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Simplified estimations of the heat radiation and blast effects of selected hazardous events

Birgit Marlene Sauerwein, BSc

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Kurzfassung:

Wenn ein Störfall eintritt und eine Person Rettungskräfte alarmiert, sollten diese über die erhaltenen Informationen in der Lage sein, mögliche Effekte sowie Gefahrenzonen abzuschätzen. Diese Masterarbeit beschäftigt sich mit vier Arten von Störfällen, an welchen brennbare Fluide beteiligt sind. Der Fokus liegt auf deren Auswirkungen auf Menschen und Gebäude in Form von Wärmestrahlung und Druckwellen. Bei der Simulation von Störfallszenarios sind die sogenannten Quellterme (beispielsweise die Freisetzungrate) des realen Störfalls nicht bekannt. Diese Parameter haben jedoch einen nicht zu vernachlässigenden Einfluss auf die Auswirkungen und werden in dieser Arbeit berücksichtigt. Ziel ist es, mit möglichst wenig Inputdaten und vereinfachten Formeln (keine Iterationen), Ergebnisse zu erhalten, die zur Abschätzung der drei Risikozonen (basierend auf Expositionsgrenzwerten) genügen. Die vier betrachteten Szenarien sind BLEVEs, Jet-Feuer (Strahlfeuer), Lachenverdampfungen/-feuer und Dampfwolkenfeuer/-explosionen. Aufgrund des Mangels an Daten vergangener Störfälle, insbesondere in Bezug auf die Distanzen der Effekte, ist die Übertragbarkeit der Ergebnisse möglicherweise begrenzt.

Abstract:

If a hazardous event takes place and a person calls rescue personnel, they should be able to estimate possible effects and the distances they may appear in only with the information provided. This thesis discusses four types of hazardous events involving flammable fluids. The focus is on their effects on people and structure in the form of heat radiation and pressure waves. When an accident is simulated the so called source terms (such as the release rate) are not known. However, these parameters have a relevant impact on the effects. Hence, they should not be neglected and are considered in this thesis. The aim is to obtain an output sufficient to estimate three risk zones (based on critical exposition values) from as little input data as possible and simplified formulae (no iterations). The four scenarios considered are BLEVEs, jet fires, pool evaporation/fires and vapour cloud fires/explosions. Due to a lack of data from past events, especially if it comes to the distances of the effects, the transferability of the results is potentially limited.

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Glossary of terms [1] [2]

Ambient	Surrounding atmosphere
Auto-ignition temperature	The lowest temperature at which a substance/material spontaneously ignites without any additional energy source.
Blast (wave)	A rapidly propagating pressure or shock-wave in atmosphere with high pressure, high density and high particle velocity.
BLEVE	A Boiling Liquid Expanding Vapour Explosion (BLEVE) results from the sudden failure of a vessel containing pressurised liquid at a temperature well above its normal (atmospheric) boiling point.
Burning rate	The linear rate of evaporation of material from a liquid pool during a fire, or the mass rate of combustion of a gas or solid. The context in which the term is used should be specified.
Continuous release	Release during a long time with a constant contaminant mass flow rate.
Critical (choked) flow	The critical (choked) outflow is reached when the downstream pressure is low enough for the stream velocity of the fluid to reach the speed of sound in the mixture, which is the maximum possible flow velocity.
Critical temperature	The highest temperature at which it is possible to have two fluid phases of a substance in equilibrium: vapour and liquid. Above the critical temperature there is no unambiguous distinction between liquid

	and vapour phase.
Deflagration	A propagating chemical reaction of a substance in which the propagation of the reaction front is determined by conduction and molecular diffusion
Detonation	A propagating chemical reaction of a substance in which the propagation of the reaction front is determined by compression beyond the auto-ignition temperature.
Evaporation	Evaporation is a type of vaporization without the liquid reaching boiling temperature. It occurs at the surface of a pool if the saturated vapour pressure is bigger than the fluid's partial vapour pressure just above the pool.
Explosion	A sudden release of energy that causes a blast.
Explosive	Explosives lead to a special type of chemical energy release followed by a pressure wave. They already contain the oxygen necessary for combustion in their compound and can detonate without air.
Fire	A process of combustion characterized by heat or smoke or flame or any combination of these.
Fireball	A fire, burning sufficiently rapidly for the burning mass to rise into air as a cloud or ball.
Flash fire	The combustion of a flammable vapour and air mixture in which flame passes through that mixture at less than sonic velocity, such that negligible damaging overpressure is generated.
Fluid	Material of any kind that can flow, which may extend to gases to highly viscous substances, like gases and liquids and gas/liquid-mixtures; meaning not fixed or rigid, like solids.
Gas	State of aggregation of chemical or mixture of chemicals that is fully in the gaseous state under the present pressure and temperature; gases neither have independent shape nor volume.
Instantaneous release	Release during which in a (very) short time a (large) amount of gas is released.
Jet fire	The combustion of material emerging with significant momentum from an orifice (hole).

LFL	The Lower Flammability Limit (LFL) or Lower Explosion Limit is the concentration in air of a flammable material below which combustion will not propagate. Below this concentration too little flammable gas is present in the air to maintain combustion
Partial pressure	Fraction of total pressure due to the presence of a gas; total pressure is the sum of all partial pressures of the gases present in a mixture.
Pool fire	The combustion of material evaporating from a layer of liquid at the base of the fire.
Pressurised liquefied gas	Gas that has been compressed to a pressure equal to saturated vapour pressure at storage temperature, so that the larger part has condensed to the liquid state.
Pressure wave or shock-wave	Rapidly propagating wave in atmosphere causing a gradual change in gas-dynamic-state: high density, pressure and particle velocity.
Saturation pressure	The pressure of a vapour which is in equilibrium with its liquid (gas is at saturated state). It depends on temperature only and is the maximum pressure possible by vapour at that temperature.
SEP or surface flux	The Surface Emissive Power (SEP) of a flame is the heat radiated outwards per unit surface area of the flame. There is considerable confusion in the literature about the meaning of these empirical parameters characterising flame radiation.
Source term	Physical phenomena that takes place at a release of a chemical from its containment before entering the environment of the failing containment, determining release rate and quantity, thermodynamic state and the relevant area. For example the release rate.
Superheat	The extra heat of a liquid that is available by decreasing its temperature, for instance by vaporisation, until the vapour pressure equals that of its surroundings.
TNT-equivalent	The amount of TNT (trinitrotoluene) that would produce observed damage levels similar to those of the explosion under consideration.
Transmissivity	The fraction of incident thermal radiation passing unabsorbed through a path of unit length of a medium.
Triple point	A point on a phase diagram representing a set of conditions (pressure

	and temperature), under which the gaseous, liquid and solid phase of a substance can exist in equilibrium. For a pure stable chemical the temperature and pressure at triple point are physical constants.
Two-phase flow	Flow of material consisting of a mixture of liquid and gas, while the gas (vapour) phase is developing due to the vaporisation of the superheated liquid during the flow, caused by decreasing pressure along the hole or pipe due to the pressure drop over the resistance.
UFL	The Upper Flammability Limit (Upper Explosion Limit) is the concentration in air of a flammable material above which combustion will not propagate/above this concentration too little oxygen is available to maintain combustion.
Vapour	Chemical in the gaseous state which is in thermodynamic equilibrium with its own liquid under the present saturation pressure at a given temperature.
VCE (Vapour cloud explosion)	The explosion resulting from an ignition of a premixed cloud of flammable vapour, gas or spray with air, in which flames accelerate to sufficiently high velocities to produce significant overpressure.
View factor	The view factor quantifies the geometric relationship between the emitting and receiving surfaces; it describes how much of the field of view of the receiving surface is filled by the flame. The view factor is equal to unity if the flame completely fills the field of view of the receiving surface, otherwise is a fraction of unity. The view factor depends on the dimensions, shape of the flame, the distance and the orientation of the receiving object.

Acronyms and abbreviations

ATV	All-terrain Vehicle
ASchG	[*from German: ArbeitnehmerInnenschutzgesetz*] workers protection act
BLEVE	Boiling Liquid Expanding Vapour Explosion
CAPECO	Caribbean Petroleum Corporation
CCTV	Closed Circuit Television (basically a security camera)
CCPS	Center for Chemical Process Safety
cf	[*from Latin: confer*] compare
DN	[*from French: diámetre nominal*] nominal diameter
eg	[*from Latin: exempli gratia*] for example
et al.	[*from Latin: et alii*] and others
etc	[*from Latin: et cetera*] and the rest
eMARS	(electronic) Major Accident Reporting System
ie	[*from Latin: id est*] that is
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
GmbH	[*from German: Gesellschaft mit beschränkter Haftung*] Limited Company
HSE	Health and Safety Executive
LFL	Lower Flammability Limit

LPG	Liquefied Pressurised Gas
Ltd.	Private limited company
p.	Page
SEP	Surface Emissive Power
TNT	Trinitrotoluene
UFL	Upper Flammability Limit
VCE	Vapour Cloud Explosion

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Symbol	**Unit**	**Description**	**Value (constant)**
A	-	Constant for F_{view} of tilted cylindrical flames	
a	-	Constant for F_{view} of tilted cylindrical flames	
A_j	m²	Surface area of the jet flame	
a_j	-	Constant for the dimensions of the jet flame	
A_{out}	m²	Surface area of the leak	
A_p	m²	Surface area of the pool	
B	-	Constant for F_{view} of tilted cylindrical flames	
b	-	Constant F_{view} of tilted cylindrical flames	
b_j	-	Constant for the dimensions of the jet flame	
C	-	Constant for F_{view} of tilted cylindrical flames	
c_1	$m/kg^{0.325}$	Constant for the radius of the fireball	3.24
c_2	$s/kg^{0.26}$	Constant for the duration of the fireball	0.852
c_{dis}	-	Discharge coefficient	1
c_{pb}	kJ/(kg*K)	Specific heat capacity at constant pressure at boiling temperature	
c_{pg}	kJ/(kg*K)	Specific heat capacity at constant pressure (gas)	
c_{pl}	kJ/(kg*K)	Specific heat capacity at constant pressure (liquid)	

D	-	Constant for F_{view} of tilted cylindrical flames	
d_j	m	Diameter of the jet flame	
D_L	m²/s	Diffusion constant in air	
d_{out}	m	Diameter of the circular leak	
D_p	m	Diameter of the (equivalent) circular pool	
E	-	Constant for F_{view} of tilted cylindrical flames	
E_{TNT}	kJ/kg	TNT blast energy per unit mass	4,500
f	%	Fraction of the volume of the tank/container filled	
F	-	Constant for F_{view} of tilted cylindrical flames	
F_h	-	Geometrical view factor for the horizontal plane of the radiated object	
F_s	-	Fraction of the generated heat radiated from the flame surface	
F_j	-	Constant for M_j for subcritical flow	
F_v	-	Geometrical view factor for the vertical plane of the radiated object	
F_{view}	-	Geometric view factor	
g	m/s²	Gravitational acceleration	9.81
H_{bleve}	m	Distance from the centre of the fireball to the ground	
j_m	-	Volume fraction of gas	
K_j	-	Constant for the dimensions of the jet flame	
k_m	m/s	Mass transfer coefficient	
l_j	m	Flame length of the jet flame	
l_p	m	Average flame height of the pool fire	
m	kg	Mass of the substance	
m_{pool}	kg	Mass of the substance forming the pool	
m_{out}	kg	Mass of the substance released	
m_{vc}	kg	Mass of the substance forming the vapour cloud	
M_j	-	Mach number of the expanding jet	
MM	kg/mol	Molecular weight	

m_{vap}	kg	Mass vaporised	
m'	kg/s	Mass flow rate	
m'_{vap}	kg/s	Evaporation rate	
m''	kg/(m²*s)	Burning flux at still weather conditions	
m''_w	kg/(m²*s)	Burning flux under windy weather conditions	
n_1	-	Constant for the radius of the fireball	0.325
n_2	-	Constant for the duration of the fireball	0.26
P_0	Pa	Atmospheric pressure (considered constant)	101,325
P_c	Pa	Static pressure at the hole exit plane	
P_{init}	Pa	Initial pressure	
P_{sv}	N/m^2	Vapour pressure of material inside the vessel	
p_{TNT}	kPa	Maximum over-pressure according to the TNT model	
Q'	kJ/s	Combustion energy per second	
q''	kJ/(m²*s)	Heat flux at a certain distance	
r_1	M	Distance with 0.01 probability of fatality	
r_{1p}	M	Distance with 0.01 probability of fatality (parallel position)	
r_{50}	M	Distance with 0.5 probability of fatality	
r_{50p}	M	Distance with 0.5 probability of fatality (parallel position)	
R_c	J/(mol*K)	Ideal gas constant	8.314
r_{ex}	m	Distance from the source of the explosion	
r_{fb}	m	Radius of the fireball	
r'_{TNT}	$m/kg^{-1/3}$	Scaled distance from the centre of the explosion	
Sc	-	Schmidt number	
SEP_{act}	kJ/(m²*s)	Actual surface emissive power	
SEP_{max}	kJ/(m²*s)	Maximum surface emissive power	
SEP_{theor}	kJ/(m²*s)	Theoretical surface emissive power	
S_p	m	Pool perimeter	
T_0	K	Ambient temperature	
T_{boil}	K	Boiling temperature	

T_c	K	Critical temperature	
t_{ex}	s	Exposition time	
t_{fb}	s	Burning duration of the fireball	
T_{init}	K	Initial temperature of the gas	
T_j	K	Temperature of the gas in the jet	
t_{out}	s	Duration of release	
t_p	s	Maximum burning time of the pool	
T_p	K	Temperature of the pool	
t_{vap}	s	Time of evaporation	
u_j	m/s	Exit velocity of the expanding jet	
u_w	m/s	Wind speed	
V_{out}	m^3	Volume of the released substance	
V'_{out}	m^3/s	Volume outflow rate	
V'_{outl}	m^3/s	Volume outflow rate (liquid)	
V_{rel}	m^3	Volume of the substance released (total content of tank)	
V_{tank}	m^3	Volume of the tank	
W	-	Stoichiometric mass fraction	
x_{42}	m	Distance from the centre of the heat source to the object	
X_{centre}	m	Distance from the centre of the fireball to the object	
x_{fb}	m	Distance from the surface of the fireball to the object	
α_c	-	Absorption factor due to CO_2	
α_w	-	Absorption factor due to water vapour	
γ	-	Poisson constant (ratio of specific heats)	
δ	m	Thickness of the pool	**Table 14**, p. 48
ΔH_c	kJ/kg	Heat of combustion at boiling point	
ΔH_{fb}	kJ/kg	Net heat available for heat radiation	
ΔH_v	kJ/kg	Heat of vaporisation at boiling point	
ΔT_{fb}	K	Temperature difference between flame and ambient	
η	-	Efficiency factor for TNT-equivalents	**Table 13**, p. 40

Θ	°	Tilt angle of the flames (vertical = 0°)	**Figure 7**, p. 52
ν	m^2/s	Kinematic viscosity	
ρ_{air}	kg/m^3	Density of air	
$\rho'_{g,a}$	-	Ratio between the density of air and the density of the jet	
ρ_{init}	kg/m^3	Initial density of the substance	
ρ_j	kg/m^3	Density of the gas in the jet	
ρ_l	kg/m^3	Density of liquid	
ρ_v	kg/m^3	Density of vapour	
τ_a	-	Atmospheric transmissivity	
φ	%	Relative humidity of the ambient	
ψ	-	Outflow coefficient	

1 Introduction

The daily work of many industries includes dealing with high amounts of various substances – some of them are hazardous. Substances of physical hazard according to GHS [3] are (amongst others) gases under pressure, explosives, toxic and/or flammable substances. If the operations run according to plan and sufficient safety measures are taken, hazardous incidents are unlikely to happen. Commonly they are the consequence of a combination of unintended and unexpected factors, but if the minimum safety requirements are not fulfilled the chances of incidents rise drastically. Generally, the number of unexpected events and possible mistakes is endless or to quote Murphy's law: "*Whatever can go wrong, will go wrong.*"

In the CSB investigations the hazardous incidents are usually based on a minimum of two factors. The first one is a long-term malfunction, for instance due to a mistake during installation, difficulties in communication with the supplier or a lack of maintenance. It has been around for a while and sometimes even known and criticised for a couple of months by employees. However, the plant could still run with this malfunction. Maybe some additional measures had to be taken, like walking to the vessel to check the filling level instead of being able to check it on a screen [4] but the plant was still running. Then the second, the unexpected factor appears: Maybe teenagers driving an ATV on the site (as in [5]). This would still be ok, if they would not crash into a piping system that should be protected from such an impact. Only the combination of both of these factors leads to the final hazardous event. In theory, especially the first factor must not exist or at least only for a very short time frame. However, at this moment the probability of these factors is not relevant anymore, only the protection of people and the prevention of secondary fires.

During a hazardous event it is necessary to react the right way in the fastest way possible. Especially for rescue personnel, who cannot know every site and every substance in detail it is crucial to make the right decisions: Not only to save people, but also to protect their team members. With every minute passed and every wrong reaction, the number of victims and the severity of injuries will rise. Dangerous effects of fires and explosion are mainly dependent on the substance, the amount of it, the time of exposition and the distance to it. Only the last, to some extend the last two factors can be influenced by the decisions made. Therefore a tool for quick estimations might be helpful to make the right decisions. The results of this thesis can be used as the base for such a tool.

For the effects of thermal radiation distance and exposition time are the key parameters. Naturally, people will try to leave areas with harmful levels of radiation themselves. However, within short distance to the fire they will not be able to because they are weakened by the heat. Additionally, doors can be damaged or too hot to be touched. [6] The effects of blast waves can be reduced by safety measures taken beforehand. Generally, the main factor of influence on the harmfulness is the distance to the explosion. When the blast wave develops, it is impossible to outrun it. Another critical issue is unexpected follow-up explosions, especially when people have already hidden in safety zones and are starting to leave them, when these explosions occur.

The aim of this thesis is to analyse selected scenarios of hazardous events and their harmful effects on people and structure. The two dangerous effects focused on are heat radiation and blast waves. There are many influential factors on the effects of any hazardous event, some of them will be known beforehand, like the size of the container or the substance. However, other parameters, so-called source terms such as the size of leakage cannot be predicted. Sometimes they are not only unpredictable but even unobtainable. Nevertheless, they would be necessary for exact modelling of possible effects. The desired output is a three zone model in which the severity of effects is visualised.

The output data is intended to be helpful for people who have to make quick decisions in an emergency such as the fire brigade. There are safety measures that have to be taken according to law (eg in Austria ASchG). Nonetheless, if it comes to storage of fuels for private purposes and especially older buildings it is not always assured, that these measures are taken. Even if according to law something would be impossible, it is not worth risking the death of rescue personnel. In the past unexpected BLEVEs have led to the death of firefighters standing too close to LPG tanks engulfed by fire, underestimating the chance of an explosion. This should not happen ever again.

2 Scope of work

2.1 Problem statement

Hazardous events, involving huge fireballs and explosions are still relevant today. Half a year ago pictures and videos of the incident at the motorway bridge in Bologna went around the globe, incidents at plants are often not present in international media, except there are high numbers of fatalities. These kinds of accidents cannot be modelled, since the effects are too dangerous or safety measures would reduce the effects to extend that the results of the experiment are not useful anymore. Up-scaling the results of small-scale experiments is not feasible due to a too strong adulteration. The approach of improving models by analysing accidents is still one of the only options.

Most of the literature about calculating the effects of explosions and fires at sites is based on the same couple of experiments conducted and models developed in the 1980s. The Yellow Book [1], the guidelines for evaluating these kinds of events by CCPS [7] and even more recent literature show hardly any innovative approaches. According to EU law (Annex VI of the Seveso III Directive (201218/EU)), incident data for major accidents has to be collected, but usually only information about the amount and substance are submitted, only the absolute minimum of the effects is described.

This thesis is about the safety of rescue personnel for incidents not happening on a daily basis. It takes time to analyse the situation, there is a lack of data and the chances to generate any money with these research topics are very limited. That might be the reason for the big potential of improvement in this field.

The main challenge is to determine which data can be considered easily available and which useful output can be produced with little input. The models presented in literature were not developed for limited input, but rather with the estimation of sufficient time, detailed data and the aim of simulating the incident.

2.2 Research objectives

The aim of this thesis is to simplify common calculation methods for four different scenarios in a way that with very little input a relevant output can be provided. The considered scenarios are: BLEVEs, fireballs, vapour cloud explosions and pool fires on land. The expected input data necessary are reduced to the absolute minimum. It is based on the idea, that when an incident takes place someone from the site alarms the fire brigade and this person is the only source of information. The available information is unlikely to be that exact and factors which have only a small influence on the effects therefore will be cut. This thesis attempts to reduce the input factors to the inevitable ones. The challenge is to provide simplified calculations for which that information is enough to gain useful results. The outputs of the calculations are three risk zones (distances from the incident) with different levels of hazardousness.

In the first part of this thesis basic terms and process conditions will be described. This knowledge is necessary to understand the four scenarios of hazardous events chosen. Then those scenarios are described in more detail as well as the harmful effects they can cause. Based on the critical values defined by law or health standards the three risk zones are defined.

The second part presents simplified calculation models for the scenarios in a step-by-step description. Existing calculation models will be taken and reduced to essential factors. In this chapter the necessary input information is defined. The results are exposition times, safety distances, heat radiations and overpressures. Likelihood calculations are not covered, the assumed likeliness is always one.

In the third part of this paper the results based on these calculation models are compared with the actual values of historic events. That way it can be identified whether the proposed calculations are feasible or too simplified. This is followed by a discussion of those results.

3 Theoretical background

All scenarios of accidents considered in this thesis contain the release of a flammable substance which either ignites and/or explodes. The occurring heat radiation and/or pressure wave are likely to have harmful effects on people and structure. Depending on the expected severity of these effects three risk zones are defined. This chapter starts with some basic definitions, then harmful effects of heat radiation and blast waves - firstly on humans, secondly on structure - are described. Finally the chosen accident scenarios and the risk zones with their properties will be described.

3.1 Basic definitions and descriptions

On the following pages the most relevant terms used in this thesis are described. Additional, but very short definitions are provided at the beginning of this paper in the Glossary of terms.

3.1.1 Relevant process conditions

The hazardous events considered in this thesis only involve substances in either liquid or gaseous aggregation state. Depending on the chemical composition and the storage parameters (pressure, temperature) the process conditions are defined. They define the thermodynamic state of a chemical, which has significant influence on its outflow. Liquid leaking rates are 10 to 20 times higher than gas mass flow rates whose main driving force is the pressure gradient. Hence, the magnitude of the outflow depends on the process conditions. Additionally, the process conditions are the main factor of influence for the physical phenomena that will occur during and immediately after the release of the substance, as presented in **Table 1**. [1]

Table 1: Overview of physical phenomena during release depending on process conditions [1] p. 8.7

Process conditions	Pre-dispersion effects
Compressed gases	(sub-) Sonic release into the atmosphere
Refrigerated (liquefied) gases	Pool formation, initially boiling and later non-boiling evaporation
Non-boiling liquids	Pool formation, evaporating but non-boiling
Pressurised liquefied gases	Flash-off, possibly followed by (immediate) evaporation of a liquid spray due to entrainment of atmospheric air; (partial) rain-out may lead to pool formation and subsequent pool evaporation

3.1.1.1 Differences between compressed gases, liquefied pressurised gases and refrigerated liquefied gases

A substance is referred to as a gas if it is completely in the gaseous state (no independent shape or volume) underlying the given temperature and pressure conditions. For this the temperature must be either higher than the critical temperature of the chemical or it can be below the critical temperature in case the pressure is under its saturated vapour pressure.

A compressed gas is a gas stored under higher than atmospheric pressure. It is reduced in volume but not under enough pressure to be liquefied.

A liquefied pressurised gas is a two-phase system in which the vapour phase is in thermodynamic equilibrium with the condensed (liquid) phase. This equilibrium can only exist along the saturation curve of the phase diagram of a chemical, which means the temperature of the gas must be between the critical temperature and the triple point temperature of the chemical. The necessary pressure is the saturation pressure at the given temperature.

A refrigerated liquefied gas would be in the gaseous state at normal conditions, but has been liquefied by lowering its temperature underneath its boiling point and not (only) by raising pressure. [1]

3.1.1.2 Differences between non-boiling liquids, liquefied pressurised gases and refrigerated liquefied gases

Liquid is the state of aggregation in which a chemical or mixture has a defined volume but not a defined shape. This is the case when the temperature of a chemical is over its melting point, but lower than its boiling point at a given pressure. These kind of liquids are also called non-boiling liquids (liquids below boiling temperature) to distinguish them from LPGs, which are also in a liquid phase. Refrigerated liquefied gases below atmospheric pressure are also non-boiling liquids. [1]

3.1.2 Fires

Whenever a flammable substance is released, there is a chance of a fire. To estimate the resulting heat flux, it is necessary to know the amount released as well as the process conditions, on which the physical phenomena and therefore the type of fire depend. The heat a fire generates is based on the heat of combustion and the burning rate, which vary for different types of fires. A static situation, with the shape and size of the fire constant, is assumed in the model.

3 types of fires are of interest for the chosen scenarios:

- Jet flame: burning rate = release rate (mass flow) of the flammable substance
- Pool fire: burning rate = evaporation rate from the pool
- Fireball: burning rate = (total amount of flammable substance / duration of the fireball)

For the listed fires heat radiation is the main type of heat transfer. The flames of a hydrocarbon fire consist of high-temperature combustion products with a radiation temperature between 800 and 1600 Kelvin.

For impinging fires (objects are engulfed by fire), which are not further covered, also heat transfer by convection and conduction through the vessel walls have to be taken into account. [1]

The most dangerous fires for humans develop whenever high amounts of various hazardous chemicals are released. The chemicals released and/or their combustion products might be toxic. Additionally mixtures of flammable gases make fires less predictable.

3.1.3 Flammability

A fire or an explosion is basically a chemical reaction, in which a substance reacts with oxygen and heat is released. The definition of a flammable substance is a substance that will react in the described way, if the boundary conditions allow it.

To start a fire a flammable material (solid) must be in contact with a heat source. In contrast to this, when fluids are heated they will form vapour clouds. Their flammability is primarily dependent on the temperature necessary to make them form a cloud of vapour-air mixture within its lower- and upper flammability limits. This cloud will ignite or - depending on the chemical - explode, the moment it gets in contact with a sufficient ignition sources.

Most substances do not form ignitable air/gas mixtures at normal or ambient temperature, but the few that do may suddenly ignite or explode. The necessary ignition energy for some of them is very small. As a consequence ambient temperature will rise and substances not ignitable at normal temperature will also ignite.

For a fire to start, it is necessary to fulfil the three factors of the fire triangle. The right amount of combustible material, oxidant (eg air) and energy (ignition source) have to be present. The flammability of a substance depends on its (auto-) ignition temperature, the lower- and upper flammability limit and the minimum ignition energy. [1] [2] [8]

3.1.4 Thermal radiation

Thermal radiation, also referred to as heat radiation or heat flux, is electromagnetic radiation generated by the thermal motion of charged particles in matter when the movement of charges is converted into electromagnetic radiation. The strength of the heat radiated depends on the temperature of the emitter (the object radiating the heat). Anything with a temperature over 0 Kelvin (no thermal motion taking place) radiates heat. Thermal radiation is a type of heat transfer that does not require any material to transmit heat – it also occurs in vacuum.

If a person is sitting close to a bonfire he or she will feel the heat even if the air between is cold. The level of thermal radiation decreases according to the inverse square law over distance, but solid barriers and clothing will reduce its strength noticeably. It is possible to obtain injuries (burns) by thermal radiation. The most common example is a sunburn. The severity of a burn depends on the dose, hence the strength of the source and the distance from it, wavelength and exposition time. [1]

Important parameters to estimate the resulting heat radiation on an object are: [1]

- Surface Emissive Power (SEP)
- View Factor (F_{view})
- Atmospheric transmissivity (τ_a)

The relationship between these factors is presented in **Formula (1)** [1], its result is the heat flux a receiver at a certain distance from a fire will be exposed to.

$$q'' = SEP_{act} * F_{view} * \tau_a \tag{1}$$

3.1.4.1 Surface emissive power (SEP)

The heat flux by radiation, hence the heat radiated outwards per surface area of the flame, is the **S**urface **E**missive **P**ower. It is measured in W/m^2 (= $kJ/(m^2*s)$).

Usually the heat radiated from a surface is calculated with the Stefan-Boltzmann equation, but for flames it is only of limited use. Firstly, it is difficult to calculate the temperature of the flame, which varies across its surface. Secondly the flame is generally not a black radiator with an emittance < 1. A flame is a very complex, three-dimensional heat radiator and the use of SEPs is a two-dimensional simplification.

If the emittance factor is set to 1, which means it is considered a black radiator, the calculated SEP_{theor} is the maximum heat flux achievable in theory.

SEP_{theor} can be estimated from the energy generated by the combustion per second, which is derived from the burning-rate, the heat of combustion of the substance and the surface area of the flame.

SEP_{max} can be calculated with SEP_{theor} by multiplying it with the fraction of the heat radiated. It is still a higher than the actual heat radiated from the flame surface. For further reductions additional, hardly available input (eg black smoke or soot produced by the flame) would be necessary. Experiments have shown that the emissivity decreases with an increase of the flame diameter. [1]

3.1.4.2 Fraction of the heat radiated

The factor F_s reflects the fraction of heat generated by combustion, which is emitted in the form of heat radiation. Its value varies depending on the type of fire and on the combusting substance. For some fuels SEP_{max} has been measured, for others it is necessary to select an estimated value for F_s. The Yellow Book [1] advises to choose the highest value according to literature for F_s for conservative results.

3.1.4.3 View factor

The view factor is a geometrical value which reflects the ratio between the emitted and received heat radiation. It depends on the size and shape of the flame on the one hand and on the position of the receiving object on the other.

For simplification purposes the flame shapes considered are only the most common ones. For a circular pool fire, the view factor of a cylinder, for a square or rectangular pool fire, the values for a flat plate will be taken into account. For a fireball the view factor of a sphere is a good estimation. If the influence of wind is considered, which makes the flames lean in a direction, the calculation has to be adjusted.

Basically the view factor considers the following factors:

- Shape of the flame or fire (influence of wind)
- Distance between receiver and emitter (outside surface)
- Orientation of the receiving surface (horizontal, vertical and maximum value) [1]

3.1.4.4 Atmospheric transmissivity

The atmospheric transmissivity takes the reduction of radiation due to absorbing properties of the air into account. In the wavelength spectrum of heat radiation there are two components responsible for the highest amounts of absorption: water vapour and carbon-dioxide, therefore the approximation presented in **Formula (2)** [1] can be made.

$$\tau_\alpha = 1 - \alpha_w - \alpha_c \qquad \textbf{(2)}$$

Both factors depend on the partial vapour pressure, the distance between emitter and receiver, the radiator (flame) temperature and the ambient temperature. For the amount of water vapour the relative humidity is a necessary input parameter. [1] [2]

3.1.5 Explosions

An explosion is a rapid release of a high amount of energy into the atmosphere. It results in a rise in temperature and/or in pressure. The severity of the explosion depends on the energy release rate. If the same amount of energy is released within a longer timeframe no explosion will occur. It can then be distinguished between deflagration (energy release slower than the speed of sound) and detonation (faster than the speed of sound and producing a blast wave). [8]

A characteristic of explosions is the blast. The pressure wave is caused by parts of the chemical energy being converted into mechanical energy. At atmospheric conditions, the theoretical maximum thermodynamic efficiency for conversion of chemical energy into mechanical energy is approximately 40%. This indicates that less than half of the heat produced by the combustion can be transmitted as blast-wave energy. [1]

Categorization of explosions depending on the type of energy: [2]

- Release of pressure energy (eg pressurized gas)
- Release of energy during phase transformation of an LPG
- Release of bound chemical energy (eg explosives, flammable gas, decomposition)
- Release due to rapid surface reactions (eg dust or vapour explosions, aerosols)
- Heat explosions (caused by eg runaway reactions)

Thermal radiation and over-pressure are the two main effects of any explosion. If the exploding substance is in some kind of containment, the container will be ripped into pieces and missiles will form. Depending on the speed of the expansion of the pressure wave effects will vary. Pressure waves will damage surroundings, crater might form and the shock waves will hit the ground.

A reliable calculation of the strength of an explosion is currently, even with complicated numerical methods, not always possible. In this thesis the method used to estimate the over-pressure is the rather simple and conservative equivalent TNT-amount model. [1] [2]

3.1.6 Equivalent TNT-amount

Effects of explosions depend on the energy released. The equivalent TNT-amount is introduced to give a comparable effect measurement for explosions. For instance the danger of a BLEVE with 100 kg of propane can be compared to a BLEVE involving 100 kg of acetylene. The calculation is based on the estimation of the quantity of TNT necessary to cause similar effects. The main factor of influence is the efficiency factor, which reflects the relation of any fuel ($\eta < 1$) to TNT ($\eta = 1$) in terms of explosion power. TNT is an explosive and has therefore fundamental differences in its effects. Its explosion is based on a special type of chemical energy release and a, for explosives typical, very short pressure wave. Nevertheless the equivalent TNT-model is commonly used to estimate explosion effects, due to its simplicity. Depending on the chosen literature, the amount of energy released by 1 kg of TNT varies from 4,190 kJ/kg to 4,681 kJ/kg. In this thesis 4,500 kJ/kg will be used, the same value as proposed in the Yellow Book [1]. [2]

3.1.7 Failure mode and release area

The substance release rate depends on the phase of the substance released (see 3.1.1, p. 5), the area of release (the size of the hole) and the difference in temperature and pressure compared to ambient conditions. For an estimation of the consequences of a substance release it is necessary to know the outflow rate. If the outflow is big enough to empty the container within 10 to 15 minutes, the leak will be treated like a full rupture. Only for smaller leakages or for continuous outflow after full rupture (eg pipelines) the outflow rate will be taken into perspective. [1]

It has to be distinguished between: [1]

- Leakage of a vessel
- Leakage of a pipe
- Full rupture of a vessel
- Full rupture of a pipe

Leakages are either caused by excessive stress on the components or by damage of them. The damage might occur due to corrosion, fabrication defects, mechanical or chemical weakening or destruction. Mechanical ruptures can be completely unexpected, such as a car crashing into a pipe.

Common areas of release: [8]

- Demolition of a pipe line or flexible line (likely at filling or discharging stations)
- Overfilling, overflowing or spilling of a transportation container
- Exhaust port of mechanical pressure relief facilities (eg safety valve)
- Malfunction, failure or leakiness of detachable connections (eg seal of a flange joint)
- Leakiness of vessels or pipes due to wall break

For feasible calculations the diameter of the leakage is necessary. This input value will often be estimated, which is not that simple. **Table 2** compares the size of the outflow to parts of the human body. A description of that type tends to be easier to estimate than a diameter in centimetres. The numbers are not exact though a practical and acceptable approximation.

Table 2: Rules of the thumb for leakage diameters and outflow [9]

Visible leakage size	Nominal diameter	Outflow - damaged seal/flange leakage	Outflow – pipe tear-off or vessel hole
Dropping leakage – controls and accessories, size can be ignored		-	1 l/min
As thick as a finger	DN 25-50	25-50 l/min	125-500 l/min
As thick as an arm	DN 80		1,300 l/min
As thick as an arm/a fist	DN 100	100 l/min	2,000 l/min
Comparable to a fist	DN 125		3,125 l/min
Comparable to a fist	DN 150		4,500 l/min

3.1.8 Source terms

Possible consequences of, for instance, worst case scenarios are usually known after the development of the safety concept of a site. However, the circumstances leading to the incident as well as the date and time of the accident can be considered unforeseeable. Source terms are the physical phenomena during the release of a substance, which have an influence on:

- The rate and/or duration of release (total quantity of the chemical released)
- The height of the source and the dimensions of the area affected by the release
- The thermodynamic state, concentration, pressure and temperature of the released substance
- The velocity with which the substance exits the area of release [1]

The wind velocity and the ambient temperature (examples of source terms) at the moment of release have a strong influence on the evaporation rate of a volatile fluid and therefore on how fast an explosive cloud can develop. [2]

In the prevention and the prohibition phase of hazardous events these factors are only assumed, based on the suggestions given in legal documents or literature. They are not supposed to be chosen randomly, but not every weather condition will be considered in detail.

When it comes to the calculation of effects, for source terms with little influence on the results or a high imprecision when estimated (eg wind velocity), only giving a limited number of default options would be an option. This generates an acceptable distortion of results, but without a wrong impression of precision.

3.2 Scenarios

In this chapter the selected scenarios and their effects are explained. Since this is still part of the theoretical background the descriptions are only theoretical. In chapter 4**.** Calculation models (p. 33) the formula and steps for calculations are presented. The scenarios have been chosen based on the main scenarios found in literature. Only models for flammable fluids and gases are covered. Fires and explosions involving explosives or solid state material (such as dust explosions) are not taken into account.

3.2.1 BLEVE and fireballs

BLEVE is an acronym for **B**oiling **L**iquid **E**xpanding **V**apour **E**xplosion. Depending on the literature selected there are slightly different definitions of what a BLEVE is.

The word BLEVE was introduced in 1957 and defined "*as the failure of a major container into two or more pieces, occurring at a moment when the containing liquid is at a point about its boiling point at atmospheric pressure*" [7] p. 157. The very basic definition is solely, what the word BLEVE indicates: A liquid, whose temperature is significantly above its boiling point at atmospheric pressure, will evaporate fast (due to a rupture) and have an explosion like effect. This caused by the sudden pressure drop and the consequent instant vaporisation of the substance.

The definition by Reid from 1976/80 describes a BLEVE as "*a sudden loss of containment of a liquid that is at a superheat temperature for atmospheric conditions.*" [7] p. 157. According to Reid, for a BLEVE not the boiling point at atmospheric pressure is relevant, but the superheat limit temperature. Due to the higher pressure inside the vessel, the normal boiling point temperature is not high enough to let the liquid vaporize.

The third definition of a BLEVE includes the presence of a flammable substance. Lewis (1985) suggested defining a BLEVE "*as a rapid failure of a container of flammable material under pressure during fire engulfment.*" This would likely result in an explosion followed by a fireball. [7] p. 157.

In this thesis the third definition is taken to describe a BLEVE. This means the presence of a fire or flammable substance is necessary, because to use the equivalent TNT-amount model the substance must be flammable.

Cause and process

The explosion is caused by the rupture of the container and the rapid vaporisation of the stored substance when released. The rupture can be caused by something hitting the vessel (possibly a missile of an exploding container close by or an exploding gas flask), material failure or a fire heating the container. A fire will weaken the material of the vessel walls and increase the temperature inside the container. As a consequence, the stored substance will start to vaporize and the pressure in the container increases. As long as the substance in the container is in liquid .state it will help cooling down the walls of the container. When more and more of it vaporizes this effect disappears. Due to the further increasing heat, loss of cooling power and increasing internal pressure the container will rupture at some point. This can be slowed down or even completely prevented by cooling down the container externally. For instance water can be sprayed on the container by automatic safety systems or by firefighters. A step-by-step description of a BLEVE is presented in **Figure 1.** [10]

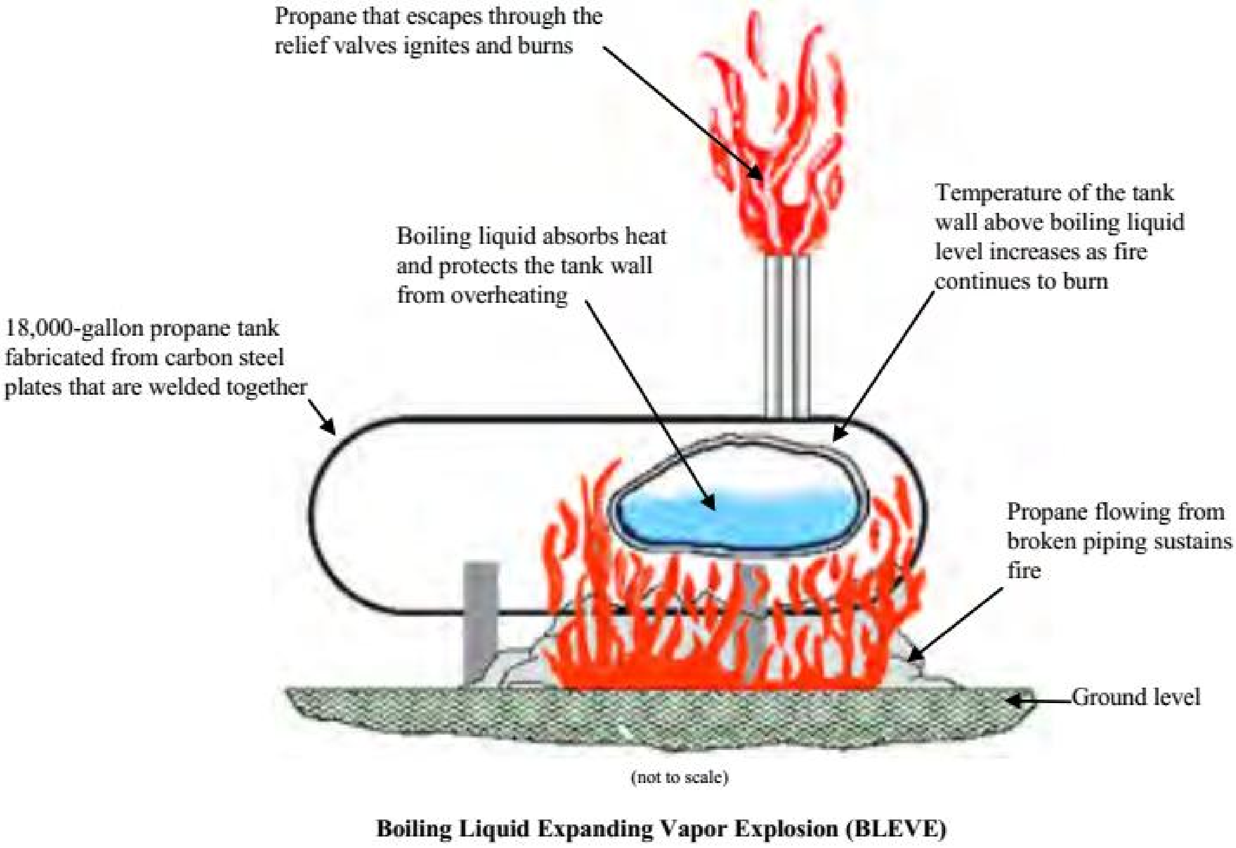


Figure 1: Description of the BLEVE at Herrig Brothers Creek Farm [5] p. 22

Steps leading up to the BLEVE at Herrig Brothers Creek Farm [5] p. 22

1. *After the piping is broken, propane begins leaking from the tank and flows along the ground surface.*
2. *Soon after ignition of the leaking propane, a fire burns out of control in the vicinity of the 18,000-gallon tank.*
3. *The fire heats the propane inside the tank, causing it to boil and vaporize.*
4. *The pressure inside the tank increases as the temperature of the propane increases.*
5. *When pressure inside the tank reaches about 250 psi, the relief valves opens to vent the tank. The propane escaping from the relief valves ignites and burns.*
6. *As boiling continues, the pressure inside the tank exceeds 250 psi, the temperature of the tank wall increases, and the strength of the steel used to construct the tank decreases.*
7. *At some point, the weakened steel can no longer resist pressure-induced forces inside the tank so the wall of the tank ruptures, allowing propane to escape rapidly into the surrounding atmosphere.*
8. *Immediately following rupture, the escaping propane ignites, resulting in an explosion that causes the tank wall to separate into at least 36 pieces. Fire quickly consumes the remaining propane.*
9. *Tank fragments are propelled at a high velocity in many different directions.*

Effect of a safety valve

A safety measure in the form of a relief valve is not sufficient to prevent a BLEVE. When the set pressure of the valve is reached, it will release the hot vapour and consequently decrease the liquid level in the vessel. The liquid left will vaporize exposing more and more area of the vessel wall to the fire without liquid cooling it. After some time the material will weaken and eventually rupture. Through the hole the overheated and over pressurized vapour escapes, leads to an explosion of the container and when ignited forms a fireball. A safety valve may only provide a longer time span until the BLEVE occurs, but does not prevent it. At the incident in Albert City, which is further described in chapter 5.1.1, the relief valve reacted after 10 minutes and 8 minutes later the BLEVE took place. The highest permitted response pressure of a safety valve is the highest allowed working pressure. [7]

Effects

The effects of the explosion are the blast wave and missiles - parts of the container flying in all directions. The blast and fragmentation effects, such as the size and speed of missiles, are a result of the energy released. They therefore depend on the temperature at rupture compared to ambient temperature and overpressure in the containment to ambient pressure. They also depend on the substance in the containment and its chemical and physical properties. If the temperature of the liquid rises over its superheating limit temperature, instantaneous boiling occurs and the fragmentation effects will increase. [10]

The bursting pressure depends on the reason for failure: [2] [7] p. 216-218

- Mechanical failure: working pressure
- Failure due to fire: 1.21 times the pressure of the safety valve
- Material failure of the container walls: about 2.5 times the pressure of the safety valve

Fireball

For a fireball to develop the substance released must be flammable. The harmful effects of a fireball depend on four characteristic values: [7]

- The size of the fireball (the surface area radiating heat)
- The height of the centre over the surface (the distance to objects affected)
- The duration of combustion (the lifetime of the fireball)
- The SEP of the fireball (the heat radiated per surface area)

From the resulting heat the distance can be derived at which the heat radiation is harmful to people, damages buildings or may cause consecutive BLEVEs.

Characteristics of a fireball are that the flammable substance is in the centre of the fireball, surrounded by a mixture of air and fuel whose ignition leads to the fireball. The ignition is followed by a rise in temperature, which makes the fireball float in the air. At the moment of ignition the fireball has usually almost spherical shape, which then, due to the rising, turns into a mushroom like shape. [10]

Compared to a fireball during a BLEVE, a fireball based on a vapour cloud is different. This is due to the fast vaporization and expansion in difference to a vapour cloud, which develops slower and has only a small concentration gradient. A vapour cloud will consist almost completely of vapour and mist - including a higher amount of ambient air. It is possible that a fireball during a BLEVE has very similar properties to a vapour cloud. For that the flammable substance must have enough time to mix with air. These kinds of fires are more likely to appear if the BLEVE is not caused by fire impingement but, for instance, by a mechanical rupture. [2]

"There is a much greater degree of uncertainty associated with predicting the consequences of BLEVEs than with predicting consequences of gas/vapour cloud explosions. This is because of the central roles played by superheated liquids and pressurized gases." [10] p. 158

The harmful effect of a fireball is heat radiation. The heat radiation is not consistent over the surface of the fireball, but usually a uniform heat radiation is assumed. Peak emissions come from the top of the fireball. The highest values of SEP are during the initial period then a gradual decrease can be noticed. SEPs measured for butane were usually between 300 and 350 kJ/m²s. At the top of the fireballs values up to 500 kJ/m²s have been measured. [1]

Time frame

The induction time of a BLEVE may range between a couple of minutes and a couple of hours. Cases have been documented in which the time between fire engulfment or damage of the container and BLEVE was about 24 hours. A couple of experiments have shown peak times within the first hour, often with a maximum likeliness after 10 to 30 minutes. It can be expected that the time will be shorter in case the vessel is not full. Nevertheless, the experimental data also show that rescue personnel should not feel safe, even if the tank did not rupture within the first hour. Only after 24 hours and if the situation is completely under control they may consider reducing the safety distance. Also, the first crack does not always lead to a BLEVE, since it may be too small. But after some time it can widen and cause a BLEVE. In experiments conducted in 1994 about 20% of BLEVEs took place in the first run, but did not happen immediately after the first crack. [10]

Available data

There is little experimental data available for BLEVEs. Simple up-scaling cannot be applied and these kinds of experiments are extremely expensive and dangerous. The literature sources used refer to the same couple of experiments. Most of which were conducted in the 1980s. Additional data can be derived from past hazardous events.

3.2.2 Jet fires

A jet fire is the result of a flammable gas with a perceivable momentum and direction, which is released continuously and results in a diffusion flame. [1]

Cause and process

The release can happen through small leakages in pipes or vessels, or a full rupture of a pipe. Depending on the boundary conditions, it results from a one- or two-phase flow. After release the gas will mix with air and ignite easily between the UFL and LFL. For big radii the release and expansion of the gas already produce enough energy for ignition. To identify the danger of a jet fire the substance, the process conditions and the size of the leak are necessary. They define the length and the direction of the flame. [1]

Effects

Jet fires radiate heat and can also directly affect an object when hitting it. Its most dangerous version is a jet fire in the horizontal direction due to the higher chances of direct impact on people or objects. Direct impact on people has usually fatal results, buildings will ignite and vessels under pressure hit by jet flames are likely to explode as a BLEVE.

In **Figure 2** the effect of an LPG jet fire on the structural support of a pipe bridge is presented. Jet fires can lead to rapid heating and exposed structural components may fail within minutes. Due to the early collapse of the bridge, the magnitude of the fire was increased greatly.

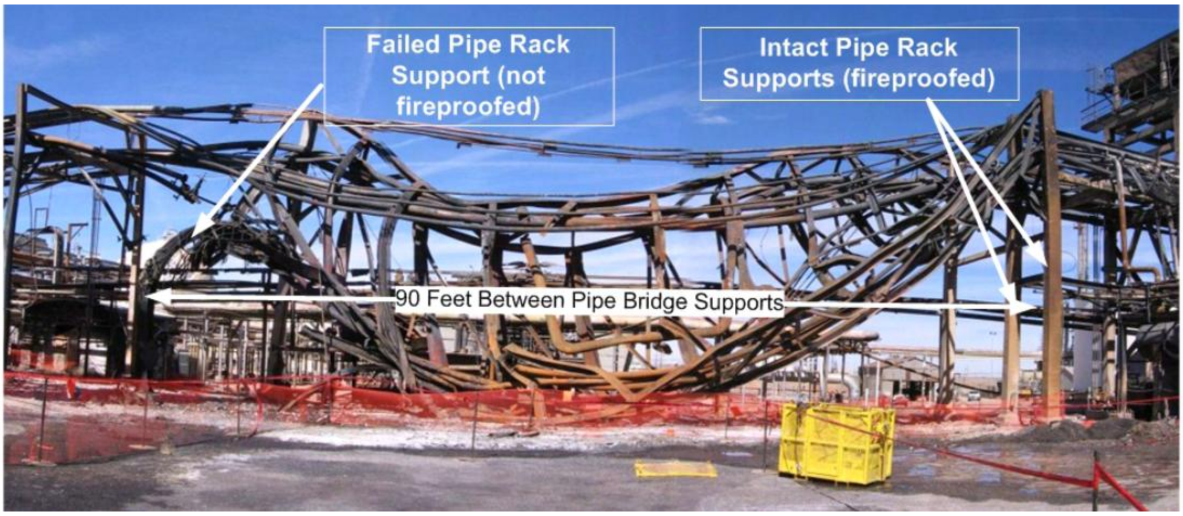


Figure 2: Effects of fireproofed and not fireproofed supportive structure [11] p. 30

Time frame

Big radii and high pressure jet fires will ignite immediately after release. Others will ignite as soon as a sufficient ignition source is present. The duration of the fire depends on the possibility to cut the gas source. It is not helpful to distinguish the jet fire, as long as its fuel source is not cut. Otherwise the flammable gas will spread, form a cloud and waits for the next ignition source. A burning gas is a gas slightly under control. [2]

One can distinguish between single point source models, consider the source of heat radiation to be a single point and multiple point source models, where the radiating points are considered to form a line in the centre of the flame, some of them take into account the flame geometry. In this thesis the surface emitter model will be used which assumes that the heat is radiated as if the envelope of the flame is a solid object. [1]

3.2.3 Pool evaporation and pool fires on land

Pool evaporation takes place whenever a fluid stored in liquid state is released and has the chance to form some kind of pool. The fluid will then vaporise to reach thermodynamic equilibrium with the ambient and turn into a pool fire if the vapour-air mixture above the pool is ignited. It is possible that the ignition does not take place immediately and a vapour cloud is formed instead, which may ignite later. [2] Vapour cloud fires and explosions are described in chapter 3.2.4.

Influence of the thermodynamic state of fluids on vaporisation rates

Either heat or mass transfer is the dominating factor influencing the speed of vaporisation. This depends on the substance forming the pool and the ambient temperature. In case the substance only evaporates, hence its vapour pressure is lower than ambient pressure. The evaporation rate reflects the difference between vapour pressure and partial pressure of the vapour in the air above the pool. The concentration gradient and therefore the speed of evaporation are influenced by the diffusion caused by wind. The vapour will mix with air and when the UFL and LFL are met and a sufficient ignition source is present, the vapour combusts. It is not the pool itself that burns, but the vapour just above it. Due to the heat of combustion and concentration gradient due to combustion even more of the flammable liquid will vaporise. The properties of the formed pool depend on the phase of the fluid released. [1]

Four situations can be distinguished: [12]

- Release of a substance liquid at ambient conditions
- Release of an overheated liquid
    - At ambient temperature and under pressure
    - At high temperatures and under pressure
- Release of a refrigerated liquefied gas at low temperatures and ambient pressure

Water is an example of the first type of fluid - a substance liquid under ambient conditions. When spilled, it slowly evaporates over time. The second type is a gas that has been liquefied by an enlargement of pressure. It will evaporate a lot faster, because its vapour pressure at atmospheric conditions is remarkably higher. [13] The third type is a fluid, which is in gaseous state at ambient conditions but has been stored at deep temperatures (refrigeration) to lower its vapour pressure and to store it as a liquid. It will also vaporise rapidly after release. For type two and three shortly after release the fluid is far away from the thermodynamic equilibrium with the ambient which triggers the fast vaporisation. The energy needed for the endothermic vaporisation process will cool down the rest of the fluid and force them to condense. The condensed part will rain down and form a pool. Afterwards the pool will also evaporate by using energy from its surroundings. [1]

Confined and unconfined pools

Besides the type of fluid, the ambient temperature and the mass transfer coefficient, the size of the pool surface is an essential parameter for calculating the vaporisation rate. Generally there are two types of pools: pools within bunds and without.

With bunds the size of the maximum surface area is clearly defined and it will not grow over time, except the containment is overfilled. This slows down the speed of evaporation, because the liquid cannot spread to minimum thickness. As a consequence the surface of the liquid is further away from the subsoil and the total surface of the pool is not as large as it could be, hence the energy transfer is slowed down. There is a bigger difference in temperature between the subsurface and the surface of the pool.

Without bunds, the size of the pool will grow until the whole fluid is released and has spread to its minimum thickness or until the speed of vaporisation and the release rate reach equilibrium. The minimum thickness depends on the surface the liquid is spreading on. For very smooth surfaces the expected thickness is around five millimetres, which increases up to a couple of centimetres for a very rough surface.

Pools can also form on liquids instead of solid subsoil. Depending on the fluids involved mixing will occur, the spilled substance will float on top or will sink. A typical example is an oil spill on a lake. This topic is not covered in this thesis. [1]

Effects

Dangerous effects are heat radiation from the pool fire, a pool fire impinging structure and causing BLEVEs or the formation of vapour clouds. Vapour clouds are able to move far away from the pool before ignition or explosion (or complete diffusion). How dangerous pool fires are, depends mainly on the released substance, its amount, its thermodynamic state before release and the size of the pool. Pool fires themselves are of comparably little danger. However, they might be the initial event leading up to a mayor incident. [1]

3.2.4 Vapour cloud fires and vapour cloud explosions

A vapour cloud fire is defined as the combustion of a flammable gas- or vapour-air-mixture, in which a flame moves through the mixture in a way that only a negligible, not damage causing overpressure is generated. A vapour cloud explosion (VCE) is defined by the additional generation of damage causing overpressure. [2]

Cause and process

For a VCE the release of a big amount of flammable vaporising liquid or gas is necessary. The source can be any kind of container: A vessel, a tank, a pipe. Usually the release happens over a longer time span, with no immediate ignition of the released gas. Gas or vapour will form a cloud and after ignition a vapour cloud fire will occur, an explosion will take place, or nothing happens. Vapour clouds are especially dangerous due to their ability of moving fast and probably unrecognized to populated areas or close to containers filled with hazardous substances. The minimum ignition energy is often very little. A hot surface may be sufficient for ignition. [1] [2]

When the ignition of a flammable cloud at rest occurs the consequence will only be a huge flash fire, but not an explosion. The mode of flame propagation is the key parameter whether the result is a flash fire, a deflagration or a detonation. The other, important factor of influence is turbulence. High turbulence will significantly enhance the combustion rate in deflagrations. The results of high flame speeds are higher blast pressures. Turbulence may be caused by the type of release, but also by the industrial installations the cloud gets in contact with. [1]

For an explosion to take place one of the following requirements has to be fulfilled: [2]

- A partly enclosure or/and obstacles
- The release takes place with a high initial energy
- The dispersion of the cloud is explosion like
- A high ignition energy is present

Time frame

The most likely timeframe for a VCE to occur is within the first 5 minutes after release. Though major incidents have also taken place with ignition delays of as little as a couple of seconds and higher than 30 minutes. [1]

Effects

A vapour cloud fire can be compared to a fireball and will radiate heat. A vapour cloud explosion will additionally cause a pressure wave. For both, a vapour cloud fire as well as a vapour cloud explosion, the consequences for someone standing in the cloud are likely to be fatal. Since they are able to move and often cover big areas. It is especially dangerous for workers who try to fix the leakage and underestimate the danger they are exposed to. [2]

3.3 Hazardous consequences of fires and explosions

There are two main effects due to fires and explosions: Heat radiation and pressure waves. Besides to process conditions and source terms, both are dependent on the type and amount of the substance involved. Both effects are distance and duration sensitive. In this chapter they are discussed with focus on those two factors.

After an accident, it is often hard to reproduce, how far from the explosion the individuals were standing the moment the pressure wave or the fireball occurred. It is also unknown how fast they managed to escape from the danger zone. In the event of an accident the main focus is on saving people and not on collecting data.

When someone with severe burns arrives at the hospital, it is not always obvious whether those are second or third degree burns. To obtain this information the person would have to be injured even more. Also, there is not much data available about the effects of explosions on the human body. The data existent is from real accidents and war scenarios (for instance effects of atomic bombs).[4]

3.3.1 Thermal radiation

Thermal radiation is a type of heat transfer which does not need any matter between the sender and the receiver. Its strength mainly depends on the temperature of the emitter, the distance to the receiver and the substances in-between. [1]

3.3.1.1 Harmful effects on the human body of thermal radiation

Burns are caused by direct or indirect contact with heat. Thermal radiation is an example of indirect contact. Burns can lead to cell death and depending on the severity even to fatality. The right treatment will soften the effects. However second and third degree burns can cause disability or lead to death. The severity of a burn depends on its depth and on its position on the body. [14] In **Table 3** the some guidance values for different types of burns are given. Depending on the exposition time the effects become more severe. This is reflected in **Table 4**.

Table 3: Guidance values for injuries caused by heat radiation [2] p. 627 after [12]

Effect	**Critical value in kJ/m²**
Critical value for pain, no redness or blister formation on the skin	65
1st degree burns	125
2nd degree burns	250
3rd degree burns	375

Table 4: Guidance values for injuries caused by heat radiation (time sensitive) [8] p. 411

Effect	**Critical heat flux in kW/m²**
Sun radiation in summer at noon	1.2
Max. radiation for an undefined time frame	< 1.3
Formation of blisters after 30 s (tolerable for 13 s)	5
Threshold of pain after 3 s Formation of blister after 10-12 s Fatality after 40 s	10.5

The highest heat flux that the skin can absorb without immediate harms is about 1 kW/m² according to the Green Book [14]. Even though no pain is felt, tissue damage might happen, if the exposure time is long enough. The highest temperature that an average person can tolerate for a longer period of time is about 45°C, without leading to a sensation of pain. [14]

Categorization of burns

Burns are categorised in two systems: depending on depth and depending on severity. It is possible to have more than one type of burn at a time.

Categorization of burns based on their depth [14] [15]:

- First-degree (superficial) burns: they only affect the outer layer of skin (epidermis, thickness about 0.07 to 0.12 mm). They cause pain, redness, swelling, dryness, but no blisters. Mild sunburn is an example. Long-term tissue damage is unlikely and if it occurs it will be visible by a slight change of skin colour.
- Second-degree (partial thickness) burns: affect the epidermis and parts of the underlying secondary skin layer (dermis, contains blood vessels, hair follicles and sweat glands, up to 5 mm thick, usually around 2 mm). They cause pain, redness, swelling, 'wet skin' and blistering.
- Third-degree (full thickness) burns: affect the deep layers of skin (hypodermis) and completely destroy the epidermis and dermis. They cause white, yellow or blackened, charred, burned skin. The skin may be numb (nerves are damaged) and is unable to heal itself. Third degree burns leave scars and may cause loss of function and/or sensation.
- Fourth-degree burns: These burns even affect the underlying bones, muscles and tendons. In the area of the burn there is no pain and feeling at all because the nerve endings are destroyed. They are not always considered as a separate category, but as parts of third-degree burns.

In **Figure 3** the different degrees of burnings and their effects on the skin are illustrated

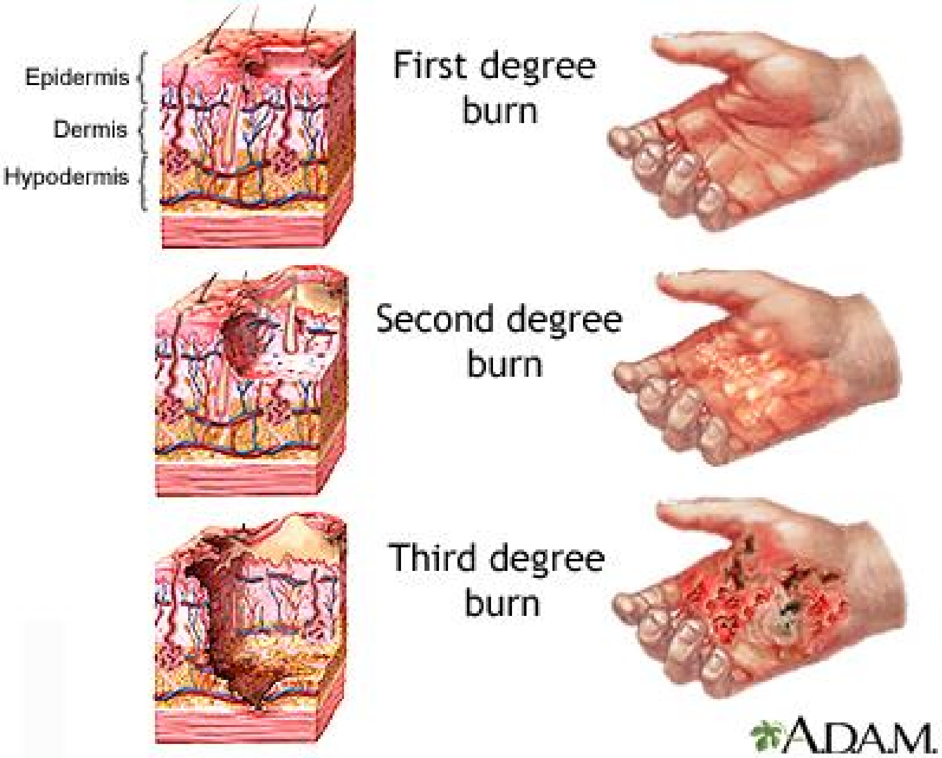


Figure 3: Different types of burns [15]

Categorization of burns depending on their severity: [16]

- Minor burns
    - First degree burns anywhere on the body
    - Second degree burns less than 5 to 7.5 cm wide
- Major burns
    - Third degree burns
    - Second degree burns more than 5 to 7.5 cm wide
    - Second degree burns on the hands, feet, face, groin, buttocks, or over a major joint

Severe burns need urgent medical care. This may prevent death, scarring, disability and deformity. Burns on the face, hands, feet, and genitals can be particularly serious. Depending on the total area burnt and the age of the person the theoretical chances of survival are defined. Very intense heat sources can lead to a carbonization (blackening) of the upper layers of skin, which then will protect the deeper layers. [16]

A person's skin changes depending on age. It is remarkably thinner for little children and people older than 60. As a consequence, they are more likely to suffer under complications or even die from severe burns. Additionally, it will take them longer to escape, which indicates a higher exposure time and as a consequence a higher severity of the burns. Children from 0 to 16 years and elderly people over 60 are considered critical groups. [4] [14]

Effects of clothing

Clothing will ideally protect a person from any harm or reduce the burning injuries caused by thermal radiation. This can be compared to sunburns – areas covered by clothing are less likely to get burnt. On the other hand, in the case of ignition, clothing can also radically increase the damaging effects of thermal radiation. Especially tights and any other material that has a low ignition point and or melting point are riskier for the wearer and will cause burn injuries of second or third degree. Some data say, that ignition of clothing is only fatal in 5% of the cases. Other reports suggest that the ignition of clothing leads to 100% fatality. The 5% rate was derived from hospital data, which is not only about burns and ignition caused by thermal radiation but any kind of burn. As a consequence of thermal radiation the use of a 100% fatality rate is reasonable to make conservative assumptions. [8] [14]

The protective (or harmful) effect of clothing depends on various factors. The humidity in clothing will reduce its resistance to heat because of the heat transfer of the hot water vapour. The layers of air between layers of clothing will have an additional, protective isolation effect. This topic will not be covered in detail because it cannot be influenced during an incident. The type of clothes worn by the workers is part of the safety concept of a company. [14]

3.3.1.2 Harmful effects on structure

A lot of data is available for critical values of heat radiation on different materials. But it has to be considered for which time span they are relevant. Pool fires or jet fires might burn for a longer time, but fireballs and VCEs are usually finished within a couple of seconds.

The possible damages have been divided into two levels: [14]

- Damage level 1: Ignition of surface, collapse of structural elements
- Damage level 2: decolourization of surfaces, deformation of structural elements

In **Table 5** the some guidance values for damages by thermal radiation are given. For exposure times over 30 minutes critical values, split by damage levels are given in **Table 6**.

Table 5: Guidance values for structural damage caused by heat radiation [2] p. 627 after [12]

Damage type and material	Critical heat flux in kW/m²
Parts of process plants are damaged	37.5
Auto-ignition of wood and textiles	35
Wire insulation melting	18-20
Plastic melting	12

Table 6: Guidance values for structural damage for exposition times > 30 min [14] p. 47

Material	Critical heat flux in kW/m²	
	Damage level 1	Damage level 2
Wood	15	2
Synthetic	15	2
Glass	4	-
Steel	100	25

3.3.2 Blast waves

A blast wave is a sudden release of energy in the form of pressure caused by an explosion.

3.3.2.1 Harmful effects on the human body

Explosions can injure a person, for instance by causing loss of hearing or an acoustic trauma. Its harmful effects can be reduced or even prevented by a fast and effective evacuation process. The effect of pressure waves strongly decreases with distance from the explosion. Blast lung is the most common fatal injury. For the definitions of the three risk zones the peak overpressure is used as the key parameters. In **Table 7** critical overpressure levels and their impact on humans are presented.

Table 7: Guidance values for injuries caused by blast waves [8] p. 416

Harmful effect	Overpressure in kPa
Uncomfortable bang at low frequency	0.15
Very loud bang	0.3
People will get knocked over	1
Critical value for injuries by missiles	1.5
Lower limit for eardrum ruptures	17.5
Lower limit for damage to the lung	85
Lower limit for severe damage to the lung	185
Fatality limit	205

The type and severity of an injury caused by the consequences of an explosion depend on the strength, the pressure wave of the explosion, the material, the delivery method, the surroundings and the distance to the exploding object. Especially whether the buildings collapse or are seriously damaged by the explosion influences the type of injury. Additionally, if the person hurt is in a heavily damaged building it will take rescuers longer to gain access and lowers the chances of survival. Blast injuries can be divided into four main categories, depending on the actual cause as presented in **Table 8**.

Table 8: Categorization and examples of injuries due to blast waves [17] p. 3

Category	Characteristics	Body part affected	Examples of injuries
Primary	Results from the impact of the overpressure wave on body surfaces.	Gas filled structures are most sensitive	Blast lung Eardrum rupture or middle ear damage Abdominal bleeding and perforation Globe (eye) rupture Concussion (without physical signs of head injury)
Secondary	Results from flying debris and bomb fragments	Any body part may be affected	Penetrating ballistic (fragmentation) or blunt injuries Eye penetration (can be occult)
Tertiary	Results from individuals being thrown by the blast wind	Any body part may be affected	Fracture and traumatic amputation Closed and open brain injury
Quaternary	All explosion related injuries, illnesses, or diseases not due to the other 3 mechanisms	Any body part may be affected	Burns Crush injuries Closed and open brain injury Asthma or other breathing problems from dust, smoke or toxic fumes

3.3.2.2 Harmful effects on structure

Damages to cars, car tyres and windows can be used as visible pressure indicators (see **Table 9**). For instance, polymer deformation of a car indicates a certain overpressure and emergency personnel can use what they see, to understand where the critical zones begin. Trees and traffic lights might be bent and can be used to identify the direction of the maximum pressure wave.

Table 9: Guidance values for structural damage caused by blast waves [8] p. 417

Description of damage	Overpressure in kPa
Damage to windows, doors, roofs	0.5
Minor damage to structure	3.5
Destruction of roofs and walls of wooden houses	6
Deformation of steel-plates	7.5
Demolition of masoned walls	10
Rupture of oil tanks	21.5
Destruction of cars (strong deformation)	34
Almost complete destruction of common buildings	40
Destruction of steel-walls	70

3.3.3 Evacuation behaviour and critical groups

How much time a person needs to escape is not clearly defined. Suggested velocities vary from 2.5 to 6 m/s for an average person and goes down to 1 m/s for vulnerable populations. One study has shown that a person usually requires at least 5 seconds to react and, after that, can cover a distance of 30 metres per 5 seconds to get away from the fire. These values can be taken as a representation of the ideal evacuation behaviour. [4] [14]

Vulnerable population and risk groups

A ‘vulnerable population’ is defined as one that includes people who may not respond effectively to evacuation procedures in an emergency. The ability to find or move to a protected area is important, as well as the general sensibility to heat radiation. Due to their skin properties, little children and elderly people suffer under more severe burns faster. Besides them, there are also other risk groups. They are used to define critical buildings. [4]

Risk groups [14] p.31:

- *People who are treated in hospitals, nursing homes, etc.*
- *Residents of houses for old-age people*
- *Children in schools*
- *Vacationers on beaches or in campings*

Effects of burning injuries on evacuation behaviour

Individuals suffering from pain or first degree burns will leave the critical areas themselves as fast as possible. Therefore, those distances are only critical for babies, children, elderly people or other individuals who are unable to escape themselves.

Second degree burns indicate temperatures where it is painful to touch surfaces such as handles, opening doors, etc. Those levels can be already risky for a healthy adult, because escaping without help is difficult.

Third degree burns cause pain and indicate surroundings that make it impossible for individuals to escape to safe areas. [4] [14]

3.3.4 The three risk zones

The output from the proposed calculation models will be used to define distances from the fire/explosion with harmful effects. This is done by comparing values for heat radiation and peak overpressure to critical values for human health and structural damages.

The main idea of this thesis is to keep things simple; especially the outcome of the calculations should be easy to understand. For this reason three risk zones have been defined. The chosen colours are Red – Orange – Yellow. Each of these colours gives some natural feeling of being in an unsafe or risky area. A safe (green) zone is not defined. Everything behind the yellow zone is left as an area with low, but undefined danger. The exact values where the line between the zones is drawn are presented in **Table 10**.

Table 10: Critical values selected for the definition of the risk zones [2] p. 628-629 and [14] p. 47

Colour of the zone	Heat radiation in kW/m²	Fireballs in kJ/m²	Overpressure in kPa	Description
Yellow	1.6	125	2	Reversible consequences
	2		3.5	(Structure: Minor damage)
Orange	3	200	5	Irreversible consequences
	12		17	(Structure: Moderate damage)
Red	5	350	14	Possibility of fatality
	35		35	(Structure: Heavy damage)

The Red Zone marks the most dangerous area, the zone closest to the fire/explosion. It is in the circumference where fatal injuries and collapsed walls can be expected.

The Orange Zone is still dangerous, the people there are likely to be hospitalized, but it is rather unlikely that a healthy person gets fatally injured there. More vulnerable people are still at risk of dying in this zone. About 2% of patients with only second-degree burns die. [4]

As a consequence in this thesis the zone where only second degree burns are expected will be considered critical but not fatal.

The Yellow Zone is primarily dangerous for vulnerable population and risk groups, such as children or people who are unable to flee. However, if the evacuation is conducted within a certain time frame, fatalities are unlikely. Hence, even if the third zone is not too dangerous for an average, healthy person choosing green would give a wrong impression of safety.

4 Calculation models

This chapter presents simplified models to calculate the consequences of the described scenarios. The intended output of the calculations is the thermal radiation, the expected blast wave and any other easily available value to better define the risk zones.

Calculations are offered in a step by step description and where necessary further explanations are provided. The “List of symbols” can be found at the very beginning of this thesis on p. XVII. For some calculations additional input values are provided in the tables.

The models presented in this chapter are mainly taken from models selected in the Yellow Book [1], but were compared to and complemented by input from other literature sources. The Yellow Book [1] provides a wide overview of different calculation methods and models. Only a few models, which were chosen with focus on a high degree of validation against experimental data and based on their complexity, are described in detail.

All calculation models presented in this chapter are non-iterative, often empirical and always comparably simple. This approach has been chosen because detailed simulations take longer and depend on many, often hardly available input parameters. They may give the false impression of creating facts rather than assumptions.

The biggest differences concerning the output of the selected models compared to more complex models appear in the first minutes of the release, when the conditions are non-stationary. For rescue teams it does not make a difference whether a vessel empties within 30 or 50 seconds after a full rupture. A detailed simulation of the first 5 minutes is therefore not necessary. Time frames starting from 10 to 20 minutes are more reasonable. [1]

Input data and considered source terms

The aim is to use as little input data as possible to receive a reasonable output. In **Table 11** the parameters required for the different scenarios are listed. If the substance is known, then its density, its heat capacity et cetera does not have to be provided. It is assumed that those values are easily available or already stored in the background.

If more than one value is in a row, the input value can be chosen. For instance, if the substance and the phase are known it does not matter if the mass or the volume released is communicated. The parameters in gaps can be calculated. However, it is helpful to have the real value.

Table 11: Necessary input parameters for the different scenarios

Category	Symbol	Unit	Description	BLEVE	Jet fire	Pool fire	VCE
Basic			Substance and phase	x	x	x	x
	x_{42}	m	Distance from the fire/explosion	x	x	x	x
Ambient	T_0	K	Ambient temperature	x	x	x	x
	φ	%	Relative humidity	x	x	x	x
	u_w	m/s	Wind speed			x	
Process	T_{init}	K	Initial temperature	x	x		x
	P_{init}	Pa	Initial pressure		x		
Total Amount	m	kg	Mass of the substance	x	x	x	x
	V_{out}	m^3	Volume of the substance				
	V_{rel}	m^3	Max. Volume released				
	V_{tank}	m^3	Volume of the tank				
	f	%	Fraction of the tank filled				
Leak rate	m’	kg/s	Mass flow rate		x	x	x
	V’$_{out}$	m^3/s	Volume flow rate				
Leak size	A_{out}	m^2	Area of the leak		x	x	x
	d_{out}	m	Diameter of the circular leak				
Time	t_{ex}	s	Exposition time		x		

	t_{out}	s	Time of release		x	x	x
	t_{vap}	s	Time of evaporation			x	x
Pool	A_p	m²	Surface area of the pool			x	x
	D_p	m	Diameter of the pool				
	S_p	m	Pool perimeter (confined pool)			x	x
Geometrics	Θ	°	Angle of the flames		x	x	

4.1 BLEVE

The defining part of a BLEVE is the explosion of a container filled with flammable liquefied gas. This happens when the pressure inside rises due to a rise in temperature to a limit the container cannot withstand or due to rupture caused by mechanical damage. The effects of a BLEVE are a blast wave, missiles and thermal radiation in case a fireball forms.

4.1.1 Calculation of the heat radiated by the fireball

If a BLEVE takes place and the involved fluid is flammable, a fireball will form. Fireballs not resulting from BLEVEs have some different properties, for instance concerning the concentration gradient in the vapour-air mixture. The model for calculating the heat flux/SEP is the same as for both, vapour clouds and BLEVEs. The primary harmful effect of a fireball is the heat radiation. It can hurt people, damage structure or containers and even lead to auto-ignition. [2] In **Table 12** additional constants necessary to calculate the properties of a fireball are offered.

Table 12: Constants for the calculation of the size and duration of a fireball [2] p. 520 after [12]

Model	Substance	c_1	n_1	c_2	n_2
1	Propane	2.78	0.333	–	–
2	Hydrocarbons	3.18	0.325	2.57	0.167
3	n-Pentane	2.63	0.314	1.07	0.181
4	Hydrocarbons	2.90	0.333	0.45	0.333
5	Propane	2.94	0.333	1.09	0.167

6	Butane	2.86	0.333	0.45	0.333
7	Hydrocarbons	2.67	0.327	0.923	0.303
8	LPG	3.24	0.325	0.852	0.26
9	Hydrocarbons	2.75	0.333	0.38	0.333

Step 1 - Calculation of the mass released in case of total failure

First the released mass of the substance has to be calculated if it is not directly provided. Usually at least 0.1% of the liquefied gas are in the gas phase to better withstand changes in temperature. Since the input given may not be that exact and this is a conservative calculation, it will be treated as if it were 100% in liquid state. **Formula (3)** [1].

$$m = V_{rel} * \rho_l = V_{tank} * f * \rho_l \qquad \textbf{(3)}$$

Step 2 - Calculation of the radius of the fireball

There are different values for the constants c_1 and n_1 suggested in **Table 12**, but the basic equation is the same. The chosen values for c_1 and n_1 are based on the Model 8 and are the same as selected in the Yellow Book, [1] p. 6.91. **Formula (4)** [1].

$$r_{fb} = c_1 * m^{n_1} \qquad \textbf{(4)}$$

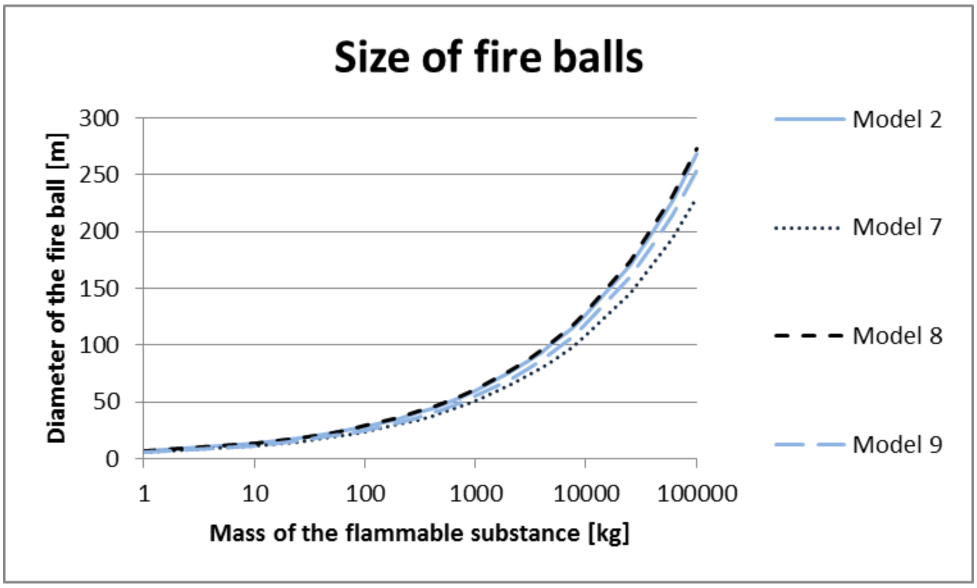


Figure 4: Influence of the constants from **Table 12** on the size of the fireball [2]

Step 3 - Calculation of the combustion duration of the fireball

The heat radiated by a fireball depends on its lifetime, the combustion duration. As shown in **Table 12** depending on the source there are different values for the constants suggested, but their relation to the basic equation is the same. The selected values are based on Model 8. **Formula (5)** [1].

$$t_{fb} = c_2 * m^{n_2} \tag{5}$$

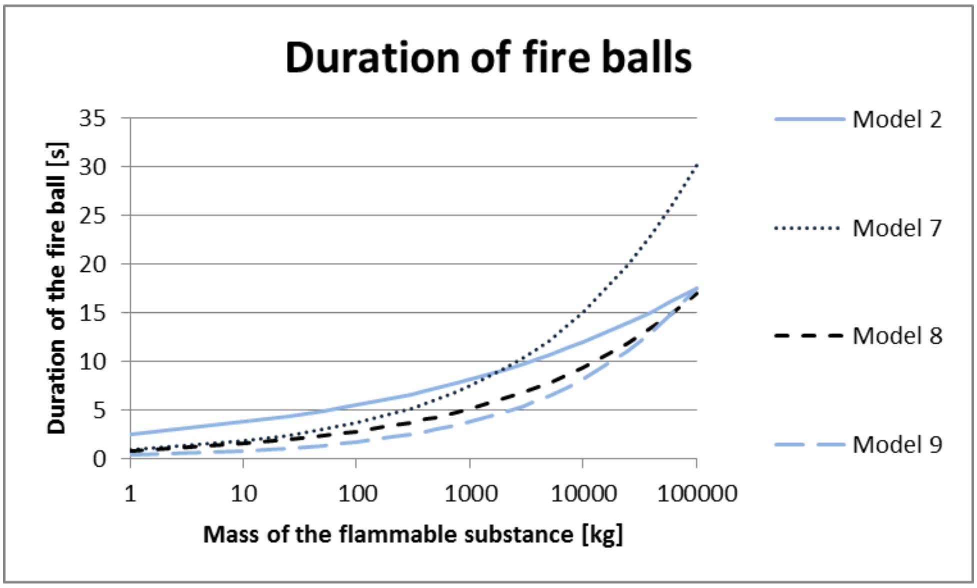


Figure 5: Influence of the constants from **Table 12** on the duration of the fireball [2]

Step 4 - Lift-off height of the fireball

The lift-off height of the fireball is the height in which the fireball is floating in the air. This value influences the distance to objects on the ground and therefore the strength of heat radiation received. It only depends on the radius of the fireball. **Formula (6)** [1].

$$H_{bleve} = 2 * r_{fb} \tag{6}$$

Step 5 - Distance from the centre of the fireball to an object

A fireball usually floats and as a consequence the distance from the centre of the fireball to some object is not the same as if it was on the ground. The relation between these geometric variables is simply based on the theorem of Pythagoras' as visible in **Figure 6.** The names of the variables have been changed to prevent confusion whether x or X is used in a formula.

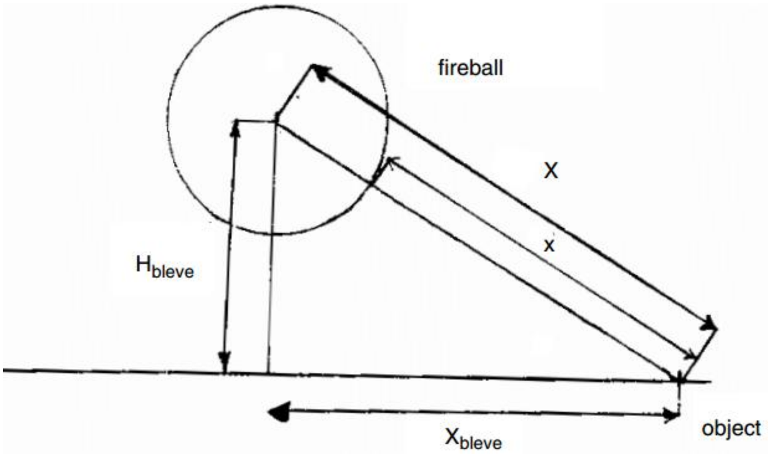


Figure 6: Distances from the centre of the fireball to the object after lift-off [1] p. 6.92

with $X_{bleve} = x_{42}$, $X = X_{centre}$ and $x = x_{fb}$

$$X_{centre} = \sqrt{{x_{42}}^2 + {H_{bleve}}^2} \tag{7}$$

Step 6 - Calculation of the actual path length between the surface of the fireball and the object

In **Figure 6** another geometric value is pictured: x (= x_{fb}). x_{fb} is the distance between the surface of the fireball and the selected object.

$$x_{fb} = X_{centre} - r_{fb} \tag{8}$$

Step 7 - Calculation of the view factor

The view factor is a geometrical value that reflects the reduction of the heat radiation due to the distance from the fire and it's the shape. **Formula (9)** [1].

$$F_{view} = \left(\frac{r_{fb}}{X_{centre}}\right)^2 \tag{9}$$

Step 8 - Calculation of the fraction of the generated heat radiated by the fireball

The factor F_s reflects the fraction of heat generated by combustion, which is emitted in the form of heat radiation. This factor reduces the total energy generated to the amount emitted as heat radiation. It depends on the type of fire and the substance. **Formula (10)** [1].

$$F_s = 0.00325 * P_{sv}^{0.32} \tag{10}$$

Step 9 - Calculation of the net heat available heat for radiation

This step can be skipped if necessary because it has little influence on the output. Instead of ΔH_{fb} just ΔH_c can be used, a slightly higher value. **Formula (11)** [1].

$$\Delta H_{fb} = \Delta H_c - \Delta H_v - c_{pg} * \Delta T_{fb} \tag{11}$$

ΔT_{fb} represents the temperature difference between flame and ambient. In the Yellow Book [1] it is recommended to assume 1700 Kelvin as an approximation. The real temperature of the flame is difficult to obtain.

Step 10 - Calculation of the surface emissive power

The surface emissive power depends on the net heat released by combustion, the fraction of the heat radiated and the surface area of the fireball. **Formula (12)** [1].

$$SEP_{act} = \frac{\Delta H_{fb} * m * F_s}{4 * \pi * r_{fb}^2 * t_{fb}} \tag{12}$$

Under the assumption of no soot formation ($SEP_{act} = SEP_{max}$)

Step 11 - Calculation of the transmissivity

The transmissivity reflects the reduction of the radiation due to the effects of the air between the radiated object and the fireball. **Formula (13)** [2] is only applicable if the relative humidity φ is ≥ 20%.

$$\tau_a = 0.4343 * ln\left(14.1 * (\varphi * 100)^{-0.108} * {x_{fb}}^{-0.13}\right) \tag{13}$$

Step 12 - Calculation of the heat flux at a certain distance from the centre of the fireball

The heat flux at a certain distance is the radiated heat reduced by the radiation that gets lost on the way from the emitter to the object. **Formula (14)** [1].

$$q'' = SEP_{act} * F_{view} * \tau_a \tag{14}$$

The thermal radiation of BLEVE fireball exceeds the radiation of normal flame emissions. [7] It is estimated that there is a maximum radiation value for fireballs of 450 kW/m². Experiments have shown that a reduction of emissive power occurs with an enlargement of scale. [10]

The result of this model is q'' in kJ/m²*s. The risk zones depending on the heat flux are presented in **Table 10** on p. 31.

4.1.2 Calculation of the peak over-pressure (TNT-equivalence model)

The equivalent TNT-amount model is very simple and can be used for a BLEVE as well as for a VCE. It converts the heat of combustion heat of the fuel into an equivalent charge weight of TNT. The factors of influence are the chosen combustion heat of TNT and the efficiency factor which reflects the different properties of explosives to other flammable substances. [2]

Step 1 – Calculation of the equivalent mass of TNT

The released heat in the selected combustion process is put in relation to the energy released by TNT. **Formula (15)** [1].

$$m_{TNT} = m \ * \eta * \frac{\Delta H_c}{E_{TNT}} \tag{15}$$

The efficiency factor reflects the explosive power of any fuel (η < 1) to TNT (η =
1). Depending on the substance and the considered literature different values are chosen for different substances. In **Table 13** selected values for certain substances are offered.

Table 13: Different values for η for selected substances [1] [13] p.154

Substance	η
Acetone, butadiene, propane	0.003
Cyclohexane, ethylene, propylene oxide	0.06
Acetylene, ethylene oxide, hydrazine	0.19
Other substances	0.04; 0.1 or 0.2

Step 2 – Calculation of the scaled distance from the explosion

The distance of the object to the explosion has to be put in relation with the TNT equivalent. **Formula (16)** [2]

$$r'_{TNT} = \frac{x_{42}}{m_{TNT}^{\frac{1}{3}}} \tag{16}$$

Step 3 – Calculation of the peak over-pressure

To define the risk zone of a pressure wave, the maximum explosion-overpressure is an important indicator. **Formula (17)** [2] is based on the Marshall-Diagram and easier to use for calculations. For pressures exceeding 620 kPa the diagram is not defined. But since the fatality rate at 620 kPa is 100%, this is not relevant. [2]

$$p_{TNT} = 159.5077 * \frac{\left(808 * \left(1 + \left(\frac{r'_{TNT}}{4.5}\right)^2\right)\right)}{\sqrt{\left(1 + \left(\frac{r'_{TNT}}{0.048}\right)^2\right) * \left(1 + \left(\frac{r'_{TNT}}{0.32}\right)^2\right) * \left(1 + \left(\frac{r'_{TNT}}{1.35}\right)^2\right)}} \tag{17}$$

The result of this model is p_{TNT} in kPa. The risk zones depending on over-pressure are presented in **Table 10** on p. 31.

4.1.3 Additional calculation of safety distances for BLEVEs

A few estimations have been made on a how far away from the container firemen should be standing to not get injured when a BLEVE takes place. The safety distance is derived from the radius of the potential fireball and is therefore dependent on the substance and mass. The calculation is really simple, which makes it very useful for quick estimations. However, the minimum distance should always be at least 90 metres for firemen. [10] The radius of the fireball has to be calculated according to **Formula (4)**.

Safety distance for firemen [10]

$$x^*_{min} = 4 * r_{fb} \tag{18}$$

Safety distance for other people [10]

$$x_{min} = 30 * r_{fb} \tag{19}$$

For vessels with volumes > 5 m^3 the factor 15 instead of 30 is recommended due to scale effects and prevention of an overestimation.

4.2 Jet fires

A jet fire needs a continuous source of fluid, which ignites and forms a flame with a defined momentum and direction. In the Yellow Book [1] the so-called “Thornton-model” was selected for the calculation of jet fires due to its validation against large scale experiments and acceptable computational effort. The flame is represented by the frustum of a cone, with the radiation properties of a solid body. The SEP can be considered uniform for the relevant flow and ambient conditions. [1]

4.2.1 Calculation of the heat radiated by the jet fire

The heat radiated by the jet fire is correlated to the heat of combustion of the flammable gas, the amount of substance, the fraction of heat radiated and the view factor. Also whether the outflow is critical or not has to be considered. For critical outflow, the mass flow rate is not dependent on the pressure ratio. It is basically the same calculation as for a BLEVE fireball, but with differences concerning F_{view} and F_s. F_{view} depends on the shape, size and angle of the flame, F_s depends, besides other factors, on the exit velocity of the expanding jet.

Step 1 – Determination of the mass flow (gaseous state)

The mass flow of the released substance is necessary to calculate further properties of the jet flame. If the mass flow is not known, especially if it is just a leakage and not a full rupture, it can be calculated according to **Formula (20)**. [1].

$$\mathrm{m}' = c_{dis} * A_{out} * \psi * \sqrt{\rho_{init} * P_{init} * \gamma * \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{20}$$

With

$$A_{out} = \left(\frac{d_{out}}{2}\right)^2 * \pi \tag{21}$$

The value of the c_{dis} depends on whether the edges of the hole are sharp (c_{dis} = 0.62) or round (c_{dis} = 0.95-0.99). Since this detail is unlikely to be known, the maximum value (c_{dis} = 0.99) should be used. [1]

The value for the ψ depends on if the outflow is critical or not. If **(22)** is true the outflow is critical. When that is known, ψ^2 can be calculated and ψ can be derived.

$$\frac{P_{init}}{P_0} \geq \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \approx 1.89 \quad (for\,\gamma = 1.4) \tag{22}$$

For critical outflow: [1]

$$\psi^2 = 1 \tag{23}$$

For sub-critical outflow: [1]

$$\psi^2{}_{sub} = \frac{2}{\gamma-1} * \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} * \left(\frac{P_0}{P_{init}}\right)^{\frac{2}{\gamma}} * \left(1 - \left(\frac{P_0}{P_{init}}\right)^{\frac{\gamma-1}{\gamma}}\right) \tag{24}$$

For sub-critical outflow the driving force is the pressure difference between inside the container and the ambient. $\psi^2_{sub} < 1$. The bigger the difference is the faster the fluid will leave the container. This effect stops at critical outflow. In most cases P_{init} will bigger than two times P_0, hence the outflow will be critical.

Step 2 – Calculation of the critical temperature

In [8] it is mentioned, that the formula of the so-called Chamberlain model the way they are presented in the Yellow Book [1] are not in compliance with the original model. Instead the following formulas are given: [8]

$$T_c = \frac{2 * T_{init}}{1+\gamma} \tag{25}$$

Step 3 – Calculation of the critical pressure [8]

$$P_c = 3.6233 * \frac{m'}{d_{out}^2} * \sqrt{\frac{T_c}{\gamma * MM}} \tag{26}$$

Step 4 - Determination of the Mach-number of an expanding jet

The Mach-number reflects the ratio between the velocity of the flow (the released gas) to the surrounding fluid (air)

Mach-Number for super-critical flow ($P_c > P_0$) [8]

$$M_j = \sqrt{\frac{(\gamma+1) * \left(\left(\frac{P_c}{P_0}\right)^{\frac{\gamma-1}{\gamma}} - 2 \right)}{\gamma - 1}} \tag{27}$$

For sub-critical flow the Mach-Number is defined as [8]

$$M_j = \sqrt{\frac{\sqrt{1 + 2 * (\gamma - 1) * F_j^2} - 1}{\gamma - 1}} \tag{28}$$

With [8]

$$F_j = 3.6233 * 10^{-5} * \frac{m'}{d_{out}^2} * \sqrt{\frac{T_{init}}{\gamma * MM}} \tag{29}$$

Step 5 – Calculation of the temperature of the jet after release [8]

$$T_j = \frac{2 * T_{init}}{2 + (\gamma - 1) * M_j^2} \tag{30}$$

Step 6 – Calculation of the density of the jet after release [8]

$$\rho_j = \rho_{init} * \frac{273.15}{T_j} \tag{31}$$

Step 7 – Determination of the exit velocity of the expanding jet [8]

The exit velocity of the jet is necessary to determine the fraction of heat radiated.

$$u_j = M_j * \sqrt{\gamma * R_c * T_j} \tag{32}$$

Step 8 - Calculation of the surface area of the flame

Ideally the dimensions of the jet fire (diameter, length) are provided as input parameters. If not, the length and the diameter of the jet flame have to be calculated before the surface area can be determined. According to [2] the following formulas are only meant for natural gas, but it is assumed that they are an acceptable approximation for other substances.

For jet fires of natural gas very simplified formula are provided in [2]

$$l_j = 9.1 * \sqrt{m'} \tag{33}$$

And for the diameter at the tip [2]

$$d_j = 0.5 * l_j \tag{34}$$

After determination of the approximate diameter and the length of the flame, it is possible to calculate the area of the jet flame based on the shape of a cylinder.

$$A_j = 2 * \pi * \left(\frac{d_j}{2}\right) * \left(\frac{d_j}{2} + l_j\right) \tag{35}$$

Step 9 – Calculation of the rate of net heat released

The rate of heat released during combustion depends on the heat of combustion and the mass flow. [1]

$$Q' = m' * \Delta H_c \tag{36}$$

Step 10 - Determine the fraction of heat radiated from the surface of the flame

For jet fires the relationship between the fraction of heat radiated and the type of fire only depends on the exit velocity of the jet. [1]

$$F_s = 0.21 * e^{-0.00323 * u_j} + 0.11 \tag{37}$$

Step 11 – Calculation of the surface emissive power

The SEP can be calculated with the net heat released from combustion of the flammable gas, the fraction of that part of the heat radiated and the surface area of the cylinder. [1]

$$SEP = F_s * \frac{Q'}{A_j} \tag{38}$$

Step 12 - Calculation of the view factor

The view factor is calculated the same way as for a pool fire. The shape is similar and the angle due to the deformation by wind is considered. The steps for calculation are presented in chapter 4.3.2., p. 50.

Some of the variables used in the description for pool fires have to be exchanged for a jet fire. In **Figure 7** on p. 52 the following variables have to be exchanged:

$L_f = l_j$; $R = d_j/2$; $X = x_{42}$ applies.

For formula **(57)** to **(68)**

$l_p = l_j$; $d_p = d_j$;

Step 13 - Calculation of the transmissivity

The transmissivity reflects the reduction of the radiation due to the effects of the air between the radiated object and the flame. [2]

$$\tau_a = 0.4343 * ln\left(14.1 * (\varphi * 100)^{-0.108} * \left(x_{42} - \frac{d_j}{2}\right)^{-0.13}\right) \tag{39}$$

With the relative humidity $\varphi \geq 20\%$

Step 14 - Calculation of the heat flux at a certain distance

Under the conservative assumption there is no soot formation and $SEP_{act} = SEP_{max}$ applies. [1]

$$q'' = SEP_{act} * F_{view} * \tau_a \tag{40}$$

The result of this model is q'' in kJ/m^2*s. The risk zones depending on the heat flux are presented in **Table 10** on p. 31.

4.2.2 Calculation of distances with high chances of fatalities (natural gas)

This simple calculation of the risk zones of jet fires depends only on the exposure time and the mass flow as input parameters. The formulas **(41)** to **(44)** are exclusively valid for natural gas. Jet fires are likely to appear in combination with natural gas anyway. The jet is considered to be horizontal. Depending on the position of the person towards the flame (parallel/in front) different factors have to be used. r_{50} stands for the distance with a 50% probability of fatality. r_1 for distances with a 1% probability of fatality.

For positions in front of the flame [2] - edited

$$r_{50} = 1.6 * t_{ex}^{0.4} * (m')^{0.47} \tag{41}$$

$$r_1 = 2.8 * t_{ex}^{0.38} * (m')^{0.47} \tag{42}$$

Formula **(41)** has been edited in comparison to [2] and [12], because the result would have given a lower probability of fatality for a person standing closer to the jet. Hence, there must have been an error. It has been assumed, that instead of “16” the factor “1.6” has to be used.

For a parallel position to the jet fire [2]

$$r_{50p} = 1.9 * t_{ex}^{0.4} * (m')^{0.47} \tag{43}$$

$$r_{1p} = 2.8 * t_{ex}^{0.38} * (m')^{0.47} \tag{44}$$

Formula **(41)** to **(44)** are only valid for $1 < m' < 3000$ and $10 < t_{ex} < 300$ s

4.3 Pool evaporation and pool fires on land

A pool can be formed from fluids in liquid or gaseous state at ambient conditions. This determines, whether they form a boiling or non-boiling pool, which has a major impact on the time it takes the fluid to vaporise.

In this chapter fluids are covered that form pools for at least a relevant amount of time, hence the comparably slow evaporation process of non-boiling, pools and pool fires will be covered. The heat flux of selected boiling and non-boiling liquids are listed in the **Table 15** and **Table 16**. For boiling liquids the evaporation speed can be neglected, with the assumption of an immediate complete evaporation of the liquid and the formation of a vapour cloud. Boiling but low-volatile liquids will form pools and their speed of vaporisation depends primarily on the source terms. They will only evaporate at considerable rates if the surface area is comparably big. For safety considerations both effects, VCEs and pool fires, will be considered.

Pool fires cause thermal radiation. Explosions are only indirect consequences of pool fires, for instance if a pool fire heats up a container and causes a BLEVE. Also the vaporised fuels can form a cloud and cause a VCE. [1] [2]

4.3.1 Calculation of the evaporation rate

For the estimation of the dimensions of the pool it is assumed that all liquid released immediately spreads to its minimum thickness, which correlates with its maximum surface area and consequently the maximum evaporation rate. [1]

Step 1a – Calculation of the dimensions of the pool

The shape of liquid pools will be irregular in reality. If either the amount of fluid released (Step 1a) or the area of the pool can be estimated (Step 1b) the diameter of an equivalent sphere shaped pool can be calculated. The third option (Step 1c) is for a confined pool, which has to be calculated differently since it will not spread to its minimum thickness.

Step 1a – Calculation of the equivalent diameter (volume released is known)

If the total volume released or the volume flow and the time of release can be determined, the equivalent circular pool diameter can be calculated. [1]

$$D_p = \sqrt{\frac{4 * V_{out}}{\pi * \delta}} \quad \textbf{(45)}$$

With

$$V_{out} = V'_{out} * t_{out} \quad \textbf{(46)}$$

The minimum thickness of the pool depends on the type of ground. A selection of common types is provided in **Table 14**.

V'$_{out}$ can be estimated according to Table 2: Rules of the thumb for leakage diameters on p. 13. Conversion: 1 l/min = (10^{-4} / 6) m³/s.

Table 14: Minimum pool thickness depending on the type of ground [1] p. 3.28

Type of sub-surface	δ in m
Flat sandy soil, concrete, stones, industrial site	$5*10^{-3}$
Normal sandy soil, gravel, railroad yard	$10*10^{-3}$
Rough sandy soil, farmland, grassland	$20*10^{-3}$
Very rough, grown over sandy soil with potholes	$25*10^{-3}$

Step 1b – Calculation of the equivalent diameter for irregular pool shapes

If the pool is not circular and the size of the area can be estimated, it is necessary to calculate the diameter of an equivalent pool.

$$D_p = \sqrt{\frac{4 * A_p}{\pi}} \quad \textbf{(47)}$$

In case the ratio between length and width of a pool is larger than 2 it is necessary to calculate an equivalent diameter for a spherical pool.

Step 1c – Equivalent diameter of a confined pool (area and perimeter is known)

If the pool is confined in a bund, surface area, length and width should be known, but the thickness will be above the minimum. With this input the equivalent pool diameter can be determined. [1]

$$D_p = 4 * \frac{A_p}{S_p} \tag{48}$$

Step 2 – Calculation of the evaporation rate (non-boiling liquid only)

If the pool is not boiling the evaporation rate mainly depends on the difference between vapour pressure and the difference between vapour pressure and partial pressure in the surrounding air. Usually the saturated vapour pressure is much bigger than the saturated vapour pressure and is therefore neglected in formula **(49)**. Also the wind velocity is taken into consideration through k_m. This situation is reflected in the formula **(50)**. [2]

$$m'_{vap} = A_p * \frac{k_m * P_{sv} * MM}{R_c * T_p} \tag{49}$$

The mass transfer coefficient k_m can be calculated according to MacKay and Matsugu [2]

$$k_m = 0.004435 * u_w^{0.78} * \left(\frac{D_p}{2}\right)^{-0.11} * Sc^{-0.67} \tag{50}$$

With the Schmidt number (ratio between viscous and mass diffusion rate) [2]

$$Sc = \frac{\nu}{D_{air}} \approx 0.8 \tag{51}$$

Step 3 – Calculation of the mass vaporised after a certain amount of time

A vapour cloud is very mobile and has the potential to explode. To calculate its possible effects mass of substance vaporised has to be known

$$m_{vap} = t_{vap} * m'_{vap} \tag{52}$$

If there is no ignition within a short time frame the vapour will form a cloud and move away from the pool. For the quantification of possible effects the steps described in chapter 4.4 Vapour cloud explosions (and vapour cloud fires) have to be taken.

4.3.2 Calculation of the heat radiated by a pool fire

For pool fires a couple of experiments have been conducted. As an alternative to calculate the SEP_{act} it can be assumed based on **Table 15** for boiling pools and **Table 16** for non-boiling pools.

Table 15: Relative flame height (L/D) and SEP_{act} of the flame surface of boiling pools ($T_b < 20°C$) [1] p. 6.70

	D = 1 m		D = 10 m	
Substance	**L/D (-)**	**SEP_{act} in 10^3 J/(m²*s)**	**L/D (-)**	**SEP_{act} in 10^3 J/(m²*s)**
Acetaldehyde	2.88	35	1.43	64
Ammonia	1.57	17	0.78	30
Butane	4.84	86	2.40	165
Ethene	4.52	90	2.24	173
Hydrogen sulphide	2.20	18	1.09	32
Methane	4.59	100	2.29	193
Propane	5.08	98	2.52	188
Propylene	4.90	92	2.43	178
Vinylchloride	2.68	26	1.41	46

Table 16: Relative flame height (L/D) and SEP_{act} of the flame surface of non-boiling pools ($T_b \geq 20°C$) [1] p. 6.71

	D = 1 m		D = 10 m	
Substance	**L/D (-)**	**SEP_{act} in 10^3 J/(m²*s)**	**L/D (-)**	**SEP_{act} in 10^3 J/(m²*s)**
Acetone	3.06	42	1.52	79
Acrylonitrile	2.64	36	1.31	67
Benzene	4.16	71	2.06	135
Carbon Disulphide	2.37	15	1.18	28

Hexane	4.53	87	2.24	166
Methanol	1.59	19	0.79	34
Methyl Acetate	2.59	26	1.28	48

Step 1 - Calculation of the burning rate

To estimate the heat radiated the burning rate is a necessary input factor. Burning rates for different substances can be taken from experimental results. Alternatively the burning rate can be calculated according to **Formula (53)** [1].

$$m'' = \frac{0.001 * \Delta H_c}{\Delta H_v + c_{pl} * (T_{boil} - T_0)} \tag{53}$$

Step 1a – Consideration of the influence of the wind

It has been observed that the speed of wind has a relevant influence on the burning rate. The following formula is based on the outcome of large scale experiments to quantify the effect. [1]

$$\frac{m''_w}{m''} = 1 + 0.15 * \frac{u_w}{D_p} \tag{54}$$

This formula is not applicable for alcohols or for conditions under which a fire is blown out (u_w > approximately 5 m/s).

Step 2 - Calculation of the maximum burning time

The burning time until there is no substance left to fuel the fire can be estimated according to [1]

$$t_p = \frac{\delta * \rho_l}{m''} \tag{55}$$

m'' has to be replaced with m''_w for windy conditions.

Step 3 – Determination of the surface emissive power of a pool fire

Values for the heat flux of boiling and non-boiling pools can be either calculated or taken from **Table 15** or **Table 16**. These experimentally derived data shows that the flux from a pool with a diameter of 10 m is only about twice the amount of a pool with 1 m diameter.

There are two formulas which can be used to calculate SEP of a pool fire. To make it easier to distinguish them, the first one is referred to as SEP_{max} as in the Yellow Book [1]. For both formulae the assumption is made, that the pool fire radiates a uniform amount of heat over the whole of the flame surface. The radiation factor, F_s of pool fires has only little certainty. Small scale experiments have shown that its value ranges between 0.1 and 0.4. The more conservative approach of $F_s = 0.4$ is used here. [1]

Formula for smaller pools ($D_p \approx 1$ m) [1]

$$SEP_{max} = F_s * m'' * \frac{\Delta \mathrm{H_c}}{\left(1 + 4 * \frac{l_P}{D_P}\right)} \tag{56}$$

Formula for bigger pools ($D_p \approx 10$ m) with a tilted cylindrical flame [1]

$$SEP_{act} = 140 * e^{-0.12 * D_p} + 20 * (1 - e^{-0.12 * D_p}) \tag{57}$$

SEP_{act} does only depend on the diameter of the pool. The substance does not have any influence on the result. For a further explanation why the decision was made to use SEP_{max} for small pools and SEP_{act} for bigger pools, have a look at 5.3.1 on p. 77.

Step 4 - Calculation of the view factor

F_{view} for cylindrical flames is rather complicated to calculate. It takes the angle of the flames the length and the pool diameter into consideration. **Figure 7** describes the used variables and which angle to consider. [1]

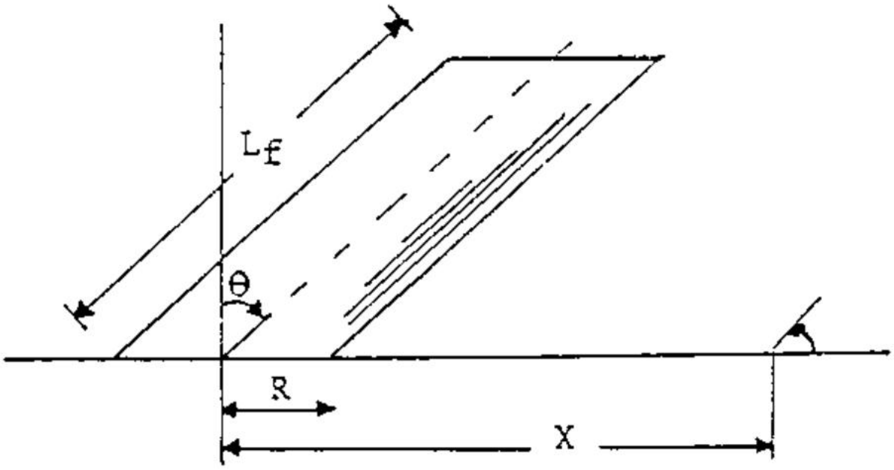


Figure 7: Target and flame geometry for a tilted cylindrical flame [1] p. appendix 6.1-6

For pool fires: $L_f = l_p$; R = $D_p/2$; X = x_{42} with $x_{42} > D_p/2$

(For jet fires: $L_f = l_j$; R = $d_j/2$; X = x_{42} with $x_{42} > d_j/2$)

Calculation of the basic constants [1]

$$a = \frac{2 * l_p}{D_p} \tag{58}$$

$$b = \frac{2 * x_{42}}{D_p} \tag{59}$$

Calculations of further constants [1]

$$A = \sqrt{a^2 + (b+1)^2 - 2 * a * (b+1) * \sin\theta} \tag{60}$$

$$B = \sqrt{a^2 + (b-1)^2 - 2 * a * (b-1) * \sin\theta} \tag{61}$$

$$C = \sqrt{1 + (b^2 - 1)^2 * \cos^2\theta} \tag{62}$$

$$D = \sqrt{\frac{b-1}{b+1}} \tag{63}$$

$$E = \frac{a * \cos\theta}{b - a * \sin\theta} \tag{64}$$

$$F = \sqrt{b^2 - 1} \tag{65}$$

Calculation of the maximum horizontal and vertical view factor [1]

$$\pi * F_v = -E * \tan^{-1} D + E * \left[\frac{a^2 + (b+1)^2 - 2 * b * (1 + a * \sin\theta)}{A * B}\right] * \tan^{-1}\left(\frac{A * D}{B}\right) * \frac{\cos\theta}{C} + \left[\tan^{-1}\left(\frac{a * b - F^2 * \sin\theta}{F * C}\right) + \tan^{-1}\left(\frac{F^2 * \sin\theta}{F * C}\right)\right] \tag{66}$$

$$\pi * F_h = \tan^{-1}\left(\frac{1}{D}\right) + \frac{\sin\theta}{C} * \left[\tan^{-1}\left(\frac{a * b - F^2 * \sin\theta}{F * C}\right) + \tan^{-1}\left(\frac{F^2 * \sin\theta}{F * C}\right)\right] * \left[\frac{a^2 + (b+1)^2 - 2 * (b + 1 + a * b * \sin\theta)}{A * B}\right] * \tan^{-1}\left(\frac{A * D}{B}\right) \tag{67}$$

$$F_{view} = \sqrt{F_v^2 + F_h^2} \tag{68}$$

Step 5 - Calculation of the transmissivity

The transmissivity reflects the reduction of the radiation due to the effects of the air between the radiated object and the flame. [2]

$$\tau_a = 0.4343 * ln\left(14.1 * (\varphi * 100)^{-0.108} * \left(x_{42} - \frac{D_p}{2}\right)^{-0.13}\right) \tag{69}$$

With the relative humidity φ ≥ 20%

Step 6 - Calculation of the heat flux at a certain distance

The heat flux at a certain distance of the pool fire is the radiated heat, reduced by the loss due to the air between and the shape of the fire. Any soot formation is neglected. [1]

$$q'' = SEP_{act} * F_{view} * \tau_a \tag{70}$$

The result of this model is q'' in kJ/m²*s. The risk zones depending on the heat flux are presented in **Table 10** on p. 31.

4.4 Vapour cloud explosions (and vapour cloud fires)

For a vapour cloud explosion a big amount of carbohydrates in the form of a cloud is necessary, which will blow up in an explosion after ignition. A typical example is an unrecognized release of fuel from a pipeline. Due to the slow formation of the cloud the mixture of air and gas is ideal for an explosion.

In the situation that a very volatile fluid is released, parts of it may form a temporary pool. Then it is easiest and safest to consider the whole amount released to be part of the developing vapour cloud. If it is expected that a pool, as well as a vapour cloud will be present for a longer time, the amount of the vaporised fluid can be calculated by the difference of mass released and mass in liquid state. The mass in liquid state can be estimated by the size and thickness of the pool. This is covered in chapter 4.3, starting on p. 47. The effects of a pool fire and vapour cloud fire/explosion have to be calculated separately and parallel. It is safest to also consider the effects of the worst case scenario of the whole substance released vaporising and participating in the VCE.

The effects of vapour cloud explosions are heat radiation and blast waves. The calculations of these effects are basically the same as for a BLEVE. To reflect the differences, more complex models would be necessary. [1]

4.4.1 Calculation of the heat radiated by a vapour cloud fire/explosion

To calculate the heat radiated by an ignited vapour cloud it is necessary to know its mass. For pipelines or something similar the mass rate only depends on release time and grows until the source is cut. If there is a hole in a vessel mass will be released over time, but the maximum that can be released is defined. Basically the heat radiated is determined exactly the same way as for a fireball caused by a BLEVE.

Step 1 - Calculation of the participating mass of substance

In a first step it is necessary to determine the amount of substance released. For smaller leakages of a fluid in gas phase Step 1 from chapter 4.2.1 (p. 42) can be applied. To calculate the total mass released the duration of release is necessary.

$$m = m' * t_{out} \qquad \textbf{(71)}$$

For very volatile substance, released in liquid state, but vaporising quickly

$$m = V'_{outl} * \rho_l * t_{out} \tag{72}$$

V'_{outl} can be estimated according to Table 2: Rules of the thumb for leakage diameters on p. 13. Conversion: 1 l/min = (10^{-4} / 6) m^3/s

For leakages from containers with a defined maximum volume, it must be considered, that the substance release will end when the total mass is released.

$$m_{max} = V_{tank} * \rho_l \tag{73}$$

Check if m < m_{max}, otherwise use m_{max}.

Also, if the size of the hole or the duration of release is unknown, m_{max} will be used for assumptions.

For fluids forming pools the calculations will consider the total amount released and if a considerable big pool is visible also additionally only for the already vaporised part.

$$m_{vc} = m_{out} - m_{pool} \tag{74}$$

Step 2 to 12 – Size of the fireball, burning time and heat flux at a certain distance

The steps 2 to 12 from chapter 4.1.1 can be applied.

The result of this model is q'' in kJ/m^2*s. The risk zones depending on the heat flux are presented in **Table 10** on p. 31.

4.4.2 Calculation of the peak over-pressure (TNT-equivalence model)

The peak over-pressure due to a vapour cloud explosion is calculated according to the TNT-equivalent model. If a vapour cloud fire or a vapour cloud explosion will occur is hard to predict. In the past, there have been vapour cloud explosions that started as vapour cloud fires before the explosion took place.

For an explosion to occur some factors have to be fulfilled, which lead to a high enough turbulence if the ignition energy is high enough, if the release takes place with high initial energy or if the cloud spreads explosively.

Depending on the timeframe of a VCE deflagration or detonation will occur, the equivalent TNT model reflects the worst case scenario, the effects of a detonation. [1] [2]

Step 1 – Calculation of the mass released

For calculating the mass released see step 1 of chapter 4.4.1.

Step 2 to 4 – Mass equivalent of TNT and peak over-pressure

The steps of the calculation will not be repeated here, they are presented in chapter 4.1.2 starting on p. 40.

The result of this model is p_{TNT} in kPa. The risk zones depending on over-pressure are presented in **Table 10** on p. 31.

5 Comparison of model results with historic data

For the verification of the calculation models presented in chapter 4 the results of the models are compared to data from hazardous events of the past. That data are obtained from press releases, reports, Health and Safety Executive (HSE) and Center for Chemical Process Safety (CCPS) websites. CCPS is a US-database where selected hazardous events are documented, including lessons learned and recommendations to prevent them in the future. HSE is something comparable to CCPS but from Great Britain. The European eMARS (electronic Major Accident Reporting System) was established by the Seveso Directive and is meant to improve the exchange of lessons learned from major accidents and near misses involving hazardous substances. This database has only limited data provided, the necessary input parameters according to **Table 11** are usually not offered. Especially when it comes to the effects and the distances in which these effects appeared, the information is not sufficient.

For (almost) each scenario two past accidents have been selected. In this chapter the real effects of accidents are compared to the results of the presented calculation models and to the results according to EFFECTS [0]. EFFECTS is a software to estimate the effects of hazardous events. It is mainly based on the Yellow Book [1], but also includes some additional calculation models. The used model is always stated. The selection of comparable incidents is challenging, due to a lack of data, a combination of scenarios with combined effects or other factors. Often it is not detectable, which effect was due to which amount of which substance. For instance, in a publication by HSE a VCE is described with an unknown amount of the substance involved. After considering the effects the volume was estimated to range between 400 and 1360 m^3 [18]. This reflects the problem of back-calculations being imprecise and only of limited helpfulness to verify the models.

5.1 BLEVE and fireballs

In this chapter two accidents which include a BLEVE are presented. First a short description of each incident is given, then the documented data and effects are compared to the expected effects based on the calculation models. The selected cases are a propane tank explosion at a turkey farm in the US in 1998 and an LPG tanker explosion on a motorway in Bologna, Italy in 2018.

5.1.1 Propane tank explosion – Albert City, US 1998 (Herrig turkey farm)

Figure 8: Aerial view of the farm on the day after the explosion [5] p. 11

5.1.1.1 Summary of the incident

On 9 April 1998 around 23:28 an 18,000 gallon (≈ 68 m^3) tank filled with liquefied propane exploded at the Herrig Brothers Feather Creek Farm in Albert City, Iowa. Some teenagers driving an all-terrain vehicle (ATV) crushed into two propane lines. The accident caused a fire which engulfed the propane tank. About half an hour after the crash the tank exploded in the form of a BLEVE. Fragments of the tank hit two firemen fatally and severely damaged buildings of the farm. Another seven people got injured during the accident. In **Figure 8** some of the damage and the original position of the tank are visible. The arrow points to the spot where the propane tank was located. [5]

5.1.1.2 Cause of the BLEVE

On the night of the incident some teenagers were having a party at the farm. This was without the permission or the knowledge of the owner of the farm. The teenagers were driving around with an ATV and hit two above ground propane pipes (liquid and vapour lines) running parallel to each other. There was an excess flow valve which was supposed to protect the liquid line, but could not stop the propane from leaking. The released liquid propane immediately vaporized and probably additional propane was leaking from the damaged vapour line. Soon after the release the propane ignited. It is assumed that the source of ignition was one of the direct-fired vaporizers, which were located about 11 metres from the damaged pipes. Then the fire fed by the leaking propane engulfed the propane tank and eventually caused the BLEVE.

Firefighters were called and arrived at the farm around 23:20. They witnessed flames under the tank and on top of the tank, where the pressure relief valve pipes were located. According to [5] p. 2 a fireman stated that *"the propane tank was fully engulfed and flames were 70-100 yards* (≈ 65-90 metres) *in the air."* Other firefighters compared the noise from the pressure relief valve to *"standing next to a jet plane with its engines at full throttle."*

Immediately before the blast a swelling of the tank was witnessed. In the next moment there was a loud explosion and the tank with the connected piping were disrupted into over 35 pieces. In **Figure 10** the spots where the fragments landed are visible. [5]

5.1.1.3 Hazardous effects of the BLEVE

The major damages were caused by flying fragments of the tank and the heat radiated by the fireball. Two firefighters who were standing about 105 feet (≈ 30 metres) from the side of the tank were killed by missiles. Six firefighters and a deputy chief suffered under varying degrees of burns and other injuries. [5]

The firefighters were badly informed about the risks of a BLEVE, especially the risk of flying missiles. They were standing too close to the tank and thought that the only critical zones are in the area of the ends of the tank. 90% of the department's firefighters had watched a video about propane tank fires recently, which recommended to *"approach the* *container from the sides and from upwind."* As stated in [5] p. 33, it did not warn about tank fragments which might shoot in any direction and even stated: *"should the container rupture, it can and will, most likely, travel in the direction it is pointed."* [5] p. 33

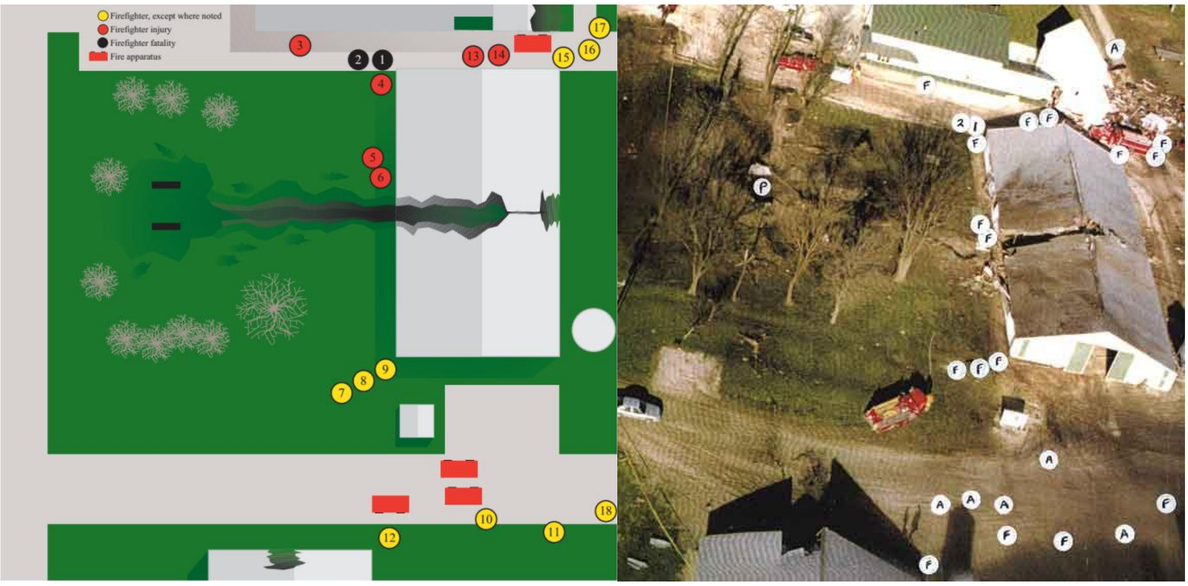


Figure 9: Illustration and photograph of the area with the positions of the firemen [19] p. 4, [20]

The farm does not exist in a similar formation today, therefore no information from recent satellite pictures can be derived. To obtain relevant distances the information from **Figure 11** was used on the locations of the firemen (see **Figure 9**) and the spots, where fragments landed (**Figure 10**). From the aerial view (see **Figure 8**) it can be derived, that the main impact area with blackening was around the tank and up to the seriously destroyed building. The distance from the tank to that building was around 26.5 metres as stated in **Figure 11**.

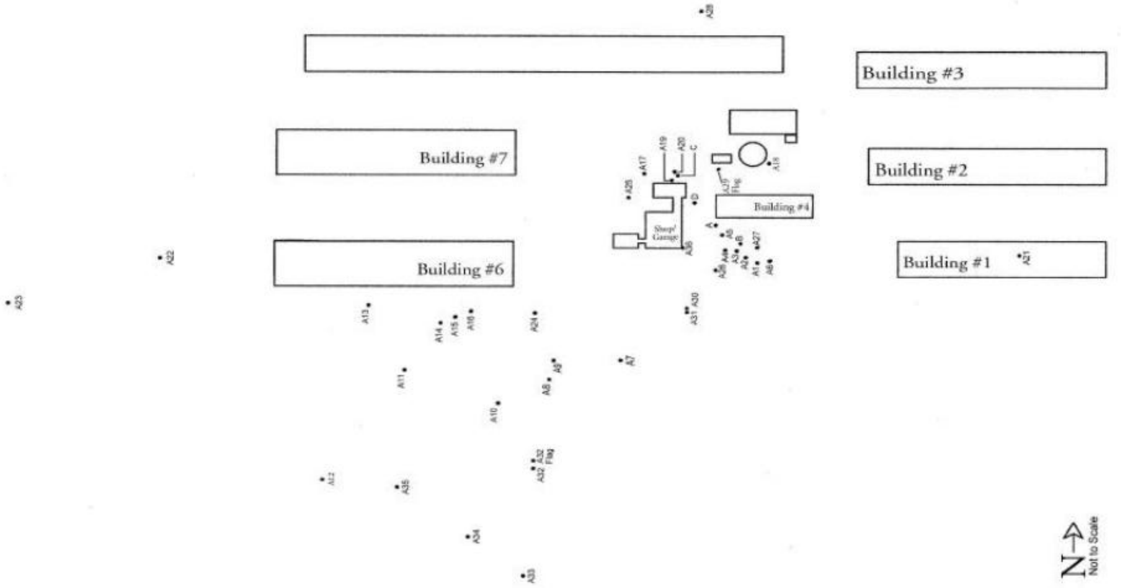
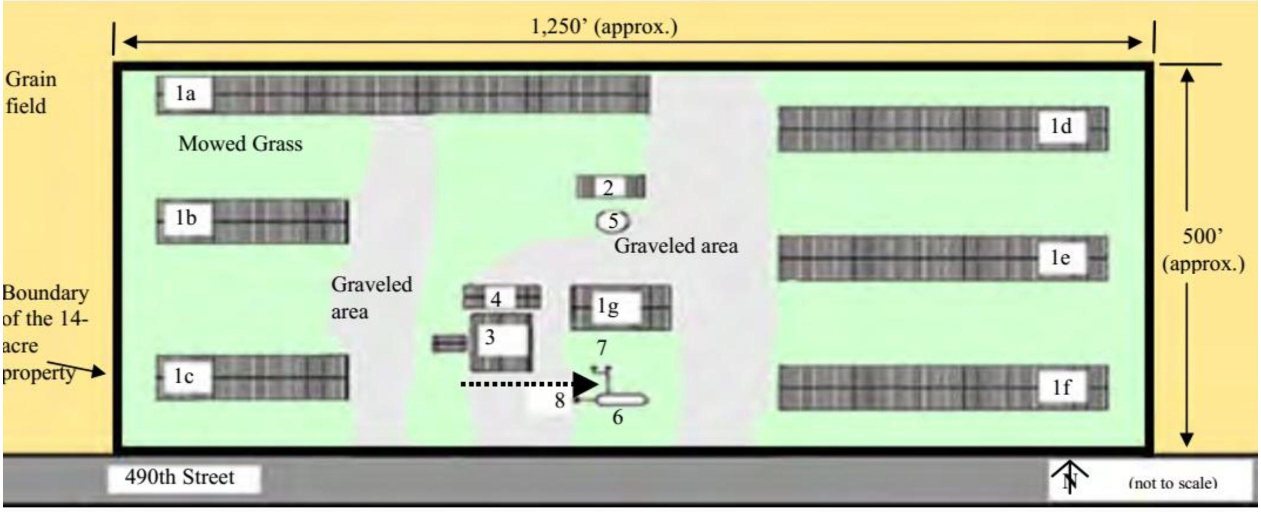


Figure 10: Debris map of the Herrig incident [5] p. 66



Major Buildings and Structures

1. Turkey barns (1a - 1g)
2. Machine shed
3. Office
4. Workshop
5. Feed storage bin
6. 18,000-gallon propane tank
7. Direct-fired vaporizers
8. Fueling truck point-of-transfer

Note:

1. Direct-fired vaporizers (Item 7) are located approximately 37 ft north of the 18,000-gallon propane tank (Item 6).
2. Fueling truck point-of-transfer (Item 8) is located approximately 40 ft west of the 18,000-gallon propane tank (Item 6).
3. South side of turkey barn 1g is approximately 87 ft north of the 18,000-gallon propane tank (Item 6).
4. Centerline of 490th Street is approximately 78 ft south of the 18,000-gallon propane tank (Item 6).

Figure 11: Plot plan of the farm, 2243 490th Street, Albert City, Iowa [5] p. 10

5.1.1.4 Calculation input data and results

The input data presented in **Table 17** has been obtained from the information in the CSB report [5]. All the values in the table were necessary for the calculation of the expected results, except the additional information in gaps.

Table 17: Input parameters for the calculation of effects (BLEVE, Albert City) [5]

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Propane, liquefied
	x_{42}	m	Considered distances	1 to 500
Ambient	T_0	°C	Ambient temperature	3.33
	φ	%	Relative humidity	86%
Process	T_{init}	°C	Initial temperature	T_0
Amount	V_{out}	m³	Volume of the flammable substance	37.85
	(V_{tank}	m³	Volume of the tank	68.14)

In **Table 18** the information gathered from the report about the distances of harmful effects is compared to the results of the calculation models from chapter 4. On the basis of the real effects only the red zone could be derived, which is in fact close to the value calculated. According to the simplified calculation for the safety distances of firemen presented in [10], the results would have suggested a distance where only one of the missiles landed. Most of the missiles landed within 150 to 200 metres from the tank. [5] Missiles, even if they are small, can kill or seriously injure a person, especially in case the head is hit.

Table 18: Comparison of the results of the calculation models, EFFECTS and the report data (BLEVE, Albert City) [0] [5]

Symbol	**Unit**	**Description**	**Calculation**	**EFFECTS**	**Report**
r_{fb}	m	Radius of the fireball	80	81	
t_{fb}	s	Burning time of the fireball	11.1	11.2	-
x_{smin}	m	Safety distance for firemen	320		380
x_{min}	m	Safety distance for other people	1,200		
x_{red}	m	Red zone according to heat radiation	53	155	50
x_{redex}	m	Red zone according to explosion	49	26	30 (fatalities)
		For people	93	58	150-200 (fragments)
x_{orange}	m	Orange zone according to heat radiation	149	245	
$x_{orangeex}$	m	Orange zone according to explosion	79	49	
		For people	251	140	
x_{yellow}	m	Yellow zone according to heat radiation	221	325	
$x_{yellowex}$	m	Yellow zone according to explosion	325	185	
		For people	400	195	

The data from EFFECTS [0] are based on the "Static BLEVE model (Yellow Book)". A comparison of the results shows, that the size and the burning time of the fireball are very similar. However the maximum overpressure is slightly lower and the heat radiation is considerably higher according to EFFECTS. If it comes to the explosion effects, the distances resulting from the formulae in chapter 4 are higher, but they are closer to the distances in which fragments of the tank and the piping system were found.

5.1.2 LPG tanker explosion – Bologna, IT 2018

Figure 12: The different stages of the explosion of the LPG tanker in Bologna [22]

5.1.2.1 Summary of the incident

On 6 August 2018, at approximately 15:50, a 50 m³ (estimation) LPG road tanker exploded on a motorway bridge in Bologna, Italy. The exact size of the tanker, the exact substance loaded and the amount of loading have not been made public. As visible in **Figure 12** the road tanker crashed into a truck transporting cars at the end of a traffic jam. Both cars immediately caught fire, which after some minutes, eventually led to a BLEVE. The driver of the road tanker was killed and about 145 people got injured, 4 of them seriously. Luckily those four people survived. [21] [23]

5.1.2.2 Cause of the BLEVE

The BLEVE was caused by the pool fire resulting from the tanker crashing into the truck in front of it. Whether the driver of the tanker fell asleep or did not pay attention when he crashed into the traffic jam is unknown. As a consequence of the accident gasoline from the truck or the loaded cars was spilled and ignited immediately as visible in **Figure 12**. This pool fire heated up the tank, weakened its shell and started to vaporise the loaded LPG. It took a couple of minutes until the BLEVE took place. The exact time span was not published, only a CCTV video, with a cut between the accident and the moment when the fireball appears. Also videos by witnesses did not show the whole incident without a break. [21] [23]

5.1.2.3 Hazardous effects of the BLEVE

After the first explosion a chain reaction started. Burning missiles hit cars on the motorway and in front of a car dealership close by. The motorway bridge, where the incident took place, partly collapsed due to the high temperature of the fire. Explosions were going on for about 8 minutes. The fire ball itself had a lifetime of about 9 to 10 seconds and was probably the source of ignition of the cars pictured in **Figure 13** which were located between the motorway bridge and the car dealership. Not only the destroyed cars but also the border zone of the heat radiation, hence the maximum distance in which the cars caught fire is visible. The cars either ignited or were not damaged at all. Interestingly, not even the polymer parts of the cars directly next to the burnt out cars have melted. From other photographs the distances of additional pressure indicators such as shattered windows and blinds could be identified. There is no information available about where the people who got injured were standing when the BLEVE took place. [21] [23]

Figure 13: Destroyed cars of the car dealership underneath the motorway bridge [24]

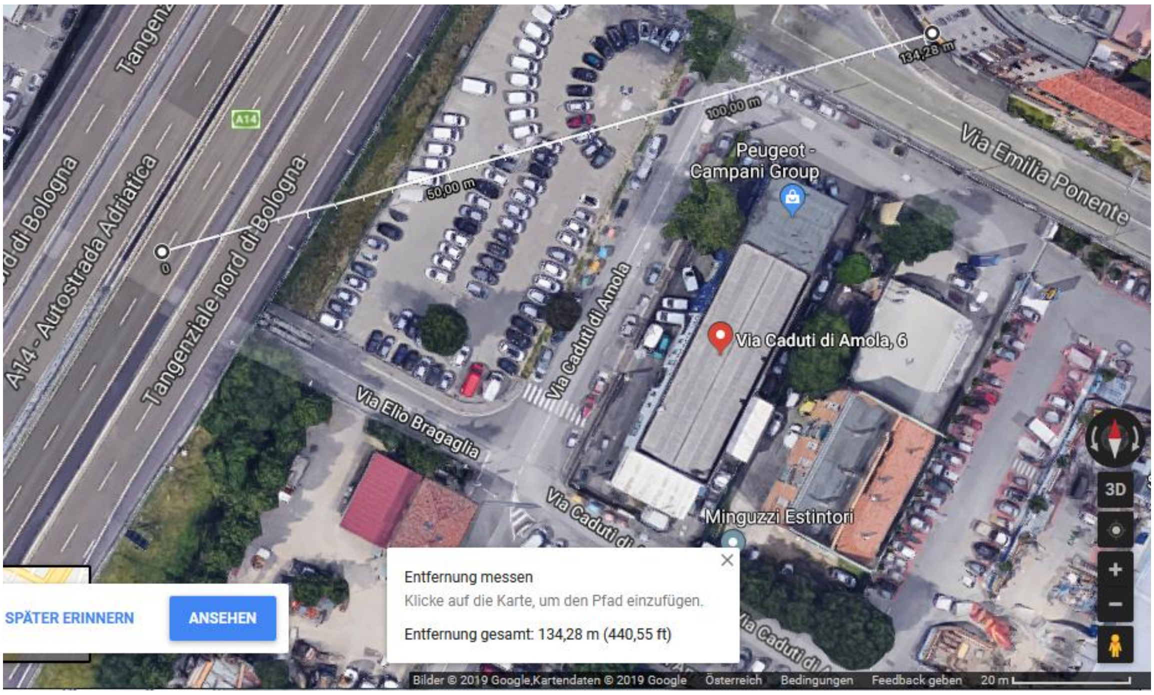
5.1.2.4 Calculation input data and results

The input data presented in **Table 19** has been obtained from various sources, such as newspaper articles, videos and pictures of the incident. Since the substance transported by the tanker and its actual amount are unknown, the calculation was conducted for a 100%, 75%, 50% and 25% filling ratio. Based on pictures of the tanker its total volume was assumed. In the reports the loaded substance was only referred to as LPG, for the calculation it is assumed that it was propane.

Table 19: Input parameters for the calculation of effects (BLEVE, Bologna) [25]

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Propane (LPG) , liquefied
	x_{42}	m	Considered distances	1 to 500
Ambient	T_0	°C	Ambient temperature	34
	φ	%	Relative humidity	36%
Process	T_{init}	°C	Initial temperature	T_0
Amount	V_{tank}	m³	Volume of the tank	50
	f	%	Filling ratio	100%; 75%; 50%; 25%

In **Table 20** the information gathered about distances with harmful effects is compared to the results of the calculation models from chapter 4. On the basis of the real effects only the red zone for heat radiation – structure based (burning cars) – could be derived. The broken windows are an indicator of minor structural damage. It is possible, that there were more broken windows further away from the accident, which has not been taken into account. The car dealership (Peugeot) with the broken windows was about 100 metres from the exploding tanker and the shop with the yellow blinds was about 135 metres away (see **Figure 14**).



Entfernung messen

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Entfernung gesamt: 134,28 m (440,55 ft)

Figure 14: Distance of shattered windows of a shop (yellow blinds) close to the motorway bridge [26]

Table 20: Results of the calculation of effects in comparison to data from reality (BLEVE, Bologna) [22] [26]

Symbol	Unit	Description	f=100%	f=75%	f=50%	f=25%	Reality
r_{fb}	m	Radius of the fireball	87.6	79.8	69.9	55.8	
t_{fb}	s	Burning time of the fireball	11.9	11.1	9.9	8.3	9-10
x_{smin}	m	Safety distance for firemen	350	319	280	223	
x_{min}	m	Safety distance for other people	1314	1197	1049	837	
x_{red}	m	Red zone according to heat radiation	139	111	79	29	
x_{redex}	m	Red zone according to explosion	53	49	43	35	
		For people	101	91	79	63	
x_{orange}	m	Orange zone according to heat radiation	231	197	155	99	
$x_{orangeex}$	m	Orange zone according to explosion	87	79	69	55	
		For people	249	227	197	157	
x_{yellow}	m	Yellow zone according to heat radiation	317	273	219	149	
$x_{yellowex}$	m	Yellow zone according to explosion	> 500	319	279	221	
		For people	> 500	> 500	483	383	
	m	Shattered glass					134
	m	Burning cars					66

The filling ratio of the tanker, according to the effects, was most likely between 50% and 75% (which equals 25 to 37.5 m^3 of liquefied propane). Since it was already afternoon when the accident happened, it can be assumed that the tanker already had a stop where it unloaded a part of its original load. 75% filling would indicate almost the same amount of substance involved in this event as in the first scenario, the propane tank explosion at the turkey farm in Albert City.

Table 21: Comparison of the results of the calculation models, EFFECTS and data from reality (BLEVE, Bologna) [0] [22] [26]

Symbol	Unit	Description	Model	EFFECTS	Model	EFFECTS	Reality
f	%	Fraction of the volume filled	75	75	50	50	
r_{fb}	m	Radius of the fireball	79.8	78.4	69.9	69.4	

t_{fb}	s	Burning time of the fireball	11.1	10.9	9.9	9.9	9-10
x_{smin}	m	Safety distance for firemen	319		280		
x_{min}	m	Safety distance for other people	1197		1049		
x_{red}	m	Red zone according to heat radiation	111	145	79	105	
x_{redex}	m	Red zone according to explosion	49	25	43	22	
		For people	91	56	79	49	
x_{orange}	m	Orange zone according to heat radiation	197	225	155	175	
$x_{orangeex}$	m	Orange zone according to explosion	79	47	69	41	
		For people	227	131	197	120	
x_{yellow}	m	Yellow zone according to heat radiation	273	300	219	240	
$x_{yellowex}$	m	Yellow zone according to explosion	319	180	279	155	
		For people	> 500		483		
	m	Shattered glass					134
	m	Burning cars					66

In **Table 21** only the results of the most likely tank filling ratios that are (50%, 75%) compared. The data from EFFECTS [0] are based on the “Static BLEVE model (Yellow Book)”. A comparison of the results shows that the size and the burning time of the fireballs are very similar, the maximum overpressure is slightly different and the differences due to heat radiation are in a range of about 30 to 50 metres.

5.2 Jet fire

In this chapter two accidents involving jet fires are presented. First a short description of each incident is given, then the documented data and effects are compared to the expected effects based on the calculation models. The selected cases are a jet fire at the Baumgarten gas terminal in Austria in 2017 and a propane fire at a Refinery in Sunray, US from 2008.

5.2.1 Natural gas jet fire – Baumgarten, AT 2017 (Gas distribution)

Figure 15: Natural gas jet fire at the gas distribution centre in Baumgarten [APA/ÖAMTC] [27]

5.2.1.1 Summary of the incident

On 12 December 2017, at approximately 08:45, a pipeline with natural gas got hit by a missile in the form of a heavy locking cap. This led to a full rupture of a natural gas pipe at the gas distribution centre of Gas Connect Austria GmbH in Baumgarten, Austria. Natural gas was released and auto-ignited immediately. It formed a jet fire and caused a minor blast followed by a fire. After over an hour the major parts of the fire were extinguished.

1 person died during the accident, another 21 people got injured. The site was shut down completely and only started operating again about three months after the incident. In **Figure 16** the destroyed site is visible. [28] [29] [30]

Figure 16: Aerial view of the area of the accident after the fires were extinguished [31]

5.2.1.2 Cause of the jet fire

During start-up the locking cap of a filter separator, a 100 kilogram metal piece (locking cap) got lose and crashed against another part of the plant. The missile hit a natural gas pipeline, which suffered full rupture. Gas was released and auto-ignition occurred immediately. Hence a jet fire was formed. Auto-ignition is not uncommon for full ruptures of pipelines with big diameters, because the expansion of the gas has already causes a sufficient energy release. [30]

5.2.1.3 Hazardous effects of the jet fire

The most dangerous effect of a jet fire is when it directly hits parts of a site and causes follow up explosions or releases additional amounts of hazardous substances. Luckily in Baumgarten no follow up explosions or further pipe ruptures were caused. All observed impacts are consequences of the heat radiation and the fire at the site caused by the incident. The affected area was about 100 times 100 metres. A vehicle that was located within that area (40 metres distance) caught fire during the incident. Also a building that was about 170 metres from the jet flame, started to burn. The cars the polymer parts (eg lights) of the cars next to that building melted. The front of a truck located 145 metres (see **Figure 17**) from the flame source was significantly damaged, two smaller trucks that were parked only about 5 metres in front of it were completely destroyed. Additionally, the caused pressure wave as strong enough to be still sensible and sensible in the town of Baumgarten, for instance in the grocery store which is located about 1 kilometre away from the site. [29]

Entfernung messen
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Entfernung gesamt: 144,14 m (472,90 ft)

Figure 17: Distance of damaged truck to the source of the jet flame [32]

5.2.1.4 Calculation input data and results

The input data presented in **Table 22** has been derived from information from official statements, press reports and photographs. Since natural gas is a mixture of gases with a high amount of methane, methane was used for the calculations. Also the exposition time is just an assumed value. A person running away from the jet should be able to leave the most dangerous zone within 30 seconds.

Table 22: Input parameters for the calculation of effects (Jet fire, Baumgarten)

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Methane, liquefied
	x_{42}	m	Relevant distances	1 to 500
Ambient	T_0	°C	Ambient temperature	10
	φ	%	Relative humidity	60%
Process	T_{init}	K	Initial temperature	30

	P_{init}	Pa	Initial pressure	$5*10^6$
Time	t_{ex}	s	Exposition time	30
Leak size	d_{out}	m	Diameter of the circular leak	0.3
Geometry	Θ	°	Angle of the flames	90

In **Table 23** the information gathered from about the distances with harmful effects is compared to the results of the calculation models from chapter 4. The mentioned zone of main impact with the radius of 100 metres is a too small area for the red zone. It can be prolonged up to the building that caught fire and the severely damaged trucks. Since a jet fire has a clear direction, its impact will not have the same strength in all directions. The recognized indicators of heat radiation all reflected a higher level, than acceptable for the yellow zone. Blackening of the grass could have been taken, but was not visible enough.

The selected model in EFFECTS [0] is the Chamberlain model. Hence, it is basically the same model as used for the calculation models in chapter 4. Though, it is not clear, whether EFFECTS integrated the error (according to [8]) in the Chamberlain model from the Yellow Book [1]. There is a significant difference between the results. The length of the jet flame according to EFFECTS is only half as long as expected. However the effects documented are supporting the longer jet flame.

Table 23: Comparison of the results of the calculation models, EFFECTS and data from reality (Jet fire, Baumgarten) [0]

Symbol	Unit	Description	Calculation	EFFECTS	Report/Reality
l_j	m	Length of the jet flame	82	38.7	
d_j	m	Diameter of the flame	41	15	
r_{50j}	m	Distance with 50% probability of fatality	49		
r_{1j}	m	Distance with 1% probability of fatality	81		
x_{red}	m	Red zone according to heat radiation		17	170
	m	For people	>102	82	
x_{orange}	m	Orange zone according to heat radiation		54	
	m	For people		104	
x_{yellow}	m	Yellow zone according to heat radiation		125	180 (melted lights)
	m	For people		140	

5.2.2 LPG fire – Sunray, US 2008 (Valero Refinery)

Photo: Associated Press

Figure 18: Photograph of the burning Valero's McKee Refinery in Texas [11]

5.2.2.1 Summary of the incident

On 16 February 2007, at approximately 02:09 the release of liquid propane – about 4,500 pounds per minute (≈ 2,040 kg/min) – resulted in a massive fire at Valero's McKee Refinery near Sunray, Texas (**Figure 18**). The release was caused by a freeze-related failure, resulting in the formation of a vapour cloud and a jet fire leading up to multiple pipe failures. 15 minutes after the fire ignited the whole refinery was evacuated. It caused extensive equipment damage and the refinery had to be shut down for two months. Four people got injured during the incident. The fire was completely extinguished 54 hours after ignition. [11]

5.2.2.2 Cause of the jet fire

The people working close to the unit that failed suddenly heard a "pop" and saw something steam like blowing from a control station near the No. 1 extractor tower (**Figure 19**). It was quickly determined, that the steam actually was a cloud of propane. Consequently the workers were told to evacuate. The liquefied, pressurized propane was released from a cracked control station piping – an elbow leading to a valve which was currently not in use

Figure 19). Most likely the vapour cloud ignited when it reached the boiler house. The flames then flashed back to the leak source and directly impinged the piping close by. This led to the release of additional propane and the formation of a jet fire (**Figure 20**). The jet fire directly hit the steel support of a pipe rack (**Figure 2** on p. 19), which collapsed and led to multiple pipe failures. More liquid petroleum products were released, feeding the fire and destroying big parts of the site (**Figure 21**). [20]

Figure 19: Crack in the 10'' propane pipe and the site 90 seconds after ignition (CCTV) [11] p. 23+16

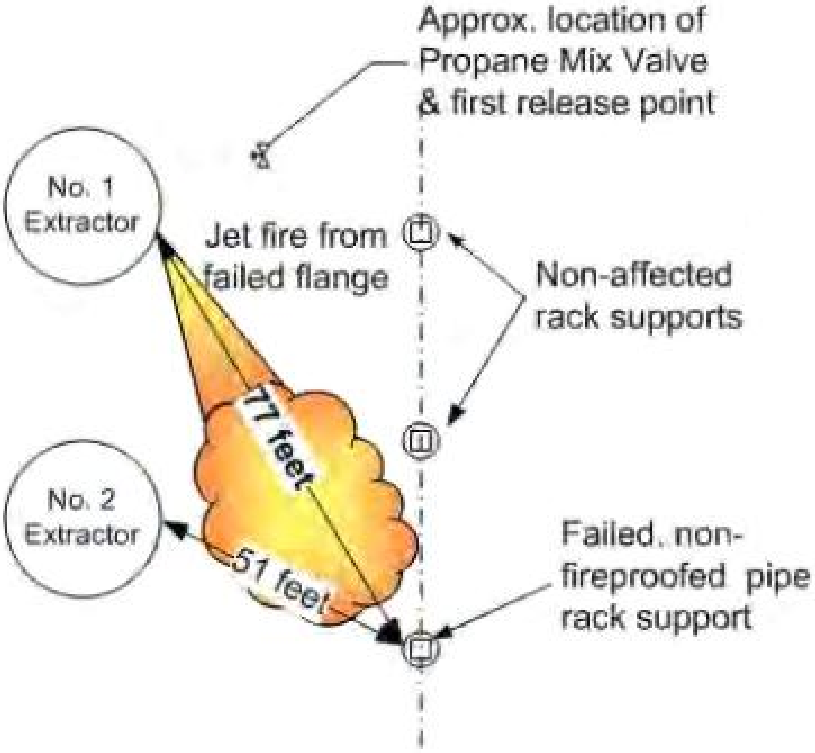

Figure 20: Distances between the pipe rack supports and the extractors [11] p. 32

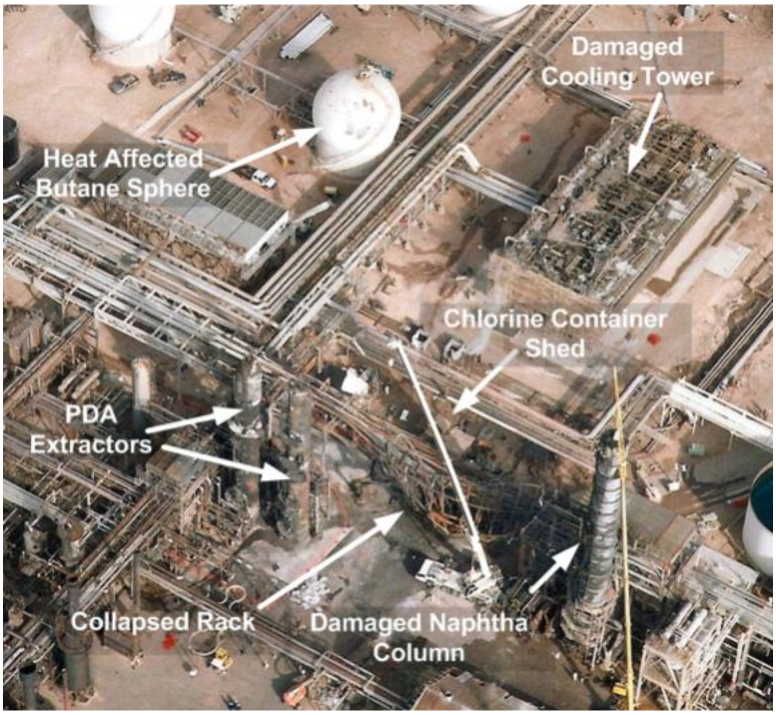

Figure 21: Aerial photograph of the damages [11] p.19

5.2.2.3 Hazardous effects of the jet fire

After the initial formation of the vapour cloud, the jet fire was the key event, which led to the destruction of big parts of the refinery. Its main impact was on the structure, especially a bridge with pipelines, of which only one side was fireproofed (see **Figure 2** on p. 19). Three of the four workers injured were seriously burned. All other kinds of damages were caused by heat radiation or fire impingement. [20]

5.2.2.4 Calculation input data and results

The input data presented in **Table 24** has been obtained from the information provided in the CSB report. For this event the focus is on the jet fire only.

Table 24: Input parameters for the calculation of effects (Jet fire, Sunray) [11] [33]

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Propane, liquefied
	x_{42}	m	Relevant distances	1 to 500
Ambient	T_0	°C	Ambient temperature	12.8

	φ	%	Relative humidity	44%
	u_w	m/s	Wind speed	5.4
Process	T_{init}	K	Initial temperature	$= T_0$
	P_{init}	Pa	Initial pressure	$3.447 * 10^6$
Time	t_{ex}	s	Exposition time	30
Leak rate	m’	kg/s	Mass flow rate	34
Leak size	A_{out}	m²	Area of the leak	$1*10^{-3}$
Geometry	Θ	°	Angle of the flames	90

In **Table 25** the information gathered from the report about the distances with harmful effects is compared to the results of the calculation models from chapter 4. The major harmful effect of the jet fire was the impingement of the piping rack. Due to the huge amount of follow up explosions and fires it is not possible to identify which effects were only based on the jet fire. It is also not sure whether the jet fire was as long as presented in **Figure 20** or whether it was actually longer and this graphic is only to demonstrate, that the jet fire hit the piping rack.

The selected model in EFFECTS [0] is the Chamberlain model. Hence, it is basically the same model as used for the calculation models in chapter 4. Though, it is not clear, whether EFFECTS integrated the error (according to [8]) in the Chamberlain model from the Yellow Book [1]. There is a significant difference between the results. The length of the jet flame according to EFFECTS is only half as long as expected. However the effects documented are supporting the longer jet flame. But in this case the report data support the shorter flame.

Table 25: Comparison of the results of the calculation models, EFFECTS and report data (Jet fire, Sunray) [0] [11]

Symbol	Unit	Description	Calculation	EFFECTS	Report/Reality
l_j	m	Length of the jet	53.1	30.3	> 23.5
d_j	m	Diameter of the jet	26.5	12.6	
r_{50j}	m	Distance with 50% probability of fatality	33		
r_{1j}	m	Distance with 1% probability of fatality	53		
x_{red}	m	Red zone according to heat radiation		29	> 23.5
	m	For people	> 66	73	

x_{orange}	m	Orange zone according to heat radiation	49	
	m	For people	91	
x_{yellow}	m	Yellow zone according to heat radiation	109	
	m	For people	121	

5.3 Pool evaporation and pool fire

There is hardly any record of hazardous events including only pool fires. The events mentioned, which started up with a pool often lead to a VCE or a BLEVE. Since the major effects are not caused by the pool fire itself (it is “only” the trigger), it is usually not the event focused on. But for pool fires and their heat radiation a couple of experiments have been conducted. In this chapter the outcomes of such experiments are compared to the effects of pool fires based on the calculation models and for another event that started with a pool, the theoretical effects without the follow up explosions are calculated.

5.3.1 Experimental pool fires

Figure 22: Pool of 0.6 l gasoline on concrete before and after ignition [8] p. 335

5.3.1.1 Introduction

In the Yellow Book [1] a couple of pool fire experiments are presented. The substance, the area of the pool and the resulting heat radiation are documented. To verify the calculation models, the experimental data are compared to the results based on the models from chapter four.

5.3.1.2 Calculation input data and results

For very volatile substances (T_b < 20°C) the assumption is made, that the formed pool vaporizes within very little time. Hence, the relevant calculations and hazardous effects are the ones for vapour clouds. In **Table 26** the data from pool fire experiments and the SEP according to calculations are compared.

Table 26: Comparison of effects according to experiments and calculation models [1] p. 6.70

	Experimental			Calculated		Experimental			Calculated	
Substance	**D [m]**	**L/D [ ]**	**SEP_{act} [kJ/m²*s]**	**SEP_{act} [kJ/m²*s]**	**SEP_{max} [kJ/m²*s]**	**D [m]**	**L/D [ ]**	**SEP_{act} [kJ/m²*s]**	**SEP_{act} [kJ/m²*s]**	**SEP_{max} [kJ/m²*s]**
Acrylonitrile	1	2.64	36	126.4	46.8	10	1.31	67	56.1	354.9
Carbon Disulphide	1	2.37	15	126.4	20.3	10	1.18	28	56.1	144.8
Methanol	1	1.59	19	126.4	15.9	10	0.79	34	56.1	88.7

The temperature at which the experiments were conducted was not given. 20°C was taken as a realistic assumption. The SEP_{act}, calculation based, is not dependent on the substance or temperature, but only on the diameter of the pool. SEP_{max} depends on the substance. To gain the most realistic results, SEP_{act} should be taken for big diameters and SEP_{max} for small diameters. For the decision up to which pool size, which formula should be used, further experiments would be necessary.

5.3.2 Diesel evaporation – Richmond, US 2007 (Chevron Refinery)

Figure 23: Initial vapour cloud formation (white cloud) and ignition (black smoke) [34] p. 30

5.3.2.1 Summary of the incident

On 6 August 2012 at approximately 18:33, a pipe rupture followed by an explosion took place at the Chevron U.S.A. Inc. Refinery in Richmond, California. At the time of the incident light gas oil was flowing through the pipe at a rate of approximately 10,800 bpd (≈ 19.9 l/s). The released substance partially vaporized into a large vapour cloud. About two minutes after the release, the cloud ignited. Six people suffered minor injuries during the incident. The release, ignition and burning of the hydrocarbon fluid caused a huge cloud of vapour, particulates and black smoke moving to the surrounding areas (**Figure 23**). In the weeks following the incident about 15,000 people from communities around the refinery requested medical treatment. [34]

5.3.2.2 Cause of the pool evaporation and VCE

The original cause of the incident was a leaking pipe. Three hours before the explosion took place an outside operator discovered an 18-inch (0.46 metre) puddle of a diesel-like liquid (**Figure 24**). He could identify a leaking pipe 4 meters above the ground, which was releasing the substance at a rate of about 40 drops per minute. Since the pipe was insulated it was not possible for him to spot the leak. The operator realized that the pipe could not be isolated from the process. However, the leak was considered not dangerous enough to require a complete shutdown. Firefighters were alarmed which then defined a six times six metre hot zone. The rest of the area was considered to be safe. [34]

Figure 24: CSB animation of the operator identifying the leaking pipe [34] p. 23

Additional people were called to the spot to support the analysis of the leak. Later on it was decided to reduce the feed from 10,800 to 5,000 bpd (≈19.9 to 9.2 l/s). Then the insulation was removed from the pipe, so the cause of the leak might be visible and further measures, repair or shut down of the unit, could be taken. The firefighters were aware of the risk of vapour leaking from under the insulation could mix with air and ignite. During the removal white hydrocarbon vapour began to emerge. The insulation that was soaked with hot hydrocarbon auto-ignited only feet from the firefighters. Immediately the fire was put out and the attempt was made to remove the rest of the insulation. Within minutes the situation had gotten worse. Hydrocarbon liquid was now spraying from the pipe. This was the moment when it was finally decided to shut down the unit, an action that takes hours to complete. It was only a question of time when the quickly growing vapour cloud was going to ignite. That moment people only tried to escape as fast as possible. In **Figure 25** the timeline of the whole incident is presented. [34]

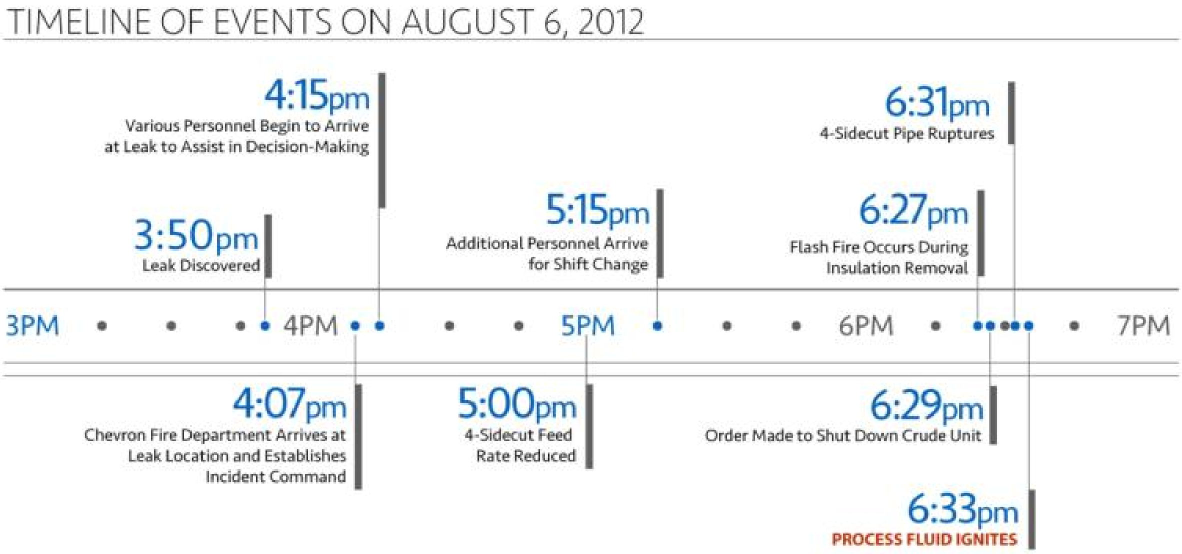

Figure 25: Timeline of events 6 August 2012 [34] p. 25

5.3.2.3 Hazardous effects of the pool evaporation and VCE

When the vapour cloud started to form the firefighters tried to keep it at bay by spraying it with water. But suddenly the firefighters as well as the operators, which were standing in the supposedly save zone were engulfed by the hot and extremely dense cloud. People inside the cloud could hardly see a thing and tried to escape. Two minutes after formation the cloud ignited. At that time only one fireman had not made it out of the cloud. Due to his full body protective equipment he managed to escape through the flames without any injuries.

During the incident six people were injured. The main hazardous impact was within the following weeks, when about 15,000 people from nearby communities visited medical facilities suffering under the consequences of polluted air such as breathing problems, chest pain, shortness of breath, sore throat and headaches. [34]

5.3.2.4 Calculation input data and results

The input data presented in **Table 27** has been obtained from the report about the incident by CSB. In this case the aim is to calculate the effects of a vapour cloud only resulting from the diesel from the pool plus the dropping. The additional amount of substance dropping is considered as 2 ml/min (20 drops equal 1 ml). There is no sufficient information provided for a more exact calculation. Based on the idea of a vapour cloud developing from the whole substance released, it is decided whether the 6 x 6 metre hot zone would have been big enough to protect the workers. The actual substance involved was Diesel, but due to a lack of parameters, gasoline was used as an assumption instead. [34]

Table 27: Input parameters for the calculation of effects (Pool evaporation, Richmond) [34]

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Gasoline, liquid
	x_{42}	m	Distance from fire/explosion	1 to 10
Ambient	T_0	°C	Ambient temperature	30
	φ	%	Relative humidity	33%
	u_w	m/s	Wind speed	5.4
Leak rate	V'_{out}	m^3/s	Volume flow rate	$3.3*10^{-8}$
	t_{vap}	s	Time of evaporation	9,600
Pool	D_p	m	Diameter of the pool	0.46
	δ	-	Type of subsurface	Concrete

In **Table 28** the theoretical effects of an ignited vapour cloud, that is only based on the amount of substance vaporised from the pool and the additional dropping is calculated. It is not documented, how much substance was released when the isolation was completely removed and it started spraying out of the leak. Based on the knowledge of the diesel pool and the additional dropping the 6x6 metre hot zone was defined by the firefighters. According to the calculation the fireball would have had a radius of about 2.9 metres. The zone would not have been too small, but for safety purposes, it would have been better to at least consider the safety distance for firemen of around 12 metres.

Table 28: Results of the calculation models compared to results from EFFECTS (VCE, Richmond) [0]

Symbol	Unit	Description	Calculation	EFFECTS
m_{vap}	kg	Mass of the substance in the pool	0.7022	
m_{out}	kg	Mass of the substance including drops	0.7105	
r_{fb}	m	Radius of the fireball	2.90	
t_{fb}	s	Burning time of the fireball	0.78	
x_{smin}	m	Safety distance for firemen	11.6	
x_{min}	m	Safety distance for other people	43.5	
x_{redex}	m	Red zone according to heat explosion		4
		For people		7

$x_{orangeex}$	m	Orange zone according to explosion	6
		For people	15
$x_{yellowex}$	m	Yellow zone according to explosion	22
		For people	35

The selected model in EFFECTS [0] is the “Multi Energy model”. This model is useful to estimate the pressure effects of VCEs. Hence, for the potential VCE based on the substance evaporated from the pool. Since for both calculations gasoline was used, the results are comparable. The main area of danger in both cases is about 6 metres, which supports the 6x6 metre safety zone.

5.4 Vapour cloud explosion

In this chapter two accidents which include a VCE are presented. First a short description of each incident is given, then the documented data and effects are compared to the expected effects, according to the calculation models from chapter 4. The selected cases are a VCE at the Buncefield terminal in the UK in 2005 and a tank fire at CAPECO in Puerto Rico in 2009. In both cases overfilling was the initial cause of the vapour cloud.

5.4.1 Gasoline VCE – Hertfordshire, UK 2005 (Buncefield oil storage depot)

Figure 26: Burning tanks and pump-house marked [18] p. 60

5.4.1.1 Summary of the incident

On the early morning of 11 December 2005, at approximately 05:30, a gasoline tank was overfilled at the Hertfordshire Oil Storage Ltd Terminal for Gasoline, Diesel and Jet Fuel. The filling rate was about 550 m^3/h for 23 minutes (rising up to 900 m^3/h for the final 8 minutes). Then the released gasoline formed a vapour cloud that spread all over the site. The cloud was ignited by a fire pump, which automatically started when the emergency system was activated. It caused a massive explosion as well as follow up fires which lasted for five days. Fortunately, nobody got seriously injured or died as a consequence of the incident. [18] [35]

5.4.1.2 Cause of the VCE

The overfilling was caused by failures of design and a lack of maintenance. Technically the tank that got overfilled had two types of level control, however both failed. The tank had a gauge for the workers to monitor the filling operation (which was stuck since August 2005) and an independent high-level switch that was supposed to close down operations automatically when overfilling occurs. Due to a lack of communication between the supplier and the operator (the switch needed a padlock to retain its check lever in working position), it was inoperable. Consequently the staff in the control room did not notice the overflow. There was a secondary containment (a bund retaining wall around the tank) and a tertiary containment, both of them also failed. At the time of the release it was still dark outside, but the areas covered by CCTV captured the development of white mist as visible in **Figure 28**. The mist was first visible about 25 minutes before the explosion. It developed up to a depth of about 2 metres over most of the area covered by cameras.

Finally, when the cloud reached the tanker loading gantry, a tanker driver reported it. Immediately the emergency system was activated, which automatically started the site fire pump. This ignited the vapour cloud and led to the explosion. [18] [35]

Figure 27: Accumulation of the vapour cloud caught on CCTV [18] p. 54

5.4.1.3 Hazardous effects of the VCE

The footprint of the vapour cloud was about 500 times 350 metres (see **Figure 28**), with a depth of 2 to 3 metres. It caused a peak-overpressure exceeding 200 kPa. All site buildings engulfed by the cloud were destroyed. The Buildings of which only the basis was exposed to the cloud got significantly damaged, but not completely destroyed. [18] [35]

Figure 28: The site before and after the explosion, area of the vapour cloud marked [18] p. 49-50

In **Figure 29** the difference of the effects depending on whether the area was covered by the cloud or not, is presented. All product tanks located within the cloud were set on fire. Below the liquid level they did not split, but were only deformed. Severe explosion effects were observed close to the edges of the cloud. Houses within distances of 100 metres to the cloud were wrecked. Minor damages to the surroundings of the site extended to a distance of 1.5 kilometres. However, no one got severely injured during the incident. [18] [35]

Figure 29: The edge of the vapour cloud marked by scorching and blast damage [18] p. 53

5.4.1.4 Calculation input data and results

The input data presented in **Table 29** has been obtained from the data provided in the HSE reports. All values in the table were necessary for the calculation of the possible consequences. Except the ones in brackets, they are only for information purposes.

Table 29: Input parameters for the calculation of effects (VCE, Hertfordshire) [18]

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Gasoline, liquid
	x_{42}	m	Considered distances	1 to 2,000
Ambient	T_0	°C	Ambient temperature	0
	φ	%	Relative humidity	100%
	(u_w	m/s	Wind speed	2.2)
Process	T_{init}	°C	Initial temperature	14
Amount	m	kg	Mass of the flammable substance	195,000

In **Table 30** the information gathered from the report about distances with harmful effects is compared to the results of the calculation models from chapter 4. This example reflects the main problem with the TNT-equivalent model, if the substance is not listed in **Table 13** (p. 40). To figure out which value for η is the best choice, the different values have been compared. It is clearly visible that simply choosing the highest value would provide unrealistic results. In the Yellow Book [1] it is proposed to use 4% for incidents at refineries and 10% as an upper limit. The results support this hypothesis.

Table 30: Results of the calculation of effects compared to data from reality (VCE, Hertfordshire) [18]

Symbol	Unit	Description	η=0.003	η=0.04	η=0.1	η=0.2	Report
r_{fb}	m	Radius of the fireball	170	170	170	170	236
t_{fb}	s	Burning time of the fireball	20.2	20.2	20.2	20.2	
x_{smin}	m	Safety distance for firemen	679	679	679	679	
x_{min}	m	Safety distance for other people	2,546	2,546	2,546	2,546	
x_{red}	m	Red zone according to heat radiation	58	58	58	58	
x_{redex}	m	Red zone according to explosion	105	250	339	>2,000	256-336
		For people	197	467	635		

x_{orange}	m	Orange zone according to heat radiation	290	290	290	290	
$x_{orangeex}$	m	Orange zone according to explosion	170	403	547	>2,000	536
		For people	491	1,167	1,585		
x_{yellow}	m	Yellow zone according to heat radiation	440	440	440	440	
$x_{yellowex}$	m	Yellow zone according to explosion	697	1,655	>2,000	>2,000	1,736
		For people	1,223	>2,000			

There was sufficient information documented to derive all three zones, but only for structural damage. Also, it is not stated whether the damages were due to heat radiation or the blast wave. However, from the description (eg wrecked houses) it can be assumed that the effects were due to the pressure wave.

In **Table 31** the results of the calculations which are closest to the observed effects are compared to the effects according to EFFECTS [0]. The selected models in EFFECTS are the “Static BLEVE model (Yellow Book)” and the “Multi Energy model”. Both models are presented, because the scenario was actually a VCE, not a BLEVE and the results from the “Multi Energy model” are more realistic.

Table 31: Comparison of the results of the calculation models and EFFECTS to report data (VCE, Hertfordshire) [0] [18]

Symbol	**Unit**	**Description**	**η=0.04**	**η=0.1**	**EFFECTS BLEVE**	**Multi Energy**	**Report**
r_{fb}	m	Radius of the fireball	170	170	164		236
t_{fb}	s	Burning time of the fireball	20.2	20.2	19.7		
x_{smin}	m	Safety distance for firemen	679	679			
x_{min}	m	Safety distance for other people	2,546	2,546			
x_{red}	m	Red zone according to heat radiation	58	58	546		
x_{redex}	m	Red zone according to explosion	250	339	26	236	256-336
		For people	467	635	58	431	
x_{orange}	m	Orange zone according to heat radiation	290	290	763		
$x_{orangeex}$	m	Orange zone according to explosion	403	547	48	374	536
		For people	1,167	1,585	145	1010	
x_{yellow}	m	Yellow zone according to heat radiation	440	440	984		

$x_{yellowex}$	m	Yellow zone according to explosion	1,655	>2,000	200	1385	1,736
		For people	>2,000		217	2280	

5.4.2 Gasoline VCE - San Juan, Puerto Rico 2009 (CAPECO Gasoline terminal)

Figure 30: Multiple tank fires at the CAPECO gasoline terminal in San Juan [4] p. 24

5.4.2.1 Summary of the incident

On 23 October 2009, around 00:23, a large explosion took place at the Caribbean Petroleum Corporation (CAPECO) facility in Bayamón, Puerto Rico. It involved about 194,000 gallons (≈ 735 m^3) of gasoline. A tanker ship was offloading gasoline to the CAPECO tank farm onshore, when the storage tank overflowed into a secondary containment dike, vaporized and formed a vapour cloud. The release happened over a time span of 26 minutes. About 3 minutes after the overfilling stopped the cloud reached an ignition source and exploded. Multiple secondary explosions and fires occurred (**Figure 30**). They were extinguished after burning for almost 60 hours. Fortunately, there were no fatalities and only three people suffered from minor injuries. The structure suffered under significant damage. [18] [4]

5.4.2.2 Cause of the VCE

When the unloading took place, the gasoline was not filled into two storage tanks, since the amount of gasoline would have been too much for one. The first tank (Tank 411) was full at around 22:00. Then the valve to the second tank (Tank 409) was opened fully. The CAPECO operators did not rely on the measurement data transmitted to the computer, because the transmitters have been regularly out of service. This was also the case that night and the operators manually recorded the data in hourly readings. It was expected that the tank would be full at 01:00. Hourly checks were conducted. At the check at 23:00 there was no vapour cloud visible. At 00:00 the tank farm operator observed a vapour cloud and a strong smell of gasoline. He contacted the dock operator to stop the filling of the tank and met up with his supervisor and the operator. They were aware of the potential danger and started to look for the source of the leak and the developing vapour cloud.

The cause of the overfilling was probably a combination of a couple of malfunction. One of the failures was the tank side gauge or the float and tape apparatus, since wrong filling levels were recorded. Another possible factor is the failure of the internal floating roof of the tank, for instance due to turbulence or other factors.

Figure 31: Tank geometry and suggested trajectories of over spilled gasoline [18] p. 126

The release of the gasoline took place in the form of a cascade of volatile liquid and happened through six vents which were located on the top of the tank. This implicates a kind of spray release, which quickly aerosolized due to the high volatility of gasoline, quickly forming a vapour cloud. What the release exactly looked like is still not clear; a suggestion is presented in **Figure 31**.

At 00:23 the vapour cloud ignited, it exploded about seven seconds later. The source of ignition is unknown what was, but it is recorded, that it must have happened in the area of the waste water treatment. [18] [4]

5.4.2.3 Hazardous effects of the VCE

While the fire propagated through the vapour cloud it ignited multiple other tanks, causing follow up explosions. When the fire was finally extinguished 17 of the 48 tanks had burnt. The firefighters were mainly focused on preventing other tanks from ignition rather than distinguish the fire of the already burning tanks.

Figure 32: CAPECO site with marked area of the vapour cloud [18] p. 123

The footprint of the vapour cloud is presented in **Figure 32**. It covered an area of about 465,000 m². Within the cloud heave damage occurred. The explosions reached a 2.9 on the Richter scale. Hence, it was comparable to a very light earthquake. Moderate damage was caused within 50 metres of the cloud and light damage occurred within 500 metres of the cloud. The blast of the VCE caused a pressure wave that damaged houses up to a distance of 1.25 miles (over 2 km) from the site. Three people off-site suffered minor injuries. There were no severe injuries or fatalities. [18] [4]

Figure 33: The site prior to and after the incident [4] p. 24

5.4.2.4 Calculation input data and results

The input data presented in **Table 32** has been obtained from data provided by the HSE and CSB report.

Table 32: Input parameters for the calculation of effects (VCE, San Juan) [4] [18]

Category	Symbol	Unit	Description	Report/Reality
Basic			Substance and phase	Gasoline, liquid
	x_{42}	m	Considered distances	1 to 2,000
Ambient	T_0	°C	Ambient temperature	26.7
	φ	%	Relative humidity	76%
	u_w	m/s	Wind speed	0
Process	T_{init}	K	Initial temperature	26.7
Amount	V_{out}	m^3	Volume of the flammable substance	735

In **Table 33** the information gathered from the report about the distances with harmful effects is compared to the results of the calculation models from chapter 4. On the basis of the real effects all three zones can be derived, but only based on damage to the structure. The information where the people, which suffered under minor injuries, were located is not provided. It is only stated that it was “off-site”.

This example reflects the main problem with the TNT-equivalent model. To figure out which value for η is the best choice, different suggested values have been compared. It is clearly visible that simply choosing the highest value would provide unrealistic high results. In the Yellow Book [1] it is proposed to use 4% for incidents at refineries and 10% as an upper limit. The results support this hypothesis.

Table 33: Results of the calculation of effects in comparison to data from reality (VCE, San Juan) [18]

Symbol	Unit	Description	η=0.003	η=0.04	η=0.1	η=0.2	Report
r_{fb}	m	Radius of the fireball	237	237	237	237	
t_{fb}	s	Burning time of the fireball	26.4	26.4	26.4	26.4	
x_{smin}	m	Safety distance for firemen	948	948	948	948	
x_{min}	m	Safety distance for other people	3554	3554	3554	3554	

x_{red}	m	Red zone according to heat radiation	381	381	381	381	385
x_{redex}	m	Red zone according to explosion	148	351	477	>2,000	
		For people	277	657	893	>2,000	
x_{orange}	m	Orange zone according to heat radiation	632	632	632	632	435
$x_{orangeex}$	m	Orange zone according to explosion	239	567	769	>2,000	
		For people	687	1,629	>2,000	>2,000	
x_{yellow}	m	Yellow zone according to heat radiation	862	862	862	862	885
$x_{yellowex}$	m	Yellow zone according to explosion	969	>2,000	>2,000	>2,000	>2,000
		For people	1,681	>2,000	>2,000	>2,000	

The radius of the cloud was calculated on the basis of a circle with the reported area of the cloud. This radius reflects the red zone according to the report. In the HSE report the area of the cascade compared to the volatility of the gasoline is a point of discussion. As stated in the description of the calculation models, for such cases the assumption of a quick, complete vaporisation of the spilled substance is made. The details of the real area of the cascade are not necessary or feasible for an improvement of results.

In **Table 34** the results of the calculations which are closest to the observed effects are compared to the effects according to EFFECTS [0]. The selected models in EFFECTS are the “Static BLEVE model (Yellow Book)” and the “Multi Energy model”. Both models are presented, because the pressure effects according to the static model seem unrealistic and the results from the “Multi Energy model” are closer to the observations in the report.

Table 34: Results of the calculation of effects in comparison to data from reality (VCE, San Juan) [0] [18]

Symbol	**Unit**	**Description**	**η=0.04**	**η=0.1**	**EFFECTS BLEVE**	**Multi Energy**	**Report**
r_{fb}	m	Radius of the fireball	237	237	228		
t_{fb}	s	Burning time of the fireball	26.4	26.4	25.63		
x_{smin}	m	Safety distance for firemen	948	948			
x_{min}	m	Safety distance for other people	3554	3554			
x_{red}	m	Red zone according to heat radiation	381	381	868		385
x_{redex}	m	Red zone according to explosion	351	477	35	330	330
		For people	657	893	77	607	607

x_{orange}	m	Orange zone according to heat radiation	632	632	1191		435
$x_{orangeex}$	m	Orange zone according to explosion For people	567 1,629	769 >2,000	66 193	527 1421	527 1421
x_{yellow}	m	Yellow zone according to heat radiation	862	862	1523		885
$x_{yellowex}$	m	Yellow zone according to explosion For people	>2,000 >2,000	>2,000 >2,000	272	1950 3210	>2,000

6 Conclusion

In this chapter the main outcomes of this thesis, their scope and limitations are discussed.

6.1 Summary

It is generally possible to gain useful results with very limited input factor. The results will not be too exact, but good enough for rough estimations of the safety distances. Effects of source terms were intended to be considered in more detail, but the number of the source terms that are easy to obtain and have a relevant influence is very limited. Basically only ambient (weather) conditions and the size of the leak are considered.

Most of the formulas have been developed in the 1970s-1980s. Since then, not much improvement has been made, especially if it comes to the effects of explosions. The TNT-equivalent model is considered outdated. However, there is no alternative yet.

The effects of explosions of both, BLEVEs and VCEs have been calculated based on the TNT-equivalent model. Currently the main challenge is to choose the correct value for the efficiency factor. It is only clearly defined for a few substances.

The calculation of fireballs, for both BLEVEs and vapour clouds is quite simple and for improvement soot formation and more source terms would have to be considered, whether it would improve the results remarkably is unclear. The comparison of the results from the calculation models to the results according to EFFECTS [0] shows little variation in the size and burning time of the fireball, however the heat radiation effects according to EFFECTS are higher. Considering the maximum overpressure the effects were comparable, but for the VCEs the “Multi Energy model” has to be used. This is probably the case, because a VCE has different properties than a BLEVE. There is no container and the substance had more time to mix with air in the case of a VCE. Also the substance considered in the cases is gasoline, which would be unlikely to be involved in a BLEVE, since it is not liquefied pressurised gas.

If it comes to jet fires, the crucial information is the size of the leak. Compared to vapour clouds they have the great feature of being unable to move. Their biggest risks are direct impingement and follow up explosions. If the source of the stream is cut, the jet fire is extinguished. Also, people if not trapped by their surroundings are able to leave the red zone themselves. Only in the case of being directly hit or standing extremely close to the jet fire, they are at risk of dying. Compared to this the danger of a vapour cloud or a BLEVE may be hidden. The flames of jet fires according to EFFECTS [0] are only about half as long as the flames according to the calculation models from chapter 4. However, compared to historic data one time the short flame is closer to reality and in the Baumgarten case a longer flame is more realistic.

Pool fires are most of the times not the major threat during an incident, but the cause of further release of substances. Compared to the other scenarios they are not really dangerous if they do not heat other equipment or someone is trapped by it. Also the fire brigade usually will not have too many troubles handling them.

The calculation models for all four scenarios provide acceptable results compared to the observed effects. Also the comparison of the calculated results with the distances according to EFFECTS [0] shows an acceptable variation. The results are not identical, but similar and in some cases EFFECTS [0] was closer to reality, sometimes the presented models. However the data from past events, especially for jet fires and pool fires is very limited. There is a lack of data for a real verification of the models.

6.2 Scope and limitations

The main challenge is the lack of data to verify results. In theory, hazardous events should be documented to allow learning from them. In reality (not talking about the couple of detailed reports from HSE/CCPS), the substance is documented, quite likely the amount released, but not the size of the leak, the process conditions, the exposition time or the distances of the hazardous effects. To use the TNT-equivalent model, η has to be known for a various amount of substances. It could be determined for more substances, if there would be any data provided by the industry.

There are a lot of different hazardous substances. Some of them (eg natural gas, propane) are involved in incidents more regularly. In theory, there should be at least 100 comparable events, involving the same substance to obtain good data. Hence, for some substances the models are not too bad, but as soon, as it comes to a mixture of substances or a combination of the scenarios it not possible to estimate the effects in detail. The moment a chain reaction starts at a refinery the whole thing will just burn to the ground. However, the recent safety mechanisms aim to prevent chain reactions.

As long as there is such a lack of data, it is possible to fit every calculation to a good result, because influential values can be fitted.

6.3 Outlook

The database of hazardous events by the EU should be used in a different way. Currently it is hardly helpful to prevent harmful events from happening again. It is very difficult to conduct experiments with such huge amounts of flammable substances and therefore it is crucial to use the data from past events. Only that way, the safety of people can be improved.

It is unacceptable that firefighters die because of a lack of information that would not be difficult to obtain. Maybe at some point some app will be used, that immediately warns about the risk of a BLEVE or VCE if that scenario is possible due to the substances involved. Additionally, it should provide at least the safety distances for firemen, which are really easy to estimate based on only the amount of the flammable material.

Ideally the results of this thesis will be combined with some map, potentially from the internet and the estimated risk zones will be combined with information about vulnerable population. That way children and elderly people could be protected. For instance if a similar scenario as in Bologna happens again, it could be estimated up to which distance buildings or playgrounds have to be evacuated. However, to estimate those distances it is necessary to know, what the tanker has loaded and whether it is full or only half full.

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