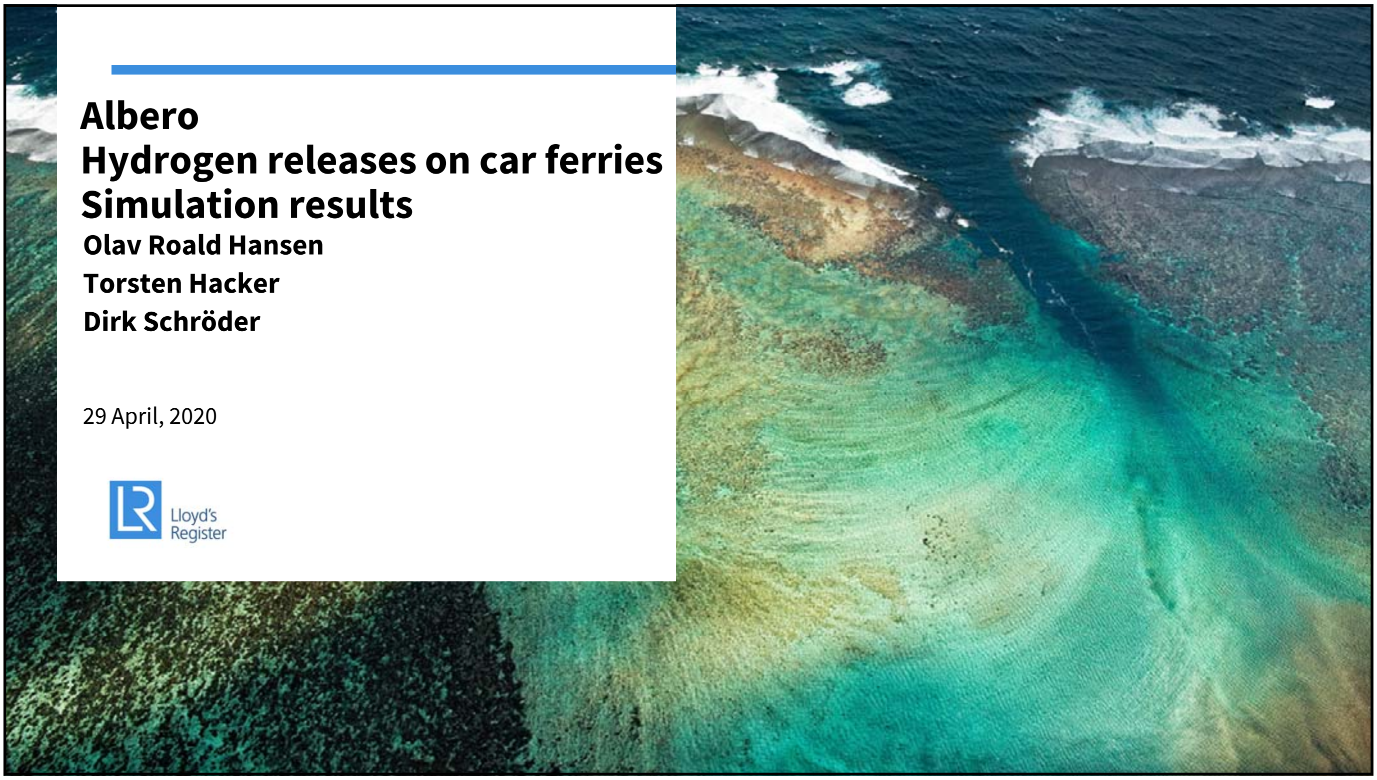


Albero
Hydrogen releases on car ferries
Simulation results

Olav Roald Hansen
Torsten Hacker
Dirk Schröder

29 April, 2020

Lloyd's Register

Albero CFD simulation study

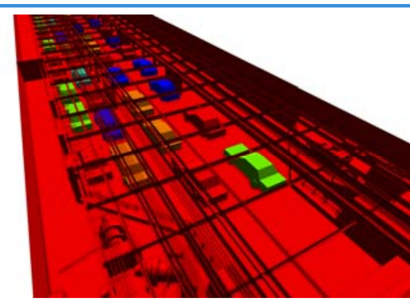
Lloyd's Register

Model prepared with inspiration from actual ferry

Car T-PRD release with delayed ignition evaluated as "worst credible event"

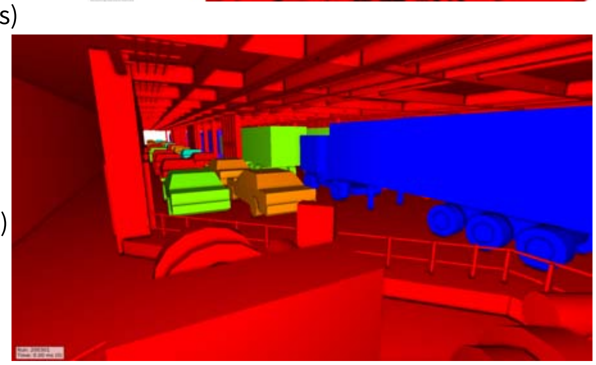
Release direction down and backwards (from below car) and up simulated

Release flow restriction orifice 2.5mm assumed (sensitivity with 1.5mm)



Car deck:

- Free elevation 2.5m (total 3.0m, 0.5m beams/piping/armatures)
- Cars realistically distributed across entire deck (8 car lanes)

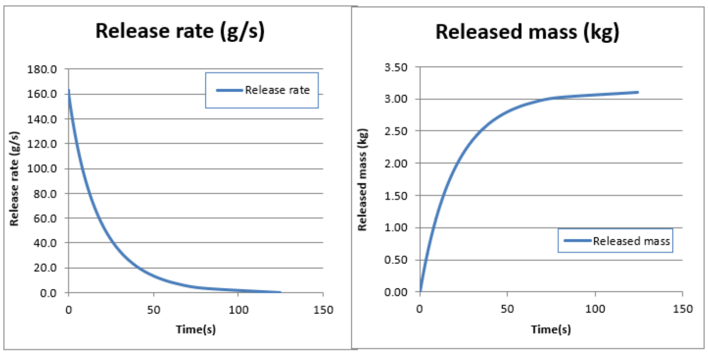


Truck deck:

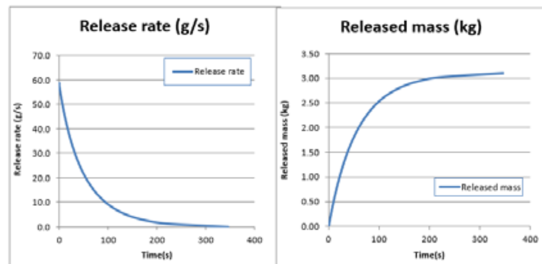
- Free elevation 4.6m (total 5.1m, 0.5m beams as for cars)
- Cars lanes near leak similar (minor differences to car deck)
- Trucks in adjacent lanes

Albero CFD simulation study

- **T-PRD release from FC-car**
  - Relevant cars have 2 or 3 tanks and 4-6.3 kg hydrogen
  - Based on information worst-case size of tank is assumed 75L @ 700 bar i.e. 3.1 kg @ 15°C
  - With 2.5mm T-PRD orifice this gives initial release rate 160 g/s
  - Sensitivity with 1.5mm T-PRD orifice (60 g/s) performed for downwards car release



Sensitivity (downwards car release only)



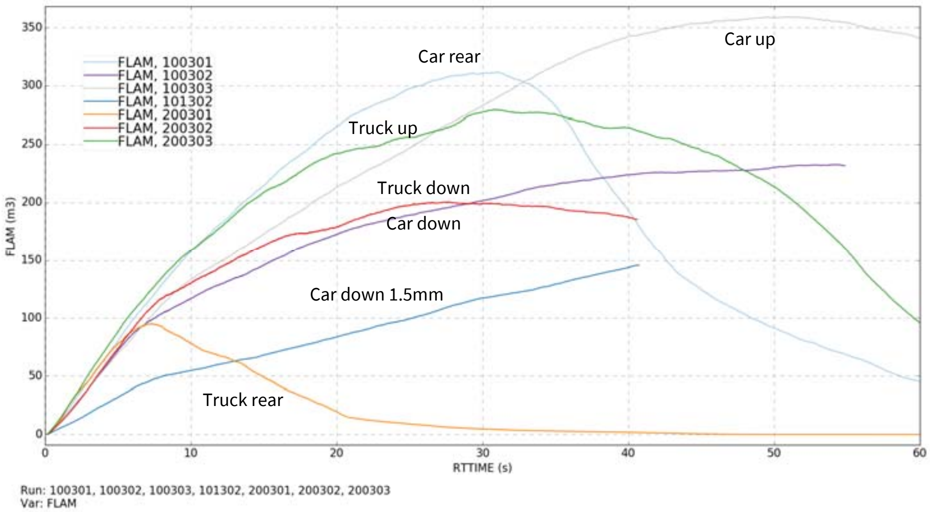
Albero CFD study – Overview simulations

- **Dispersion simulation (3.1 kg tank), explosion simulation with ignition at 2s, 5s, 10s and 30s (cars only)**
  - 101302 is sensitivity simulation to 100302 with reduced flow restriction orifice to 1.5mm
  - 100302# is sensitivity simulation to 100302 using preliminary version of car configuration

Jobno	Geometry	Orifice	Leak	Explosion 2s	Explosion 5s	Explosion 10s	Explosion 30s
100301	Car deck	2.5mm	Rear	120301	150301	110301	130301
100302	Car deck	2.5mm	Down	120302	150302	110302	130302
100303	Car deck	2.5mm	Up	120303	150303	110303	130303
101302	*Car deck*	*1.5mm*	*Down*	*121302*	*151302*	*111302*	*131302*
200301	Truck deck	2.5mm	Rear	220301	250301	210301	
200302	Truck deck	2.5mm	Down	220302	250302	210302	
200303	Truck deck	2.5mm	Up	220303	250303	210303	
100302#	*Test sim car deck*	*2.5mm*	*Down*		*105302#*	*110302#*	

Albero CFD study – FLAM – flammable cloud

- **FLAM is total volume at concentration above LFL (4%)**
  - Volume that can be ignited and where flames could be seen (flame zone likely 8 times smaller within 8% cloud)

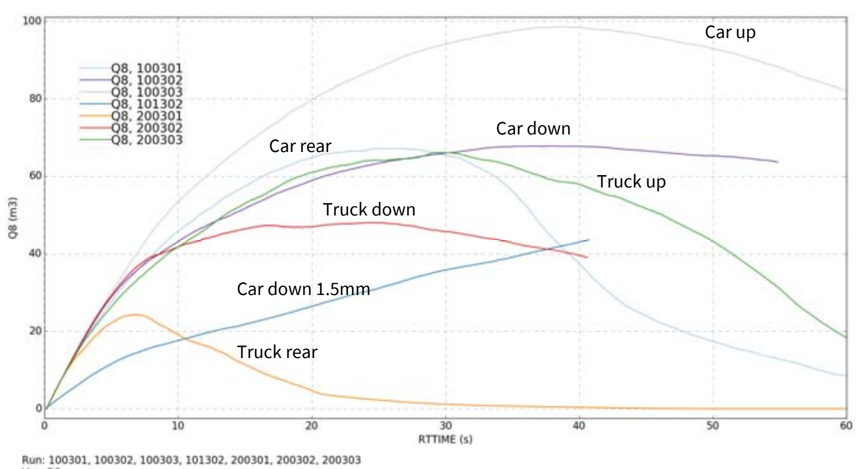


Albero CFD study – Q8 –explosion energy

- **Q8 is energy based equivalent stoichiometric cloud size (fuel volumes scaled by expansion E)**
  - Stoichiometric cloud size which would give same energy release as actual dispersed cloud

Hansen, O. R., Gavelli, F., Davis, S. G., & Middha, P. (2013). Equivalent cloud methods used for explosion risk and consequence studies. Journal of Loss Prevention in the Process Industries, 26(3), 511-527.

$$Q8\left(m^3\right) = \sum Volume_{Fuel} \times E/E_{max}$$

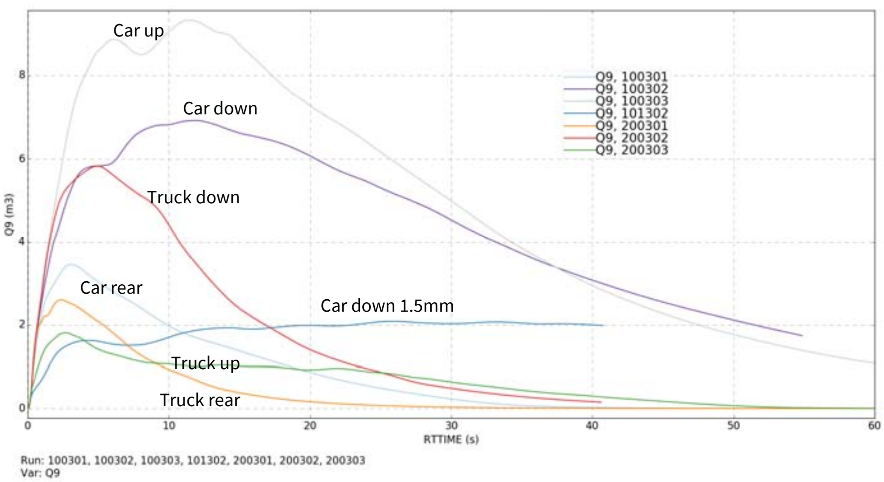


Albero CFD study – Q9 –high reactivity cloud

Lloyd's Register

- **Q9 is equivalent stoichiometric cloud size (fuel volumes scaled by burning velocity S and expansion E)**
  - Explosion severity of dispersed cloud assumed similar to stoichiometric Q9 cloud size
  - Hansen, O. R., Gavelli, F., Davis, S. G., & Middha, P. (2013). Equivalent cloud methods used for explosion risk and consequence studies.
  - Journal of Loss Prevention in the Process Industries, 26(3), 511-527.

$$Q9(m^3) = \sum Volume_{Fuel} \times (SE)/(S \times E)_{max}$$

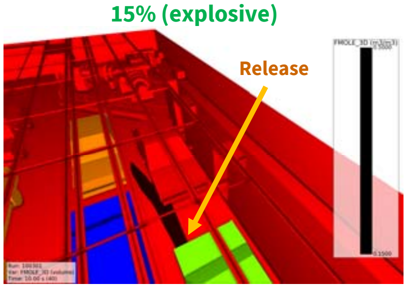


Albero CFD study – Car deck- REAR release

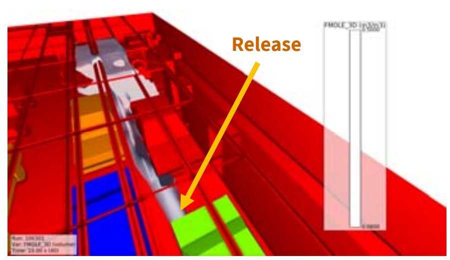
Lloyd's Register

Gas clouds shown at time=10s, when extension of clouds are near maximum

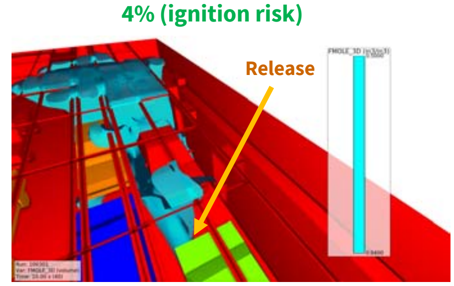
15% (explosive)



8% (flash-fire risk)



4% (ignition risk)

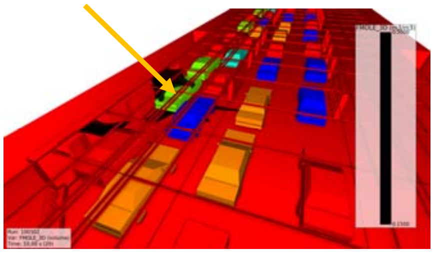


- Small explosive zone where fast flame propagation can be feared, the extent is consistent with 15% contour for sonic jet 4.3m initially (160g/s) and 3.3m at 10s (100 g/s).
- Limited flashfire zone (>8%, downwards propagation limit). Almost no 8% zone after 20s, only thin plume close to release.
- If 4% cloud ignites (at concentration < 8%) flame will only propagate upwards. If it spreads to 8% cloud (could do so near ceiling) the entire 8% cloud region could burn (T~700°C at 8%). Flashfire risk outside 8% cloud will be negligible.
- Low risk, some potential for burns.

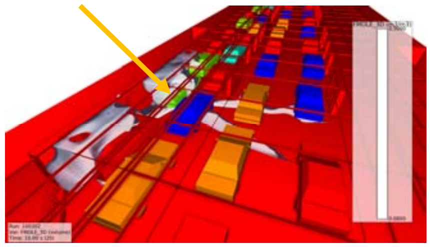
Albero CFD study – Car deck- Release DOWN

Gas clouds shown at time=10s, when extension of clouds are near maximum

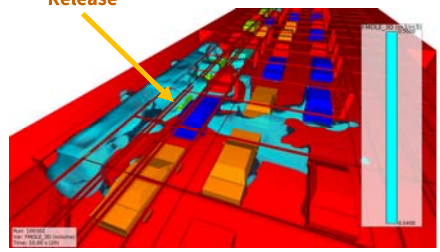
Release 15% (explosive)



Release 8% (flash-fire risk)



Release 4% (ignition risk)

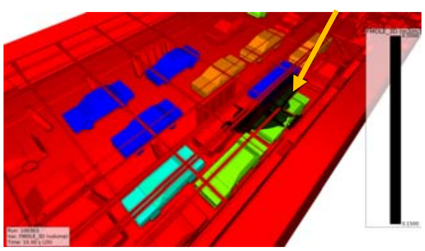


- Small explosive zone, spread thin along floor and wall due to floor impingement.
- Limited flashfire zone (>8%, downwards propagation limit) also spread out.
- Low risk, some potential for burns locally.

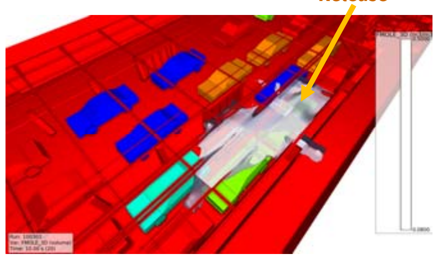
Albero CFD study – Car deck- Release UP

Gas clouds shown at time=10s, when extension of clouds are near maximum

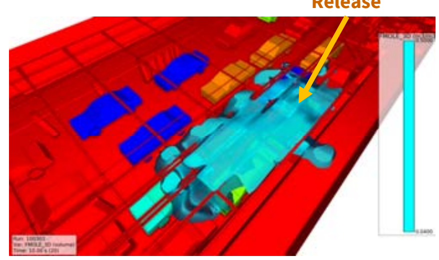
15% (explosive) Release



8% (flash-fire risk) Release



4% (ignition risk) Release

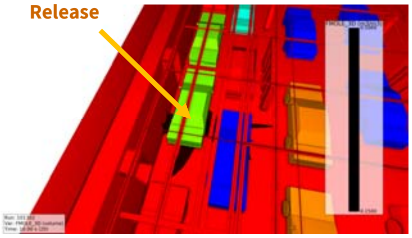


- Small explosive zone above car where fast flame propagation can be feared.
- Limited flashfire zone (>8%, downwards propagation limit).
- Low risk, some potential for burns locally.

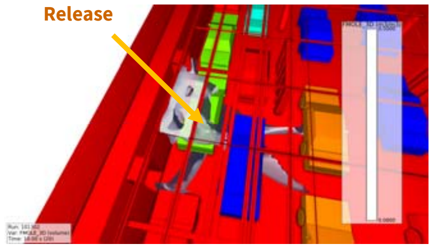
Albero CFD study – Car deck- Release 1.5mm DOWN

Gas clouds shown at time=10s, when extension of clouds are near maximum

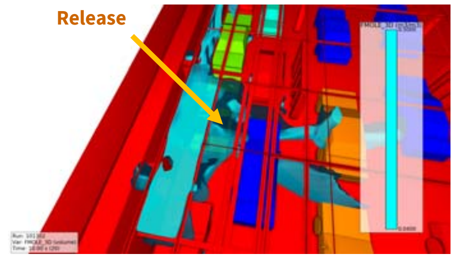
15% (explosive)



8% (flash-fire risk)



4% (ignition risk)

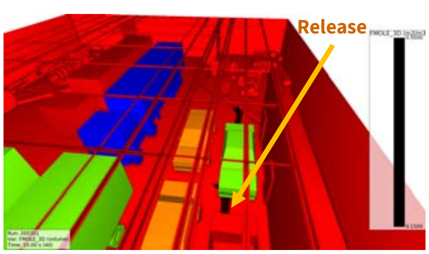


- Negligible explosive zone, spread thin along floor.
- Small flashfire zone (>8%, downwards propagation limit) also spread out.
- Reduction from 2.5mm to 1.5mm orifice (160 g/s to 60 g/s initial release rate) had significant effect reducing explosive zone.
- Very low risk, potential for limited burns.

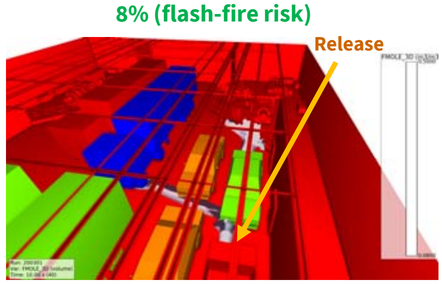
Albero CFD study – Truck deck- REAR release

Gas clouds shown at time=10s, when extension of clouds are near maximum

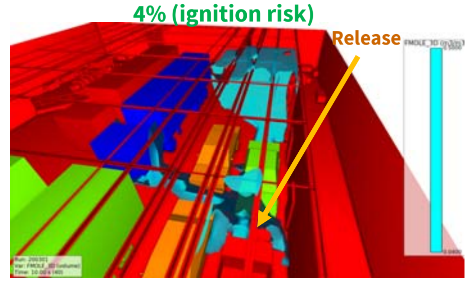
15% (explosive)



8% (flash-fire risk)



4% (ignition risk)



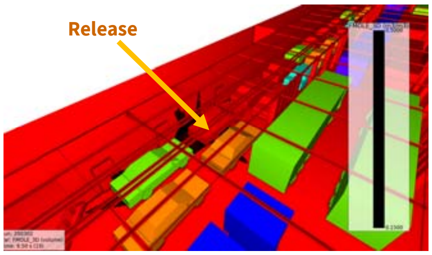
- There may be a small difference in the detailed positioning of cars compared to car deck case, but not significantly.
- Small explosive zone where fast flame propagation can be feared.
- Limited flashfire zone (>8%, downwards propagation limit), less extensive with taller ceiling.
- 4% zone also reduced with increased ceiling height.
- Very low risk, potential for limited burns.

Albero CFD study – Truck deck- Release DOWN

Gas clouds shown at time=10s, when extension of clouds are near maximum

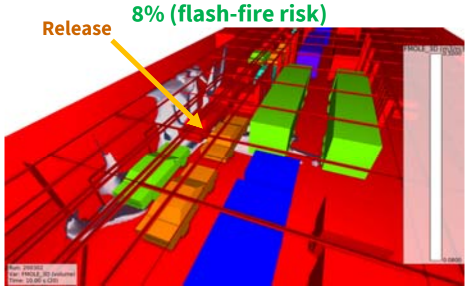
15% (explosive)

Release



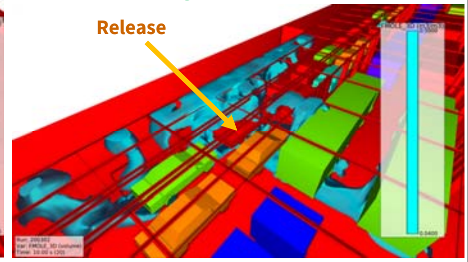
8% (flash-fire risk)

Release



4% (ignition risk)

Release



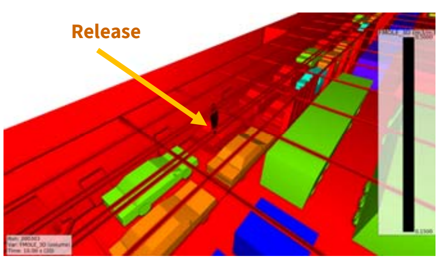
- Small explosive zone, spread thin along floor and wall due to floor impingement .
- Limited flashfire zone (>8%, downwards propagation limit) also spread out.
- Limited risk, potential for limited burns.

Albero CFD study –Truck deck- Release UP

Gas clouds shown at time=10s, when extension of clouds are near maximum

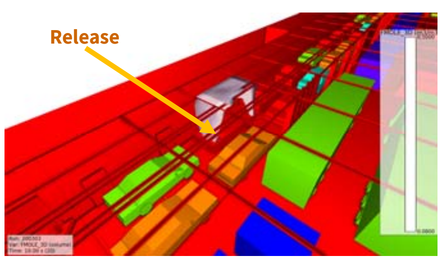
15% (explosive)

Release



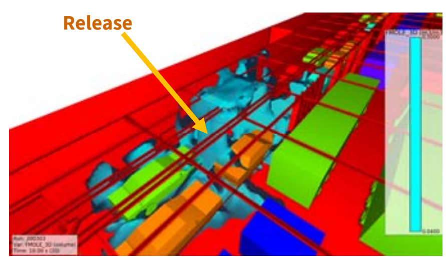
8% (flash-fire risk)

Release



4% (ignition risk)

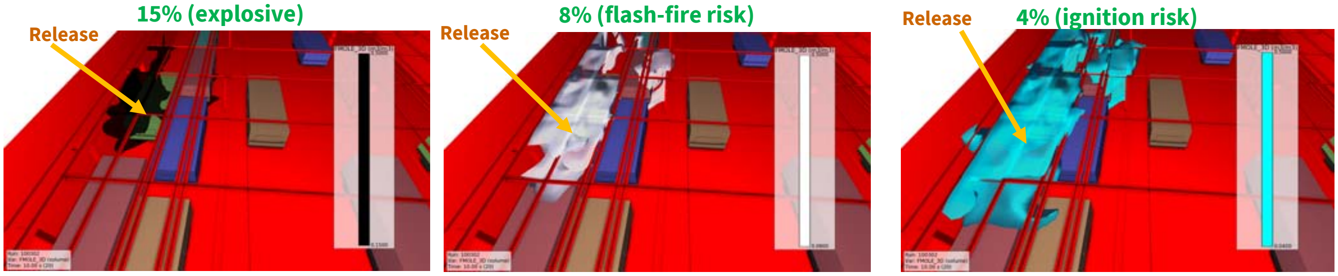
Release



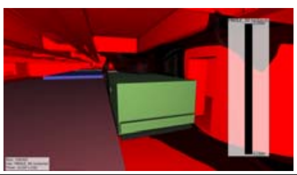
- Explosive zone only in free jet above car (~3m length after 10s).
- Limited flashfire zone (>8%, downwards propagation limit). Release is captured and returned to car by ceiling beams.
- Zero risk to people expected.

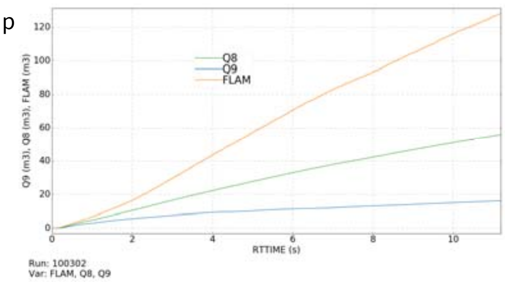
Albero CFD study – Car deck test sim Release DOWN

Gas clouds shown at time=10s, when extension of clouds are near maximum



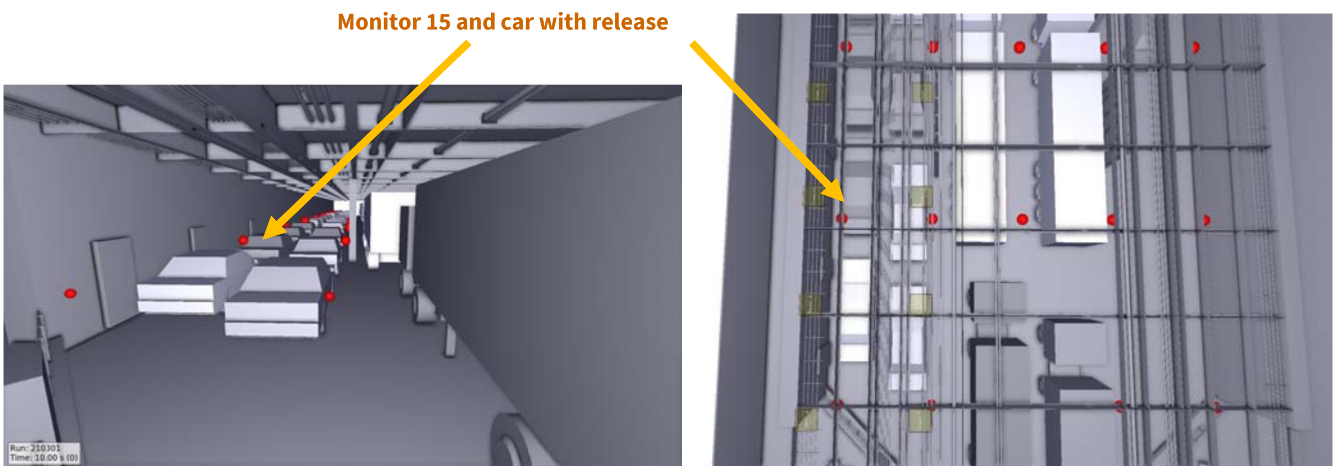
- In this first “appetizer” simulation “cars” were place much closer together
- Not feasible to open doors, majority of gas was diverted towards wall and up
- More than twice as high reactive cloud, and significant confinement
- Scenario shows potential for worse scenarios in confined/packed settings





Albero CFD study – Explosion pressures

- **Pressures reported 1.5m above deck – monitors with spacing 10m (along) and 5m (across) vessel**
- **Also reported on ceiling panels, but due to low pressure level and robust deck these are not of interest**



Albero CFD study – Explosion pressures 2 seconds

- **Reported pressures Monitor 15**

Maximum explosion pressures around 80 mbar

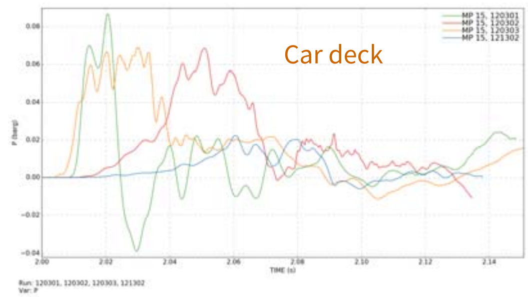
Car deck
- All release directions give 60-80 mbar
- Reduced orifice (1.5mm) gives 20 mbar
- 20-30 ms duration

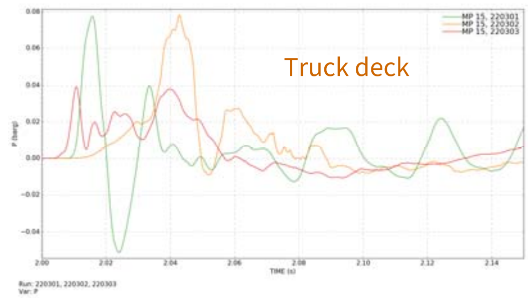
Truck deck
- Rear and down give 60-80 mbar
- Upwards release gives 40 mbar
- 10-15 ms duration

Domestic windows might break at 20 mbar

Car windows robust, local damage may be seen

People should not be at any significant risk from pressures





Albero CFD study – Explosion pressures 5 seconds

- **Reported pressures Monitor 15**

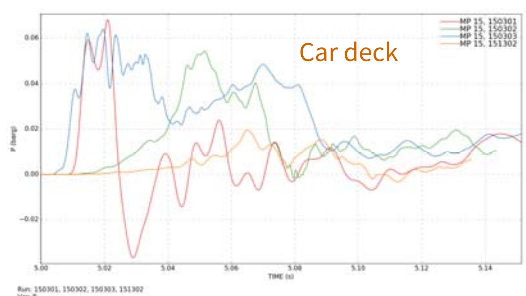
Maximum explosion pressures around 60 mbar

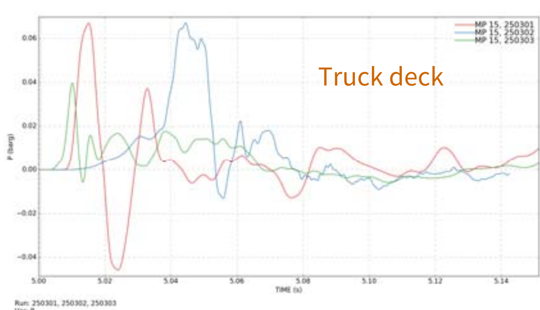
Car deck
- All release directions give 50-60 mbar
- Reduced orifice (1.5mm) gives 20 mbar
- 20-60 ms duration

Truck deck
- Rear and down give 60 mbar
- Upwards release gives 40 mbar (jet plume only)
- 10-15 ms duration

Reduced pressures, longer duration (car deck)

No loads of significant concern





Albero CFD study – Explosion pressures 10 seconds

- **Reported pressures Monitor 15**

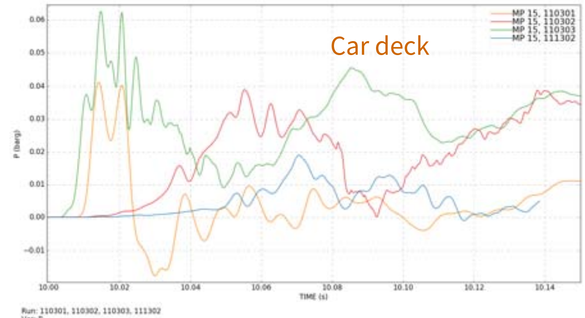
  Maximum explosion pressures around 60 mbar

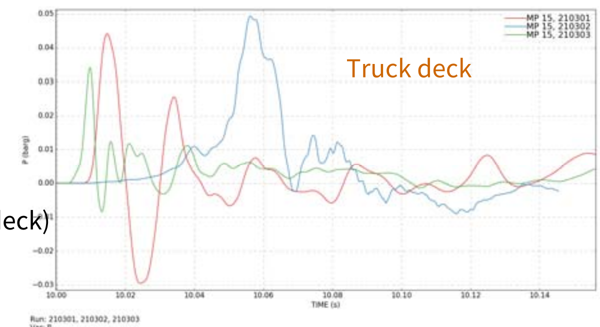
  Car deck
  - Upwards release gives 60 mbar
  - Down and rear give 40 mbar
  - Reduced orifice (1.5mm) gives 20 mbar
  - Multiple peaks due to pockets and reflections

  Truck deck
  - Rear and down give 40-50 mbar
  - Upwards release gives 35 mbar (jet plume only)
  - 10-15 ms duration

  Lower pressures than early ignition, longer duration (car deck)

  No loads of significant concern





Albero CFD study – Explosion pressures 30 seconds

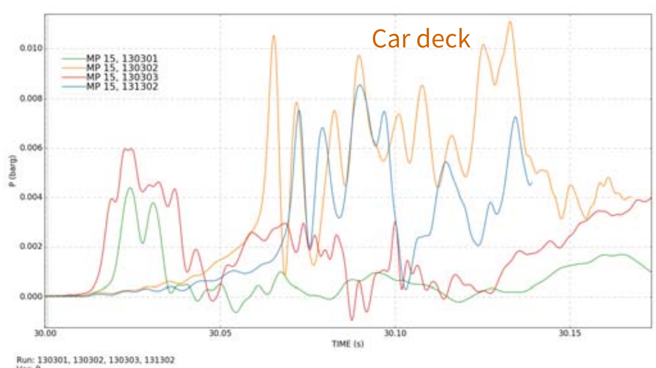
- **Reported pressures Monitor 15**

  Maximum explosion pressures around 10 mbar

  Car deck
  - Much lower pressures than with earlier ignition

  Truck deck
  - Not simulated, would give even less pressures

  No loads of significant concern

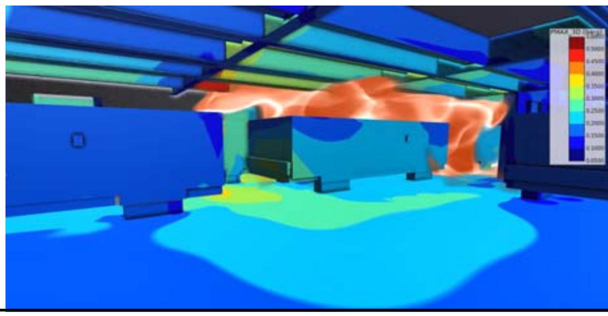


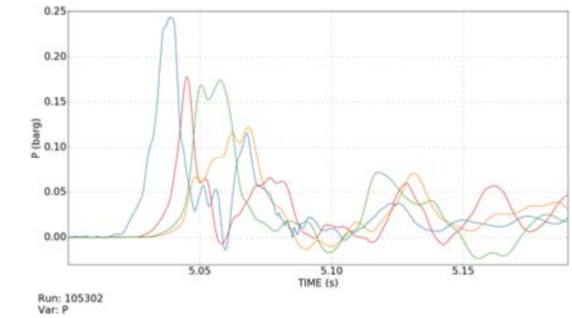
Truck deck not simulated

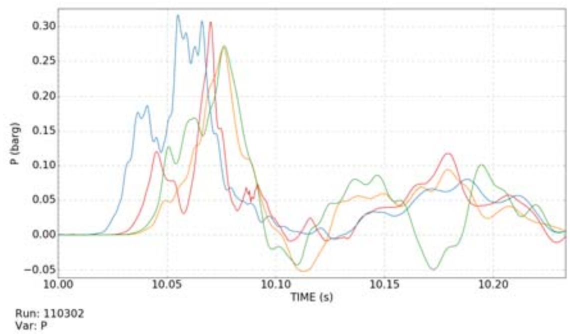
Albero CFD study – Explosion pressures

Lloyd's Register

- **Reported pressures early "Appetizer simulation"**
  - Overpressures of 250mbar (5s) and 300 mbar (10s).
  - Cars laterally placed too close to wall (45cm) and adjacent car(25cm), "square tires" and coincidences regarding car placement, led to >2x larger reactive clouds which were also strongly confined between walls/deck and car.
  - Predicted pressure levels could represent risk to people as they may fall over and get hurt by impact. 250 mbar is sometimes defined as eardrum rupture threshold.
  - Avoid parking FC-vehicles very close to walls and vehicles





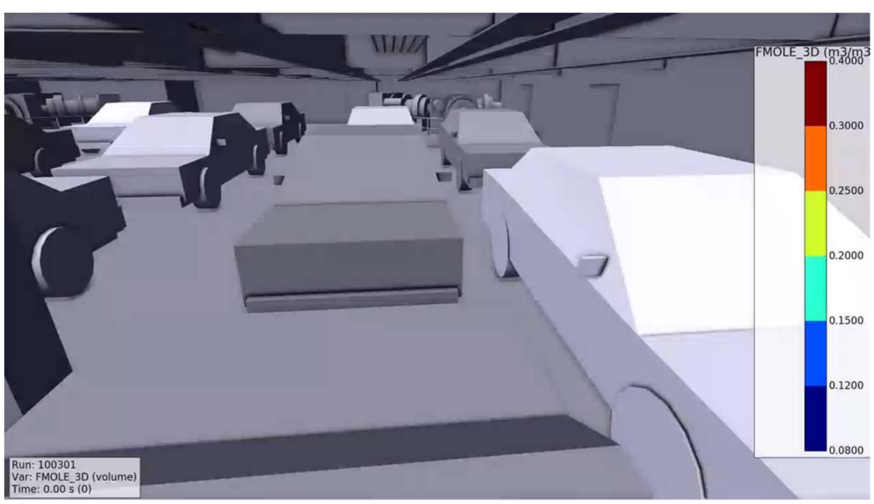


Albero CFD study – dispersion simulation videos

Lloyd's Register

Car deck release backwards

Concentration above 8% shown



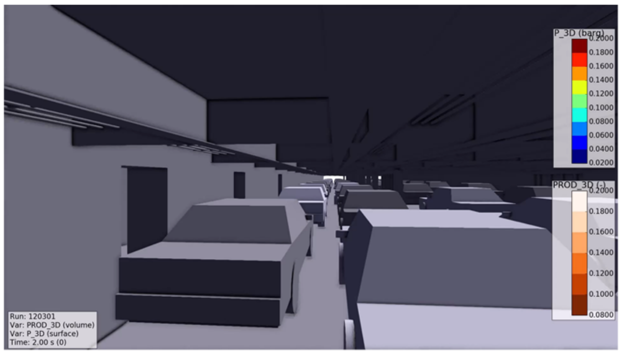
3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – explosion simulation videos

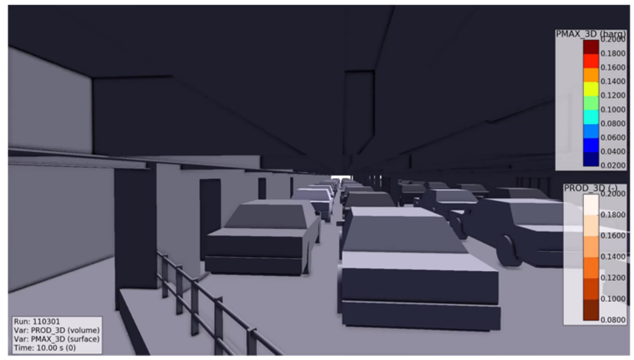
Lloyd's Register

Car deck release backwards – flame and maximum pressure shown

Ignition 2s (PS-pressure not max pressure shown in this video)



Ignition 10s



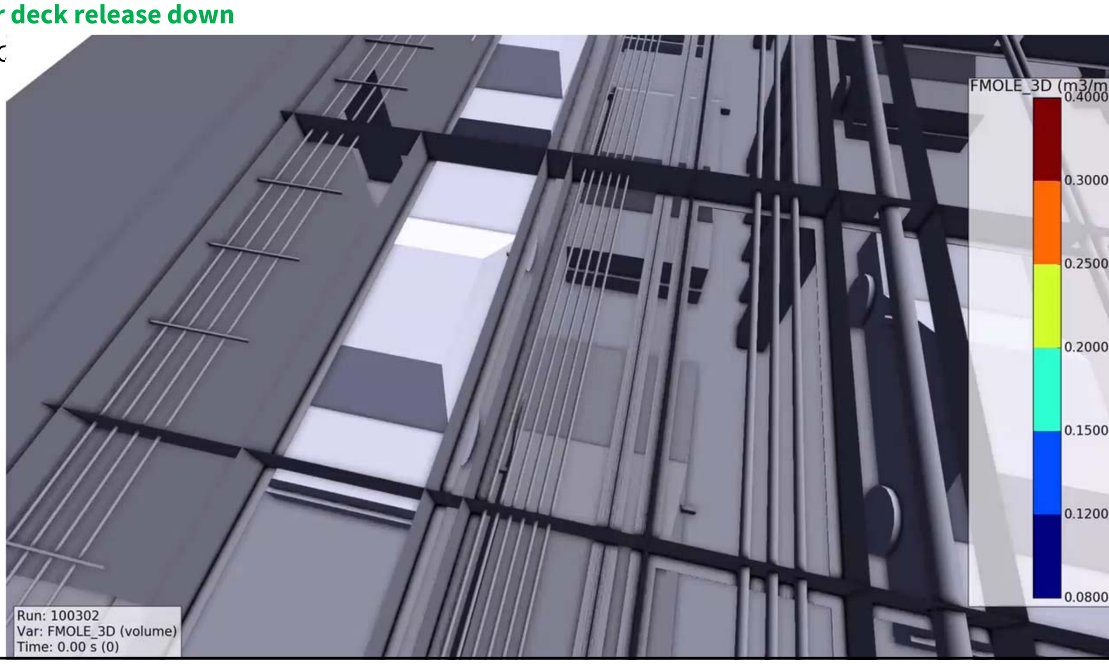
3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – dispersion simulation videos

Lloyd's Register

Car deck release down

C



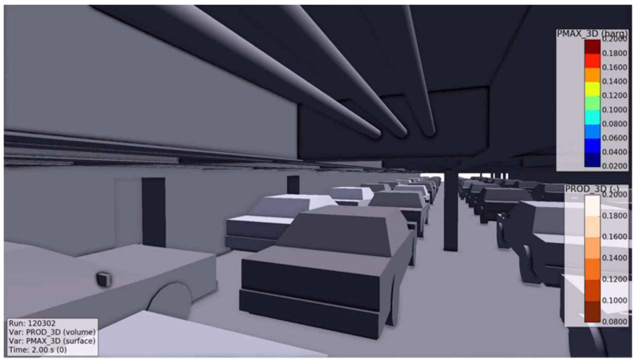
ve some smearing

Albero CFD study – explosion simulation videos

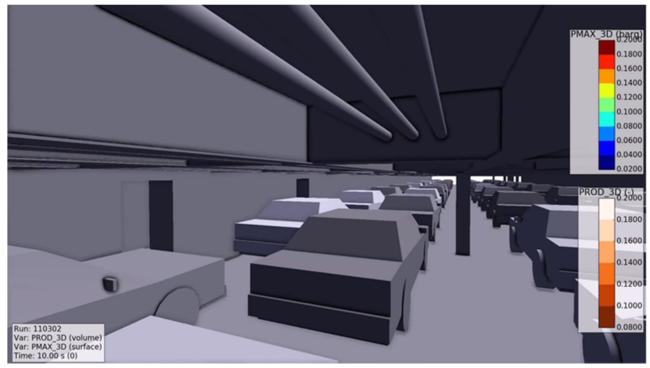
Lloyd's Register

Car deck release down – flame and maximum pressure shown

Ignition 2s



Ignition 10s



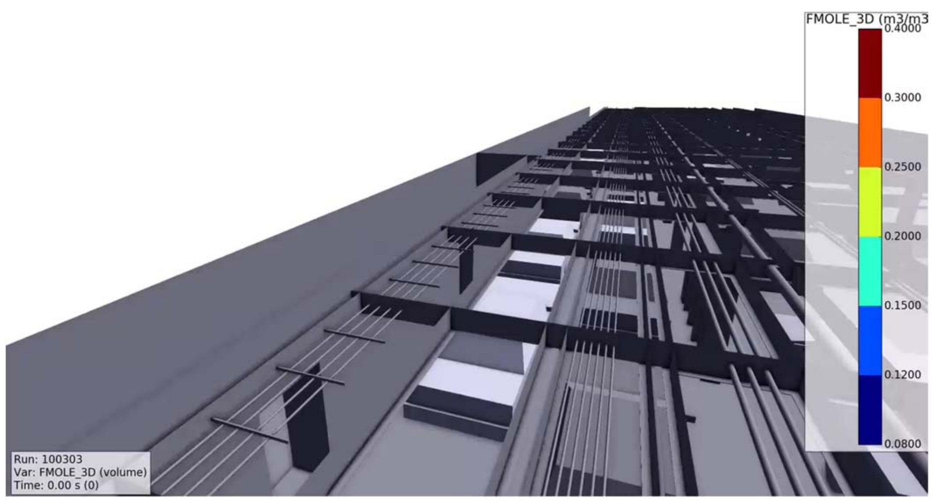
3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – dispersion simulation videos

Lloyd's Register

Car deck release up

Concentration above 8% shown

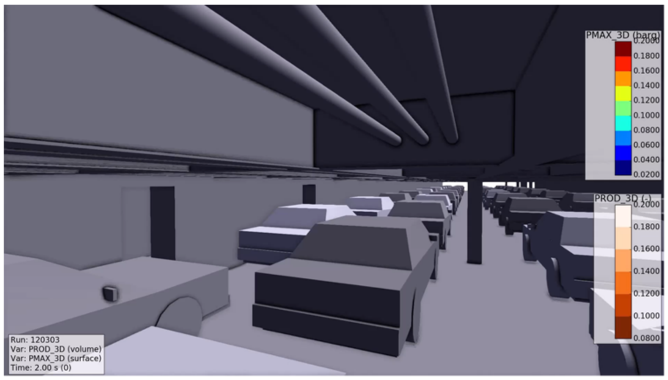


3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – explosion simulation videos

Car deck release up – flame and maximum pressure shown

Ignition 2s



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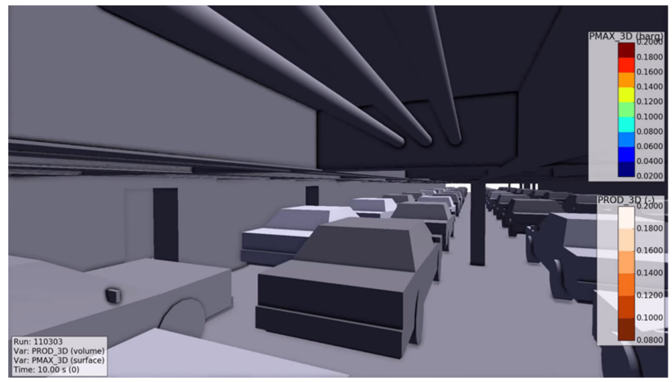


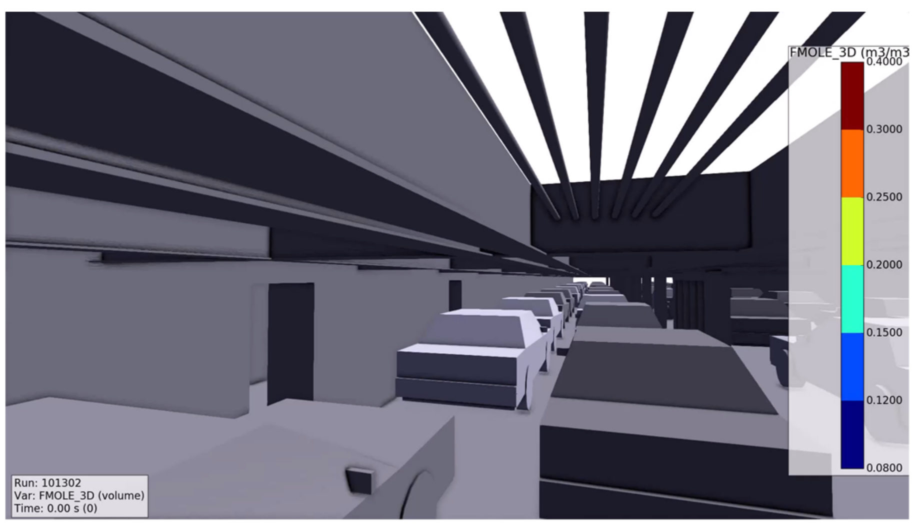
3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – dispersion simulation videos

Car deck release down

1.5mm reduced orifice

Concentration above 8% shown

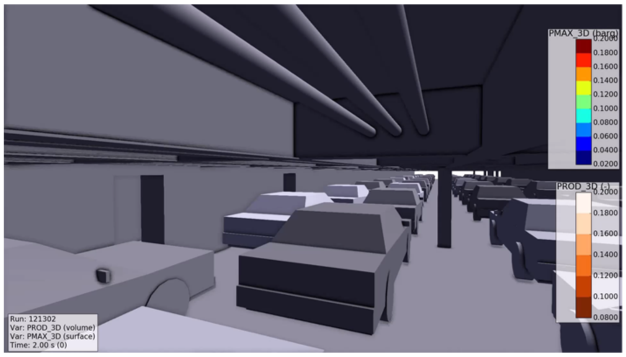


3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – explosion simulation videos

Car deck release down (1.5mm orifice) – flame and maximum pressure shown

Ignition 2s

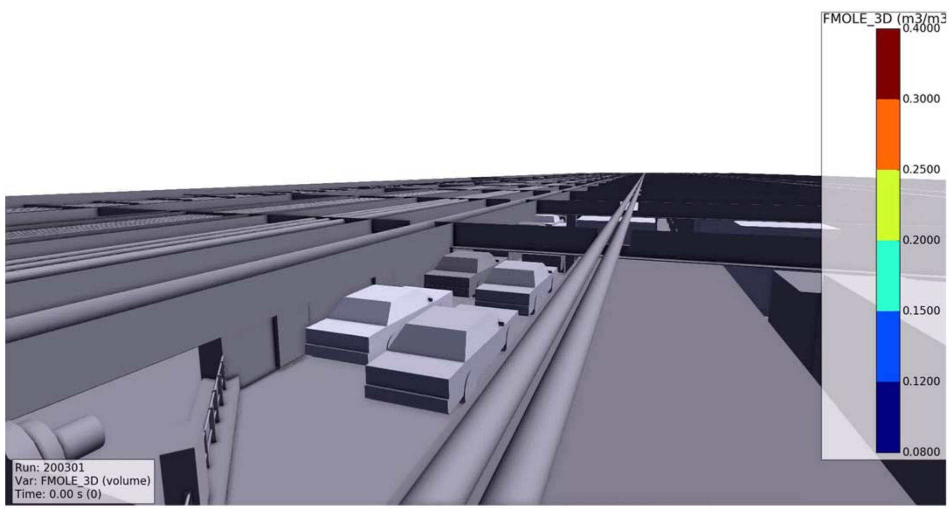


3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – dispersion simulation videos

Truck deck release backwards

Concentration above 8% shown

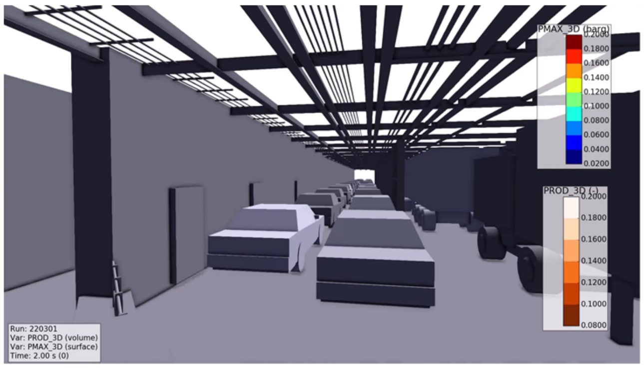


3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

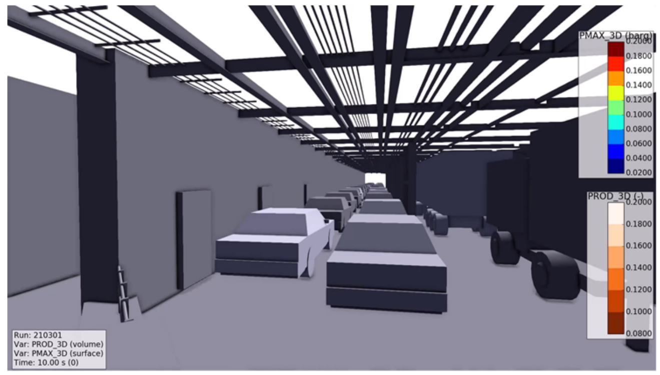
Albero CFD study – explosion simulation videos

Truck deck release backwards – flame and maximum pressure shown

Ignition 2s



Ignition 10s

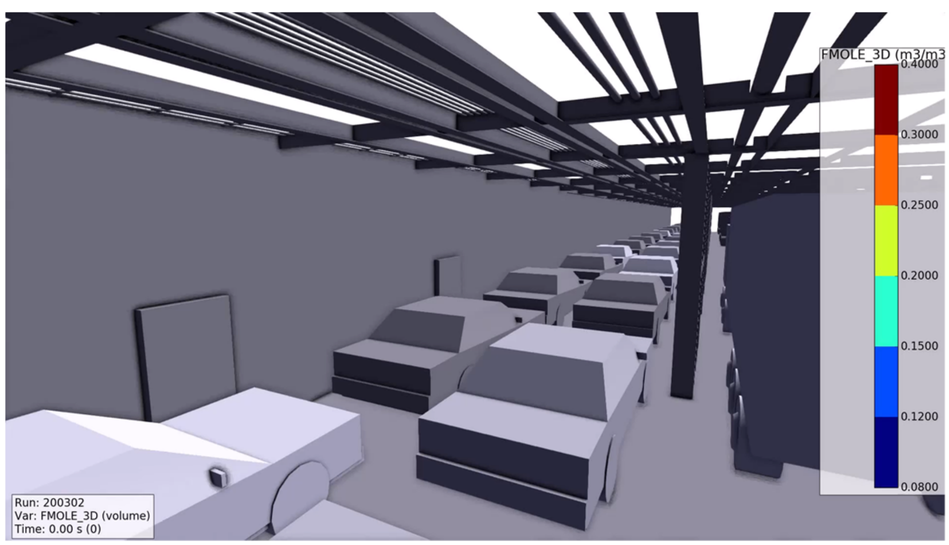


3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – dispersion simulation videos

Truck deck release down

Concentration above 8% shown



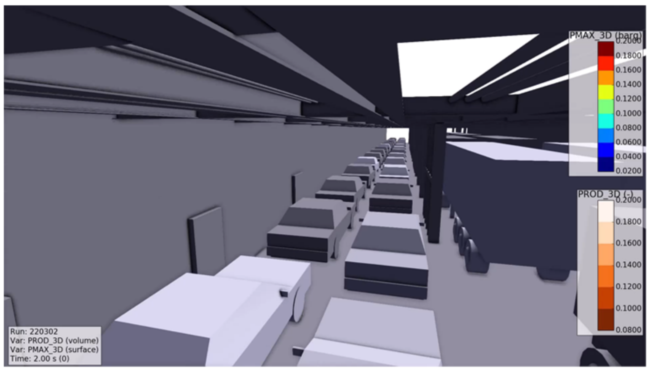
3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

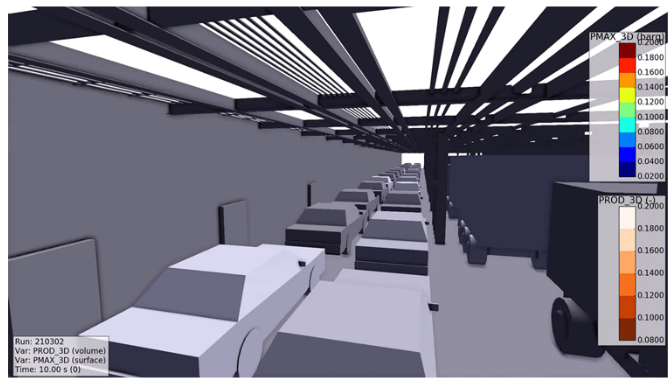
Albero CFD study – explosion simulation videos

Lloyd's Register

Truck deck release down – flame and maximum pressure shown

Ignition 2s | **Ignition 10s**





3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero

Lloyd's Register

Truck deck

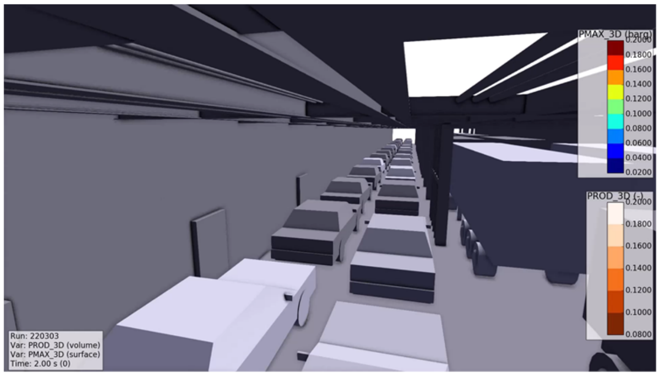
Concentra

3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

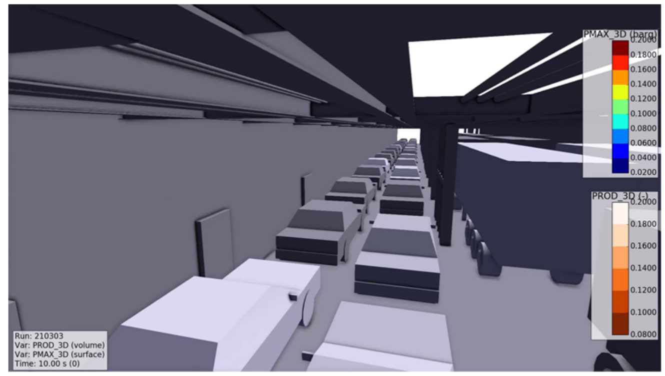
Albero CFD study – explosion simulation videos

Truck deck release up – flame and maximum pressure shown

Ignition 2s



Ignition 10s



3D volume visualization is not always 100% accurate, transparency and grid resolution may give some smearing

Albero CFD study – summary videos

- **Reflections regarding risk for fatalities and damage**
  - Risk to people is primarily related to flame exposure and high pressures
  - If people would be inside flames shown in videos this could be dangerous. Flame temperatures of the lean flames shown are mostly moderate (rather 700°C than 1000°C), and flames consist of water vapour which is not toxic. For comparison hydrocarbon flames at LFL-concentration are 1300°C and may be toxic (e.g. CO_2 and CO). Due to a very short duration of flame/heat exposure, burns may be expected on exposed skin, but it can be assumed that fatalities from flame exposure would be rare.
  - Fatality risk from explosion pressures below 100 mbar of short duration should be limited. In the flame zone near the release higher pressures (100-200+ mbar + reflected onto deck/wall) can be seen very locally, these should also not represent any major risk, but a moderate fatality risk can be feared if people are at the core of explosion and pushed off their feet. Beyond 10m away from explosion pressures will be lower and may shake people but should not represent any fatality risk. Due to the confined deck repeated shock waves can be expected across the entire deck.
  - Neither flames nor pressures should represent any risk for damage to ferry deck, some local damage to cars may be possible (glass damage).
  - Based on the above the risk potential for the various scenarios can be interpreted from the various videos.

Albero CFD study – conclusions

- The main conclusion is that risk from this type of scenarios should be limited and very local, fatality risk from flame exposure or pressures cannot be ruled out, but would be low.
- Due to the large volume of the car deck relative to the released amount of gas, the high release velocity, and the quickly reducing release rate when tank pressure reduces, the primary hazard is related to ignition within the first 10-15s.
- Hazards for truck deck releases are generally lower than for the narrower car deck, for early ignition for downwards/rear releases hazards could be similar.
- Like seen from the initial test simulation cars placed very close together and close to the wall could lead to worse explosions and a more significant risk. The same applies with lower ceiling and cars placed in corners. Thus, it would be recommended to ensure certain minimum distances around FC-vehicles to adjacent cars.
- A reduced T-PRD orifice (1.5mm compared to 2.5mm, initial release rate reduced from 160 g/s to 60 g/s, tank 90% empty within 140s rather than 50s) gives a very significant reduction of explosion consequences.
- The worst-case scenario studied (T-PRD release with delayed ignition) is assumed unlikely, but possible. In most cases where T-PRD would open there is already a fire, and immediate ignition could be expected, resulting in a more local jet-fire rather than flashfire and explosion.

Tank rupture scenarios with immediate or slightly delayed ignition, is another category worst-case scenarios not considered. Those would normally be a result of an extended fire with failing T-PRD, thus no people should be nearby in a closed car deck. Such scenarios could be modelled, to understand possible risks to vessel and fire-fighters. For such a severe fire scenario all types of fuel tanks will represent a major risk.

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