



Risk Analysis for LH2 transfer operations

ELVHYS Dissemination Conference

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OUTLINE

- Introduction
- Major Steps for QRA
- Case Studies: Liquid Hydrogen Bunkering
- Conclusions

MAJOR STEPS FOR QRA

HAZARD IDENTIFICATION

WHAT CAN GO WRONG?

ACCIDENT SEQUENCE MODELING

HOW OFTEN THIS CAN HAPPEN?

FREQUENCY ESTIMATION

CONSEQUENCE ASSESSMENT

WHAT ARE THE POSSIBLE CONSEQUENCES?

RISK INTEGRATION

HOW FREQUENT ARE THESE CONSEQUENCES?

ACCIDENT SEQUENCE MODELING



SAFETY SYSTEMS FOR INITIATING EVENT “External fire (near tank)”:

- Fire Fighting System
- Pressure Safety Valves (PSV)

External fire near tank	Fire fighting system	Pressure safety valve		SEQUENCES
IE	FFS	PSV		
			1	SAFE
			2	RELEASE FROM PSV
			3	TANK RUPTURE

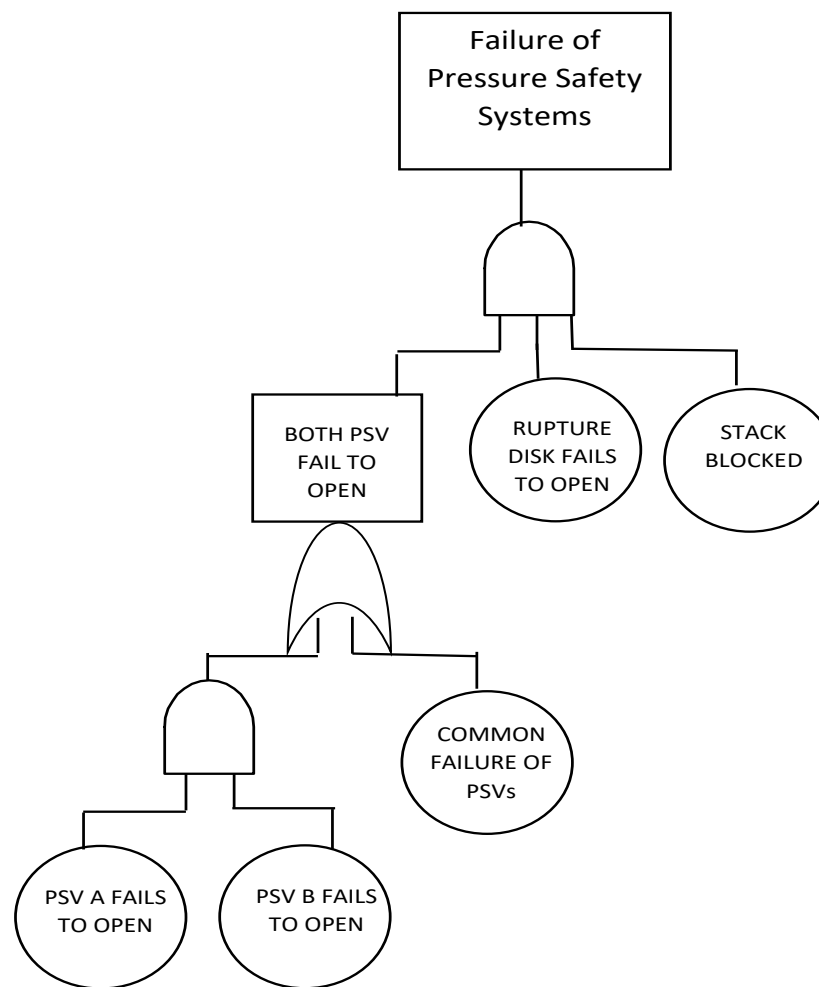
DAMAGE STATE



List of Fault Trees to be quantified

- *Pressure Safety System (PSVs, rupture disks, stack)*
- *Firefighting system (trailer)*
- *Manual operation of blow down valve*
- *Manual stop of send out*
- *Emergency shut down system (ESD)*
- *High pressure in trailer, owing to vaporizer malfunction*
- *Inadequate purging or cooling of hoses*
- *High level in tank owing to overfilling*
- *Extra loads (trailer, vessel, hose)*

Fault tree with top event Failure of Pressure Safety Systems



FREQUENCY ASSESSMENT OF DAMAGE STATES



Data and Parameter Assessment

- ✓ Estimate *frequencies of the initiating events*, **component unavailability**, **probabilities of human errors**

Accident Sequence and Plant damage State Quantification

- ✓ Calculate frequency of occurrence of accident sequences and Damage states using the event trees of the logic model

SOURCES OF DATA

- Offshore and Onshore Reliability Data (OREDA, 2015)
- RIVM 2009, Reference Manual Bevi Risk Assessments
- EMSA, Reliability and safety analysis, Study investigating the safety of Hydrogen as fuel on ships by DNV, 2024
- D. Ehrhart, Ethan S. Hecht, and Benjamin B. Schroeder. Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.1 Technical Reference Manual.

SAT FREQUENCIES

- ✓ LH2 hose full rupture $4 \times 10^{-4}/y$ – (100 hours bunkering/yr) [RIVM]
- ✓ LH2 hose 5% rupture $4 \times 10^{-3}/y$ – (100 hours bunkering/yr) [RIVM]
- ✓ LH2 tank full rupture $1.0 \times 10^{-5}/y$ [RIVM]
- ✓ BLEVE of an LH2 trailer $5.0 \times 10^{-8}/y$ (100 hours bunkering/yr) [RIVM]

Frequencies of damage states (/y)

CASE STUDY 3

Damage state	Frequency /y
Rupture of trailer	7.07×10^{-5}
Full bore hose rupture	5.02×10^{-5}
Ship tank rupture	6.87×10^{-5}

CONSEQUENCE ANALYSIS



Jet fire

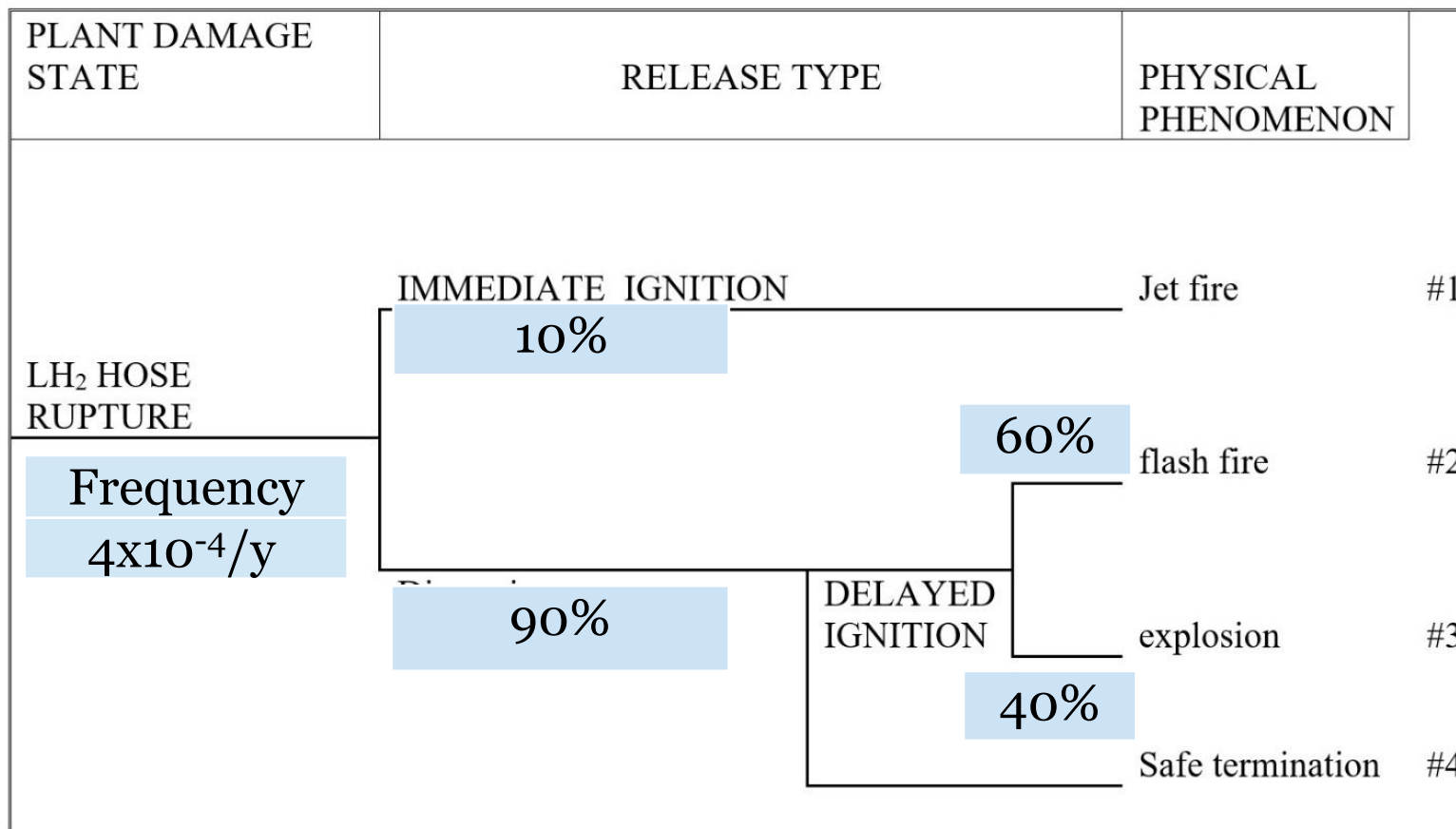


Fireball

PLANT DAMAGE STATE	RELEASE TYPE		PHYSICAL PHENOMENON	
LH ₂ HOSE RUPTURE	IMMEDIATE IGNITION		Jet fire	#1
			flash fire	#2
	Dispersion Cloud heavier than air	DELAYED IGNITION	explosion	#3
			Safe termination	#4

- ✓ Hose rupture –jet fire
- ✓ Hose rupture - flash fire
- ✓ Hose rupture – explosion (combustion)

CONSEQUENCE ANALYSIS - Liquid hose



✓ $4 \times 10^{-5}/y$

✓ $2.16 \times 10^{-4}/y$

✓ $1.44 \times 10^{-4}/y$

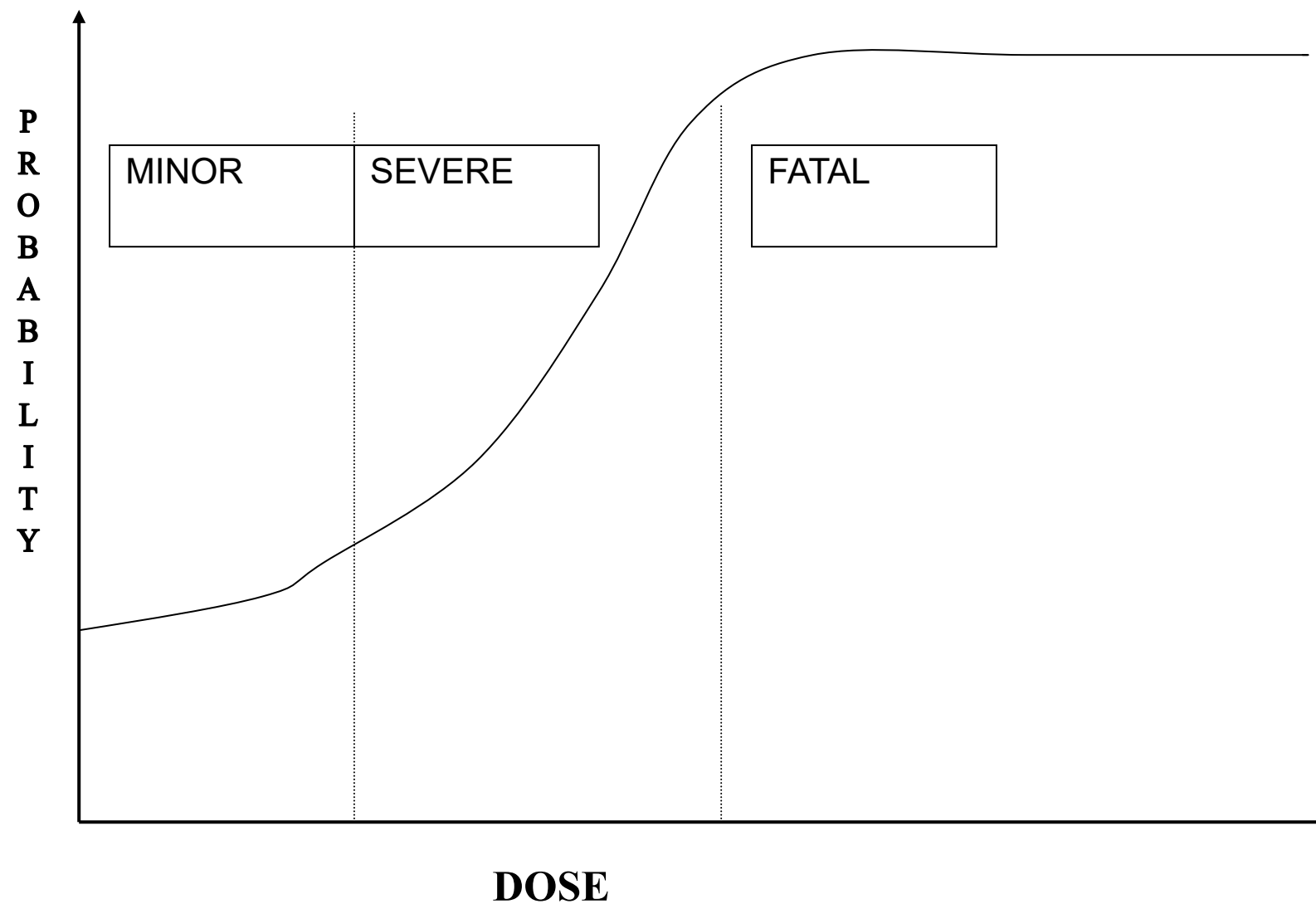
CONSEQUENCE ASSESSMENT



$$d(x,y)=t q(x,y)^{4/3}$$

q: radiation

t: exposure





Probit Equations – Thermal radiation

Impact



Fatality	$P = -14.9 + 2.56 \ln(tq^{4/3} 10^{-4})$ or $P = -38.48 + 2.56 \ln(tq^{4/3})$	Eisenberg et al, 1975. (Based on nuclear blasts)
<i>Fatality</i>	$P = -36.38 + 2.56 \ln(tq^{4/3})$	<i>Tsao and Perry, 1979. (Eisenberg model modified to account for infrared radiation)</i>
Fatality	$P = -37.23 + 2.56 \ln(tq^{4/3})$	TNO, 1992 (Tsao and Perry, 1979 model modified to account for clothing)
Fatality	$P = -29.02 + 1.99 \ln(tq^{4/3})$	Lees, 1994 (Accounts for clothing, based on porcine skin experiments using ultraviolet source to determine skin damages. Uses burn mortality information)
1 degree burns	$P = -39.83 + 3.0186 \ln(tq^{4/3})$	TNO, 1992
2 degree burns	$P = -43.14 + 3.0186 \ln(tq^{4/3})$	TNO, 1992
Radiation ($t=s$, $q=W/m^2$)		

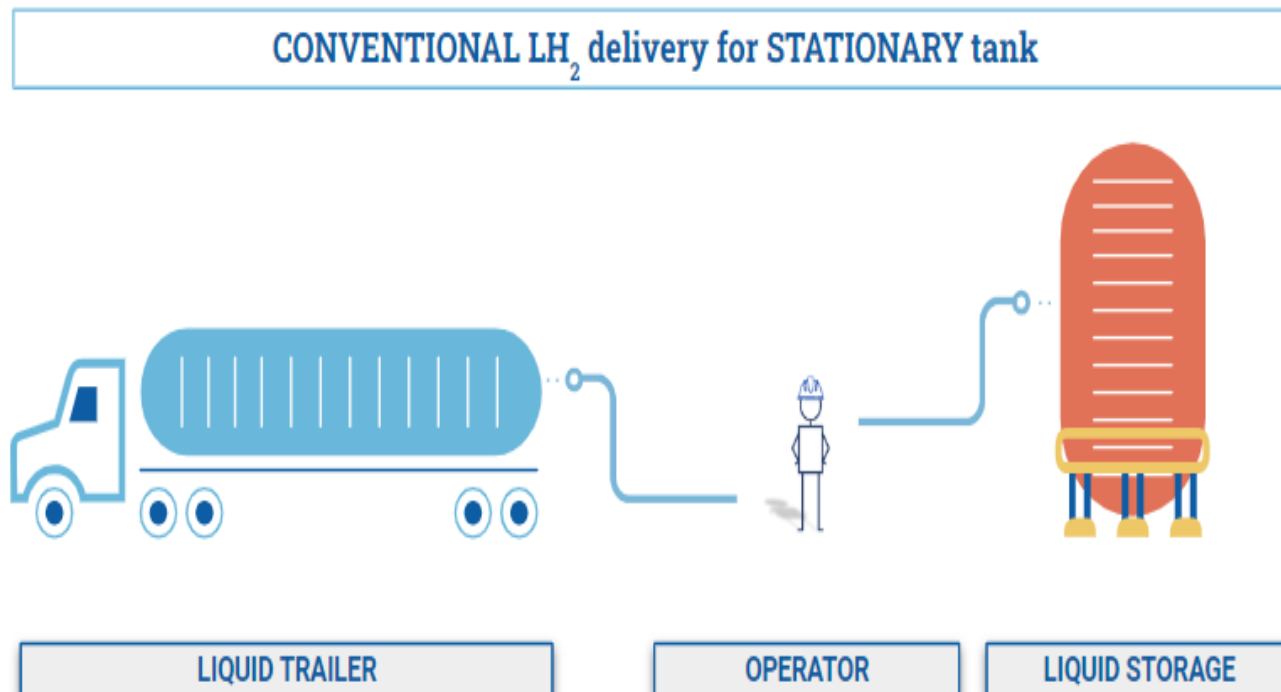
Probit Equations – Overpressure



Application	Probit Function	Reference
Structure Failure Collapse	$d(x, y) = \left(\frac{40000}{P_s} \right)^{7.4} + \left(\frac{460}{I_s} \right)^{11.3}$ $P = 5 - 0.22 \ln(d(x, y))$ Ps in Pa, Is in (Pas)	TNO, 1992 (also included in HyRAM)
Total damage	$P = -23.8 + 2.92 \ln(P_s), P_s \text{ in Pa}$	CCPS, 2000 /Eisenberg et al., 1975
Minor damage	$d(x, y) = \left(\frac{4600}{P_s} \right)^{3.9} + \left(\frac{110}{I_s} \right)^5$ $P = 5 - 0.26 \ln(d(x, y))$ Ps in Pa, Is in (Pas)	TNO, 1992
Major Damage	$d(x, y) = \left(\frac{17500}{P_s} \right)^{8.4} + \left(\frac{290}{I_s} \right)^{9.3}$ $P = 5 - 0.26 \ln(d(x, y))$ Ps in Pa, Is in (Pas)	Ehrhart and Hecht, 2022
Human Fatality Death due to lung hemorrhage	$P = -77.1 + 6.91 \ln P_s$ Ps in Pa	Eisenberg et al., 1975, CCPS, 2000 (also in HyRAM)
Death due to lung hemorrhage	$d(x, y) = \frac{4.2 P_o}{P_{pref}} + \frac{1.3}{I_{sc}} I_{sc} = I_s / (P_o^{0.5} x m^{0.33})$ $P_{pref} = P_s + 5x(P_s)^2 / (2P_s + 1.4x10^6)$ Ps in Pa, Po atmospheric pressure in Pa, m mass of person in kg $P = 5 - 5.74 \ln(d(x, y))$	TNO, 1992
Death due to lung hemorrhage	$P = 5.13 + 1.37 \ln(P_s x 10^{-5}), P_s \text{ in Pa}$ $P = 1.47 + 1.37 \ln P_s, P_s \text{ in psig}$	HSE, 1994 (also in HYRAM)
Death due to head impact	$d(x, y) = \frac{2430}{P_s} + \frac{4x10^8}{P_s I_s}$ $P = 5 - 8.49 \ln(d(x, y))$ Ps in Pa, tp in s	TNO, 1992 (also included in HyRAM as default)
Death due to whole body impact	$P = 5 - 2.44 \ln(d(x, y))$ $d(x, y) = \frac{7380}{P_s} + \frac{1.3x10^9}{P_s I_s}$ Ps in Pa, tp in s	TNO, 1992

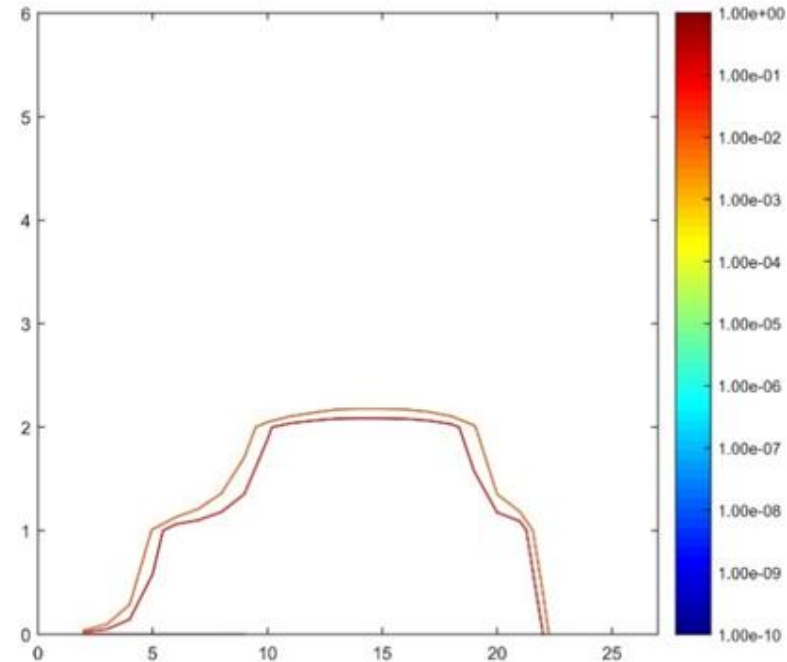
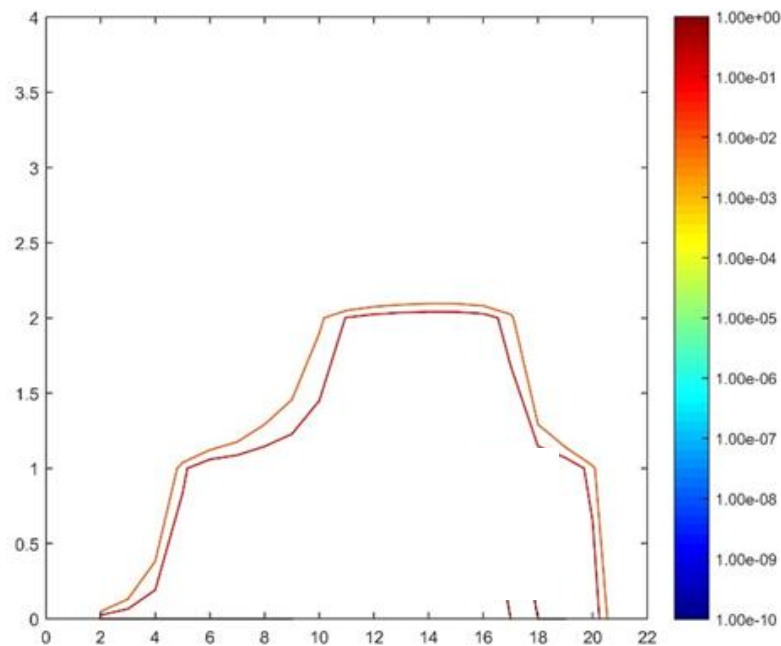
CASE STUDY 1

- a) Trailer area with capacity up to $57\text{m}^3 \text{ LH}_2$
- b) The transfer hose from the truck to the tank
- c) Storage tank section. It comprises the containment tank with capacity up to $56\text{m}^3 \text{ LH}_2$ together with the vent stack.



Probability of fatality (10^{-2} , 10^{-1}) from hose jet fire

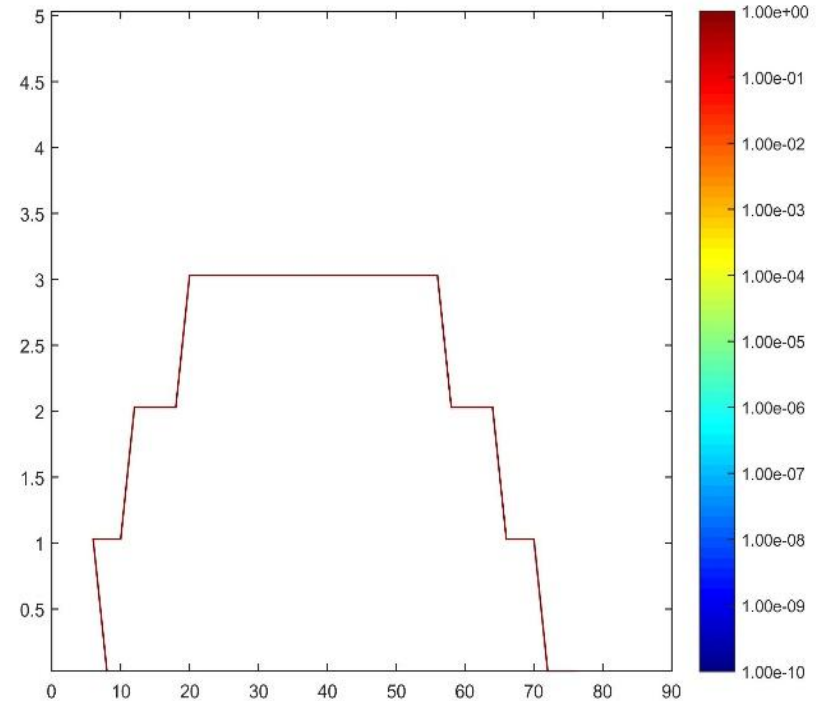
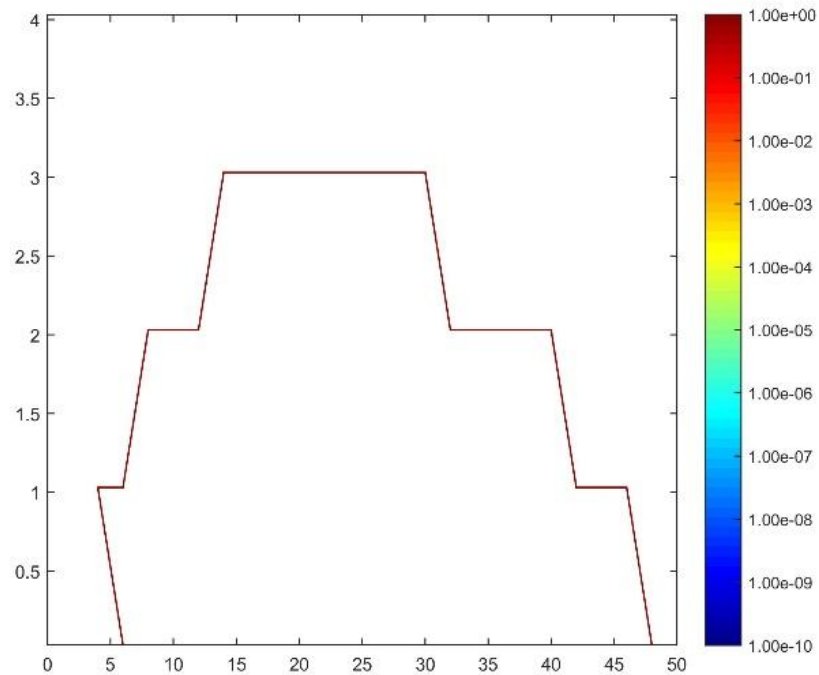
Full rupture – 10bar CFD ADREA (0, 5m/s)



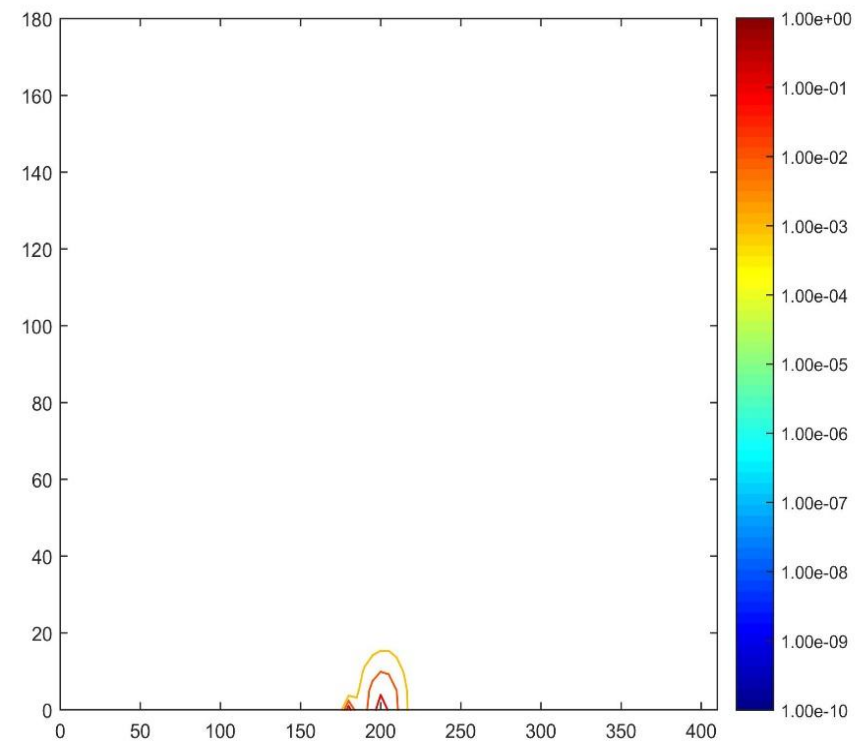
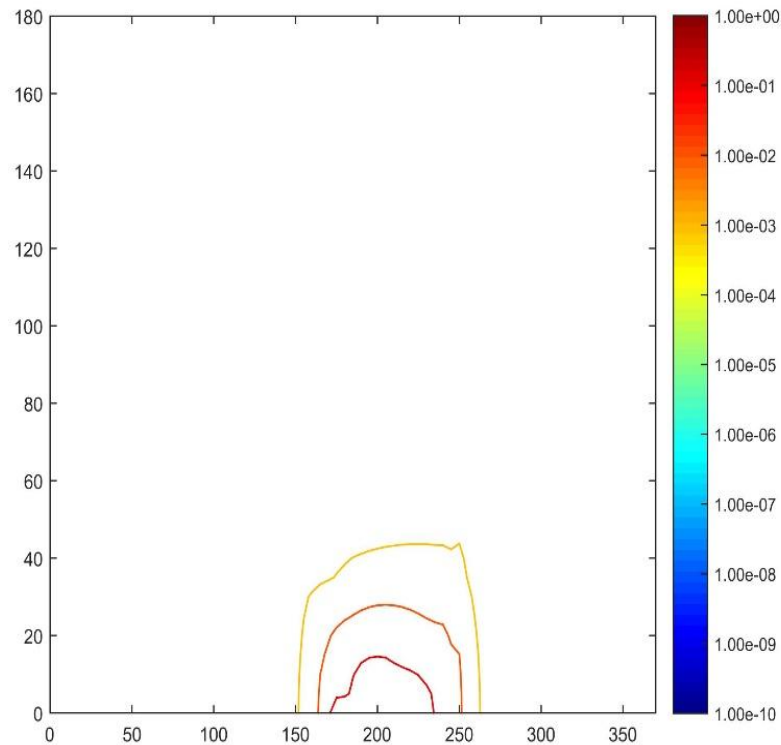


Probability of fatality (1) from hose flash fire

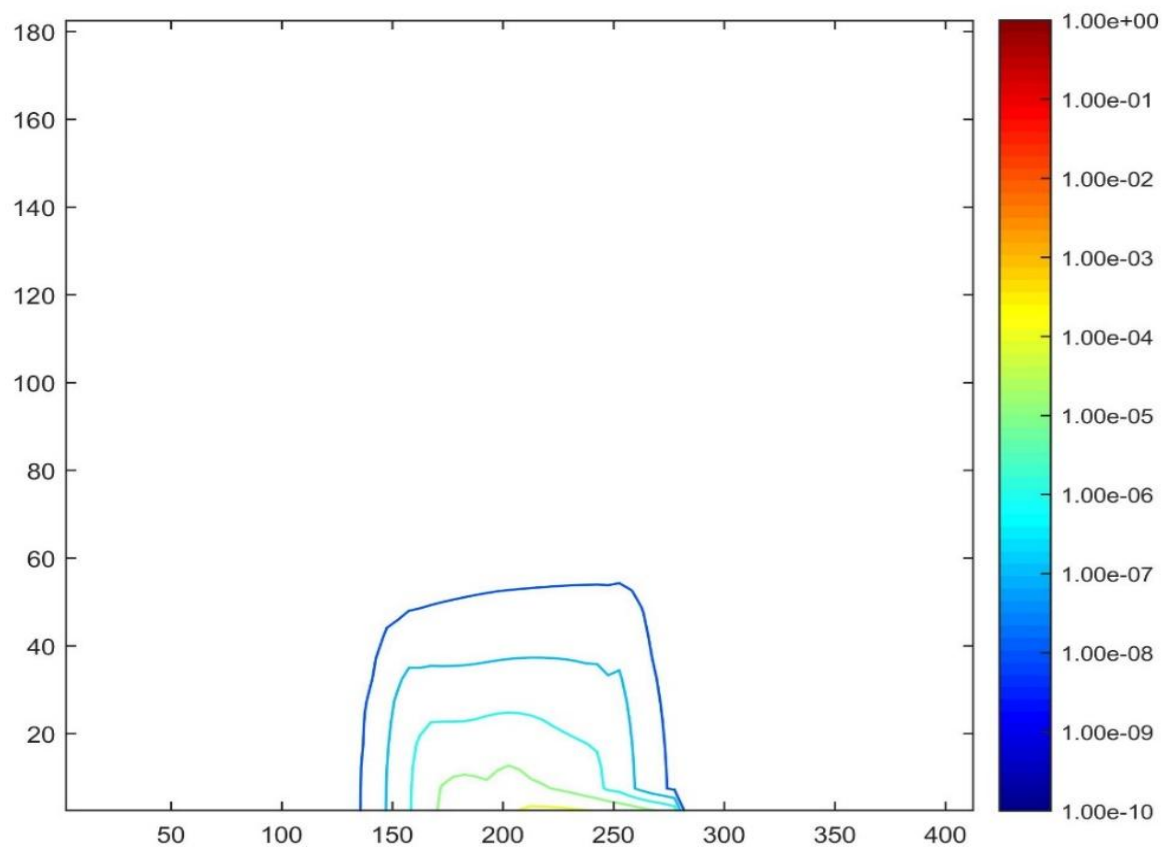
Full rupture – 10bar CFD ADREA (0, 5m/s)



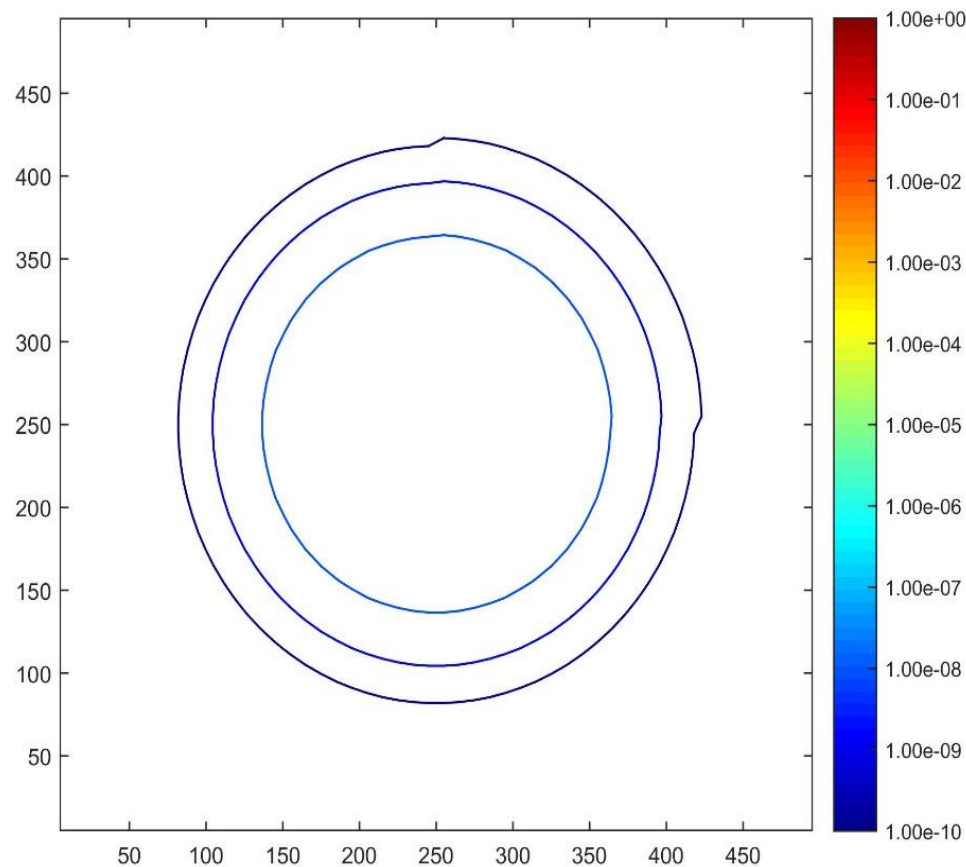
Probability of fatality from hose explosion (10^{-3} - 10^{-1}). 10 bar Full rupture – 10bar CFD ADREA (0, 5m/s)



Risk contours from hose full rupture (10^{-5} - 10^{-8} /yr)



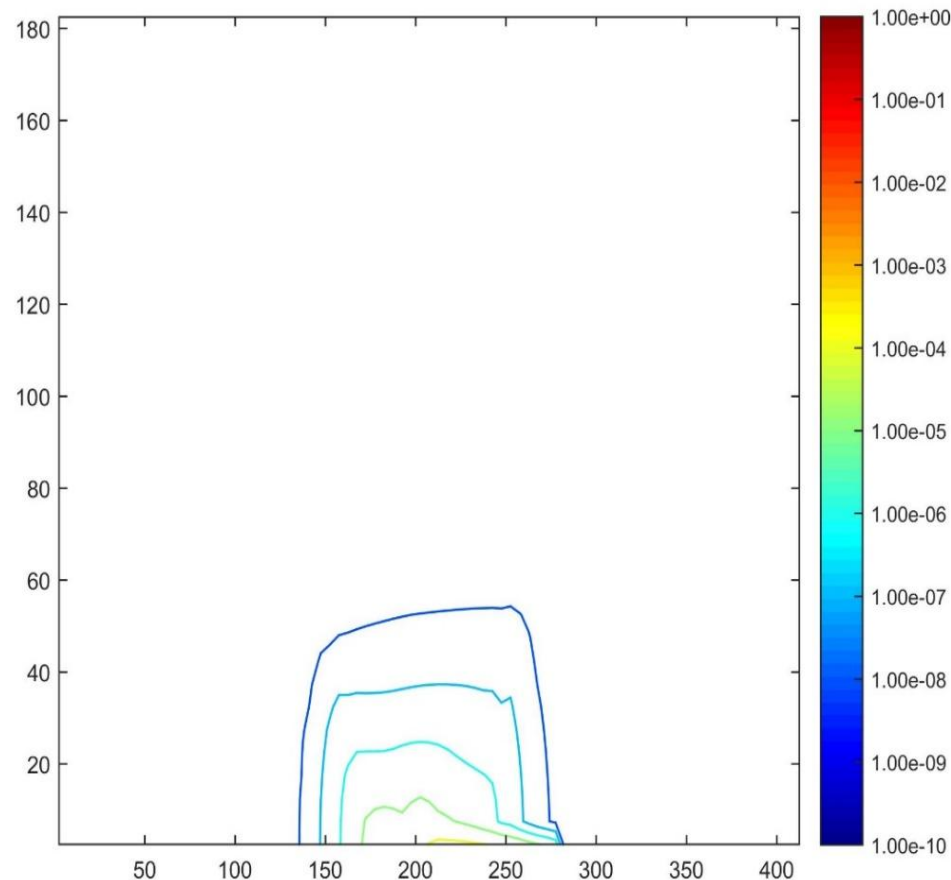
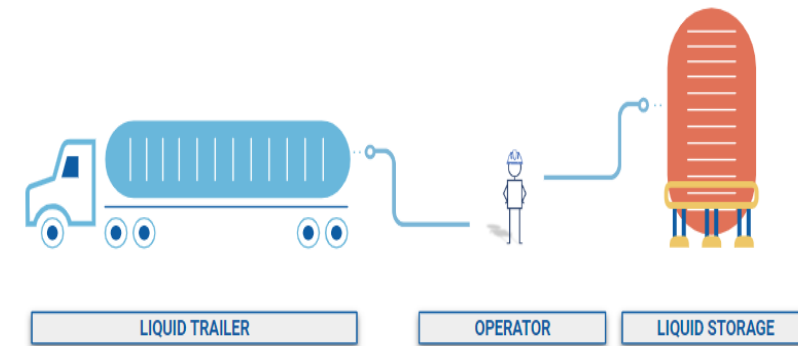
Unconditional iso-risk contours from “BLEVE of trailer tank” (10^{-8} , 10^{-9} , $10^{-10}/y$)



DISTANCES CONDITIONAL RISK= 0.01

RELEASE TYPE	Distance in meters
Trailer tank rupture and BLEVE (overpressure)	135
Trailer tank rupture and BLEVE (radiation)	150
Pipe full rupture and jet fire	22
Pipe full rupture and flash fire (conditional risk =1)	70
Pipe full rupture and explosion	50
Pipe 5% rupture and jet fire	9
Pipe 5% rupture and flash fire	34
Pipe 5% rupture and explosion	8

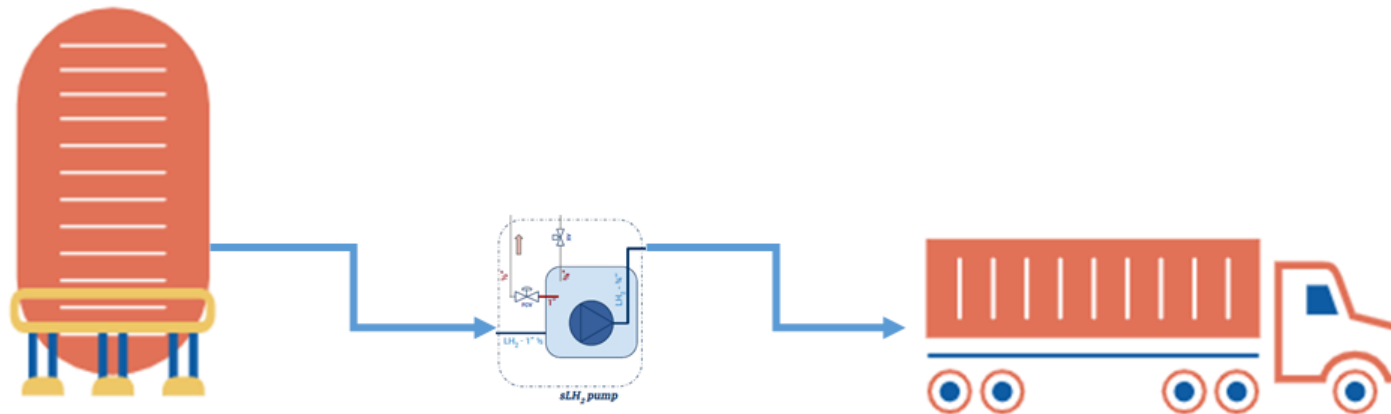
CASE STUDY 1 – TOTAL INDIVIDUAL RISK 10^{-4} - 10^{-8} /y



Total individual risk:
 10^{-4} , 10^{-5} , 10^{-6} /yr at 30, 70, and 80
m. from the centre of the case
study. Total individual risk is
influenced by the hose rupture.

CASE STUDY 2

- a) Stationary tank section. It comprises the containment tank with capacity up to 56m^3 LH_2 together with the vent stack.
- b) The transfer hose from the stationary tank to the truck
- c) The LH_2 heavy duty truck. It comprises two storage tanks on the truck with capacity about 40kg LH_2 each



DISTANCES CONDITIONAL RISK= 0.01

TANK AND PIPE



RELEASE TYPE	Distance in meters
Storage tank rupture and BLEVE	150
Tank rupture and explosion (conditional risk =1)	9(NCSRD)-60 (UU)
Pipe full rupture and jet fire before pump	15-20
Pipe full rupture and flash fire before pump (conditional risk =1)	29-50
Pipe full rupture and explosion fire before pump	30
Pipe full rupture and jet fire after pump	5-8
Pipe full rupture and flash fire after pump (conditional risk =1)	3-35
Pipe full rupture and explosion fire after pump	2
Pipe 5% rupture and jet fire before pump	8-10
Pipe 5% rupture and flash fire before pump (conditional risk =1)	9-40
Pipe 5% rupture and explosion before pump	0



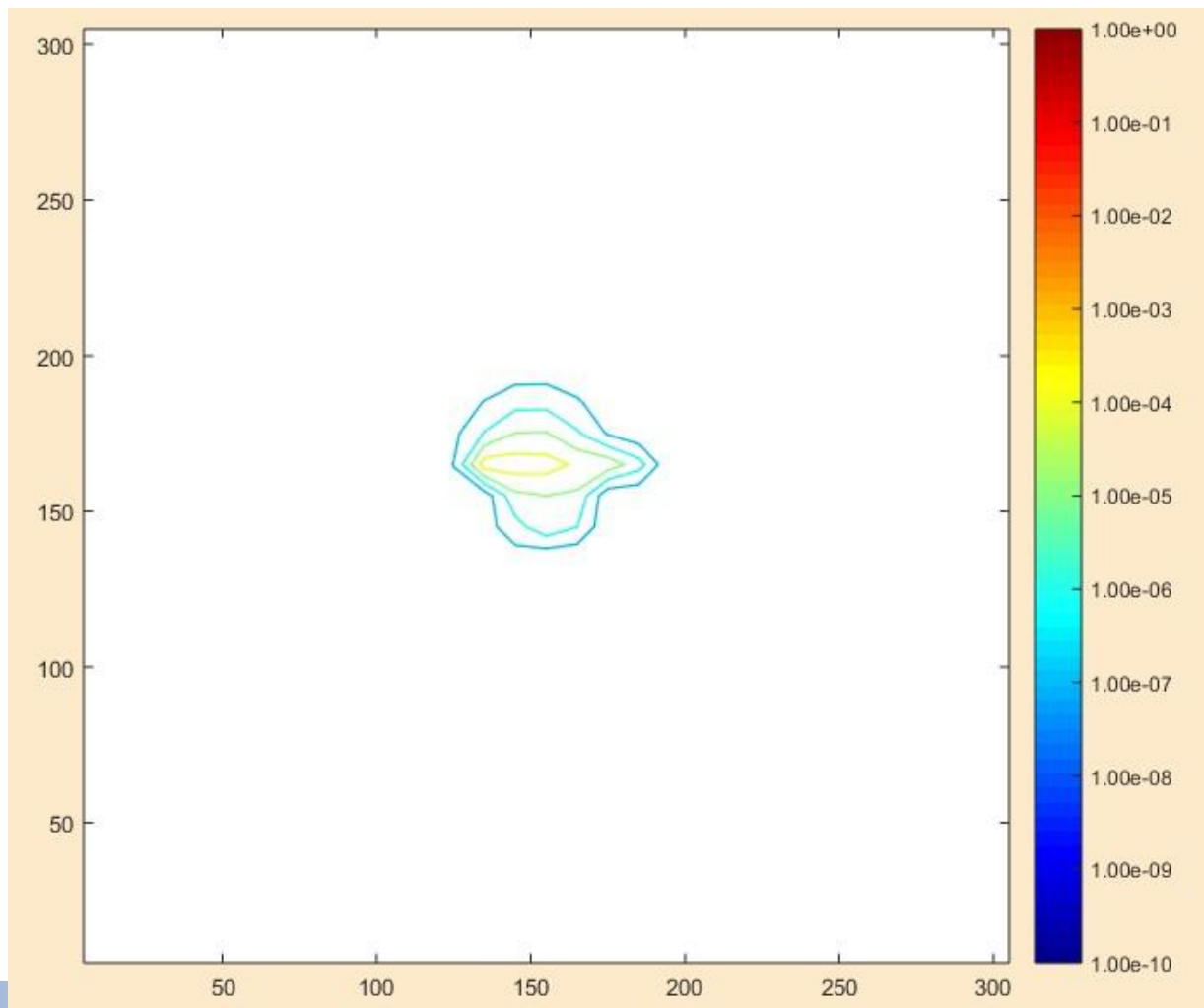
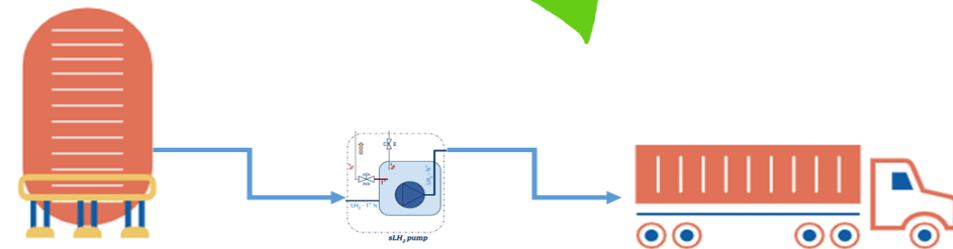
DISTANCES CONDITIONAL RISK= 0.01

TRUCK



Accidental Scenario	Distance in m
Bottom of truck, flash fire, 18mm wind speed 0m/s	9
Bottom of truck, flash fire, 18mm wind speed 5m/s	30
Side of truck, flash fire, 6 mm wind speed 0m/s (conditional risk =1)	14
Side of truck, flash fire, 6 mm wind speed 5m/s South	17
Side of truck, flash fire, 6 mm wind speed 5m/s North	28
Bottom of truck, flash fire, 6 mm wind speed 5m/s West	22
Release from side truck, 6mm jet fire	9-14
Release from side truck, 6mm flash fire (conditional risk =1)	14-22
Release from side truck, 6mm combustion	4
Release from side truck, 18mm flash fire (conditional risk =1)	9-30
Release from side truck, 18mm combustion	0-12

CASE STUDY 2 – TOTAL INDIVIDUAL RISK 10^{-4} - 10^{-7} /yr



Total individual risk:
 10^{-4} , 10^{-5} , 10^{-6} /yr at distance of 15,
 25, and 35 m. from the centre of
 the case study. Total individual risk
 is influenced by the pipe rupture.

CASE STUDY 3

- a) Trailer area with capacity up to 57m^3 LH₂
- b) The transfer hose from the stationary tank to the vessel (ship)
- c) LH₂ vessel (ship) tank. It comprises a storage tank with capacity about 80 m^3 LH₂

FILLING a LH2 VESSEL from LtL REFUELLING STATION



TRAILER

OPERATOR

LH2 Vessel

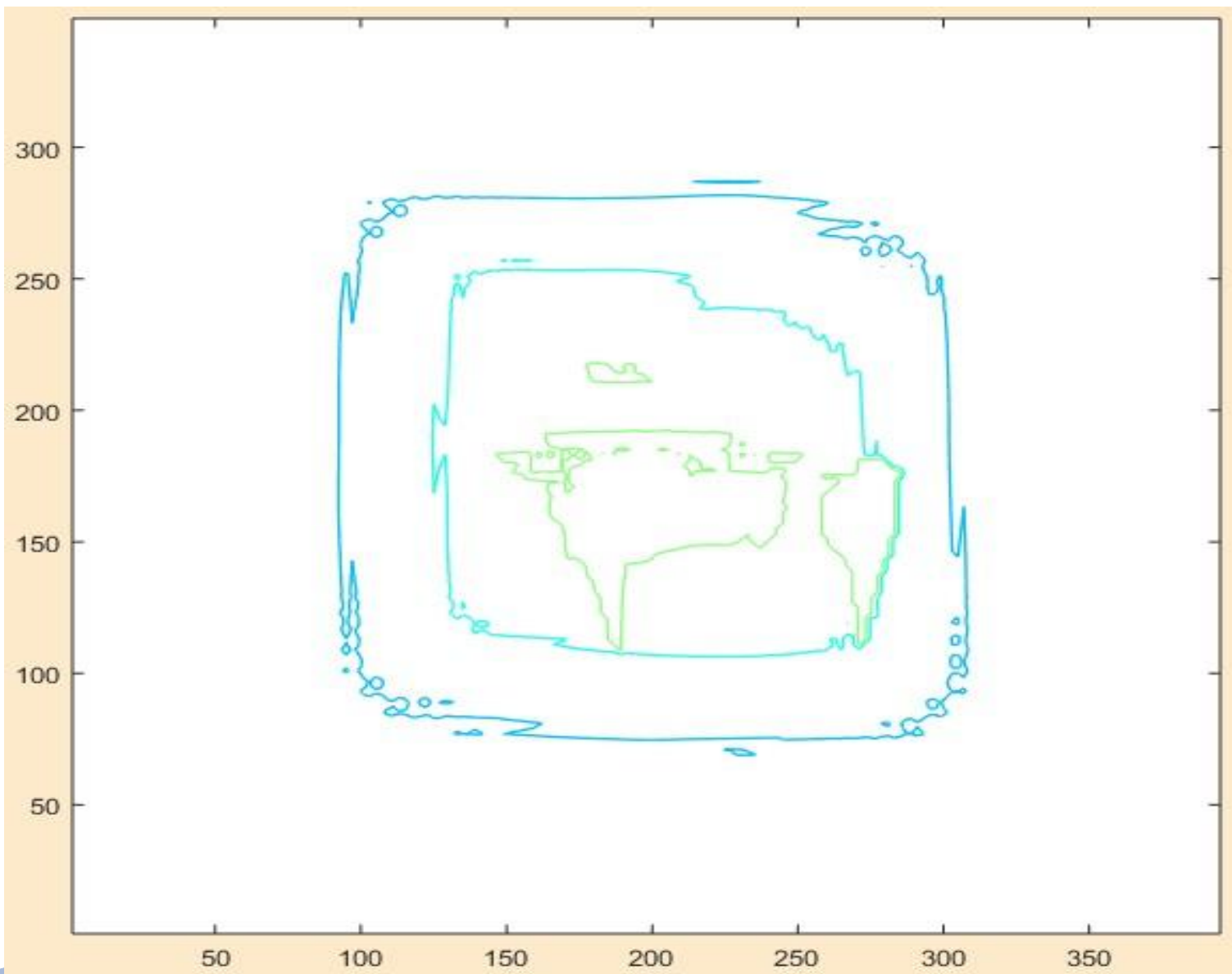
DISTANCES CONDITIONAL RISK= 0.01



RELEASE TYPE	Distance in meters
Trailer rupture and BLEVE (radiation)	150
Ship rupture (20cm hole at the bottom) and flash fire	30
Ship rupture (20cm hole at the bottom) and combustion	110
Hose rupture at tower, 50mm, and jet fire	25
Hose rupture at tower, 50mm, and flash fire (conditional risk =1)	70
Hose rupture at tower, 50mm, and combustion	20
Hose rupture before tower, 50mm, and jet fire	22
Hose rupture before tower, 50mm, and flash fire (conditional risk =1)	35
Hose rupture before tower, 50mm, and combustion	50

CASE STUDY 3: TOTAL INDIVIDUAL RISK

(10^{-7} , 10^{-6} , 10^{-5} /y)



Total individual risk:
 10^{-6} , 10^{-7} /yr at distances of
110 and 120 m from the
centre of the case study
Influenced by: a) ship
rupture 20 cm and
combustion and b) hose
rupture at tower and flash
fire

CONCLUSIONS

- QRA estimates the risk level of Liquid Hydrogen transfer operations
- Safety of transfer operations is depicted by accident sequences, their frequencies of occurrence and the corresponding consequences
- QRA provides information to decision makers and assists risk reduction strategies in hazardous installations



Thank you for your attention

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