability for a vertically downward LNG release with a diameter of 10 mm

As with the horizontal jets, the maximum dispersion distance does not always occur for the lowest wind speeds, and subsequent parameter variations examine the maximum dispersion distance over a range of wind speeds and atmospheric stabilities. Using this approach also allows the maximum vertical height of the plume, which probably occurs at a different wind speed to the maximum horizontal extent, to be captured.

Atmospheric conditions tend to have more effect on these low momentum releases compared to the two-phase jet releases considered in previous sections. When warm air mixes into the cold LNG vapour, heat is transferred from the air to the LNG vapour. In particular, if the resulting mixture is colder than the freezing point of water, then the water in the atmosphere will freeze to form ice, releasing latent heat. This latent heat tends to be significant compared to the heat released by cooling the air, particularly for high relative humidities combined with high ambient temperatures, where the concentration of water in the atmosphere is high. This greater heat transfer tends to decrease the density of the dispersing plume, decreasing the slumping of the plume due to gravity and the associated air entrainment and increasing the dispersion distance.

Weather data from 164 ports around the world was examined to identify the combinations of relative humidity and temperature that were likely to occur in practice. Dispersion calculations were carried out for various combinations of ambient temperature and relative humidity, as shown in Figure 9. This figure also shows combinations of temperature and humidity recorded at the 164 ports.

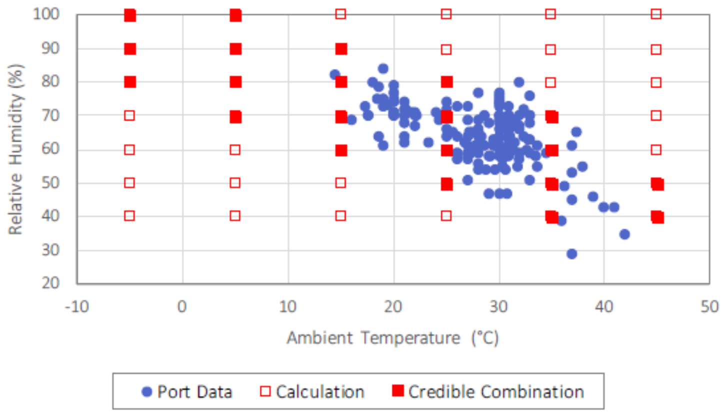


Figure 9 Temperature and humidity combinations recorded at ports

This shows that some combinations of ambient temperature and relative humidity are unlikely to occur at ports. Figure 10 shows the variation of the dispersion distance to the LFL for a 10 mm diameter release for a range of ambient temperatures and relative humidities. Predictions are only shown for credible combinations of these parameters, as shown in Figure 9.

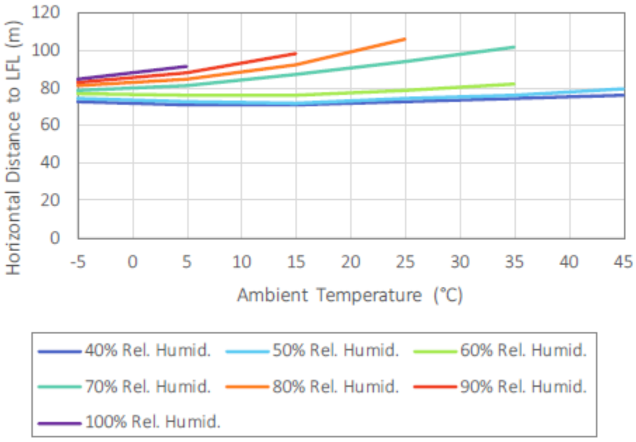


Figure 10 Variation of dispersion distance to the LFL with ambient temperature and relative humidity for a vertically downward LNG release with a diameter of 10 mm

This shows that the dispersion distance is sensitive to the ambient temperature and relative humidity, with the sensitivity being greater when both the temperature and relative humidity are high.

For some combinations of temperature and humidity the concentration of water in the air is very high, and the heat transferred between the air and the LNG is sufficiently high that the predicted density of the plume drops to less than the density of air. When this occurs, long dispersion distances can be predicted. However, this was not predicted to occur for any of the credible combinations of temperature and humidity.

Development of a Tool for Industry Use

The sample analysis in the previous section shows that the dispersion distances depend on many of the parameters listed in Table 1. This is significantly different to gaseous releases, such as the natural gas releases considered in SR/25 (IGEM 2013), which for several situations uses lookup tables in the diameter of the releases and either the mass flow rate or the operating pressure. Cautious values were assumed for other parameters when the tables were generated. The approach of using printed lookup tables would not be practical for the LNG releases used to define the Safety Zone, due to the large number of parameters. An alternative approach would be to run the linked outflow, liquid spread and dispersion models to calculate the Safety Zone. Although this would take all the parameters into account, it could take some time to perform calculations, particularly if the Safety Zone was based on the maximum dispersion distance for a range of wind speeds. There could also be issues with installing the software on different platforms and with making the tool easy to use for people with no modelling experience.

Hence, an intermediate approach was selected, which would use large lookup tables to account for all relevant parameters, with a simple spreadsheet interface to do the look ups and interpolations.

This section describes the development of the spreadsheet tool.

Scaling

The accuracy of the spreadsheet model depends on how closely the interpolated values match the results of running the linked outflow, dispersion and possibly liquid spread models. One way to make the interpolation more accurate would be to generate the lookup tables based on a large number of values of each parameter. Due to the large number of parameters which affect the dispersion, this slightly inelegant approach would generate a very large quantity of data. Other ways to improve the accuracy of the interpolation is to use an appropriate form for the interpolation and to scale, or non-dimensionalise the parameters with physically relevant variables.

Figure 3 shows the variation of the horizontal jet dispersion distance with the pressure and temperature of the LNG in the transfer hose. Although both parameters significantly affect the dispersion, the dependence is not close to being linear. A lookup table would need a reasonably large number of temperatures and pressures to give an accurate interpolation. Plotting the dispersion distance against the mass flow rate suggests that the dispersion distance is approximately proportional to the square root of the mass flow rate, as shown in Figure 11. This figure shows dispersion predictions for release with diameters of 5, 10 and 20 mm, for 21 combinations of pressure and temperature in the hose. The grey line is a multiple of the square root of the mass flow rate.

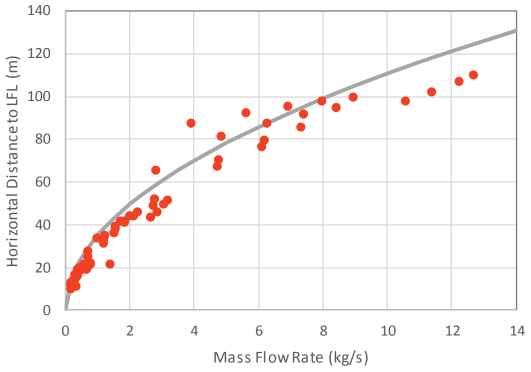


Figure 11 Variation of dispersion distance to the LFL with mass flow rate

This suggests that the dispersion distance can be scaled with the square root of the mass flow rate. It should be noted that this scaling would not be dimensionally correct. Further dependencies must be identified to ensure that the parameter group used to scale the dispersion distance has units of length. Various simple correlations exist for gas jet dispersion which suggest that the dispersion distance is proportional to the diameter of the source after it has flashed to atmospheric pressure. These correlations are of the form

$X_{LFL} \propto \frac{2}{C_{LFL}}\sqrt{\frac{\dot{M}}{\pi\rho U}}$ where, X_{LFL} is the distance to the LFL, $\dot{M}$ is the mass flow rate, ρ is a representative density, taken to be the density of the LNG vapour at the bubble temperature, U is the velocity of the source after flashing to atmospheric pressure and C_{LFL} is the lower flammable limit as a mole fraction of vapour in air. X_{LFL} can be used to non-dimensionalise the dispersion distance. Figure 12 shows the variation of this dimensionless dispersion distance with the velocity of the source.

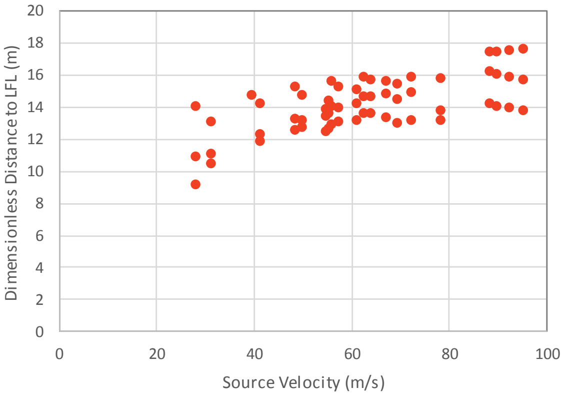


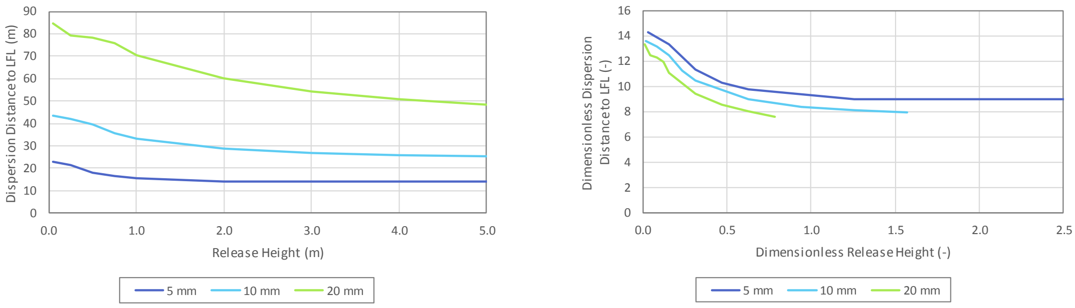
Figure 12 Variation of dimensionless dispersion distance to the LFL with source velocity

This shows that the dimensionless dispersion distance varies slowly with the source velocity.

The purpose of the scaling is to make the dimensionless quantity vary more slowly with the input parameters, compared to the original, dimensional quantity. If this is the case, then interpolating to find the value of the dimensionless quantity will introduce smaller errors than interpolating on the dimensional quantity.

The strong correlation of the dispersion distance with the mass flow rate, and the slow variation with the source velocity suggests that the interpolation can be carried out in two steps, a first interpolation to get the mass flow rate and source velocity from the operating conditions in the hose, and other source conditions, and a second interpolation to get the dispersion distance from the source conditions and other parameters. The model for interpolating to find the mass flow rate and source velocity is considered later in this section.

Another parameter affecting the dispersion of horizontal jets is the height of the release above the ground. For releases closer to ground level, the ground reduces the amount of air which can be entrained on the lower edge of the plume, increasing the dispersion distance. The release height can be scaled using the diameter of the source after flashing to atmospheric pressure, $D_{SRC} = 2\sqrt{\frac{\dot{M}}{\pi\rho U}}$. Figure 13 shows the variation of the dispersion distance with release height for both the dimensional and dimensionless distances.

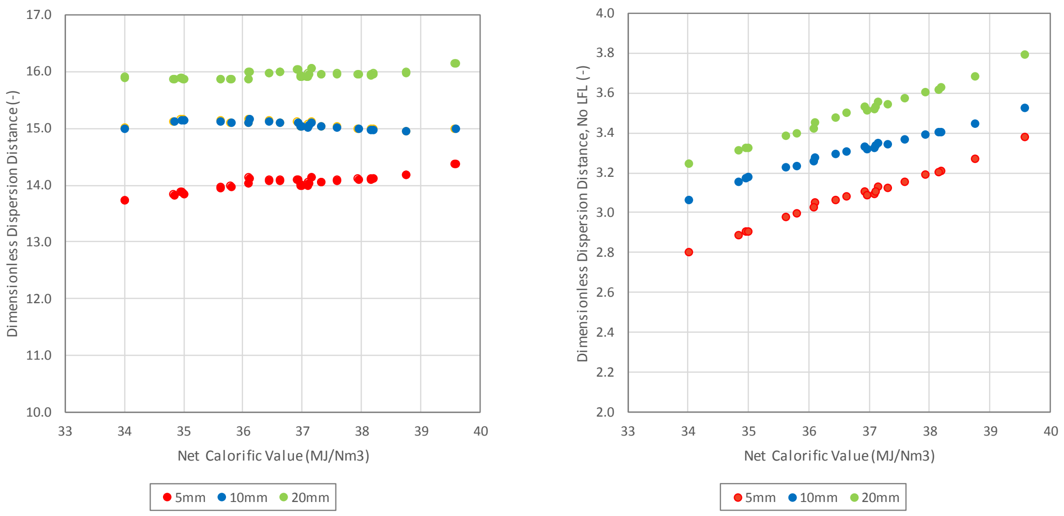

a) True dispersion distance and release height

b) Dimensionless dispersion distance and release height

Figure 13 Variation of dispersion distance with releases height

As for the previous cases, non-dimensionalising the distances gives graphs that are very similar for the different release diameters. Although the dimensionless dispersion distance varies significantly with the dimensionless releases height when the latter is less than about 0.6, this is the consistent for all release sizes. Hence, it is possible for the lookup tables to contain more dimensionless release heights in the range 0.0 to 0.6, increasing the resolution for all release sizes.

The earlier analysis showed that the dispersion distances were sensitive to the composition of the LNG. The dimensionless dispersion distance depends on the LFL of the LNG, which also depends on the composition. It is unlikely that users of the spreadsheet tool would know the composition of the gas, and even if the information was available, it could be time consuming to enter the composition into the model, with the potential for users to make errors. Hence, the dependence of the dispersion distances on parameters which depend on the composition, such as the molecular weight and calorific value was investigated. All of these LNG properties were found to be good proxies for the composition, with the dispersion distances varying approximately linearly with each of the properties. It was considered that the calorific value of the LNG was more likely to be available to companies carrying out bunkering operations than the other properties, hence it was used in the lookup tables. The LFL, which is used to scale the dispersion distance, was found to vary smoothly with the calorific value. Figure 14 shows the variation of the dimensionless dispersion distance with the calorific value for a range of release sizes. Part a uses the standard scaling and part b omits the LFL from the scaling. This suggests that the main effect of the composition on the dispersion distance could be due to changes in the LFL.



a) Standard Scaling

b) LFL omitted from scaling

Figure 14 Variation of dispersion distance with releases height

The dependence of the dispersion distance with ambient temperature and relative humidity was also investigated. The dependence on several parameters including the absolute concentration of water in the atmosphere was investigated. However, the dispersion distance did not appear to be better correlated with any of these parameters than with the atmospheric temperature and relative humidity, so these were used in the lookup tables.

Release Rate

As noted above, the spreadsheet tool uses two interpolations, the first to find the source conditions, such as mass flow rate, from the operating conditions, and the second to find the dispersion distance from the source conditions. This section describes the derivation of the first correlation.

All the predictions assume that the release is from a circular leak, hence the flow rate is proportional to the area of the circular hole. This means that lookup tables are only needed for the mass flow per unit area, immediately eliminating one of the parameters. Figure 15 shows the variation of the mass flow per unit area with the pressure and temperature of the LNG being transferred. Predictions are made for two representative compositions from the GIIGNL report. Predictions are only made for temperatures where the LNG is wholly in the liquid phase inside the hose.

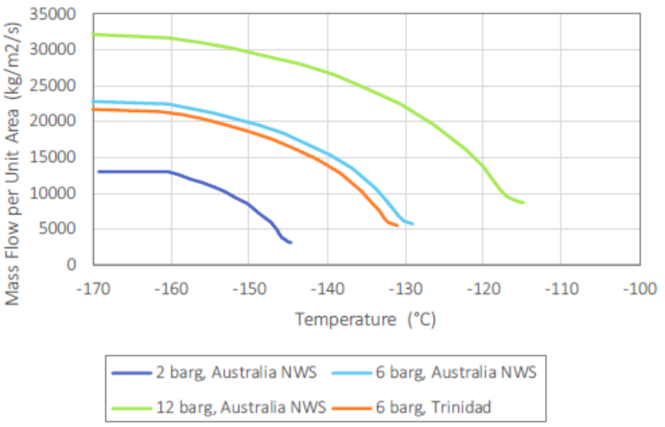


Figure 15 Variation of mass flow rate per unit area with temperature, pressure and composition

For a non-flashing liquid, the mass flow rate per unit area is proportional to $\sqrt{2P\rho}$ where P is the gauge pressure and ρ is the density of the liquid. A dimensionless mass flow rate per unit area G_{ND} can be defined by

$G_{ND} = \frac{G}{\sqrt{2P\rho}}$ where G is the mass flow per unit area.

A dimensionless temperature τ_G can be defined by

$\tau_G = \frac{T - T_{NB}}{T_{Bub88\%} - T_{NB}}$ where T is the temperature of the LNG in the hose, T_{NB} is the normal boiling point of the LNG at atmospheric pressure and $T_{Bub88\%}$ is the boiling point of the LNG at 88% of the gauge pressure inside the hose. Figure 15 shows the mass flow rate decreasing as the temperature of the LNG increases, but the flow rate starts to level off as the temperature approaches the boiling point of the LNG at the transfer pressure. $T_{Bub88\%}$ is a pragmatic estimate of the temperature at which this occurs, and it approximately collapses the data onto single curve.

Figure 16 shows the variation of the dimensionless mass flow per unit area with the dimensionless temperature of the LNG being transferred, for the same cases shown in Figure 15.

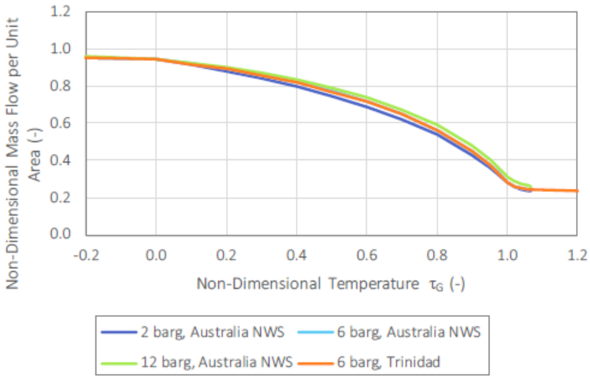
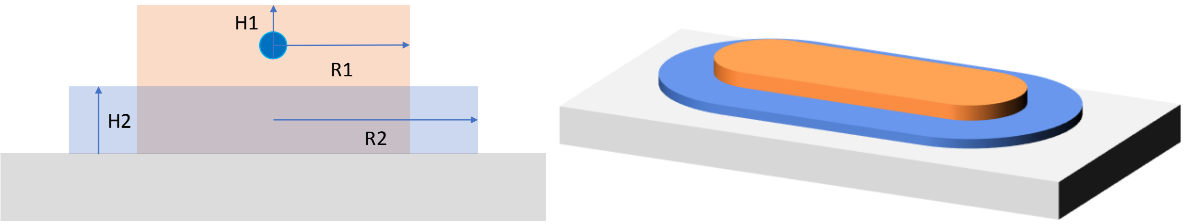


Figure 16 Variation of dimensionless mass flow rate per unit area with dimensionless temperature

This shows that the dimensionless mass flow varies very little with the pressure in the hose and the composition of the LNG. Hence, the interpolation in composition and pressure does not need to be too detailed, and only a small number of pressures and compositions are needed in the lookup table. This means that a larger number of temperatures can be used, particularly around the higher temperatures where the flow rate changes more quickly with temperature. A similar approach was used for the velocity of the source after flashing to atmospheric pressure, which was non-dimensionalised using $\sqrt{2P\rho}$.

Definition of the Safety Zone

The vertical extent of the Safety Zone above the hose is defined by the maximum distance to the LFL for a vertically upward jet. The horizontal extent of the main Safety Zone is defined by the distance to the LFL for a horizontal free jet release. This is measured from the hose and extends from the ground or sea surface up to the maximum height defined by the vertical jet. In addition, there is a safety zone at ground or sea level, defined by the maximum height and length to the LFL for a downward directed release forming a pool on land or water. Figure 17 shows the safety zone around a section of the hose on the land. R1 and H1 are the maximum horizontal extent of a horizontal jet and the vertical extent of a vertically upward jet respectively. R2 and H2 are the maximum horizontal and vertical extents of the plume formed from a vertically downward jet which forms a pool on the land.


a) Cross section

b) 3-dimensional view

Figure 17 The safety zone for a section of hose on the land

Other parts of the safety zone take a more complicated shape to account for the presence of the ship, and the possibility of a pool forming on the sea surface.

The BASiL tool

The BASiL tool is a spreadsheet based model which contains a database of 0.8 million combinations of the input parameters important to gas dispersion, each of which is the maximum of dispersion predictions for 26 combinations of wind speeds and stability. This allows multiple parameters to be considered simultaneously, which is important because many parameters interact, and the combined effect can be significantly greater than the effects of changing the individual parameters, leading to different safety distances. This is achieved by converting the input parameters into dimensionless groups to allow more accurate interpolation within the database. The initial parametric analysis allowed specific targeting with more data combinations in parameter ranges where results changed more significantly so enhancing accuracy.

To ensure conservatism BASiL uses the worst case combination of atmospheric stability and wind speed in its database., i.e. the longest safety distance from its database. Similarly, safety distances for all leak orientations are shown in BASiL to create the most conservative Safety Zone envelope.

In examples examined so far, BASiL predicts safety distances ranging from 7 to 140 m in the horizontal direction, primarily based on transfer flowrate/pressure considerations and 3 to 45 m in the vertical direction.

The accuracy of the BASiL predictions compared with the original model results (derived from and tested against the experimental data) was tested using a wide range of combinations of input parameters. The results of the comparison for the horizontal dispersion distance for a spill on the sea are shown in Figure 18. The vast majority of BASiL predictions are within +/- 10% of the original model predictions. The LNG composition appears to be the source of most of the exceptions where a single parameter, nett calorific value (also known as Lower Heating Value), is being used to cover several different effects.

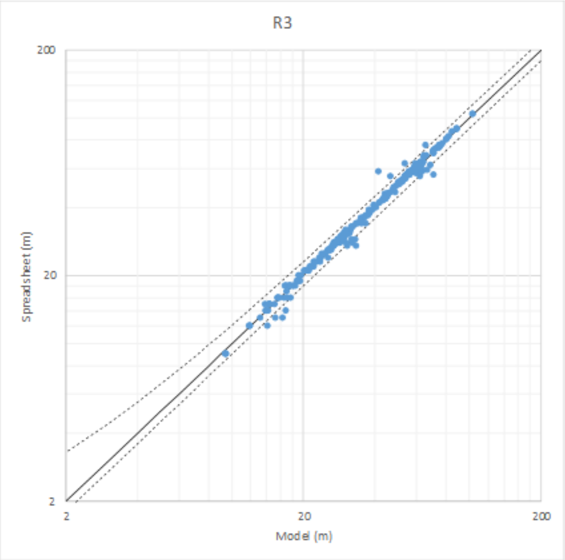


Figure 18 Accuracy assessment of BASiL against rigorous calculations

Conclusions

SGMF believes that this research is pioneering in the gas fuelled shipping space. The extensive modelling has led to a much better understanding of gas dispersion that can be disseminated and understood by the lay person.

The BASiL model appears robust and can quickly calculate a range of safety distances for different ships over a variety of climatic conditions worldwide. It should allow Safety Zones/distances to be consistently calculated by the industry.

BASiL is a generic model. It is not a QRA and will not replace QRAs or CFD modelling if a jurisdiction requires a more in depth analysis of risks for specific geometries and conditions. The value of BASiL as an assessment technique is in its fast assessment of three-dimensional zones, repeatability and conservative basis.

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