APPENDIX C

BEAR HEAD LNG TERMINAL RISK ASSESSMENT COMPONENT STUDY

TITLE:	**BEAR HEAD LNG TERMINAL – RISK ASSESSMENT COMPONENT STUDY**
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EXECUTIVE SUMMARY

ANEI has approached Lloyd's Register North America Inc (LRNA) for a Risk Assessment Component Study for the proposed Liquefied Natural Gas (LNG) Receiving Terminal at Bear Head, Cape Breton Island, Canada. The main conclusion of such work is that the site is fully compliant with formal code requirements CSA Z276-01 and NFPA Standards. Fire and gas hazards from site sumps have been shown not to extend beyond the site boundary. A second conclusion is that a terrorist attack either direct to ship/terminal installation and indirect via an aircraft incident presents an extremely low risk to the public in the vicinity of the Bear Head LNG Terminal.

LRNA has analysed the consequences of LNG spills according to the design codes to be followed by the designers, constructors, and operators of the proposed facility. The codes referenced in the Section 2 of the Report are CSA Z276-01 [2003], *Liquefied Natural Gas (LNG) – Production, Storage, and Handling,* and applicable NFPA Standards. These codes contain requirements related to siting, design, construction, fire protection, and safety.

It is adherence to these codes and standards that have led to the LNG industry having an excellent safety record. This safety record is far better than other commonly used and potentially dangerous products. Until the recent fire and explosion incident at Skikda in Algeria only four incidents have been identified worldwide over the last 38 years of operational experience. These have been small incidents involving releases of LNG from storage tanks and/or associated fittings. None of these four incidents have involved a major failure of an LNG tank and/or associated systems. It should be noted that LNG safety should only be looked at in terms of activities in such recent years. The regulatory requirements for LNG sites have changed significantly and only recent years present a true picture of how well the industry minimises risks.

Section 2 of the LRNA report contains the analysis that has been undertaken for the Bear Head LNG facility to satisfy CSA requirements. However, ANEI has taken the additional step of having LRNA undertake an evaluation of the facility in case of a terrorist attack. It should be noted that taking such a step goes significantly beyond formal requirements, and has been carried out for discussion purposes only to ensure that the risks from the facility are as low as reasonably practicable. The likelihood of such an attack is low and will get lower as new measures are taken to ensure that potential terrorist incidents are prevented.

Contained in Sections 3 and 4, this additional report is a generic assessment of the worse case consequences resulting from a deliberate damaging action against a membrane LNG tanker (tanker sizes range from 48,000 to 250,000m^3) at berth, or against one of the two 170,500m^3 net volume storage tanks (potential for third in future) at the Bear Head Terminal. This additional assessment provides an overview of the typical consequences that would result from the following initiating events: The fire consequences are then included in a hazard footprint to identify those areas outside the perimeter of the LNG Terminal which are at risk from methane gas cloud dispersion or radiated heat from an LNG fire.

- missile attack on the external hull or structure;
- external explosive device placed next to the hull or against the external single containment structure of the land based storage tank.

The analysis includes an evaluation of the deformation of the ship/tank structure and containment systems from the initiating blast, subsequent partial/total loss of containment, and the formation of an LNG pool, gas plumes and ignition hazards within and external to the Terminal.

The assessments of the consequences are backed up by an evaluation of historical, experimental, and theoretical evidence. This evidence has been presented within a number of attached Appendices to this report.

A summary of the main findings of the assessment are presented below.

CONCLUSIONS

Component Study Requirements

This analysis has been performed only for the purposes of determining if the proposed facility, at its maximum future expansion storage capacity of 500,000m^3, could meet applicable siting requirements of CSA Z276-01/NFPA Standards with regard to the design spills specified in Section 4.2 "Major Site Provisions for Spill and Leak Control" and Subsections 4.2.2 and 4.2.3.

The sump impounding fire and dispersion analysis for storage tank LNG releases and the process/jetty area LNG/ethane/propane releases has shown that the respective thermal flux and LFL concentration hazard ranges do not extend beyond the terminal perimeter. The analysis has therefore demonstrated that the requirements of CSA Z276-01 for sump impounding hazards have been satisfied.

The dispersion calculations have shown that the largest plumes could be generated from only two worst case major events - the ship grounding and the transfer pipeline full bore rupture. The maximum plume distance from the ship grounding would be approximately 773m to ½LFL and 554m to LFL, which if it were to take place at the near the jetty shore line the cloud would extend over the terminal boundaries. However, it does not constitute a hazard to any residential areas the nearest of which are situated about 5km to the East of the terminal and 2½km South of the terminal (Guysborough County). The dispersion contours of a full bore pipeline release have a shorter duration and impact and the largest plume distance would be approximately 2.1km to ½LFL and 1.2km to LFL. Based on historical records for LNG offloading to onshore plants world wide, both above events have an extremely low probability of occurrence.

Terrorist Attack Requirements

The actual size, likelihood and mechanism of a terrorist attack cannot be predicted and therefore is not covered explicitly here. For such a large release of LNG the actual consequences are extremely similar. As such the following description is valid for both an attack against an LNG ship or the Bear Head Terminal single containment storage tanks.

Loss of containment from an attack against an LNG ship may occur through shock mechanism caused by small amounts of explosive. There may not be a visible hole so the release to atmosphere would be minimal during the early stages of an incident and emergency measures can be taken in response. Larger attacks will leave a definitive hole in the ship or storage tank structure from which LNG and LNG vapour will escape. A missile or explosion event will leave a large number of ignition sources close to the loss of containment, which could then ignite the LNG as soon as it is released. There is a possibility of escalating failure of the ship structure due to embrittlement, followed by a Rapid Phase Transition (RPT) event, however, this would be minimised by water ingress through the outer hull. There is the possibility of an early internal explosion at the hole caused by the gas-air mixture being ignited by explosive debris, but this is thought to be highly unlikely, as there would not be enough ignition sources present within the ship structure.

An attack against the single containment storage tank could cause loss of containment. No RPT event is expected within the storage tank structure. There is, however, the potential for a small scale confined vapour cloud explosion within the storage tanks once almost all the LNG has been burnt and oxygen is allowed to enter the tank. It is likely that the storage tank(s) may collapse prior to all LNG being released through a 1m diameter hole (note: this diameter of hole has been taken as an assumed hole size to work with as the actual results of a terrorist attack cannot be readily predicted).

Once the LNG ship or LNG single containment storage tank has been damaged, the

LNG will escape and form a pool of LNG. In terms of pool spread, LPG and gasoline present a greater hazard than LNG. The Lower Flammability Limit (LFL) for methane/air mixtures is 5% by volume so the LFL boundary of the vapourised LNG is well within the visible cloud of condensed water vapour present in the air. As the methane gas cloud warms to a temperature of about -100^{o}C, the flammable gas cloud will become buoyant, i.e. lighter than air, and will rise away from the surface. As LNG will vapourise and is non-toxic, there is no significant direct environmental damage caused by a spill and hence no direct clean up costs.

Depending on the wind direction, the gas cloud will spread and drift either inland in a NNW direction towards Port Hawkesbury or in a SW direction across the Strait of Canso towards Guysborough County or in an Easterly direction across Inhabitants Bay towards Isle Madame. It is highly likely that this gas cloud will encounter ignition sources at the Bear Head Terminal. Ignition and sustained combustion of a vapourised LNG cloud under normal release conditions is difficult. However, due to the number of ignition sources at the Terminal, numerous gas cloud ignitions are likely.

Ignition would produce a slow moving flame rather than a detonation type explosion. Unconfined LNG vapour cloud detonation type explosions have not been demonstrated in experimental work and are most unlikely in practice. A confined vapour cloud detonation can occur, but is limited to the area of confinement and buildings within the Terminal and will have a limited affect beyond such a confined area. They are thought not to cause the main unconfined gas cloud to detonate.

Thus, any release due to terrorist action would reasonably likely ignite quickly and prevent the flammable gas cloud from leaving the Terminal. Besides that, calculations indicate that the gas cloud will be below its flammability limits long before reaching any populated areas such as Port Hawkesbury.

The radiated heat from a single containment LNG storage tank release into the diked area will reach a value of 30kWm^{-2} at a distance of 154m from the perimeter of the 200m x 200m storage dike. The radiated heat from a ship release will reach a value of 30kWm^{-2} at a distance of 100m from the perimeter of a pool fire based on a maximum pool size of 180m diameter. There are no industrial premises or communities close enough to the Terminal to be affected by high radiated heat levels (30kWm^{-2}). Note that the maximum distances of dangerous levels of radiated heat will occur when the pool is at its largest. Although it will not be giving out such high levels of radiated heat the size of the pool means that the dangerous distances are increased.

Following a major release from the LNG storage tanks or an LNG ship, it is likely that the methane gas cloud would cover significant parts of LNG Terminal, i.e.

within the Terminal Control Land, before ignition would occur. Depending on the wind direction, it would be expected that those personnel at the LNG Terminal with no protection will be fatalities.

There are no small towns or communities within approximately a 2½km distance from the perimeter of the Terminal. On this basis public exposure is expected to be extremely small. The only likely exposure in this zone will be individuals using the Bear Head Cove public road close to the Terminal.

An Easterly direction release towards Inhabitants Bay could cause a large gas plume to be developed as there are few sources of ignition. However, the fact that the release is over water means that the general public exposure is likely to be very low. Ignition would be delayed, or could fail to occur at all. In such a case the gas cloud would dissipate naturally into the atmosphere, limiting the potential for damage.

GLOSSARY

AGRI	American Gas Research Institute
BLEVE	Boiling Liquid Expanding Vapour Explosion. These are associated with high pressure storage of liquefied petroleum gases (LPG's).
Bund	A retaining wall or dyke designed to contain liquid released usually as a result of the failure of a storage tank.
CSA	Canadian Standards Association
CSA-Z276-01	Liquefied Natural Gas (LNG) – Production, Storage, and Handling.
Deflagration	The low speed combustion of a flammable gas cloud in which no damaging overpressures are produced.
DEGADIS	Dense gas dispersion. Heavy gas dispersion simulation software
Detonation	When the combustion flame speed in an ignited gas cloud increases up to or above the speed of sound in the gas a detonation is said to occur. The flame front is directly coupled to the pressure profile which takes the form of a shock wave. Damaging overpressures can occur which are transmitted outside the region of the gas cloud. Detonations generally occur in pipework or highly congested regions of process plant. To date no detonations have been produced in unconfined methane cloud tests.
Dispersion Models	Mathematical models which are used to predict the spread and shape of a gas cloud. The models may be used to predict distances to specified concentration levels within the cloud and hence give concentration contour plots.
Embrittlement	Changing of a materials properties so that it is more brittle
Emissive Power	The heat flux measured at the surface of a flame. There are two forms of emissive power:

a) Average emissive power is measured by several wide angle radiometers over a projected area of visible flame.

b) Point emissive power measured by several narrow angle radiometers. Values are time averaged and individual measurements may be considerably higher than the average emissive power.

EXPERT Propriety source model used with DEGADIS+ to evaluate parameters such as evaporation rate, pool radius, etc.

FMEA Failure Modes and Effects Analysis. An analytical technique used to identify failure scenarios

Flame Speed The speed of propagation of a combustion flame through a gas cloud. The faster the speed the higher the associated overpressure produced. Flame speeds greater than 100m/s may result in damaging overpressures.

FRED Fire, release, explosion and dispersion. Simulation software from Shell Global Solutions

HEGADAS Heavy Gas Dispersion Software from Shell

IMO International Maritime Organization

Impounding Area An area defined through the use of dikes or site topography for the purpose of containing any accidental spill of LNG or flammable refrigerants.

Lift-off The effect whereby an ignited gas cloud lifts from the ground through buoyancy to form a fireball.

LNG Liquefied Natural Gas. Natural gas which has its temperature lowered to a point where it becomes liquid.

Lower Flammable Limit (LFL) The minimum quantity of flammable gas (usually expressed as % by volume) which when mixed with air will support combustion. For methane air mixtures the LFL is 5% by volume, and for propane air mixtures the LFL is 2% by volume.

MHIDAS	Major hazards incidents data service. The UK Health and Safety Executive's database of incidents relating to hazardous materials.
MMSCFD	Million standard cubic feet per day
NFPA 59A	National Fire Protection Association standard for the production storage and handling of liquefied gas
Overpressure	For a pressure pulse (blast wave), the pressure developed above atmospheric pressure.
PERC	Powered emergency release couplings
Rapid Phase Transition (RPT)	Rapid phase transition is a phenomenon that occurs when LNG comes into contact with relatively large amounts of water. It is a localised overpressure, with no ignition. It is not thought to ignite vaporised LNG clouds
SEADATA	LR's internal casualty database of casualties of ocean going merchant ships of 100 gross tonnes or above (incidents since 1982)
SIGTTO	Society of International Gas Tanker and Terminal Operators
TNT Equivalence	Trinitro Toluene equivalence is a standardised method of describing explosive energy
Upper Flammable Limit	The maximum quantity of flammable gas (usually expressed as % by volume) which when mixed with air will support combustion. For methane-air mixtures the UFL is 15% by volume, and for propane-air mixtures the UFL is 8% by volume.
Unconfined Vapour Cloud Explosion	An unconfined vapour cloud explosion (UVCE) describes an explosion of a flammable vapour-air mixture either in the open air or in partially confined circumstances due to the presence of buildings, structures, trees, etc.

1 INTRODUCTION

This document comprises an evaluation of the Bear Head LNG Terminal's compliance with Regulatory requirements referred to as the Component Study (Section 2), and a specifically requested evaluation of the consequences of a terrorist attack (Sections 3 and 4).

Component Study Report (Section 2)

The codes referenced in the Section 2 of the Report are CSA-Z276-01, *Liquefied Natural Gas (LNG) – Production, Storage, and Handling, and referenced* NFPA Standards. These codes contain requirements related to siting, design, construction, fire protection, and safety of LNG facilities. The Component Study Report presents the results of an analysis conducted to:

- determine if CSA Z276-01 requirements regarding thermal radiation protection distances and flammable vapour cloud hazards could be met by the proposed facility design, at the proposed site;
- provide hazards analysis results that might be of assistance in the general layout of the facility; and
- identify any impact to third parties outside the plant boundaries and any societal impact.

Deliberate Attack & Scenarios Report (Sections 3 & 4)

Sections 3 and 4 of the report provide a generic assessment of the consequences resulting from a deliberate damaging action against a membrane LNG tanker at berth, or against one of the two/three 170,500m^3 single containment storage tanks at the LNG Terminal. This evaluation includes hazard footprints of the local consequences to the Bear Head area.

The report has drawn together a mix of existing information on LNG consequences, and carried out a high level assessment of the likely consequences specific to the membrane ships, storage tanks and incident type. The assessment carried out here represents the known consequences and so provides a suitable guide to how an incident will probably manifest itself. It is acknowledged that there is the potential for complex failure processes to occur that are not covered by this assessment.

The report provides an overview of the typical consequences that would result from the following initiating events:

- missile attack on the external hull or LNG tank structure;
- external explosive device in a dingy placed next to the hull or against the external wall of the single containment storage tank.

This includes evaluation of the deformation of the LNG ship hull structure and containment systems from the initiating blast, subsequent loss of containment, and the formation of LNG pools, gas plumes and ignition hazards.

1.1 Report Structure

Section 2 of this report contains the results of the Component Study carried out for compliance with CSA and referenced NFPA standards requirements. This includes an evaluation of thermal radiation and vapour dispersion for LNG release scenarios associated with ship, pipeline transfer and re-gasification events.

Sections 3 and 4 of the document address the consequences of a terrorist attack. Section 3 presents the findings of the assessment of the structural deformation resulting from a missile or explosive device. Section 4 provides an assessment of the likely release scenario considered, i.e. pool fires, radiated heats and associated hazardous footprints using the BREEZE HAZ Professional software.

The Appendices to this report include a review of Marine and Storage Tank Incidents given in Appendix A1, and Experimental Work on LNG Release Consequences given in Appendix A2. An Overview of Typical Consequences from LNG Release as Predicted by Theoretical Models is then given in Appendix A3. Appendix A4 provides an evaluation of the Explosive Process needed to damage the ship structures and Appendix A5 contains the ship FMEA.

In conducting this review an extensive literature search has been undertaken to identify references applicable to the scope of the study. The sources of material and references reviewed are listed at the end of each section in which they are used. Throughout the text references to the bibliography are shown thus [x.y].

A special thanks is given to QinetiQ (a branch of the Defence Evaluation and Research Agency, DERA) for their previous assistance in developing the approach for assessing the impact of explosive devices in close proximity to ship structures as used in this report.

2 COMPONENT STUDY REPORT

2.1 INTRODUCTION

The proposed LNG import terminal is similar to the many active LNG import terminals around the world. The codes referenced in this report are CSA Z276-01 [2003], *Liquefied Natural Gas (LNG)-Production, Storage and Handling,* National Standard of Canada, and NFPA 59A [2001], *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG*). These codes contain requirements related to siting, design, construction, fire protection, and safety.

This report presents the results of a study conducted to:

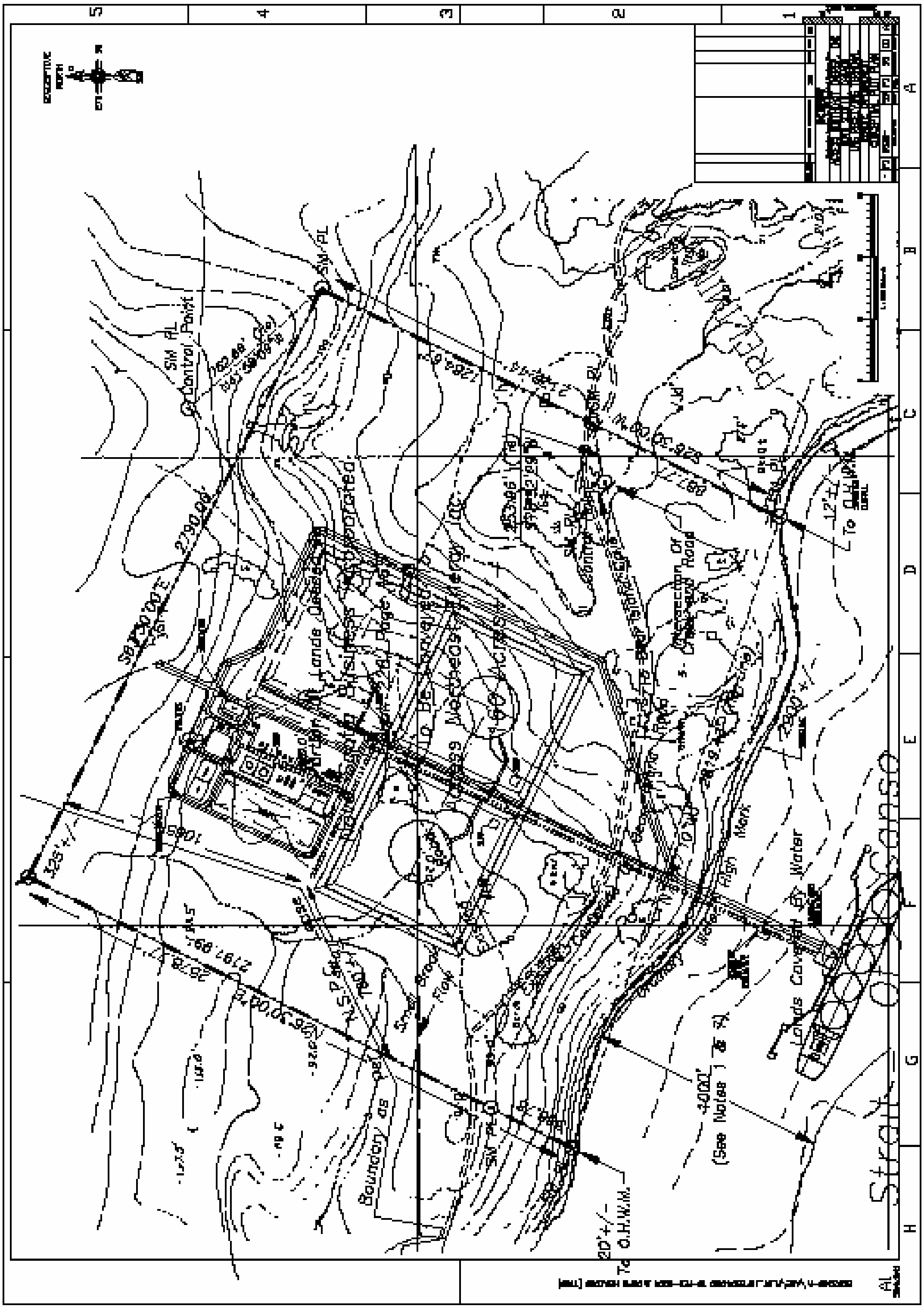
- determine if Z276-01 requirements regarding thermal radiation protection distances and flammable vapour clouds could be met by the proposed facility design, at the proposed site;
- provide hazards analysis results that will be of assistance in the general layout of the facility; and
- identify any impact to third parties outside the plant boundaries and any societal impact.

The scope of this analysis covers the jetty, pipeline transfer, LNG storage, and vapourisation areas (LNG, ethane/propane/hazards), as well as any related impounding or drainage systems. Many of the design parameters for the facility may be still subject to change. Changes in these parameters could affect the results of this safety study and might require additional analysis.

2.2 DESCRIPTION OF THE LNG TERMINAL FACILITY

The proposed site of the import terminal is at the vicinity of Bear Head Land Reserve near the Strait of Canso. A general site layout showing the surrounding area is presented in Figure 2.1. The import facility will include equipment to transport LNG from an ocean-going tanker to large LNG storage tanks, move the LNG from the storage tanks to high pressure booster pumps, vapourise and process (remove ethane, propane, etc. from heavy LNG) the LNG to produce high pressure natural gas, and meter the natural gas before introduction into a natural gas pipeline.

The base case send-out is 1 BCFD, with potential expansion to 1.5 BCFD. The proposed LNG Terminal is designed to receive LNG from several possible LNG production facilities and due to this, statistical methods have been used to synthesize a composition which covers the richest case with 95% statistical confidence in order to be able to create a "worst scenario" on which on material and energy balances will be based. It is intended that design will prepare heat and material balances for an "average" and "worst case".



Plant Layout

2.3 LNG CODE GUIDELINES

This section discusses requirements for siting. With a few exceptions, the siting requirements of CSA Z276-01 [2003], are the same as the siting requirements of NFPA 59A, 2001 edition.

2.3.1 Impounding Systems Required by CSA Z276-01/NFPA Standards

Both CSA Z276-01 and NFPA 59A require any LNG container, process area, vapourisation area, or transfer area to have an impounding system capable of containing the quantity of LNG that could be released by a credible incident involving the component served by each particular impounding system. According to the definitions in the code, an LNG container is any vessel used for storing LNG. A transfer area is defined as any area where LNG or other flammable liquid is introduced to or removed from the facility. Transfer areas do not include permanent plant piping. Process areas would include pump installations and process vessels that contain LNG, but are not used for LNG storage. Thus, within the scope of this analysis, for the proposed facility, LNG spill impounding systems would need to be provided for the following equipment.

(a) LNG storage tanks;
(b) LNG process areas;
(c) LNG transfer areas;
(d) LNG vaporisation areas.

Each of the areas listed above must have an LNG spill impounding system, (although each one is not required to have its own, separate impounding system). CSA Z276-01 (similarly NFPA 59A) does not prohibit one impounding system from serving two or more areas. In such cases, spills of LNG would be directed to one or more shared impounding basins by the use of curbing and drainage trenches (channels). Requirements for impounding systems for vaporiser areas and transfer areas are basically the same. Therefore, the following discussion pertains to the impounding systems for both of them.

Clause 4.2.2.2 **"Impounding areas, if provided to serve only vaporisation, process, or LNG transfer areas, shall have a minimum volumetric capacity equal to the greatest volume of LNG, flammable refrigerant, or flammable liquid that could be discharged into the area during a 10-minute period from any single accidental leakage source or a shorter time period based upon demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction."**

Although CSA Z276-01 does not require impounding systems to be provided for permanent piping, the "single accidental leakage source" normally assumed for the purpose of computing the minimum acceptable volumetric capacity of an impounding system for process equipment is the full rupture of the largest diameter pipe connected to the process equipment.

For LNG containers (i.e., storage tanks), the impoundment sizing requirements are very simple, as follows:

Clause 4.2.2.1 **"Impounding areas serving LNG containers shall have a minimum volumetric holding capacity" equal to the "total volume of liquid in the container, assuming the container is full."**

The liquid containment portion of an LNG spill impounding system required by the code need not be located such that it surrounds the container or piece of equipment that is assumed to be the leak source, so long as that container or piece of equipment is surrounded by a drainage system that will direct any released LNG to an impounding area of sufficient volume. Such systems are often used for impounding spills from process or transfer areas. We have assumed that two such systems will be incorporated in the design of the proposed facility, one for spills in the vaporisation area, and one for the 10- minute design spill for the LNG tanks.

2.3.2 CSA Z276-01 Design Spills

For LNG containers with over-the-top connections, the design spill is defined in CSA:

Clause 4.2.3.3 **"The largest flow from any single line that could be pumped into the impounding area with the container withdrawal pumps(s) delivering the full rated capacity. The duration of the design spill shall be 10 minutes, provided demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction exist; otherwise, the duration shall be the time needed for the initially full container to empty."**

"Impounding areas serving only vaporisation, process, or LNG transfer areas," the design spill flow rate and duration are "The flow from any single accidental leakage source for 10 minutes or for a shorter time based on demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction."

To maintain compliance with CSA requirements, the Bear Head LNG facility will be equipped with a comprehensive spill detection system and an emergency shutdown system. In the event of a large LNG spill, these systems should be capable of detecting the spill and initiating an emergency shutdown (thereby isolating the release source) in less than two minutes. Thus, the sizes of design spills and volumes of impounding systems for process and transfer areas could be based on a two- or three minute spill time, with allowances for drainage of LNG from piping and for rainwater. However, in order to be conservative, we have based our analysis on onshore spills of a 10 minute duration. Jetty head spills are assumed to last for a period of two minutes as explained later on. The reduction in spill volume through the use of plant instrumentation and shutdown systems should be analysed when the facility design is in a more detailed state.

It is recommended when calculating the required size of the LNG spill impounding area for the vapourisation area, the design should assume that the leak rate from the LNG piping downstream of the LNG booster pump will be 30% greater than the normal flow rate. The same assumption should be made when calculating the size of the impounding for the 10-minute design spill from the LNG storage tanks. (The actual difference between the normal flow rate and the spill rate for each of these releases will depend on the specified pump curves at detail design).

To minimise a possible LNG spill from the loading arms at the jetty head, Powered Emergency Release Couplings (PERCs) will be installed in the loading arms, which is the normal design criteria for LNG Terminals. With these devices, a leak or rupture within the transfer system can be quickly shut down. Because this area is continuously manned during transfer operations, and the PERC devices can be triggered based on several signals, (e.g. gas detection, low temperature), it has been conservatively assumed that a release will last, at most, two minutes. Thus, the spill rate for a loading arm failure should consist of the maximum loading rate for two minutes plus 30% (as a pump run-up of 30% was assumed for this spill).

2.3.3 CSA Z276-01 LNG Vapour Dispersion Scenarios

Clause 4.2.3.3

"Consideration shall be given to controlling the possibility of a flammable mixture of vapours from a design spill, as defined in Clause 4.2.3.4 item (a) or (b), as appropriate, of reaching a property line that can be built upon at an elevation above grade, which would result in a distinct hazard."

"**Flammable mixture dispersion distances shall be determined in accordance with items (a) to (c) of the clause. Item (a) "Distances shall be computed in accordance a vapour dispersion model that takes into account physical factors influencing LNG vapour**

dispersion, including gravity spreading, heat transfer, humidity, wind speed, atmospheric stability, buoyancy, and surface roughness."

A Note to Clause 4.2.3.3, the DEGADIS vapour dispersion model is described in the GRI report 0242. For compliance the calculations presented in this study were made using the BREEZE HAZ Professional suite of vapour dispersion models (DEGADIS, SLAB, etc.).

2.3.4 CSA Z276-01 LNG Pool Fire Scenarios

Clause 4.2.3.2.3 **"Thermal radiation distances shall be calculated either in accordance with the model described in GRI Report 0176 or in accordance with items (a) or (b) of the clause. Item (a)(i) "Take into account impoundment configuration, wind speed and direction, humidity, and atmospheric temperature."**

A typical model is the model described in GRI Report 0176 which refers to the LNGFIRE3 model. For compliance the calculations presented in this study were made using the BREEZE HAZ Professional (LNGFIRE3) model. Unconfined pool area calculations were based on the assumption that the surface area generated is from a Terminal spill of 10 minutes duration and the LNG is burning. Confined pool areas were determined by the proposed impounding areas. It is noted that, if the plant detail design were to propose additional spill drainage trenches and impounding systems that are not required by the code, it is standard practice to calculate thermal radiation protection distances for those systems as well.

2.4 CONSEQUENCE MODELLING

The focus of this analysis was to estimate potential hazards resulting from releases of hazardous fluids at the unloading jetty, during transfer of LNG to the storage tanks and during processing and re-gasification process.

2.4.1 Modeling Parameters

The wind speed, atmospheric stability, and relative humidity to be used when calculating the extent of each flammable vapour cloud are specified in the CSA Regulations. For this study, CSA Z 276-0 requires the following conservative conditions to be used for all vapour dispersion calculations.

Wind speed 0 m/s (Note: BREEZE 0.5 m/s minimum);
Atmospheric stability 'Pasquill-Gifford Class F;

Air temperature 21 C (294 K);
Relative humidity 50%; and
Surface roughness 0.01meters.

2.4.2 Hazard Endpoints

CSA Z276-01 provides specific guidelines with respect to the maximum thermal radiation flux levels that are acceptable at specific locations. In compliance the endpoints chosen for use in fire radiation hazard calculations were as follows:

Source	Flux Level (kW/m^2)	Description
CSA	30	Maximum flux at a property line that can be built upon for an impounding area fire containing an LNG volume V whose size is determined by CSA Clause 4.2.2.1.
	9	Maximum flux at the nearest point on a building or structure outside the property line used for assembly, education, health care, detention or correction, or residence, for an impounding area fire containing a LNG volume V whose size is determined by CSA Clause 4.2.2.1.
	5	Maximum flux at the nearest point outside the property line used for outdoor assembly groups of 50 or more persons, for an impounding area fire containing a LNG volume V whose size is determined by CSA Clause 4.2.2.1.
		Maximum flux at a property line that can be built upon for ignition of a design spill as specified in CSA Clause 4.2.3.4

Thermal Radiation Flux Endpoints

2.4.3 Results for LNG Sump Impounding - Fire and Gas Dispersion Scenarios

LNG Sump Scenarios

LNG Storage Tank Sump dimensions are indicated to be 10m x 10m x 6m and liquid filled. The Process Area and Jetty Area Sump dimensions are indicated to be 9m x 2m, however, they have been modelled as 6m x 3m and likewise liquid filled. In compliance with CSA Z276-01 for a "design spill" the release duration has been taken to be 10 minutes.

The BREEZE HAZ Professional Confined GRI pool fire model has been used for the thermal flux modelling. It has been assumed that the sumps are sized such that sump fires are contained within the respective sumps. The thermal flux range to $5kWm^{-2}$ for the LNG Tank Sump is 42.46m from the perimeter of the sump. For the Process and Jetty Sump areas the thermal flux range to $5kWm^{-2}$ is 16.24m. In relation to the size of the respective areas the hazard range is not great and does not have any off site impact. Tables 2.6 (LNG Storage), 2.7 (LNG Processing) and

2.8 (LNG Jetty) show the calculations associated with Figures 2.8, 2.10 and 2.12. Figures 2.9, 2.11 and 2.13 show the variation of thermal flux (kWm^{-2}) with distance from the pool centres and the three CSA criteria of 5, 9 and $30kWm^{-2}$. Process area ethane & propane fire hazards have been modelled in addition to LNG, for the ethane sump fire the maximum thermal flux range to $5kWm^{-2}$ is 16.64m from the perimeter of the sump and for the propane sump fire the maximum thermal flux range to $5kWm^{-2}$ is 17.28m. The calculations are shown in Tables 2.12 and 2.13 with the respective fire radiation plots shown in Figures 2.20 and 2.22 and respective contours in Figures 2.21 and 2.23. As with the LNG process area sump scenarios the ethane and propane scenarios do not have any offsite impact.

BREEZE HAZ Professional DEGADIS has been used for methane dispersion modelling from the sumps. The dispersion modelling has assumed that the surface area of the confined LNG within the sump is represented as a circular pool of a fixed area equal to the surface area of the containment systems. This has been conservatively based on sump dimensions of 10m x 10m for the Storage Tank Area and 6m x 3m for the Process and Jetty Areas. The maximum gas dispersion ranges from the sump centre for LFL and ½LFL are given in the Tables below. Tables 2.9, 2.10 and 2.11 at the end of Section 2 show the calculations associated with Figures 2.14, 2.16 and 2.18. Figures 2.15, 2.17 and 2.19 show the variation of plume concentration with distance from the pool centre and the LFL and ½LFL criteria.

LNG Concentration Criteria	Maximum Distance from LNG Tank Dike Sump Centre (m)
½ LFL	252.116
LFL	206.073

LNG Concentration Criteria	Maximum Distance from Process/Jetty Sump Centre (m)
½ LFL	107.068
LFL	70.889

2.4.4 LNG Storage Tank Dike Fire Scenarios

LNG Storage Tank Dike fire scenarios have been analysed in Section 4.6 "Radiated Heat Modelling". The LNG storage tanks are dike protected with square dimensions estimated to be approximately 200m by 200m. The square pool shape has been used within BREEZE Haz Professional to calculate the potential radiated heat at the maximum distance from the centre of the LNG storage tanks.

The radiation contours for LNG storage tank dike (impounding) fires are shown in Section 4, Figures 4.3 to 4.5. The confined pool fire radiation vs distance plots for the Terminal tanks are shown in Figure 4.6. In accordance with Section 4.2.3.2.2 of CSA Z276-01 the fire scenarios have been modeled for the environmental conditions of $0.5ms^{-1}$, 21^oC and 50% humidity (note: although CSA Z276-01 stipulates $0ms^{-1}$ wind speed BREEZE Haz Professional like other similar types of software has a minimum wind speed capability of $0.5ms^{-1}$) with radiation distances for 5, 9 and $30kWm^{-2}$. As can be seen in the contour plots for each of the LNG storage tank dikes, the respective $30kWm^{-2}$ radiation contours (red) do not extend beyond the Terminal boundary. Both the $5kWm^{-2}$ and $9kWm^{-2}$ radiation contours (green & yellow) in Figures 4.3, 4.4 and 4.5 are shown to extend beyond the Bear Head Terminal boundary. The two radiation flux levels extend 486m and 351m respectively from the three inland facing dike walls closest to the Terminal perimeter.

2.4.5 Results for LNG tanker grounding – Dispersion scenarios

The scenario was based on the grounding of a standard LNG 'Moss' carrier at the bay area near the jetty The grounding assumed impairment of the hull and a single LNG tank at a forward position. This very conservative scenario has involved simultaneous impairment of the tanker's double bottom and penetration (through the hold space) of an independent type tank.. The 0.5m diameter tank hole size modelled, could only be generated from a large penetration of the bottom hull. Such a scenario could only involve the grounding of an errant vessel which is considered to be a very low probability event given the controlled operations during the approach to the terminal and also during jetty approaches.

The scenario modelled a release of LNG with evaporation and plume dispersion. The scenario involved no ignition but mixing of the released LNG with seawater was included in the model BREEZE HAZ Professional (DEGADIS). Plume distances to ½ LFL and LFL were calculated as follows:

Hole Diameter (m)	Distance to ½ LFL (m)	Distance to LFL (m)
0.5	773.4	554.2

Figure 2.1 shows the gas dispersion contours for a ship grounding for a single hole sizes of 0.5m diameter. Tables 2.1 shows the calculations associated with Figure 2.1.

2.4.6 Results of LNG Transfer – Dispersion Scenarios

The scenarios addressed accidental LNG release, spill, evaporation and dispersion in the pipeline area between the jetty ESD valve and the ESD valve prior to the first storage tank. Based on the Plot Plan detail and preliminary process information provided the length of the isolatable section is estimated to be approximately 800m and the pipeline diameter 32". Three scenarios are modelled for releases through a

50mm hole, 100mm hole and full bore. The 50 and 100 mm holes are considered typical installation leak scenarios which could be caused by dropped objects, construction, or material defects. The full bore scenario is considered worst case. In compliance with the CSA code the release time for all scenarios was assumed to be 10 min and the evaporation is assumed to be taking place on damp ground. The following plume distances to ½ LFL and LFL were calculated using BREEZE HAZ Professional (SLAB):

Hole Diameter (m)	Distance to ½ LFL (m)	Distance to LFL (m)
0.050	0.0	0.0
0.100	232.5	113.1
Full Bore	2128.2	1273.8

Figures 2.2 and 2.3 show the gas dispersion contours for a pipeline release for 3 hole sizes of full bore and 100mm diameter. It is noted that the 50 mm case does not reach LFL. Tables 2.2 and 2.3 show the calculations associated with Figures 2.2 and 2.3.

2.4.7 Results of LNG offloading arm/pipeline – Fire Scenarios

The intention of the approach was to address unconfined pool fire scenarios in areas where diking is not currently proposed and establish incident radiation contours at the predetermined endpoints. The scenarios covered LNG release, pool formation on concrete, ignition and fire on top of the Jetty and similarly pool fires on “regular soil” at the transfer pipeline area. Releases were considered for 2 minutes and 10 minutes on the jetty depending whether the release is from the offloading arm or the jetty pipeline area and CSA standard flux radiation distances were calculated. Offloading arm releases from a range of hole sizes including full bore are presented in Section 2.4.7. For the pipeline due to evaporation effects pool formation will be feasible for pipe hole sizes of 100 mm and over. The following fluxes were calculated using BREEZE HAZ Professional:

Pipeline	Thermal Flux (kW/m^2)	Pool Distance (m)
Hole Diameter (m): 0.100 **Max Pool Diameter (m): 3.35**	30	10.50
	9	22.27
	5	30.59

Pipeline	Thermal Flux (kW/m^2)	Pool Distance (m)
Hole Diameter (m): full bore	30	50.11

Pipeline	Thermal Flux (kW/m²)	Pool Distance (m)
Max Pool Diameter (m): 18.99	9	101.04
	5	135.48

Figures 2.4 and 2.6 show the pool fire radiation contours for the 100mm pipeline diameter hole and the pipeline full bore release respectively. Tables 2.4 and 2.5 show the calculations associated with Figures 2.4 and 2.6. Figures 2.5 and 2.7 show the variation of thermal flux (kWm^{-2}) with time from the pool centres.

2.4.8 Results of Re-gasification Equipment - Pressurise Releases/Jet Fires

In line with the statistical approach which has been followed during concept design in order to determine product composition, the appropriate scenarios associated with the process equipment releases were based on a typical onshore LNG re-gasification plant.

It is expected that after the definition of the re-gasification equipment and piping sizing a more detail approach would address potential equipment releases. This should include the following steps:

- Identification of isolatable sections;
- Determine parts count/inventory volumes;
- Application of release data;
- Safety systems availability;
- Consequence analysis including;
    - gas dispersion,
    - fire analysis
    - explosion analysis

Based on data from LR's Consequence Data Base equipment releases were modeled for the four major equipment groups within a re-gasification process train namely HP Pumps, S/T Exchanger and BO Gas Compressors. Example releases have been provided at four hole sizes, namely 3, 10, 30 and 100mm and at full bore. Note that releases from the S/T Exchanger system have assumed a number of different process design parameters (pressure/temperature).

Gas dispersion contours were determined for gas systems using the Shell FRED programme. The limits of the LFL contour, 50000 ppm, were determined assuming the CSA Code modelling parameters (see 2.4.1).

BREEZE DEGADIS was used to model the gas dispersion for LNG releases at similar atmospheric conditions. An LNG release produces a dense gas cloud which is generally lower in momentum than a similar natural gas release but the LFL contour is larger due to the reduced amount of turbulent mixing taking place which would dilute the gas cloud.

The LNG and gas inventory jet fires were modelled as methane using the Shell FRED programme. Atmospheric conditions, similar to those assumed for the gas dispersion analysis, were adopted for fire scenarios with the exception that a wind speed of 5 m/s was assumed. Flame characteristics are not very sensitive to wind speed but will tend to increase with wind speed, hence the larger wind speed was adopted to be conservative.

For gas systems the decay in the release rate with time was estimated again using FRED in order to determine the change in flame length with time and the impact on escalation potential. A 5 minute delay was assumed for ESD/Blowdown initiation as it was conservatively assumed that the systems may not act automatically. The impact of blowdown was taken into account in the decay of gas systems with time.

A constant discharge rate was assumed for LNG liquid releases. The actual pressure decay is difficult to model accurately for such releases, as gas will tend to flash of the liquid during the release which will to some extent compensate for the loss of pressure due to the liquid outflow. The jet fire lengths, radiation fluxes s and LFL were calculated and presented below:

Name	Fluid	Release Hole (mm)	Vol (m3)	Press (Barg)	Temp (Deg C)	BD & ESD 5 mins to initiate Initial Flame (m)	12.5kW/m2 Contour Flame15min (m)	Flux Length (m)	LFL (m)
LNG Unload Arms 1	LNG	3	1.3	3.8	-160	4.4	4.4	6.3	0
LNG Unload Arms 1	LNG	10	1.3	3.8	-160	11.6	11.6	19	18
LNG Unload Arms 1	LNG	30	1.3	3.8	-160	27.8	0.0	47	82
LNG Unload Arms 1	LNG	100	1.3	3.8	-160	72.4	0.0	132	333
LNG Unload Arms 1	LNG	Full Bore	1.3	3.8	-160	270.0	0.0	506	
HP Pumps	LNG	3	15.7	80	-150	8.2	8.2	10	0
HP Pumps	LNG	10	15.7	80	-150	21.2	21.2	28	29
HP Pumps	LNG	30	15.7	80	-150	50.9	0.0	70	110
HP Pumps	LNG	100	15.7	80	-150	131.7	0.0	188	438
HP Pumps	LNG	457	15.7	80	-150	461.0	0.0	642	
S/T Exchangers	LNG	3	5.0	80	-150	8.2	8.2	10	0
S/T Exchangers	LNG	10	5.0	80	-150	21.2	0.0	28	29
S/T Exchangers	LNG	30	5.0	80	-150	50.9	0.0	70	110
S/T Exchangers	LNG	100	5.0	80	-150	131.7	0.0	188	438
S/T Exchangers	LNG	356	5.0	80	-150	377.0	0.0	527	
S/T Exchangers	LNG	3	20.0	80	-150	8.2	8.2	10	0
S/T Exchangers	LNG	10	20.0	80	-150	21.2	21.2	28	29
S/T Exchangers	LNG	30	20.0	80	-150	50.9	0.0	70	110
S/T Exchangers	LNG	100	20.0	80	-150	131.7	0.0	188	438
S/T Exchangers	LNG	Full Bore	20.0	80	-150	419.0	0.0	585	
BO Gas Compressor	NG	3	11.9	9	6	1.5	1.1	2	0.64
BO Gas Compressor	NG	10	11.9	9	6	4.2	2.4	5.7	2.1
BO Gas Compressor	NG	30	11.9	9	6	10.9	0.0	14	6.25
BO Gas Compressor	NG	100	11.9	9	6	31.4	0.0	39	20.47
BO Gas Compressor	NG	762	11.9	9	6	162.0	0.0	207	
S/T Exchangers	NG	3	12.3	77	5	3.4	1.7	5.5	20.6
S/T Exchangers	NG	10	12.3	77	5	10.1	3.7	15	6.77
S/T Exchangers	NG	30	12.3	77	5	26.6	0.0	38	20
S/T Exchangers	NG	100	12.3	77	5	76.3	0.0	102	65
S/T Exchangers	NG	Full Bore	12.3	77	5	223.0	0.0	289	
S/T Exchangers	NG	3	42.3	77	5	3.4	1.8	5.5	20.6
S/T Exchangers	NG	10	42.4	77	5	10.3	4.7	15	6.77

S/T Exchangers	NG	30	42.4	77	5	26.9	6.4	38	20
S/T Exchangers	NG	100	42.4	77	5	77.5	0.0	102	65
S/T Exchangers	NG	Full Bore	42.4	77	5	249.0	0.0	321	
Export Pipeline	NG	3	7752.6	77	5	3.6	3.6	5.5	20.6
Export Pipeline	NG	10	7752.6	77	5	10.3	10.3	15	6.77
Export Pipeline	NG	30	7752.6	77	5	26.7	26.7	38	20
Export Pipeline	NG	100	7752.6	77	5	72.7	72.7	102	65
Export Pipeline	NG	762	7752.6	77	5	412.0	110.0	353	

2.5 SHIP COLLISION RISK

A ship collision may arise from a variety of sources and may involve fishing vessels, pleasure craft, large merchant ships, etc. Data within LR indicates that merchant vessels of sizes ≥ 100,000 tons dwt will have a typical speed of 13knots and those vessels of sizes < 100,000 tons dwt will have a typical speed range of 10 to 16knots. The impact energy as a result of a collision at full speed on the broadside may be as high as 8,000MJ, however, typical impact energy ranges from 436MJ to 4631MJ.

Collision events discussed above are considered to be unlikely on the basis that an appropriate navigation zone system will be established around the terminal facility. The purpose of this system will be to:

- provide early warning for all approaching vessels;
- manage the safe approach of the offloading LNG ships;
- manage the operation of the tugs; and
- prohibit the approach of unauthorized vessels.

In the worst case scenario a collision may cause the rupture of an LNG cargo tank resulting in a large scale release of product forming a gas plume. The plume may or may not ignite.

2.6 AIRCRAFT COLLISION RISK

Collisions involving aircraft are those associated with commercial or military aircraft. Commercial aircraft cover a range of sizes from the relatively small private jets to short/long haul aircraft carrying 50 to 400 passengers. All these aircraft can be assumed, on impact with the facility, to possess sufficient energy to inflict severe damage rupturing tanks and destroying process facilities. It is very likely that aircraft impact will lead to ignition, both of the remaining aircraft fuel and product released.

Statistically the major threat to the terminal is from aircraft accidents during take off and landing and to a lesser extent inflight risk. From information provided in the form of aerial views of the Bear Head peninsula it would appear that there are no major airports in the vicinity of the LNG Terminal, therefore the take off and landing risk is considered to be negligible and not analysed further. For inflight risk, using published statistical data, the likelihood of collision with the terminal is considered to be extremely low. An internal LR study has assessed the frequency value for such an event involving a similar installation at $3x10^{-10}$ $year^{-1}$ (based on an aircraft accident rate of at $3x10^{-7}$ $year^{-1}$[2.7]).

Terrorist activity incidents involving the Bear Head LNG terminal will have the same end results as described above for other aircraft events. However, with the high level of security at major airports today and the availability of other higher profile targets in Morth America, such incidents involving the Bear Head LNG facility are considered to be very unlikely and not considered further.

2.7 TSUNAMI & EARTHQUAKE EVENTS

A tsunami is a long period wave created by large scale movement of the seafloor from submarine earthquake, landslide, or volcanic eruption. At sea, tsunamis travel as a shallow water wave with a small height (>1 m) and usually go unnoticed. On reaching shallow water, speed diminishes but the energy in the wave remains constant, hence the wave height must increase. Tsunamis are damaging in shallow coastal areas. The probability of a tsunami event on the Scotian Shelf is estimated to be extremely low (around 1 in 10,000 years).

The Straight of Canso is not in a high earthquake zone (Zone 1). There have been no recordings of earth tremors at Melford point. There have been two small tremors of < 3 on the Richter scale recorded at Chedabucto Bay and at Canso Head. There is no history of soil liquefaction or landslide movement in the area. It is noted that further studies with respect to seismicity will be completed by Jacques Whitford Environment as part of the engineering (geotechnical) for the project.

2.8 EXTERNAL FIRE THREAT

The Bear Head area is heavily wooded (clearly shown in Figures 4.1 and 4.2) consequently there is likely to be significant moisture present during a typical summer period. On this basis the external threat of fire to the Terminal during the summer period is not considered to be significant, i.e. very low risk, and has not been analysed further.

2.9 ACCEPTABILITY OF PROPOSED SITE

With regard to public safety, CSA Z276-01 would judge a proposed site for an LNG facility to be acceptable if the proposed facility can be placed on the site without violating any of the siting restrictions, particularly those related to flammable vapour clouds and fire radiation hazard zones. This Section discusses the acceptability of the proposed site.

Based on the information currently available, the proposed Bear Head LNG facility layout meets the thermal radiation and flammable gas dispersion hazard distance requirements of CSA Z276-01 based on concrete impounding sumps and drainage trenches are to be used to collect and impound the required design spills.

The dispersion calculations have shown that the largest plumes could be generated from only two worst case major events the ship grounding and the transfer pipeline full bore rupture. The maximum plume distance from the ship grounding would be approximately 554m to LFL and 773m to ½LFL which, if it were to take place close to the jetty shore line, depending on the wind direction, the cloud could extend over the terminal boundaries. The plume does not constitute a hazard to any residential areas which are situated about 5 km to the East of the terminal and 2½km to the South West towards Guysborough County. More importantly, taking into account the established operational procedures for a tanker approach with the assistance of tugs, the scenario for an errant tanker grounding within the terminal's shore line is considered a non credible event.

The dispersion contours of a full bore pipeline release have a shorter duration and impact (due to ESD isolation action) and the largest plume distance would be approximately 1.2km to LFL and 2.1km to ½LFL. Existing records for offloading and transfer pipelines inside the plants boundaries have not identified any single operational event which could cause full rupture of such a line (32"). Based on the above information this event can be identified as a non credible operational event.

Unconfined pool fires at the jetty area and the pipeline nearest to the shore do constitute a hazard for proposed/expected plant equipment and the tank farm. Only the case of a full bore transfer pipeline rupture with fire nearest to the LNG tank (approximately 100m) would constitute a design hazard as per CSA requirements. It is also noted that the scenario of full bore rupture is considered very conservative as it is extremely unlikely to take place at any pipeline location within a controlled plant under normal operating conditions.

The jet fire scenarios based on typical re-gasification equipment sizing and process parameters have identified that full bore releases at the HP pumps are capable of generating large jet fires up to 400m in length but of a very short duration. Atmospheric conditions, similar to those assumed for the gas dispersion analysis, were adopted for fire scenarios with the exception that a wind speed of 5 m/s was assumed. Flame characteristics are not very sensitive to wind speed but will tend to increase with wind speed, so it is noted that the results are very conservative. However, it is assumed that after the definition of the re-gasification equipment and piping sizing a more detail approach would address potential equipment releases. This should include the following steps:

- Identification of isolatable sections;
- Determine parts count/inventory volumes;
- Application of release data;

- Safety systems availability;
- Consequence analysis including;
    - gas dispersion,
    - fire analysis,
    - explosion analysis.

The Component Study has considered a number of initiating scenarios including ship/aircraft collision events, tsunami/earthquake events, and external fire threat. In the case of ship collision risk, resulting from a collision at full speed on the broadside, the typical impact enegy is likely to range from 436MJ to 4631MJ. Given that a Navigation Zone System will be in place for managing the movement of merchant vessels in the vicinity of the Bear Head Terminal collision risk is considered to be very unlikely. In the case of aircraft collision risk, either accidental or deliberate action, both incidents are considered to be very unlikely for the Terminal. Tsunami, earthquake, and external fire events at the Bear Head facility have been considered and concluded to be low risk and therefore very unlikely events.

REFERENCES

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[2.2] NFPA 59A (2001), *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG*). National Fire Protection Association, Boston, Massachusetts, 2001.

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[2.4] GRI (1990a), *LNG Vapour Dispersion Prediction with the DEGADIS Dense Gas Dispersion Mode*l. Gas Research Institute, GRI-89/0242, April 1988-July 1990.

[2.5] GRI (1990b), *LNGFIRE: A Thermal Radiation Model for LNG Fire*s. Gas Research Institute, GRI-89/0176, June29, 1990.

[2.6] Shell FRED User's Guide.

[2.7] Boeing Aircraft Corporation, Commercial Aircraft Accident Statistics.

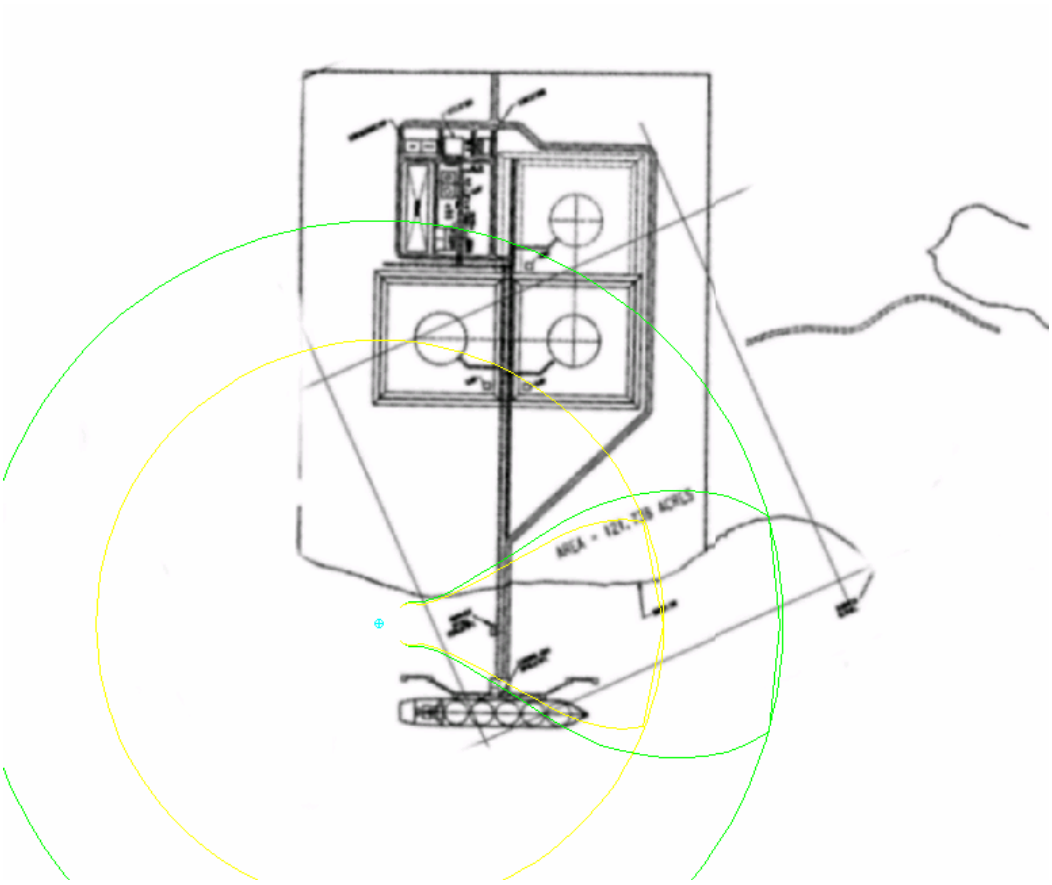


Figure 2.1: Ship Grounding 0.5 m Diameter Hole – Dispersion Contours

```
DEGADIS+ SUMMARY

METEOROLOGY:
  Ambient temperature          20.0 ° C
  Ambient pressure             1.0 atm
  Relative humidity            30 %
  Wind direction               270 degrees
  Wind speed                   1.5 m/s
  Anemometer height            10.0 meters
  Surface roughness            0.01 meters
  Stability option             Stability class
  Stability class              6 (F)

CHEMICAL:
  ID                           LNG1
  Name                         LNG Light (Methane)
  Molecular weight             16.043 g/g-mole
  Boiling point                111.6 K
  TWA                          6666 mg/m**3
  LFL                          33000 mg/m**3

RELEASE:
  Source type                  Ground-level release
  Release type                 Continuous
  Emission rate                16471.98 lb/min
  Source radius                3.89 meters
  Mass fraction                1
  Release temperature          111.6 K
  Isothermal mode              Non-isothermal
  Heat transfer                DEGADIS correlation
  Ground temperature           293.15 K
  Water transfer               DEGADIS correlation

OUTPUT:
  Height of interest           1.6 meters
  Averaging time               10000.0 seconds
  Lower contour                16500 mg/m**3
  Middle contour               33000 mg/m**3

RESULTS:
  Concentration                                     Distance
    mg/m**3                                          meters
  ----------------------------------------------------------
    16500                                           773.487
  ----------------------------------------------------------
    33000 (LFL)                                     544.238
  ----------------------------------------------------------
```

Table 2.1: Ship Grounding 0.5m Diameter Hole – Dispersion Calculations

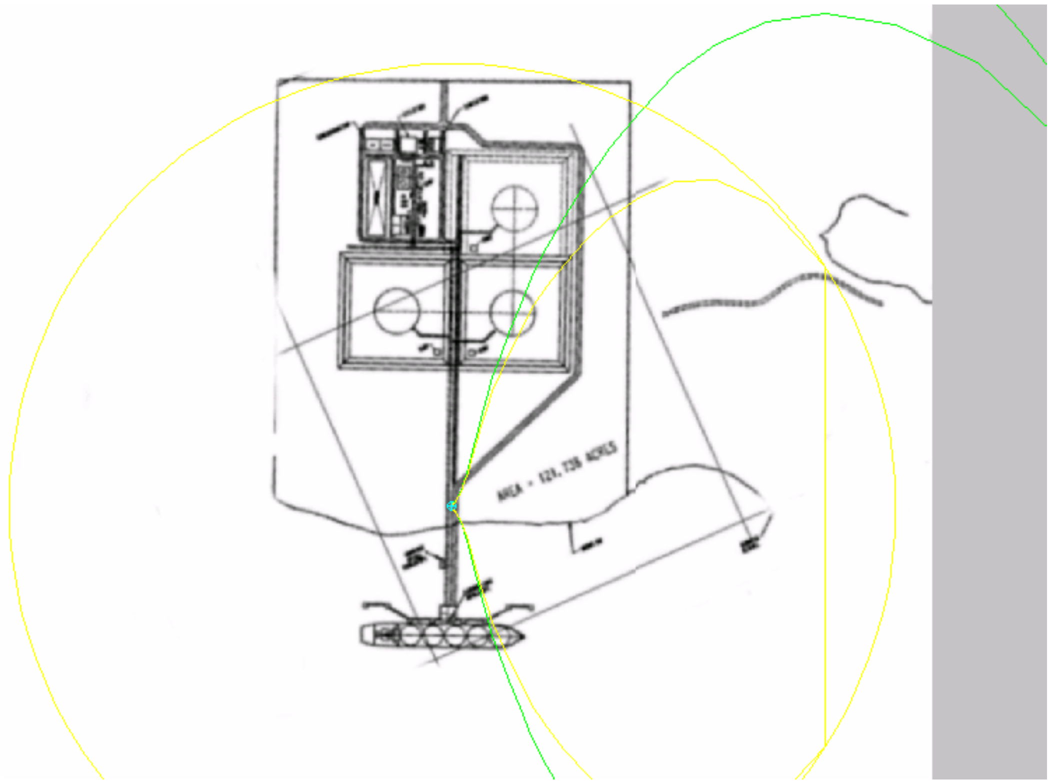


Figure 2.2: Pipeline Full Bore Release – Dispersion Contours

```
SLAB SUMMARY

METEOROLOGY:
  Ambient temperature          21.0 ° C
  Ambient pressure             1.0 atm
  Relative humidity            50 %
  Wind direction               270 degrees
  Wind speed                   0.5 m/s
  Anemometer height            10.0 meters
  Surface roughness            0.01 meters
  Stability option             Stability class
  Stability class              6 (F)

CHEMICAL:
  ID                           LNG1
  Name                         LNG Light (Methane)
  Molecular weight             16.043 g/g-mole
  Boiling point                111.6 K
  TWA                          6666 mg/m**3
  LFL                          33000 mg/m**3

RELEASE:
  Source type                  Horizontal jet
  Release type                 Continuous
  Emission rate                41980.98 lb/min
  Source area                  133.5114 m**2
  Release height               3.28 feet
  Release temperature          -258.79 ° F
  Liquid mass fraction         0

OUTPUT:
  Height of interest           1.6 meters
  Averaging time               3600.0 seconds
  Lower contour                16500 mg/m**3
  Middle contour               33000 mg/m**3

RESULTS:
  Concentration                                    Distance
    mg/m**3                                         meters
  ----------------------------------------------------------
    16500              steady-state                2128.268
  ----------------------------------------------------------
    33000 (LFL)        steady-state                1273.831
  ----------------------------------------------------------
```

Table 2.2: Pipeline Full Bore Release – Dispersion Contours

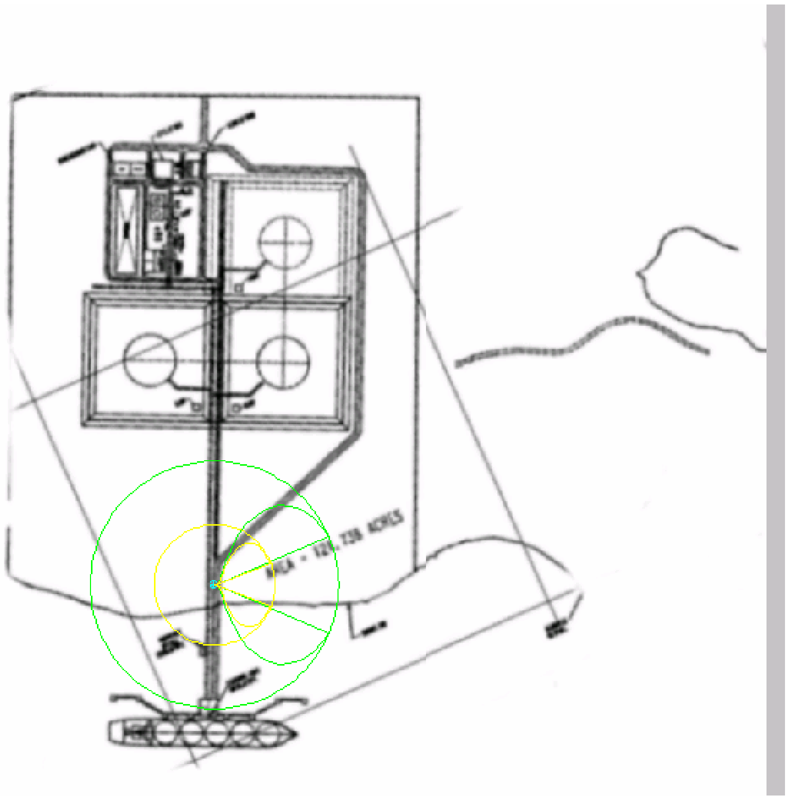


Figure 2.3: Pipeline Release 0.100m Diameter hole – Dispersion Contours

```
SLAB SUMMARY

METEOROLOGY:
  Ambient temperature         21.0 ° C
  Ambient pressure            1.0 atm
  Relative humidity           50 %
  Wind direction              270 degrees
  Wind speed                  0.5 m/s
  Anemometer height           10.0 meters
  Surface roughness           0.01 meters
  Stability option            Stability class
  Stability class             6 (F)

CHEMICAL:
  ID                          LNG1
  Name                        LNG Light (Methane)
  Molecular weight            16.043 g/g-mole
  Boiling point               111.6 K
  TWA                         6666 mg/m**3
  LFL                         33000 mg/m**3

RELEASE:
  Source type                 Horizontal jet
  Release type                Continuous
  Emission rate               1195.629 lb/min
  Source area                 1.90121 m**2
  Release height              3.28 feet
  Release temperature         -258.79 ° F
  Liquid mass fraction        0

OUTPUT:
  Height of interest          1.6 meters
  Averaging time              3600.0 seconds
  Lower contour               16500 mg/m**3
  Middle contour              33000 mg/m**3

RESULTS:
  Concentration                                   Distance
    mg/m**3                                        meters
  ----------------------------------------------------------
    16500              steady-state                232.521
  ----------------------------------------------------------
    33000 (LFL)        steady-state                113.117
  ----------------------------------------------------------
```

Table 2.3: Pipeline release 0.100m diameter hole – Dispersion calculations

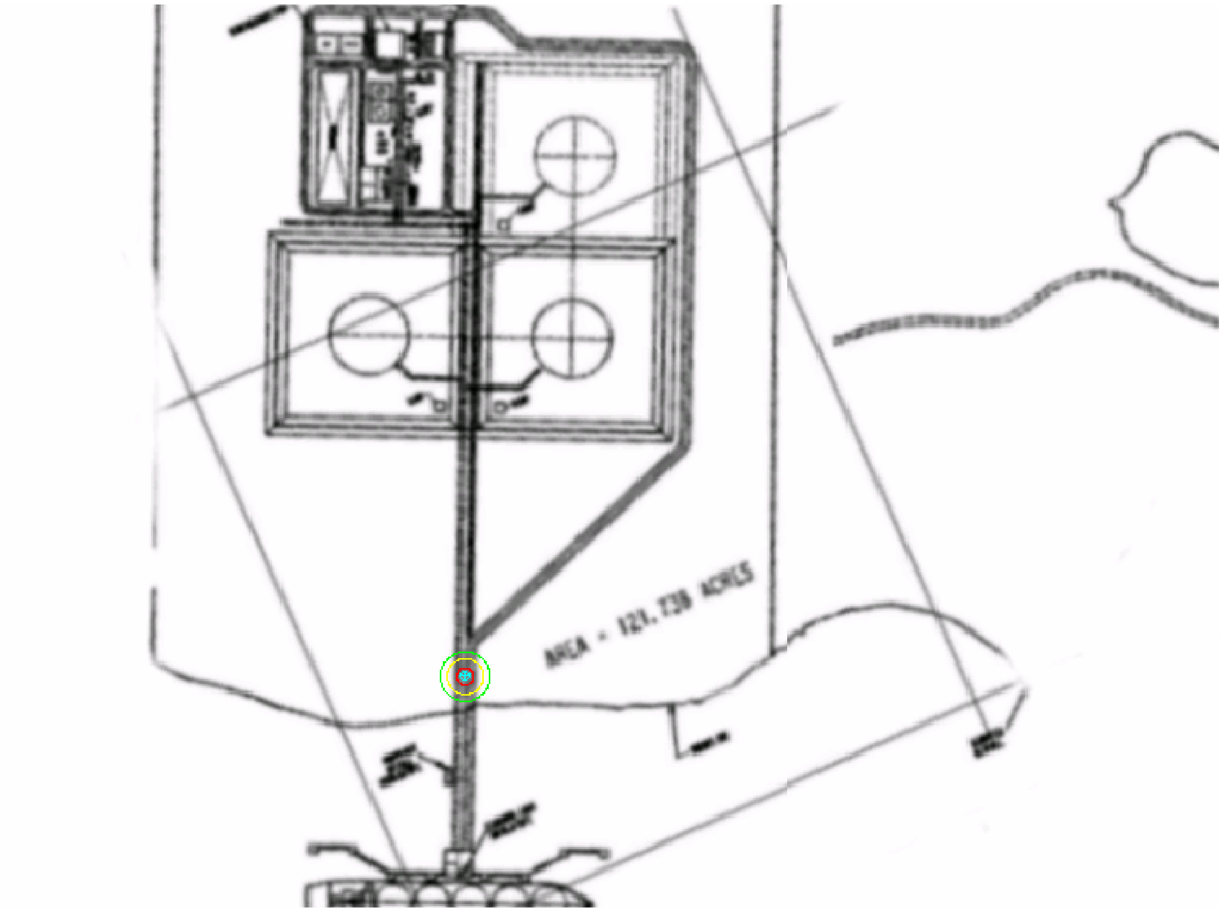


Figure 2.4: Unconfined Pool Fire Radiation Contours for Pipeline 0.100m diameter. hole

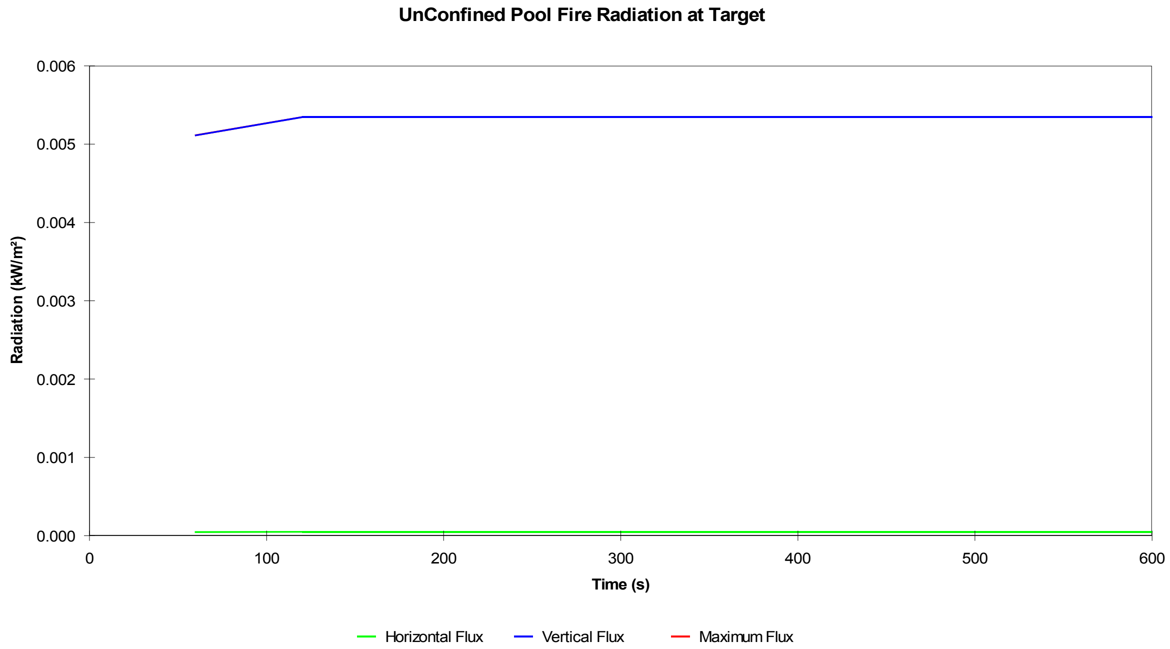


Figure 2.5 Unconfined Pool Fire Radiation Plots

UNCONFINED POOL FIRE MODEL

STORAGE TANK LEAK WITH IMMEDIATE IGNITION OF SPILLED CONTENTS

FUEL
- Name : LNG LIGHT (METHANE)
- Temperature : -162.15 °C
- Pressure (absolute) : 1.01 bar
- Physical state : Liquid phase only

CONSTANT PROPERTIES
- Molecular weight : 16.04
- Boiling point : -161.55 °C
- Critical temperature : 190.55 K
- Critical pressure : 46.0 bar
- Heat of combustion : 5.00E+07 J/kg
- Flame temperature : 1300 K

CALCULATED PROPERTIES
- Liquid compressibility factor : 0.004
- Liquid density : 476.6 kg/cu m

RELEASE DATA
- Type of spill : Continuous
- Substance release rate : 9.04 kg/sec
- Surface type : Average soil
- Target distance : 800.0 m
- Elevation of target : 1.6 m

LOCAL AMBIENT CONDITIONS
- Air temperature : 21.0 °C
- Ambient pressure : 1.01 bar
- Wind speed : 0.5 m/s
- Relative humidity : 50.0%

STEADY STATE RESULTS
- Maximum emissive power : 190.0 kW/m²

Time Interval (s)	Burning Rate (kg/m² s)	Flame Length (m)	Flame tilt from vertical (deg)	Flame drag ratio	Effective emissive power (kW/m²)
60.00	0.105	17.48	0.00	1.02	164.59
120.00	0.105	17.78	0.00	1.02	165.60
180.00	0.105	17.78	0.00	1.02	165.60
240.00	0.105	17.78	0.00	1.02	165.60
300.00	0.105	17.78	0.00	1.02	165.60
360.00	0.105	17.78	0.00	1.02	165.60
420.00	0.105	17.78	0.00	1.02	165.60
480.00	0.105	17.78	0.00	1.02	165.60
540.00	0.105	17.78	0.00	1.02	165.60
600.00	0.105	17.78	0.00	1.02	165.60

Time Interval (s)	Pool Radius (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
60.00	3.28	0.00	0.01	0.01
120.00	3.35	0.00	0.01	0.01
180.00	3.35	0.00	0.01	0.01
240.00	3.35	0.00	0.01	0.01
300.00	3.35	0.00	0.01	0.01
360.00	3.35	0.00	0.01	0.01
420.00	3.35	0.00	0.01	0.01
480.00	3.35	0.00	0.01	0.01
540.00	3.35	0.00	0.01	0.01

```
    600.00        3.35             0.00                0.01                0.01
--------------------------------------------------------------------------------------

Distance to Radiation Levels at Maximum Pool Size

Maximum pool radius                      : 3.35 m
Mass burning rate                        : 0.105 kg/m² s
Flame length                             : 17.78 m
Flame tilt from vertical                 : 0.0°
Flame drag ratio                         : 1.02
Maximum emissive power                   : 190.0 kW/m²
Effective emissive power                 : 165.6 kW/m²
```

Thermal flux (kW/m²)	Distance From center of Pool (m)
30.0	10.50
9.0	22.27
5.0	30.59

Table 2.4: Unconfined Pool Fire Radiation Calculations for Pipeline 0.100m Diameter. Hole

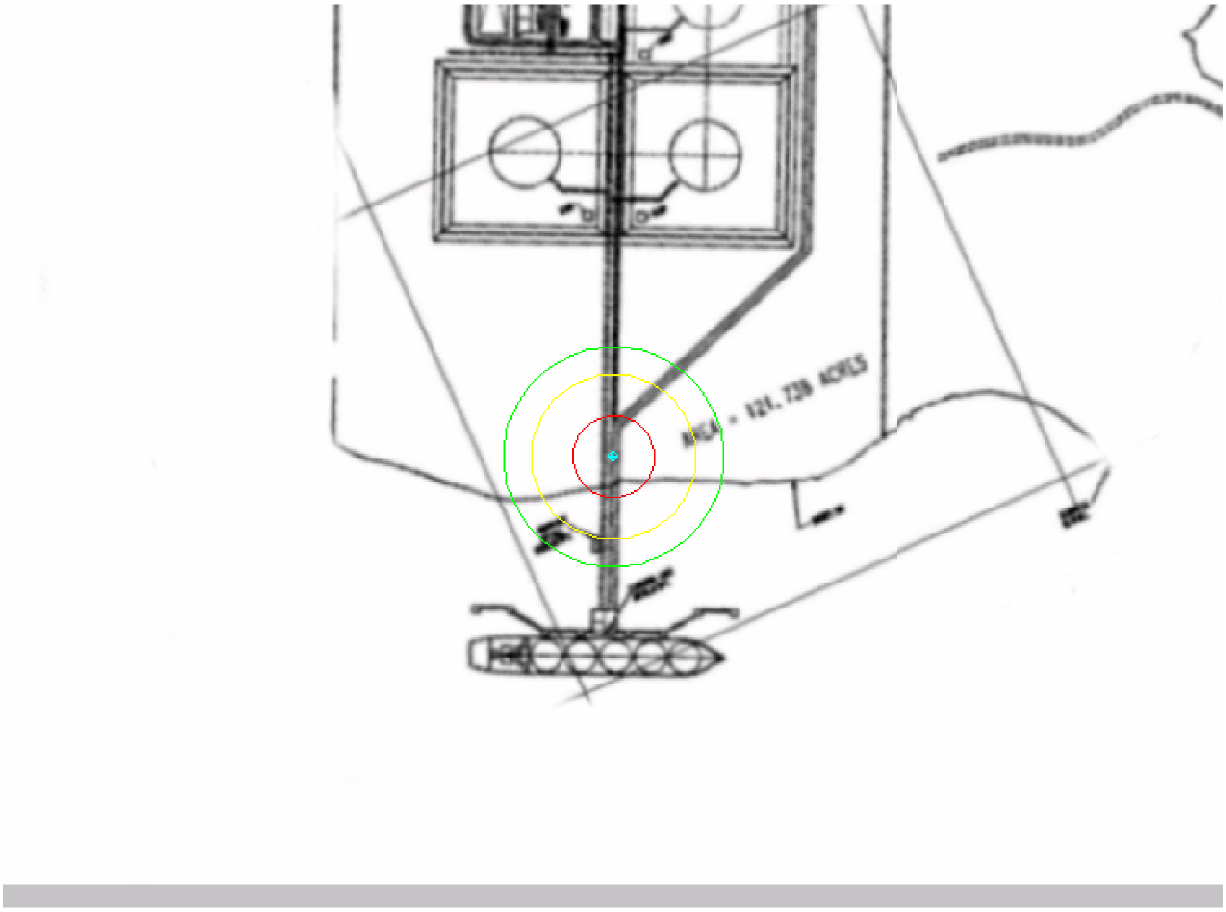


Figure 2.6: Unconfined Pool Fire Radiation Contours for Pipeline Full Bore release

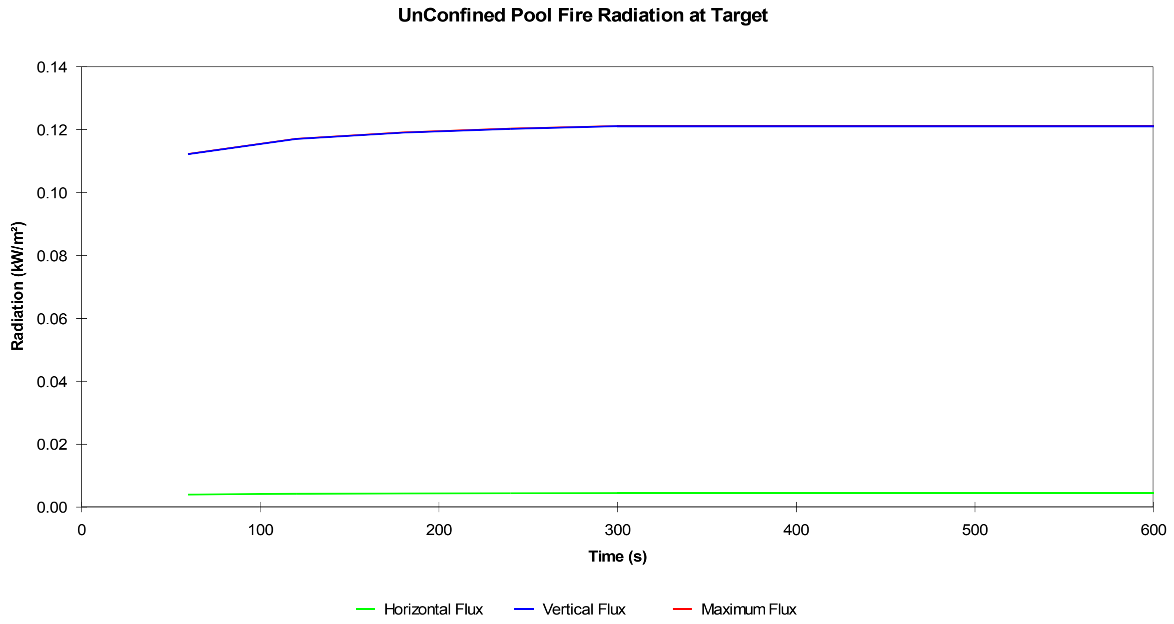


Figure 2.7 Unconfined Pool Fire Radiation Plots

UNCONFINED POOL FIRE MODEL

STORAGE TANK LEAK WITH IMMEDIATE IGNITION OF SPILLED CONTENTS

FUEL

Name	: LNG LIGHT (METHANE)
Temperature	: -162.15 °C
Pressure (absolute)	: 1.01 bar
Physical state	: Liquid phase only

CONSTANT PROPERTIES

Molecular weight	: 16.04
Boiling point	: -161.55 °C
Critical temperature	: 190.55 K
Critical pressure	: 46.0 bar
Heat of combustion	: 5.00E+07 J/kg
Flame temperature	: 1300 K

CALCULATED PROPERTIES

Liquid compressibility factor	: 0.004
Liquid density	: 476.6 kg/cu m

RELEASE DATA

Type of spill	: Continuous
Substance release rate	: 317.37 kg/sec
Surface type	: Average soil
Target distance	: 800.0 m
Elevation of target	: 1.6 m

LOCAL AMBIENT CONDITIONS

Air temperature	: 21.0 °C
Ambient pressure	: 1.01 bar
Wind speed	: 0.5 m/s
Relative humidity	: 50.0%

STEADY STATE RESULTS

Maximum emissive power	: 190.0 kW/m²

Time Interval (s)	Burning Rate (kg/m² s)	Flame Length (m)	Flame tilt from vertical (deg)	Flame drag ratio	Effective emissive power (kW/m²)
60.00	0.110	59.23	0.00	1.00	190.00
120.00	0.110	60.25	0.00	1.00	190.00
180.00	0.110	60.67	0.00	1.00	190.00
240.00	0.110	60.92	0.00	1.00	190.00
300.00	0.110	61.09	0.00	1.00	190.00
360.00	0.110	61.09	0.00	1.00	190.00
420.00	0.110	61.09	0.00	1.00	190.00
480.00	0.110	61.09	0.00	1.00	190.00
540.00	0.110	61.09	0.00	1.00	190.00
600.00	0.110	61.09	0.00	1.00	190.00

Time Interval (s)	Pool Radius (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
60.00	18.16	0.00	0.11	0.11
120.00	18.61	0.00	0.12	0.12
180.00	18.80	0.00	0.12	0.12
240.00	18.91	0.00	0.12	0.12
300.00	18.99	0.00	0.12	0.12
360.00	18.99	0.00	0.12	0.12
420.00	18.99	0.00	0.12	0.12
480.00	18.99	0.00	0.12	0.12
540.00	18.99	0.00	0.12	0.12
600.00	18.99	0.00	0.12	0.12

```
-------------------------------------------------------------------------------------

Distance to Radiation Levels at Maximum Pool Size

Maximum pool radius                      : 18.99 m
Mass burning rate                        : 0.11 kg/m² s
Flame length                             : 61.09 m
Flame tilt from vertical                 : 0.0°
Flame drag ratio                         : 1.00
Maximum emissive power                   : 190.0 kW/m²
Effective emissive power                 : 190.0 kW/m²
```

Thermal flux (kW/m²)	Distance From center of Pool (m)
30.0	50.11
9.0	101.04
5.0	135.48

Table 2.5: Unconfined Pool Fire Radiation Calculations for Pipeline Full Bore Release

```
RECTANGULAR DIKE FIRE
TRENCH FIRE

FUEL
  NAME                                    : LNG LIGHT (METHANE)
  POOL TEMPERATURE                        : -161.55 °C

CONSTANT PROPERTIES
  MOLECULAR WEIGHT                        : 16.04
  BOILING POINT                           : -161.55 °C
  CRITICAL TEMPERATURE                    : 190.55 K
  CRITICAL PRESSURE                       : 46.0 BAR
  HEAT OF COMBUSTION                      : 5.00E+07 J/KG
  FLAME TEMPERATURE                       : 1300 K

CALCULATED PROPERTIES
  LIQUID COMPRESSIBILITY FACTOR           : 0.004
  LIQUID DENSITY                          : 475.5 KG/CU M

DIMENSIONS
  POOL WIDTH                              : 10.0 M
  POOL LENGTH                             : 10.0 M
  POOL LIQUID HEIGHT                      : 0.5 M
  HEIGHT OF FLAME BASE                    : 0.5 M
  HEIGHT FOR RADIATION CALCULATIONS       : 1.5 M

LOCAL AMBIENT CONDITIONS
  AIR TEMPERATURE                         : 21.0 °C
  AMBIENT PRESSURE                        : 1.01 BAR
  WIND SPEED                              : 0.5 M/S
  RELATIVE HUMIDITY                       : 50.0%

RESULTS
  MASS BURNING RATE                       : 0.11 KG/M² S
  FLAME LENGTH                            : 24.16 M
  FLAME TILT FROM VERTICAL (FRONT VIEW)   : 0.0°
  FLAME TILT FROM VERTICAL (SIDE VIEW)    : 0.0°
  FLAME DRAG RATIO (FRONT VIEW)           : 1.00
  FLAME DRAG RATIO (SIDE VIEW)            : 1.00
  MAXIMUM EMISSIVE POWER                  : 190.0 KW/M²
  EFFECTIVE EMISSIVE POWER (FRONT VIEW)   : 180.54 KW/M²
  EFFECTIVE EMISSIVE POWER (SIDE VIEW)    : 180.54 KW/M²
```

FRONT VIEW (VIEW ALONG DIKE/TRENCH WIDTH)

THERMAL FLUX (KW/M²)	DISTANCE FROM CENTER OF POOL (M)
30.0	18.02
9.0	35.38
5.0	47.46

SIDE VIEW (VIEW ALONG DIKE/TRENCH LENGTH)

THERMAL FLUX (KW/M²)	DISTANCE FROM CENTER OF POOL (M)
30.0	18.02
9.0	35.38
5.0	47.46

```
  MAXIMUM EMISSIVE POWER                  : 60,230 BTU/FT² HR
  FRONT VIEW (VIEW ALONG DIKE/TRENCH WIDTH)
```

DISTANCE FROM CENTER OF POOL (M)	THERMAL FLUX TO HORIZONTAL TARGET (KW/M^2)	THERMAL FLUX TO VERTICAL TARGET (KW/M^2)	MAXIMUM FLUX TO TARGET (KW/M^2)
7.50	65.26	126.55	104.82
10.00	44.17	79.68	72.94
12.50	30.38	56.29	53.02
15.00	21.71	41.89	40.18
20.00	12.10	25.97	25.26
25.00	7.27	17.66	17.19
30.00	4.60	12.70	12.32
40.00	2.09	7.31	7.06
60.00	0.63	3.22	3.12
100.00	0.12	1.03	1.01

SIDE VIEW (VIEW ALONG DIKE/TRENCH LENGTH)

DISTANCE FROM CENTER OF POOL (M)	THERMAL FLUX TO HORIZONTAL TARGET (KW/M^2)	THERMAL FLUX TO VERTICAL TARGET (KW/M^2)	MAXIMUM FLUX TO TARGET (KW/M^2)
7.50	65.26	126.55	104.82
10.00	44.17	79.68	72.94
12.50	30.38	56.29	53.02
15.00	21.71	41.89	40.18
20.00	12.10	25.97	25.26
25.00	7.27	17.66	17.19
30.00	4.60	12.70	12.32
40.00	2.09	7.31	7.06
60.00	0.63	3.22	3.12
100.00	0.12	1.03	1.01

Table 2.6 LNG Storage Tank Dike Sump LNG Pool Fire Results

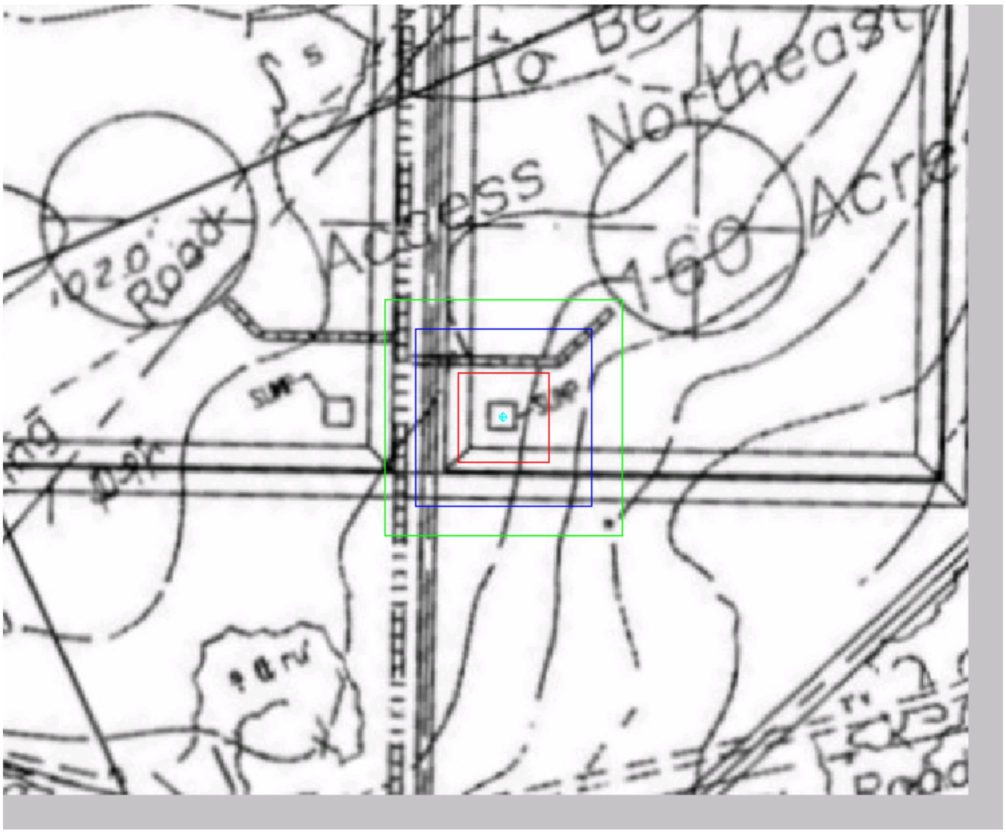


Figure 2.8 LNG Storage Tank Dike Sump LNG Fire Radiation Contours

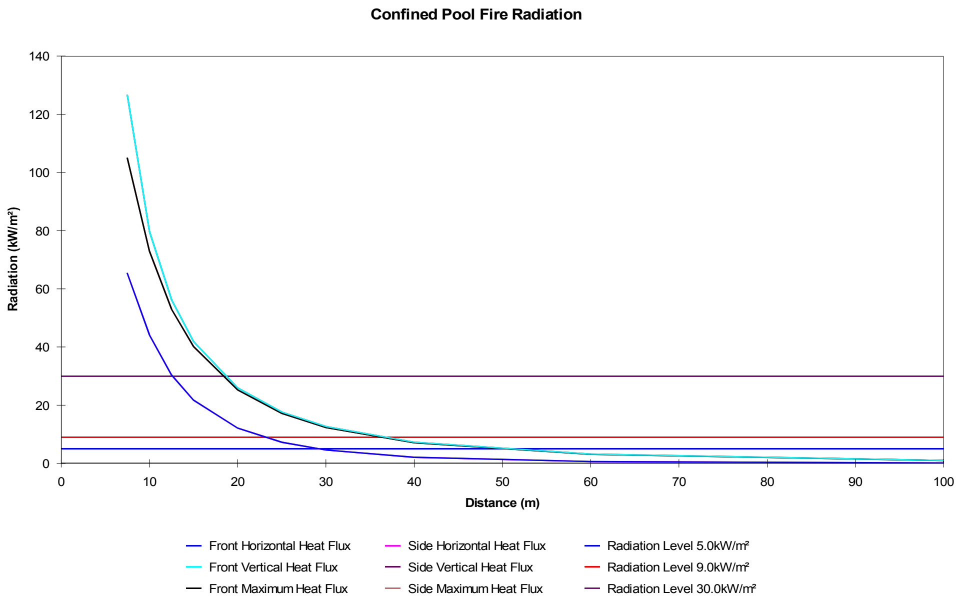


Figure 2.9 LNG Storage Tank Dike Sump LNG Pool Fire Radiation Plots

RECTANGULAR DIKE FIRE
TRENCH FIRE

FUEL

Name	: LNG LIGHT (METHANE)
Pool temperature	: -161.55 °C

CONSTANT PROPERTIES

Molecular weight	: 16.04
Boiling point	: -161.55 °C
Critical temperature	: 190.55 K
Critical pressure	: 46.0 bar
Heat of combustion	: 5.00E+07 J/kg
Flame temperature	: 1300 K

CALCULATED PROPERTIES

Liquid compressibility factor	: 0.004
Liquid density	: 475.5 kg/cu m

DIMENSIONS

Pool width	: 3.0 m
Pool length	: 6.0 m
Pool Liquid Height	: 0.5 m
Height of flame base	: 0.5 m
Height for Radiation Calculations	: 1.6 m

LOCAL AMBIENT CONDITIONS

Air temperature	: 21.0 °C
Ambient pressure	: 1.01 bar
Wind speed	: 0.5 m/s
Relative humidity	: 50.0%

RESULTS

Mass burning rate	: 0.107 kg/m² s
Flame length	: 10.3 m
Flame tilt from vertical (front view)	: 0.0°
Flame tilt from vertical (side view)	: 0.0°
Flame drag ratio (front view)	: 1.00
Flame drag ratio (side view)	: 1.00
Maximum emissive power	: 190.0 kW/m²
Effective emissive power (front view)	: 112.75 kW/m²
Effective emissive power (side view)	: 158.59 kW/m²

Front view (view along dike/trench width)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	6.86
9.0	14.18
5.0	19.24

Side view (view along dike/trench length)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	7.40
9.0	13.41
5.0	17.73

Maximum emissive power : 60,230 Btu/ft² hr
Front view (view along dike/trench width)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
2.25	Target in flame	Target in flame	Target in flame
3.00	Target in flame	Target in flame	Target in flame
3.75	41.79	90.01	62.27
4.50	33.93	73.30	51.45
6.00	22.07	48.64	36.08
7.50	14.62	33.98	26.32
9.00	9.96	24.88	19.85

12.00	4.97	14.75	12.20
18.00	1.59	6.61	5.70
30.00	0.33	2.23	2.02

Side view (view along dike/trench length)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
4.50	Target in flame	Target in flame	Target in flame
6.00	34.93	85.08	46.11
7.50	18.80	44.53	29.13
9.00	11.50	27.71	20.21
12.00	5.15	14.16	11.31
15.00	2.64	8.57	7.12
18.00	1.48	5.68	4.84
24.00	0.57	2.94	2.59
36.00	0.15	1.16	1.06
60.00	0.03	0.37	0.35

Table 2.7 LNG Process Area Sump LNG Pool Fire Results

Figure 2.10 LNG Process Area Sump LNG Fire Radiation Contours

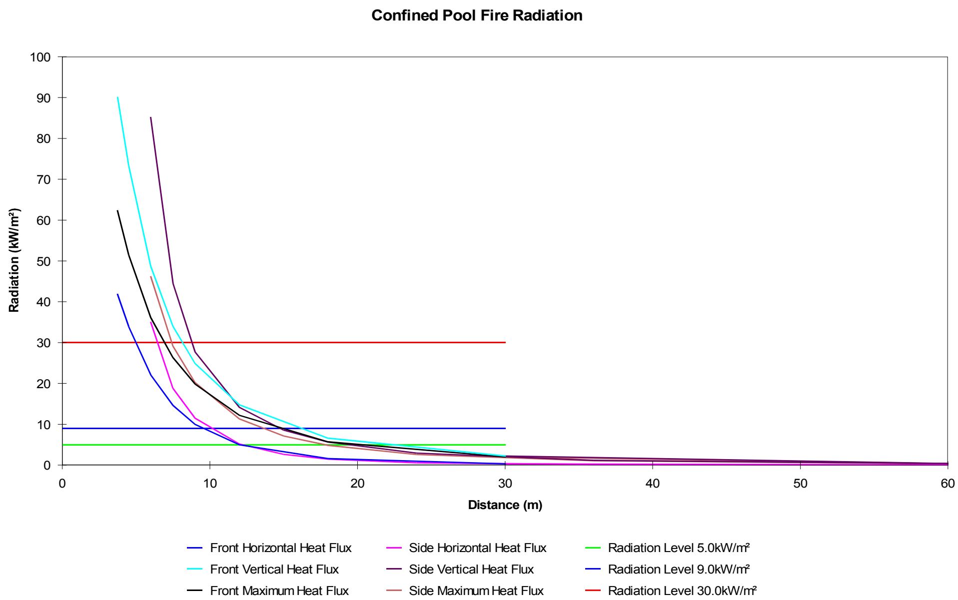


Figure 2.11 LNG Process Area Sump Pool LNG Fire Radiation Plots

RECTANGULAR DIKE FIRE
TRENCH FIRE

FUEL

Name	: LNG LIGHT (METHANE)
Pool temperature	: -161.55 °C

CONSTANT PROPERTIES

Molecular weight	: 16.04
Boiling point	: -161.55 °C
Critical temperature	: 190.55 K
Critical pressure	: 46.0 bar
Heat of combustion	: 5.00E+07 J/kg
Flame temperature	: 1300 K

CALCULATED PROPERTIES

Liquid compressibility factor	: 0.004
Liquid density	: 475.5 kg/cu m

DIMENSIONS

Pool width	: 3.0 m
Pool length	: 6.0 m
Pool Liquid Height	: 0.5 m
Height of flame base	: 0.5 m
Height for Radiation Calculations	: 1.6 m

LOCAL AMBIENT CONDITIONS

Air temperature	: 21.0 °C
Ambient pressure	: 1.01 bar
Wind speed	: 0.5 m/s
Relative humidity	: 50.0%

RESULTS

Mass burning rate	: 0.107 kg/m² s
Flame length	: 10.3 m
Flame tilt from vertical (front view)	: 0.0°
Flame tilt from vertical (side view)	: 0.0°
Flame drag ratio (front view)	: 1.00
Flame drag ratio (side view)	: 1.00
Maximum emissive power	: 190.0 kW/m²
Effective emissive power (front view)	: 112.75 kW/m²
Effective emissive power (side view)	: 158.59 kW/m²

Front view (view along dike/trench width)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	6.86
9.0	14.18
5.0	19.24

Side view (view along dike/trench length)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	7.40
9.0	13.41
5.0	17.73

Maximum emissive power : 60,230 Btu/ft² hr
Front view (view along dike/trench width)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
2.25	Target in flame	Target in flame	Target in flame
3.00	Target in flame	Target in flame	Target in flame
3.75	41.79	90.01	62.27
4.50	33.93	73.30	51.45
6.00	22.07	48.64	36.08
7.50	14.62	33.98	26.32
9.00	9.96	24.88	19.85

12.00	4.97	14.75	12.20
18.00	1.59	6.61	5.70
30.00	0.33	2.23	2.02

Side view (view along dike/trench length)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
4.50	Target in flame	Target in flame	Target in flame
6.00	34.93	85.08	46.11
7.50	18.80	44.53	29.13
9.00	11.50	27.71	20.21
12.00	5.15	14.16	11.31
15.00	2.64	8.57	7.12
18.00	1.48	5.68	4.84
24.00	0.57	2.94	2.59
36.00	0.15	1.16	1.06
60.00	0.03	0.37	0.35

Table 2.8 LNG Jetty Area Sump LNG Pool Fire Results

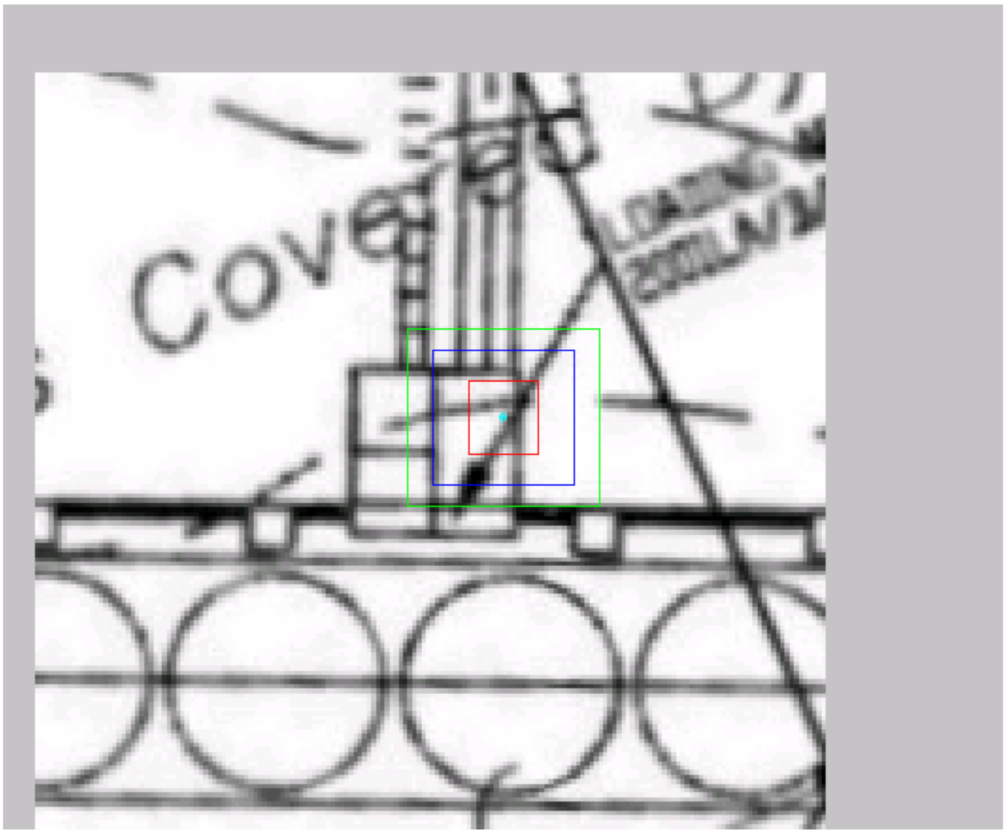


Figure 2.12 LNG Jetty Area Sump LNG Fire Radiation Contours

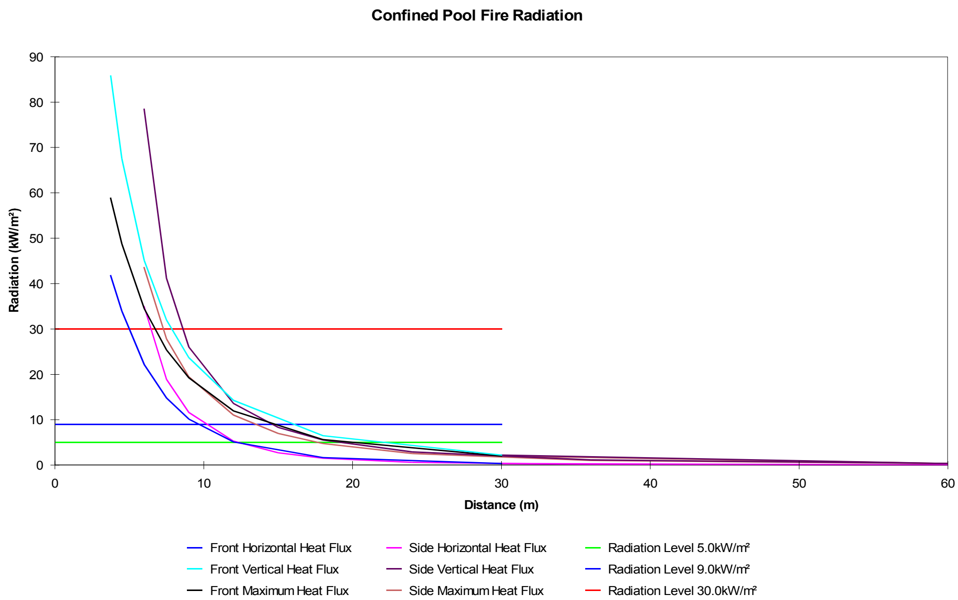


Figure 2.13 LNG Jetty Area Sump Pool LNG Fire Radiation Plots

DEGADIS+ SUMMARY

METEOROLOGY:

Ambient temperature	21.0 ° C
Ambient pressure	1.0 atm
Relative humidity	50 %
Wind direction	270 degrees
Wind speed	0.5 m/s
Anemometer height	10.0 meters
Surface roughness	0.01 meters
Stability option	Stability class
Stability class	6 (F)

CHEMICAL:

ID	LNG1
Name	LNG Light (Methane)
Molecular weight	16.043 g/g-mole
Boiling point	111.6 K
TWA	6666 mg/m**3
LFL	33000 mg/m**3

RELEASE:

Source type	Ground-level release
Release type	Finite duration
Emission rate	2516.0 lb/min
Source radius	5.64 meters
Mass fraction	1
Release temperature	111.6 K
Release duration	600 seconds
Isothermal mode	Non-isothermal
Heat transfer	DEGADIS correlation
Ground temperature	294.15 K
Water transfer	No

OUTPUT:

Height of interest	1.6 meters
Averaging time	600.0 seconds
Lower contour	16500 mg/m**3
Middle contour	33000 mg/m**3

RESULTS:

MAXIMUM DISTANCE TO MINIMUM CONCENTRATION

Concentration mg/m**3	Maximum Distance meters
16500	252.116
33000 (LFL)	206.073

MAXIMUM DISTANCE TO MINIMUM CONCENTRATION AT EACH TIME STEP

Concentration mg/m**3	Elapsed Time seconds	Distance meters
16500	186	77.633
16500	306	104.545
16500	426	139.214
16500	546	169.559
16500	666	202.677
16500	786	238.754
16500	906	245.671
16500	1026	252.116
16500	1146	0.000
16500	1266	0.000
16500	1386	0.000
16500	1506	0.000
16500	1626	0.000
16500	1746	0.000
16500	1866	0.000

16500	1986	0.000
16500	2106	0.000
16500	2226	0.000
16500	2346	0.000
33000 (LFL)	186	69.736
33000 (LFL)	306	98.488
33000 (LFL)	426	121.670
33000 (LFL)	546	147.430
33000 (LFL)	666	178.242
33000 (LFL)	786	198.333
33000 (LFL)	906	206.073
33000 (LFL)	1026	0.000
33000 (LFL)	1146	0.000
33000 (LFL)	1266	0.000
33000 (LFL)	1386	0.000
33000 (LFL)	1506	0.000
33000 (LFL)	1626	0.000
33000 (LFL)	1746	0.000
33000 (LFL)	1866	0.000
33000 (LFL)	1986	0.000
33000 (LFL)	2106	0.000
33000 (LFL)	2226	0.000
33000 (LFL)	2346	0.000

Table 2.9 LNG Storage Tank Dike Sump Methane Plume Dispersion Results

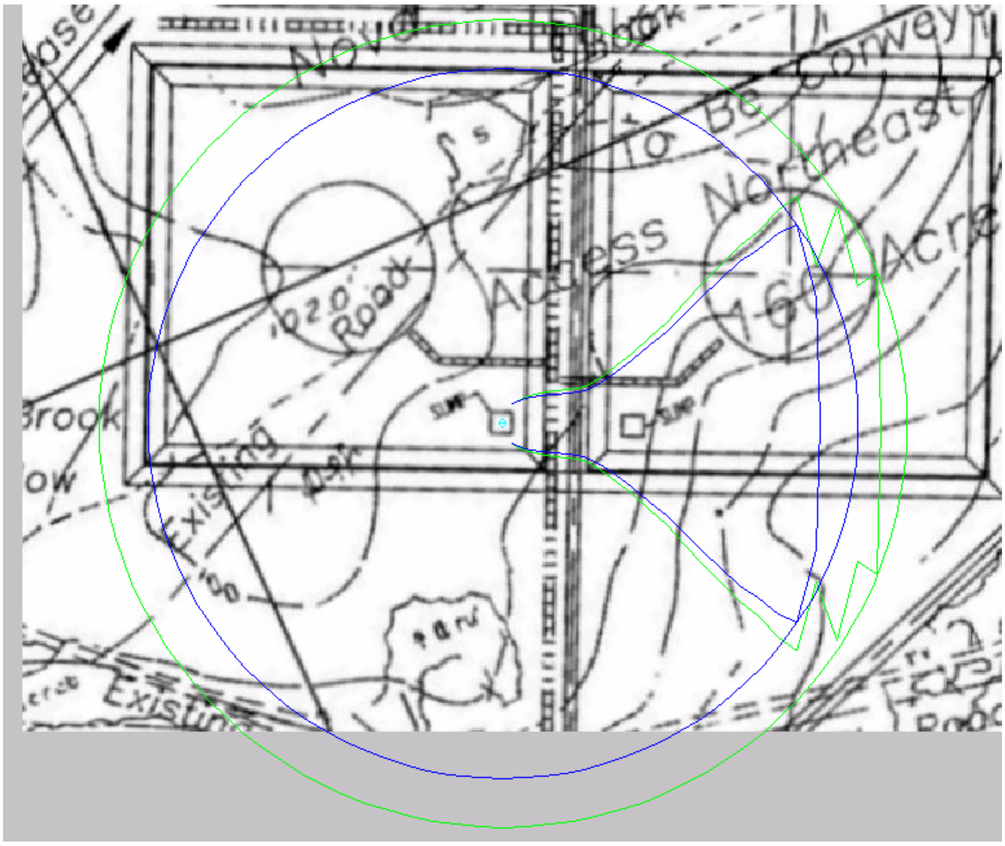
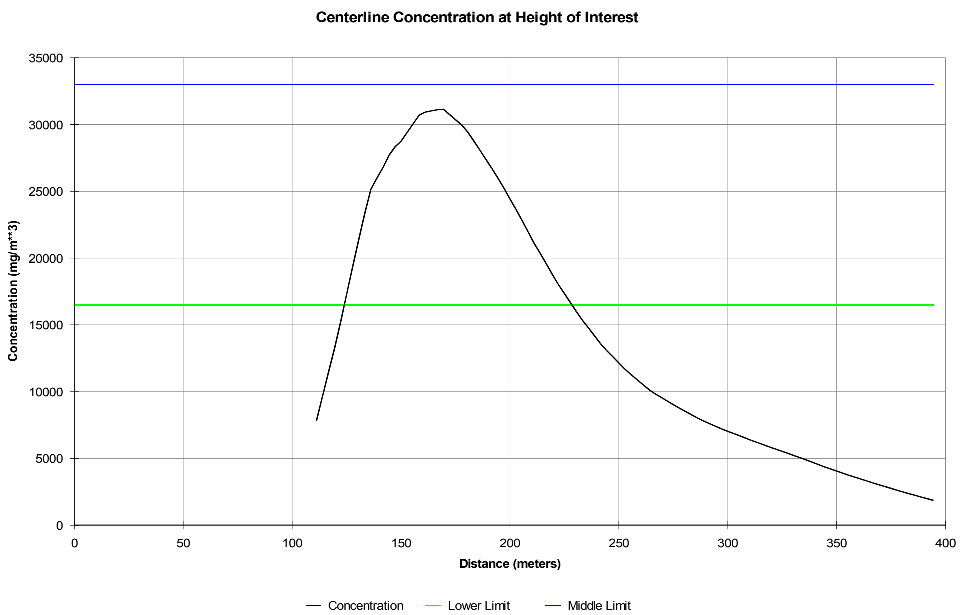


Figure 2.14 LNG Storage Tank Dike Sump Methane Plume Dispersion Contours



Time 1026

Figure 2.15 LNG Storage Tank Dike Sump Methane Plume Dispersion Plot

```
DEGADIS+ SUMMARY

METEOROLOGY:
  Ambient temperature         21.0 ° C
  Ambient pressure            1.0 atm
  Relative humidity           50 %
  Wind direction              270 degrees
  Wind speed                  0.5 m/s
  Anemometer height           10.0 meters
  Surface roughness           0.01 meters
  Stability option            Stability class
  Stability class             6 (F)

CHEMICAL:
  ID                          LNG1
  Name                        LNG Light (Methane)
  Molecular weight            16.043 g/g-mole
  Boiling point               111.6 K
  TWA                         6666 mg/m**3
  LFL                         33000 mg/m**3

RELEASE:
  Source type                 Ground-level release
  Release type                Finite duration
  Emission rate               452.8799 lb/min
  Source radius               2.39 meters
  Mass fraction               1
  Release temperature         111.6 K
  Release duration            600 seconds
  Isothermal mode             Non-isothermal
  Heat transfer               DEGADIS correlation
  Ground temperature          294.15 K
  Water transfer              No

OUTPUT:
  Height of interest          1.6 meters
  Averaging time              600.0 seconds
  Lower contour               16500 mg/m**3
  Middle contour              33000 mg/m**3

RESULTS:

  MAXIMUM DISTANCE TO MINIMUM CONCENTRATION

  Concentration                                Maximum Distance
    mg/m**3                                         meters
  ----------------------------------------------------------
    16500                                          107.068
    33000 (LFL)                                    70.889


  MAXIMUM DISTANCE TO MINIMUM CONCENTRATION AT EACH TIME STEP

  Concentration          Elapsed Time              Distance
    mg/m**3                seconds                  meters
  ----------------------------------------------------------
    16500                 132                      33.713
    16500                 223                      59.032
    16500                 314                      74.434
    16500                 405                      93.136
    16500                 496                      104.653
    16500                 587                      106.115
    16500                 678                      106.424
    16500                 769                      107.068
    16500                 860                      106.604
    16500                 951                      0.000
    16500                 1042                     0.000
    16500                 1133                     0.000
    16500                 1224                     0.000
    16500                 1315                     0.000
    16500                 1406                     0.000
    16500                 1497                     0.000
    16500                 1588                     0.000
    16500                 1679                     0.000
    16500                 1770                     0.000
  ----------------------------------------------------------
    33000 (LFL)           132                      31.847
```

33000 (LFL)	223	46.637
33000 (LFL)	314	60.241
33000 (LFL)	405	68.949
33000 (LFL)	496	69.688
33000 (LFL)	587	70.108
33000 (LFL)	678	70.613
33000 (LFL)	769	70.889
33000 (LFL)	860	0.000
33000 (LFL)	951	0.000
33000 (LFL)	1042	0.000
33000 (LFL)	1133	0.000
33000 (LFL)	1224	0.000
33000 (LFL)	1315	0.000
33000 (LFL)	1406	0.000
33000 (LFL)	1497	0.000
33000 (LFL)	1588	0.000
33000 (LFL)	1679	0.000
33000 (LFL)	1770	0.000

Table 2.10 LNG Process Area Sump Methane Plume Dispersion Results

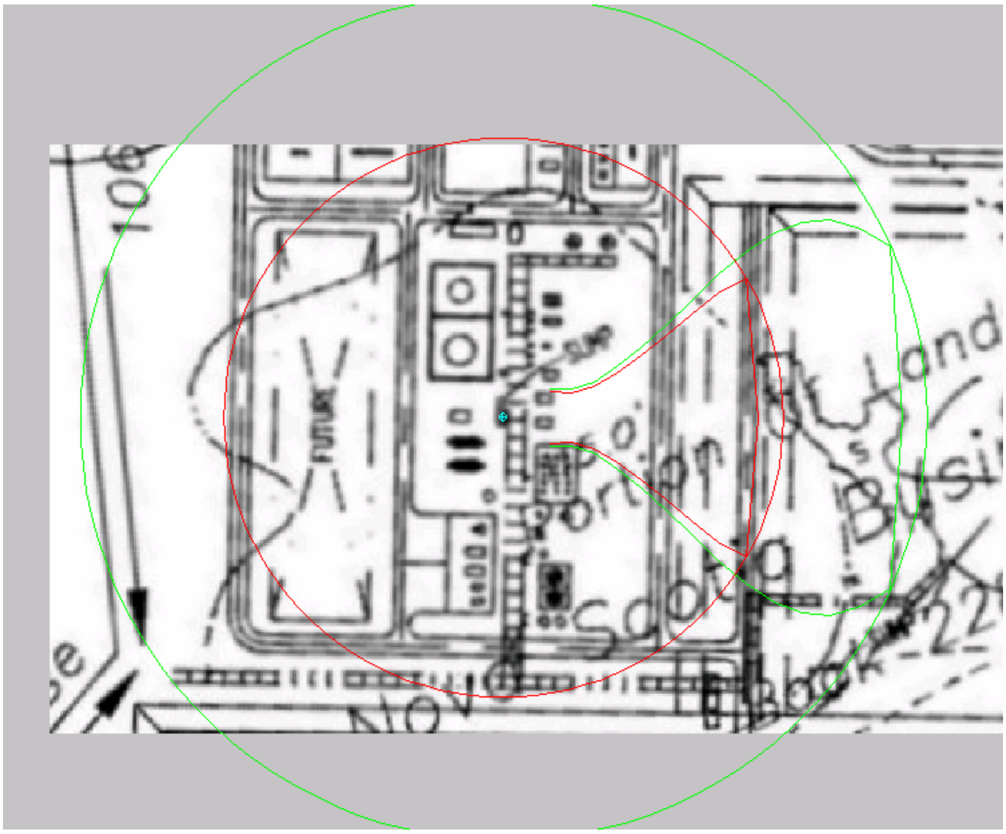
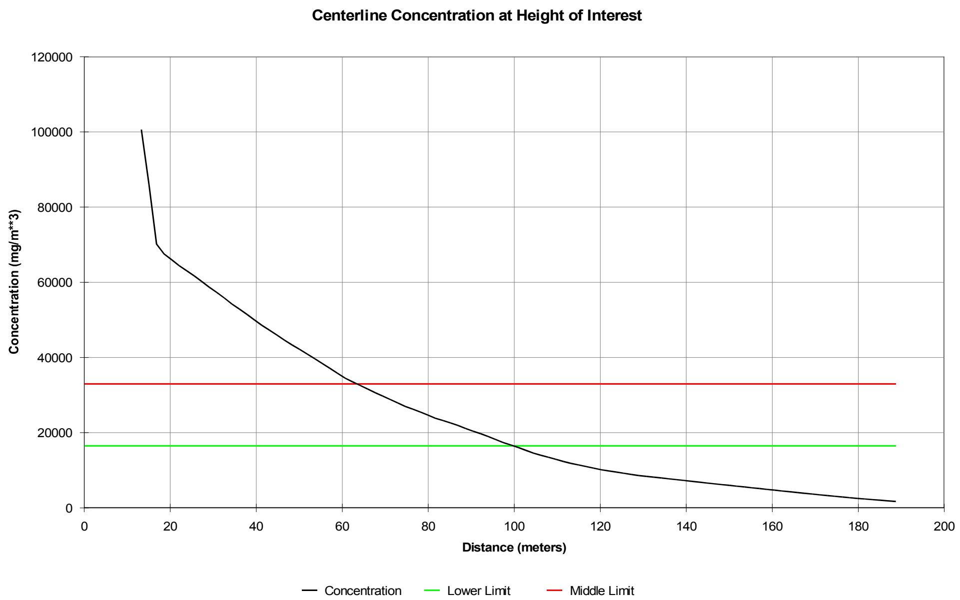


Figure 2.16 LNG Process Area Sump Methane Plume Dispersion Contours



2.17 LNG Process Area Sump Methane Plume Dispersion Plot

DEGADIS+ SUMMARY

METEOROLOGY:

Ambient temperature	21.0 ° C
Ambient pressure	1.0 atm
Relative humidity	50 %
Wind direction	270 degrees
Wind speed	0.5 m/s
Anemometer height	10.0 meters
Surface roughness	0.01 meters
Stability option	Stability class
Stability class	6 (F)

CHEMICAL:

ID	LNG1
Name	LNG Light (Methane)
Molecular weight	16.043 g/g-mole
Boiling point	111.6 K
TWA	6666 mg/m**3
LFL	33000 mg/m**3

RELEASE:

Source type	Ground-level release
Release type	Finite duration
Emission rate	452.8799 lb/min
Source radius	2.39 meters
Mass fraction	1
Release temperature	111.6 K
Release duration	600 seconds
Isothermal mode	Non-isothermal
Heat transfer	DEGADIS correlation
Ground temperature	294.15 K
Water transfer	No

OUTPUT:

Height of interest	1.6 meters
Averaging time	600.0 seconds
Lower contour	16500 mg/m**3
Middle contour	33000 mg/m**3

RESULTS:

MAXIMUM DISTANCE TO MINIMUM CONCENTRATION

Concentration mg/m**3	Maximum Distance meters
16500	107.068
33000 (LFL)	70.889

MAXIMUM DISTANCE TO MINIMUM CONCENTRATION AT EACH TIME STEP

Concentration mg/m**3	Elapsed Time seconds	Distance meters
16500	132	33.713
16500	223	59.032
16500	314	74.434
16500	405	93.136
16500	496	104.653
16500	587	106.115
16500	678	106.424
16500	769	107.068
16500	860	106.604
16500	951	0.000
16500	1042	0.000
16500	1133	0.000
16500	1224	0.000
16500	1315	0.000
16500	1406	0.000
16500	1497	0.000
16500	1588	0.000
16500	1679	0.000
16500	1770	0.000
33000 (LFL)	132	31.847

33000 (LFL)	223	46.637
33000 (LFL)	314	60.241
33000 (LFL)	405	68.949
33000 (LFL)	496	69.688
33000 (LFL)	587	70.108
33000 (LFL)	678	70.613
33000 (LFL)	769	70.889
33000 (LFL)	860	0.000
33000 (LFL)	951	0.000
33000 (LFL)	1042	0.000
33000 (LFL)	1133	0.000
33000 (LFL)	1224	0.000
33000 (LFL)	1315	0.000
33000 (LFL)	1406	0.000
33000 (LFL)	1497	0.000
33000 (LFL)	1588	0.000
33000 (LFL)	1679	0.000
33000 (LFL)	1770	0.000

Table 2.11 LNG Jetty Area Sump Methane Plume Dispersion Results

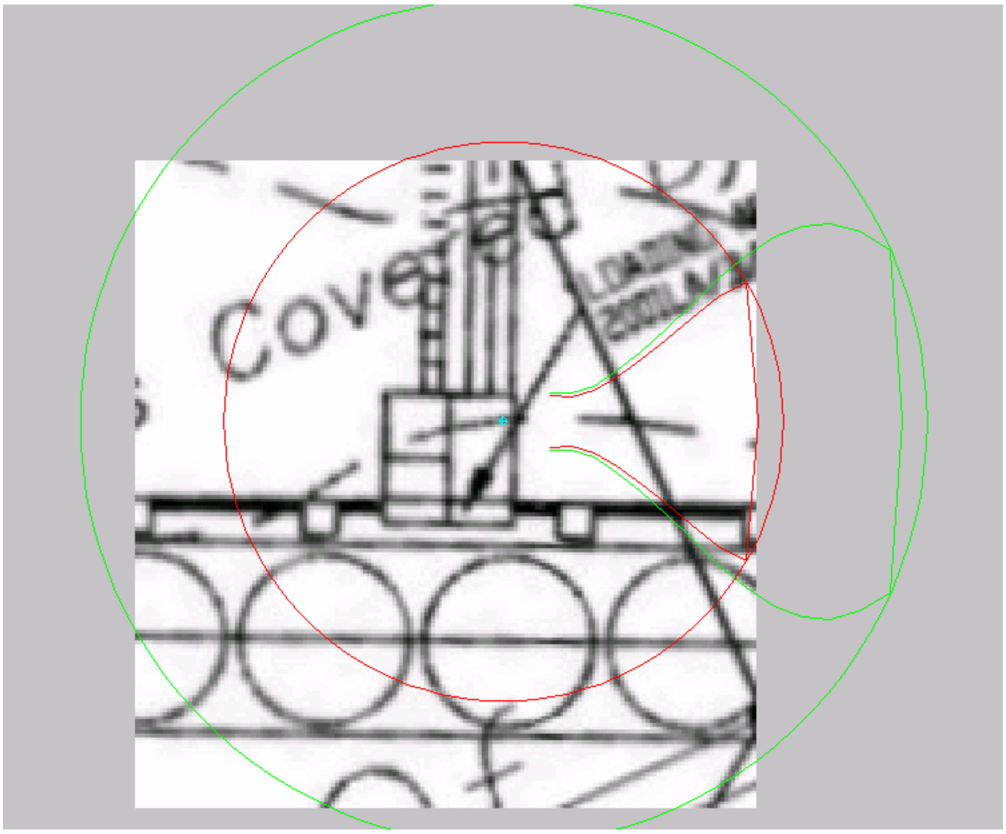
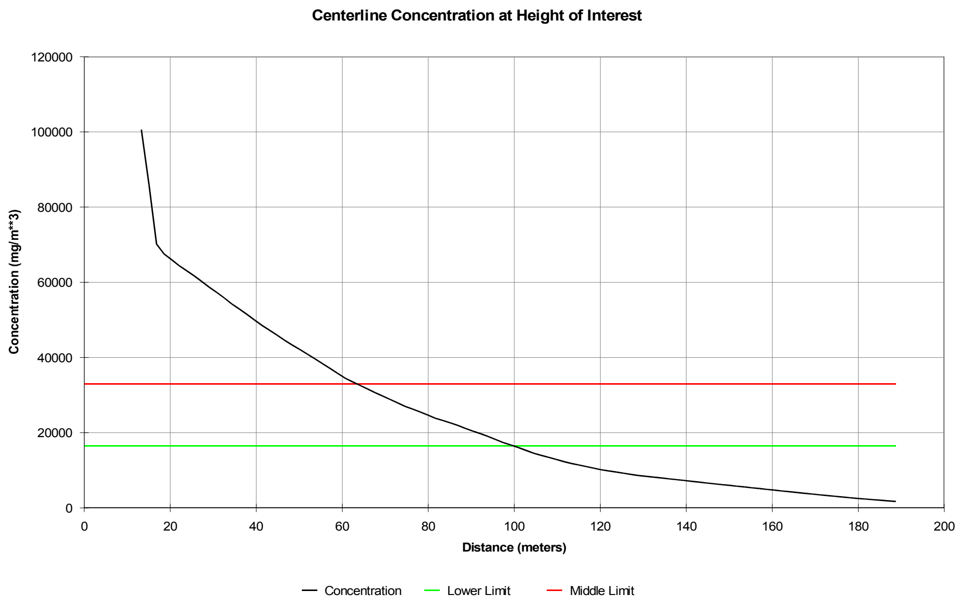


Figure 2.18 LNG Jetty Area Sump Methane Plume Dispersion Contours



2.19 LNG Jetty Area Sump Methane Plume Dispersion Plot

RECTANGULAR DIKE FIRE
TRENCH FIRE

FUEL

NAME	: ETHANE
POOL TEMPERATURE	: -88.63 °C

CONSTANT PROPERTIES

MOLECULAR WEIGHT	: 30.07
BOILING POINT	: -88.63 °C
CRITICAL TEMPERATURE	: 305.4 K
CRITICAL PRESSURE	: 49.45 BAR
HEAT OF COMBUSTION	: 4.75E+07 J/KG
FLAME TEMPERATURE	: 1300 K

CALCULATED PROPERTIES

LIQUID COMPRESSIBILITY FACTOR	: 0.003
LIQUID DENSITY	: 602.6 KG/CU M

DIMENSIONS

POOL WIDTH	: 3.0 M
POOL LENGTH	: 6.0 M
POOL LIQUID HEIGHT	: 0.5 M
HEIGHT OF FLAME BASE	: 0.5 M
HEIGHT FOR RADIATION CALCULATIONS	: 1.6 M

LOCAL AMBIENT CONDITIONS

AIR TEMPERATURE	: 21.0 °C
AMBIENT PRESSURE	: 1.01 BAR
WIND SPEED	: 0.5 M/S
RELATIVE HUMIDITY	: 50.0%

RESULTS

MASS BURNING RATE	: 0.088 KG/M² S
FLAME LENGTH	: 9.15 M
FLAME TILT FROM VERTICAL (FRONT VIEW)	: 0.0°
FLAME TILT FROM VERTICAL (SIDE VIEW)	: 0.0°
FLAME DRAG RATIO (FRONT VIEW)	: 1.00
FLAME DRAG RATIO (SIDE VIEW)	: 1.00
MAXIMUM EMISSIVE POWER	: 185.0 KW/M²
EFFECTIVE EMISSIVE POWER (FRONT VIEW)	: 109.78 KW/M²
EFFECTIVE EMISSIVE POWER (SIDE VIEW)	: 154.42 KW/M²

FRONT VIEW (VIEW ALONG DIKE/TRENCH WIDTH)

THERMAL FLUX (KW/M²)	DISTANCE FROM CENTER OF POOL (M)
30.0	6.63
9.0	13.45
5.0	18.14

SIDE VIEW (VIEW ALONG DIKE/TRENCH LENGTH)

THERMAL FLUX (KW/M²)	DISTANCE FROM CENTER OF POOL (M)
30.0	7.25
9.0	12.87
5.0	16.87

MAXIMUM EMISSIVE POWER : 58,645 BTU/FT² HR

FRONT VIEW (VIEW ALONG DIKE/TRENCH WIDTH)

DISTANCE FROM CENTER OF POOL (M)	THERMAL FLUX TO HORIZONTAL TARGET (KW/M²)	THERMAL FLUX TO VERTICAL TARGET (KW/M²)	MAXIMUM FLUX TO TARGET (KW/M²)
2.25	TARGET IN FLAME	TARGET IN FLAME	TARGET IN FLAME
3.00	TARGET IN FLAME	TARGET IN FLAME	TARGET IN FLAME
3.75	40.69	88.06	60.57

4.50	32.78	71.64	49.82
6.00	20.86	47.31	34.55
7.50	13.44	32.77	24.88
9.00	8.89	23.73	18.53
12.00	4.22	13.74	11.15
18.00	1.27	5.95	5.08
30.00	0.25	1.96	1.77

SIDE VIEW (VIEW ALONG DIKE/TRENCH LENGTH)

DISTANCE FROM CENTER OF POOL (M)	THERMAL FLUX TO HORIZONTAL TARGET (KW/M²)	THERMAL FLUX TO VERTICAL TARGET (KW/M²)	MAXIMUM FLUX TO TARGET (KW/M²)
4.50	TARGET IN FLAME	TARGET IN FLAME	TARGET IN FLAME
6.00	33.87	83.18	44.74
7.50	17.85	43.36	27.95
9.00	10.61	26.76	19.14
12.00	4.49	13.35	10.45
15.00	2.19	7.91	6.46
18.00	1.19	5.15	4.33
24.00	0.45	2.62	2.29
36.00	0.11	1.02	0.93
60.00	0.02	0.32	0.31

Table 2.12 LNG Process Area Sump Ethane Pool Fire Results

Figure 2.20 LNG Process Area Sump Ethane Fire Radiation Contours

Figure 2.21 LNG Process Area Sump Ethane Fire Radiation Contours

RECTANGULAR DIKE FIRE
TRENCH FIRE

FUEL

Name	: PROPANE
Pool temperature	: -42.07 °C

CONSTANT PROPERTIES

Molecular weight	: 44.1
Boiling point	: -42.07 °C
Critical temperature	: 369.8 K
Critical pressure	: 42.5 bar
Heat of combustion	: 4.63E+07 J/kg
Flame temperature	: 1300 K

CALCULATED PROPERTIES

Liquid compressibility factor	: 0.004
Liquid density	: 623.3 kg/cu m

DIMENSIONS

Pool width	: 3.0 m
Pool length	: 6.0 m
Pool Liquid Height	: 0.5 m
Height of flame base	: 0.5 m
Height for Radiation Calculations	: 1.6 m

LOCAL AMBIENT CONDITIONS

Air temperature	: 21.0 °C
Ambient pressure	: 1.01 bar
Wind speed	: 0.5 m/s
Relative humidity	: 50.0%

RESULTS

Mass burning rate	: 0.099 kg/m² s
Flame length	: 9.81 m
Flame tilt from vertical (front view)	: 0.0°
Flame tilt from vertical (side view)	: 0.0°
Flame drag ratio (front view)	: 1.00
Flame drag ratio (side view)	: 1.00
Maximum emissive power	: 188.0 kW/m²
Effective emissive power (front view)	: 111.56 kW/m²
Effective emissive power (side view)	: 156.92 kW/m²

Front view (view along dike/trench width)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	6.76
9.0	13.89
5.0	18.78

Side view (view along dike/trench length)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	7.34
9.0	13.19
5.0	17.36

Maximum emissive power : 59,596 Btu/ft² hr
Front view (view along dike/trench width)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
2.25	Target in flame	Target in flame	Target in flame
3.00	Target in flame	Target in flame	Target in flame

3.75	41.36	89.24	61.60
4.50	33.48	72.65	50.82
6.00	21.59	48.12	35.48
7.50	14.15	33.51	25.75
9.00	9.53	24.43	19.32
12.00	4.66	14.34	11.78
18.00	1.45	6.34	5.45
30.00	0.29	2.11	1.91

Side view (view along dike/trench length)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
4.50	Target in flame	Target in flame	Target in flame
6.00	34.52	84.33	45.57
7.50	18.42	44.07	28.67
9.00	11.15	27.34	19.78
12.00	4.88	13.84	10.97
15.00	2.45	8.30	6.85
18.00	1.36	5.46	4.63
24.00	0.52	2.81	2.47
36.00	0.13	1.10	1.01
60.00	0.02	0.35	0.33

Table 2.13 LNG Process Area Sump Propane Pool Fire Results

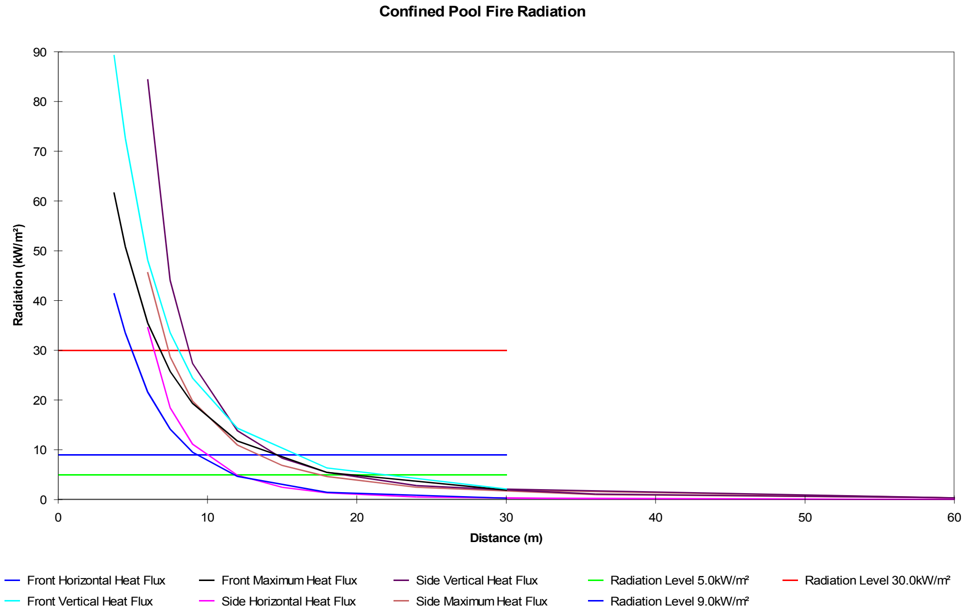


Figure 2.22 LNG Process Area Sump Propane Fire Radiation Contours

Figure 2.23 LNG Process Area Sump Propane Fire Radiation Contours

3 DELIBERATE ATTACK

Introduction

Section 2 "the Component Study Report" has identified the risks associated with the facility as required by the CSA Regulations. Such Regulations have been created to evaluate the consequences of "conventional" failure profiles, i.e. corrosion/erosion, impact, fatigue, etc. However, it is important to evaluate the consequences of a failure caused by a deliberate action, i.e. terrorist attack.

It is essential to put such an event into context. A terrorist attack against a specific facility would be extremely rare given the large number of potential targets available. Instead LNG safety should be judged upon the risk of conventional accidents, as evaluated in Section 2.

This Section and Section 4 discuss the immediate consequences of an attack, and the subsequent dispersion and ignition of the methane gas respectively.

3.1 Overview

A deliberate damaging action on a LNG ship or on an LNG single containment storage tank can be by several methods. The various attack methods are not considered specifically in this document but the application of explosives and the consequences of an attack to the LNG ship/LNG tank are outlined.

This Section specifies the nature of the attack, the ability to damage the LNG ship/LNG tank structures, likely loss of containment, and the resulting effects on the respective containments. This provides an indication of the way in which LNG will escape from the ship/tank

Two scenarios are considered. These are:

- missile attack on the external hull of the LNG ship or against the external carbon steel containment of a Terminal LNG storage tank:
- external explosive device placed next to the ship's hull, or against the external carbon steel containment of the Terminal LNG storage tank.

Appendix A5 contains an evaluation of the failure process resulting from an attack against an LNG ship. Within this Appendix, a Failure Modes and Effects Analysis (FMEA) has been used for the failure process associated with the LNG ship's structure.

The analysis has been used to produce the following discussion on the failure process.

3.2 Structural Response – LNG Shipping

3.2.1 Structural Description

There are a number of LNG ship types available. The most common of these are the Membrane, and the Moss-Rosenberg.

The Moss-Rosenberg system [Figure 3.1] is based upon self-supporting tanks resting on a cylindrical skirt. The tanks are made from aluminium, or 9% nickel steel. Inside each tank there is a cylindrical tower, inside which are located the piping for loading and discharging, pumps, level gauges, etc. The tanks and parts of the shell are insulated with polystyrene.

On this ship type the tanks are built on the leak-before failure principal, which means that a crack can be detected and repaired before it attains critical length. From the time a gas leak is first detected more than a year is required for the crack concerned to reach critical length. Because such tanks are designed and built to such high safety standards, a secondary barrier is not required. Under each tank there is only a small insulated space designed to contain small leakages.

The membrane type LNG tanker is a double-hull ship where the inner hull is the boundary of the liquid gas cargo tanks [Figure 3.2]. The outer hull is smooth externally but the inside contains an egg-box type structure of steel webs and stiffeners. About 2 metres inside this is a second hull which is supported by the same egg-box structure and is smooth on the inside. The shape of the inner hull is that of the cargo tanks as the internal surface forms the boundary of the tanks. The space of the inner hull is subdivided along the length of the ship and is used to contain water ballast when the ship is not carrying cargo. Between each of the cargo tanks and across the ship is another space, again about 2 metres wide, which is either normally empty or provides space for another set of ballast tanks. On top of the cargo tanks is a double deck with another void between the 2 decks.

The cargo tank itself has an inner surface of a thin membrane laid on blocks of insulation. Behind the insulation is the inner hull which gives the support to the insulation and the cargo tank membrane.

Although these two types of ship contain significant design differences, the overall method through which a release of LNG could occur and the resulting consequences are similar. Neither ship represents a more significant risk to the Bear Head Terminal area than the other, when the potential release sizes are taken into consideration. However, the membrane ship has been used throughout this report as their design would be more susceptible to a bomb type terrorist attack.

3.3 Immediate Structural Consequences - Shipping

Given an explosive or missile attack, there are 2 potential outcomes;

- outer hull only is breached; and
- outer and inner hulls are breached and the LNG cargo tanks are ruptured.

The consequences of these outcomes are as follows:

3.3.1 The Outer Hull only is Breached

Where the outer hull only is breached, the LNG ship will remain largely intact. If the explosion is underwater the inner hull space will be filled with seawater up to the same level as the outside waterline. The ship is expected to heel over to the damaged side by approximately 10 degrees. Once the LNG cargo is discharged the ship can be brought upright by ballasting the remaining inner hull tanks. The LNG ship will be out of commission as a gas carrier until the damage is repaired.

A side effect of this outcome is that the seawater in contact with the inner hull will provide additional heat into the LNG cargo (stored at –163^{0}C), increasing boil-off in that tank. Power requirements at this time may be insufficient to absorb the extra boil-off and emergency venting could be needed to maintain the tank at a safe pressure.

3.3.2 The Inner and Outer Hulls Breached

If there is an equivalent opening in the inner hull, the LNG cargo is likely to escape to the atmosphere. LNG that falls to the sea will spread on the surface and will gradually evaporate into its natural gaseous state.

If the inner and outer hulls are damaged then the cargo, which is carried in liquid form at a temperature of -163°C, will be exposed to the atmosphere. The breach is likely to be below the level of LNG in the tanks and therefore the cargo will discharge into the surrounding space. The steel with which the structure is made of is not capable of withstanding cryogenic temperatures. Steel structures will fracture extensively wherever there is contact with the LNG although influx of water from outside will minimise this damage. The complete inner hull space for the complete length of the cargo tank will be in contact with the cargo and the fractures will be extensive. At the ends of this tank the fractures may extend into the next tank but should not be sufficient to allow the cargo to penetrate the tank boundary. However, the structure will be significantly weakened.

The extent of the fractures within the tank will be every part that the LNG contacts. Being mainly liquid it will drain to the bottom of the inner hull which is the bottom of the ship. The fractures will open to the extent that seawater will enter and gradually fill the space until there is equilibrium of sea water and LNG with the outside water level. LNG will continue to vapourise within the space until it has all dissipated into its natural gaseous form.

Wherever gas exists, either in the cargo tank, the inner hull space or the outside atmosphere after such a breach, oxygen will mix with the gas and will have parts within the flammable range. The temperature inside the cargo tanks will be very low and the atmosphere may not be able to support combustion (through lack of oxygen). However, inside the inner hull and certainly outside the hull, the gaseous mixture will be capable of being ignited.

The occurrence of a confined explosion in the inner hull space is dependant on the time of ignition but overall it is thought to be extremely unlikely. If there is an internal ignition source immediately after loss of containment then an explosion could occur, but would be local to the confined area only. If immediate ignition does not occur, then the large amounts of vapourised gas would purge the inner hull space of a flammable air mix thus preventing internal ignition to taking place. Ignition can then only take place external to the ship. Finally, internal ignition could occur once most of the LNG has vapourised or burnt off. This is because at this stage out flow is so low that air could enter the inner hull space. However, due to the earlier surplus of vapourised LNG in the inner hull spaces, ignition sources would be limited.

If ignited in the open there will be a deflagration type explosion as all the flammable mixture is ignited and the flammable gas will continue to burn until all gas is consumed.

If ignition takes place within the inner hull there is likely to be a detonation type explosion. Early ignition prior to brittle fracturing taking place would cause damage to the ship structure depending on its location. There is also the possibility that, with a large release, brittle fracturing could occur prior to an early ignition. Taking place in a confined space the forces acting upon the tank sides, already weakened by fractures, will be severe. The structure will collapse further exposing the liquid gas inside the cargo tank. Also the explosion will collapse the structure beyond the ends surrounding adjacent cargo tanks. This structure has already fractured, but although still secure, it will not be able to withstand the blast and the adjacent cargo tanks will likely be opened thereby releasing more liquid gas into the structure. With further ignitions and explosions following, the ship would then become a total loss with a continuous fire that would be inextinguishable until all gas has been consumed. **It should be**

noted that although theoretically possible this event is considered difficult to achieve and hence highly unlikely.
This would likely be the case of a ship at berth. If the ship were at sea then it is unlikely that the gas cloud would ignite, and the ship would likely remain relatively intact.

3.4 Structural Response – LNG Single Containment Storage Tank

3.4.1 Structural Description

The single containment LNG storage vessel design is a short cylinder with a double wall steel tank designed and constructed so that only the inner tank wall (9% nickel) in contact with LNG has the mechanical properties required to contain the cryogenic liquid and a carbon steel dome shaped roof with an insulated suspended deck. The outer carbon steel tank wall has the primary functions to contain cool methane gas, provide support for the steel roof and to resist wind and normal external loadings, and additionally functions as an insulation container. The space between the inner and outer tank walls will be filled with loose fill insulation. The tanks will be constructed at ground level and a heater provided in the foundation to prevent frost heave. The diameter of the storage vessel is approximately 78m inner and 80m outer with a height of approximately 42m. The storage vessel will be designed for a maximum liquid head of 38m. The three tanks are located in individual 200m x 200m diked impounding areas with 6m high walls. The dikes have been designed to CSA requirements. A schematic is given in Figure 3.3.

3.5 Immediate Structural Consequences - Storage Tank

Three modes of terrorist attack have been identified and discussed in the Sections below.

3.5.1 Single containment outer wall only is breached

Where the single containment outer wall only is breached, cool (>-29^{o}C) methane gas will be released from the loose fill insulation to the environment. The initial driving force for this release is likely to be a small positive pressure differential of between 100 to 140mbarg (maximum design pressure is 180mbar) between the LNG tank's inner space (above the suspended deck) and the external atmospheric pressure with some resistance provided by the loose insulation. Provided the insulation between the carbon steel outer tank and the inner containment is not extensively damaged then a localised breach of the outer tank is very unlikely to result in a significant increase in the LNG boil-off rate and corresponding release rate from the hole in the tank wall. The LNG boil-off rate and gas release rate will increase progressively with the extent of damage to the insulation and therefore exposure of the extremely cold inner containment to atmospheric conditions. There is a risk of a flammable gas mixture forming in the insulation in the vicinity of the release. It is highly unlikely that there will be ignition sources of sufficient energy to present an explosion risk.

If the outer wall is fractured but not breached, it is possible for a fire outside the storage tank caused by the detonating explosive charge to immediately ignite the escaping methane gas. However, the small rate of gas release is unlikely to be sufficient to sustain a continuous burning fire at the point of damage. Depending upon the severity of the fire there is likely to be moderate heat induced distortion to the carbon steel tank wall in the vicinity of the damage, however, this is not considered likely to structurally impair the inner containment.

Assuming that the gas release does not ignite, a small cool methane gas cloud will be formed initially close to the point of release. The size of this cloud will be dependent upon a number of factors such as the extent of the breach or the damage to insulation, tank pressure differential, etc. It would not be a significant release and would be no worse than the releases identified and assessed in Section 2.

3.5.2 Single containment outer & inner wall is breached

Where the explosive charge is sufficient to breach both the outer wall and inner containment simultaneously, there will be a major release of LNG from the LNG storage tank to the environment. Water is not likely to be present within the LNG storage tank internal spaces therefore the risk of damage due to the effects of Rapid Phase Transition (RPT) events can be neglected. RPT effects external to the tank are likely if the released LNG makes contact with large areas of residual water (pooled rainwater), however, the impact of such an event on the LNG tank and surrounding structures is expected to be minimal.

The proposed single containment storage design will comply with the requirements of CSA Z276-01 and specifically Section 4.2.2 with respect to the provision of dikes, impounding walls and sumps. Any large scale LNG release as a result of a failure of the outer wall and inner containment will be contained by the dike producing a maximum pool size of boiling LNG.

The hazards are associated with the effects of either a delayed or an immediate ignition, and the thermal impact of a very cold gas release. Based on the above contained (diked) LNG spill the consequence assessment given in Section 4 will consider a methane cloud that disperses and is ignited beyond the remote LNG storage facility bounds and a LNG release that is ignited within the confines of the terminal dike.

LNG remaining within the tank will continue to vaporise at a rate that will be governed by the thermal gradient between the inner tank space environment and the external environment (will be greater if burning LNG external to the tank is radiating heat back towards the tank). Towards the end of the vaporisation cycle, there is a significant risk of oxygen entering the tank and forming an explosive mixture. Hot structural materials or smoldering combustibles from the initiating fire event may well ignite the mixture with the risk of a confined explosion. This will be limited in size due to the reduced amount of LNG present. There is a risk that the tank will collapse due to the excessive heat weakening the structure prior to all LNG being released.

An LNG pool fire in one of the diked impoundment areas will generate radiation levels that will impact on adjacent storage tanks. Due to sump drainage after an LNG spill and the radiation from the burning LNG pool the duration of a pool fire is not considered to be significant to have an affect on the integrity of an adjacent tank. There may be a nominal increase in boil-off rate, however, this is expected to be handled safely by the LNG tank venting system.

3.5.3 Single containment domed roof is breached

It is possible for the carbon steel roof of the LNG tank to be damaged by an "in contact" explosive device and for the inner insulated suspended deck containment to remain un-damaged. As a consequence of this event cool methane gas will be released from the dome space to the atmosphere reducing the space pressure close to that of atmospheric conditions. If not ignited by the initiating event the cool methane gas will be buoyant and rise vertically upwards. As the insulation remains undamaged in this scenario the LNG boil-off rate will remain relatively unaffected and the amount of methane gas generated will be limited and not considered sufficient to support combustion.

Catastrophic failure of the carbon steel roof will result in collapse of the roof and the supported insulated suspended deck into the LNG tank. The LNG in the tank will be displaced to the atmosphere in a violent manner initially producing a cloud of extremely cold vaporising LNG and a limited amount of LNG aerosol. The LNG remaining within the tank will continue to boil vigorously and produce a steady state cloud of methane gas. The main hazards associated with this scenario are: methane cloud disperses and is ignited beyond the LNG Terminal bounds or the LNG release is ignited within the confines of the Terminal. The ignited gas cloud will flash back to the release source resulting in a tank fire and a fire within the diked area if LNG is released to form a pool.

3.6 References

[3.1] Century Dynamics, 1998 "Autodyn theory manual-revision 4.0" Published by Century Dynamics.

3.7 Conclusions – Structural Damage

Loss of the LNG ship containment may occur through shock mechanism's caused by small amounts of explosive. There may not be a visible hole so the release to atmosphere would be minimal during the early stages of an incident. The amount of explosive required is difficult to predict.

There is a possibility of escalating failure of the LNG ship's structure due to embrittlement, followed by an internal explosion caused by either Rapid Phase Transition (RPT), or by a flammable gas-air mixture being ignited. This is difficult to achieve and hence extremely unlikely.

A missile or explosion will leave a large number of ignition sources near to the damaged containment. This could result in early ignition.

There is a possibility of an internal ignition immediately after an attack. This is likely to be limited to a localised ignition close to the hole.

No RPT event is expected within a single containment storage tank structure.

There is the potential for a small scale confined vapour cloud explosion within a single containment storage tank once most of the LNG has been burnt and oxygen is allowed to enter the tank but with limited chance due to the reduced LNG content.

It is very likely that a single containment storage tank will collapse prior to all the LNG being released through a 1m diameter hole.

An attack resulting in loss of containment will cause an LNG to pool to form within the diked area of an LNG storage tank or around the hull of an LNG ship at the Terminal Jetty.

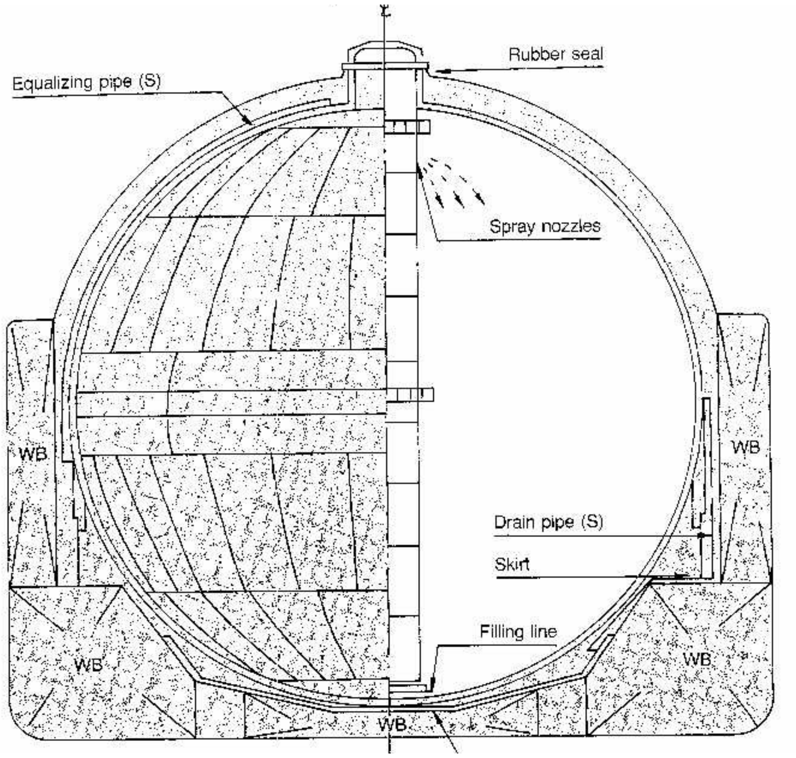


Figure 3.1 : General overview of an Moss Rosenberg type LNG Ship Structure

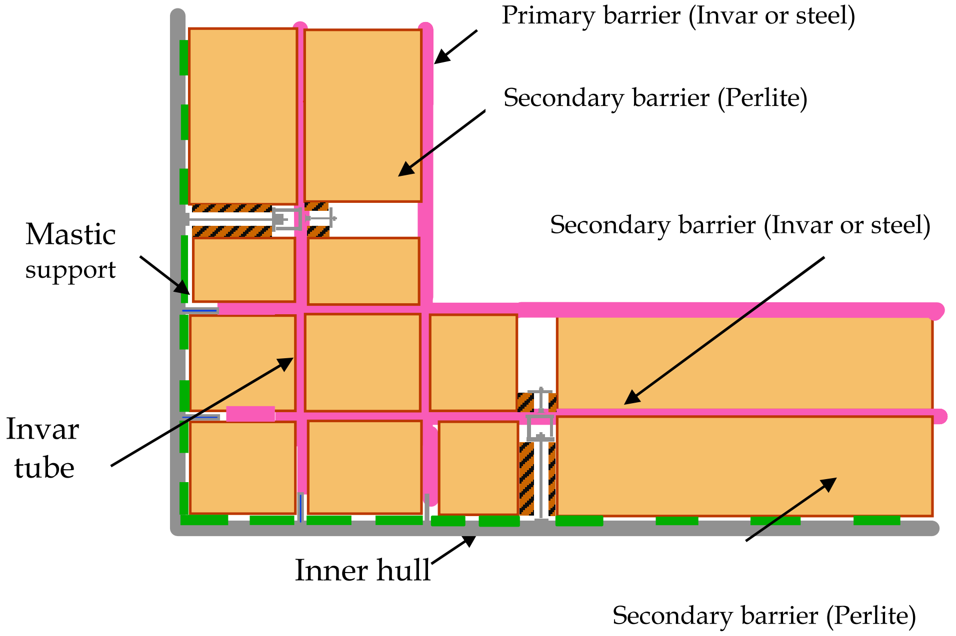
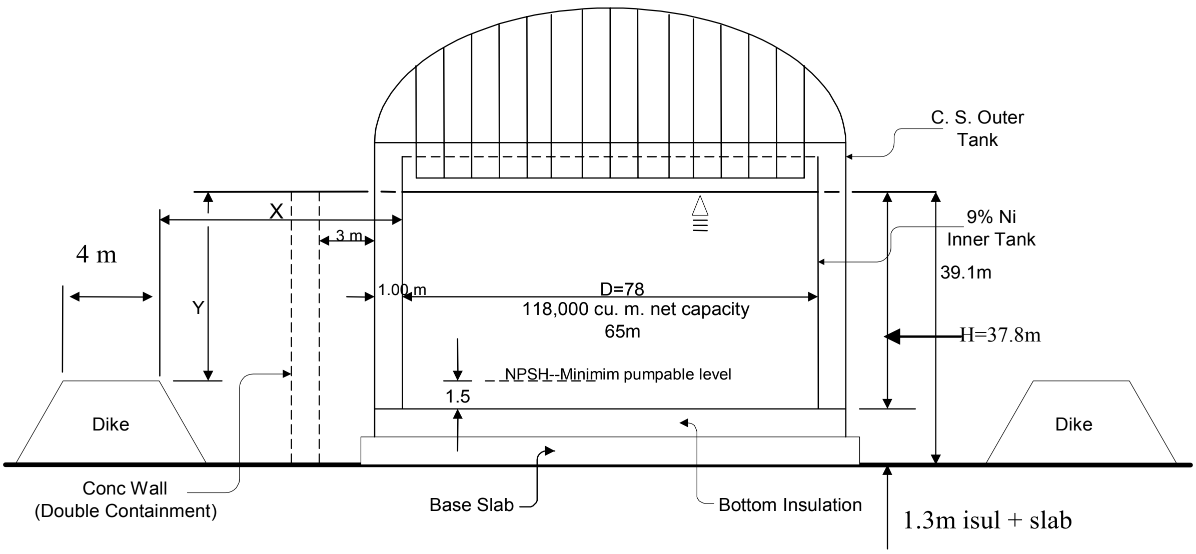


Figure 3.2: Typical Section of LNG Membrane Tank Insulation



NFPA 59A Fig. 2.2.2.6
Dike Proximity to LNG Tank

Figure 3.3 Detail for Single Containment LNG Tank with Dike Arrangement

4 EXPECTED RELEASE SCENARIO AT THE BEAR HEAD TERMINAL

Section 3 has presented evidence that an attack on a single LNG containment storage tank(s) and an LNG ship following a terrorist attack could lead to a release of the LNG contents.

This Section describes the subsequent consequences that would be expected to occur given a release caused by a terrorist attack. The Appendices provide knowledge gained from various historical, experimental and theoretical analyses of LNG releases, upon which the following failure process has been based.

These findings are based around an expected worst case scenario. Although other scenarios can occur the worst case is being used here as a basis for consequence evaluation.

The worst case is described in Section 4.2. The hazardous footprints for the radiated heat for the Terminal are shown in Figures 4.3 to 4.5 for the terminal case and 4.7 for the ship case.

4.1 Overview of Appendix A1: Review of Marine and Storage Tank Incidents

A review of the marine incidents for LNG carriers involving the loss of containment during loading, transportation and discharging confirms a good safety record. The rate of serious casualties per ship year for LNG carriers is approximately one half of that for other liquefied gas carriers. In addition the nature of the incidents involving LNG carriers were minor compared with those for other vessels.

In the incidents that have been reported there has been no loss of life, damage to land-based property or harm to the environment and on each occasion the LNG has dispersed without igniting. Even in the two grounding incidents where bottom damage has occurred, there was no release of LNG.

There are a number of design factors that have minimised the consequences of these incidents. These include:

- double hull protection;
- containment systems specifically designed for the transportation of LNG at very low temperatures; and
- transportation at atmospheric pressure.

Until the very recent fire/explosion incident at the Skikda LNG Terminal in Algeria on the 19th January 2004 only four LNG Terminal incidents have been identified worldwide over a period of 38 years of operational experience. These incidents have been small releases of LNG from LNG storage tanks and/or process systems/facilities. None of the four incidents involved a major failure of an LNG storage tank and/or the associated process systems.

Although the Skikda LNG Terminal fire and explosion incident has dented the good safety record of the LNG industry it should be noted that according to information from a reliable source the particular incident involved LNG technology dating back to the 1970s. The regulatory requirements and standards for production, storage, and handling of LNG has changed significantly since the early days of LNG production, for this reason with the exception of the Skikda incident only recent years present a true picture of how well the industry can minimises risks. However, full conclusions cannot be made until the Skikda enquiry is complete.

4.2 Overview of Appendix A2: Release Consequences – LNG Experiments

Much of the experimental work associated with LNG was carried out by the LNG industry in the 1970's and 1980's. Experiments were undertaken to gain a better understanding of the behavior of cold dense gases when released from containment. A further objective was to study the combustion characteristics of LNG vapour. The results from the experiments were used in the validation and development of computational methods for predicting the behavior of these substances. There was also a need to confirm the feasibility of jettisoning cargo safely if required.

The tests concentrated on vapour cloud dispersion, vapour cloud ignition, pool fires and Rapid Phase Transition (RPT) events, i.e. the instantaneous change from liquid to vapour. The tests have shown that following a release, without ignition:

- LNG vaporises rapidly to produce extremely cold methane gas;
- cold methane gas forms a dense low lying cold gas cloud;

- gas cloud warms, expands due to mixing with the surrounding atmosphere and becomes lighter than air; and
- buoyant gas cloud then disperses safely.

The Lower Flammability Limit (LFL) for methane-air mixtures is 5% by volume so the LFL boundary is well within the visible white water vapour cloud formed by the extremely low LNG vapour temperature.

RPT events can occur if the LNG comes into contact with water. This phenomenon has an associated localised overpressure with no associated flame front. RPT events will not ignite the gas cloud, but could cause damage to the ship or machinery through localised overpressures.

Tests have shown that should an unconfined methane cloud ignite it will not detonate. A confined methane cloud will detonate, however, the effects of the detonation may be limited to the confined area only or missiles may be projected over a large distance. Such a confined detonation does not cause the unconfined methane cloud to detonate.

From one series of seven tests only one burnt back to the source of the release following ignition, and in two tests the cloud extinguished completely. These tests have indicated that if ignited it is unlikely that combustion will be sustained throughout the whole gas cloud.

These tests must be placed into context with the situation after an explosion or missile strike. There are likely to be many sources of ignition in the vicinity of the LNG ship and LNG storage at the Bear Head Terminal. These sources of ignition are highly likely to cause a methane gas cloud to ignite. Although the combustion may not burn back to source, it is likely that the sheer size of a catastrophic spill, along with the number of local ignition sources will cause multiple ignition events of the flammable gas cloud. It is expected that at least one ignition event will burn back to the source causing a pool fire to develop.

4.3 Overview of Appendix A3: Release Consequences – Theoretical Models

Within the public domain, risk analysis models have been successfully developed to consider the outcome of significant incidents and to place them in perspective with other, lesser incidents. These models are required as it can be difficult to extrapolate the behavior of large-scale releases purely from small-scale experimental work.

Major LNG releases may follow a deliberate damaging action. The largest release scenario may be characterised by the release of the contents of a single storage tank. For average conditions, a flammable methane cloud could extend several kilometres and if ignited could result in almost total fatalities within the flammable gas cloud footprint. However, the likelihood of the cloud extending that far before igniting is extremely remote, particularly with the high likelihood of residual ignition sources directly resulting from the initial explosion or missile strike.

Thus the theoretical distance is not relevant due to early ignition. As such no single value or model of dispersion ranges has been specifically used in this analysis. Instead it has been assumed that a gas cloud produced from a release through a 1m diameter hole, or from a catastrophic failure has the potential to cover a large area of the Bear Head Terminal and surrounding areas. This assumption is well within the suggested ranges put forward by most major gas dispersion models.

CFD modeling has shown that a release from a single 35,000m^3 cryogenic cargo tank of a 135,000m^3 LNG vessel with a 1m diameter hole would produce an unconfined pool with a maximum area of 25,000m^2, equivalent to a diameter of approximately 180m.

4.4 Expected Worst Case Release Scenario

It can be expected that the release of LNG following a terrorist attack against a land based LNG storage tank or an LNG ship could at worst involve a release of up to 170,500m^3 at the storage site (based on a single containment LNG tank) and 35,000m^3 at the LNG ship (based on the failure of a single LNG cargo tank). If these are taken as the worst case scenarios then the following principal points can be drawn about the consequences and their immediate effect on the Bear Head Terminal and surrounding area.

In the case of the single containment LNG storage facility all release scenarios will be contained by the diked containment system. For the LNG ship case there is difficulty in predicting exactly where any released LNG may flow to within the Terminal Jetty area.

This has led to the following assumptions:

- when calculating unconfined pool sizes pessimistic values should be taken;
- storage tank releases are limited to the dike dimensions for both catastrophic releases and 1m diameter hole size releases;
- a pool caused by a 1m hole size release from the LNG ship is limited to the pool size equivalent to that for land, this is pessimistic as the evaporation rate on water is significantly higher than for land;

- a catastrophic release from an LNG ship is not evaluated as it is not thought realistic given the release mechanism for a sinking ship preventing instantaneous release of all contents;
- for the situation of a catastrophic release from the LNG storage tanks or an LNG ship, the final consequences are very similar to that from a 1m diameter hole. For the LNG ship case involving an instantaneous release of all LNG during a catastrophic release, the pool fire will be of shorter duration (faster overall burning rate due to large surface area). The large pool size will also limit the heat generation in comparison with the slow release. The creation of a larger gas cloud makes the likelihood of an early ignition higher due to its larger footprint;
- a missile attack against the storage tanks or the ship at berth is discounted as it would leave a relatively small hole with a low discharge rate, thus preventing a pool from forming. The low discharge rate means that the gas will warm up quickly and disperse upwards into the atmosphere prior to it leaving the Bear Head Terminal similar to the discussion in Section 2 of this report.

In summary, a missile attack against the LNG ship or LNG storage tanks has been discounted due to the limited consequences. A catastrophic release from a ship is difficult to achieve, and impossible to predict. A catastrophic release from an LNG storage tank or an LNG ship is potentially less damaging than a slow release.

Thus the following process flow is specifically for the worst case of failure from a 1m diameter hole caused by an explosive device detonated next to either the LNG ship hull or to the LNG storage tank. All other scenarios have either been discounted or are less severe in consequence.

Initial attack and LNG release:

Initial attack against the storage tank or ship using explosives ;

⇩

Creation of 1m diameter hole in the outer wall of a single containment LNG storage tank/LNG ship hull, with equivalent damage to the inner containment. Some RPT occurring;

⇩

Outflow of LNG. Potential for early ignition at the hole from explosive residue;

⇩

Formation of LNG pool around the base of the LNG storage tank/LNG ship;

⇩

Initial gas cloud formed from immediate evaporation;

Gas cloud travels away from LNG storage tank/LNG ship (assume any potential wind direction);

Gas cloud reaches an ignition source either at the Terminal or beyond depending on the wind direction. A release blown towards Inhabitants Bay may not encounter an ignition source, and would remain as a gas plume.

Wind Direction Causes Gas Cloud to Disperse Towards Inhabitants Bay:

Where a gas cloud does not reach an ignition source whilst crossing Inhabitants Bay, it will continue to travel as a large cold white plume of methane and water vapour until warming causes it to become buoyant and rise away from the surface and away from ignition sources. At this point the methane gas will be sufficiently warm and will exist as an invisible cloud.;

⇩

Un-ignited gas continues to rise until it dissipates into the atmosphere without any hazardous consequences;

Wind Direction Causes Gas Cloud to Disperse Inland Towards Populated Areas:

Gas cloud spreads from LNG tank/LNG ship and is blown in a NW direction towards populated areas;

⇩

Where ignition occurs (from cars, buildings, electrical devices, hot surfaces, etc.), experiments show that this does not always cause burn back to a pool. However, even ignition that doesn't result in burn-back will cause a number of new ignition sources to be created closer to the LNG tank/LNG ship. Unconfined ignition does not cause a detonation, thus there are no damaging overpressures created. It would be expected that ignition sources would occur at the Terminal, preventing the gas cloud from traveling inland populated areas;

⇩

Potential vapour cloud detonations in confined spaces (any buildings at the Terminal surrounded by LNG vapour). Detonations are limited to the confined areas, and are not thought to cause detonation of the larger unconfined vapour cloud;

⇩

Newly encountered or self-created ignition sources eventually cause burn back to the pool;

⇩

Pool fire is developed based on inflow and outflow;

⇩

Radiated heat is produced along with significant amounts of smoke (See Section 4.4 for radiated heat footprint)

⇩

Burning will occur for a period of up to around 15 hours depending on any pooling of LNG and hence exposed surface area. Due to release rates the expected shortest burning rate would be around 1 hour;

⇩

Likely further failure of the LNG storage tank or the LNG ship (from fire, or embrittlement or RPT). Storage tank failure is catastrophic, but with reduced LNG content.

⇩

During burning the pool will reduce in depth until all LNG is burnt or methane gas is evaporated and dispersed.

The footprints the radiated heat will make are defined in Section 4.5 and 4.6.

4.5 LNG Vapour Cloud Plumes

The methane gas cloud could extend in any direction depending on the wind direction at the time of the incident. As described in Sections 4.2 and 4.3 above there is a wide variety of opinion on how far a methane gas cloud could potentially travel following evaporation from a release of LNG.
Any offsite building or major road would probably contain ignition sources of sufficient energy to ignite the cold LNG methane gas. Although the electrical equipment at the Terminal is designed to be intrinsically safe there are still likely to be a significant number of such sources at the Terminal itself such as the administration offices, etc. It has been assumed that there are sufficient ignition sources surrounding the LNG ships/LNG storage tanks (cars and buildings, etc.) to cause ignition before the gas cloud travels beyond the Terminal.

A release from the LNG ship could result in a gas cloud drifting in one of two directions. Firstly it could drift over the Bear Head Terminal. In this case the gas cloud would ignite due to a significant number of ignition sources in the area. Alternatively the gas cloud could disperse beyond the Terminal towards Inhabitants Bay, probably resulting in delayed ignition or no ignition at all and an associated long plume over the water. Calculations using gas dispersion software have indicated that a 2.5% (½ LFL) gas cloud from a spill through a 1m diameter hole would extend several kilometers over the water. For reasons described earlier, the length of the plume is not important in calculating the risk from a terrorist attack.

It is likely that potential fatalities from gas cloud dispersion and associated ignition will be limited to the Bear Head Terminal. Depending on the wind direction, there will be a variety of Terminal personnel exposed.

The historical wind directions [4.2] are taken from the Atmospheric Environmental Services AES40 Data Set. These data are the results of a wind and wave analysis/hind cast and consist of time series of 6 hourly data over a 42 year period (1958 to 1999). AES40 winds represent 1 hour averages at a height of 10m above sea level. The closest AES40 grid point to the Bear Head Terminal is grid point 5394 (45N, 60.83W).

An annual wind rose for this grid point is given in Figure 4.11 along with the map showing the AES40 grid location.

Wind Direction	Percentage Occurrence
N	9.5%
NE	6.7%
E	6.2%
SE	7.6%
S	12.8%
SW	21.4%
W	19.5%
NW	16.2%

The AES40 wind rose does not specify the number of calm days therefore it is concluded that as a % occurrence calm days must be very small for this region. The predominant wind directions are from SW and W with % occurrences of 21.4 and 19.5 respectively. Winds from the W will direct a gas cloud towards Inhabitants Bay (shown in Figure 4.11) and from the SW will direct a gas cloud towards Richmond County but away from heavily populated Port Hawkesbury.

These wind directions can be translated into the expected number of exposed personnel at an incident. This is based upon an estimated population density for personnel at the Bear Head Terminal at the time of an incident and in occupied buildings beyond the Terminal area. A typical LNG Terminal may have 50 to 70 daytime personnel and 20 to 40 night time personnel. The estimation of the number of people within a 10km radius of the Terminal is based upon correspondence LR/JWE, however, Figures 4.1 and 4.2 show the area around the proposed Bear Head Terminal to be wooded and uninhabited. The nearest populated area is the Statia Oil & Gas Trans-shipment Terminal approximately 2½km from the Terminal which has 80 employees over a 24 hour period. At a distance of 5km from the Terminal there is the Exxon Mobile Canada natural gas processing plant and the Novia Scotia coal fired generating plant involving 150 employees over a 24 hour period. The Stora Enso pulp and paper mill, which has 800 employees over a 24 hour operation, is approximately 6¼km from the Terminal. The Town of Port Hawkesbury is approximately 6.7km from the Terminal and has a population density of 1425 per km^2. Based on this information an estimation has been made of the day and nigh time populations affected by winds blowing from the following directions.

For a gas cloud dispersing from an LNG spill towards a populated area; as soon as it comes into contact with a populated area it will be exposed to numerous ignition sources. With so many sources it is likely that the edge of the cloud will soon ignite and burn back to cause a pool fire. It will not be continuously burning over large populated areas, it will be burning at the source of the pool. For a gas cloud spilling into an unpopulated area such as at sea,.the cloud will not meet many sources of ignition so it will continue to drift until it warms up enough to disperse naturally into the atmosphere. The cloud doesn't meet any populated areas so doesn't cause any major harm

There are no small towns or communities within approximately a 2.5 km distance from the perimeter of the Terminal. On this basis public exposure is expected to be extremely small. The only likely exposure in this zone will be individuals using the Bear Head Cove public road close to the Terminal.

4.6 Radiated Heat Modeling

Trinity Consultant's (BREEZE) HAZ Professional software has been used to model pool fires and the associated radiated heat following the ignition of an LNG gas cloud.

The single containment LNG storage tanks at the Bear Head Terminal will be protected by dikes designed to contain LNG in the event of a major or catastrophic tank incident. The size of a potential LNG pool is therefore fixed, however, the rate of LNG accumulation within the diked area is dependent upon the rate of release of LNG into it, the rate of evaporation of LNG from it, and any losses due burning of the LNG itself. For a 1m diameter hole the rate of release of LNG into the diked pool is initially moderately high due to the storage hydrostatic pressure head. This release rate drops progressively as the hydrostatic pressure head falls.

Thus initially the pool size will increase within the diked area as the inflow of LNG is greater than the outflow due evaporation and/or burning and at some point the diked area will become flooded with LNG. Inflow of LNG into the diked area will continue until there is no appreciable difference in level between the damaged LNG tank and bunded area (worst case with hole close to tank base). After this the evaporation/burning process will continue causing the LNG pool size to reduce in depth until eventually the LNG fuel source is exhausted and the fire is extinguished.

As indicated earlier the LNG storage tanks are dike protected with rectangular dimensions estimated to be approximately 200m by 200m. The rectangular pool shape has been used within BREEZE Haz Professional to calculate the potential radiated heat at the maximum distance from the centre of the LNG storage tanks.

The radiation contours for LNG storage tank dike (impounding) fires are shown in Figures 4.3 to 4.5 based on the calculations given in Table 4.1. The confined pool fire radiation vs distance plots for the Terminal tanks are shown in Figure 4.6. In accordance with Section 4.2.3.2.2 of CSA Z276-01 the fire scenarios have been modeled for the environmental conditions of $0.5 ms^{-1}$, $21^{o}C$ and 50%

humidity (note: although CSA Z276-01 stipulates $0ms^{-1}$ wind speed BREEZE Haz Professional like other similar types of software has a minimum wind speed capability of $0.5ms^{-1}$) with radiation distances for 5, 9 and $30kWm^{-2}$. As can be seen in the contour plots for each of the LNG storage tank dikes, the respective $30kWm^{-2}$ radiation contours (red) do not extend beyond the Terminal boundary. Both the $5kWm^{-2}$ and $9kWm^{-2}$ radiation contours (green & yellow) in Figures 4.3, 4.4 and 4.5 are shown to extend beyond the Bear Head Terminal boundary. The two radiation flux levels extend 486m and 351m respectively from the three inland facing dike walls closest to the Terminal perimeter.

The radiation contours for an LNG ship event are shown in Figure 4.7 based on the calculations given in Table 4.2. The confined pool fire radiation vs distance plots for the LNG tanker case is shown in Figure 4.8. CFD modeling for a release from a $35,000m^3$ LNG cargo tank has shown the maximum LNG pool size diameter to be in the region of 180m (centred at a point 90m from the LNG ship side) for a below water level release. This pool size has been used in the worst case scenario as a basis for developing a water level pool fire.

Typical radiated heat levels vs time to pain (taken from API 521) are shown in the Table below. An individual exposed to a thermal flux of $5kWm^{-2}$ will experience pain after a period of 16 seconds.

Radiated Heat (Kw/m^2)	Time to Pain (s)
1.74	60
2.33	40
2.9	30
4.73	16
6.94	9
9.46	6
11.67	4
19.87	2

The nearest industrial operations/developments to the proposed Bear Head Terminal are several kms away (Section 4.5 above), the nearest being the Statia Oil & Gas Trans-shipment Terminal at a distance of 2½km. Highway 105 passing through Port Hawkesbury and Port Richmond is sufficiently distant not to be affected by the Terminal dike pool fires. Information sources provided for this study do not identify townships of any size within this same distance. There is, however, the Bear Island Road (Figure 4.1) that passes very close to the proposed Terminal and provides access to Bear Island Cove, however, use is likely to be infrequent. At present there appear to be no other land use planning developments planned for the area close to the proposed Bear Head Terminal.

The fire events developed above under current land use planning arrangements have negligible offsite public impact.

The radiated heats from these large pool fires appear low when compared to the small scale tests described in Appendix A2. However what is being seen is the reduction in radiated heat that is experienced with large fires due to smoke generation. The rate at which this radiated heat changes with pool size is shown in Figure 4.6. Although smaller pool sizes create larger heat, their size means that the point at which radiation occurs is closer to the initial storage tank location.

4.7 Conclusions

There are a number of conclusions that can be reached for a terrorist attack. The following conclusions are the main points that can be drawn and represent events that would be common to most scenarios.

A wind blowing from a SE direction will tend to blow an un-ignited gas cloud about 2.1 km (to ½ LFL) distance in the direction of Port Hawkesbury. However, since Port Hawkesbury is about 6.7 km away from the terminal it will not present any danger to the public. Besides that, given the potential number of ignition sources at the Terminal this cloud is very likely to be ignited by any one or more of these ignition sources. The resulting flash fire is not likely to extend much beyond the bounds of the Bear Head Terminal.

There will be no detonation type overpressure events that will effect the general public.

Detonations would be limited only to confined areas within the LNG Terminal.

The radiated heat from an ignited release, from an LNG storage tank into the tank dike, will reach a value of $30kWm^{-2}$ at a distance of 154m, $9kWm^{-2}$ at a distance of 351m and $5kWm^{-2}$ at a distance of 486m from the perimeter of the tank dike. In the case of the $30kWm^{-2}$ scenario the thermal hazard range is within the Terminal perimeter, however, for the $9kWm^{-2}$ and $5kWm^{-2}$ scenarios the thermal hazard ranges extend beyond the Terminal perimeter.

4.8 References

[4.1] "Frozen Fire – Where Will it Happen Next", Lee Niedringhaus Davis, Friends of the Earth.

[4.2] "Overview of Physical Oceanographic Conditions near Bear Head" Coastal Ocean Associates Inc, December 2003.

Figure 4.1 Ariel View of Bear Head Area Showing Proposed Terminal Location

Figure 4.2 View Across Strait of Canso Towards Bear Head & Inhabitants Bay

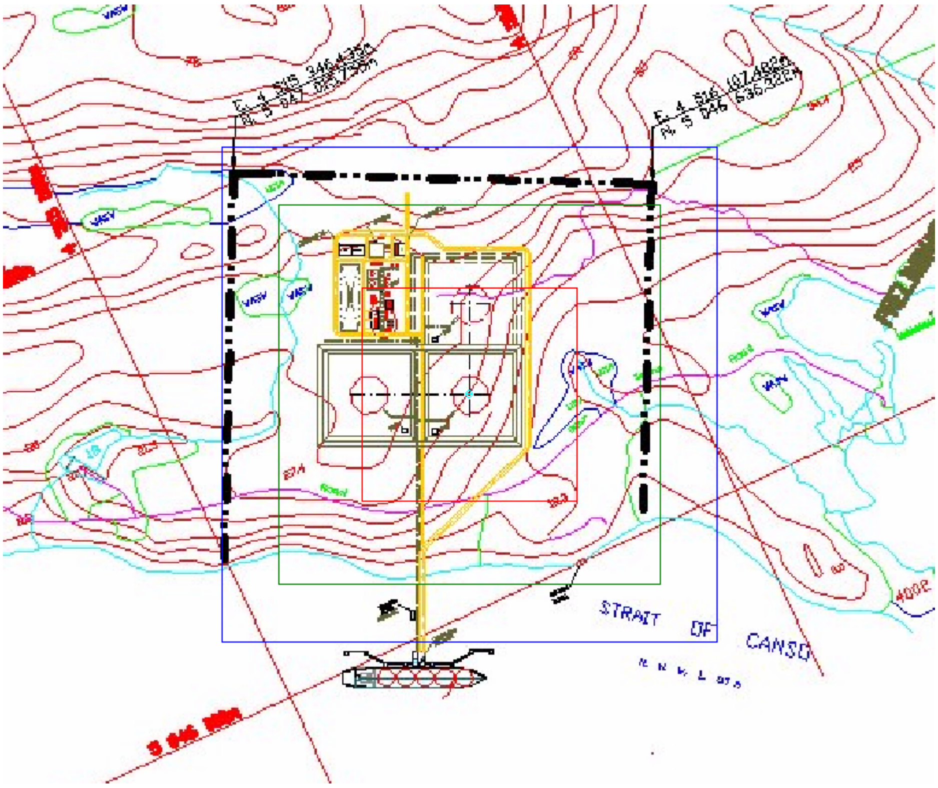


Figure 4.3 Confined Pool Fire Radiation Contours for South LNG Tank

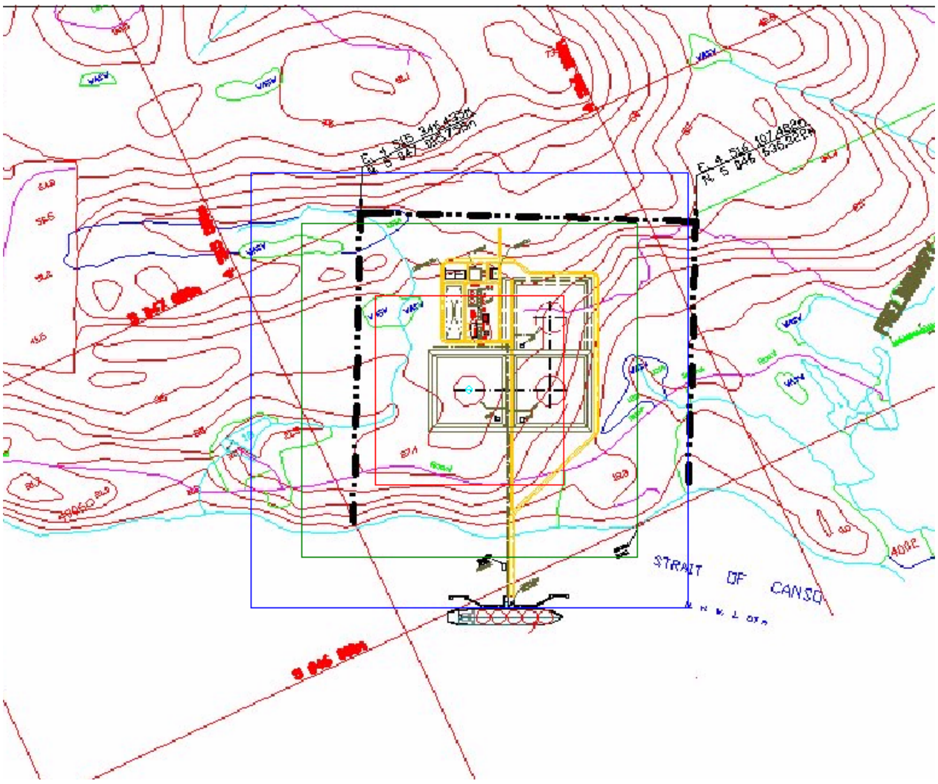


Figure 4.4 Confined Pool Fire Radiation Contours for West LNG Tank

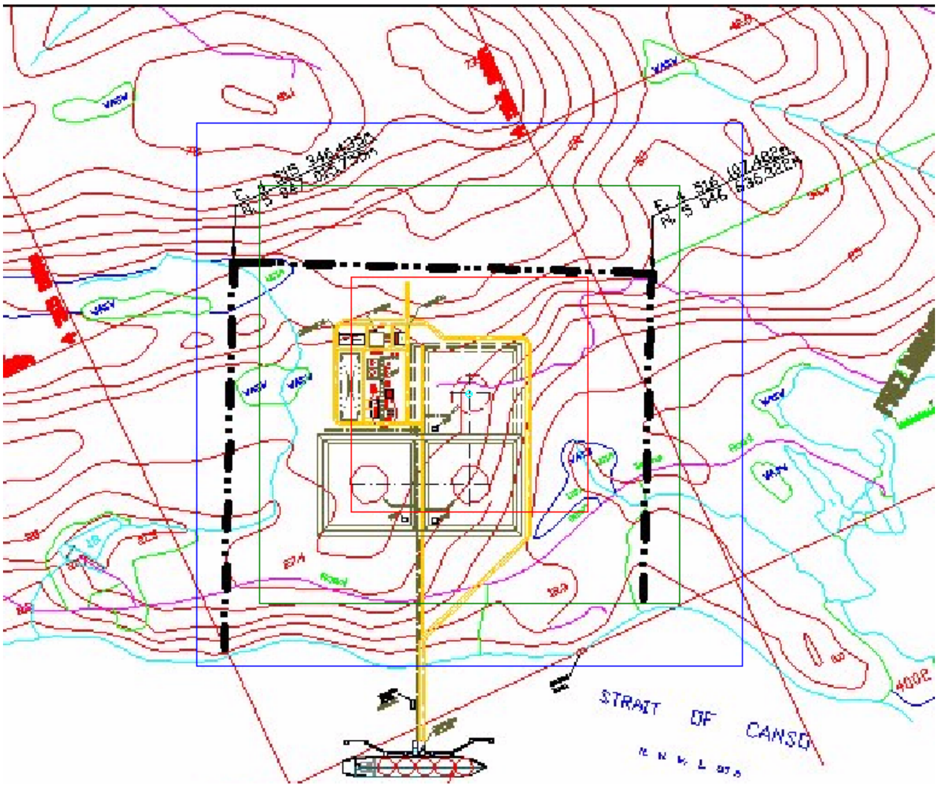


Figure 4.5 Confined Pool Fire Radiation Contours for East LNG Tank

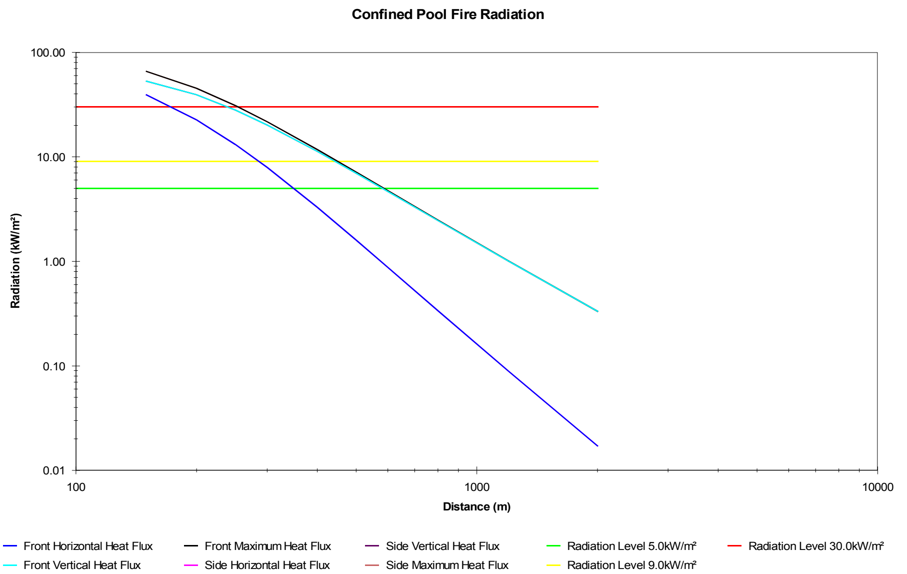


Figure 4.6 Confined Pool Fire Radiation vs Distance Plots for Terminal Tanks

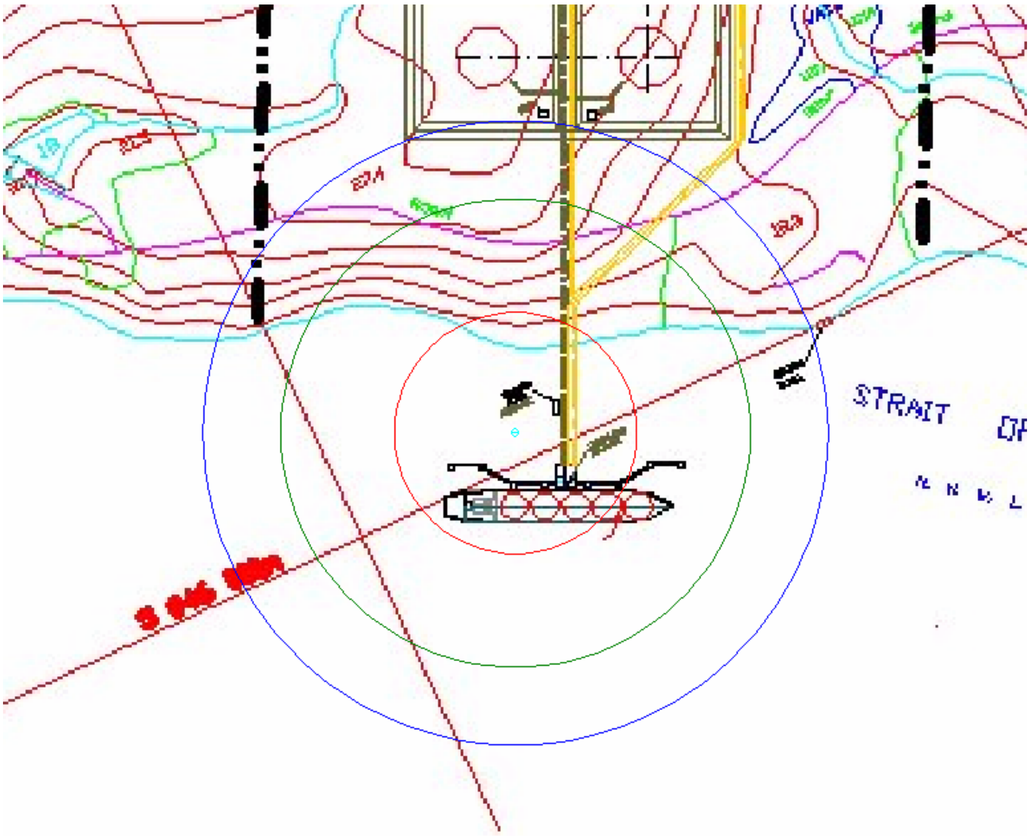


Figure 4.7 Pool Fire Radiation Contours for LNG Tanker Release

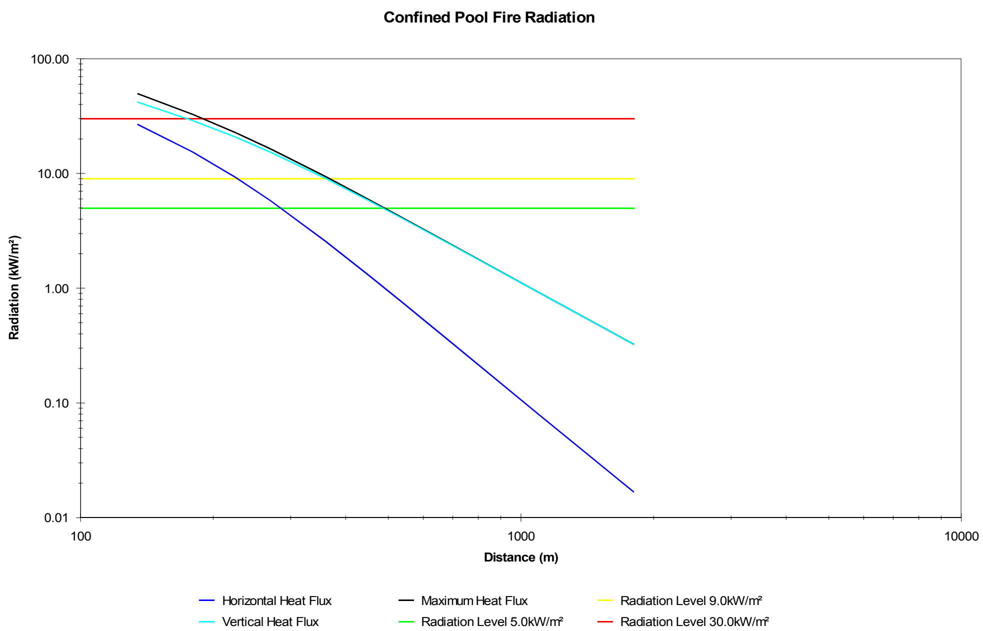


Figure 4.8 Pool Fire Radiation vs Distance Plots for LNG Tanker Release

CONFINED POOL FIRE MODEL

RECTANGULAR DIKE FIRE
TRENCH FIRE

```
FUEL
  Name                                    : LNG LIGHT (METHANE)
  Pool temperature                        : -161.55 °C

CONSTANT PROPERTIES
  Molecular weight                        : 16.04
  Boiling point                           : -161.55 °C
  Critical temperature                    : 190.55 K
  Critical pressure                       : 46.0 bar
  Heat of combustion                      : 5.00E+07 J/kg
  Flame temperature                       : 1300 K

CALCULATED PROPERTIES
  Liquid compressibility factor           : 0.004
  Liquid density                          : 475.5 kg/cu m

DIMENSIONS
  Pool width                              : 200.0 m
  Pool length                             : 200.0 m
  Pool Liquid Height                      : 2.0 m
  Height of flame base                    : 2.0 m
  Height for Radiation Calculations       : 0.5 m

LOCAL AMBIENT CONDITIONS
  Air temperature                         : 21.0 °C
  Ambient pressure                        : 1.01 bar
  Wind speed                              : 0.5 m/s
  Relative humidity                       : 50.0%

RESULTS
  Mass burning rate                       : 0.11 kg/m² s
  Flame length                            : 193.83 m
  Flame tilt from vertical (front view)   : 0.0°
  Flame tilt from vertical (side view)    : 0.0°
  Flame drag ratio (front view)           : 1.00
  Flame drag ratio (side view)            : 1.00
  Maximum emissive power                  : 190.0 kW/m²
  Effective emissive power (front view)   : 190.0 kW/m²
  Effective emissive power (side view)    : 190.0 kW/m²
```

Front view (view along dike/trench width)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	254.13
9.0	451.40
5.0	586.23

Side view (view along dike/trench length)

Thermal flux (kW/m²)	Distance from center of pool (m)
30.0	254.13
9.0	451.40
5.0	586.23

Maximum emissive power : 60,230 Btu/ft² hr

Front view (view along dike/trench width)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
150.00	39.14	52.88	65.78
200.00	22.55	39.31	45.31
250.00	13.13	28.01	30.93
300.00	7.93	20.18	21.68
400.00	3.29	11.29	11.76
500.00	1.60	6.98	7.16
600.00	0.88	4.66	4.74
800.00	0.34	2.46	2.48
1,200	0.09	1.00	1.01
2,000	0.02	0.33	0.33

Side view (view along dike/trench length)

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
150.00	39.14	52.88	65.78
200.00	22.55	39.31	45.31
250.00	13.13	28.01	30.93
300.00	7.93	20.18	21.68
400.00	3.29	11.29	11.76
500.00	1.60	6.98	7.16
600.00	0.88	4.66	4.74
800.00	0.34	2.46	2.48
1,200	0.09	1.00	1.01
2,000	0.02	0.33	0.33

Table 4.1 Confined Pool Fire for Dike Scenario Model Results

```
CIRCULAR DIKE OR TANK FIRE

 FUEL
   Name                                   : LNG LIGHT (METHANE)
   Pool temperature                       : -161.55 °C

 CONSTANT PROPERTIES
   Molecular weight                       : 16.04
   Boiling point                          : -161.55 °C
   Critical temperature                   : 190.55 K
   Critical pressure                      : 46.0 bar
   Heat of combustion                     : 5.00E+07 J/kg
   Flame temperature                      : 1300 K

 CALCULATED PROPERTIES
   Liquid compressibility factor          : 0.004
   Liquid density                         : 475.5 kg/cu m

 DIMENSIONS
   Pool diameter                          : 180.0 m
   Pool liquid height                     : 0.5 m
   Height of flame base                   : 0.5 m
   Height for Radiation Calculations      : 0.5 m

 LOCAL AMBIENT CONDITIONS
   Air temperature                        : 21.0 °C
   Ambient pressure                       : 1.01 bar
   Wind speed                             : 0.5 m/s
   Relative humidity                      : 50.0%

 RESULTS
   Mass burning rate                      : 0.11 kg/m² s
   Flame length                           : 180.14 m
   Flame tilt from vertical               : 0.0°
   Flame drag ratio                       : 1.00
   Maximum emissive power                 : 190.0 kW/m²
   Effective emissive power               : 190.0 kW/m²
```

Thermal flux (kW/m²)	Distance From center of Pool (m)
30.0	189.56
9.0	367.63
5.0	489.96

Distance from center of pool (m)	Thermal flux to horizontal target (kW/m²)	Thermal flux to vertical target (kW/m²)	Maximum flux to target (kW/m²)
135.00	26.67	41.38	49.23
180.00	15.33	28.69	32.52
225.00	9.24	20.65	22.62
270.00	5.79	15.28	16.34
360.00	2.57	9.03	9.39
450.00	1.31	5.82	5.96
540.00	0.74	4.01	4.08
720.00	0.30	2.21	2.23
1,080	0.08	0.94	0.95
1,800	0.02	0.33	0.33

Table 4.2 Unconfined Pool Fire for Ship Scenario Model Results

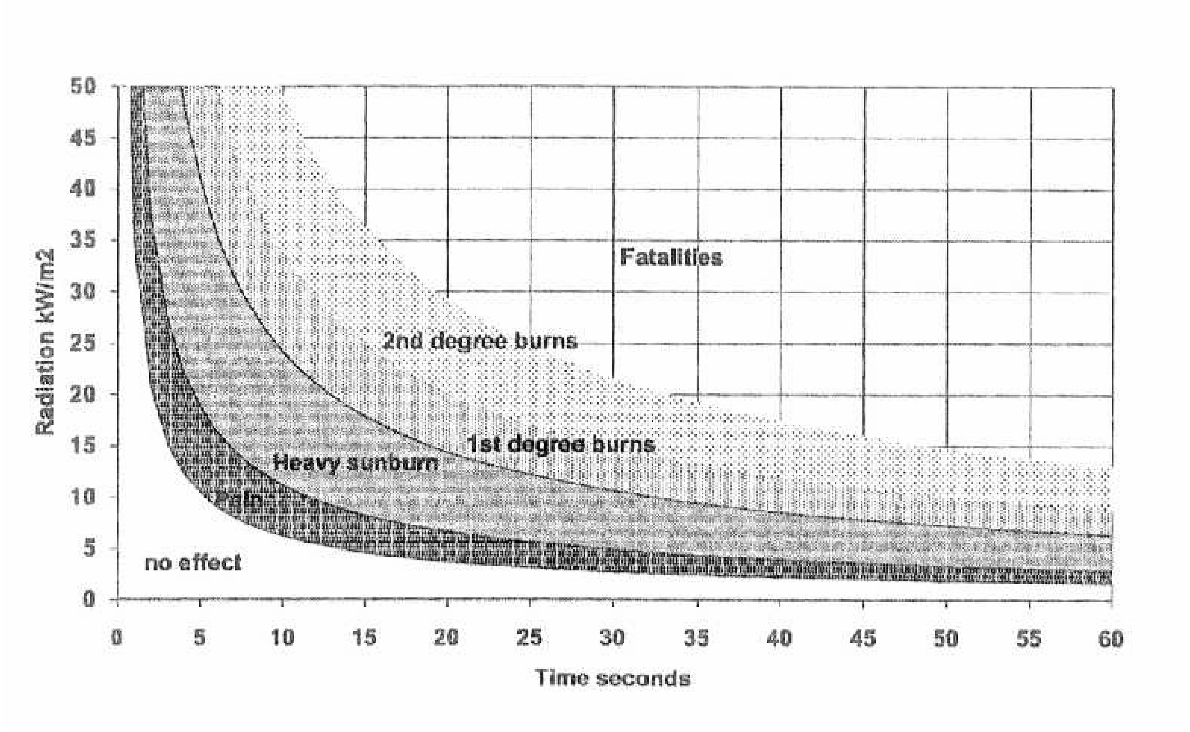


Figure 4.9 : Radiation Effects on Naked Skin

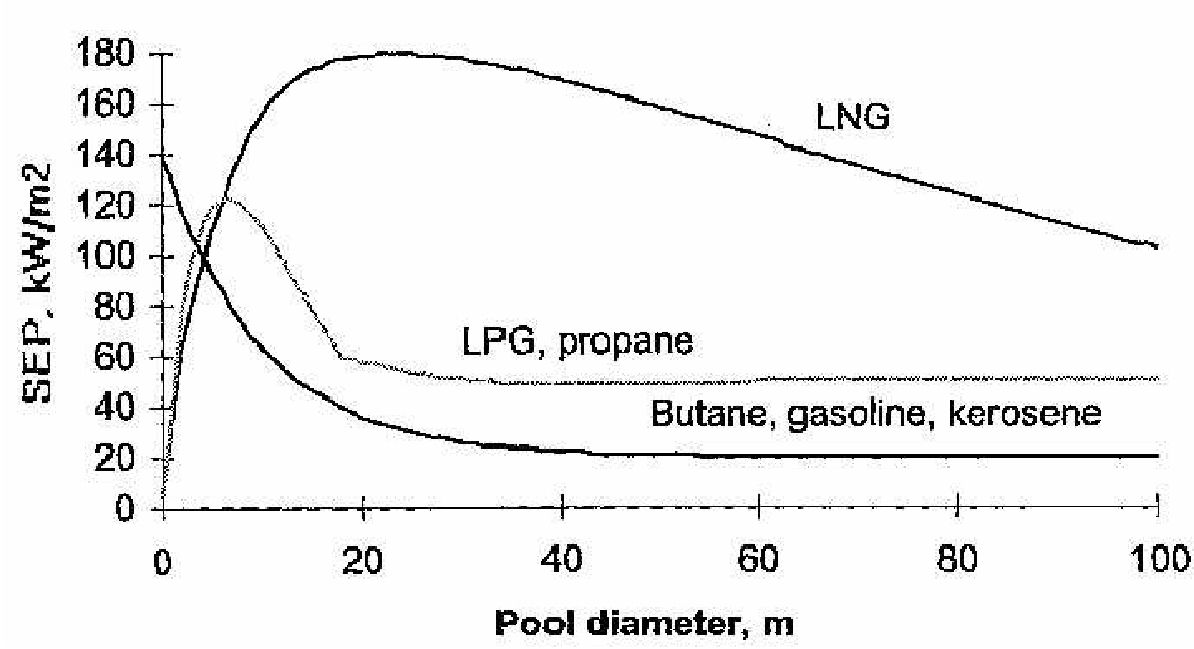


Figure 4.10 : Emissive Radiation Reduction due to Smoke Development

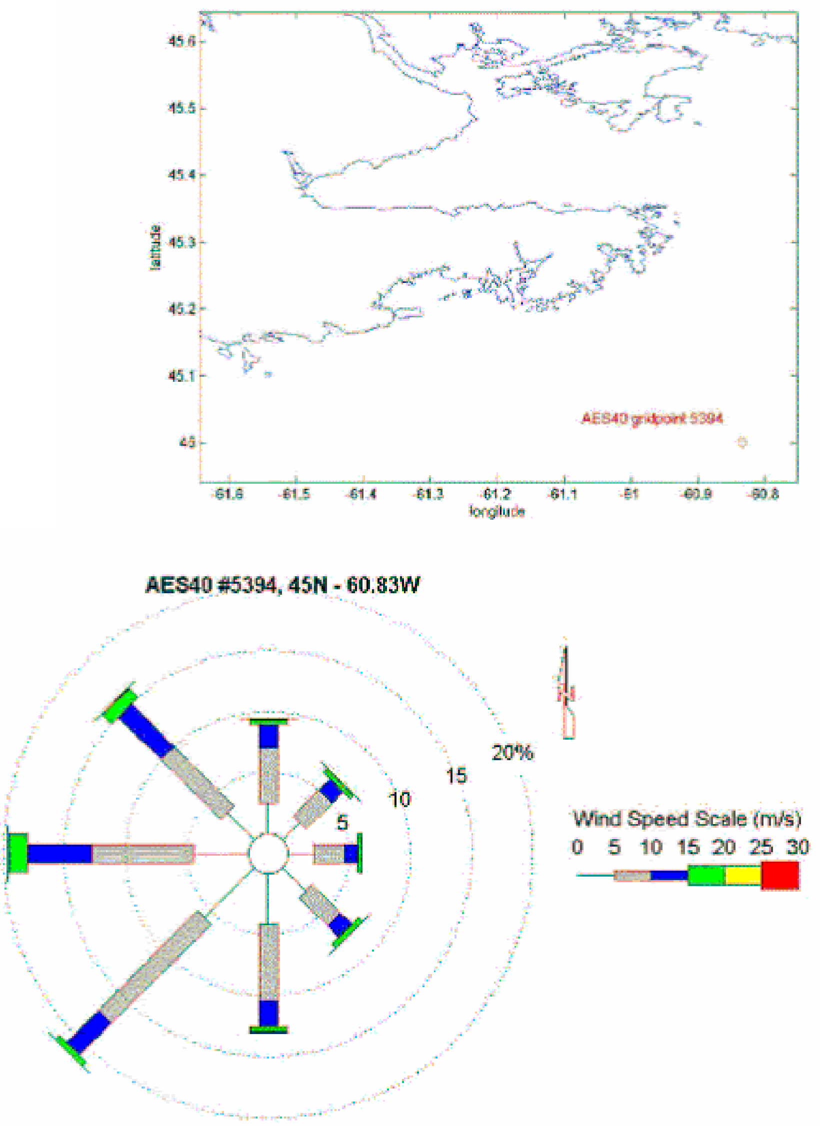


Figure 4.11: Annual Wind Rose for Grid 5394

APPENDICES

APPENDICES CONTENTS

A1 APPENDIX 1: REVIEW OF MARINE INCIDENTS

A.1.1 OVERVIEW

The purpose of this section was to research incidents, including those involving the accidental discharge or spill of LNG, in the course of terminal storage tank containment, tanker loading, transportation at sea and discharge in order to identify any reported human casualties, damage to the environment, and damage to property. For means of comparison similar research has been undertaken into incidents involving liquefied gas carriers for the carriage of cargoes other than LNG. The distinguishing features of these casualties are identified and discussed.

This historical search is a general discussion of the relative merits of the LNG system rather than specific to the threats from a deliberate damaging action. However, this review is relevant in that it provides an indication of two areas:

- Historical evidence of the consequences of actual LNG releases
- Validation on how LNG spills manifest themselves in reality rather than in controlled experiments or theoretical models.

Thus it is important that the evidence of history is evaluated prior to the assessment of the likely consequences of a deliberate damaging action.

A.1.2 SOURCES OF INFORMATION

MHIDAS Database System

The HSE's Major Hazard Incidents Data Service (MHIDAS) is a database that currently holds details of over seven thousands incidents which have occurred during the transport, processing or storage of hazardous materials which resulted in or it is considered had the potential to cause off-site impact. This includes incidents which incurred casualties, required evacuation of either on-site or off-site personnel or caused damage to property or the natural environment, together with incidents which could, but for mitigating circumstances, have led to the above occurring. All the information in the MHIDAS database is taken from public domain information sources and the database aims to collect information on incidents that have occurred world-wide.

Each incident in the MHIDAS database is coded in a standard format to include details such as the hazardous material involved in the incident and the number of fatalities, injuries and evacuations attributable to the incident. A text field is also included in the database giving a brief description of the incident and searches can thus be made both on the coded information and the textual description available for each incident.

The MHIDAS Database has been searched to identify onshore storage terminal incidents. The search criteria included storage, handling, LNG, liquid methane, methane and natural gas. MHIDAS has not been interrogated for detail on the recent fire and explosion incident at Skikda in Algeria.

SEADATA Database System

Reported shipping casualty incidents have been identified by means of LR's SEADATA database system. The system allows access to a comprehensive casualty database containing details of reported serious casualties (including total losses) to all known self-propelled sea-going merchant ships in the world of 100 gross tonnage and above occurring since 1982. In addition, all reported incidents to tankers, including combination carriers and gas carriers since 1976 are included in the database.

As the purpose within this part of this study is to identify incidents to gas carriers active in service, the complete LMIS database has been interrogated in the first instance to obtain all reported casualties to known LNG carriers since 1976. It should be noted that a casualty is defined as an incident in which the condition of the ship suffers adversely. The LNG casualties were manually identified from the descriptive text and codes contained in the database records using SEADATA. The database contains details of the main known ship particulars at the time of the casualty.

SIGTTO Database System

In addition to the above, the Gas Shipping Incident Report as published by the Society of International Gas Tanker & Terminal Operators (SIGTTO) was referred to [Reference A1.7]. This specifically lists all reported incidents to both LNG and non-LNG carriers between 1982 and 1999.

A literature search has also been undertaken to identify operational incidents of accidental discharge not as a consequence of a casualty. Such incidents are reported in References A1.1, A1.2, A1.3 and A1.4.

A.1.3 INCIDENTS INVOLVING LNG TERMINAL STORAGE LOSS OF CONTAINMENT

The incidents of LNG released from storage tanks and associated fittings that have been identified in the MHIDAS literature search [A1.8] are reported here and are summarised in Table A1.4. Incidents not directly associated with terminal LNG storage tanks, i.e. Raunheim in 1966 (LNG released from a vaporiser vent), Montreal in 1972 (compressed methane enters nitrogen system) and Arzew in 1980 (lighting causes failure of two LNG terminal pipelines), have been excluded from this review.

This data search has been limited to incidents occurring since 1965. Although incidents have occurred prior to this date which resulted in significant damage, their design, operation and location are so different from modern practice that they do not form appropriate examples. For example in the Cleveland disaster of 1944 significant damage was caused to the site and surrounding districts. However these districts were particularly close to the incident site and hence were subject to significant damage. Such a close location would not be seen under any circumstances at modern LNG facilities.

Similarly incidents where the storage tank is out of operation (e.g. major maintenance) are also discounted. This is because such incidents, although perhaps linked to the consequences of LNG ignition, are more related to a general structural failure in the immediate vicinity of the site, and hence do not represent a danger to the general public.

Canvey Island, UK (1965): Terminal operators were shutting down a section of piping from one of the above ground LNG storage tanks for the repair of a faulty valve. This required the contents of the LNG tank in question to be transferred to another tank before repair could be started. Whilst removing the faulty valve in the piping LNG was released and ignited. The burning gas was reported to have risen to a height of 10 to 15 feet. A maintenance fitter working at the faulty valve was enveloped in flames and received burns to the face.

La Spezia, Italy (1971): The roll-over phenomenon was responsible for a pressure rise inside a 50,000 m^3 LNG storage tank at the terminal. Excess pressure in the LNG tank was relieved through the vent and safety valves. Approximately 300m^3 of LNG was reported to have been released from the tank during the roll-over incident, this resulted in a cold methane vapour cloud being formed. The methane cloud was blown out to sea without further incident, i.e. there was no ignition of the flammable gas cloud and there were no injuries to terminal personnel.

Canvey Island, UK (1973): Due to a pressure build-up in one of the LNG storage tanks LNG was released from the tank's pressure relief disc. LNG was discharged to a drainage ditch near the tank and containing water. A violent reaction took place when the LNG came into contact with the water in the ditch producing an RPT type incident. There was no ignition of methane gas released during the incident. Effects of the RPT were felt up to a mile away from the centre of the incident.

Cove Point (1979): An explosion occurred within an electrical substation at Cove Point. LNG leaked through an inadequately tightened LNG pump electrical penetration seal, vaporised, passed through 200 feet of underground electrical conduit, and entered the substation. Since natural gas was never expected in this building, there were no gas detectors installed in the building. The natural gas-air mixture was ignited by the normal arcing contacts of a circuit breaker resulting in an explosion, which killed one operator in the building, seriously injured a second and caused about $3 million in damages. The Cove Point Terminal had been designed and constructed in conformance with all appropriate regulations and codes.

Skikda (2004): The explosion at Sonatrach's Skikda LNG Export Plant in Algeria, which reportedly killed 27 people and injured a further 74, is reported to have originated in a boiler that produces the steam necessary to run the main turbine associated with train 40. Early reports suggested that it occurred when plant personnel attempted to restart the boiler, whose furnace may not have been properly purged. The explosion triggered a fire that immediately spread to the mixed-refrigerant compressor. From there, the fire jumped to trains 30 and 20, trains in adjacent liquefaction units 10, 5P and 6P were not affected in this 1970s vintage process facility. As investigations continue attention is likely to focus on maintenance and operational issues as well as the space needed to provide sufficient blast dissipation in case of accident.

A.1.4 INCIDENTS INVOLVING LNG CARRIERS WITH LOSS OF CONTAINMENT

The incidents of LNG spillage that have been encountered in the literature search [A1.1, A1.2, A1.3, A1.4, A1.7] and by inspection of the LR marine casualty database are reported here and summarised in Table A1.1.

Jules Verne (1965). The Jules Verne, a ship carrying 25,500m^3 of LNG, had an LNG spill onto tank cover plates due to overfilling while loading at Arzew in May 1965. The spill was attributed to an inadequately trained cargo handling officer. The spill caused minor damage to the ship which delivered its cargo before repairs were affected.

Methane Princess (1965). In early 1965 the Methane Princess, an LNG ship carrying 27400 m^3, had a spill while disconnecting after discharging at Canvey Island, UK before the liquid lines had been completely drained. The spill was caused by a splinter of Polytetrafluoroethylene blocking a valve slightly open. LNG accumulated in a drip tray and a small amount spilled onto the deck causing cracks. Temporary repairs allowed the ship to continue its voyage undelayed.

Massachusetts (1974). The Massachusetts, a barge carrying 5000 m^3 of LNG, suffered two incidents of cryogenic spillage on 4 June and 16 July 1974. The first incident occurred when a quick release coupling failed and liquid nitrogen spilled on the deck causing the plate to crack. The second incident happened during LNG loading at Everett, Massachusetts when a valve gland leaked spilling LNG onto the deck. The LNG spill caused cracking in the deck plates.

LNG Aquarius (1977). The LNG Aquarius, a ship carrying 126000m^3 of LNG, overfilled a tank while loading at Bontang on 16 September 1977. The high level alarms failed allowing LNG to spill on the tank cover plating. There was no damage to the ship.

Mostefa Ben Boulaid (1979). The Mostefa Ben Boulaid, a ship carrying 125000m^3 of LNG, had an LNG spill onto the deck and cargo tank during unloading at Cove Point, USA on 8 April 1979. The spill caused cracking to the deck and some damage to the cargo tank. The damage did not prevent sailing.

Pollenger (1979). The Pollenger, a ship carrying 87000m^3 of LNG, had an LNG spill onto the steel plate cover of cargo tank no. 1 during unloading at Everett, USA on 25 April 1979. The spill caused cracking in the steel plate.

Name Withheld (1984). A vessel with a cargo capacity 130000m^3, suffered cargo pump failure causing a secondary fault. Inducers at pump section end broke up. Metal fragments pierced the Invar membrane. Dealt with by adopting manufacturers set procedure.

Isabella (1985). The Isabella of 35500m^3 cargo capacity had an LNG spill onto its deck due to a cargo tank overflow on 14 June 1985. The spill has been attributed to cargo valve failure during discharging of cargo. The spill caused severe cracking of steelwork.

Name Withheld (1985). A vessel with a cargo capacity 130000m^3, suffered cargo pump failure causing a secondary fault. Inducers at pump section end broke up. Metal fragments pierced the Invar membrane. Dealt with by adopting manufacturers set procedure.

Tellier (1989). The Tellier of 40000m^3 capacity had an LNG spill onto its deck during loading at Skikda on 12 June 1989. The spill caused severe cracking to the deck. The spill resulted from the vessel breaking free from its moorings.

More minor spillages are reported in reference [A1.4]. On 3 April 1977 the US Coast Guard witnessed several gallons of LNG spilled on the deck of the Kenai Multina due to a leaking gasket. No damage occurred. They also witnessed spills for the Descartes and the Lucian in 1976 due to valves on the ship being left open during discharge.

Although, in none of the reported cases has the LNG spillage ignited, there have been four additional incidents reported [A1.1] where a vented gas has ignited, the Methane Progress (1964, 1965), Jules Verne (1966) and the LNG Aquarius (1977). Each of these incidents occurred while the ship was loading or discharging and the ship was struck by lightning; igniting gas that was **routinely** vented under these conditions. In each case the fire was extinguished quickly.

The above incidents indicate the relatively small quantities of spillage of LNG that have occurred to date. In total these spills have resulted in:

- 2 cases of severe deck fractures
- 5 cases of minor deck/tank cover fractures
- 2 cases of Invar membrane rupture
- 1 case of no damage.

Four of the incidents were due to valve leakage. Such incidents have resulted in improved valve design [A1.1]. In no incident have human casualties, damage to the environment or shore-based property been reported. There are no recorded incidents of collision, grounding, fire, explosion or hull failure which have resulted in cargo spillage and no LNG carrier has been lost at sea.

The above safety record demonstrates that maintaining safety is a principal aim of the LNG marine transportation industry. The IMO Gas Carrier Code and LR's Rules for Gas Ships [A1.5] provide requirements for design, construction and the equipment these vessels should carry so as to minimise the risk to the ship, its crew and the environment with regard to the hazards involved.

A.1.5 INCIDENTS INVOLVING OTHER LIQUEFIED GAS CARRIERS WITH LOSS OF CONTAINMENT

To provide a comparison of the consequences LR have also investigated the loss of containment from LNG against other liquefied gas carrier types.

The incidents of non-LNG spillages that have been encountered in the literature search [A1.1, A1.2] and by inspection of LR's casualty database are summarised in Table A1.2. Some of these incidents have resulted in fatalities and vessel loss.

The distinguishing features of these casualty incidents compared with those to LNG carriers (Table A1.1) are as follows:

Eight of the incidents involving non-LNG carriers were initiated by collision, whereas there have been no collision incidents involving LNG carriers resulting in breach of the containment system and cargo spill. In general, this is probably due to the larger size of typical LNG carriers giving increased collision protection afforded by the wide side tanks of their double hull construction, and the resilience of the containment systems.

Fourteen of the incidents to non-LNG carriers involved fire or explosion, whereas there have been no fire or explosion incidents on LNG carriers which have involved cargo spill. Even though the minimum ignition energies of hydrocarbon gases are comparable at the same temperature, the containment of non-LNG cargoes at considerably higher temperatures and at pressures greater than LNG, possibly approaching ambient temperature under pressure, increases the risk of non-LNG vapour releases followed by ignition. The lower limit of flammability and lower auto ignition temperatures of non-LNG cargoes tends to further increase this risk.

A.1.6 SERIOUS CASUALTIES INVOLVING LNG CARRIERS WITH NO LOSS OF CONTAINMENT

There have been no marine incidents involving spillage due to collision, grounding, fire, explosion or hull failure and no LNG carrier has been lost at sea.

Of the seven reported serious casualties not involving spillage, there have been two cases of severe bottom damage caused by grounding. It is evident in these cases that the double bottom structure and the resilience of the containment system, even when deformed, have prevented LNG loss.

This represents occasions when the LNG ships have been involved in a serious event but have not lost containment. This is relevant as it provides an indication of the inherent properties of the hull system against external damage. In the cases below this relates to grounding, but is demonstrable of the capability of LNG tankers to sustain external damage yet retain their containment integrity.

Serious casualties to LNG carriers which have not involved spillage are summarised in Table A1.3. These casualties have been identified by the literature search [A1.1, A1.2, A1.3, A1.7] and by inspection of the LR marine casualty database.

Three of the casualties involved extensive bottom damage and even though set-up of the bottom of the containment system has been reported there has been no resultant breach of tanks and LNG loss. It is evident that the double bottom structure and the resilience of the containment system even when deformed have played a major part in preventing any outflow of LNG, and the design of the containment system and double hull have been a prime contributor to the inherent safety of LNG transportation. It is considered that the reported case of fatigue cracking of the inner hull would not have posed an immediate threat to LNG containment. It should be noted that the records of serious casualties show there have been no reported incidents involving collision or fire or explosion in the LNG tank region.

A.1.7 CONCLUSIONS – REVIEW OF TERMINAL STORAGE AND MARINE INCIDENTS

A comparison of casualty data for LNG carriers and non-LNG gas carriers gives a clear identification of the differences in terms of both the cause and extent of damage and the consequences of an incident. This is due to differences in vessel size, design and the nature of the cargo, as well as service and operational factors.

It is evident that the marine casualties as presented and discussed reflect the general expectation that historically, LNG carrier casualties are of relatively minor consequence with respect to loss of LNG cargo.

Of the eight identified marine incidents where there has been spillage there have been two cases of serious cold fractures of the vessel's decks, five of minor cracking and no damage in the remaining incident. In none of the reported cases has the release resulted in a fire or explosion or any other hazardous event; the gas dispersing without further incident. The review has shown that there have been no marine incidents involving spillage due to collision, grounding, fire, explosion or hull failure and no LNG carrier has been lost at sea.

Prior to the recent LNG incident at Skikda in Algeria there have been four incidents involving LNG representing the last 39 years of operational experience where there have been releases of LNG from LNG storage tanks and/or associated process equipment. None of these earlier four incidents have involved a major failure of an LNG tank and associated systems.

A.1.8 REFERENCES

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A1.4 COMPTROLLER GENERAL (1978). Liquefied Energy Gases Safety. Report to the Congress of the United States. 31 July 1978 EMD-78-28.

A1.5 LLOYD'S REGISTER (1986). Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquefied Gases in Bulk. Lloyd's Register of Shipping, London. July 1986.

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A1.7 SOCIETY OF INTERNATIONAL GAS TANKER & TERMINAL OPERATORS (SIGTTO). Gas Shipping Incident Report. (1999) www.sigtto.org

A1.8 HSE MHIDAS Database Records, version 2.01.

A1.9 Lee Niedringhaus Davis, Frozen Fire – Where Will it Happen Next, Friends of the Earth.

	Ship Name	Ship Size	Incident Date	Ship Status	Fatalities	Ship Damage	Comment
1	Jules Verne	14,070dwt 25,500m^3	1965	Loading	0	Yes	Overfilling. Tank cover and deck fractures.
2	Methane Princess	24,600dwt 27,400m^3	1965	Disconnecting after discharge	0	Yes	Valve leakage. Deck fractures.
3	Massachusetts	2,570dwt 6,000m^3	1974	Loading	0	Yes	Valve leakage on closure. Deck fractures.
4	LNG Aquarius	72,620dwt 126,000m^3	1977	Loading	0	No	Tank overfilled.
5	Mostefa Ben-Boulaid	67,170dwt 125,000m^3	1979	Unloading	0	Yes	Valve leakage. Deck fractures.
6	Pollenger	50,750dwt 87,600m^3	1979	Unloading	0	Yes	Valve leakage. Tank cover plate fractures.
7	Name Withheld	130000m^3	1984	At berth	0	Yes	Cargo pump failure caused inducer fragments to pierce Invar membrane
8	Isabella	27,235dwt 35,500m^3	1985	Unloading	0	Yes	Cargo valve failure. Cargo overflow. Deck fractures.
9	Name Withheld	130000m^3	1985	At berth	0	Yes	Cargo pump failure caused inducer fragments to pierce Invar membrane
10	Tellier	21,300dwt 40,080m^3	1989	Loading	0	Yes	Broke moorings. Hull and deck fractures.

Table A1.1 : Main Reported Incidents to LNG Carriers Involving Loss of Containment
Sources: LR, Refs.: A1.1, A1.2, A1.3, A1.4, A1.7

	Ship Name	Ship Size	Incident Date	Ship Status	Cargo Loaded	Fatalities	Ship Damage	Comments
1	Birgit Hoyer	1,335dwt 1,150m3	1972	Unloading	LPG	0	Yes	Tank overfilled. Damage details not reported.
2	Yuyo Maru No.10	53,680dwt 47,400m3	1974	At sea	LPG & Naphtha	5	Yes	Collision, F/E then scuttled. Refrigerated LPG tanks remained intact.
3	Pythagore	11,000dwt 14,260m3	1975	Loading	Butane	0	Yes	Cargo line leakage. Damage to cables on deck.
4	Izumi 88Maru No.38	1,020dwt 1,850m3	1976	At sea	LPG	0	Yes	Collision. Vessel broken in two. Cargo tank adrift and exploded.
5	Milli	1,120dwt 1,260m3	1979	At sea	Butane	0	Yes	Sprang leak and sank. No reported spillage.
6	Babounis Costas	360dwt 670m3	1979	In port	Butane	0	Yes	Severe leakage of cargo. Vessel scuttled.
7	Olav Trygvason	4,775dwt 4,110m3	1981	Unloading	Ethylene	1	Yes	Discharging arm disconnected during unloading. Hull damaged.
8	Vasco da Gama	6,325dwt 6,080m3	1982	Unloading	Butadiene	0	Yes	F/E after cargo valve leakage, minor damage.
9	Name Withheld	1000m^3	1982	Loading	LPG	0	Yes	Ship's valve shut against shore loading pump caused rupture of hose and explosion/fire.
10	Name Withheld	675m^3	1982	Unknown	LPG	0	Yes	Believed arson attempt during discharge. Explosion and fire limited to fwd part of vessel.

Table A1.2 : Reported Incidents to Liquefied Gas Carriers other than LNG Carriers Involving Loss of Containment (Cont..)
Sources: LR Refs. A1.1, A1.2, A1.3, A1.7

	Ship Name	Ship Size	Incident Date	Ship Status	Cargo Loaded	Fatalities	Ship Damage	Comments
11	Name Withheld	13250m^3	1982	Cooldown	LPG	0	Yes	Fire due to lightning strike. Fire on deck and cargo insulation.
12	Name Witheld	1750m^3	1983	Unknown	Liquid ammonia	0	No	Explosion and release of ammonia on jetty due to bursting hose.
13	Puerto Rican	35,240dwt 40,740m3	1984	At sea	Petro-chemicals	1	Yes	F/E. Vessel broke apart and sank.
14	Chemicarry No.21	720dwt 900m3	1985	Unloading	Liquefied butadiene	Unknown	Yes	Broken hose during unloading. Pressurised cargo tank & deck area badly burned. Vessel broken up.
15	Name Withheld	4000m^3	1985	Unloading	LPG	0	Yes	Caught fire whilst discharging. Explosion occurred during disconnection.
16	Name Withheld	35500m^3	1985	Unloading	LPG	0	Yes	Explosion during discharge due to valve breakage in tank producing gas leak when tank overflowed.
17	Name Withheld	22000m^3	1985	Unknown	Unknown	0	Yes	Accommodation damaged when leaking gas entered cabin windows.
18	Name Withheld	57000m^3	1985	Unknown	LPG	0	Yes	LPG vapour cloud from spill on berth ignited by passing launch.
19	Blue Star	10,940dwt 14,270m3	1988	At sea	Liquid ammonia	0	Yes	Collision. Part of cargo spilled.
20	Name Withheld	1000m^3	1988	Unknown	Butadiene	0	Yes	Fire from hose leak led to subsequent constructive loss.

Table A1.2 : (Cont..) Reported Incidents to Liquefied Gas Carriers other than LNG Carriers Involving Loss of Containment(Cont..)

	Ship Name	Ship Size	Incident Date	Ship Status	Cargo Loaded	Fatalities	Ship Damage	Comments
21	Name Withheld	19500m^3	1988	Loading	Liquid ammonia	0	No	Release of ammonia whilst loading. Cloud spread to nearby settlement. No reports of casualties.
22	Name Withheld	14250m^3	1988	Berthing	Liquid ammonia	0	Yes	Collided with crude carrier at berth. 3500MT ammonia lost through cargo containment breach.
23	Name Witheld	750m^3	1988	At sea	LPG	Unknown	Yes	Ran aground due to Typhoon. Abandoned due to ingress of water. Assumed sunk
24	Name Withheld	1000m^3	1988	At sea	LPG	3	Yes	Sunk in severe weather.
25	Name Withheld	5000m^3	1989	At sea	LPG	Unknown	Yes	Vessel discovered capsized. No survivors. Subsequently sank.
26	Name Withheld	1500m^3	1989	Navigating	Propylene-oxide	0	Yes	Collision with Ro-Ro. Fire from tank rupture.
27	Name Withheld	54000m^3	1990	Navigating	Liquid ammonia	0	Yes	Heavy weather caused severe damage. Subsequent leakage of ammonia detected.
28	Val Rosandra	3,500dwt 4,470m3	1990	Unloading	Petro-chemicals	0	Yes	Fire in compressor room and cargo tank. Vessel scuttled.
29	Name Withheld	3500m^3	1991	At berth	LPG	0	No	Operations suspended and hoses disconnected following four releases of cargo to atmosphere.
30	Borthwick	2,100dwt 2,450m3	1992	Loading	Propylene	0	No	Valve fracture. Gas released.

Table A1.2 : (Cont..) Reported Incidents to Liquefied Gas Carriers other than LNG Carriers Involving Loss of Containment (Cont..)

	Ship Name	Ship Size	Incident Date	Ship Status	Cargo Loaded	Fatalities	Ship Damage	Comments
31	Name Withheld	750m^3	1995	At sea	LPG	8	Yes	Sank with 382MT of LPG aboard.
32	Name Withheld	3000m^3	1996	At sea	Butane	0	Yes	Sank with 1500MT of butane aboard
33	Name Withheld	1000m^3	1997	Navigating	VCM	10	Yes	Struck rocks and sank. One tank of VCM lost immediately. Remainder salvaged.
34	Name Witheld	2000m^3	1997	At sea	LPG	0	Yes	Sunk off Japanese coast. Cause unknown.
35	Name Withheld	35369m^3	1999	At berth	Liquid ammonia	0	No	Release of ammonia whilst preparing for tank cleaning. No reports of casualties.
36	Name Withheld	1500m^3	1999	Navigating	LPG	Unknown	Yes	Collision with bulk carrier. Subsequently sank. LPG released underwater.

Table A1.2 : (Cont..) Reported Incidents to Liquefied Gas Carriers other than LNG Carriers Involving Loss of Containment

	Ship Name	Ship Size	Incident Date	Ship Status	Fatalities	Ship Damage	Comments
1	Methane Progress	24,500dwt 27,400m3	1974	In port	0	Yes	Touched bottom at Arzew.
2	El Paso Paul Kayser	64,750dwt 125,000m3	1979	At sea	0	Yes	Stranded. Severe damage to bottom, ballast tanks, motors water damaged, bottom of containment system set up.
3	LNG Libra	64,620dwt 126,750m3	1980	At sea	0	Yes	Shaft moved against rudder. Tailshaft fractured.
4	LNG Taurus	64,620dwt 126,750m3	1980	In port	0	Yes	Stranded. Ballast tanks all flooded and listing. Extensive bottom damage.
5	Name Withheld	126,500m^3	1982	At sea	0	Yes	Heavy weather damage to dome fittings, deck platings and longitudinal bulkhead.
6	Name Withheld	126,500m^3	1983	At sea	0	Yes	Rudder damage and cracks in way of cargo domes.
7	Name Withheld	126,500m^3	1983	At sea	0	Yes	Heavy weather damage. Rudder damage and fractures in way of tank domes.
8	Name Withheld	87,500m^3	1983	Unknown	0	Yes	Stern tube leakage

Table A1.3 : Reported Serious Casualties to LNG Carriers Involving No Loss of Containment (Cont..)

Sources: LR, Ref.: A1.1, A1.2, A1.3, A1.7

	Ship Name	Ship Size	Incident Date	Ship Status	Fatalities	Ship Damage	Comments
9	Name Withheld	126,500m^3	1984	Unknown	0	Yes	Rudder damage
10	Name Withheld	126,500m^3	1984	At berth	0	Yes	Fire whilst under repair. Damage to 25m^2 of spherical tank insulation.
11	Name Withheld	126,500m^3	1984	Unknown	0	Yes	Main deck cracked in way of tank dome centreline girder. Pilot valves failed.
12	Name Withheld	125,250m^3	1984	At sea	0	Yes	Various underdeck and ballast tank cracks attributed to heavy weather.
13	Melrose	2,7l0dwt 2,740m^3	1984	At sea	0	Yes	Fire in engine room. No structural damage sustained - limited to engine room.
14	Name Withheld	130,000m^3	1984	Unknown	0	Yes	Port & Starboard Boiler furnace floor tubes damaged.
15	Gardinia	51,580dwt 75,055m^3	1985	In port	0	Unreported	Steering gear failure. No details of damage reported.
16	Name Withheld	126,000m^3	1985	Navigating	0	Yes	Damage to port bow following collision

Table A1.3 : (Cont..) Reported Serious Casualties to LNG Carriers Involving No Loss of Containment (Cont..)

	Ship Name	Ship Size	Incident Date	Ship Status	Fatalities	Ship Damage	Comments
17	Name Withheld	87500m³	1989	Unknown	0	No	Main cooling water circulating pump failed
18	Name Withheld	129,500m³	1989	At berth	0	Yes	Vessel's moorings parted in high winds. Vessel laid up at time. Some damage to vessel. Extent unknown.
19	Bachir Chihani	66,750dwt 129,500m3	1990	At sea	0	Yes	Sustained structural cracks allegedly caused by stressing and fatigue in inner hull.
20	Name Withheld	126,500m³	1992	Navigating	0	Yes	Slight propeller damage sustained as result of contact with buoy at Pyong Taek.
21	Name Withheld	40750m³	1993	Dry-dock	0	Yes	Accommodation block fire
22	Name Withheld	125,750m³	1993	Navigating	0	Yes	Hit on portside whilst traversing Singapore straits. Bunker tanks penetrated.
28	Name Withheld	35500m³	1994	At berth	0	Yes	Ethylene carrier struck jetty whilst moored up awaiting departure.
29	Name Withheld	125,250m³	1996	Unloading	0	Yes	Electrical fire in ER. Disabled boilers. Cargo discharged at reduced rate

Table A1.3 : (Cont..) Reported Serious Casualties to LNG Carriers Involving No Loss of Containment (Cont..)

	Ship Name	Ship Size	Incident Date	Ship Status	Fatalities	Ship Damage	Comments
30	Name Withheld	65,000m^3	1996	At sea	0	Yes	Small fire in ER. Result of diesel spillage onto hot surface. Contained by hand-held extinguishers and CO_2 system.
31	Name Withheld	127,750m^3	1997	Navigating	0	Yes	Collision with fishing boat caused damage to port side and bulwark. No water ingress or fuel spill.
32	Name Withheld	126,250m^3	1997	Navigating	0	Yes	Sustained damage to ballast tank when coming into contact with unfendered stores jetty.
33	Name Withheld	129,299m^3	1998	Drydock	0	Yes	Cracking discovered in way of cargo tank dome.
34	Name Withheld	133,000m^3	1998	At sea	0	No	Complete electrical failure 200 miles from nearest land.
35	Name Withheld	71,500m^3	1999	Navigation	0	Yes	Struck oil berth whilst approaching LNG berth. Minor damage.
36	Name Withheld	126,500m^3	1999	At sea	0	No	Tail shaft problems. Vessel drifted for several days before being taken under tow.

Table A1.3 : (Cont..) Reported Serious Casualties to LNG Carriers Involving No Loss of Containment

	Terminal Name	Tank Size	Incident Date	Casualties	Tank Damage	Comments
01	Canvey Island UK	Not Given	1965	1 Injury	Minor	Whilst removing faulty valve in the piping LNG was released and ignited. Burning gas was reported to have risen to a height of 10 to 15 feet. A maintenance fitter working at the faulty valve was enveloped in flames and received burns to the face.
02	La Spezia Italy	50,000m^3	1971	0 Injuries	No	Excess pressure in LNG tank was relieved through vent and safety valves. About 300m^3 of LNG was reported to have been released from the tank during a roll-over incident, this resulted in a cold methane vapour cloud being formed.
03	Canvey Island UK	Not Given	1973	0	Yes	A violent reaction took place when the LNG came into contact with the water in the ditch producing an RPT type explosion. There was no ignition of methane gas released during the physical explosion.
04	Cove Point	Not Given	1979	1 Fatality 1 Injury	No	LNG leaked through an inadequately tightened LNG pump electrical penetration seal, vaporised, passed through 200 feet of underground electrical conduit, and entered the substation. Natural gas-air mixture was ignited by the normal arcing contacts of a circuit breaker resulting in an explosion, which killed one operator in the building.

Table A1.4 : Reported Incidents Involving Terminal Storage Loss of Containment

A2 RELEASE CONSEQUENCES - LNG EXPERIMENTS

A.2.1 OVERVIEW

A deliberate damaging action involving either missiles or explosives would potentially result in a number of different consequences. We have seen in Section 3 of the report how there is a possibility that the LNG storage single containment system could be breached, with the result that LNG escapes.

This Section discusses the likely consequences of a loss of containment by reviewing the aims, results and conclusions of large scale tests carried out over the last 25 years to study hazards and consequences associated with releases of LNG on land and water.

The review of the published work on experimental tests has shown that the main potential consequences resulting from an release of LNG are:

- the dispersion of a cloud of vapour spreading downwind from the release point;
- subsequent ignition of the cloud which will burn back towards the release point;
- pool fires burning at the release point;
- rapid phase transition of LNG on contact with water resulting in localised physical explosions (without ignition) producing significant overpressure.

The results of the individual experiments are provided in Section A2.2, with a summary of their conclusions in Section A2.3. For reference purposes a description of the basic physical properties of some liquefied gases, including LNG, are presented in Table A2.1. A general summary of the experiments considered is given in Table A2.2.

An overview of theoretical consequence characteristics is provided as follows.

A.2.2 DISPERSION

Natural gas may be liquefied at atmospheric pressure if it is cooled to -160 degC. At this temperature it forms a clear, colourless liquid with a density about half that of water. Due to its low temperature, a spillage of LNG onto land or water results in rapid vaporisation which produces a dense cloud of cold heavy gas. The cloud is often visible due to the presence of condensed water vapour. As it vaporises the LNG mixes with air, warms up and the gas concentration decreases as the cloud disperses assisted by the effect of wind. Since LNG is less dense than air at ambient temperature, as it warms the cloud becomes buoyant and will rise further facilitating dispersion.

Evaporation from a LNG pool on water is more rapid than from a pool on land. This is because convection processes in the water underlying the pool lead to a constant temperature in the water, whilst on land a temperature gradient is imposed, the solid nearest the pool is cooled and the evaporation rate decreases with time.

A.2.3 IGNITION

LNG vapour is flammable between concentrations of typically 5% and 15% by volume when mixed with air. A powerful spark or very hot surface (above 540 degC) will ignite the vapour if it is between these limits.

Throughout an LNG cloud the level of mixing with air will not be uniform and pockets of flammable gas may exist in regions of the cloud which generally are outside the flammability limits (Figure A2.2). For this reason a level of 0.5 LFL is commonly used in assessing the hazard range of dispersing gas clouds.

If an unconfined LNG vapour cloud is ignited the result is most likely to be a flash fire which may not be sustained through the cloud. Explosive effects involving blast damage are unlikely because the combustion characteristics of methane, the main constituent of LNG, are not conducive to detonation type explosions.

A2.3.1 POOL FIRES

If an LNG pool is ignited on land or water a fairly clean flame with little smoke will be produced. As thermal radiation from the flame heats the LNG in the pool the evaporation rate and hence the emissive power generated by the flame, increases. The emissive power increases with the size of the pool up to a certain limit. The limiting value of emissive power is between 270 and 300 kW/m^2 for a pool of about 20m diameter. Thereafter, soot produced by the larger fires tends to obscure the flame. Wind has the effect of dragging the flame outside the confines of the pool in smaller fires, however in bigger pool fires buoyancy of the flame can overcome wind forces (Figure A2.3). The shape of the fire and the amount of obscuring soot has a marked effect on the transmitted heat flux and the incorporation of such effects in predictive models is of importance.

A2.3.2 RAPID PHASE TRANSITIONS

When LNG forms a pool on water this results in an instantaneous change of phase from liquid to vapour with a corresponding increase in volume of about 200 times. This effect is attributed to the superheating of the LNG due to a lack of nucleation sites (which prevents boiling), breakdown of the interface between the two liquids and subsequent rapid transfer of heat from the water to the LNG. No ignition is associated with the RPT effect and it has a limited capability for damage to structures due to the physical explosive effects.

A.2.4 REVIEW OF PUBLISHED EXPERIMENTAL RESULTS

A2.4.1 SHIPBOARD JETTISON OF LNG ONTO THE SEA - 1974

In 1974 Shell carried out tests [A2.1] on the stern discharge system of its LNG carrier Gadila. These tests followed earlier test (1959) in which the Methane Pioneer successfully jettisoned $20m^3$ of LNG over a period of 7 minutes.

The objective of the Shell tests was to assess the effectiveness of the discharge system and examine the environmental hazard associated with a large release of LNG in terms of vapour cloud formation and its dispersion. Circumstances under which such a discharge would be judged necessary were deemed to be after damage to the containment system which threatened the ship, or where the ship had run aground and needed to lighten its load.

Discharges of up to $1188m^3/hr$ over a period of 10 minutes were achieved with the ship stationary and under way. A fixed water curtain was in operation around the stern and the electric field strength in the discharge stream was monitored during the test.

Natural gas liquid was visible up to two metres from a 102mm nozzle but not visible from a 51mm nozzle. Isolated pools of LNG formed on the sea surface during discharges from the 102mm nozzle only, but no ice formation or RPTs were observed. A "vigorous" dense white cloud with clearly defined edges formed on the sea surface. However, the cloud completely dispersed within 5 to 10 minutes of the discharge ceasing from the 51mm nozzle and 15 to 20 minutes in the case of the 102mm nozzle, the extra time being due to the larger inventory discharged.

Static build up was not found to be a problem and the cloud remained about 50m from the vessel provided exit velocities of 40-50m/sec were achieved.

It was concluded that this type of discharge should only be attempted with the wind direction between 30° and 60° off the bow and during daylight in order that the cloud boundary could be monitored.

Measurement of the vapour cloud from cine film indicated that the visible region extended downwind 1370m for the smaller discharges (456m^3/hr) and up to 2250m for the larger discharges (1188m^3/hr), see Figures A2.4 and A2.5. Maximum plume heights were in the order of 10-12m. Dispersion coefficients were deduced for the Pasquill equation which enabled a hazard zone of 0.5 LFL i.e. 2.5% by volume to be estimated. This was found to extend 700m downwind for the larger discharge rates. The plume length of 2250m was estimated to correspond to 0.1 LFL i.e. 0.5% by volume. Standard dispersion coefficients predicted a plume length of 3450m for this concentration. Generally the clouds were found to be very wide and flat due to the heavy, cold nature of the vapour, and did not extend as far as predicted by standard dispersion calculations.

In summary, a release of 193m^3 of LNG over a 10 minute period resulted in a visible vapour cloud extending 2250 m downwind. The cloud boundary was estimated to correspond to a natural gas concentration of 0.5% by volume. The hazard zone 0.5 LFL i.e. 2.5% by volume was inside the cloud boundary and estimated to extend only some 700m.

A2.4.2 U.S. COASTGUARD CHINA LAKE TESTS - 1978

The aim of these tests [A2.2 and A2.3] was to evaluate the hazard posed by spills up to 5.7m^3 of LNG during marine transportation. Deflagration and detonation of methane was studied initially, then the dispersion and ignition of LNG vapour on water was investigated.

Methane was found not to detonate when in a shock tube or held in light polythene hemispheres. Detonations were observed when the proportion of propane in the LNG vapour was increased substantially above 10%. However in these tests a high explosive initiator was used rather than a spark. This would not be considered a reasonable scenario for the ignition of a gas cloud under normal circumstances.

The pool fire tests confirmed boil off rates predicted from earlier tests. Visible flame heights correlated well with the Thomas' equation which relates flame length with vaporisation rate and pool diameter. Radiometry data provided average emissive powers of 210±65kW/m^2 for fires up to 15m diameter.

Vapour fire tests in which the gas cloud was ignited at its edge again showed that fireball 'lift off' does not occur. The flame propagation was observed to cease at the pool edge which may have been due to the topography of the test site. The width to height ratio of the burning zone was found to be unity and lateral flame spread was observed, as in the Shell Maplin Sands Tests[A2.5].

Mass burning rates for LNG fires were found to be in the order of 0.3kg/m^{2}s. For high fill rates (i.e. 5m^3 in 50 sec) the burning rates were found to increase by 50%. This was thought to be due to the greater turbulence levels as a result of the high LNG flowrates. The effect, in the event of an accidental release and ignition involving high spill rates would be considered to produce taller fires of smaller diameter and lower radiating area.

Subsequent pool fire tests using LPG and gasoline gave markedly different results from LNG. LNG spills resulted in a maximum pool fire diameter of 15m. The LPG spill gave a high initial flame spread to 18m diameter and then totally engulfed the pool (approximately 50m diameter). After ignition it contracted to give a fire 11m in diameter. Gasoline was observed to spread quickly and continue to grow as long as the spill continued. This would suggest that in terms of pool spread LPG and gasoline present a greater hazard than LNG.

In summary, methane-air mixtures were not found to be detonable by a low energy ignition source (i.e. a spark). No fireball was observed on ignition of a dispersed LNG cloud and a 15m diameter LNG pool fire on water resulted in emissive power levels of 210±65kW/m^2. Tests using similar quantities of LPG liquid gave greater pool diameters in the early stages of the fire and gasoline pools were observed to grow as long as liquid was supplied.

A2.4.3 ANALYSIS OF BURRO SERIES 40M^3 LNG SPILL EXPERIMENTS - 1980

These experiments, [A2.4] carried out at China Lake in 1980, involved the spillage of up to 39m^3 of LNG onto water in order to measure dispersion of the resulting vapour cloud.

Over a series of nine tests, LFL of 5% by volume was measured between 140 and 400m depending primarily on wind velocity. The maximum distance of approximately 400m occurred during very still atmospheric conditions and in this case the cloud also extended 40m upwind of the spill point. Cloud widths were between 75 and 80m and their depths were approximately 10m.

Splitting of the gas cloud into "fingers" (bifurcation) was observed. In this case care is necessary in measuring an average distance to LFL. It is possible for the average concentration to be below the LFL at a given distance but the concentration in an individual finger may be above LFL.

Several of the tests were severely affected by RPTs which disrupted the gas cloud and caused some damage to the LNG release equipment. Overpressures of l2mbar were measured 30m from the RPTs, the single most violent being 50mbar.

Parametric studies were subsequently performed using the one dimensional SLAB computer model for heavy gas dispersion. This model was found to successfully predict the results of the above tests but was highly dependant on ground and water heat flux.

It was concluded that gravity flow increased the width of the cloud, especially at low wind speeds. Density stratification reduced the mixing with air which, in turn reduced dispersion.

In summary, spills of 40m^3 of LNG onto water resulted in vapour clouds in which the LFL of 5% by volume concentration level extended between 140 and 400m. Dispersion distances were highly dependant on wind speed. Computer predictions of dispersion distances, although successful, were found to be very sensitive to ground and water heat flux levels.

A2.4.4 SHELL UK - MAPLIN SANDS TESTS - 1982

Shell UK have carried out large scale releases of LNG and refrigerated LPG onto water at Maplin Sands in the South of England [A2.5 and A2.6]. The objective of the tests was to study the characteristics of a release of the size likely to occur accidentally during cargo transfer operations (up to 20m^3). Larger releases not considered in this programme were considered to be more likely on open water where the ship would be in transit travelling at greater speed and where collision or grounding damage to the containment system could occur.

The visible boundary of the LNG plumes created in the tests occurred at gas concentrations of 2% by volume with the concentration decreasing further outside the visible cloud. The lower flammability limit (LFL) for methane air mixtures is 5% volume so the LFL boundary was well within the visible clouds. This contrasts with propane whose cloud boundary forms at 3% volume and whose LFL is 2% by volume implying that its LFL boundary is outside the visible cloud.

LNG generally formed a relatively narrow vapour cloud at all wind speeds however propane was observed to spread much more in a lateral direction at low wind speeds. Also at normal temperature and pressure, propane has a higher density than air whereas methane is lighter than air. Hence after mixing with air and warming of the vapour cloud, methane will become buoyant and disperse but propane will continue to spread at ground or sea level.

The dispersion distance (from source to LFL) for LNG was measured between 110 and 150m and was observed to be inside the confines of the cloud. Distances to LFL for propane were measured to be 210 to 400m for similar wind conditions. The dispersion model used by Shell to predict gas dispersion (HEDAGAS II) over predicted dispersion distances for LNG.

Several ignition tests were carried out in order to investigate combustion characteristics of the vapour clouds. Earlier work had predicted BLEVE type fireballs and significant overpressures due to high flame speeds. In fact, low burning velocities (10m/sec) and overpressures (1mbar) were measured in LNG clouds. Emissive power levels of 173±20kW/m^2 for cloud fires and 203±31kW/in^2 for pool fires were measured which, when compared with earlier smaller scale work, indicated that emissive power increases with pool diameter.

From seven LNG cloud ignition tests only one burnt back to source and produced a pool fire and two clouds extinguished completely. In contrast, four propane cloud fires resulted in two pool fires, and none extinguished.

The main conclusions derived from these tests were that measured distances to LFL concentrations were greater for propane than methane. Furthermore the predictive model, although fairly accurate for propane, over predicted LNG dispersion distances. Flame speeds in ignited LNG vapour clouds were low and resulting overpressures were insignificant.

In summary, for LNG spills of up to 20m^3 onto water the distance to LFL (5% by volume) was measured between 110 and 150m. Tests using propane gave distances up to 400m. Visible LNG cloud boundaries corresponded to 2% by volume (i.e. LFL inside the visible cloud) and LPG cloud boundaries corresponded to 3% by volume (i.e. LFL outside the visible cloud). Ignition of the clouds resulted in low flame propagation velocities (10m/sec) and negligible overpressures. Combustion of the flammable vapour clouds was found to be a low energy phenomenon. Pool fire emissive power levels of 203±31kW/m^2 were measured.

A2.4.5 HEAVY GAS DISPERSION TRIALS AT THORNEY ISLAND - 1984

The Heavy Gas Dispersion Trials [A2.7] were carried out at Thorney Island near Southampton, England during 1983 and 1984. Refrigerant-12 was selected as the test gas which was released instantaneously from a container 13m high and 14m across (2000m^3). A wide variety of instrumentation was set up to monitor gas concentrations and weather conditions. Specific gravities of 1.65 to 4 were achieved for the test gas releases. These trials emphasised the importance of thermal effects in the case of LNG spills in contrast to 'warm' gas spills as was the case in these tests and could be with LPG. Vast quantities of data were obtained which were subsequently used to refine gas dispersion models.

Comparison of predictions with test results indicated a degree of scatter, attributable mainly to variations in atmospheric conditions throughout the test period, which significantly affected gas dispersion.

A2.4.6 MONTOIR 35M DIAMETER POOL FIRE TESTS - 1989

The object of the work [A2.8] was to examine the effects of scale on heat flux emissions from pool fires. Hazard assessment models rely generally on data from experimental fires of a much smaller scale than those considered in the tests. The tests reported here were designed to provide data from a pool fire as near as possible to full scale. In this case a 35m diameter bund, approximately 1m deep was constructed into which up to 238m^3 of LNG was discharged. The initial composition of the LNG was 99mol% methane and 0.2mol% ethane.

Two types of emissive power were identified, namely that of the part of the visible flame not shielded by smoke and that of an idealised representation of the flame including the smoke shielded portions. The emissive power of the visible flame was expected to decrease with pool diameter due to smoke shielding and that of an idealised flame to increase. Smaller LNG pool fires up to 20m do not produce very much smoke and both types of emissive power increase with scale. However, LPG pool fires produce copious amounts of smoke and the idealised emissive power decreases even for small scale fires.

It was concluded from the test measurements that both types of emissive power were higher than in smaller scale tests but smoke shielding in the upper part of the flame reduced the idealised values (as in the small scale LPG tests).

The rate of increase of average emissive power flattened off when compared to smaller tests (Figure A2.6), indicating that for even larger fires there would not be a further significant increase. Calculated values derived from Thomas' equation and the Walker and Skep equations also levelled off at larger pool diameters but they under predict the measured emissive power by significant amounts.

Values of emissive power measured were in the order of 250 to 270kW/m^2 compared to 140 to 200kW/m^2 for smaller scale tests. Mass burning rates were also measured as 0.14kg/m^2s and these were seen to be slightly higher than in smaller scale tests.

In summary, 35m diameter LNG pool fires involving up to 238m^3 of liquid resulted in heat flux levels of 250 to 270kW/in^2. When compared with earlier work these results indicate that there is a limiting pool diameter (less than 35m) above which heat flux levels cease to rise, due to smoke shielding.

A2.4.7 OVERVIEW OF LNG VAPOUR DISPERSION RESEARCH - AGRI - 1989

This report [A2.9] covers The American Gas Research Institute sponsored test programme involving wind tunnel simulations, numerical modelling and large scale validation tests. The object of the work was the evaluation of the hazards associated with LNG storage and transport, and the investigation of mitigation techniques in the event of a spill. This work was subsequent to the China Lake (Section A2.3.2) and Maplin Sands (Section A2.3.4) test programs carried out in the early 1980s. Unlike the earlier tests four spill lines were distributed across a 40m x 60 m pond. A fibreglass vapour fence 9.1m high and enclosing an area 3872m^2 was constructed around the release points and an upwind fence was built to simulate a storage tank. Wind tunnel testing had been used initially for the design of the fence configuration, simulating releases of LNG up to 40m^3 at a scale of 1:250.

Gas concentration, temperature and wind measurements were made within the fence and up and down wind. An initial spill of 66.4m^3 was found to exceed the capacity of the fence. Maximum spill sizes of 50m^3 were used for later tests. Stable cold gas layers were detected at a height of 2m above the pond. At heights of 6m and above large temperature fluctuations and levels of turbulence were observed.

Measurements made 50m downwind of the fence indicated that at no point did the gas concentration rise above the LFL, hence demonstrating the efficiency of the fence in preventing dispersion of the gas cloud.

Vortex inducing structures were also studied, but for higher boil-off rates the fences were found to be more efficient with respect to reducing down wind dispersion. By 1986 the test program had defined a range of limitations to wind tunnel simulations of LNG releases. These were largely concerned with turbulence length scales, low wind speeds, boundary layer effects and density stratification. A wind tunnel simulation sponsored by the AGRI and carried out by British Maritime Technology was compared with the results of the Thorney Island Heavy Gas Dispersion Trials. Comparison with the field data indicated wide point by point deviations between the modelled and field peak concentration data. This was attributed to the randomness of turbulent fluctuations in the field and wind tunnel. Generally, however, reductions in downwind concentration were reproduced in the wind tunnel.

The final stage in the programme concerned the validation of numerical models, as an alternative to the vapour dispersion approach required by US regulations, which is based on a simple Gaussian dispersion method and does not take into account processes such as heat transfer and stratification of the heavy cold vapours.

Laboratory scale tests were first carried out to establish the characteristics of buoyancy dominated dispersion of heavy gases. The Shell HEDAGAS model was adapted to include stable stratified shear flow and far field turbulent diffusion. Heat transfer, stratified layer mixing and convective turbulence effects were also included. The new model named DEGADIS (Dense Gas Dispersion) was also capable of modelling both continuous and large scale releases.

A comparison of the Maplin Sands tests, Burro 7 LNG field experiments and results modelled by DEGADIS is shown in Figures A2.7 and A2.8. The graphs show reasonable agreement in the near to intermediate field. But in the far field there is less agreement due to the domination of turbulent dispersion effects.

Finally, it was determined that the HEDAGAS, DEGADIS and Gaussian dispersion models cannot simulate the effects of obstacles or varying terrain as these features have a significant effect on dispersion distances and flammable concentrations.

In summary, the efficiency of a 9.1m high fenced area in containing LNG spills of up to $50m^3$ was demonstrated, by reducing dispersion distances to the order of 50m. Gas dispersion modelling and wind tunnel testing gave reasonable agreement with full scale test results. However it was found that the effects of terrain could not be modelled accurately.

A2.4.8 FIRE SAFETY ASSESSMENTS FOR LNG STORAGE FACILITIES - 1992

This paper [A2.10] describes a model developed by British Gas for the prediction of thermal radiation from LNG pool fires as a function of distance. Earlier correlation's represent the flame shape by a skewed cylinder which extends further downwind than observed in experiments. Buoyancy forces are predominant, especially in large scale pool fires and tend to lift the top part of the flame reducing the downwind spread. As correlation's for flame tilt are based on the lower part of the flame there is an over prediction of radiation levels at downwind positions.

The British Gas model is based on a large number of pool fire tests and takes into account buoyancy effects on flame tilt. It also allows for flame drag, i.e. the distance the flame is pulled by the wind outside the bund at low level. Smoke shielding is included by treating the upper part of the flame as a separate zone.

The remainder of the paper is primarily concerned with passive and active fire protection for LNG tank installations and the methodology of fire hazard assessments based on predictions of thermal radiation from pool fires using the predictive model is described.

A2.4.9 HAZARDS OF SPILL ONTO WATER - U.S. COASTGUARD 1971 - 1972

The object of the work [A2.11] was to reproduce RPTs and repeat earlier vapour dispersion tests on a larger scale. No definitive RPTs were produced and more fruitful information was obtained in later studies. A strip mine lake, 90m wide and 200m long, was used as the location of the gas dispersion test. The bank sides in this case were quite steep which brought into doubt the validity of the tests in terms of wind velocity profiles and turbulence.

Up to 8m^3 of LNG was released over a ten minute period and gas concentrations were measured across the gas cloud. Unsuccessful ignition trials were carried out using an instantaneous spill system but ignition was eventually achieved using continuous release. Although burn-back to the source was observed no measurable overpressures occurred. Results concerning thermal radiation levels have been largely superseded by more recent work.

A2.4.10 RAPID PHASE TRANSITION SHELL R&D LABS USA - 1972

The occurrence of an RPT due to the spillage of LNG onto water can result in damaging overpressures close to the source of the spill, but the overpressures decay rapidly with distance. This paper [A2.12] covers the theory of the process which results in an RPT, experiments carried out to investigate the phenomena and predictions of spill size required. The properties of LNG, specifically after ageing, are examined in detail.

Spill sizes which produced adventitious RPTs, occurring unexpectedly during a test involved volumes between 190 and 265 litres of LNG.

Fresh unaged LNG was not found to be susceptible to an RPT when spilled onto water. However LNG held in storage for a period of time over which the methane content has decreased due to boil off was found to undergo an immediate RPT when spilled onto water. Alternatively fresh LNG when spilled onto water was found to age over a period of up to 10 seconds after which a spontaneous RPT could occur.

A method is presented for determining the time taken for a given LNG to age into the critical "vapour explosion region" under known storage conditions. No measurements of overpressure were presented but the description of RPT incidents which occurred during other tests suggest violent reactions.

A2.4.11 LARGE SCALE RAPID PHASE TRANSITION EXPLOSIONS - 1983

Following observation of RPTs which occurred unexpectedly during earlier LNG spill experiments the BURRO COYOTE series of tests, [A2.13] carried out in 1981, were instrumented to specifically study the phenomena, if it occurred. During this series of tests in which up to 30m^3 of LNG was released at rates of up to 19m^3/min, eight of the 26 releases produced RPT's. Some were small scale, occurring during the early stages of the release and several were large after a time delay.

Overpressures measured at 30m distance during one test from the spill point ranged from 8 to 50mbar as a result of 11 RPTs occurring over a period of 70 seconds. TNT equivalents were calculated from the overpressure data giving yields up to 3.5kg. However, these were admitted to be overestimates by a factor of almost 2 due to the difference between the explosive characteristics of an LNG RPT and TNT.

Comparison of laboratory scale experiments involving small quantities of cold liquids and these tests indicated anomalies in predictions of superheat limits for LNG on water. Further problems arise due to the possibility of some RPTs initiating below the water surface. This invalidates air blast measurements as the sole source of data for estimating TNT equivalents. Several RPT explosive yield models are discussed and again a divergence between theoretical predictions and experimental results occurred. The main conclusions were that RPTs fall into 2 categories, namely:

i) early RPTs below water level and close to the spill point

ii) delayed RPTs of larger magnitude near the edge of the LNG pool and at the surface.

In all cases some form of ageing process was required, either due to the initial venting and cooldown process or naturally, due to evaporation of the LNG pool.

A2.4.12 RECENT WORK

Recent work, as yet unreported but known to be relevant and valid, has involved spills of up to 100kg of aged LNG and liquid nitrogen on a specially constructed pond. RPTs are initiated by firing a detonator, suspended below the water surface. Although violent explosions are produced in which virtually all of the LNG is involved no damage to the supporting steel gantry has occurred, over a large number of tests. In only one case did ignition of the LNG vapour occur and this was associated with the explosive detonating cord used to initiate the spill. Even then, the bulk of the released LNG produced an RPT which did not ignite although adjacent to the burning vapour. Overpressure measurements have not been reported.

Tests on liquid pool spreading of LNG, again unreported, have been carried out to study the characteristics of the LNG water interface and vapour cloud. In these tests small scale ‘pops’ reported in earlier work have occurred. The LNG aged as it flowed across the pool and then produced small RPTs which occurred spontaneously at different positions across the surface. Again, no structural damage of the pool walls has occurred.

A.2.5 CONCLUSIONS – RELEASE CONSEQUENCES – LNG EXPERIMENTS

A2.5.1 DISPERSION

Dispersion trials on water (Maplin Sands, Thorney Island, China Lake and Burro/Coyote) show that an LNG release results in a low lying heavy cloud of vaporised LNG with well defined edges made visible by condensed water vapour. The LFL is contained within the limits of the visible cloud with distances from the release point to LFL for a 20m^3 release over 10 minutes typically between 110 and 150m (propane ranged between 210 and 400m). These distances increase up to 400m for a 40m^3 spill.

Larger spills of up to 200m^3 over a similar period from a shipboard jettison system also resulted in inferred downwind distances to LFL of up to 400m although a visible cloud extending up to 2000m is possible. Generally the limit of the danger zone is taken to be the 0.5 LFL level which is well within the confines of the cloud. In each test the cloud height was found to be in the order of 10 to 12m. By comparison propane was found to give a similar cloud (i.e. cold and ground hugging) but the spread was much greater. The LFL of propane (2% volume) was found to be outside the limits of the visible cloud. Tests carried out to study the effectiveness of a restraining fence indicated that the distance to LFL would be significantly reduced with such a fence in place.

Bifurcation of a gas cloud can produce fingers of higher concentration gas than the average predicted for that distance.

All vapour dispersion tests carried out on flat ground and water surfaces are acknowledged to give conservative results. The effect of obstructions, barriers, etc., would have the effect of reducing the spread of the cloud due to improved mixing and higher atmospheric turbulence levels.

A2.5.2 IGNITION

Ignition trials on dispersed unconfined LNG vapour clouds have confirmed that no significant overpressures are developed. Flame speeds are in the order of 10m/sec and measured overpressures less than 1mbar and the flame may not be sustained throughout the whole cloud.

In order to produce high flame speeds (i.e. > 100m/sec) in a methane gas cloud a high degree of confinement and congestion is required, for example in and around buildings, process plant and pipework. Overpressures in this event would be damaging but restricted to within the confined region, dying away rapidly in the unconfined part of the cloud. To date there have been no reports of a detonation in an unconfined methane gas explosion. Flame fronts in unconfined LNG vapour clouds have been observed to extinguish and not propagate through the whole cloud, or stop and be held stationary by the wind at some point away from the source. In seven LNG cloud ignition tests the flame burnt back to the source on only one occasion.

A2.5.3 POOL FIRES

Fire tests using pools of LNG up to 35m diameter have been carried out and measurements of emissive power show that above 20m diameter pool diameter the emissive power reaches a maximum of approximately 250kW/m^2. It should be noted that the value of emissive power obtained from test measurements is dependant on an idealised flame shape which must be adopted for the calculations. Values of emissive power from different tests should only be compared if the same idealised flame shape is adopted.

A2.5.4 RAPID PHASE TRANSITIONS

Ignition and sustained combustion of a vaporised LNG cloud under normal release conditions is difficult. However multiple ignitions are likely, probably resulting in a burn back to source.

Unconfined LNG vapour cloud explosion or detonation has not been demonstrated in experimental work and is most unlikely in practice.

Confined detonation would only occur in extremely congested areas, and the detonation is not expected to have much effect outside such confinement

External ignition will be a slow moving flame ~10m/s)

Rapid Phase Transition will not light the gas cloud, but could cause damage to the ship or machinery though localised overpressures

In Terms of pool spread, LPG and gasoline present a greater hazard than LNG

Rapid Phase Transition (RPT) occurs when LNG that has aged in storage, due to relief venting of vapour, is released onto water. Alternatively, if a volume of LNG (0.5m^3 and above) is released onto water it ages due to evaporation and can undergo a RPT after a delay of several seconds. No ignition is associated with the RPT effect and it has a limited capability for damage to structures due to the physical explosive effects.

Multiple RPTs of varying strengths can occur over the area of the release, the shock waves from each contributing to the initiation of others. Damaging overpressures occur only very close to the source. No ignition of vapour has been observed during an RPT. However, ignition of the gas cloud as a result of RPT damage to neighbouring equipment or instrumentation has occurred.

Releases onto water around jetties of a piled construction may involve the flow of the LNG pool and vapour cloud beneath the jetty. The vapour in this case could engulf the construction and any sheltering effects will prolong the duration of the cloud. In the event of an RPT beneath a jetty, damage could occur. However, a potential danger resulting from RPTs is cracking of the ship's hull as a result of low temperature embrittlement due to contact with the LNG.

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Property	LNG	Methane	Propane	Butane	Chlorine	Ammonia
Boiling point (ºC)	-161	-161	-42	-1	-35	-33
Liquid density (kg/m^3) at normal boiling point	415-435	415	585	600	1563	817
Minimum Ignition Energy (mJ)	0.29	0.29	0.25	0.25		100
Auto-ignition temperature (ºC)	540	540	450	405		651
Flammability range in air (%v/v)	5-15	5-15	2-9.5	1.9-8.5		15-28
Buoyant at NTP	Yes	Yes	No	No	No	Yes
Smoke production during fire	Low	Low	High	High		No
Toxic	No	No	No	No	Yes	Yes
Corrosive	No	No	No	No	Yes	Yes
Pollutant	No	No	No	No	Yes	Yes

Table A2.1 : Typical Properties of Selected Liquefied Gases

Sources: [A2.14, A2.15, A2.16]

Test Facility	Date	Spill Size	Release on:	Pool Fire	Vapour Cloud Dispersion	Vapour Cloud Ignition	Rapid Phase Transition
LNG Carrier (Shell)	1974	$193m^3$ over 10mins	Water	-	Dist to 0.5 LFL: 700m	-	-
China Lake (U.S. Coastguard)	1978	$5.7rn^3$ (15m diam.)	Water	EP (Average): 210±65kW/m^2	-	-	-
China Lake (Burro Series)	1980	$40m^3$	Water	-	Dist to LFL: 140 – 400m Cloud Depth: 10m Numerical modelling verification	-	Overpressure: 50mbar @ 30m
Maplin Sands (Shell UK)	1982	$20m^3$	Water	EP (Average): 203±31kW/m^2	Dist to LFL: 110 - 150m	Flame speed: 10m/s Overpressure: insignificant EP (Average): 173±20kW/m^2	-
Thorney Island (Refrigerant 12)	1984	$2000m^3$	Land	-	Vast amounts of data – numerical modelling verification	-	-
Montoir	1989	$238m^3$ (35m diam.)	Land	EP (Average): 270kW/m^2 max	-	-	-
American Gas Research Institute (AGRI)	1989	$50m^3$	Land	-	Wind tunnel models and numerical modelling verification	-	-
U.S. Coastguard	1972	$8m^3$	Water	-	-	Ignition: difficult Overpressure: insignificant	No definitive RPTs
Shell USA	1972	0.2 - $0.26m^3$	Water	-	-	-	Violent small scale reactions
China Lake 1974	1983	$30m^3$	Water	-	-	-	Overpressure: 50mbar @ 30m 0.2bar @ 15m
	1990	$0.24m^3$	Water	-	-	-	Work not yet reported – pool 'pops' experienced

Table A2.2 Summary of LNG Release Experiments

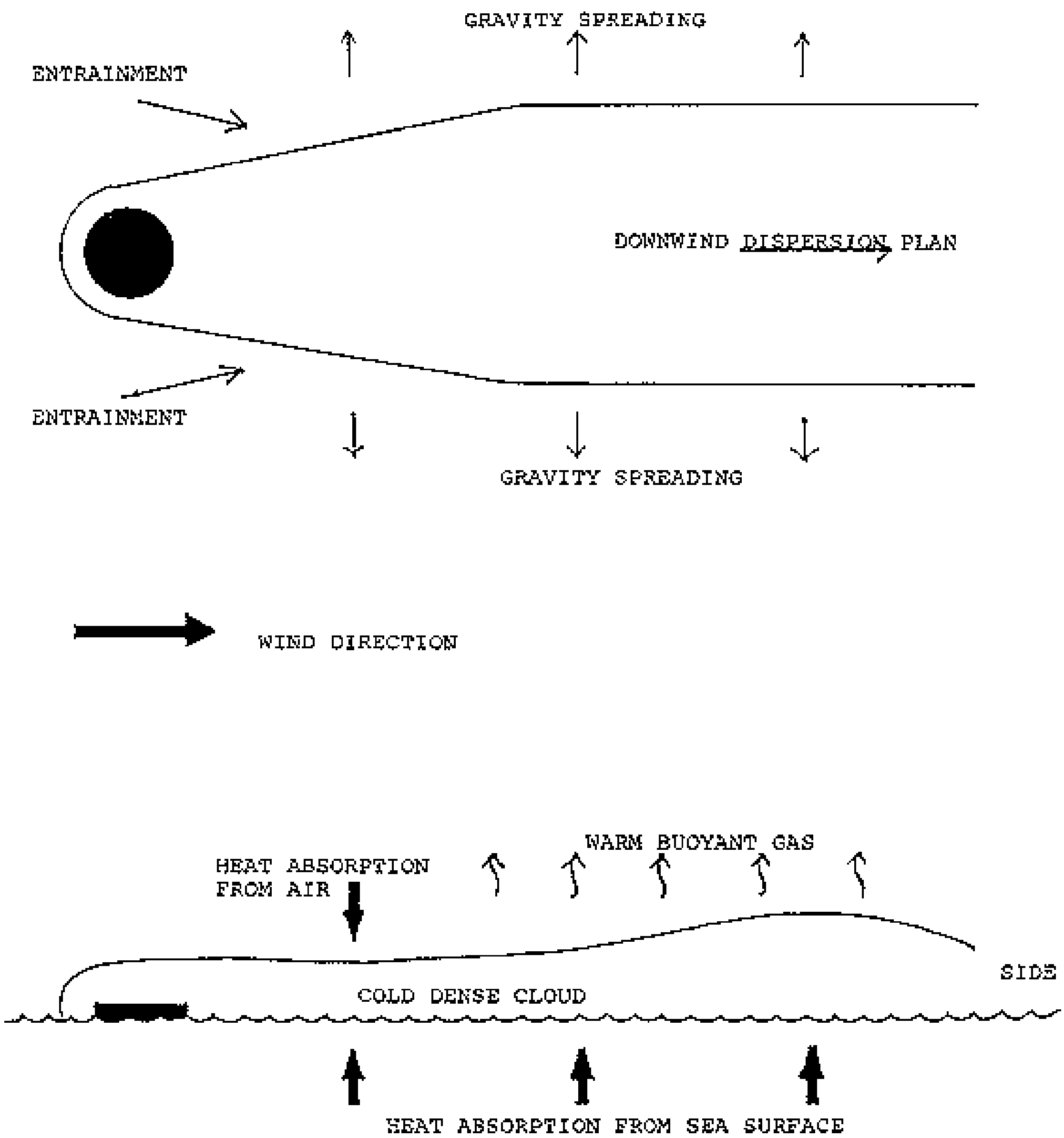

Figure A2.1 : Idealised Gas Dispersion

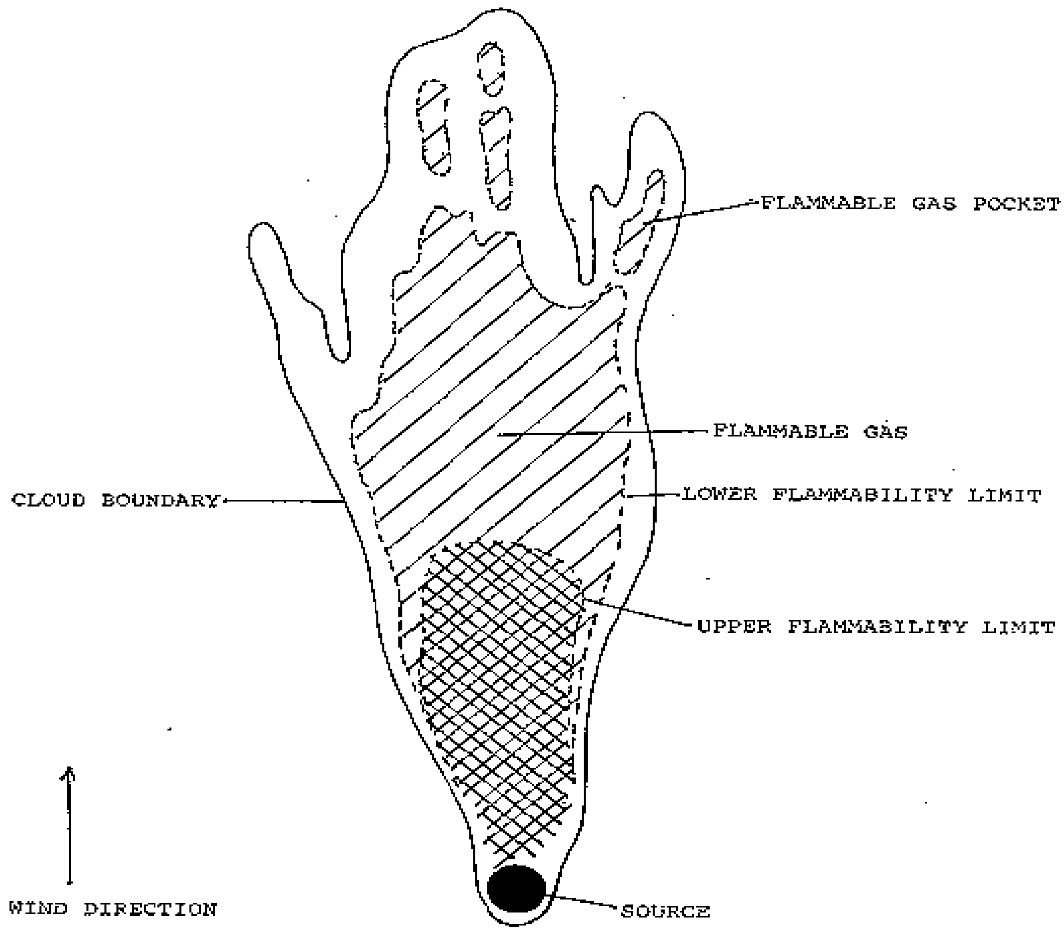

Figure A2.2 : Representation of Flammability Limits Within a Gas Cloud

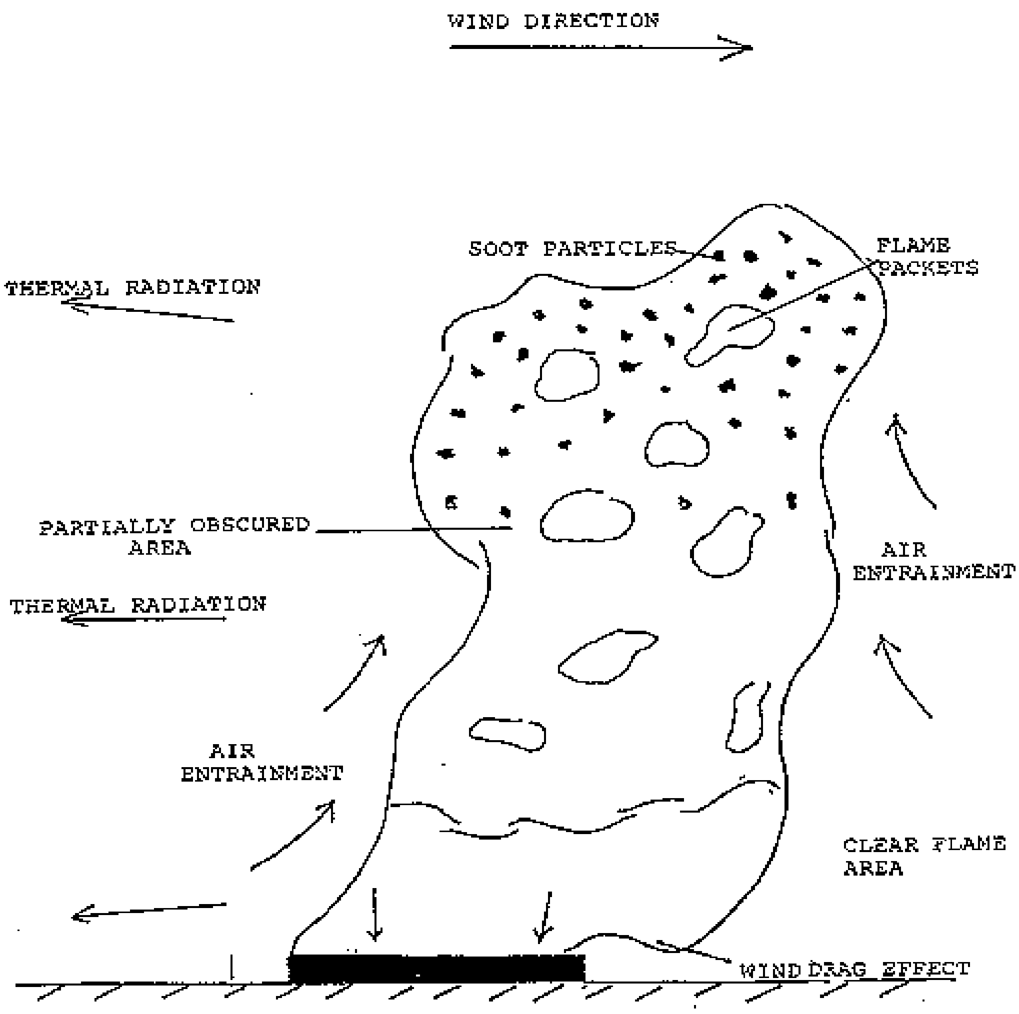

Figure A2.3 : Typical LNG Pool Fire

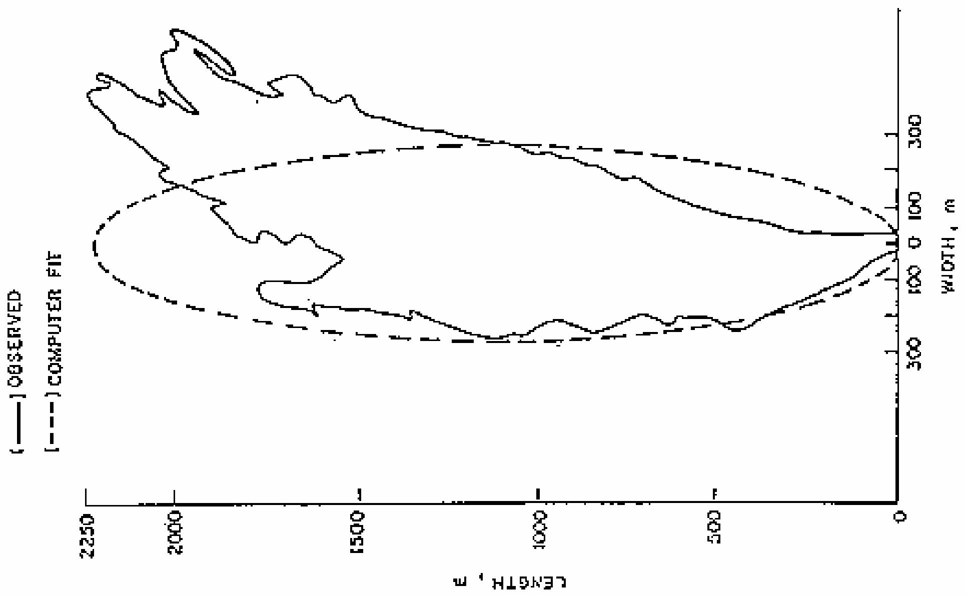

Figure A2.5 : 1188 m^3/hr LNG shipboard release

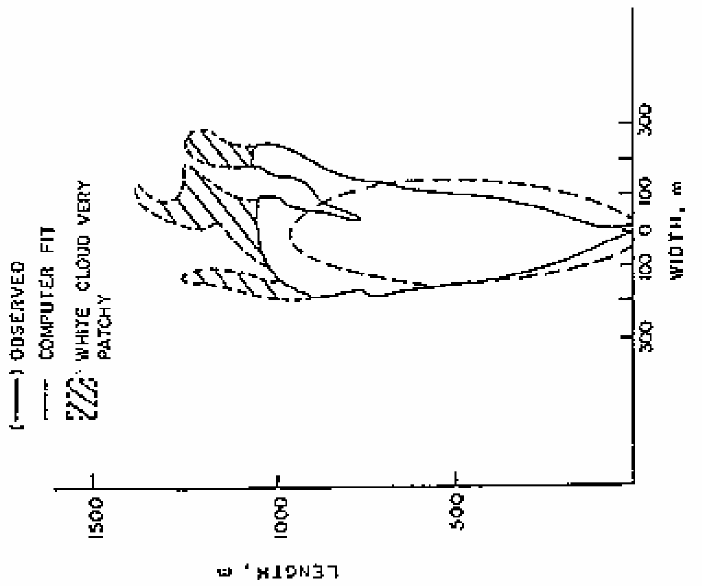

Figure A2.4 : LNG Shipboard Release [Ref. A2.1]

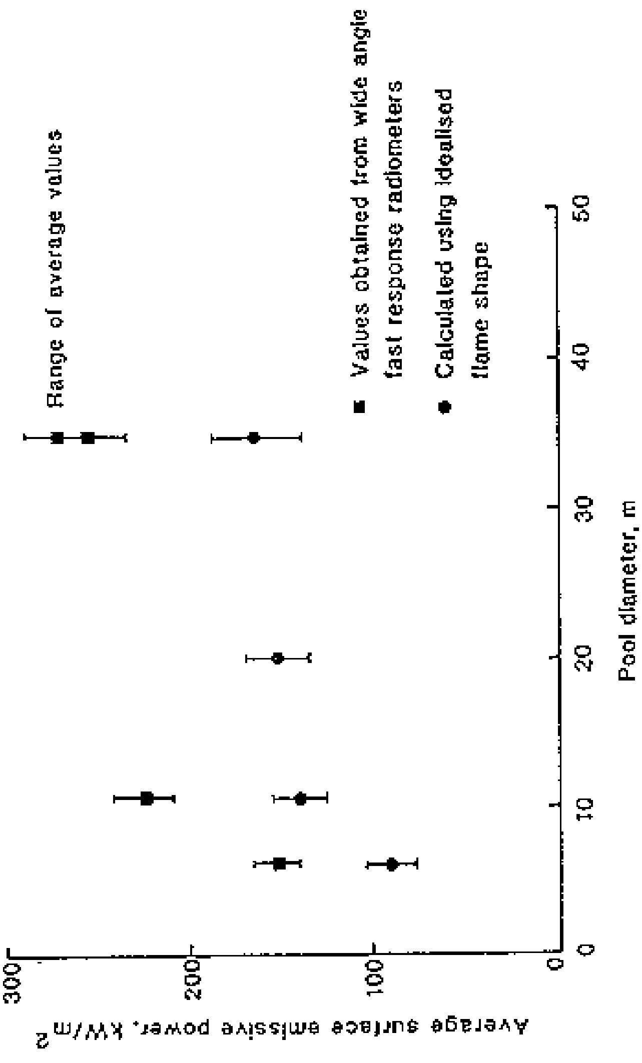

Figure A2.6 : Average Surface Emissive Power Versus Pool Diameter [A2.8]

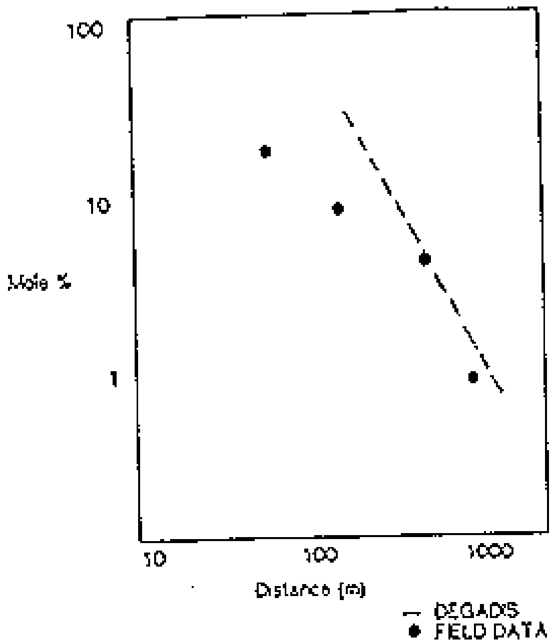

Figure A2.7: Comparison of Degadis Calculations and Maplin Field Data [4.9]

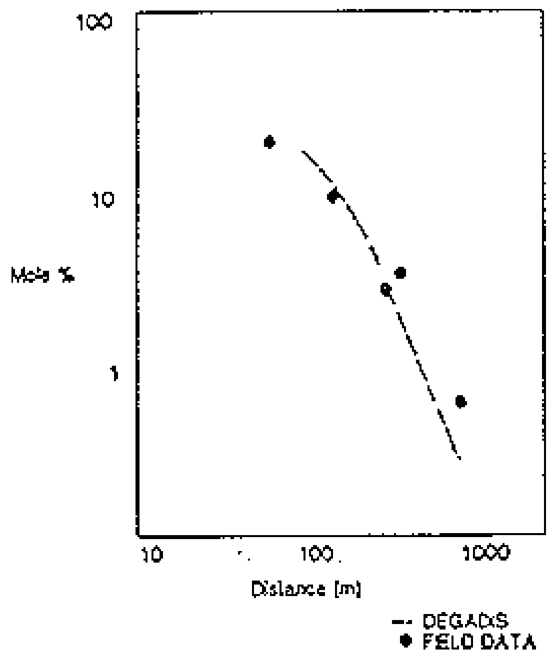

Figure A2.8 : Comparison of Degadis Calculations and Field Data

A3 RELEASE CONSEQUENCES -THEORETICAL MODELS

A.3.1 OVERVIEW

This review has covered the applicability of risk models when evaluating consequences of an incident involving LNG. These predictive models are necessary to address aspects of behavior which are outside of recorded experience, i.e. actual incidents or experimental observations.

Use has also been made of Trinity Consultants (DEGADIS) software to determine the characteristics of pool fires following a missile or explosive device attack.

A.3.2 GENERAL APPROACH TO RISK ASSESSMENT MODELS

The purpose of this section is to review models, including aspects of quantification, that have been used in risk analyses, i.e. in evaluating the likelihood and/or consequences of significant identified hazards.

The structure of the following review is firstly to consider the physical effects of the release of LNG and how these phenomena are modelled in the Section A3.3, and then to discuss the various accident scenarios resulting in release of LNG and their development in Section A3.4.

A final note on the system definition aspect is that the studies relate to the generic LNG tanker configuration, as specified by relevant statutory and classification requirements. Safety considerations have been extensively developed and expressed explicitly and implicitly in these. The SIGTTO report [A3.7], for example, provides an overview of these essential engineering safety features and assumed design accident scenarios, and these vessel configurations form the basis for review.

A.3.3 SPECIFIC THEORETICAL MODELLING OF LNG RELEASES

A3.3.1 CHARACTERISTICS

Vaporised LNG is not toxic, the gases in question being unabsorbable by the bloodstream. However, the gases can act as asphyxiants by deprivation of oxygen. Furthermore, frostbite and even complete immobilisation due to the low temperature, are possible. These effects will only occur close to the source. Frostbite may have contributed to the development of actual incidents involving the accidental discharge of liquefied gas on land. However, no instances of asphyxiation or frostbite have been reported during transport by sea. Fire and deflagration are overwhelmingly the most important potential consequences.

There are four types of significant consequence following the accidental release of LNG from a vessel, that have potential to cause injury or damage to property, i.e.

- brittle fracture of hull structure due to contact with the cold fluid;
- physical vapour explosion or 'Rapid Phase Transition' as cold liquid contacts water;
- pool and flash fire due to ignition of vapour during evaporation;
- gas cloud conflagration due to ignition of gasified LNG after evaporation.

Theoretical models, and experimental investigations exist on each of these phenomena. Using this knowledge it is possible to estimate for given circumstances, i.e. for a given size and duration of release, and for given atmospheric conditions, the effects on people and property surrounding the release. The number of people affected and the severity levels may be predicted if assumptions are made for the distribution of personnel around the incident.

A3.3.2 BRITTLE FRACTURE

Contact of LNG with metallic and non-metallic objects will cause rapid cooling and shrinkage. Whilst concrete may withstand LNG, carbon and low alloy steels are particularly vulnerable. This is because they are subject to a ductile to brittle transition at low temperatures. Incidents have occurred on LNG carriers in which deck plating has cracked due to LNG spillage. Brittle fractures do not necessarily have a significant influence on the structural integrity of the ship, but may make a further spillage of LNG possible.

The simplest approach to estimating the extent of damage is to assume that brittle fracture will occur where material is cooled to below the brittle transition temperature. A more rigorous approach using fracture mechanics will investigate stresses and parent material and weld properties.

Computer codes which model the temperature distribution in one, two and three dimensions for both steady-state and transient conditions, may be applied. An example may be found in the paper by Solberg and Skramstad, [A3.8].

A3.3.3 RAPID PHASE TRANSITION

A physical vapour explosion or Rapid Phase Transition (RPT) may occur on contact between LNG and water and has already been discussed in Section A2.

A theoretical analysis by Enger and Hartman [A3.9] has shown that explosion should occur only when methane is present in the LNG to a concentration of less than 40 mol %. This is because high concentrations of higher hydrocarbon, i.e. ethane, propane or butane, promote vapour nuclei. This concentration limit on explosion has been verified, with minor exceptions which are not considered important, by the test programmes described by McRae and Burgess et al, [A3.10 and A3.11].

The ageing of LNG may cause the 40 mol % to be reached, due to the vaporisation of methane. However the total amount of liquid evaporated would have to be very large. If the initial methane content of the LNG were 95 mol %, then more than 90% of the initial volume of liquid would have to be lost for the explosive composition to be reached.

Ageing may occur in-situ during a spill. During a spill, the LNG will spread out over the water and become enriched as the methane evaporates. Evaporation will be more rapid toward the centre of the spill. In localised areas, the superheat limit will be reached and vapour explosions may occur. However such localised explosions are of very low magnitude and are usually termed 'pops'. Their low magnitude is due to the localisation of the area over which the superheat limit is reached, and the thinness of the LNG layer after the spill has spread.

The theoretical analysis [A3.9] described above has demonstrated the validity of the Superheat Limit Theory to obtain approximate estimates of the degree of superheat. This has been applied by Vaughan and Briscoe, [A3.12] to provide theoretical estimates of explosion overpressure. From this work, it is considered that overpressures in the region of 40bar may be generated. Such overpressures could be very damaging if expressed over a wide area. However, these high initial pressures would be experienced over a very small volume, the pressure decaying rapidly with distance.

Reliance is placed on experimental studies [A3.10 and A3.11] to estimate the range of pressures which may be expressed at significant distances. From this work, it is obvious that very large pressures are experienced only very close to the interface. For instance, the overpressure will decay to 4.0bar at a distance of a few centimetres. Small distances such as this are not relevant. In one instance an overpressure of 0.2bar was experienced at a distance of 15m. An overpressure of 0.2bar would cause significant damage, in particular atmospheric tanks would be ruptured and pipe deformation would take place, but human fatality at this overpressure is unlikely. Furthermore, personnel are unlikely to be present within a distance of 15m from the source of a vapour explosion, even assuming that this 'worst case' would be experienced in practice.

In summary, the physical vapour explosion or RPT that may occur on contact between LNG and water is not considered to be a significant risk. Ignition will not occur, and it is unlikely that significant pressures will exist at distances from the source where personnel will be present. The possibility of some hull damage cannot be entirely discounted, however.

A3.3.4 EVAPORATION FROM A POOL

On release to the atmosphere, LNG rapidly vaporises. Depending on the size of the hole in the tank or loading line, a large proportion or even all of the LNG may vaporise before reaching the sea surface (or solid surface if on land). The vaporised LNG will form a cool, dense cloud. The spread of such a cloud is discussed in Section A3.3.6.

The likelihood that a pool would be formed, and the extent of any pool, is dependent on the characteristics of the discharge. There are a number of important parameters, namely;

(a) rate of discharge;
(b) rate of vapour generation during discharge;
(c) rate of spray or droplet formation during discharge, i.e. aerosol formation;
(d) distance of hole above sea (or ground) level.

(a) is dependent on the static and hydrostatic pressure within the vessel or pipe, and on the hole dimensions, and (a), (b) and (c) are mutually interdependent. The shape of the hole and degree of atmospheric humidity may also be important. The most difficult parameter to estimate is the extent of aerosol formation, (c). This parameter together with (d), determines the extent of any pool formation. The computer code HAZ Professional, offers one of the most advanced estimation techniques in respect of the evaporation and dispersion of LNG. However, in addition to using a technique which can provide accurate results, it is equally important to ensure that the conditions of discharge are realistic yet sufficiently conservative.

A pool is more likely to be formed should the discharge be instantaneous, or nearly so. For a liquid that does not evaporate, the following formula describes the rate at which the pool will spread;

$v(t)$ = rate of pool spread = $(2gf(h(t) - h_{min}))^{1/2}$

where g = acceleration due to gravity
$h(t)$ = height of pool at time t
h_{min} = minimum height that the pool can attain

In the case of spills on land, f=1. For spills on water,

$f = (1 - d_1)/d_w$

where d_l = density of the LNG
d_w = density of the water

Due to fairly rapid evaporation, a pool of LNG would spread to a lesser extent then that determined from the above formula. Heat transfer to the pool, and therefore the rate of evaporation from the pool, is dominated by heat transfer from the substrate, i.e. the water or solid underlying the pool. As explained in Section 3.2 evaporation from a pool on water is more rapid than evaporation from a pool on the ground. The rate of evaporation due to heat transfer from a water substrate can be expressed approximately as follows, although models such as HAZ Professional use more rigorous techniques;

$$Q(t) = \frac{25}{L} \pi R^2(t)$$

where L = latent heat of evaporation of the LNG = 510 kJ/kg
$R(t)$ = radius of pool as function of time

The heat transfer processes of solar radiation and convection from the air also contribute to the rate of evaporation. These latter two processes make a small contribution in comparison to the rate of heat transfer from the water. However they are included in advanced models such as HAZ Professional.

A3.3.5 POOL AND FLASH FIRES

A 'pool fire' of LNG on water will be short-lived provided the spill is not confined. Even without fire heating the pool, evaporation would take place quickly. This situation is very different to the combustion on land of a spill of LNG, where the spill may be bunded to form a deep pool. On water, for a pool fire to take place, ignition would have to occur early. In such a case burning liquid could be expelled over a wide area resulting in a pool of LNG in the order of tens of millimetres in depth.

The overall duration of a pool fire is directly dependent on the thickness of the pool and the mass burning rate. For a typical mass burning rate for LNG as given by Lees [A3.13] the thickness of the pool will be reduced at the rate of approximately 0.2mm/sec. This does not take into consideration the effect of wind and waves and localised RTP's in thin films of LNG, all of which could lead to fragmentation of the pool and more rapid evaporation.

LNG fires are unique amongst liquid hydrocarbon fires in that they produce a limited amount of smoke. This means that the emissive power generated from the flame, is higher than that generated by flames of higher hydrocarbons. The emissive power increases with the size of the pool up to a certain limit. The limiting value of emissive power has been taken to be about 200 kW/m^2 [A3.14], but recent tests reported by Nedelka et al [A3.15] indicate a higher value of up to $300kW/m^2$. This value may be reached by a pool of approximately 20m diameter. Thereafter soot produced by larger fires tends to obscure the flame.

Crucial to the evaluation of the hazard of a LNG pool fire is the estimation of the radiation level at a given distance from the pool. This is done using the view factor method [A3.13]. This method is used in the HAZ Professional computer package.

Flash fire is the term generally given to combustion of vapour during evaporation from a pool. Ignition may take place remote from the pool, and the flame could travel back to the source of the fuel where a pool fire would result. However, ignition of the pool is likely to occur in only a minority of cases (Section A2.4). The distinction between flash-fire and gas cloud conflagration (or gas cloud deflagration) is somewhat arbitrary, although if ignition were to take place in the early stages of evaporation, the phenomenon would be more correctly termed a flash fire.

A3.3.6 DISPERSION OF VAPORISED LNG LEADING TO GAS CLOUD DEFLAGRATION

Estimates of the size and shape of a cloud of vaporised LNG begin with estimates of the source term. The source term is the velocity and area over which fluid is expelled. Estimation of the source term is complicated by factors such as the velocity at which LNG is discharged, the evaporation rate of any droplets, and whether or not a liquid pool is formed from which evaporation would take place.

Continuing the discussion of Section A3.3.4, a significant proportion of the LNG may be vaporised soon after discharge. The proportion which vaporises, or 'flashes', may entrain liquid in droplet, or aerosol, form. At the temperature of discharge, -160ºC, the density of the vapour is higher than that of air, and the vapour sinks. As the vapour is diluted and warmed by air, the density of the mixture is reduced. Water vapour in the air will condense, and even crystallise, adding heat which will lead to a further rise in temperature and increased buoyancy. However, counter to this, the air entrainment during dispersion will progressively evaporate the liquid droplets, cooling the cloud.

Additional to the phase changes within the cloud, evaporation from a pool will take place, should a pool have been formed. Complex heat exchange processes accompany the dilution of the cloud by entrainment of air.

Despite the mitigating effect of air entrainment and condensation of water vapour, the cloud or plume will be denser than air for much of its length.

Dense clouds require a rather different approach to clouds that are lighter than air or nearly neutrally buoyant, the mechanism of air entrainment being different.

As LNG is stored at low vapour pressure the kinetic energy of the discharging stream is unlikely to significantly contribute to the dispersion process. Advection of the cloud is described with sufficient accuracy by a power-law wind profile. The rate of air entrainment is given by Eidsvek [A3.16] and the concentration distribution within the cloud by Colenbrander and Puttock [A3.17].

Throughout the period in which the cloud slumps due to gravity, the air entrainment rate is so low that the height of the cloud decreases. However, as time passes, air is entrained into the cloud, the density difference is decreased and the height of the cloud gradually increases. The termination of the dense cloud dispersion or 'active' dispersion regime, is considered to occur when both of the following conditions are satisfied;

$$\frac{d_c - d_a}{d_a} < 0.005$$

$$Ri = \frac{ghd(d_c - d_a)}{u^2 d_a} > 10$$

Where:

d_a = density of air

d_c = mean density of cloud

h = height of the cloud

g = acceleration due to gravity

u = windspeed
Ri = Richardson number

The Richardson number is a criterion by which to determine whether a system which is just slightly turbulent, remains turbulent or becomes laminar. The motion remains turbulent for Ri<1 and becomes laminar for Ri>1.

Subsequent to the 'active' dispersion regime, the cloud undergoes 'passive' dispersion, in which dispersion is dominated by diffusion and turbulence rather than momentum and density differences. This is typically modelled using the Gaussian formulation [A3.13].

The above techniques broadly apply whether the release is instantaneous or continuous. The concept of instantaneous release of vapour does not strictly apply to LNG which takes a finite time to evaporate. As discussed above, the source term for LNG will be continuous, two-phase, and due to the non-uniform evaporation rate, transient. The formulation for a transient release is essentially the same as that for a steady-state release, with the exception that the concentration along the centreline of the cloud is given by Havens and Spicer [A3.18]. In order to take account of a transient discharge, it is necessary to discretise the source term into finite intervals the duration of which depends on the rate of change of the release function.

Meteorological and topographical conditions are very important in the dispersion of a vapour plume. The most important meteorological parameters are wind speed, wind direction and atmospheric stability.

Higher wind speeds will impart greater momentum to a cloud and therefore, cause it to approach a given target more quickly. However, higher wind speeds also increase the rate of air entrainment. The trend is opposite for lower wind speeds and the wind speed that will cause a cloud to travel the furthest distance usually lies in the range 2-10m/s. Data on wind speed and direction are available for any given location in the form of a wind rose. This is a polar diagram in which the length of the sections of the spokes is proportional to the observed frequencies of wind direction and speed. The predominant wind direction is usually called the prevailing wind. This wind direction only applies, however, for a relatively limited proportion of time, and it is usually necessary in dispersion calculations to consider other wind directions.

Of further importance is the wind persistence. The more that the wind deviates from a given sector in a given period, the less the persistence. The lower the persistence, the lower is the likelihood that a dangerous gas concentration will reach a given location.

Windspeed varies with height. At some height above the ground the windspeed is determined by the pressure gradient, as given by the lines of equal barometric pressure, or isobars, and is therefore called the gradient level wind. Nearer the ground the windspeed is reduced by friction effects. It is only the near-ground region which is important to the dispersion of LNG, since the density of the cloud in the early stages will limit its vertical spread. In this region, the windspeed vertical profile is given approximately by the relation;

$$u = u_r \, (h/h_r)^p \qquad z < z_r$$

Where u is the wind speed and z the height above ground level. Subscript r refers to a reference height. The index p depends on the atmospheric stability condition which is discussed below.

The principal topographical factor which affects dispersion is the surface roughness. The surface roughness determines the degree of turbulence created by wind of a particular velocity as it passes over the ground. The effect is to modify the dispersion coefficients which determine the degree of air entrainment.

The stability of the atmosphere is essentially the extent to which it allows vertical motion by suppressing or assisting turbulence. It is a function of both the wind shear and the vertical temperature profile, although it is manifested by the latter. It is usually expressed in terms of Pasquill's six stability categories A to F [A3.19]. The mid range categories define neutral or nearly neutral stability, when there is only a slight or negligible deviation from the normal atmospheric vertical temperature gradient of 0.01°C/m. The most unstable condition, category A, exists when the temperature gradient is highest, in conditions of low windspeed and strong sunshine. During daylight hours the category corresponding to the most stable conditions is D, corresponding to high windspeed and/or cloudy weather. At night time, the trend of stability with windspeed is reversed, and category F is possible. Maps showing the relative preponderance of a given stability condition over given areas are available. The effect of stability level is to modify the dispersion coefficients and the index p described above.

One major area of uncertainty on the dispersion of LNG vapour from a liquid pool is the rate of entrainment of air due to turbulence generated by boiling. It is thought by Kaiser [A3.20] that this may have a significant effect, enhancing dilution of the vapour and limiting the hazard range. There is no data from which the importance of this effect may be estimated.

Ignition of a large quantity of gasified LNG in the open air will lead to a deflagration. Only that part of the cloud in which the concentration is between the lower and upper flammable limits (5% and 15% by volume respectively) can ignite immediately. Once ignition has occurred a wind is created which may draw gas that was originally too lean or too rich, into the deflagration. However, this effect is thought to be limited (Section 3.1.3).

The highest overpressure that has been obtained experimentally for a totally unconfined, quiescent ignited methane cloud is approximately 1mbar. This overpressure will cause no property damage. It assumes that the explosion is a deflagration, in which the flame front travels at a velocity equivalent to a fraction of the speed of sound. In the alternative, a detonation, the flame front travels at the speed of sound and overpressures are sufficient to severely damage structures and kill people exposed. Detonations are more likely to occur if the ignition source is very strong or if there are many obstacles to the flame front. However, detonations are thought highly improbable for a methane cloud (Section A2.1.2). Overpressures of up to 0.1bar have been measured in highly turbulent clouds with obstructions present, even though the phenomena has been one of deflagration rather than detonation. These conditions too, are most unlikely to occur during the accidental discharge of LNG since the discharge may not be pressure driven and there is little process plant, etc, to cause congestion within the cloud as is necessary to raise the overpressure.

The amount of gas that could contribute to the explosion is estimated from dispersion calculations. The overpressure will decay rapidly outside the flammable region and may be predicted by the TNT equivalence model [A3.13].

The thermal radiation from the explosion will kill all people exposed to it, although people within buildings would be likely to survive. The thermal radiation hazard from a burning cloud does not extend significantly beyond the boundary of the lower flammable limit.

A.3.4 REVIEW OF LNG RISK ASSESSMENTS

Following cargo tank rupture there are a number of considerations. Outflow can be calculated based upon the assumed or calculated hole size and its location relative to the waterline. LNG, water or both may spill or flood into the hull. LNG will cool down the structure which may receive heat input from surrounding water, flood water or ice. It is considered by Solberg and Skramstad [A3.8] that the resulting damage will be localised and will not affect the integrity of the hull overall, for example, leading to break-up.

Ignition probabilities are either instantaneous, or delayed. It is generally considered by Wicks [A3.1] that collision scenarios will result in immediate ignition due to heat generated by friction or damage to electrical circuits, etc.

The possibility of explosion of gas within the hull is considered in [A3.8]. If explosive mixtures developed over significant volumes, then the propagation of the explosion through vessel internals could develop damaging overpressures.

Delayed ignition will occur when the dispersing LNG vapour finds an ignition source. Ignition could be from a shore based source or the vessel itself. Due to the shallow nature of the cloud nearer the discharge, ignition by a source within the accommodation or engine room is of reduced probability although this is dependant on wind conditions. It should be noted that although immediate ignition is assumed more likely, delayed ignition has greater potential to threaten populations off-site. The choice of conservative or representative ignition probabilities in past work has depended upon the population at risk.

The model used by Welker [A3.2] considered a 37,500m^3 instantaneous spill. A pool of 360m radius was generated. The extent of the flammable cloud extended to a maximum of 1km to 6km with wind speed varying from calm to 15m/s.

It is not practicable to evaluate the whole range of release scenarios and so representative cases (generally conservative) are taken. An instantaneous release of an entire tank contents could be chosen, although this scenario may be considered unrealistic. Otherwise, the release of a significant portion of the volume instantaneously, or of a volume continuously over some time period will be chosen. The balance of instantaneous release with its short term consequences and the longer term consequences of a continuous release must be carefully considered to establish the most realistic measure of risk according to the subject at threat.

A.3.5 CONCLUSIONS – RELEASE CONSEQUENCES - THEORETICAL MODELS

> As the gas cloud warms up the gas will become buoyant, i.e. lighter than air, and will rise away from the surface.
>
> Upon release to the environment LNG vaporises rapidly producing a cold methane gas cloud. As this gas cloud is non-toxic there is no significant direct environmental damage caused by a spill and hence there is no clean up costs other than those arising from secondary escalation factors.

A.3.6 REFERENCES

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A4 EXPLOSIVE CALCULATION

A.4.1 EXPLOSIVES ATTACHED TO THE OUTSIDE HULL.

An explosion on the outside of the hull may or may not breach the hull. If the outer hull is breached it is likely that due to the double hull structure the internal structure will absorb the shock by deforming. There is a good possibility that the inner hull will deflect the residue of the explosive force and remain intact.

Above Water Line

A significant sized charge of TNT at a stand off of 1 m will be required to cause a hole of 1 m diameter in the external plating of the hull above the waterline due to impulse. This assumes that the threat is from a dinghy located adjacent to the hull of the tanker.

While it is not possible in the time allowed to undertake the complex analysis necessary to determine the effect of the detonation on the internal hull, it is thought that the distortion from such an charge will extend to the inner hull. The outcome is likely to include the pushing of local structure through the bulkhead causing a hole at the very least cracking or tearing of welded joints at the connection to the inner bulkhead will occur

A detonation of this size will cause a fireball, which will last for 2 seconds. As any gas is likely to start escaping from the hole while the fireball is still alight there is a significant risk of the escaping fuel being ignited.

At Water Line

An additional mechanism which must be considered is that of shock. An explosive event which takes place at the waterline initiates a shock wave that propagates through the water. When the shock wave impacts the hull of the ship, the energy in the shock wave is transferred to the structure. This can be substantial in size. A significantly sized charge will have sufficient energy to cause structural distortion of the order of 5m of the ships side plating fore and aft for the detonation site. The extent of the distortion will also extend inboard between 5-10m. The tanks of both types of LNG ship considered will therefore certainly be ruptured. In addition should the detonation site be at a location where the damage extends to two holds then both tanks will cause a 1m diameter to be ruptured. Such an event requires a specific detonation location.

For a detonation in the same location the charge required to produce a 1m diameter shock induced hole in the outer hull will require a much smaller charge than that referred to above. This assumes a rigid connection between the outer and inner hulls.

Shock transferred to the hull will propagate through the structure. Fittings such as pipes valves, etc will experience a shock that could, if the magnitude is great enough, distort or break. It is not possible to estimate the threshold at which the fittings will be broken without extensive assessment of the ship structure.

A.4.2 MISSILE FIRED AT THE SHIP

A missile fired at the ship can either explode on impact or penetrate without exploding and continue to be propelled toward the next object. In the former case the situation is similar to the second scenario of explosives placed on the outside hull. The hull may be breached and the internal structure absorbs the remainder of the blast. The latter case is similar to the first scenario where the tank is breached.

Given the practical difficulties of transporting, preparing and launching modern anti-ship missiles like Exocet, Styx, Silkworm or RBS-15, it is believed that these threats are not likely to be a threat. Smaller anti-ship weapons like the Norwegian Penguin are unlikely to penetrate the outer shell , though the detonation of the warhead almost certainly would. It would be possible work out the risk of penetrating the inner shell, but this has been omitted as the scenario is unlikely.

While the qualification of the likelihood of different weapons penetrating the inner hull has not been attempted, the result is likely to be either:

- For the case when a weapon that fails to penetrate the outer hull on impact, but does detonate. The inner hull and containment system will be penetrated by some 10's of fragments of less than 20mm.
- For a weapon that penetrates the outer hull, the detonation will either be in-between the shells or very close inside the inner shell. The resulting detonation is likely to blow a 2m^2 hole in the inner shell and a similar or smaller hole in the outer shell

More likely is an anti-tank shoulder or pillar mounted type weapon. These are more available, crew portable, and they do not need dedicated vehicles to be transported around in.

In general the anti-tank weapons have a shaped charge warhead lined with a copper cone. Obviously the actual performance varies significantly between different weapons thus the following is a very generalised guide. Shaped charge weapons detonate external to the shell of a target generating a molten copper jet which is capable of lancing through 300mm+ of shell plating. The penetrative capability is significantly eroded by void spaces within the armour of fighting vehicles, but can be expected to breach both hulls. The puncture hole will be small (less than 25mm diameter through the containment system), and behind armour effects of copper cones are limited.

Given the structure of a generic membrane ship, any attack in which the jet produced by the smaller shaped charge is not close to the horizontal is likely to fail due to interaction with the internal structure.. This is a suggested reason why shaped charges did little damage to liquid gas carriers during the first gulf war against 4 targets.

A.4.3 ATTACK AGAINST THE BEAR HEAD SINGLE CONTAINMENT TANKS

The attack methods that have been considered against these vessels are;

- an explosive device attached to the external carbon steel wall of the single containment LNG storage tank; and
- a missile fired at an LNG storage tank.

Single containment LNG storage tanks are designed with a inner 9% nickel single containment wall. The outer carbon steel wall has the primary function to contain cool methane gas, provide support for the steel roof, resist external environmental loadings and contain the storage tank's insulation. Secondary containment is provided by a tank dike designed in accordance with CSA Z276-01 Section 4.2 and NFPA 30 to contain the full tank contents. Either of the above attack mechanisms against a single containment tank is very likely to cause severe damage, in the extreme a catastrophic failure of the tank, resulting in the release of the tank's contents to the diked area around the tank. The resulting scenario will be a dike fire as modelled in Section 4 of this report or generation of a methane gas cloud if the spill is not ignited.

A5 SHIP FMEA

Failure Mode & Effect Analysis	**Date**: 20th January 2004	**By:** S T Parry; A Horwood; D Prentice; D Radosavljevic

LNG Tanker System/Subsystem Description: Under consideration is a membrane type LNG tanker with a double hull with the inner hull acting as the boundary for the liquid gas cargo tanks. On the inside of the tanker outer hull there is an egg-box type structure of steel webs and stiffeners. About 2 metres inside this is a second hull which is supported by the same egg-box structure. The shape of the inner hull is that of the cargo tanks as the internal surface forms the boundary of the tanks. The space of the inner hull is subdivided along the length of the ship and is used to contain water ballast when the ship is not carrying cargo. Consecutive pairs of LNG tanks are separated by a transverse cofferdam.

Item Identity	Event Description	Failure Mode	Failure Effects		
			Local Effects	Next Level of Effects	End Effects
1	Explosive charges are positioned outside of the LNG tanker hull between consecutive cofferdam bulkheads.	1.1 Explosive charge(s) is detonated at a position such that the explosion forces cause failure of the LNG tanker outer and inner hulls two metres above the water line.	1.1 Outer hull of the LNG tanker is likely to be breached; the extent of damage will be dependent upon the type and size of explosive charge used. 1.2 There is potential for an explosion event from a large charge to cause failure of LNG containment either through fragmentation or shock damage. 1.3 Breach of the containment system will result in release of a large volume of LNG. 1.4 Assuming the outer hull breach does not meet the waterline, seawater flooding of the space between the inner and outer hulls is considered to be very unlikely due to the damage position above the water line. 1.5 A breach may result in a large volume of LNG being released into the ballast space with potential for extensive brittle failure of the tanker structure	1.1.1.1 Accumulation of large quantities of LNG in the ballast tanks spaces may cause embrittlement of the longitudinal and transverse containment system supporting structure. It is possible, although highly unlikely, that this will cause collapse of the containment system, rapid escalation of rate of outflow of LNG, and significant loss of vessel longitudinal strength. 1.1.1.2 If the ballast space is flooded prior to failure mode 1.1, the process outlined in 1.1.1.1 will be avoided. 1.1.1.3 There is potential for brittle failure of transverse bulkhead plates at the boundary to adjacent cargo tanks, leading to	1.1 Rate of LNG release will vary depending upon the extent of damage to the containment system and the hull structure. 1.2 LNG will escape through the outer hull penetration and beyond the bounds of the LNG tanker. The release will produce a pool of LNG at sea level and a methane gas cloud. 1.3 The effects are likely to be either a localised fire given immediate ignition and/or a flash fire if the gas cloud disperses beyond the tanker before being ignited. 1.4 The extent of damage and/or number of fatalities will be largely dependent upon when the flammable gas cloud/gas cloud is ignited. The number of

Failure Mode & Effect Analysis		**Date**: 20th January 2004		**By:** S T Parry; A Horwood; D Prentice; D Radosavljevic	
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Item Identity	**Event Description**	**Failure Mode**	**Failure Effects**		
			Local Effects	**Next Level of Effects**	**End Effects**
			(including longitudinal pipe duct) in contact with the LNG. 1.6 A large volume of LNG in the ballast space will cause the vessel to heel/trim towards the vessel breach side, with the potential to lower the outer hull breach to the waterline level. 1.7 A breach of the foremost or aftermost tanks will result in the greatest heel/trim effect. 1.8 There may be a corresponding pressure rise within the confined space, which will be relieved through the outer hull. 1.9 Immediate ignition of LNG within the containment system is highly unlikely. 1.10 There will be some leakage of LNG into the containment system insulation space.	subsequent failure in adjoining spaces. 1.1.1.4 There is potential for air ingress into ballast tanks now containing methane gas. In this event, it is extremely unlikely a ignition source will enter the hole due to LNG flooding out. The space will also quickly fill up with more LNG vapour, ensuring that the resultant mixture will be above the upper flammability limit of Methane. Hence no confined explosion will occur 1.1.1.5 Rapid Phase Transition (RPT) may occur leading to ballast space overpressure against a structure weakened by brittle fracture. 1.1.1.6 Rapid Phase Transition (RPT) of the LNG may occur in the ballast spaces leading to	fatalities through asphyxiation will be largely dependent upon meteorological conditions. 1.5 Thermal radiation from LNG pool fire will affect the structural properties of vessel outer hull. This will not lead to structural failure of the vessel. 1.6 Explosion of methane gas accumulated in shore side buildings. 1.7 Embrittlement of the vessel structure will affect the structural properties of the vessel hull. It is unlikely this will lead to structural failure of the vessel.

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Item Identity	**Event Description**	**Failure Mode**	**Failure Effects**		
			Local Effects	**Next Level of Effects**	**End Effects**
				overpressure against a structure weakened by brittle fracture. However RPT overpressures are known to dissipate quickly over short distances so their effects are limited. RPT overpressures acting on the transverse bulkhead plates at the boundary to the adjacent cofferdams are unlikely to be of sufficient magnitude to cause failure and escalation due to preferential venting through the outer hull. 1.1.1.7 Pool of boiling liquid will form and extend alongside the vessel. This will have the potential for brittle failure of adjacent vessel structures. This effect will be maximised if failure mode 1.1 occurs on the land-side of the vessel whilst at berth. 1.1.1.8 It is likely that the pool of LNG outlined in 1.1.1.7 will be ignited,	

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Item Identity	**Event Description**	**Failure Mode**	**Failure Effects**		
			Local Effects	**Next Level of Effects**	**End Effects**
				forming a pool fire. Radiated heat from this fire will affect the mechanical properties of the hull. 1.1.1.9 There is the potential for ice to form a barrier between the vessel and the pool of LNG. This ice formation may modify the LNG flow characteristics. 1.1.1.10 Moderate/strong meteorological conditions will maximise dispersion of the resulting LNG vapour cloud and minimise risk of gas cloud ignition.	
		1.2 Explosive charges detonated at a position such that the explosion forces cause failure of the LNG tanker outer and inner hulls at the water line.	1.2.1 As per 1.1.1 – 1.1.3 above. 1.2.2 Rapid seawater flooding of the ballast space will occur to the same level as the outside waterline. This flooding will prevent significant amounts of LNG entering ballast space and causing embrittlement of the ballast structure. 1.2.3 A large volume of seawater in	1.2.1.1 Rapid accumulation of seawater in the ballast tanks will prevent embrittlement of longitudinal and transverse containment system. 1.2.1.2 Rapid accumulation of seawater in the ballast tanks will prevent brittle failure of transverse	1.2.1.1.1 As per 1.1.1.1.1 through 1.1.1.1.6 above.

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Item Identity	**Event Description**	**Failure Mode**	**Failure Effects**		
			Local Effects	**Next Level of Effects**	**End Effects**
			the ballast space will cause the vessel to heel/trim towards the vessel breach side. 1.2.4 A breach of the foremost or aftermost tanks will result in the greatest heel/trim effect 1.2.5 Local Failure effects as per 1.1.9 – 1.1.10 above may take place.	bulkhead plates at the boundary to adjacent cargo tanks. 1.2.1.3 Next level effects as per 1.1.1.4 - 1.1.1.12 above may take place.	
		Explosive charges detonated at a position such that the explosion forces cause failure of the LNG tanker outer and inner hulls two metres below the water line.	1.3.1 As per 1.2.1 – 1.2.5 above. Total immersion of the hull breach may cause LNG to 'bubble' into the upper ballast space in sufficient quantities to produce an explosive atmosphere.	1.3.1.1 As per 1.2.1.1 – 1.2.1.3 above.	1.3.1.1.1 As per 1.2.1.1.1 above.
2	Explosive charges are positioned outside of the LNG tanker hull in-line with a cofferdam location.	2.1 Explosive charge(s) is detonated at a position such that the explosion forces cause failure of the LNG tanker outer and inner hulls several metres above the water line.	2.1.1 Outer hull of the LNG tanker is likely to be breached at cofferdam location; the extent of damage will be dependent upon the type and size of explosive charge used. 2.1.2 There is potential for an explosion event from a large charge to cause failure of the two LNG containment systems	2.1.1.1 Accumulation of large quantities of LNG in the cofferdam and ballast tanks spaces may cause embrittlement of longitudinal and transverse containment system supporting structure. It is possible, although highly unlikely, that this will	2.1.1.1.1 Rate of LNG release will vary depending upon the extent of damage to the containment system and the hull structure. 2.1.1.1.2 LNG will escape through the outer hull penetration and beyond the bounds of the LNG tanker. The release will produce a

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Item Identity	Event Description	Failure Mode	Failure Effects		
			Local Effects	**Next Level of Effects**	**End Effects**
			either side of the cofferdam through fragmentation or shock damage. 2.1.3 Breach of the containment systems will result in release of large volumes of LNG. 2.1.4 Flooding of the cofferdam and spaces between the inner and outer hulls is considered to be very unlikely due to the damage position above the water line. 2.1.5 A breach may result in a large volume of LNG being released into the cofferdam and ballast spaces with potential for extensive brittle failure of the tanker structure in contact with the LNG. 2.1.6 A large volume of LNG in the ballast space(s) will cause the vessel to heel/trim towards the vessel breach side. 2.1.7 There may be a corresponding pressure rise within the confined space, which will be relieved through the outer hull. 2.1.8 A breach of the foremost or	cause collapse of the containment system, rapid escalation of rate of outflow of LNG, and significant loss of vessel longitudinal strength. 2.1.1.2 If the ballast space is flooded prior to failure mode 2.1, the process outlined in 2.1.1.1 will be avoided. 2.1.1.3 There is potential for brittle failure of transverse bulkhead plates at the boundary to adjacent cargo tanks, leading to subsequent failure in adjoining spaces. 2.1.1.4 There is potential for air ingress into a breached LNG containment tank containing methane gas. In this event, it is extremely likely that the resultant mixture will be above the upper flammability limit of Methane, hence no confined explosion will	pool of LNG at sea level and a methane gas cloud. 2.1.1.1.3 The effects are likely to be either a localised fire given immediate ignition and/or a flash fire if the gas cloud disperses beyond the tanker before being ignited. 2.1.1.1.4 The extent of damage and/or number of fatalities will be largely dependent upon when the flammable gas cloud/gas cloud is ignited. The number of fatalities through asphyxiation will be largely dependent upon meteorological conditions. 2.1.1.1.5 Thermal radiation from LNG pool fire will affect the structural properties of vessel outer hull. This will not lead to structural failure of the vessel. 2.1.1.1.6 Embrittlement of the vessel structure will affect

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			Local Effects	Next Level of Effects	End Effects
			aftermost tanks will result in the greatest heel/trim effect. 2.1.9 There may be a corresponding pressure rise within the confined space, which will be relieved through the outer hull. 2.1.10 Immediate ignition of LNG within the containment system is highly unlikely. 2.1.11 There will be some leakage of LNG into the containment system insulation space.	occur 2.1.1.5 There is potential for air ingress into ballast tanks now containing methane gas. In this event, it is extremely unlikely a ignition source will enter the hole due to LNG flooding out. The space will also quickly fill up with more LNG vapour, ensuring that the resultant mixture will be above the upper flammability limit of Methane. Hence no confined explosion will occur 2.1.1.6 The explosion forces acting upon the tank sides are likely to be large leading to failure of an already weakened tanker structure. 2.1.1.7 Rapid Phase Transition (RPT) of the LNG may occur in the ballast spaces leading to overpressure against a	the structural properties of the vessel hull. It is unlikely this will lead to structural failure of the vessel.

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			Local Effects	Next Level of Effects	End Effects
				structure weakened by brittle fracture. However RPT overpressures are known to dissipate quickly over short distances so their effects are limited. RPT overpressures acting on the transverse bulkhead plates at the boundary to the adjacent cofferdams are unlikely to be of sufficient magnitude to cause failure and escalation due to preferential venting through the outer hull. 2.1.1.8 RPT overpressures acting on the transverse bulkhead plates at the boundary to the adjacent cargo tanks are unlikely to be of sufficient magnitude to cause failure and escalation due to preferential venting through the outer hull. 2.1.1.9 Pool of boiling liquid will form and extend alongside the vessel. This will have the potential for	

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			Local Effects	Next Level of Effects	End Effects
				brittle failure of adjacent vessel structures. This effect will be maximised if failure mode 2.1 occurs on the land-side of the vessel whilst at berth. 2.1.1.10 It is likely that the pool of LNG outlined in 2.1.1.9 will be ignited, forming a pool fire. Radiated heat from this fire will affect the mechanical properties of the hull. 2.1.1.11 There is the potential for ice to form a barrier between the vessel and the pool of LNG. This ice formation may modify the LNG flow characteristics. 2.1.1.12 Moderate/strong meteorological conditions will maximise dispersion of the resulting LNG vapour cloud and minimise risk of gas cloud ignition	
		2.2 Explosive charges	2.2.1 As per 2.1.1. – 2.1.3 above.	2.2.1 Rapid accumulation	2.2.1.1.1 As per 2.1.1.1.1

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Item Identity	**Event Description**	**Failure Mode**	**Failure Effects**		
			Local Effects	**Next Level of Effects**	**End Effects**
		detonated at a position such that the explosion forces cause failure of the LNG tanker outer and inner hulls at the water line.	2.2.2 Rapid seawater flooding of the cofferdam and ballast spaces will occur to the same level as the outside waterline. This flooding will prevent significant amounts of LNG entering ballast space and causing embrittlement of the ballast structure. 2.2.3 A large volume of seawater in the cofferdam and ballast spaces will cause the vessel to heel/trim towards the vessel breach side. 2.2.4 A breach of the foremost or aftermost tanks will result in the greatest heel/trim effect 2.2.5 Local Failure effects as per 2.1.8 – 2.1.11 above may take place.	of seawater in the cofferdam and ballast tanks will prevent embrittlement of longitudinal and transverse containment system. 2.2.1.2 Rapid accumulation of seawater in the cofferdam and ballast tanks will prevent brittle failure of transverse bulkhead plates at the boundary to adjacent cargo tanks. 2.2.1.3 Next level effects 2.1.1.4 through 2.1.1.12 may take place.	through 2.1.1.1.5 above.
		2.3 Explosive charges detonated at a position such that the explosion forces cause failure of the LNG tanker outer hull two metres below the water line.	2.3.1 As per 2.2.1 – 2.2.5 above. Total immersion of the hull breach may cause LNG to 'bubble' into the upper ballast space in sufficient quantities to produce an explosive atmosphere.	2.3.1.1 As per 2.2.1.1 – 2.2.1.3 above.	2.3.1.1.1 As per 2.2.1.1.1 above.
	Missile fired at the	3.1 Missile penetrates	3.1 Outer hull of the LNG tanker is	3.1 The LNG tanker will remain	3.1 Risk of delayed escalation of

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			Local Effects	Next Level of Effects	End Effects
	LNG tanker at one of two locations.	outer hull only at a point several metres above the water line without exploding upon contact.	breached but there is no flooding of the space between the inner and outer hulls.	largely intact. 3.2 There will be an increased risk of a delayed explosion event involving the missile.	the event to the LNG cargo tanks.
		3.2 Missile penetrates outer hull only at or below the water line without exploding.	3.2 Outer hull of the LNG tanker is breached resulting in flooding of space between the inner and outer hulls to the same level as the outside waterline. 3.3 Seawater in contact with the inner hull may provide additional heat into the cargo thus increasing boil-off rate within that tank. Power requirements may be insufficient to absorb the extra boil-off. Emergency venting could be needed to maintain tank at a safe pressure.	3.3 The LNG tanker will remain largely intact. 3.4 There will be an increased risk of a delayed explosion event involving the missile.	3.2 Potential for the tanker to heel over towards the damaged side by a few degrees increasing the rate of flooding especially at the water line. 3.3 Risk of delayed escalation of the event to the LNG cargo tanks.
		3.3 Missile penetrates the outer hull several metres above the water line and explodes upon impact with the inner hull resulting in a breach of one of the LNG cargo tanks.	3.4 A high level breach of one of the LNG cargo tanks will result in a moderate volume of LNG being released which will largely flash upon release. There is potential for brittle failure of the tanker structure likely to be in contact with the LNG.	3.5 Given that the tanker hull space is not inerted there is a risk of an explosive mixture forming within this space. Ignition of this flammable mixture will result in a confined/partly restricted explosion event.	3.4 The forces acting upon the tank sides are likely to be large leading to failure of an already weakened structure. 3.5The overpressure forces acting upon the transverse bulkhead plates at the boundary to adjacent cargo tanks are likely to be sufficient to cause failure

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					and escalation to the two adjacent cargo tanks. 3.6 There is minimum likelihood of LNG escaping in liquid form. There will be gas release through the missile entrance hole
		3.4 Missile penetrates the outer hull in close proximity to the water line and explodes upon impact with the inner hull resulting in a breach of one of the LNG cargo tank.	3.5 A low level breach will result in a large volume of LNG being released with potential for extensive brittle failure of the tanker structure in contact with the LNG and also failure of transverse bulkhead plates at the boundary to the adjacent cargo tanks. In this case and the cases above there will be a corresponding pressure rise within the confined space, which will be relieved through in the outer hull. 3.6 There is potential for brittle failure of transverse bulkhead plates at the boundary to the two adjacent cargo tanks.	3.6 There is potential for an explosive mixture to form in this space. Ignition will result in a confined/partly restricted explosion event . 3.7 The explosion forces acting upon the tank sides are likely to be large leading to failure of an already weakened tanker structure. 3.8 The overpressure forces acting on the transverse bulkhead plates at the boundary to the two adjacent cargo tanks are likely to be of sufficient magnitude to cause failure and escalation to the adjacent cargo tank.	3.7 There is potential for LNG and/or methane gas to escape through the outer hull penetration and beyond the bounds of the LNG tanker. It is possible for a LNG/methane jet to be ejected from a breach in the cargo tank and through a breach in the outer hull to produce a gas cloud and a pool of LNG at sea level. The effects are likely to be either a localised fire given immediate ignition or a flash fire if the gas cloud is allowed to disperse beyond the tanker before being ignited. The extent of damage and/or number of fatalities will be dependent

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			Local Effects	**Next Level of Effects**	**End Effects**
					upon when the flammable gas cloud is ignited.

Table A5.1 : Failure Modes and Effects of Damaging Event