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Item 10 (a) of the provisional agenda
Facilitation of implementation:
(a) Risk assessment for industrial accident prevention

Risk assessment for industrial accident prevention: Selected case studies and available software tools*

Report submitted by the small group on risk assessment

Summary

The Conference of the Parties, at its eleventh meeting (Geneva (hybrid), 7–9 December 2020), requested the small group on risk assessment to submit, for review at its twelfth meeting, two reports on risk assessment methodologies for chemical installations in the United Nations Economic Commission for Europe region: one providing an introduction to risk assessment methodologies for industrial accident prevention; the other presenting specific case studies on risk assessment methodologies applied at selected industrial facilities in the United Nations Economic Commission for Europe region[a], also covering available software tools.

The present report was prepared by a contractor based on inputs submitted by United Nations Economic Commission for Europe member States, with regular guidance from the small group on risk assessment, the secretariat's support and thanks to the financial support of Switzerland. The report was also reviewed and supported by the United Nations Economic Commission for Europe member States that provided inputs and the Convention's Bureau and Working Group on Implementation. It should be read in conjunction with the first report (Part 1) (ECE/CP.TEIA/2022/8), which contains an overview of the risk assessment process, including risk analysis tools and risk evaluation criteria. The present report provides an overview of case studies that showcase good practice and application of the tools and methods presented in Part 1.

The Conference of the Parties is invited to:

(a) Take note of the present report, containing case studies and some available software tools for chemical installation risk assessment;

* All figures and tables contained in the present document reflect those contained in national reports submitted by United Nations Economic Commission for Europe member States in response to the request issued in that regard by the secretariat.

(b) Also take note of Part 1, providing an overview of risk assessment methods;

(c) Consider the information in, and promote the use of, the two risk assessment reports in future work, including as supporting background material;

(d) Request the secretariat to publish the reports on risk assessment in the three official United Nations Economic Commission for Europe working languages in the biennium 2023–2024.

[a] ECE/CP.TEIA/42, para. 75.

I. Introduction and case study selection

1. This report presents selected case studies where a risk assessment methodology was applied to chemical facilities in the United Nations Economic Commission for Europe (ECE) region. These case studies span five types of facilities: liquified natural gas (LNG)/liquified petroleum gas (LPG) storage tanks; ammonia refrigeration facilities; oil terminals (hydrocarbon loading/unloading/storage facilities); ammonium nitrate storage facilities; and chlorine facilities. The annex to the present report lists key software tools available to support chemical installation risk assessment.

2. Several ECE countries were asked to submit case studies on the five above-mentioned types of installations, providing information based on a template. Among the case studies submitted were five transboundary case studies, submitted by three countries; eighteen out of thirty submitted case studies, including three transboundary examples, were selected based on geographic location, facility type and transboundary considerations. Some countries, including those of Eastern Europe, the Caucasus and Central Asia, did not submit case studies due to the sensitive nature of the information requested.

3. This report is intended to be used in conjunction with the report entitled "Risk assessment for industrial accident prevention: Overview of risk assessment methods" (hereafter called "Part 1") (ECE/CP.TEIA/2022/8). Part 1 provides a general overview of risk assessment methods applicable to risks arising from hazardous activities.

II. Key information requested

4. For each case study, a template of requested information was provided, aligned with the following sections for consistency:

(a) Major incident scenarios: A summary (all case studies) of incident scenarios considered in the risk assessment, typically involving loss of containment of the primary hazardous material, and sometimes subsequent reaction or combustion effects;

(b) Release effects and consequence considerations: Discussion (all case studies) of consequences such as fatalities, injuries, environmental effects and off-site damage, including databases and software used for consequence modelling;

(c) Likelihood of occurrence: Discussion (all case studies) of possible incident causes and estimates of incident likelihood, including databases used to determine likelihood of occurrence;

(d) Risk presentation: Evaluation (all case studies) of how incident likelihood and severity were combined and communicated, including degree of analysis (qualitative, semiquantitative or quantitative) and methods for presenting risk scoring criteria;

(e) Risk acceptability criteria: Discussion (all case studies) of risk acceptability criteria used, based on regulations of country/region and stakeholders involved;

(f) Risk reduction measures implemented: In some case studies, further action was taken to reduce risk based on risk assessment results, including through prevention, preparedness, and response measures.

5. In some case studies, it was unclear whether the stated risk reduction measures were implemented explicitly because of risk assessment findings, or generally as good practices for chemical safety; the former are denoted with the term “additional” risk reduction measures implemented, the latter are denoted with an “*” in the case study summary tables below.

III. Presentation of case studies

A. Liquified natural gas/liquified petroleum gas

1. Finland

6. The facility is approximately 75,000 m^2, located by the sea, within 1 km of a residential area and a wastewater treatment plant and 1.5 km from the closest city (see table 1 for case study summary).

Table 1
Finland liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	Flammable gas/flammable liquid release; LPG gas and liquid release from tanker truck or railway car
Release effects and consequence considerations	No fatalities or injuries of population outside facility would result. No off-site damage or effects on adjacent residential areas are recognized as credible consequences. Only environmental consequences would be vegetation burning near facility. Consequence modelling conducted using Phast software and thermal radiation levels determined to be 3–8 kW/m^2
Likelihood of occurrence	Not assessed; Causes of incident were structural failure, traffic accident or human error
Risk presentation	Risk to people and environment due to incident identified. Qualitative risk assessment conducted using Bow-Tie method. Risk assessment also conducted using quantitative methods such as consequence modelling. Risk matrix not reported
Risk acceptability criteria	None specified
Risk reduction measures implemented*	Gas and fire detectors; SIS such as level control and safety valve; Preventative measures include ATmosphere EXplosible, grounding, regular maintenance, camera monitoring; Protection measures include water-cooling system, extinguishing water system; Internal and external emergency plans and training

Abbreviations: SIS, safety instrumented systems.

2. France

7. The site is approximately 65,000 m^2, surrounded by a canal, roads, factories, and railways (see table 2 for case study summary).

Table 2
France liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	Explosion and fire due to flammable gas/liquid release
Release effects and consequence considerations	Consequence estimated to be 100–1,000 injuries. People in areas surrounding facility may get exposed to overpressure and thermal radiation. IDLH values (inhalation hazard) used to measure consequences and Phast software used for consequence modelling
Likelihood of occurrence	Worst-case scenario deemed "extremely unlikely". Incident causes include equipment failure, human error and loose connections due to wear and tear. RIVM data used to determine likelihood of incident
Risk presentation	Risk to individuals and surroundings is present. Risk assessment conducted quantitatively using Bow-tie analysis
	Risk matrix consisted of four qualitative severity levels: moderate (no injury or fatality); serious (minor injury or illness); important (hospitalization due to exposure/permanent disability); catastrophic (fatality)
	Qualitative levels of likelihood were: extremely unlikely; very unlikely; unlikely; frequent
Risk acceptability criteria	Risk acceptability criteria based on national criteria (Circular of 10 May 2010), using combination of qualitative and quantitative levels. Approaches for assessing human and environmental risks were different. Environmental impacts were considered using case-by-case qualitative approach. Facility management, safety professionals and local competent authority were involved in determining risk matrix and risk acceptance criteria
Risk reduction measures implemented*	Gas and flame detectors; SIS including level control and pressure control; Preventative measures including maintenance, safety valves, training; Protection measures including fire extinguishing systems, water spraying system for cooling down; Emergency response plan

Abbreviations: IDLH, immediately dangerous to life or health; RIVM, National Institute for Public Health and the Environment of the Netherlands.

3. Sweden

8. The site area is 20,000 m^2 and consists of underground LPG storage close to a residential area and a port. The underground LPG storage at the site consists of one pressurized 47,000 m3 cavern and one 100,000 m3 refrigerated cavern (see table 3 for case study summary).

Table 3
Sweden liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	Toxic gas release resulting in fire and explosion

Key information	*Description*
Release effects and consequence considerations	Up to 50 fatalities expected. Environmental effects include release of LPG into atmosphere. No off-site damage expected. Consequence modelling utilized ALOHA
Likelihood of occurrence	Identified cause for incident was leakage (hose breakage/flange/valve). Likelihood of hose leakage was 3.8 x 10^{-7}/year. Likelihood of occurrence of incident determined using professional judgement, ETA and databases such as *Classification of Hazardous Locations*[1]
Risk presentation	Hazards identified were leakage (hose/flange/valve), fire, BLEVE. Individual and societal risks were investigated Semi-quantitative assessment used primary hazards analysis to determine scenarios, calculating risk using likelihood x consequence, followed by quantitative analysis using ETA for dimensioning scenarios Risk matrix consisted of following risk levels: low (green); middle (yellow); high (red) Likelihood levels were: < once/1000 years; < once/100-1,000 years; < once/10-100 years; < once/1-10 years; < once/year Severity levels were: minor injuries, no need for hospital visit; considerable injuries, need for hospital; serious injuries, permanent harm; significant, fatalities (1); catastrophe, fatalities (>10)
Risk acceptability criteria	In Sweden, no national risk acceptance criteria exist; instead, operators use risk criteria developed from other countries and industry organizations. According to Swedish environmental legislation, operators must prove to authorities and public that they can manage risks and keep them at a low level Operators must take all measures to prevent accident at reasonable cost. It thus becomes a legal matter for authorities and courts to determine what is reasonable cost in relation to risk in each case An individual risk of 10-7 is plotted on a map (see figure 1). Stakeholders involved in risk assessment include safety consultants and company's operating staff
Risk reduction measures implemented*	Gas detectors and alarm systems; Prevention measures including procedures and instructions; Protection measures including emergency stop systems; Emergency response plans for gas release

Abbreviations: ALOHA, Areal Locations of Hazardous Atmospheres; BLEVE, boiling liquid expanding vapour explosion; ETA, event tree analysis.

* A. W. Cox, F. P. Lees and M. L. Ang (Warwickshire, Institution of Chemical Engineers, 1990).

[1] A. W. Cox, F. P. Lees and M. L. Ang (Warwickshire, Institution of Chemical Engineers, 1990).

Figure 1
Sweden liquified petroleum gas individual risk plot

4. Switzerland

9. The site is approximately 30,000 m^2, with a facility area of 1000 m^2, consisting of two LPG tanks used to heat railway line switches in winter to prevent freezing. They are close to a residential area, a railway line, an industrial area and a hospital (see table 4 for case study summary).

Table 4
Switzerland liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	VCE and BLEVE due to flammable gas/liquid release
Release effects and consequence considerations	Consequences of release include exposure to heat radiation. Transboundary effects were not credible in incident scenario. Risk analysis stated that VCE and BLEVE would result, respectively, in 430 fatalities and 280 fatalities. No environmental effects determined in risk analysis as products of LPG combustion are not ecotoxic. Consequence modelling conducted using EFFECTS. Probit functions used for heat radiation in EFFECTS. Different radii were defined for lethality percentage, e.g., 160 m for 100 per cent lethality (green circle), 310 m for 50 per cent lethality (blue circle) and 450 m for 1 per cent lethality (red circle) (see figures 2 and 3)
Likelihood of occurrence	Initiating events included crash of small aircraft or road vehicle mechanical impact; Likelihood was dependent on fault tree and ETA. Internal Swiss guideline for risk analysis of LPG storage tanks was used. Likelihood of VCE was 10^{-11} and of BLEVE was 10^{-8}
Risk presentation	Main hazard assessed was heat radiation. Risk was presented as societal risk. Risk assessment conducted was quantitative using fault tree and event tree methods. Risk matrix consisted of three different risk levels ranging from acceptable to not acceptable (see figure 4)

Key information	*Description*
Risk acceptability criteria	Risk acceptability criteria were based on guidelines for chemical installations under scope of Manual on the Major Accidents Ordinance.[2] These guidelines were accepted by all stakeholders and are harmonized in Switzerland. Risk acceptability criteria (see figure 5) were summarized using risk sum curve for LPG gas tanks. Relevant stakeholders are federal and cantonal authorities and representatives of different industrial associations
Additional risk reduction measures implemented	Analysed risk was judged to be unacceptable. The two LPG tanks were therefore dismantled and heating carried out using small underground pipes with much lower risk potential

Abbreviations: VCE, vapour cloud explosion.

Figure 2
Switzerland liquified petroleum gas tank

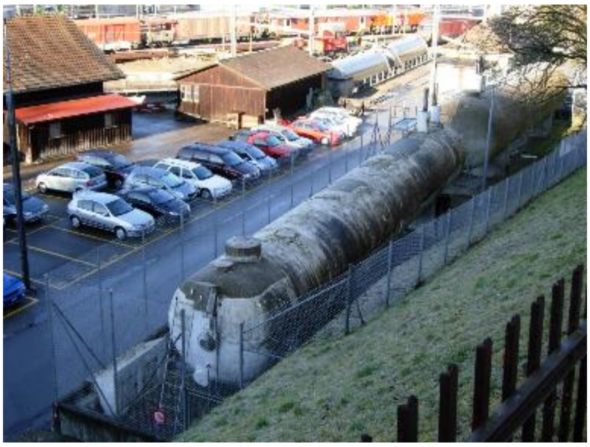
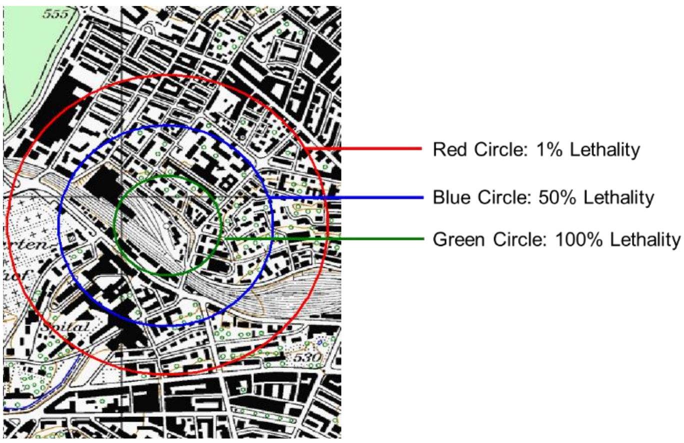
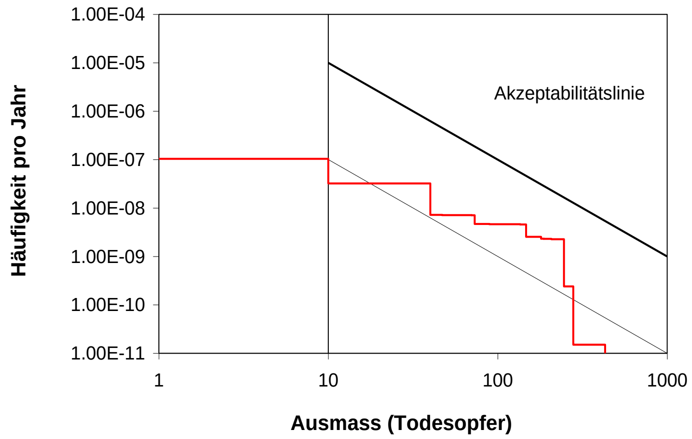


Figure 3
Switzerland liquified petroleum gas risk contours



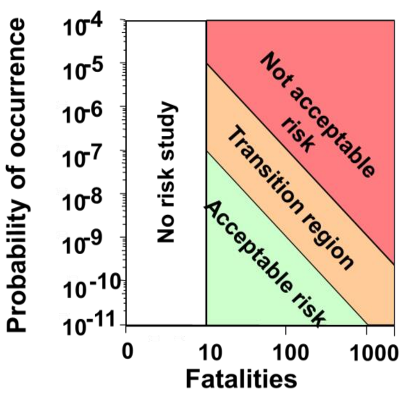
[2] Available at www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/beurteilungskriterien-zur-stoerfallverordnung-stfv.html (French, German and Italian only).

Figure 4
Switzerland liquified petroleum gas risk presentation



Note: Vertical axis title reads "Frequency per year"; horizontal axis title reads "Extent (fatalities)"; text inside graph reads "Line of acceptability".

Figure 5
Switzerland liquified petroleum gas risk acceptance criteria



Note: White and green level: "Acceptable risk". Orange level: "Transition region" acceptable after weight of interests. Red level: "Not acceptable risk".

B. Ammonia refrigeration

1. Estonia

10. The site is approximately 60,500 m^2, located in a port close to residential and sea areas (see table 5 for case study summary).

Table 5
Estonia ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Ammonia gas release results in a toxic cloud and can cause fire and BLEVE
Release effects and consequence considerations	Consequence of worst-case scenario can affect 2,945 people in danger, of whom 30 per cent directly at risk. Surrounding residential and port areas would require evacuation due to toxic release

Key information	*Description*
	Three types of zones used for measuring consequence include: IDLH, AEGL-3 (30 min), Lethal Concentration (LC_{50} at 30 minutes) ALOHA was used for consequence modelling
Likelihood of occurrence	Initiating events included human error, technological problems, or thunderstorms. The RIVM Purple Book[3] and Potential Problem Analysis were databases and references used for determining likelihood of incident. Likelihood is less than once every 50 years
Risk presentation	Individual and societal risk (people, surroundings, environment) and property loss are the different types of risks. Semi-quantitative methods were used for risk assessment. Qualitative methods used for risk assessment included Potential Problem Analysis, methods from RIVM and Purple Book Guidelines for quantitative risk assessment Quantitative methods were used for consequence modelling. Risk matrix was used for risk assessment Severity levels in risk matrix are: little importance; light; hard; very hard; catastrophic Likelihood levels in risk matrix are: very small; small; middle; big; very big
Risk acceptability criteria	Not available
Risk reduction measures implemented*	Risk reduction measures included toxic concentration detection alarms, leak and level alarms, onsite and off-site alarm systems; SIS including level control; Prevention measures including fencing, different alarms, maintenance, exercises/drills; Protection measures including personal protective equipment, water curtain to limit cloud of leaking gas, fire extinguishers; External and internal emergency response plans

Abbreviations: AEGL, Acute Exposure Guideline Level.

2. Finland

11. The site is approximately 1,300,000 m^2, located 2.7 km from the closest city and 1.7 km from the closest residence (see table 6 for case study summary).

Table 6
Finland ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Toxic ammonia leak from train car from unpressurised tank or pressurised tank

[3] P.A.M. Uijt de Haag and B.J.M. Ale, CPR 18E — Guidelines for quantitative risk assessment: “Purple Book” — Part one: Establishments (n.p., Committee for the Prevention of Disasters (CPR), 1999). Available at https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS3.html.

Key information	*Description*
Release effects and consequence considerations	Number of fatalities or injuries not assessed. Worst-case scenario consisted of leakage of 5,000-ton tank resulting in AEGL-3 concentrations at nearest buildings Environmental impact included tree and plant damage Toxic gas exposure with noticeable effects might be possible if wind direction unfavourable. Evacuations might be necessary. AEGL-2 and AEGL-3 (10 minutes, 30 minutes, 60 minutes) were used to assess consequences. EFFECTS was used for consequence modelling
Likelihood of occurrence	Initiating events included structural failure. Other details were not assessed or reported
Risk presentation	Different types of risks assessed were people or individual risk, environment, asset and reputation. Qualitative (Hazard and Operability (HazOp) analysis) and semi-quantitative (Hazard identification (HazId)) risk assessment were conducted. Risk matrix was used Severity levels used in risk matrix were: severe; major; moderate; minor; minimal Likelihood levels used in risk matrix were: extremely unlikely; very unlikely; possibility of occurring sometime; likely; very likely
Risk acceptability criteria	Not available
Risk reduction measures implemented*	Gas detectors, alarms; SIS included level and temperature control, safety automation, remote control of valves; Prevention measures included operator instructions, planning of pipeline routes, traffic planning; Protection measures included escape masks, extinguishing water systems, backup powder machine at ammonia storage, diesel powdered fire water pump, water curtain; Internal and external emergency plans

3. Hungary

12. The site is approximately 85,000 m^2, is used as a food product plant and is located within 100 m of both residential and industrial areas (see table 7 for case study summary).

Table 7
Hungary ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Liquefied ammonia releases from overpressurized pipeline. No transboundary effects considered plausible
Release effects and consequence considerations	As worst-case scenario, results for toxic gas released were studied. Scenario for risk assessment is as follows: a 30 m long, 150 mm internal diameter ammonia pipeline ruptures. Release location is 12 m high. Through rupture, 4,400 kg of liquified ammonia released (overpressure is 12.5 bar). The complex quantitative risk analysis deals with all possible weather circumstances. For following consequence considerations, 1 m/s windspeed and F-Pasquill stability class was defined (very stable condition)

Key information	*Description*
	It was assessed that there would be: 10 per cent fatality - 1 person; 1 per cent fatality - 4 persons; environmental impact included toxic gas release to atmosphere Surrounding residential areas would require evacuation due to toxic release. Probit calculation method used to define lethality probability The Green Book[4] was used as reference for consequence modelling. Safeti was used for consequence modelling (see figures 6 and 7)
Likelihood of occurrence	Initiating events included structural failure, process control failure, technological problems, and domino effects from other installations Reference Manual Bevi Risk Assessments[5] and Purple Book used to determine likelihood of incident. Frequency of pipeline rupture used was 10^{-7}/meter/year
Risk presentation	Comprehensive risk assessment of establishment refers to all possible scenarios, including loss of containment of different containers, pipelines, and process vessels All scenarios that contribute significantly to location-specific risk and/or societal risk were included in quantitative risk analysis, defined as meeting following two conditions: frequency of the scenario $\geq 10^{-9}$ per annum; lethal injury (1 per cent fatality) can also occur outside site boundary Risk matrix was not used for risk assessment. Risk presentation included following: weather matrix (wind speed, wind direction, stability); risk ranking report; individual and societal risk (see figures 8 and 9)
Risk acceptability criteria	Acceptable and unacceptable zones were based on risk level and number of deaths (see figure 10) Different criteria were used for human and environmental risks. Environmental risk criteria used were qualitative as regulations provided only practical guidance. Stakeholders involved included operator and licensed consultants
Risk reduction measures implemented*	Toxic gas detectors and alarm systems installed; SIS included level, pressure and temperature control; Preventative measures included mobile water curtain nozzle system; Supplementary Information Request at the National Entries system is in place; Internal and external emergency plans are in place

[4] C.J.H. van den Bosch and others, CPR 16E – Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials: “Green Book” (n.p., CPR, 1992).
[5] Available at http://infonorma.gencat.cat/pdf/AG_AQR_2_Bevi_V3_2_01-07-2009.pdf.

Figure 6
Hungary ammonia toxic probability of death versus distance

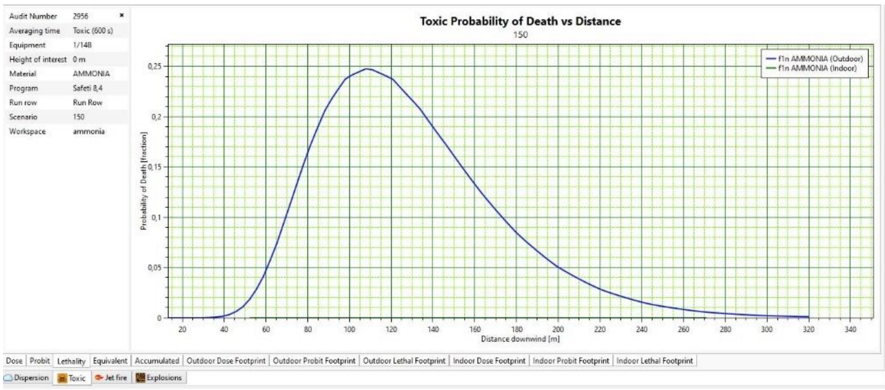


Figure 7
Hungary ammonia map of 1–10 per cent toxic lethality curves

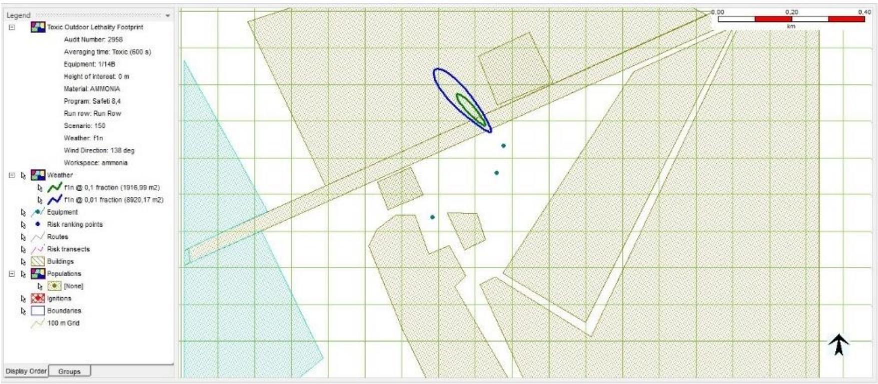


Figure 8
Hungary ammonia individual risk contours

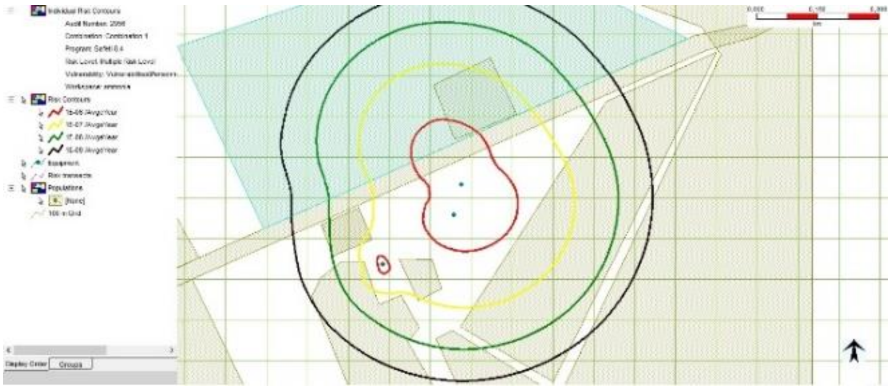


Figure 9
Hungary ammonia societal risk FN curve

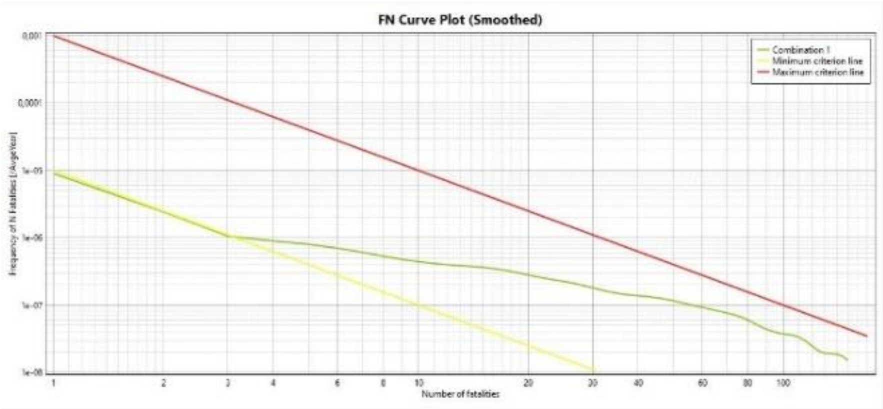
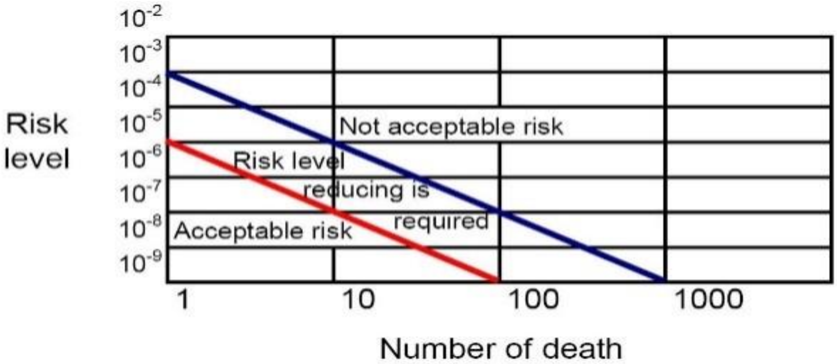


Figure 10
Hungary ammonia risk acceptance criteria



4. Switzerland (transboundary)

13. The facility area is approximately 29,100 m^2 and is located close to a residential area, school and industrial area. A transboundary exposure in France was considered, as the border is 170 m from the facility (see table 8 for case study summary).

Table 8
Switzerland (transboundary) ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Toxic ammonia leak from facility, with potential transboundary exposure in France (car park). Depending on scenario, liquified or gaseous ammonia can be released
Release effects and consequence considerations	Worst case scenario considered 80 fatalities in Switzerland and France. Number of transboundary fatalities not specifically calculated. Toxic gas exposure evaluated using EFFECTS lethal Probit function
Likelihood of occurrence	Initiating events included earthquake, fire, sabotage, mechanical action, mismanipulation, and spontaneous container failure. Likelihoods evaluated using Centre for Chemical Process Safety *Guidelines for Chemical Process Quantitative Risk Analysis* and other literature

Key information	*Description*
Risk presentation	Societal risk was assessed quantitatively using fault tree analysis (FTA) and event tree analysis (ETA). Risk matrix was used where grey and green represented acceptable risk, yellow required assessment after weighing of interests, and red represented unacceptable risk. Relevant stakeholders are federal and cantonal authorities and representatives of different industrial associations (see figure 11)
Risk acceptability criteria	See figure 12
Risk reduction measures implemented*	Ammonia detectors, quick-acting valves, direct alarms to fire brigade; SIS included temperature and pressure control; Internal emergency plans
Additional risk reduction measures implemented	Prevention measures included heat exchanger for recooling (2 circuits), reduction of hazard potential (amount of ammonia); Building seismic retrofit; School about 150 m away has ammonia sensors

Figure 11
Switzerland (transboundary) ammonia risk presentation

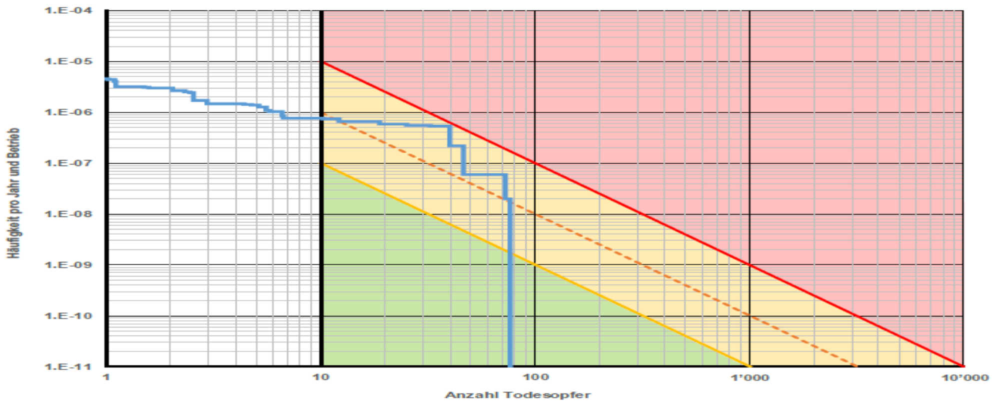
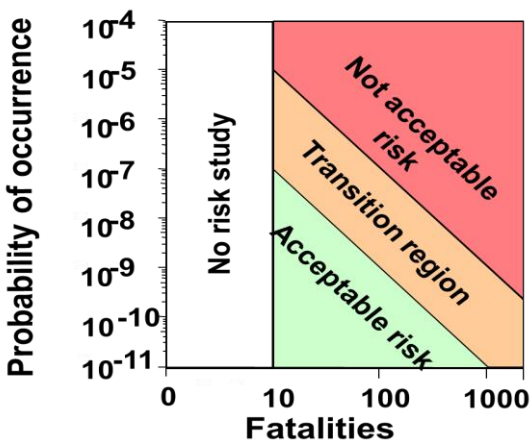


Figure 12
Switzerland (transboundary) ammonia risk acceptance criteria



Note: White and green level: “Acceptable risk”; Orange level: “Transition region” acceptable after weight of interests; Red level: “Not acceptable risk”. In Switzerland, the

same quantitative acceptability criteria are also applied for environmental risks. Another X-axis is used instead of the fatalities.

C. Oil terminals

1. Germany

14. The site is located near a residential area. The site area and other details were not reported (see table 9 for case study summary).

Table 9
Germany oil terminals case study summary

Key information	*description*
Major incident scenarios	Tank fire
Release effects and consequence considerations	Personnel injuries. Nearby people and buildings are exposed to radiation (1.6 kW/m^2, 5 kW/m^2 and 8 kW/m^2) due to tank fire. The Yellow Book[6] was used for consequence modelling along with DISaster MAnagement software (Germany) and Programme for Numerical Safety Simulations (Germany) Handbooks
Likelihood of occurrence	Professional experience and judgement were used to determine likelihood of incident
Risk presentation	Risk to people (individual risk) was identified in risk assessment. Qualitative risk assessment was conducted using German checklist procedure (Association of Technical Inspection Agencies)
Risk acceptability criteria	Determined based on qualitative risk levels
Risk reduction measures implemented*	Fire detection alarms, emergency response plans

2. Norway

15. The site is approximately 30,000 m^2, with a facility area of 700 m^2, and is in a port area close to downtown (residential areas, recreation areas, other port activities), a main road and a railroad (see table 10 for case study summary).

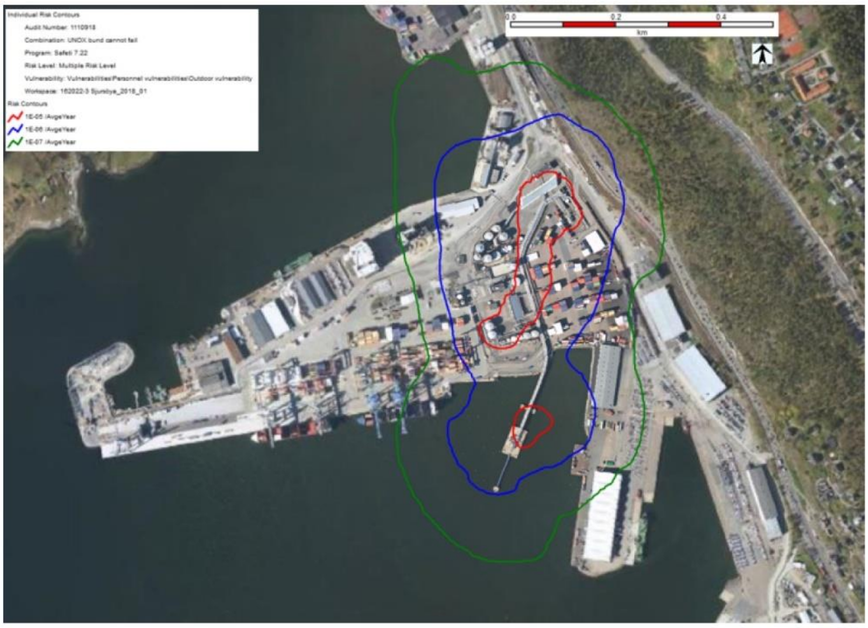
Table 10
Norway oil terminals case study summary

Key information	*Description*
Major incident scenarios	Flammable gas/liquid release due to leak of petroleum liquids resulting in fire or explosion. Quantitative risk analysis considered 13 scenarios, with most scenarios resulting in leak of petroleum and ignition of release, resulting in fire or explosion. Transboundary effects not possible for this scenario

[6] C.J.H. van den Bosch and R.A.PM. Weterings, eds., *CPR 14E – Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases): "Yellow Book"* (n.p., CPR, 1996). Available at https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS2.html.

Key information	*Description*
Release effects and consequence considerations	Individual risk and society risk were considered. No population (public) outside port area would be affected. Environmental impact not covered in the assessment. Phast and Safeti 7.2 used
Likelihood of occurrence	Based on individual risk isocurves, a probability of 10^{-5}/year was determined inside oil terminal area and in small fraction of port area. A probability of 10^{-6}/year was determined mainly inside port area and partially extending beyond site to main road and railroad. The likelihood was determined from historical data from Phast and Safeti 7.2 and Reference Manual Bevi Risk Assessments
Risk presentation	Individual risk due to personnel exposure was identified in risk assessment. Quantitative risk assessment conducted using ETA (see figure 13)
Risk acceptability criteria	Risk acceptance criteria were based on guidelines from national authorities – Norwegian Directorate for Civil Protection. Risk assessment covered only human risk
Additional risk reduction measures implemented	Risk reduction and preventative measures implemented included gas detection with automatic emergency stop, sprinkler system for foam and water on loading rack, liquid detection in pump area with automatic emergency stop. Emergency response plan was distributed to relevant local emergency authorities

Figure 13
Norway oil terminal individual risk contours



3. Serbia (transboundary)

16. The site is approximately 710,000 m^2, with a facility area of 10,000 m^2, close to industrial and residential areas and a river. A transboundary exposure in Romania was considered (see table 11 for case study summary).

Table 11
Serbia (transboundary) oil terminals case study summary

Key information	*Description*
Major incident scenarios	Transboundary (Romania) river pollution possible with failure of preventative and response measures, resulting from petroleum product discharge due to barge collapse (loading/unloading pier)
Release effects and consequence considerations	No fatalities or injuries estimated. However, there will be environmental impact due to river pollution. Oil slicks on water disrupt exchange of oxygen, moisture and heat between hydrosphere and atmosphere and prevent penetration of sunlight into water
	Consequences were determined based on Fay model of oil slick spread.[7] Width of oil slick was calculated to be 265 m (oil slick diameter) and speed of its movement on surface of water during spill was calculated to be 3 km/hour. Expected pollution time was 12.5 hours. Volume of oil evaporating was 287 m^3 and oil deposited on coast was 660 m^3
	Joint management study of transboundary emergencies from spills of hazardous substance into Danube River was used to assess consequences of this scenario
Likelihood of occurrence	Initiating event was collapse of the barge (loading/unloading pier). Databases used for determining likelihood were ARAMIS D1C-APPENDIX 10 – Generic frequencies data for critical events. Likelihood of barge collapse was determined to be 1.55×10^{-5}/year
Risk presentation	Risk to environment (river) was identified in risk assessment. Semi-quantitative risk assessment was conducted using ARAMIS methodology and the methodology for drafting safety report and the accident protection plan
	Quantitative levels of severity were used in risk matrix (see table 12)
	Likelihood categories used in risk matrix were: low ($<10^{-2}$/year); medium (10^{-1} to 10^{-2}/year); high (1 to 10^{-1}/year)
Risk acceptability criteria	Risk assessment includes determination of occurrence likelihood, assessment of possible consequences and qualitative determination of risk (available tiers are negligible, low, medium, high and very high). Risk is considered unacceptable if it is assessed as "very high risk" per the risk matrix. Stakeholders involved in determining risk matrix were facility management and safety professionals
Risk reduction measures implemented*	Manual intervention by operator; Prevention measures include following operations and health/safety/environmental procedures; Protection measures include floating absorbers and skimmers; Emergency preparedness and response planning was established at facility; Instructions for safe work with dispersant for neutralization of spilled petroleum products on water surface of manipulative surfaces were implemented. Instructions for work with equipment for accident situations at river junction

[7] J.A. Fay, "The Spread of Oil Slicks on a Calm Sea" in *Oil on the Sea*, D.P. Hoult, ed. (New York, Springer, 1969), pp. 53– 63.

Table 12
Quantitative levels of severity used in risk matrix

Severity	*Dead animals (tons)*	*Contaminated soil (hectares)*	*Material damage (Serbian dinar/€)*
Low	≤0.5	≤0.1	≤100 000/850
Significant	0.5–5	0.1–1	100 000–1 million/850–8 500
Serious	5–10	1–10	1 million–10 million/8 500–85 000
Severe	10–30	10–30	10 million–100 million/85 000–850 000
Catastrophic	>30	>30	>100 million/850 000

4. Slovenia

17. The site is approximately 250,000 m^2 and is located near industrial and residential areas, a river and the sea (see table 13 for case study summary).

Table 13
Slovenia oil terminals case study summary

Key information	*Description*
Major incident scenarios	Fire scenario. Spillage of fuel from storage tank into retention pool, ignition and fire spread to another tank
Release effects and consequence considerations	Fatalities or injuries due to fire. Environmental effects involve emissions into air. People in areas surrounding facility exposed to toxic gases, adjacent building exposed to overpressure and radiation due to fire. No transboundary effects expected. Methodology from the SLO Guidelines for hazard identification and risk assessment[8] was applied. BREEZE was used for consequence modelling
Likelihood of occurrence	Initiating events were determined to be tank failure, ignition and failure of cooling systems. Likelihood of the incident was determined to be $7.6x10^{-14}$/year. Red Book[9] was used as reference. Likelihood of failure of cooling systems was 6.9×10^{-2} /year, tank failure: 1.1×10^{-9} /year
Risk presentation	Individual risk due to personnel exposure was identified in risk assessment. Quantitative risk assessment was conducted using consequence modelling. Qualitative methods used for conducting risk assessment were HazOp, HazId and risk assessment Qualitative severity levels were used: Insignificant: no injuries to employees in facility or nearby occur and/or minor damage to machine or device occurs and/or inadequate batch and/or environmental damage is insignificant Small: minor injuries to employees and/or damage to individual machinery and/or minor production downtime and/or minor environmental pollution Serious: individual fatal injuries or serious injuries to employees or in immediate vicinity and/or significant destruction of facility and/or major production downtime and/or environmental damage, but consequences not long lasting

[8] See https://www.gov.si/assets/ministrstva/MOP/Dokumenti/Industrijske-nesrece/c93c587d86/pripravljenost_na_nesrece.pdf (Slovenian).
[9] J.C.H. Schüller and others, *CPR 12E – Methods for determining and processing probabilities: "Red Book"* (n.p., CPR, 1997). Available at https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS4.html.

Key information	Description
	Catastrophic: more fatal injuries and/or serious injuries to employees or residents and/or complete destruction of facility and/or other facility may be affected and/or surrounding population may be endangered and/or injuries may occur environment with longer-term consequence Qualitative likelihood levels were used: insignificant; small; moderate; high
Risk acceptability criteria	Risk considered acceptable if assessed as such by applying criteria from risk matrix. Stakeholders involved in determining risk matrix were facility management and safety professionals
Risk reduction measures implemented*	Fire alarm, infrared flame detector, video surveillance system, visual and audible alarm; SIS included lightning protection, double bottom tanks, connection of extinguishing agent, restraint system, overpressure protection with safety valves, fire embankment, bottom leak control; Prevention measures included level control, temperature gauges, anti-overfill control; Protection measures included automated control system for extinguishing and cooling; Emergency response plans for protection and rescue plan for accidents with hazardous substances

D. Ammonium nitrate storage

1. Estonia

18. The site is approximately 85,000 m^2, contains an ammonium nitrate and ammonium nitrate-based fertilizer storage facility at a port, and is located near a residential area and the sea (see table 14 for case study summary).

Table 14
Estonia ammonia nitrate storage case study summary

Key information	Description
Major incident scenarios	Explosion due to cargo contamination with foreign impurities than can act as catalyst in self-decomposition process. Ammonium nitrate temperature will rise, resulting in fire and explosion. Transboundary effects not considered plausible
Release effects and consequence considerations	Fatalities or injuries due to explosion and fire. Environmental effects involve pollution due to release of combustion and decomposition products. Release of extinguishing water into sea can result in environmental contamination. There will be off-site damages as port and surrounding residential areas would need to be evacuated due to incident. Three types of zones are considered based on a trinitrotoluene equivalence formula (United Kingdom of Great Britain and Northern Ireland methodology)
Likelihood of occurrence	Initiating events were determined to be human error, technological problems, process control failure, external factors and natural hazards triggering technological disasters (Natech) risks. Likelihood was determined using HazOp and failure mode and effects analysis (FMEA) databases. Likelihood of occurrence of incident considered “very small” (i.e., annual likelihood was 0.005–0.05 per cent)

Key information	*Description*
Risk presentation	Individual and societal risk (people, surroundings, environment) and property loss were different risks considered. Semi-quantitative risk assessment was conducted using HazOp and FMEA methods. Consequence modelling was used for conducting risk assessment. Risk matrix was used for determining risk Qualitative severity levels were used: little importance; light; hard; very hard; catastrophic Qualitative likelihood levels were used: very small; small; middle; big; very big
Risk acceptability criteria	Not available
Risk reduction measures implemented*	Alarm system on and off-site; Preventative measures included fencing, following fire safety requirements, video surveillance system, temperature control system, warehouse ventilation, different alarms, maintenance and exercises; Protection measures included personal protective equipment, dome warehouse, fire extinguishers and fire alarm signalization; Internal and external emergency response plans for incident scenario

2. Latvia

19. The site consists of ammonium nitrate and ammonium nitrate-based fertilizer storage, and is located close to a railway and industrial area. The site area was not reported (see table 15 for case study summary).

Table 15
Latvia ammonia nitrate storage case study summary

Key information	*Description*
Major incident scenarios	Loader or truck fire with ammonia toxic gas release. Transboundary effects not considered possible
Release effects and consequence considerations	There will be fatalities or injuries due to incident. Toxic effects of nitrogen oxides were considered by evaluating concentrations at heights of 1.5 m (considering individuals outdoors), and 5 m (considering building openings) Consequences include off-site damage, respiratory illness on exposure, fatalities, and other injuries. A 1 per cent lethality distance was used to measure consequences Purple Book used for consequence modelling
Likelihood of occurrence	Initiating event causes were determined to be human error and process control failure. Likelihood of incident determined using Red Book
Risk presentation	Individual and societal risk were considered. Qualitative risk assessment was conducted using FMEA methods. Quantitative risk assessment methods also considered and used
Risk acceptability criteria	Risk acceptability criteria for individual risk was 10^{-6}, following recommendations from the Netherlands

Key information	*Description*
Additional risk reduction measures implemented	Limit on ammonium nitrate in one pile implemented as prevention measure Emergency response plan for incident

3. Netherlands

20. The site is an ammonium nitrate-based fertilizer production and ammonia storage facility of unknown size. Details regarding proximal exposures were not provided. The evaluated scenario is very similar to the case studies for ammonia refrigeration as the material and consequences are identical (see table 16 for case study summary).

Table 16
Netherlands ammonia nitrate storage case study summary

Key information	*Description*
Major incident scenarios	Ammonia release scenarios are considered (tank failure, pipeline failure). Transboundary effects not expected in this case
Release effects and consequence considerations	Personnel fatalities outside facility premises are possible. Expected number of fatalities calculated using integral risk assessment models
	Environmental effects considered due to release. Probability of fatality and number of fatalities based on toxic Probit functions. an area where public is in danger calculated, based on intervention levels comparable to AEGL
	Consequence modelling based on Purple Book. New toxic Probit functions and toxic intervention levels used through RIVM website. Phast Safeti was used for consequence modelling
Likelihood of occurrence	Initiating events determined to be human error, process control failure and material degradation (corrosion). Red Book and Purple Book used as references to determine likelihood of incident
Risk presentation	Purple Book used to determine likelihood of incident
	Likelihood of catastrophic failure of a pressure vessel containing ammonia was 10^{-6}/year
	Hazards considered were exposure to toxic ammonia. Risk measures calculated were individual risk and societal risk. Area where people can be in danger is defined (exposure to concentrations indoors higher than life-threatening value). Quantitative risk assessment was conducted using standard set of scenarios and frequencies, combined with consequence modelling
	Risk matrix was not used. Risk summarized using Individual Risk and Societal Risk (FN-curve)
Risk acceptability criteria	Risk acceptability criteria determined per regulations: individual risk lower than 10^{-6}/year at location of houses; societal risk of $10^{-3}.N^{-2}$ /year. For societal risk graph, see Purple Book
	Criteria only for human risk, none for environmental risk
	Risk acceptability criteria was based on national legislative requirements

Key information	*Description*
Additional risk reduction measures implemented	Risk assessment was used for off-site spatial planning, not to determine risk reduction measures. Measures should be implemented by company based on risk matrix and as approved by competent authorities

E. Chlorine

1. France

21. The site is approximately 560,000 m^2 and is located near a railway, a motorway and two factories (see table 17 for case study summary).

Table 17
France chlorine case study summary

Key information	*Description*
Major incident scenarios	Toxic chlorine gas release; No transboundary effects are considered plausible
Release effects and consequence considerations	Worst-case scenario considered two fatalities and 94 injuries in an “extremely unlikely” scenario. Toxic gas released into atmosphere would result in environmental effects
	National threshold values similar to IDLH were used. Consequence (gas dispersion) modelling was conducted using ALOHA, Phast and FLame ACceleration Simulator (FLACS), referencing national database published by French National Institute for Industrial Environment and Risks
Likelihood of occurrence	Initiating events included equipment failure. Likelihood was evaluated using proprietary database belonging to Arkema (DOROTE), Safecalc and EXE for failure of risk control measures (calculated between 10^{-2} and 10^{-3}/year failure rates)
	Incident likelihood for loss of containment events ranging from 5 seconds to 60 minutes ranged from 8.5 x 10^{-6} to 8.6 x 10^{-8}/year, respectively. A 60-minute duration pipe break evaluated at likelihood of 5.3 x 10^{-5}/year
Risk presentation	Individual risk due to personnel exposure to chlorine gas was estimated. Quantitative risk assessment was conducted using Bow-Tie analysis. Risk matrix was used for risk assessment
	Qualitative severity levels were used:
	Moderate: No injury or fatality;
	Serious: Minor injury/illness;
	Important: Hospitalization due to exposure/permanent disability;
	Catastrophic/Disastrous: Fatality
	Qualitative likelihood levels were also used: extremely unlikely; very unlikely; unlikely; likely; frequent

Key information	*Description*
Risk acceptability criteria	Risk acceptance criteria were determined based on national criteria (Circular of 10 May 2010), using combination of qualitative and quantitative levels, i.e. considering gravity of scenario and associated probability. Table 18 provides an example of risk acceptability criteria Approaches for assessing human and environmental risks are different. Environmental impacts are considered using case-by-case qualitative approach Stakeholders involved in determining risk matrix and risk acceptance were facility management, safety professionals and local competent authority
Risk reduction measures implemented*	Toxic gas detectors and alarm systems installed; Prevention measures included regular tightness tests, choice of steel pipes and seals, nitrogen flushing; Protection measures including use of wedges and brakes for chlorine wagons; Emergency response plans established for toxic gas release at facility involving surrounding facilities; Specific procedure developed to prevent water pollution

Table 18
France chlorine risk acceptance criteria

GRAVITÉ des conséquences	PROBABILITÉ (sens croissant de E vers A)				
	E	D	C	B	A
Désastreux	NON partiel (établissements nouveaux : note 2) / MMR rang 2 (établissements existants : note 3)	NON Rang 1	NON Rang 2	NON Rang 3	NON Rang 4
Catastrophique	MMR Rang 1	MMR Rang 2 (note 3)	NON Rang 1	NON Rang 2	NON Rang 3
Important	MMR Rang 1	MMR Rang 1	MMR Rang 2 (note 3)	NON Rang 1	NON Rang 2
Sérieux			MMR Rang 1	MMR Rang 2	NON Rang 1
Modéré					MMR Rang 1

Note: "Gravité des consequences" means "Seriousness of consequences"; "Désastreux" means "Disastrous"; "Catastrophique" means "Catastrophic"; "Important" means "Major"; "Serieux" means "Serious"; "Modéré" means "Moderate"; "NON partiel (établissements nouveaux: note 2)" means "Partial NO (new establishments: note 2)"; "MMR rang 2 (établissements existants: note 3)" means "Risk Management Measure rank 2 (existing establishments: note 3"; "PROBABILITÉ (sens croissant de E vers A)" means "PROBABILITY (increasing order from E to A)".

2. Hungary

22. The site is approximately 33,500 m^2, close to a residential area (300 m) and an industrial area (100 m) (see table 19 for case study summary).

Table 19
Hungary chlorine risk acceptance criteria

Key information	*Description*
Major incident scenarios	Facility contains 40 m^3-volume tank wagon containing 50 tons of chlorine (fluid phase), under 4.2 bar overpressure (gauge). Three different release scenarios considered were catastrophic rupture, 10-minute release, and 10 mm leak. Worst-case scenario was a 10-minute release. No transboundary effects considered plausible in any scenario. Complex quantitative risk analysis deals with all possible weather circumstances; for following consequence considerations, 1 m/s windspeed and F-Pasquill stability class is defined (very stable condition)
Release effects and consequence considerations	Personnel fatalities and injuries are expected. Consequences quantified as below: 100 per cent fatality: 0 person (~380m); 50 per cent fatality: 1,000 persons (~700m); 10 per cent fatality: 3,800 persons (~1,300m); 1 per cent fatality: 5,000 persons (~2,400m)
	Environmental effects expected due to toxic chlorine gas release in atmosphere. surrounding residential areas would need to be evacuated due to toxic release
	Probit calculation methods were used to define lethality probability. Green Book referred to for consequence modelling. Safeti 8.4 used for consequence modelling
	Consequence modelling outputs included toxic lethal curves for worst-case scenario (10 minute release of 50 tons chlorine, see figure 15) and map of various percentages of lethality for worst-case wind speed, wind direction and stability (see figure 16)
Likelihood of occurrence	Initiating events included structural failure and domino effects from other installations. Reference Manual Bevi Risk Assessments and Purple Book used to determine likelihood of incident. Frequency of release of entire contents in 10 minutes in continuous and constant stream liquified toxic gas was 5 x 10^{-6}/year
Risk presentation	Comprehensive risk assessment of establishment refers to all possible scenarios, including loss of containment of different containers, pipelines and process vessels. All scenarios that contribute significantly to location-specific risk and/or societal risk were included in quantitative risk analysis, defined as meeting following two conditions: frequency of the scenario $\geq 10^{-9}$ per annum; lethal injury (1 per cent fatality) can also occur outside site boundary
	Risk matrix was not used for risk assessment. Risk presentation included following: weather matrix (wind speed, wind direction, stability); risk ranking report; individual and societal risk as presented in figure 17 and figure 18
Risk acceptability criteria	Risk acceptability criteria consisted of acceptable and unacceptable zones based on risk level and number of deaths (see figure 19)
	Different criteria were used for human and environmental risks. Environmental risk criteria used were qualitative, as regulations provided only practical guidance. Stakeholders involved included operator and licensed consultants

Key information	*Description*
Risk reduction measures implemented*	Toxic gas detectors and alarm systems; SIS: Level, pressure and temperature; Preventative measures include fixed water curtain nozzle system installed around tank-wagon offloading place (~20x5 m), system is manually checked periodically; Internal and external emergency plans are put in place

Figure 15
Hungary chlorine toxic probability of death versus distance

Figure 16
Hungary chlorine map of 1 per cent, 5 per cent, 50 per cent and 100 per cent lethality curves

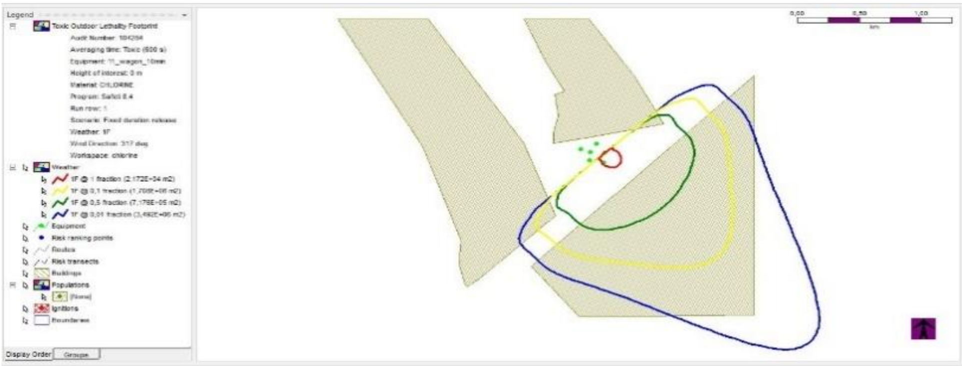


Figure 17
Hungary chlorine individual risk contours

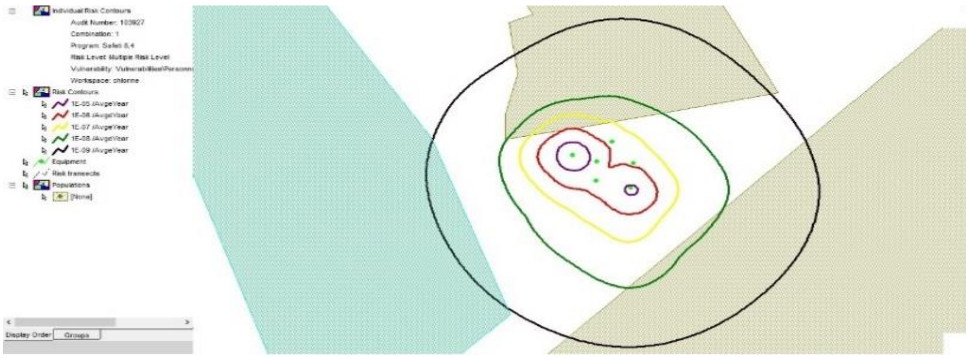


Figure 18
Hungary chlorine societal risk F-N curve

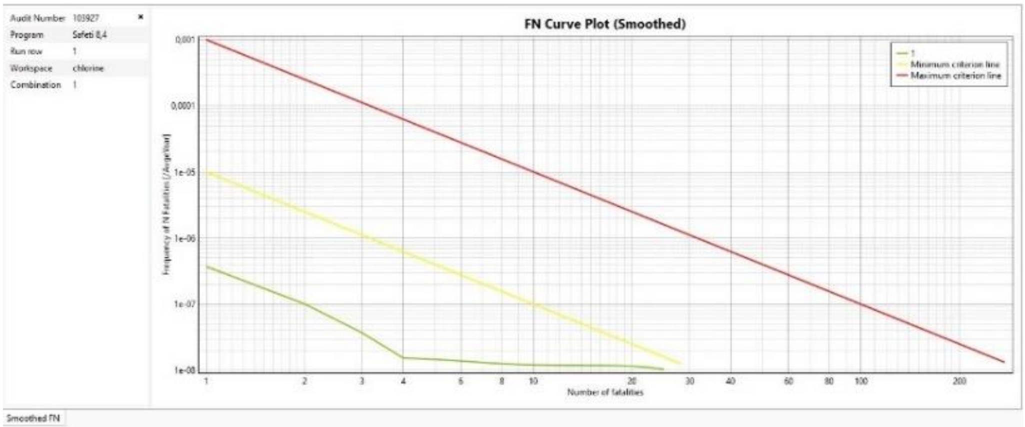
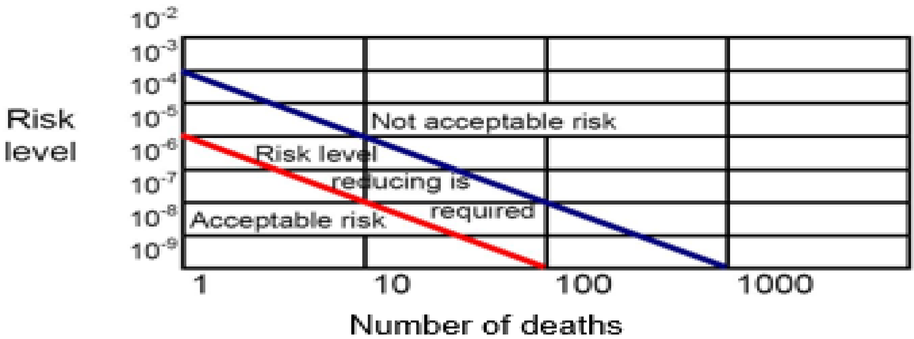


Figure 19
Hungary chlorine risk acceptance criteria



3. Switzerland (transboundary)

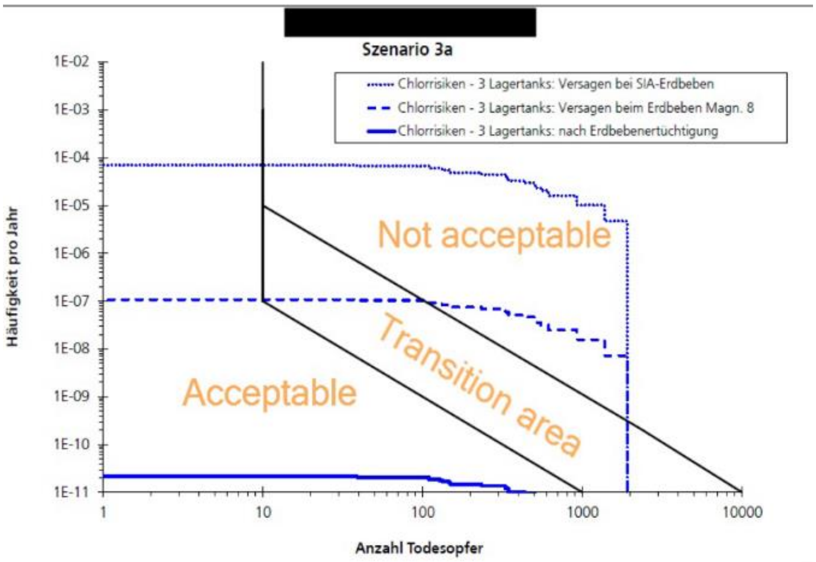
23. The site is approximately 160,000 m^2 and consists of a former chlor-alkali electrolysis facility in an industrial park. Details regarding proximal exposures were not provided. A transboundary exposure in Germany was considered (see table 20 for case study summary).

Table 20
Switzerland (transboundary) chlorine risk acceptance criteria

Key information	*Description*
Major incident scenarios	Toxic chlorine gas release due to different scenarios. Worst-case scenario was earthquake destroying chlorine storage tanks. Transboundary effects are considered possible and can affect Germany. Neighbouring country has been notified
Release effects and consequence considerations	2,000 fatalities were estimated during risk assessment. In the case of an earthquake, no evacuation would be possible, due to large-scale destruction of civil buildings and infrastructure. Affected area in Germany not populated, so no quantitative assessment of transboundary damage was conducted
	Consequence modelling was conducted using EFFECTS

Key information	*Description*
Likelihood of occurrence	Identified cause of incident was earthquake Swiss Society of Engineers and Architects (SIA)-Norm was used for determining likelihood of occurrence. Likelihood of SIA-earthquakes in area approximately 10^{-3}/year (once every 475 years)
Risk presentation	Societal risk due to personnel exposure to chlorine gas. Quantitative risk assessment was conducted using FTA and ETA Risk matrix was used for risk assessment. Quantitative severity levels used in risk matrix were based on number of fatalities. Quantitative likelihood levels used in risk matrix ranged from 10^{-1}/year to 10^{-10}/year (see figure 20)
Risk acceptability criteria	The Swiss Federal Office for the Environment provides a document with quantitative societal risk acceptance criteria. Different criteria were used for human and environmental risk evaluation. Stakeholders involved in determining risk matrix included facility management and facility safety professionals Risk acceptability criteria consisted of three different zones: “Acceptable,” “Transition Area” and “Not Acceptable,” depending on frequency of incident per year (Y-axis) and number of fatalities (X-axis) (see figure 20) In Switzerland, same quantitative acceptability criteria also applied for environmental risks. Another X-axis is used instead of fatalities
Additional risk reduction measures implemented	Earthquake retrofitting of storage building and second barrier concept; Emergency response plans established for toxic gas release at facility, for example, sodium thiosulfate added to sprinkler system and a special fire truck

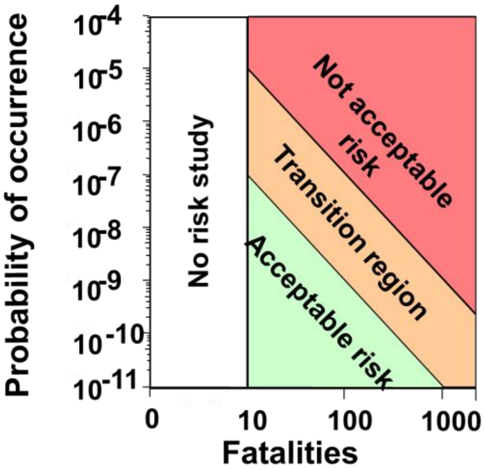
Figure 19
Switzerland (transboundary) chlorine risk presentation



Note: “Häufigkeit pro Jahr” means “Frequency per year”; “Anzahl Todesopfer” means “Number of fatalities”; Szenario 3a” means “Scenario 3a”; “Chlorrisiken” means “Chlorine risks”: “Lagertanks” means “Storage tanks”; “Versagen bei SIA-Erdbeben”

means “Failure at SIA-Earthquake”; “Versagen beim Erdbeben Magn. 8” means “Failure at magnitude 8 earthquake”; “nach Erdbebenertüchtigung” means “after seismic retrofitting”.

Figure 20
Switzerland (transboundary) chlorine risk acceptance criteria



IV. Key findings

24. Risk assessment methodologies used in 18 case studies from ECE countries, including transboundary examples from Serbia (oil terminal) and Switzerland (ammonia refrigeration and chlorine), were discussed in this report. The case studies were analysed based on five different facility types: LPG/LNG, ammonia refrigeration, oil terminals, ammonium nitrate storage and chlorine.

25. The following are some important comparisons and differences based on the risk assessment case studies:

(a) Similarities: For most case studies, there were similarities in the nearby exposure targets, databases, resources for determining risk assessment parameters such as severity and likelihood, and software used for consequence modelling;

(b) Facility type: The facility type determines the primary hazardous material of interest and thus is the driving factor impacting the type of consequence but was not a contributing factor to most of the other evaluated parameters such as environmental considerations, type of risk assessment conducted, tools used, or databases referenced. The facility scale and proximity to populated targets had more of an impact on the magnitude of consequences than the facility type;

(c) Scale: The selection of case studies covered a considerable range in scale (1,000–600,000 m^2);

(d) Incident causes: Some common incident causes considered in these assessments were human error, structural failure, equipment failure, technological failures, process control failures, natural disasters (earthquakes, thunderstorms). The type of facility did not seem to affect the incident cause significantly. The causes were more likely dependent on the exact incident scenario considered. Human error was not listed as a discrete initiating event in all scenarios;

(e) Likelihood: Initiating event likelihoods ranged considerably from 10-2/year to 10-14/year;

(f) Consequence modelling: Several case studies conducted consequence modelling to determine the onsite and off-site effects due to heat radiation, toxic dispersion levels and explosion radii. Consequence modelling, when employed, utilized a small cut set of available software platforms including Phast Safeti, EFFECTS, ALOHA and BREEZE.

The annex to the present document summarizes many other commercially available software platforms and their applications. The common use of fewer software packages may allow for easier transferability and understanding of results across diverse stakeholders;

(g) Databases: Databases and references for consequence modelling included the Purple Book, the Green Book and the Yellow Book. General databases and references used for determining likelihood of incident included the Red Book and the Purple Book:

(i) Country-specific databases included RIVM, the Classification of Hazardous Locations, the Association of Technical Inspection Agencies checklist procedure (Germany), the Administration Research Actions Management Information System database (Switzerland), the Poland and Hungary Assistance for the Restructuring of the Economy guidelines, the Swiss Society of Engineers and Architects-Norm and the Arkema proprietary database;

(ii) The “coloured books” (Green Book, Yellow Book, Purple Book, Red Book) and RIVM appear to be common references widely used across different countries;

(h) Risk presentation: Most case studies used a risk matrix to present findings. Both qualitative and quantitative risk assessment methods were used in almost every case study. Most of the incident scenarios considered for risk assessment were events having low likelihood of occurrence. The risk matrices used had 3-5 severity and likelihood levels, which appeared to be the norm for risk assessments for the United Nations Economic Commission for Europe (ECE) countries. The magnitudes of severity and likelihood levels depended on the type of risk matrix used and were highly dependent on the stakeholders involved and the selected risk acceptance criteria. Case studies that did not use a risk matrix had defined risk acceptance criteria based on severity and likelihood of the incidents, which is indicative of a similar approach as in the risk matrix;

(i) Risk acceptance criteria: The risk acceptability criteria differed significantly depending on the country, company, locality and stakeholders involved, such as process safety professionals, facility management and operators, federal and legal authorities. Ultimately, risk acceptance criteria were observed to be highly dependent on two factors: the country regulations and the risk matrix developed by the stakeholders. For all types of installations, a few countries apply consequence limit values and others have tailor-made acceptability criteria based on the individual or societal risk, with acceptable and unacceptable zones dependent on the risk levels and fatalities, aligned with a risk matrix type evaluation;

(j) Environmental considerations: Most of the case studies had different criteria for human and environmental risks. Only very few countries take environmental effects quantitatively into account. The environmental risk criteria considered in most of the case studies were qualitative;

(k) Transboundary considerations: Very few case studies addressed transboundary effects. Where transboundary risk assessments are to be conducted, the choice of acceptance criteria and data sources for both likelihood and consequences should be agreed upon prior to conducting the risk assessment.

26. The learnings assimilated from these case studies can be used to improve existing risk assessment methodologies and facilitate sharing of ideas amongst the ECE countries to enhance safety in facilities, their neighbours and the environment.

Annex

List of currently available software tools

1. This annex identifies software tools for the application of risk assessment. The lists presented in this annex are non-exhaustive and that other comparable tools are available, including discontinued and legacy software no longer supported by the publisher. The intent of this annex is to highlight the variety of options available for the various tasks within risk assessment.

I. Software tools for hazard analysis

2. While commercially available software tools specific to conducting hazard analysis are available, many entities develop their own file structures in word processing, spreadsheet, or database software (e.g., Microsoft Office platform).

3. The programmes listed in table A.1 provide a framework for conducting and documenting process hazard analysis, including the ability to build on previous studies.

Table A.1
Software tools for hazard analysis

Name	*Hazop+*[a]	*PHA Pro*[b]	*PHA-Tool*[c]	*PHAWorks*[d]
Developer	Isograph	sphere	BakerRisk	Primatech
Purpose	HazOp	Process Hazard Analysis (various methods)		
Use	Document and manage process hazards			
Benefits	Supports HazOp method	Supports HazOp, What-If methods; assumptions register, change log. Customizable interactive risk matrix; ability to group recommendations		
Limitations	Other methods unavailable	Additional modules required for advanced analysis		
Availability	Licensed			

Abbreviations: HazOp, Hazard and Operability.

II. Software tools for event tree analysis/fault tree analysis

4. It should be noted that several commercially available software tools specific to developing fault tree analysis (FTA), event tree analysis (ETA) and linked reliability/failure mode and effects analysis (FMEA)/failure mode effects and criticality analysis (FMECA) are available, including free versions with limited functionality and cloud/web-based options (see table A.2).

[a] Available at www.isograph.com/software/hazop/.
[b] Available at https://sphera.com/pha-pro-software/.
[c] Available at www.bakerrisk.com/products/software-tools/pha-tool.
[d] Available at www.primatech.com/software/phaworks.

Table A.2
Software tools for event tree analysis/fault tree analysis

Name	*CAFTA*[a]	*ITEM ToolKit*[b]	*Reliability Workbench / FaultTree+*[c]	*RAM Commander*[d]	*RiskSpectrum*[e]
Developer	EPRI	ITEM Software	Isograph	ALD Software Limited	Lloyd's Register
Purpose	FTA, ETA	FTA, ETA, FMEA/FMECA	FTA, ETA, FMEA/FMECA	FTA, ETA, FMECA	FTA, ETA
Use	Generic analysis of fault trees and event trees		Fault tree and linked event tree modelling and analysis	Evaluation of electronic/ mechanical system reliability	Fault tree and linked event tree modelling and analysis
Benefits	Simplifies accident consequence modelling using event trees. Easy integration of fault trees, event trees and reliability database	Determines element importance; integration with other modules addressing reliability and system costing	Integrated failure data libraries. Can link to other modules addressing reliability	Detailed equipment/system level analysis; sensitivity analysis	Can link to other modules addressing risk components, including human reliability analysis Can address internal, area (fire and flooding) and external (seismic) events
Site-specific conditions can be incorporated	Yes				Yes
Limitations	Software access limited to EPRI members	Reliability data must be customized by user		Aligned with aerospace, defence, transportation industry standards	Proprietary computational algorithm. Focus on nuclear industry
Availability	Licensed; Demonstration version available without ability to save files	Licensed; Demonstration version available without ability to save files and session limit	Licensed	Licensed	Licensed

Abbreviations: EPRI, Electric Power Research Institute.

[a] Available at www.epri.com/research/products/000000003002004316.
[b] Available at www.itemsoft.com/item_toolkit.html.
[c] Available at www.isograph.com/software/reliability-workbench/fault-tree-analysis-software/.
[d] Available at https://aldservice.com/reliability-products/rams-software.html.
[e] Available at www.lr.org/en/riskspectrum/technical-information/psa/.

III. Software tools for quantitative risk analysis

5. Table A.3 contains a sample of commercially available quantitative risk analysis software.

Table A.3
Software tools for quantitative risk analysis

Name	*ARIPAR*[a]	*FLACS-RISKCURVES*[b]	*QRATool*[c]	*RAPID-N*[d]	*Safeti*[e]	*SHEPHERD*[f]
Developer	JRC	TNO (Owner: GexCon)	BakerRisk	JRC	DNV	Shell (Owner: GexCon)
Description	Performs quantitative area risk assessment, evaluating risk resulting from major hazardous substance accidents	Quantifies the risks of storage and transport of hazardous substances to the surrounding population and structures, both in the urban environment and at chemical facilities	Aggregates consequences from SafeSite software and applies frequency information	Addresses Natech at critical chemical infrastructure	Quantitative risk analysis of onshore process, chemical and petrochemical facilities	Risk management software tailored for onshore facilities and operations
Purpose	General	General	General	Natech	General	Onshore oil/gas
Use	Risk contours and f-n curves	Evaluation of high-risk activities/scenarios, urban planning, regulatory and corporate criteria	Evaluation and ranking of explosion, fire, and toxic risks and mitigation strategies. Individual or societal risk results. Plot exceedance consequences	Addresses Natech involving releases of hazardous substances, fires, and explosions	Risk contours, f-n curves, and rankings of risk contributors. Accounts for local population and weather	Risk analysis
Addresses chemical transport risk	Yes	Yes	No	No	Yes	Yes
Benefits	Area risk control based on geographical information system platform	Open architecture allowing inputs from different software	Risk results in multiple options for individual or societal risk	Only known tool on Natech	Chemical library included	
Quick results	Yes				Yes	
Threat zones can be plotted on maps	Yes		Yes		Yes	Yes

[a] Available at https://publications.jrc.ec.europa.eu/repository/handle/JRC66551.
[b] Available at https://gexcon.com/products-services/riskcurves-software/.
[c] Available at www.bakerrisk.com/products/software-tools/qratool/.
[d] Rapid NaTech Risk Assessment Tool (RAPID-N) available at https://rapidn.jrc.ec.europa.eu/.
[e] Available at https://dnv.com/safeti.
[f] Available at https://gexcon.com/products-services/shell-shepherd-software/.

Name	*ARIPAR*[a]	*FLACS-RISKCURVES*[b]	*QRATool*[c]	*RAPID-N*[d]	*Safeti*[e]	*SHEPHERD*[f]
Sensitivity analysis	Yes					Yes
Verification and validation publicly available	Yes	Yes (in Yellow Book)		Yes		
Can incorporate site-specific conditions	Yes		Yes		Yes	Yes
Limitations	Physical models not described	Complex data input required	Relies on consequence analysis from SafeSite with no other import available	Uses EPA RMP Guidance for Off-site Consequence Analysis input	Integral models	No modelling of toxic releases
Does not model environmental consequences	X		X	X	X	X
Verification and validation not publicly available			X		X	X
Availability	Discontinued	Licensed	Licensed	Free with waiver	Licensed	Licensed

Abbreviations: EPA, United States Environmental Protection Agency; RMP, Risk Management Programme.

IV. Software tools for consequence analysis

6. Table A.4 contains a sample of commercially available consequence analysis software.

Table A.4
Software tools for consequence analysis

Name	*ADAM*[a]	*ALOHA*[b]	*BREEZE*[c]	*CANARY*[d]	*DEGADIS*[e]
Developer	JRC	EPA	Trinity Consultants	Quest Consultants	EPA

[a] Accident Damage Analysis Module (ADAM) available at https://adam.jrc.ec.europa.eu/en/adam/content.
[b] Areal Locations of Hazardous Atmospheres (ALOHA) available at https://epa.gov/cameo/aloha-software.
[c] Available at www.trinityconsultants.com/software.
[d] Available at www.questconsult.com/software/canary/.
[e] Dense Gas Dispersion Model (DEGADIS) available at https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=&direntryid=2904.

Name	*ADAM*[a]	*ALOHA*[b]	*BREEZE*[c]	*CANARY*[d]	*DEGADIS*[e]
Description	Calculates the physical effects of industrial accidents resulting from an unintended release of a hazardous substance, chemical fires, blast effects of VCE, and inhalation of toxic chemical vapours	Models chemical releases for emergency responders and planners. Estimates toxic cloud dispersion after a chemical release and several fire and explosion scenarios	Multi-module air dispersion modelling platform; models fire, explosion, air toxics, human health, and environmental impacts. Based on EPA-developed software (AERMOD)	Consequence and hazard modelling tool that provides thermodynamic calculations for time-varying fluid releases	Models transport of toxic chemical releases into atmosphere
Use	CA of flammable and toxic releases	CA of flammable and toxic releases	Modelling of various consequence scenarios	CA of flammable releases and loss of containment scenarios	Dispersion of toxic releases (continuous, instantaneous, finite duration or time-variant)
Source Terms[f]	Yes	Manual	Yes	Yes	Manual
Physical Effects[g]	All	Dispersion	All	All	Dispersion
Vulnerability[h]	Yes	Yes	Yes	Yes	Exposure intensity
Benefits	Easy to use for European Union competent authorities, designed with intent to include European Union regulations and directives in consequence modelling	Produces reasonable results quickly enough for emergency responder use. Can link to live conditions in United States. Easy to use in the field	Can model non-steady-state releases; Modules for LNG/LPG; Enhanced visualization and data export manipulation tools	Chemical database. Hazard models for vapor dispersion, fire radiation or VCE can be evaluated against gas concentration, radiant flux, or overpressure consequence endpoints.	Models variety of dense gas release conditions
Limitations	Software cannot be extended to non-governmental organisations.	Some models simplified for ease of use and speed of results	ExDAM not appropriate for time-variant pressure/ impulse profiles or for congested spaces	No known limitations.	Only one set of meteorological conditions can be simulated. Limited to dense gases
Availability	Free[i]	Free	Licensed[j]	Licensed	Free

[f] Amount of chemical released in a loss of containment event, including relevant chemical parameters

[g] Toxic gas dispersion, fire thermal radiation, explosion overpressure, etc.

[h] Harm produced by physical effects, accounting for likelihood, duration, intensity of exposure

[i] Reserved to European Union competent authorities, European Union countries' neighbours and Organisation for Economic Co-operation and Development countries with chemical risk management responsibilities. Not available to non-governmental organizations (NGOs) (industry, external consultants, etc.).

[j] AERMOD available through United States Environmental Protection Agency for free at www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod.

Name	*exploCFD*[k]	*FLACS-CFD*[l]	*FLACS-EFFECTS*[m]	*Fluidyn*[n]	*FRED*[o]
Developer	Advanced Analysis Australia	GexCon	TNO (Owner: GexCon)	Fluidyn	Shell (Owner: GexCon)
Description	Specific to explosion effects. Detailed models available for BLEVE, high explosives and dust clouds	3-dimensional CFD modelling for flammable and toxic releases. Incorporates contributing and mitigating effects, including confinement and congestions due to real geometry, ventilation, and deluge	Models behaviour of toxic or flammable gases, liquefied gases, and liquids from moment of release to resulting physical effects	CFD modelling platform with multiple modules for specific scenarios	Consequence modelling tool underpinned by advanced thermodynamic model which enables extended multi-component fuel representation to be used in nearly all models
Use	Explosion modelling	CA for detailed 3-dimensional scenarios	CA of flammable and toxic releases	CFD models of flammable and toxic releases	CA of flammable releases
Source Terms	Yes	Yes (DIPPR)	Yes (DIPPR)	Manual	Yes (Thermodynamic model consisting of multi-component fuel)
Physical Effects	Explosion	All	All	All	All
Vulnerability	Fire, explosion effects	Explosion overpressure, fire radiation 3-dimensional effects	Doses due to dispersion, consequences to human life/lethality	Intensity of fire exposure, toxic gas exposure, explosion pressure contours	Fire, toxic release, and explosion effects
Benefits	Ease of use, no geometry construction required, allows modelling of TNT, ammonium nitrate, along with dust and gas explosions	Geometrical features are considered for fire, explosion, and toxic releases	Considers structural damage	PANFIRE module considers effects of active and passive protection systems VENTIL module considers confined space effects FLOWSOL module evaluates liquid-	Developed and validated through extensive programme of large-scale experiments, substantial investment, joint industry projects and published scientific literature

[k] Available at www.advanalysis.com/explocfd.
[l] Available at https://gexcon.com/products-services/flacs-software/.
[m] Available at https://gexcon.com/products-services/effects-consequence-modelling-software/.
[n] Available at www.fluidyn.com/?page_id=96.
[o] Fire, Release, Explosion and Dispersion (FRED) available at https://gexcon.com/products-services/shell-fred-software/.

Name	*exploCFD*[k]	*FLACS-CFD*[l]	*FLACS-EFFECTS*[m]	*Fluidyn*[n]	*FRED*[o]
				borne environmental effects including groundwater pollution	
Limitations	Limited to fire and explosion applications, no toxic dispersion modelling	Computationally expensive	Requires significant experience to validate models and result	No known limitations	No modelling of toxic releases. Focus on offshore industry
Availability	Licensed	Licensed	Licensed	Licensed	Licensed

Name	*KFX*[p]	*MET*[q]	*Phast*[r]	*SAFER One*[s]	*SafeSite 3G*[t]
Developer	DNV	ISi Technologie GmbH	DNV	SAFER SYSTEMS	BakerRisk
Description	CFD tools for simulation of dispersion, fires, and explosions in congested areas.	Assesses chemical accidents and estimates toxic, explosion, thermal radiation, and solid particulate release	Examines progress of a potential incident from initial release to far-field dispersion analysis, including modelling of pool spreading and evaporation, and flammable and toxic effects	Models a chemical release or combustion event in real time to facilitate emergency response tactics. Facility layout is superimposed on maps with live traffic and Internet weather integrated to provide real time situational snapshot	Simulates chemical discharge, dispersion, pool spread and volatilization, jet, and pool fires, VCE, and vulnerability during fire, toxic and explosion events
Use	CA for fire and explosion scenarios in congested areas	CA of flammable and toxic releases and highly active substances	CA of flammable and toxic releases	Real-time emergency response and communication across organization	CA of multiple scenario types
Source Terms	Yes	Manual	Yes	Manual	Manual
Physical Effects	Fire, Dispersion	All	All	Dispersion	All
Vulnerability	Yes	Yes	Yes	Yes	Yes

[p] Kameleon FireEx (KFX) available at www.dnv.com/services/fire-simulation-software-cfd-simulation-kameleon-fireex-kfx-110598.

[q] Models for Effects with Toxic and flammable gases (MET) available at www.isitech.com/met-fuer-windows.html.

[r] Available at https://dnv.com/phast.

[s] Available at https://safersystem.com/products/safer-one/.

[t] Available at www.bakerrisk.com/products/software-tools/safesite/.

Name	*KFX*[p]	*MET*[q]	*Phast*[r]	*SAFER One*[s]	*SafeSite 3G*[t]
Benefits	Can account for congested areas, weather effects, and fire mitigation with water systems. Addresses a wide range of liquid and gas leak and fire scenarios. Optimization of passive fire protection	Chemical incompatibility screening. Quick results	Applicable to design and operation applications. Widely adopted and considered industry standard	Real-time simulation; integrates with chemical gas and weather sensors; cloud-based	Discharge, dispersion, and blast modelling techniques validated by historical data and testing performed by developer. Can be used for transport routes
Limitations	Focus on petroleum industry		Various versions deal with multiple components. Some explosion models are simplified	Physical models unknown, no proactive/static modelling of releases	Focus on onshore industry. Complex user interface
Availability	Licensed	Licensed	Licensed	Licensed	Licensed

Abbreviations: BLEVE, boiling liquid expanding vapour explosion; CA, consequence analysis; CFD, computational fluid dynamics; DIPPR, Design Institute for Physical Properties; TNT, trinitrotoluene; VCE, vapour cloud explosion.