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# Safety aspects of the use of LNG for marine propulsion

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**Abstract**

Liquefied natural gas (LNG) as a fuel shows a large energy to volume ratio. In addition, its combustion is characterized by low levels of production of $CO_2$, $SO_X$, $NO_X$ and particulate matter in comparison to conventional fuels. To reduce the emission of $SO_X$ into the atmosphere the sulphur content of heavy fuel oils used for marine propulsion will be restricted in the near future. However, LNG is a combustible cryogenic liquid and as such presents specific safety hazards. The large scale use of LNG in the marine sector requires appropriate transport, storage and transfer facilities. The risks connected with the operation of these facilities are analyzed. Specific safety characteristics of the equipment involved are incorporated in the analysis. Safety distances are determined based upon a study of the effects of accidents during which LNG is released. It is found that the pressure at which LNG is released during an accident greatly influences the effect distances. At pressures near atmospheric, the hazards of LNG are comparable to those of conventional liquid fuels such as gasoline. At higher pressures, it behaves more like a combustible gas liquefied by compression.



*Keywords*: LNG; safety; fuel; marine

## 1. Introduction

Liquefied natural gas or LNG is natural gas, a mixture of gases, made liquid by decreasing its temperature below its boiling point. Although its composition varies depending mainly on its location of origin, its main component is methane. For example, the LNG that is imported in Zeebrugge (Belgium) consists of 90 mass% methane and 10 mass% ethane. In this study it is assumed that LNG consists only of methane. Table 1 lists the main physical properties of methane.

Table 1. Physical properties of methane

| property | value |
|---|---|
| molar mass | 0.017 kg/mol |
| atmospheric boiling point | - 162 °C |
| liquid density relative to water | 0.42 – 0.45 |
| vapor density relative to air at 1 atm and 20 °C | 0.6 |
| auto-ignition temperature at 1 atm | 530 °C |
| flammability limits in air at 1 atm and 20 °C | 4.5 – 16.5 vol% |
| minimum ignition energy at 1 atm and 20 °C | 0.28 mJ |
| combustion energy at 1 atm and 20 °C | 50 MJ/kg |

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At atmospheric pressure methane becomes liquid at -162 °C (see Table 1). LNG therefore is a cryogenic liquid. Its saturation curve shows how its vapor pressure increases with temperature (see Fig. 1). Its vapor is flammable within a rather narrow range of concentrations. At standard atmospheric conditions methane is lighter than air. LNG is lighter than water. The main advantage of LNG with respect to natural gas is that its heat of combustion expressed per unit volume is much larger. On an equal energy basis (at atmospheric conditions) natural gas requires a 600 times larger volume than required by its liquid state i.e. LNG.

For many decades natural gas has been used as fuel for private cars. More recently it is used in heavy transport vehicles, including busses. The gas is stored in pressure vessels at high pressure (200 bars). The use of natural gas shows a number of advantages in the transport sector, in particular where heavy fuels are utilized. This is shown by Table 2 which lists the reduction of polluting products of a combustion engine when using natural gas instead of heavy diesel as fuel.

In the marine sector the use of sulphur containing heavy fuels will be severely restricted in the near future. This is the reason why in Western Europe there is considerable interest in the use of LNG for ship propulsion. This will require the storage, transport and transfer of LNG, processes which present specific safety risks.

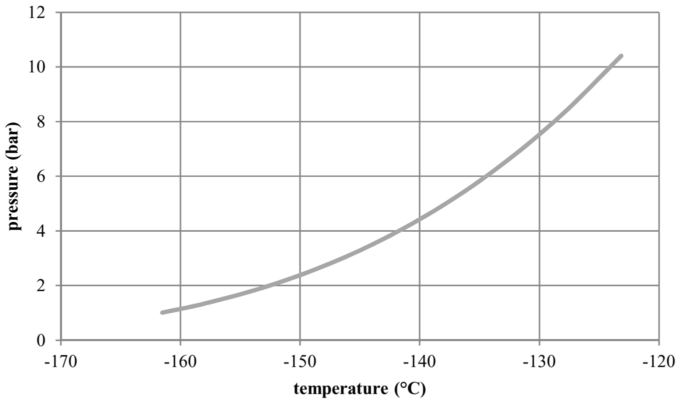


Fig. 1. Saturation curve of methane.

Table 2. Percentage reduction of pollutants of a natural gas engine versus a heavy fuel engine

| pollutant | reduction |
|---|---|
| $CO_2$ | 30% |
| $NO_x$ | 85% |
| $So_x$ | 98% |
| particulate matter | 90% |

## 2. LNG hazards

As a cryogenic fluid LNG will give rise to frost burns when it comes into contact with the human skin.

An LNG spill may give rise to metal embrittlement and metal cracks which may lead to structural failure. Special steels have been developed which do not suffer from cryogenic embrittlement. They can be applied to protect LNG sensitive areas such as LNG loading areas. Methane does not sustain breathing such that large concentrations of this gas in air may give rise to asphyxiation.

When a large spill of LNG comes into contact with another liquid such as water, intense heat transfer will occur giving rise to rapid and large scale evaporation of LNG. This phenomenon is called a rapid phase transition (RPT). It can result in strong pressure waves resulting in damage in the surroundings. Experimental studies of this phenomenon show that it occurs only when the LNG contains non-negligible amounts of substances such as ethane, propane and butane.

The most important hazards of LNG have to do with its flammability. The hazards resulting from this property are studied here.

The event tree of Fig. 2 shows the different scenarios which may develop when a spill of “cold” LNG (LNG at -162°C i.e. at atmospheric pressure) occurs. If the spill concerns the instantaneous release of the contents of a vessel and the LNG vapors are ignited at the moment of release a pool fire will occur. Heat radiation from this fire puts people and installations near the fire at risk. If the ignition of the pool vapors is delayed a vapor cloud will be formed. Upon ignition of this cloud a flash fire will occur. If the vapor cloud is enclosed the combustion of the cloud may give rise to a vapor cloud explosion (VCE). After ignition the combustion flame may travel back to the pool resulting in a pool fire. If ignition does not occur during the release process only the cryogenic effects of LNG have to be feared. If the vessel contents are released in a continuous way through a crack or a hole, the phenomena are the same.

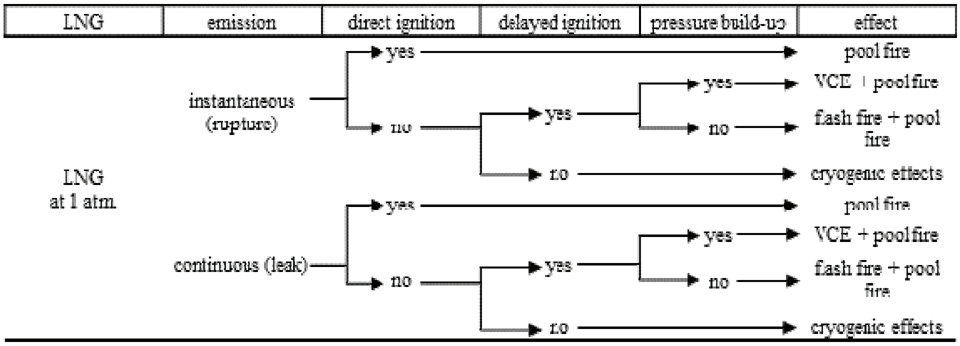


Fig. 2. Event tree for the release of LNG at 1 atm.

Fig. 3 shows the event tree for the release of pressurized LNG (e.g. 4 bar). It is seen that many scenarios of Fig. 2 may occur in this case. However, in case of an instantaneous release the spilled LNG will partially vaporize (flash) and in the process create a blast wave. This phenomenon is called a boiling liquid expanding vapor explosion or BLEVE. If the flashing cloud is ignited a fireball will occur with very high heat radiation to the surroundings. If a continuous release occurs and the LNG jet leaving the vessel is ignited a jet fire occurs with high heat radiation to the surroundings.

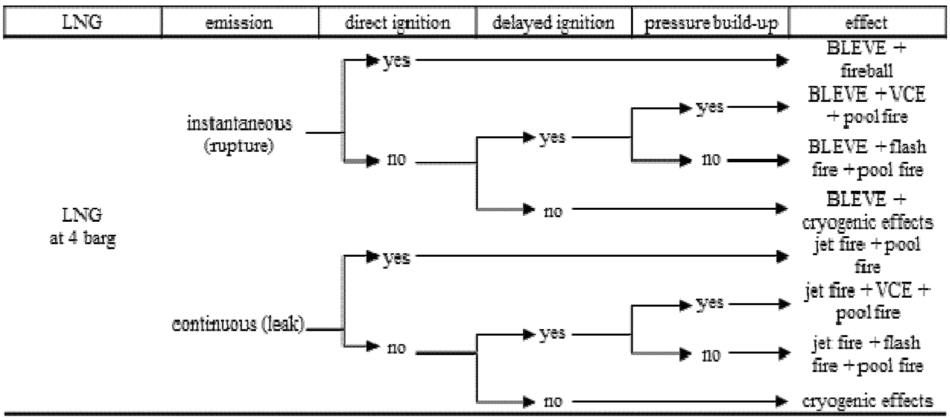


Fig. 3. Event tree for the release of LNG at elevated pressure (e.g. 4 barg).

## 3. Accident effects analyses

As shown above the accidental release of LNG can give rise to pressure waves (BLEVE and VCE), intense heat radiation and to burning clouds. Here we are concerned with the effects of these accidents on people. The maximum distances from the point of release of the LNG at which lethal effects (1% risk of mortality) may occur are calculated. For pressure waves, the 1% mortality rate is put at a blast wave of 4000 Pa[1]. The mortality rate of 1% related to heat radiation is put at 10 kW/m2 during 20 s.

The heat radiation from an LNG flame is calculated by means of the “solid flame surface emitter” model POOLFIRE6[2-3]. For jet fires the model of Chamberlain[4] is used. Calculation of the BLEVE blast wave makes use of the TNT equivalence method. The fire ball characteristics are determined by means of the correlations of Roberts[5].

With respect to the loss of containment the following causes are studied[6]:

- total rupture
- total outflow in 10 minutes
- large hole

- medium size hole
- small hole.

The use of LNG for marine applications will require the storage of large quantities at central locations from which it can be distributed to local storage facilities with smaller capacities. The storage of quantities in the order of 10.000 m3 and more takes place at a pressure slightly above atmospheric (e.g. 135 mbarg).

There are three main types of tanks which are used for this purpose[7-8]:

- single walled tanks
- double-walled tanks
- full containment tanks

Fig. 4 shows the maximum effect distances of these designs as a function of their storage capacity. The calculations are based upon typical dimensions of each design. It is found that the scenario of total rupture of the tank followed by a pool fire determines the maximum effect distances for the tanks with retention areas or retention walls. If retention areas are not present, the maximum effect distances are much larger.

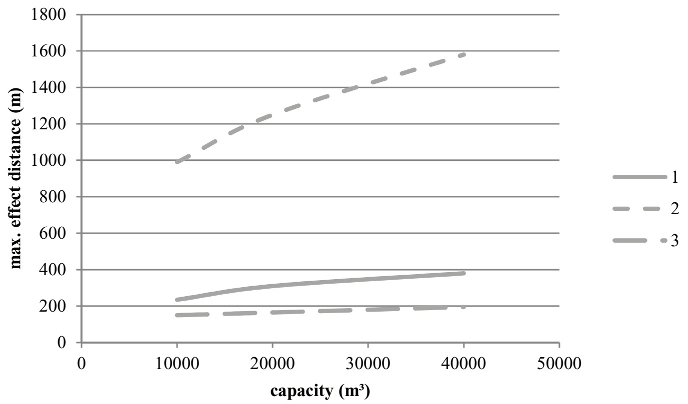


Fig. 4. Maximum effect distances for atmospheric storage of LPG in (1) single walled tanks with diked retention walls, (2) double walled of full containment tanks without a retention area and (3) double walled or full containment tanks with a retention area.

Local LNG storage facilities will have capacities in the range of 100 to 1000 m3 using double walled insulated steel tanks. The pressure in these tanks may evolve in time due to heat infiltrating into the tank (1 to 6 bar). The maximum effect distances related to such tanks are shown in Table 3 as a function of tank size. Here it is assumed that the LNG in the tank is "cold" (-162°C, 135 mbarg). It is found that these distances all are related to the scenario full rupture followed by a flash fire (weather stability class F and wind speed 1,5 m/s). Table 3 shows the substantial effect of retention walls around the tank.

Table 3. Maximum effect distances as a function of storage tank capacity and presence of a retention area (LNG at -160 °C)

| capacity ($m^3$) | max. effect distance (m) | |
|---|---|---|
| | without retention | with retention |
| 100 | 270 | 80 |
| 250 | 410 | 110 |
| 500 | 540 | 110 |
| 700 | 640 | 130 |

When the LNG is present in the tank at elevated pressure and temperature the possible accident scenarios are different (see Figs. 2 and 3). Figure 5 shows the results of the calculations. It is found that BLEVEs with fireballs become important scenarios. Due to the flashing of the LNG at the moment of release large vapor clouds are formed. For this reason flash fires are the dominant scenarios. It should be pointed out that spill retention has no effect on these scenarios.

As to the transport of LNG with trucks the safety study shows that the maximum effect distance is 230 m. It is related to the scenario rupture of the truck tank (50 m3) followed by a flash fire. A truck filled with LNG at elevated pressure (e.g. 9 bar) upon rupture can give rise to a BLEVE with lethal effects up to some 150 m. If the rupture occurs due to the fact that the truck tank is engulfed by fire, the effect distance amounts to some 190 m.

During the transfer of LNG by means of loading arms or flexible hoses spills may occur. The effect distances connected with these accidents depend upon the diameters of the equipment, the flow rates and the safety measures incorporated in the transfer system. A spill of LNG at -162°C will result in a burning liquid pool if the ignition occurs at the same time as the release. If the ignition is delayed, a flash fire will occur followed by a pool fire. When the LNG released is at elevated pressure it will flash. If it ignites immediately, a jet fire will result. If the ignition is delayed, a vapor cloud will be formed and a liquid pool. Upon ignition a flash fire, a jet fire and a temporary pool fire will occur. The calculations show the scenario flash fire to give rise to the largest effect distances. Table 4 shows the results of the calculations for the rupture of an 8’’ loading arm, a flow rate of 1000 m3/h and a spill of “cold” LNG (-162 °C) on water. It is found that the provision of an emergency stop (after 120 s) only has a significant effect on the maximum effect distance in case of rupture of the arm. Similar conclusions can be drawn for the case of a spill of “warm” LNG.

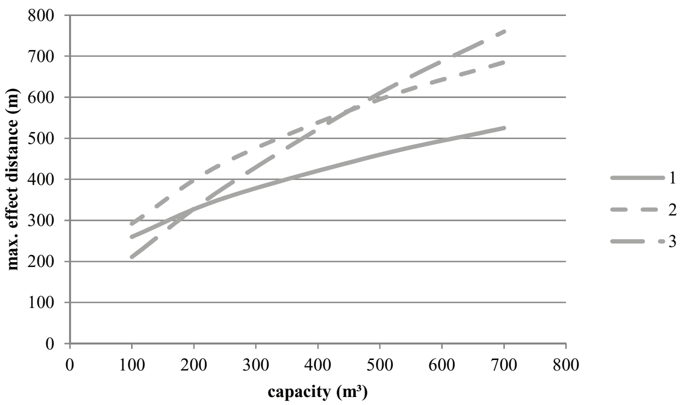


Fig. 5. Maximum effect distance as a function of tank capacity (LNG at -138 °C) for the following scenarios: (1) rupture leading to a BLEVE + fireball, (2) rupture leading to a flash fire and (3) outflow in 10 minutes leading to a flash fire

Table 4. Maximum effect distances as a function of storage tank capacity and presence of a retention area (LNG at -160 °C)

| emission | ignition | effect | max. effect distance (m) | |
|---|---|---|---|---|
| | | | without emergency stop | with emergency stop |
| full bore rupture | direct | pool fire | 136 | 136 |
| | delayed | pool fire | 162 | 162 |
| | | flash fire | 490 | 295 |
| leak (10% of diameter) | direct | pool fire | 36 | 36 |
| | delayed | pool fire | 42 | 42 |
| | | flash fire | 68 | 48 |

## 4. Conclusions

The risks connected with the use of LNG depend very much on its state at the moment of release. LNG released at atmospheric pressure may give rise to flash fires covering large distances if ignition does not occur at the moment of release. Immediate ignition results in pool fires which have less spatial impact. Large storage facilities should be provided with retention walls or dikes. LNG released at pressures larger than atmospheric additionally may give rise to BLEVEs and fireballs which can have an impact over large distances. Spill retention areas have no effect on these scenarios.

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