Consequence assessment of accidental scenarios involving LNG

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LNG accidental scenarios

EVENT TREE

LOSS OF CONTAINMENT

Consequence assessment

FAULT TREE
LNG accidental scenarios

Four questions for the sound assessment of vapour dispersion

1. What is LNG: pure methane?
2. Is LNG vapour lighter than air?
3. Is LNG vapour cloud visible?
4. What if LNG vapours are ignited?
## LNG: is it methane?

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical (% Mole)</th>
<th>Range (% Mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrocarbons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane (C1)</td>
<td>92.77</td>
<td>83.74 – 98.22</td>
</tr>
<tr>
<td>Ethane (C2)</td>
<td>3.36</td>
<td>0.52 – 7.64</td>
</tr>
<tr>
<td>Propane (C3)</td>
<td>1.51</td>
<td>0.18 – 4.74</td>
</tr>
<tr>
<td>Iso-Butane (i-C4)</td>
<td>0.41</td>
<td>0.05 – 1.10</td>
</tr>
<tr>
<td>Normal Butane (n-C4)</td>
<td>0.47</td>
<td>0.06 – 1.63</td>
</tr>
<tr>
<td>Iso-Pentane (i-C5)</td>
<td>0.19</td>
<td>0.03 – 0.50</td>
</tr>
<tr>
<td>Normal Pentane (n-C5)</td>
<td>0.13</td>
<td>0.00 – 0.42</td>
</tr>
<tr>
<td>Hexane (C6)</td>
<td>0.27</td>
<td>0.09 – 0.78</td>
</tr>
<tr>
<td><strong>Inerts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>0.30</td>
<td>0.12 – 0.91</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>Trace</td>
<td>0.00 - 0.02</td>
</tr>
<tr>
<td><strong>Impurities</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>0.59</td>
<td>0.13 – 1.86</td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>Trace</td>
<td>0.00 - 0.10</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>Trace</td>
<td>0.00 – 3.00</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>Trace</td>
<td>0.00 - 0.01</td>
</tr>
</tbody>
</table>
LNG: is vapour lighter than air?

- Boiling point: -163°C to -160°C
- Liquid density: 458 to 463 kg/m³
- \( M_{\text{LNG}} \approx 20.00 < M_{\text{AIR}} = 28.47 \)

- Vapour density @ambient temperature 0.656 kg/m³
- Vapour density @boiling temperature: 1.79 kg/m³

HEAVIER THAN AIR AT BOILING TEMPERATURE
LIGHTER THAN AIR AT AMBIENT TEMPERATURE
LNG cloud: is it visible?

- When released in the atmosphere, a visible cloud is formed if humidity approx. > 50% because of condensation
- The cloud can be not completely visible even if it is flammable
LNG cloud: first conclusions

When accidentally released, LNG floats on seawater or forms a pool on ground:

- vapours form a stratified layer (a cloud) over ground or water, with a temperature/concentration gradient
- a low-lying visible cloud is formed if humidity approx. > 50%
- the cloud can be not completely visible even if it is flammable
Ultra-low temperature (100 K – 273 K) for cryogenic fuels in air

The dependence of flammability limits (LFL, UFL) of LNG vapour with temperature

Few experiments, few correlations


Inerting methane at low temperature with nitrogen
LNG cloud: first conclusions

**LNG on water**

**Early ignition:**
- Pool fire

**Delayed Ignition**
- Pool fire
- Vapour Cloud fire (Flash Fire)
- Vapour Cloud Explosion
  (if terminal – congestion -is nearby)

**No ignition**
- Dispersion (asphyxia)
- Rapid Phase Transition

**LNG on ground**

**Early ignition:**
- Pool fire

**Delayed Ignition**
- Pool fire
- Vapour Cloud fire (Flash Fire)
- Vapour Cloud Explosion
  (if congestion)

**No ignition:**
- Dispersion (asphyxia)
What if LNG is ignited?

If the LNG cloud (either on ground or seawater) is ignited:

- The liquid pool feeds a fire convectively (pool fire), which is limited by the evaporation rate and heat exchange.

- If a large vapour cloud is formed BEFORE IGNITION (delayed ignition), a flame propagates throughout the cloud from the point of ignition to the entire gas volume. Two scenarios can be recognized:

  1. **Vapour Cloud Fire (Flash Fire):** no pressure waves
  2. **Vapour Cloud Explosion (VCE):** with pressure (shock) waves
LNG Pool Fire

Fire of LNG released on ground/water

Early ignition
- Pool fire

Delayed Ignition
- Pool fire

Pool fire: Heat radiation, No pressure waves
LNG Pool Fire

- Fire scale (Pool Geometry)
- Evaporation rate (heat, mass transfer)
- Burning Rate
- Radiation Intensity
- Lift-off Height
- Soot formation

Output: Stand-Off Distances
LNG Pool Fire: small scale-large scale

Mass Burning Rate

\[ \dot{m}_b = \dot{m}_{b,\infty} \cdot (1 - e^{-k \beta \cdot D_p}) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \dot{m}_{b,\infty} ) (kg/m(^2)-s)</th>
<th>( k \beta ) (m(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid H(_3)</td>
<td>0.169 (±0.006)</td>
<td>6.1 (±0.4)</td>
</tr>
<tr>
<td>LNG (mostly CH(_4))</td>
<td>0.078 (±0.018)</td>
<td>1.1 (±0.8)</td>
</tr>
</tbody>
</table>

Hottel’s plot for the burning rate with respect to the pool diameter
Pool fire mitigation

- High Expansion Foam
- Gas inertization
- Water Curtains
- Water Sprinklers
- Water Mist
- Powders

Water-based
Pool fire mitigation

- **Water sprinkler** affects the vaporization rate (boil-off effect): Large water particles ($d_p > 1$ mm) increases the evaporation of LNG.

- **High expansion foam** mitigates LNG vapor hazard through warming effect (raising vapor buoyancy), but with boil-off effect due to the heat from water drainage of foam. **Foaming has however a blanketing effect** on source term (vaporization rate).

- **Gaseous inertization** requires large amount of gases, and is unsustainable technologically and economically for large and medium scale application.
Temperature in the middle of the flame is significantly reduced by water mist system.
Right outside the water spray zone the mitigation effect is insignificant (T > 200°C).
Pool fire mitigation

LNG

Pool fire

Water Mist

Water Curtain

Interreg ADRION ADRIATIC-IONIAN
European Regional Development Fund - Instrument for Pre-accession II Fund
SUPER-LNG
The heat flux is significantly reduced (~40%)

The temperatures field after the onset of water curtain is tolerable by human \((T \approx 25 \text{ }\text{\textdegree}C)\)

The risk of gas dispersion is minimized
Pool fire mitigation

WATER CURTAIN SEEMS TO BE VERY EFFICIENT
Flash fire of LNG: why the cloud has not exploded?
Vapour Cloud Explosion

The flame behaves like a piston and produces a pressure wave with 
**overpressure** $\Delta P$ at any **distance** $r$ from the flame front following the 
equation:

$$\Delta P = \frac{1}{r} \cdot \frac{\gamma}{c_o^2} \cdot \frac{\rho_{\text{air}}}{4\pi} \cdot \left( S_f \frac{dA_f}{dt} + A_f \frac{dS_f}{dt} \right)$$

$S_f, A_f$ = flame speed and the flame area
$C_o$ = sound speed
Vapour Cloud Explosion

For most common gases at ambient temperature, given a mass of fuel/air, it is:

$$\Delta P \propto \frac{dS_f}{dt}$$

which means that the flame must accelerate in order to produce an intense pressure wave.
The acceleration of flame is due to the turbulence induced by obstacles, which in turns increases the turbulence.....
The Multi-Energy method gives the decay of the blast wave generated by VCEs, with respect to a combustion energy-scaled distance $\tilde{R}$ and a “strength factor” $F$, which depends on obstacle density, i.e.:

MEM recognizes that pressure wave (i.e. flame velocity) depends on congestion grade and on the total energy of fuel (or total amount of fuel within flammability limits)
Vapour Cloud Explosion

The MEM blast chart

Scaled overpressure: $\overline{\Delta P}$

Combustion energy-scaled distance $\overline{R}$

$$\overline{R} = \frac{R}{\sqrt[3]{\frac{E}{P_a}}}$$

$E$ is the total combustion energy of the cloud with mass $m$ and heat of combustion $\Delta H_c$

$$E = m_{LNG} \cdot \Delta H_c = \rho_{cloud} \cdot V_{cloud} \cdot c_{LNG} \Delta H_c$$
Vapour Cloud Explosion

Is it possible to have a VCE on water?

- The congestion level is generally very low at sea hence low F (<3): the pressure wave is characterised by very low intensity (< 0.03 bar) at a relatively small distance from the source point.

- On the contrary, VCE is possible on ground provided large amount of methane, delayed ignition and high level of congestion.

Diagram: Combustion energy-scaled distance $\bar{R}$.

- F “unconfined”
- F “congested”
Realistic conditions: high congestion

Offshore: un-congested
Onshore: congested
Vapour Cloud Explosion

Offshore terminal: can be congested
**Flash fire**

Evaporation rate is commonly over-estimated because condensation is neglected, either on water or on soil or concrete.

The conservative option fits for pool fire but produces much larger vapour cloud, hence larger safety distances for flash fires.

Tools: Integral model but CFD could be used with small effort.
Increasing the complexity...

- Small variation of geometry: large variation of pressure (geometry dependence)

- ALL physic has to be reproduced for the correct prediction of fire and gas explosion (i.e. turbulence effect on flame, chemical reactivity and coupling with fluid-dynamic, thermodynamic, ...)

Vapour Cloud Explosion
Vapour Cloud Explosion

The use of Computation Fluid Dynamic is the next future for all industrial application for LNG VCE is a major request
Physical Explosion

Rapid Phase Transition
Rapid Phase Transition (RPT) is the fast (explosive) evaporation of any cryogenic liquid (here intended as related to accidental release).

When vapour generation is very fast, RPT can generate pressure (shock) waves.

RPT does not involve fire or chemical reactions and can be considered a physical explosion (no combustion).
RPT may result in two effects:

- overpressure resulting from the rapid phase change
- modified dispersion of LNG into the atmosphere, with direct effects on flash fire, vapour cloud explosion, and pool fire

The physical (and chemical) conditions for explosive evaporation are still un-clear.

RPT blast waves are not easily predictable as the total energy involved in the explosion depends on many factors.
Rapid Phase Transition (RPT)

acoustic solution

MONOPOLE SOLUTION
Spherical source with Radius → 0

\[ P - P^o = \Delta P = \rho \frac{f'(r-c_o t)}{r} = \frac{\rho}{4\pi r} \ddot{V}(t) \]

\[ \rho = \frac{\gamma P_o}{c_o^2} \]

\[ \frac{\Delta P}{P_o} = \frac{\gamma}{4\pi r} \frac{1}{c_o^2} \ddot{V}(t) \]
For LNG release on sea-water, for an RPT to occur, it is needed that:

- A CH$_4$ content > 80% is required for LNG to RPT (the actual composition of LNG is essential for reliable and credible evaluation)
- Water temperature > 12/17 °C (depending on degree of mixing with LNG)
- RPT strength depends on spill rate (> 0.3 m$^3$/s)
- Maximum safety distances for negligible structural damage to other ships or structures from the release point (7 kPa) is 250 m (according to Sandia Lab and other studies)
Rapid Phase Transition (RPT)

- The effect of the formation of ice on water surface, and related consequences on dispersion, flash fire and VCE is still unpredicted.

- Rapid Phase Transition is credible for the release of LNG on water whereas it is unlikely on ground (concrete, earth).
Loss of containment from equipment
Jet fire

$p^* = \left(2 \frac{\gamma}{\gamma + 1}\right)^\frac{\gamma}{\gamma+1}$
Chocked flow

Standard models can be used. Chocked flow to be calculated by typically reached if any failure/rupture or hole on the vapour phase.
Loss of containment from equipment

BLEVE/Fireball

Boiling liquid expanding vapor explosion

Trucks or storage tank under fire conditions can in principle develop a secondary dramatic phenomenon which is related to the rapid expansion of vapour (which is pressurised due to external heat) and the following vapour fire (the fireball) after the shell failure due to wall temperature increase and internal pressurisation.

Cold liquid at atmospheric temperature can evaporates on ground but the evaporation rate is limited by the low heat exchange with the environment (as for RPT, the produced shock wave is rather weak).

Standard models can be used.
Safety distances

- Flash fire (delayed ignition): over-predicted scenarios because of evaporation rate
- Pool fire: standard models are effective if low T effects. Non-methane substances affects the safety distance dramatically
- Vapour Cloud Explosion: unlikely because buoyancy, low-reactivity and low-congestion of LNG plants
- Rapid Phase Transition explosion: only possible on water, strongly dependent on LNG composition and wave intensity (max 250 m)
- Jet fire on the vapour phase only

Safety barriers: effective for heat radiation (water curtain for pool fire, powder). Other technology under development or ineffective.

Domino effects for heat radiation from pool fire rather than overpressure for VCE or RPT
List of useful, recent paper on LNG and other cryogenic liquid


Thanks for your attention

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