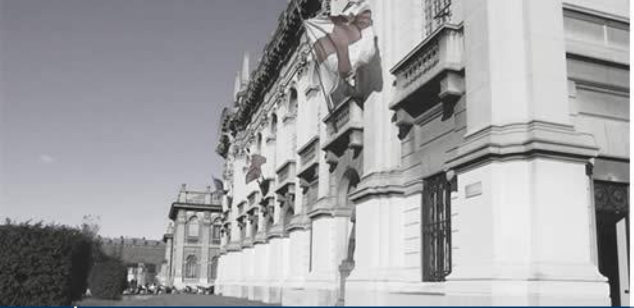


Associazione professionale Italiana Ambiente e Sicurezza
Comitato C 4.3 Energia e fonti rinnovabili

CONVEGNO AIAS

Milano, 18 Maggio 2012

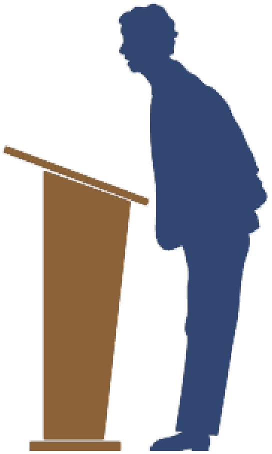
POLITECNICO DI MILANO

The Viareggio railway accident
Lessons-learnt

Davide Manca

Struttura della presentazione

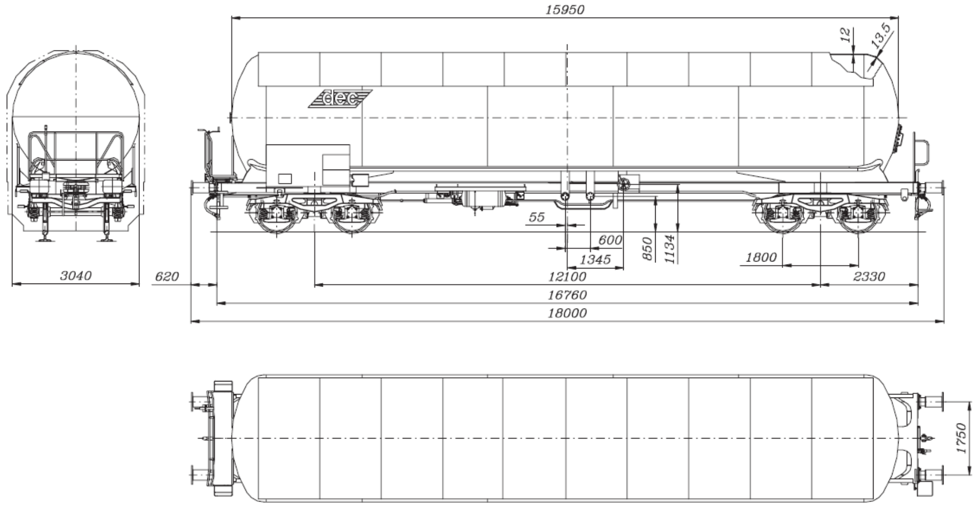
- Fenomenologia dell'incidente
- Modellazione matematica
- Risultati della simulazione
- Analisi e modellazione delle incertezze
- Conclusioni



Fenomenologia dell’incidente

Sequenza eventi

- 29 Giugno 2009 tardo pomeriggio un convoglio merci carico di GPL lascia la raffineria Sarpom di Trecate (NO) diretto a Gricignano (CE) verso il deposito della Aversana Petroli (contratto trasporto con FS Logistica per due trasporti settimanali per 48 settimane all'anno).
- Il convoglio è costituito da:
  - una locomotiva E655
  - 14 vagoni (ferrocisterne) di capacità nominale pari a 110 m^3/cad
- Quantitativo totale di GPL trasportato 630 t



Sequenza eventi

- Durante l'attraversamento della stazione di Viareggio verso mezzanotte l'asse frontale della prima ferrocisterna cede improvvisamente

- Sette ferrocisterne deragliate: 5 rovesciate e due sviate
- Sette ferrocisterne ancora su binario
- Intercorrono 590 m tra il punto iniziale di cedimento e la testa del convoglio

Sequenza eventi

- Il primo vagone deragliato e rovesciatosi striscia lungo la massicciata ed urta una trave (binario) a doppia T conficcata nel terreno (a fini misurazione e posa binari) che sporge dal terreno per circa 30 cm

Disposizione ferrocisterne

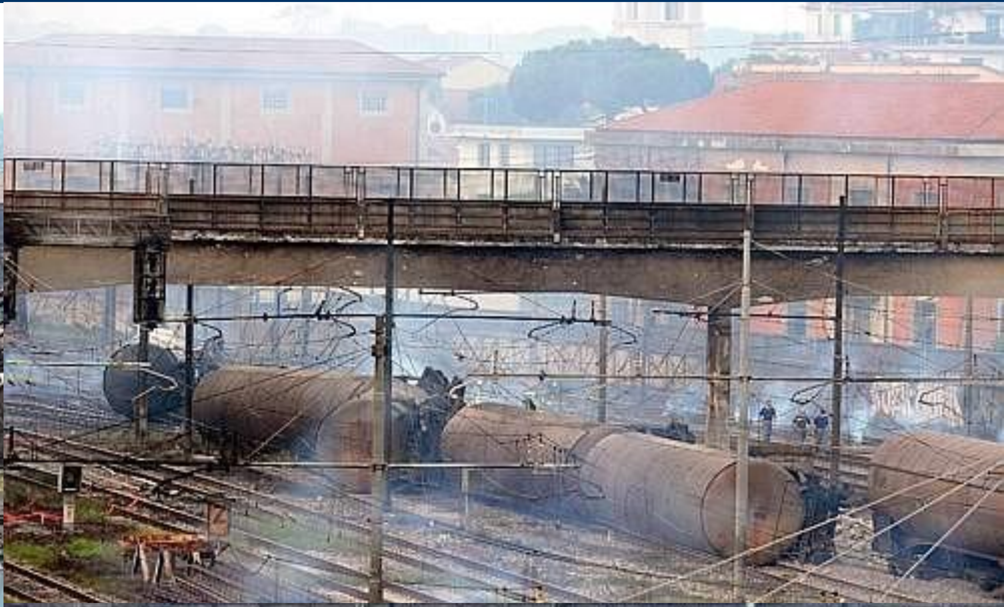
Disposizione ferrocisterne

Disposizione locomotore

Mancato effetto domino

Immagini dell'evento

Immagini dell’evento



Immagini dell'evento

Immagini dell'evento

Immagini dell’evento



Immagini dell’evento

Immagini dell'evento

Incisione e fessurazione

Incisione e fessurazione

Incisione e fessurazione

Consequences

- **32 fatalities**
  - **14 people died immediately**
    - some were literally run over by flame radiation
    - collapse of the buildings
    - inhalation of toxic substances from the burning of houses
  - **2 heart attacks**
  - the **last person** died **six months after** the accident
- More than **thirty people** were **seriously injured**
- **1100 people** had to **evacuate** their homes for safety reasons
- Infrastructure **overall damage** was valued at **32 M€**.

Modellazione matematica

Events time-line

Late afternoon ~ 5 PM

The train loaded with LPG leaves Trecate

11:48 PM

An axle breaks and the train derails

A tank car impacts an I-shaped stake

A hole forms in the tank car

Immediately after (30-60 s)

The train drivers escape finding shelter behind a wall

The LPG is released from the damaged tank car

Pool spreading
Pool-fire
Gas dispersion

Within 2-5 min

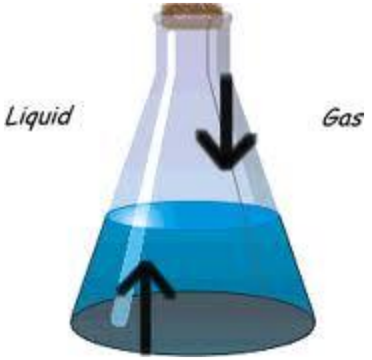
Explosions occur in the Terminetto neighborhood

Cars and houses are set on fire

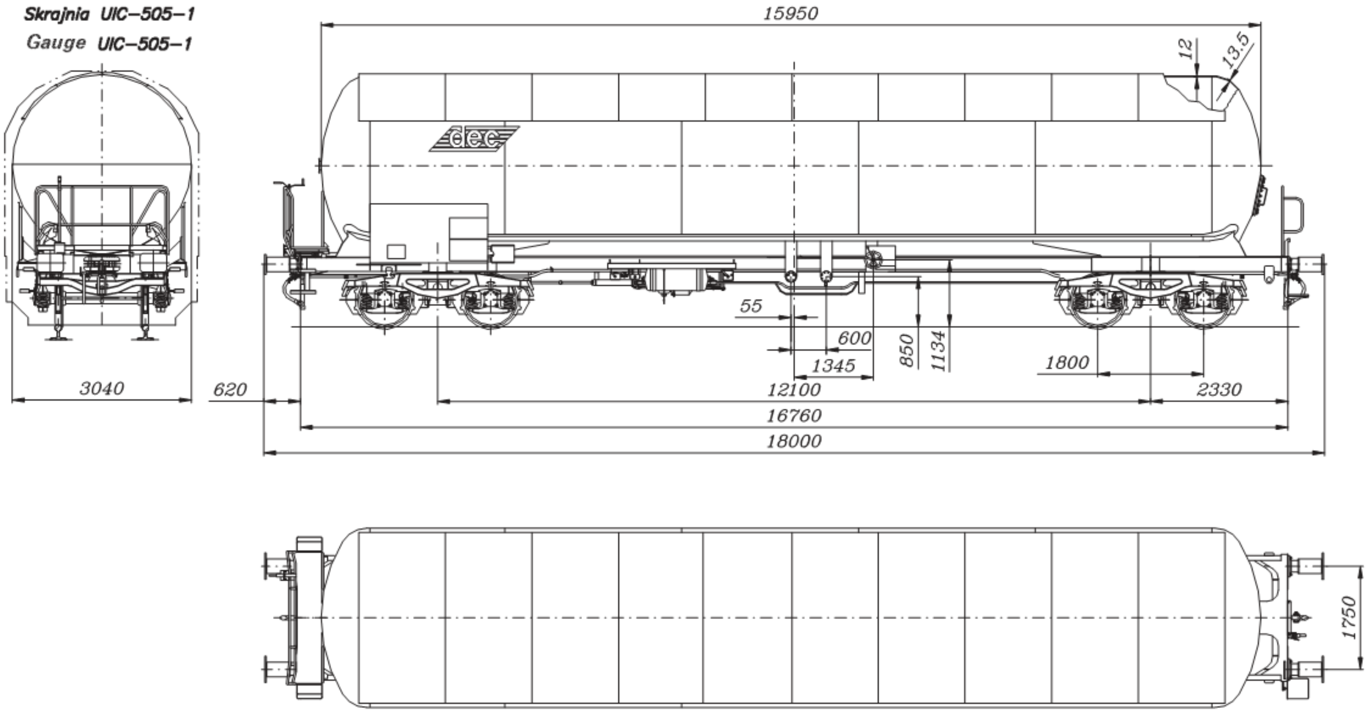
Recommended numerical features

Models for the description of:

- Thermodynamics and V-L equilibrium
- Thermal dispersion
- The source term → outflow
- Jet flash → L + V fractions with rainout
- Spreading and shrinking of the liquid pool
- Flash fire and pool-fire
- Radiative heat transfer to the tank car
- Irregular terrain and ballast roughness
- Dense gas dispersion in complex environments
- Calm wind conditions



LPG release: tank car features



LPG release: input data

LPG composition

LPG is a variable mixture of C_3 and C_4 isomers → Pure n-propane

Storage conditions

Pressure [bar]	Temperature	
9	296.15 K	23.00 °C
15	317.10 K	43.95 °C
20	330.51 K	57.36 °C
25	341.69 K	68.54 °C

← Ambient conditions

← Working pressure

Total tank capacity	**110 m^3**
Calculation pressure	**25 bar**
Working pressure	**25 bar**
Test over-pressure	**25 bar**
External over-pressure	**1 bar**

www.gatx.com

→ 23 °C, 9 bar

LPG release: input data

Mass in the punctured tank car

The train transported 630 tons of LPG distributed in 14 tank cars → 45 tons

Hole equivalent area

Only a portion of the longitudinal mark was cut open → 100 cm^2 trapezoidal hole
c_D = 0.62 (jagged-in sheet)

LPG release: input data

Ignition time

Some witnesses declared that the ignition occurred 2 min after the derailment, someone else reported 5 min

The intense emotional agitation of the witnesses in those moments did not allow analyzing objectively the course of events

→ 2 min

LPG release: input data

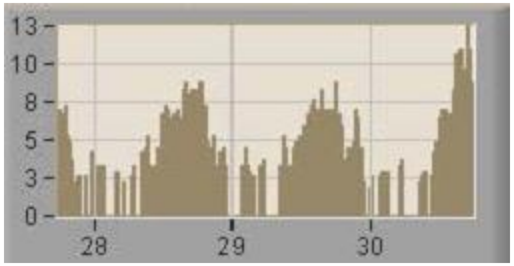
Wind speed and direction

Report measured at the top of a hotel on the seafront, 1.7 km from the epicenter of the accident

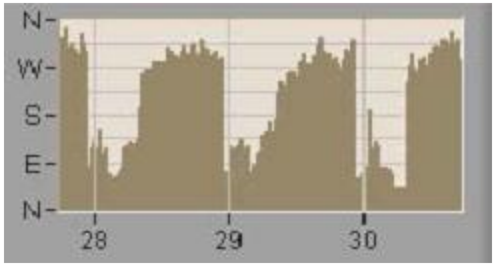
Wind direction	NEE
Wind speed [m/s]	< 1
Air temperature [°C]	23
Ambient pressure [mbar]	1008
Relative humidity	80%

0.5 m/s, NEE

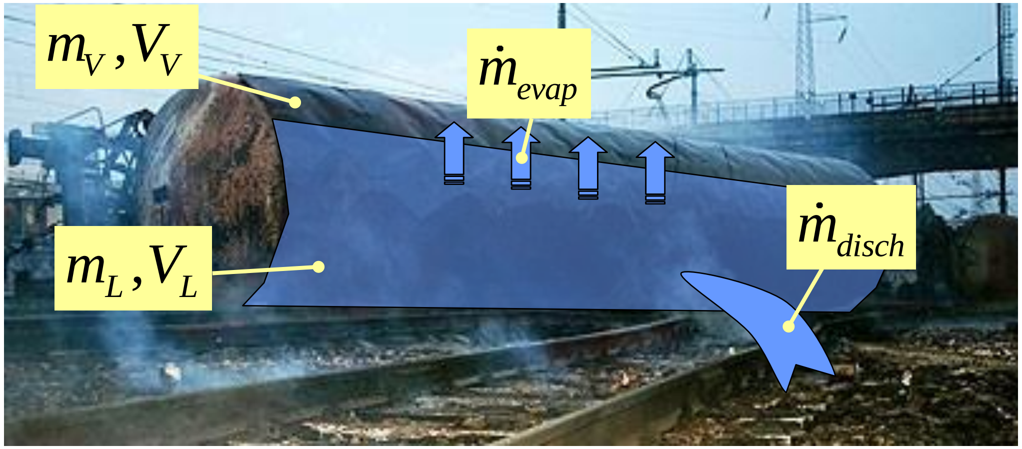
Wind speed [knot]



Wind direction



LPG release: modeling



Mass balance
Energy balance
Volume conservation

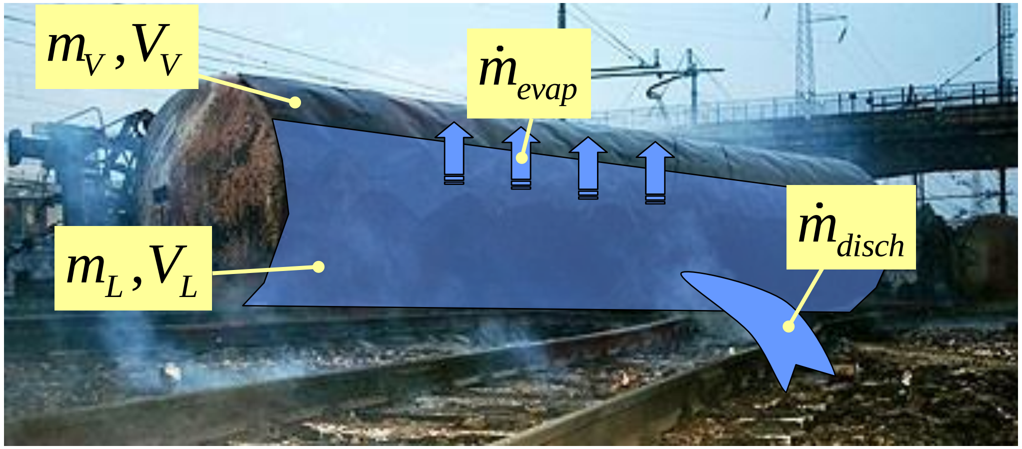
$$\begin{cases} \dfrac{dm_L}{dt} = -\dfrac{\dot{m}_{disch}}{\left(1-\dfrac{\rho_V}{\rho_L}\right)} \\ \dfrac{dm_v}{dt} = \dot{m}_{evap} \\ \dfrac{dT}{dt} = -\dfrac{\dot{m}_{evap}\Delta H_{ev} + \alpha Q_{irr} A}{m_L cp_L + m_V cp_V} \end{cases}$$

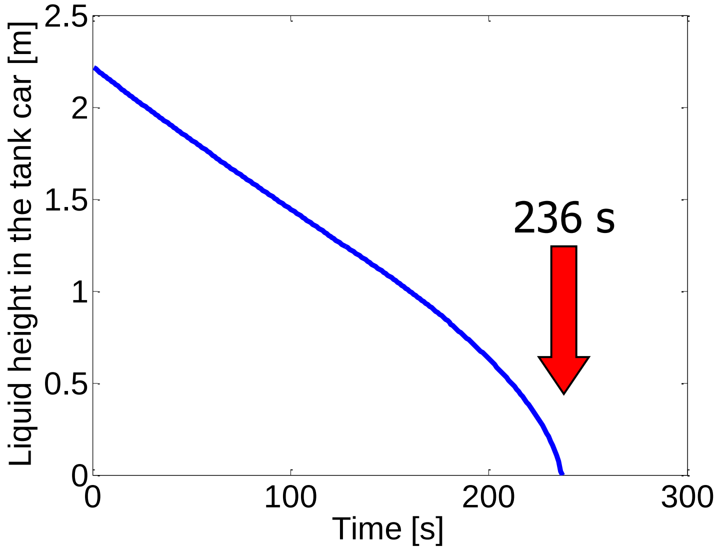
$$\dot{m}_{disch} = \rho_L A_h c_D \sqrt{\frac{2}{\rho_L}\left(P - P_a\right) + 2gh_L}$$

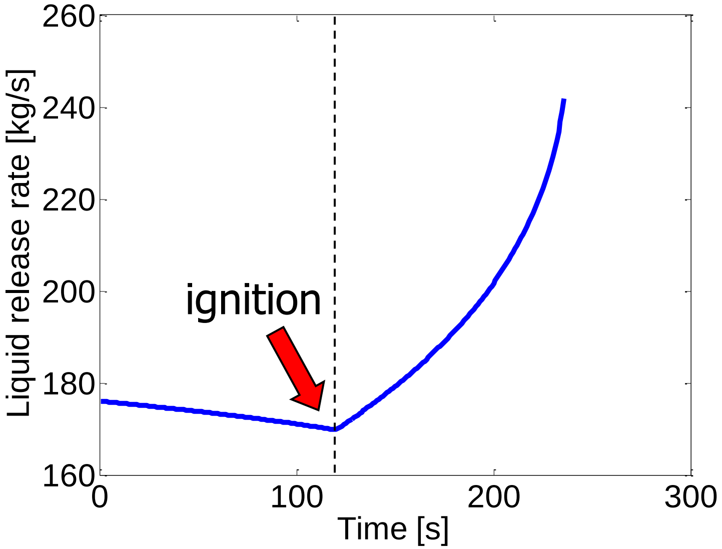
$$\dot{m}_{evap} = -\frac{dm_L}{dt}\frac{\rho_V}{\rho_L}$$

$$V_L = L\left[R^2 \operatorname{acos}\left(1 - h_L/R\right) - \left(R - h_L\right)\sqrt{2Rh_L - h_L^2}\right]$$

LPG release: results





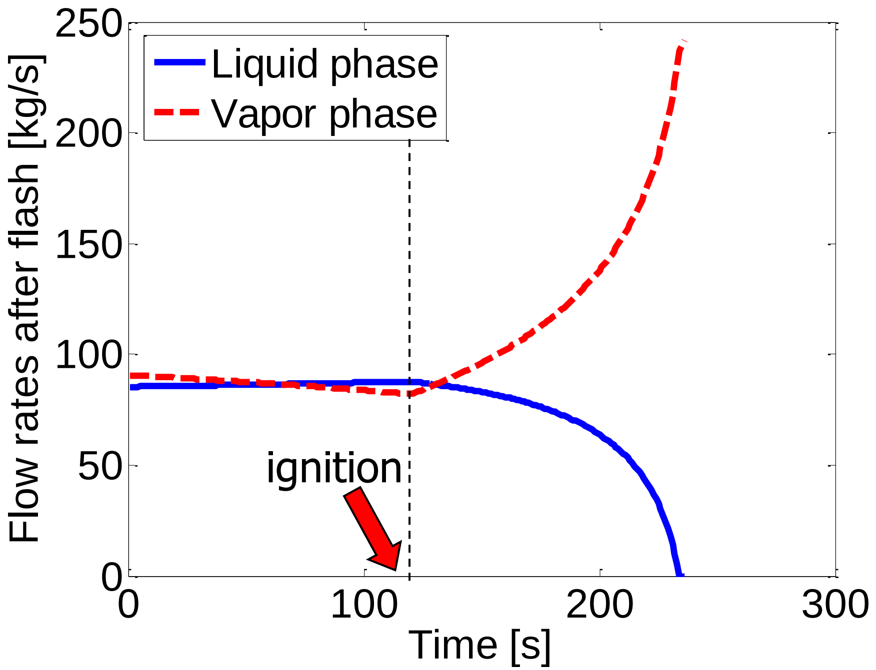


LPG flash in the atmosphere

Hypotheses

- Jet flash downstream the emission from the hole
- No liquid entrainment in the vapor phase

$$\begin{cases} x_V = \dfrac{cp_L\left(T - T_{eb}\right)}{\Delta H_{ev}} \\ x_L = 1 - \dfrac{cp_L\left(T - T_{eb}\right)}{\Delta H_{ev}} \end{cases}$$



Pool spreading and pool-fire

Pool shape

The liquid fraction spread on an irregular terrain and found some obstacles that limited a symmetric spreading

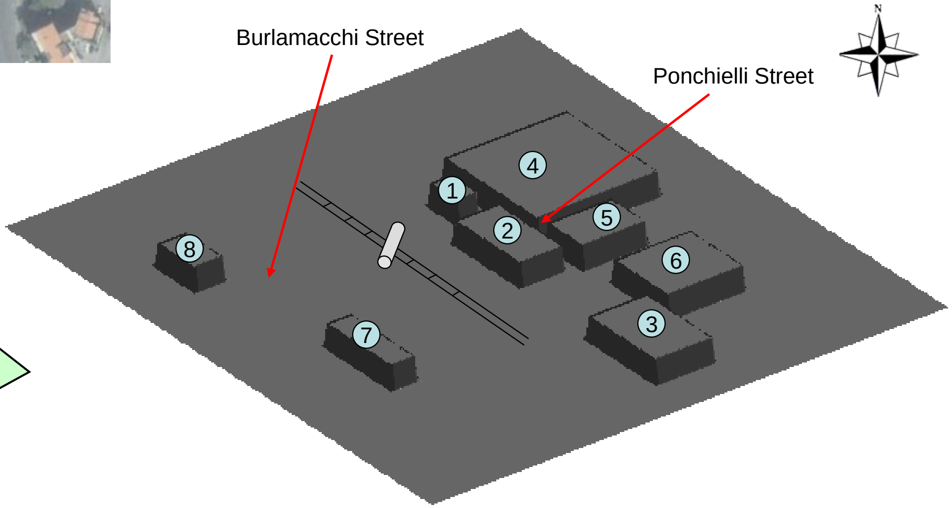
The liquid was partially absorbed by the permeable ballast made of pebbles and rocks

→ Circular, unconfined pool

Gas dispersion

Google Earth

3D reconstruction of Terminetto neighborhood



Gas dispersion: model

Simulation with TWODEE-2, a simulation code based on the Shallow Water Equations, *i.e.* equations based on depth-averaged variables to describe the flow behavior

$$\begin{cases} \dfrac{\partial h}{\partial t}+\dfrac{\partial hu}{\partial x}+\dfrac{\partial hv}{\partial y}=u_e \\ \dfrac{\partial h\left(\rho-\rho_a\right)}{\partial t}+\dfrac{\partial h\left(\rho-\rho_a\right)u}{\partial x}+\dfrac{\partial h\left(\rho-\rho_a\right)v}{\partial y}=0 \\ \dfrac{\partial h\rho u}{\partial t}+\dfrac{\partial h\rho u^2}{\partial x}+\dfrac{\partial h\rho uv}{\partial y}+S_1\dfrac{\partial\left[g\left(\rho-\rho_a\right)h^2\right]}{\partial x}+S_1 g\left(\rho-\rho_a\right)h\dfrac{\partial e}{\partial x}+\dfrac{1}{2}\rho C_D u\left|\mathbf{u}\right|+V_x+k\rho_a\left[\dfrac{\partial}{\partial t}+u_a\dfrac{\partial}{\partial x}+v_a\dfrac{\partial}{\partial y}\right]h\left(u-u_a\right)=u_e\rho_a u_a \\ \dfrac{\partial h\rho v}{\partial t}+\dfrac{\partial h\rho vu}{\partial x}+\dfrac{\partial h\rho v^2}{\partial y}+S_1\dfrac{\partial\left[g\left(\rho-\rho_a\right)h^2\right]}{\partial y}+S_1 g\left(\rho-\rho_a\right)h\dfrac{\partial e}{\partial y}+\dfrac{1}{2}\rho C_D v\left|\mathbf{u}\right|+V_y+k\rho_a\left[\dfrac{\partial}{\partial t}+u_a\dfrac{\partial}{\partial x}+v_a\dfrac{\partial}{\partial y}\right]h\left(v-v_a\right)=u_e\rho_a v_a \end{cases}$$

$$u_e=\frac{a u_{ref}}{1+b\,\mathrm{Ri}}$$

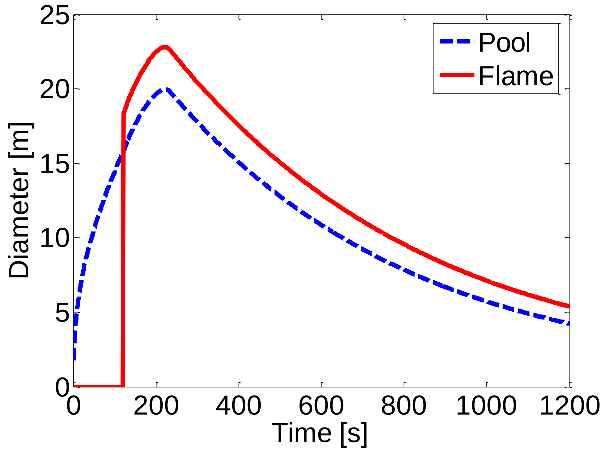
$$u_{ref}^2=\mathbf{u}_*^2+\left(\alpha_2\mathbf{w}_*\right)^2+\frac{1}{2}C_D\alpha_3^2\mathbf{u}^2+\alpha_7^2\left|\mathbf{u}-\mathbf{u}_a\right|^2$$

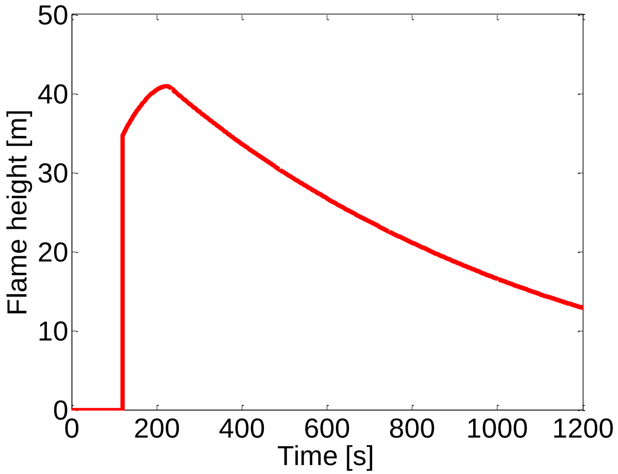
Risultati della simulazione

Pool spreading and pool-fire: results

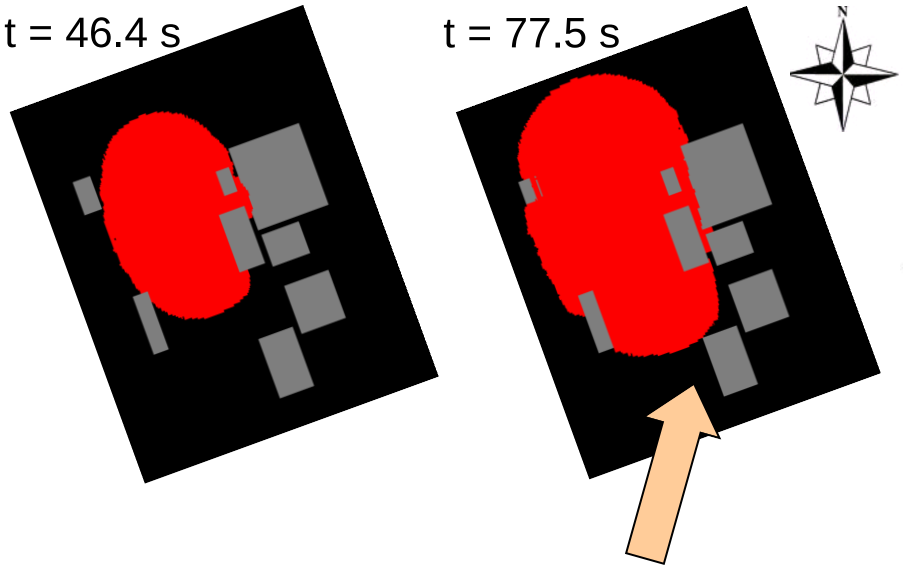
Ignition time: 2 min

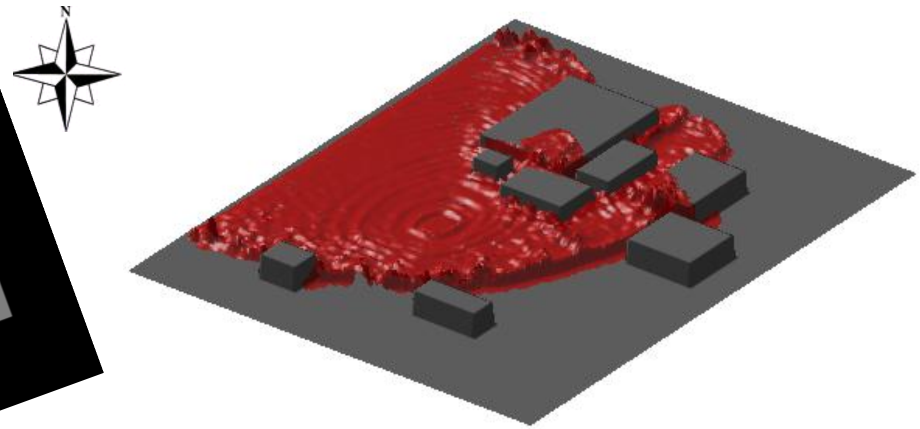
AXIM™





Gas dispersion: results

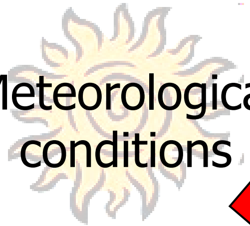




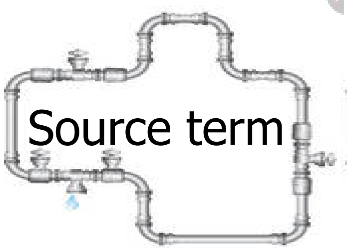
Arrival time of the gas-cloud to the <u>farthest house</u> that exploded ~ 80 s

Analisi e modellazione delle incertezze

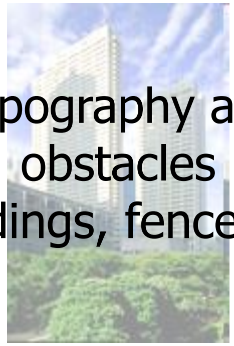
Quantification of consequences



Meteorological conditions

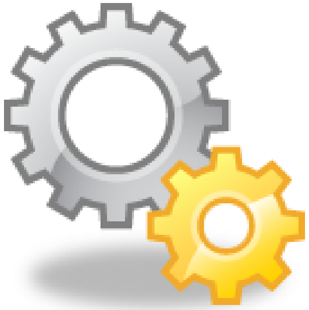


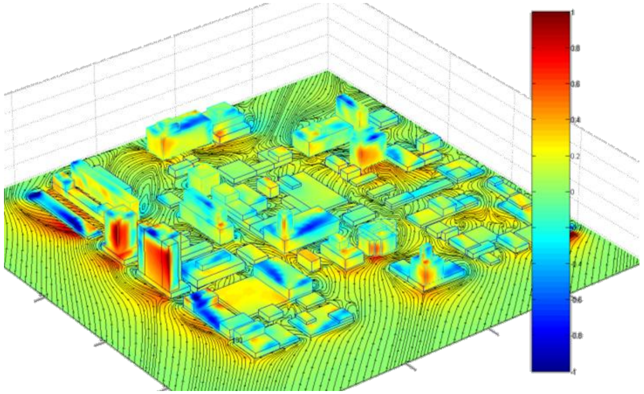
Source term



Topography and obstacles (buildings, fences, …)

Presence and location of the ignition source(s)





Uncertainties

Storage conditions

LPG composition

Crack size

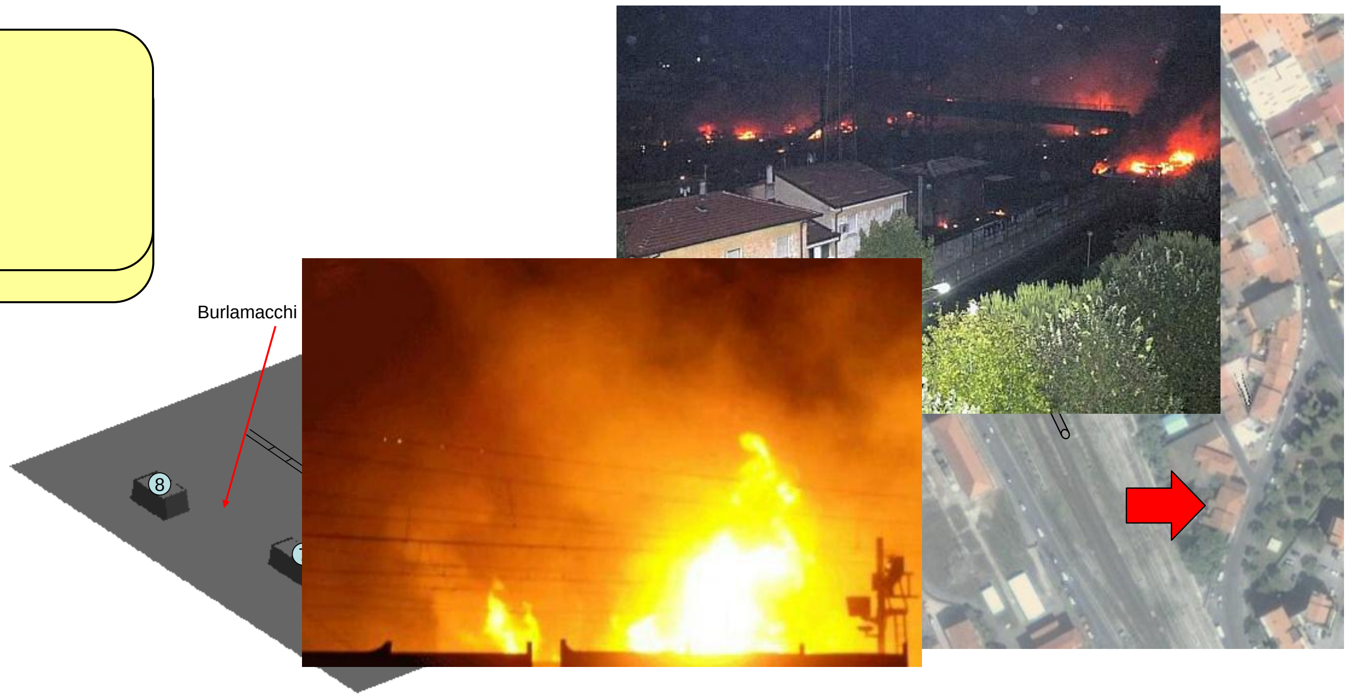
Meteorological conditions

Ignition time

Pool shape and area

Sensitivity analysis

Pool-fire size
(flame height)

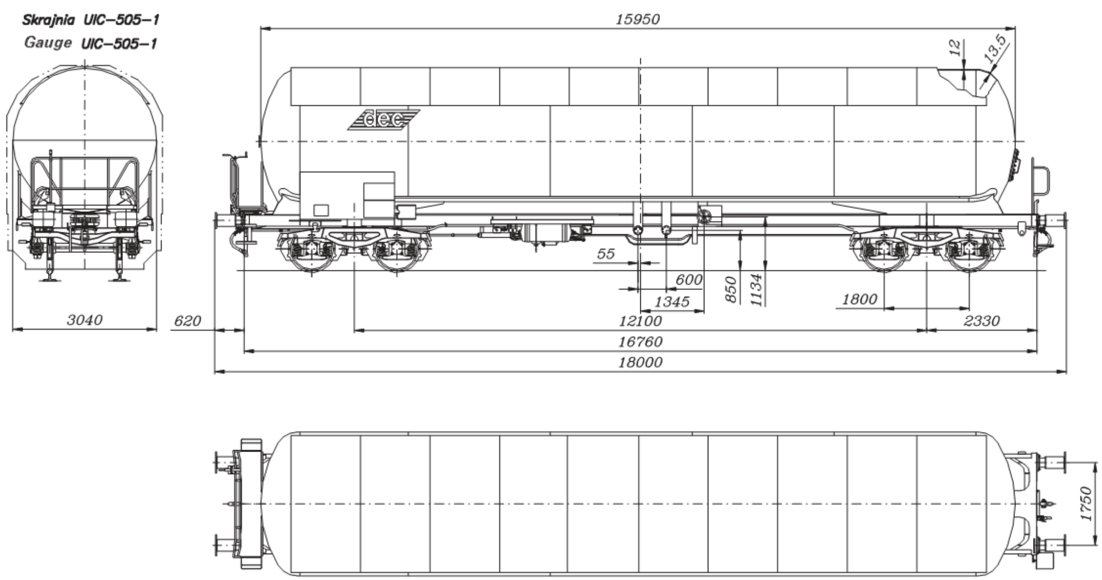


Reference case

Initial tank car conditions	9 bar, 23°C
LPG mass	45 t
LPG composition	Pure propane
Crack size	100 cm^2, jagged-in sheet
Meteorological conditions	23°C, 0.5 m/s, NEE
Ignition time	2 min
Pool shape	Circular

Uncertainties: storage conditions

Storage conditions



LPG release: storage conditions

Storage conditions

Pressure [bar]	Boiling point	
9	296.15 K	23.00 °C
15	317.10 K	43.95 °C
20	330.51 K	57.36 °C
25	341.69 K	68.54 °C

Ambient conditions

Working pressure

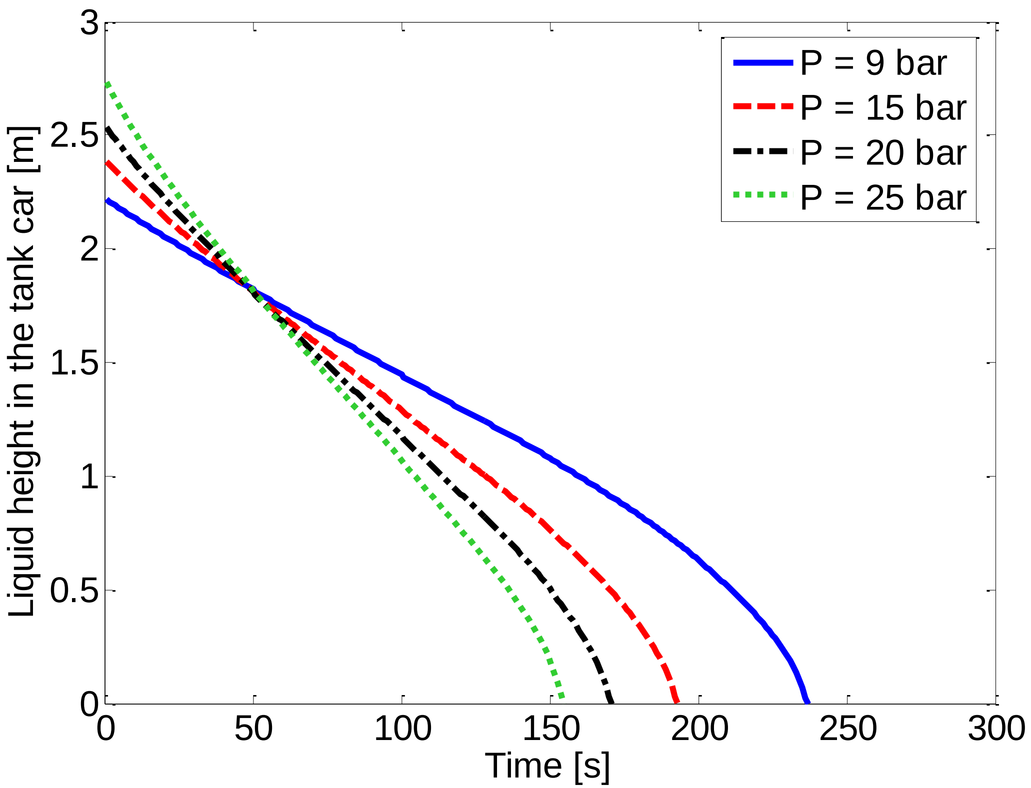
23 °C, 9 bar

Total transported LPG : 630 t

tank cars : 14

45 t/each

LPG release: storage conditions



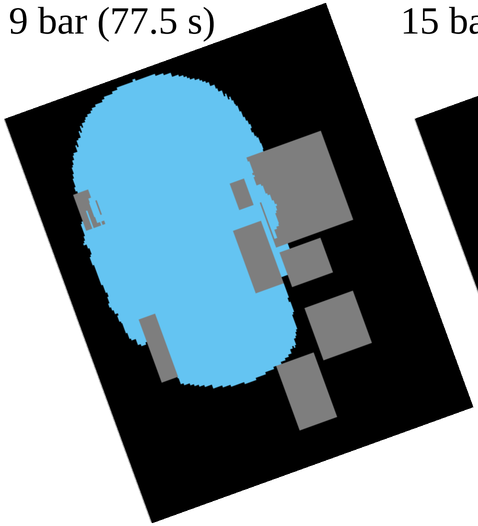
155 s

236 s

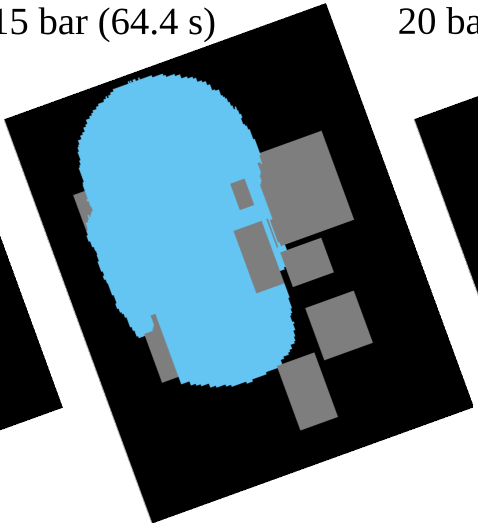
LPG release: storage conditions

Initial pressure [bar]	Pool fire diameter [m]	Pool fire height [m]
9	22.8	40.9
15	14.2	28.7
20	**Not occurred**	**Not occurred**
25	**Not occurred**	**Not occurred**

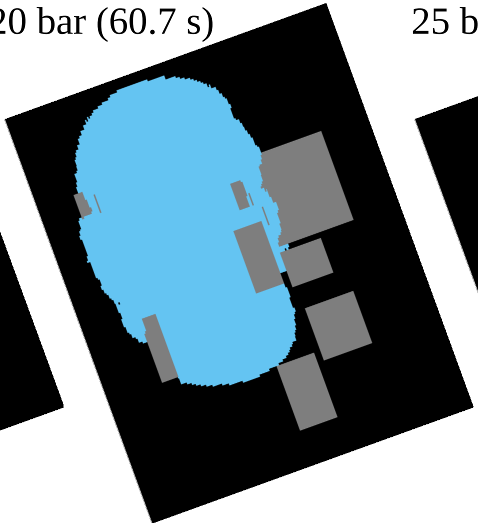
9 bar (77.5 s)



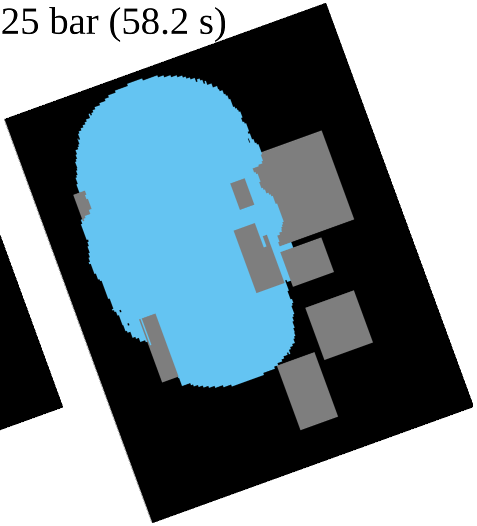
15 bar (64.4 s)



20 bar (60.7 s)



25 bar (58.2 s)

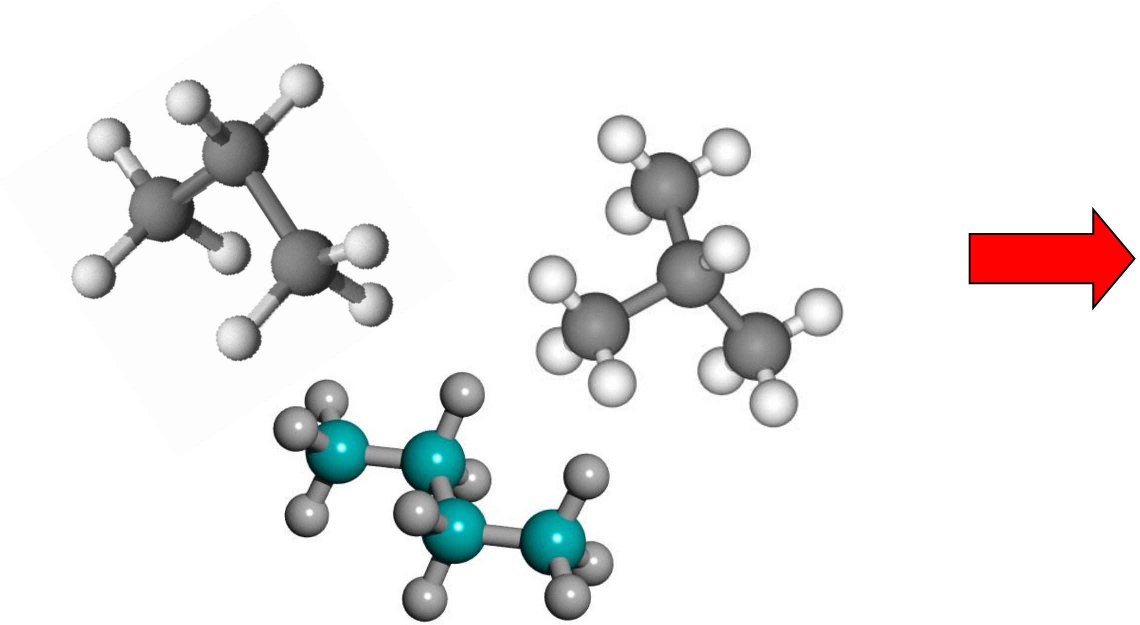


Reference case

LPG composition

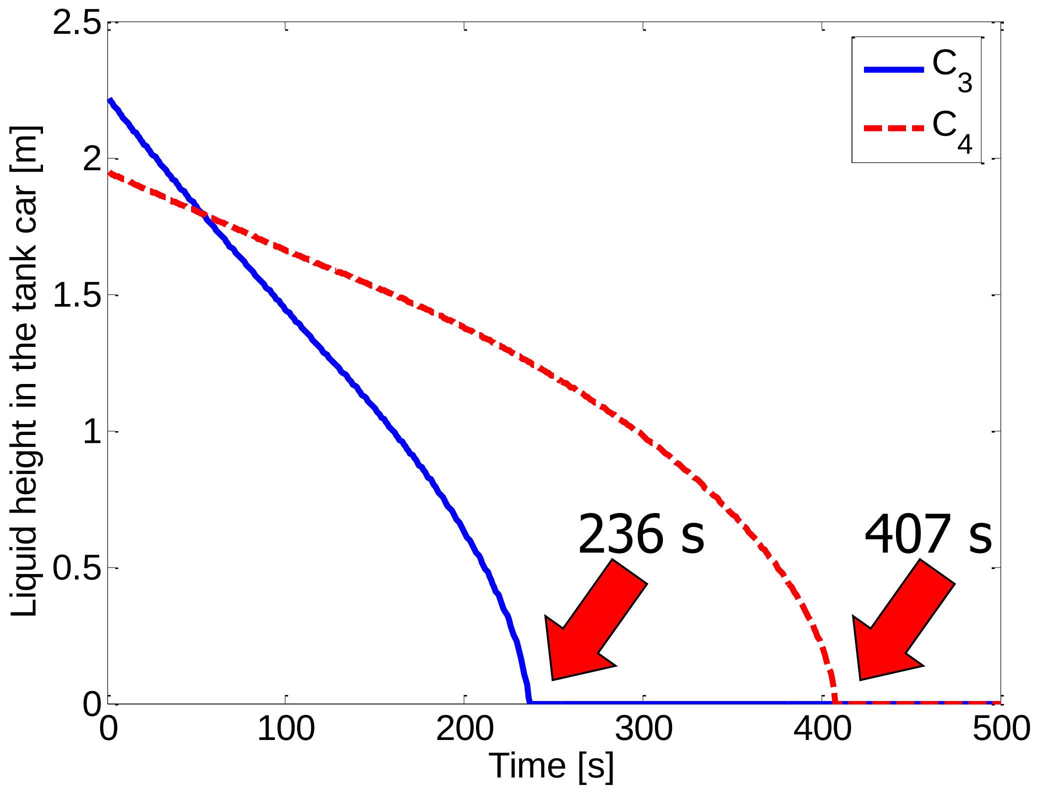
LPG is a variable mixture of C_3 and C_4 isomers

Its composition varies seasonally subject to specifications



Pure n-propane

LPG release: LPG composition



Composition	Pool fire diameter [m]	Pool fire height [m]
n-propane	22.8	40.9
n-butane	28.2	44.2

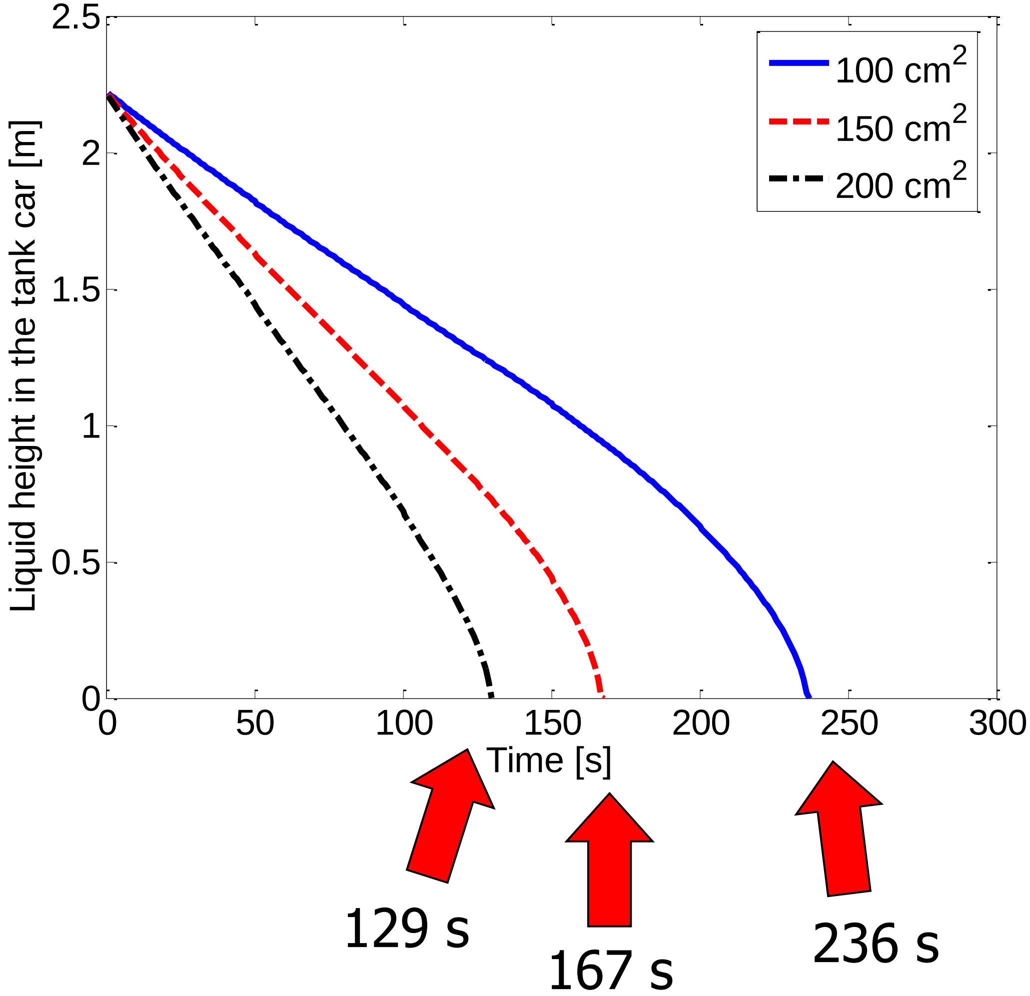
LPG release: crack size

Crack size

Only a portion of the longitudinal mark was cut open

100 cm^2 trapezoidal hole
c_D = 0.62 (jagged-in sheet)

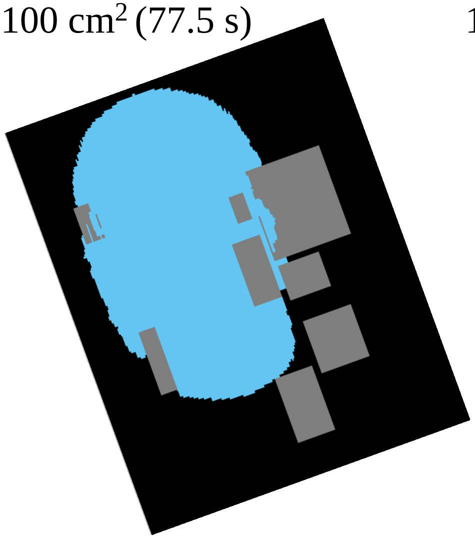
LPG release: crack size



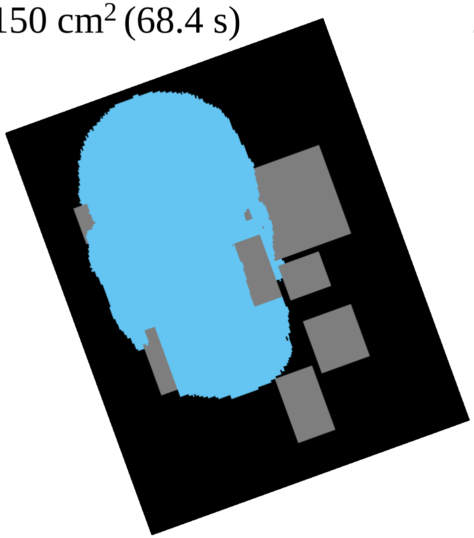
LPG release: crack size

Crack area [cm²]	Pool fire diameter [m]	Pool fire height [m]
100	22.8	40.9
150	25.5	44.5
200	26.5	45.8

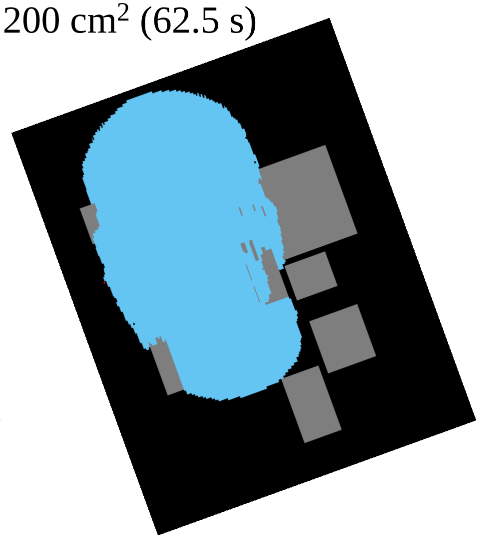
100 cm^2 (77.5 s)

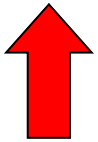


150 cm^2 (68.4 s)



200 cm^2 (62.5 s)





Reference case

LPG release: meteorological conditions

Meteorological conditions

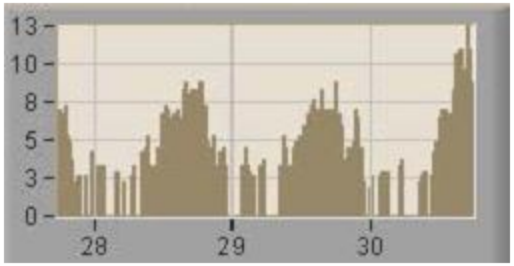
Report measured at the top of a hotel on the seafront of Viareggio about 1.7 km from the accident epicenter

Wind direction	NEE
Wind speed [m/s]	< 1
Air temperature [°C]	23
Ambient pressure [mbar]	1008
Relative humidity	80%

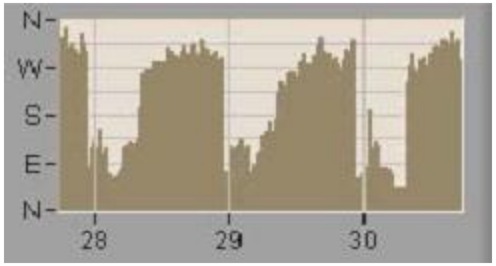
0.5 m/s
CALM CONDITIONS

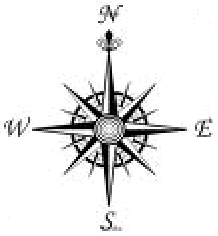
NEE direction

Wind speed [knot]



Wind direction





LPG release: ignition time

Ignition time

Some witnesses declared that the ignition occurred 2 min after the derailment, someone else reported 5 min.

The intense emotional involvement of the witnesses in those moments did not allow analyzing objectively the course of events.

→ 2 min

LPG release: ignition time

Ignition time	1 min	2 min	5 min
Discharge time [s]	226	236	262
Gas cloud arrival time [s]	Not occurred	77.5	77.5
Pool fire diameter [m]	21.8	22.8	25.9
Pool fire height [m]	39.6	40.9	45.0

LPG release: pool shape and area

Pool shape and area

The liquid fraction spread on an irregular terrain and found some obstacles that limited a symmetric spreading.

The liquid was partially absorbed by the permeable ballast made of pebbles and rocks.

Circular pool
Unconfined pool

Conclusioni

Conclusions

There are a number of uncertainties that affect the accident reconstruction

Importance of parametric studies to determine:

→ the worst-case scenario

→ the most probable scenario

→ the sensitivity of the accident consequences to input data

This analysis does not allow determining univocally the sequence and the timing of the events occurred in Viareggio

Nonetheless, it allows rejecting some scenarios, such as:

→ **Initial tank car pressure of 20 and 25 bar**

→ **Ignition at 1 min**

Conclusions

The gas cloud took ~80 s to reach the farthest exploded house (~100 m).

This evidence confirms the need for effective mitigation measures because, in case of this type of accidents, there is no time to apply any emergency response actions.

↓

CFD studies can identify the most effective mitigation measures, *e.g.*, barriers.

Riferimenti

- SIMULATION OF THE LPG RELEASE, DISPERSION, AND EXPLOSION IN THE VIAREGGIO RAILWAY ACCIDENT
  S. Brambilla, R. Totaro, D. Manca
  Chemical Engineering Transactions, 19, 195-200, (2010)

- A QUANTITATIVE ASSESSMENT OF THE VIAREGGIO RAILWAY ACCIDENT
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