Workshop on Hydrocarbon Refrigerant Safety

Quantitative Risk Assessment on RACHP equipment

21st & 22nd January 2020

Königstein, Germany

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Content

Introduction

Objective: provide guidance on how to apply QRA to R290 systems

- Risk assessment in context
- Use of EN 1127-1

Quantification

- Leak frequencies, probabilities of flammable mixtures, ignition frequencies, probabilities, etc.
- Other factors
- Estimation of primary consequences (overpressure, thermal dose, others)
- Secondary consequences (damage, fire, injuries, fatalities, etc.)

Introduction

Risk = frequency of hazardous event × consequence severity

Introduction

Establish conditions

Compliance with legislation/directives

Conformity to safety standards

Specific risk assessment

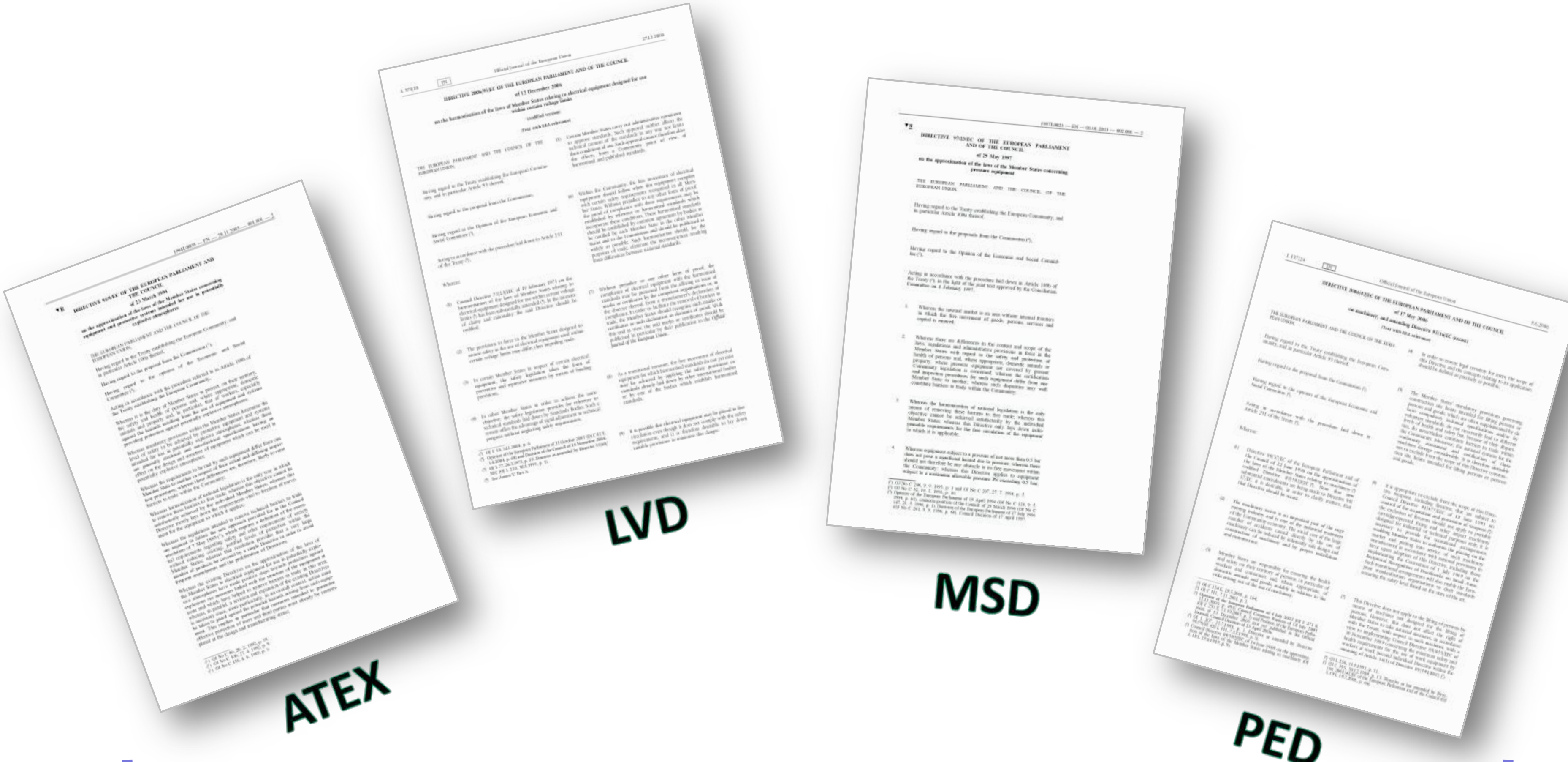
Legislation and specifics for flammable refrigerants

- Relevant Directives and Standards
- Risk assessments in Standards

Introduction

- Compliance with the law…
- In EU, necessary to comply with EHSRs of the applicable Directives/national implementing legislation
- EHSRs may be achieved
  - with harmonised standards
  - without harmonised standards
  - with non-harmonised standards
  - with other technical specification
- Product/situation has to be "safe"
  - (whatever that means…)

Relevant directives



All demand risk assessment

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Relevant standards


DD 261:2010

BSI Standards Publication

DRAFT FOR DEVELOPMENT

Human reliability – Guide to the fundamental considerations

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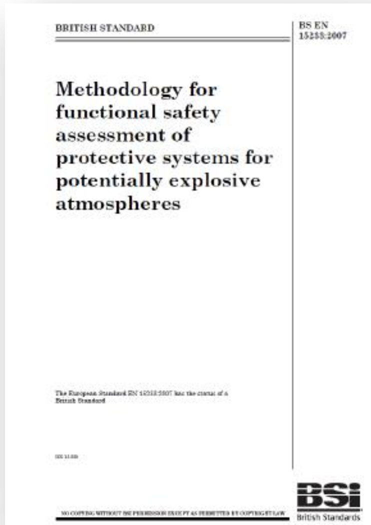
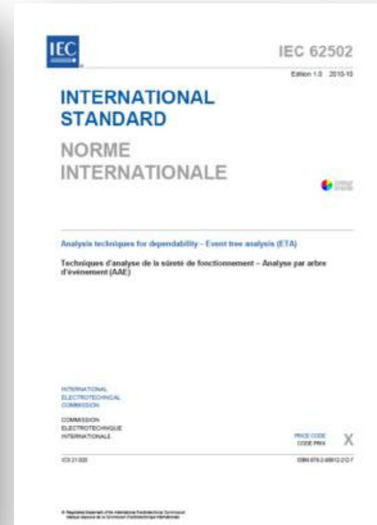
BSI


BRITISH STANDARD

BS EN 15233:2007

Methodology for functional safety assessment of protective systems for potentially explosive atmospheres

BSI British Standards


IEC

IEC 62502

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Analysis techniques for dependability – Event tree analysis (ETA)

Techniques d'analyse de la sûreté de fonctionnement – Analyse par arbre d'événement (AAE)


BS EN 31010:2010

BSI Standards Publication

Risk management

Risk assessment techniques

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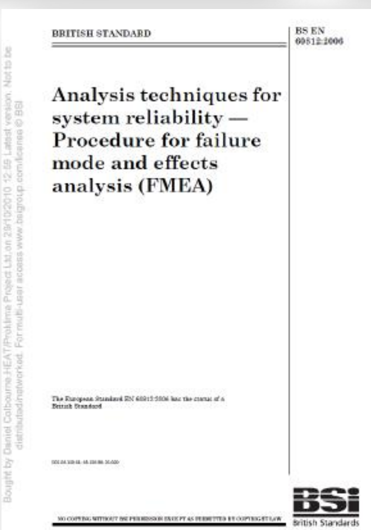
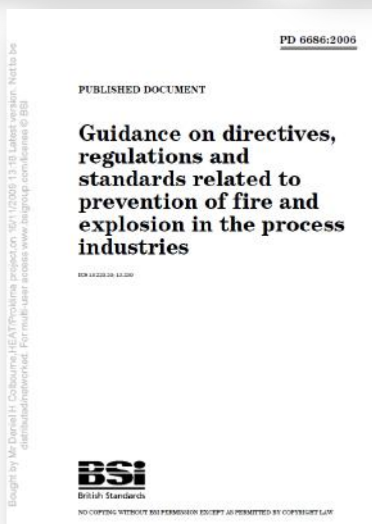

BRITISH STANDARD

BS EN 60812:2006

Analysis techniques for system reliability — Procedure for failure mode and effects analysis (FMEA)

BSI British Standards


PD 6686:2006

PUBLISHED DOCUMENT

Guidance on directives, regulations and standards related to prevention of fire and explosion in the process industries

BSI British Standards

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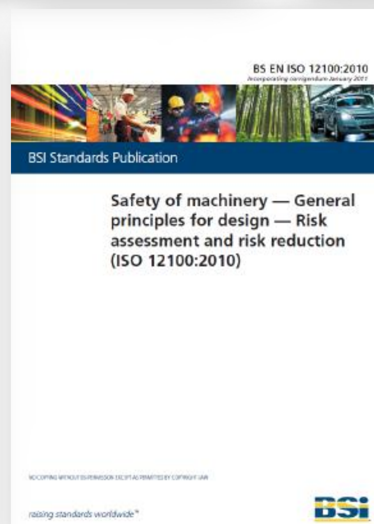
BS EN ISO 12100:2010

BSI Standards Publication

Safety of machinery — General principles for design — Risk assessment and risk reduction (ISO 12100:2010)

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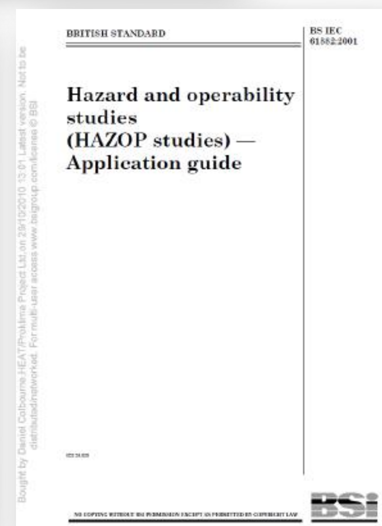
BSI


BRITISH STANDARD

BS IEC 61882:2001

Hazard and operability studies (HAZOP studies) — Application guide

BSI

Tools for risk assessment

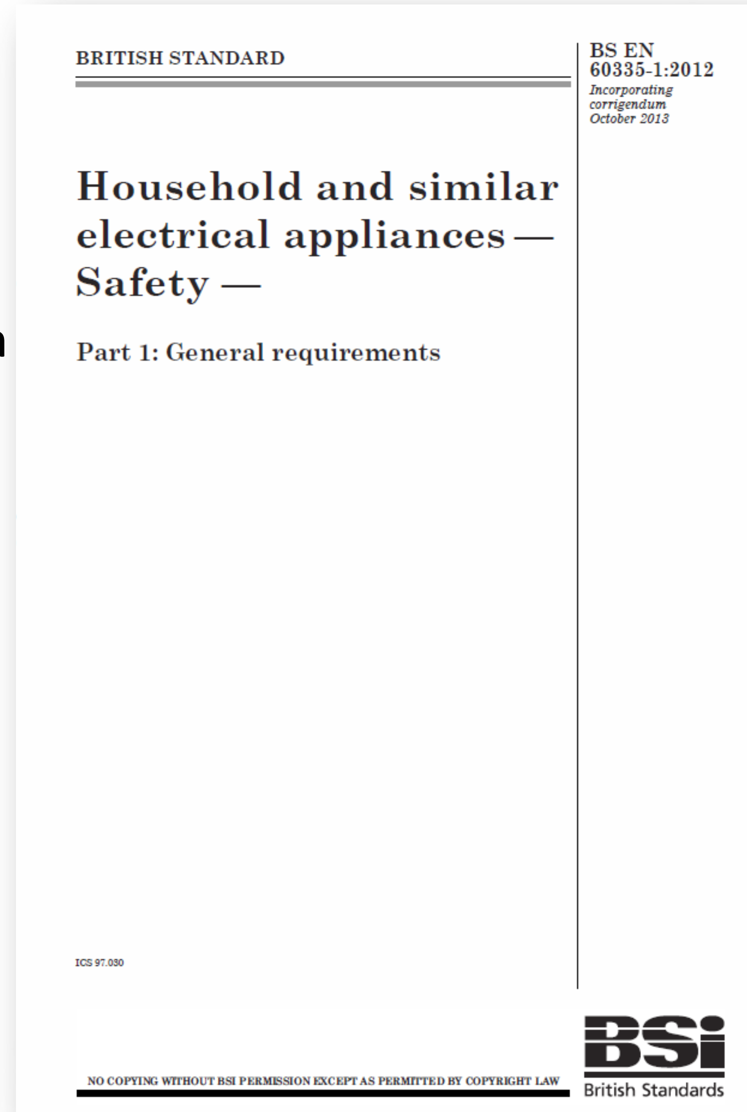
Structured or semi-structured interviews	Cause-and-effect analysis
Delphi	Layer protection analysis (LOPA)
Check-lists	Decision tree
Primary hazard analysis	Human reliability analysis
Hazard and operability studies (HAZOP)	Bow tie analysis
Hazard Analysis & Critical Control Points (HACCP)	Reliability centred maintenance
Environmental risk assessment	Sneak circuit analysis
Structure “What if?” (SWIFT)	Markov analysis
Scenario analysis	Monte Carlo simulation
Business impact analysis	Bayesian statistics and Bayes Nets
Root cause analysis	FN curves
Failure mode effect analysis	Risk indices
Fault tree analysis	Consequence/probability matrix
Event tree analysis	Cost/benefit analysis
Cause and consequence analysis	Multi-criteria decision analysis (MCDA)

Risk assessment within standard

Similar philosophy reflected in EN 60335-1, -2-24, -2-40, -2-89, etc. Stating:

- "An appliance employing materials or having forms of construction differing from those detailed in the requirements of this standard may be examined and tested according to the intent of the requirements and, if found to be substantially equivalent, may be considered to comply with the standard."

i.e., do a risk assessment



BRITISH STANDARD

BS EN 60335-1:2012

Incorporating corrigendum October 2013

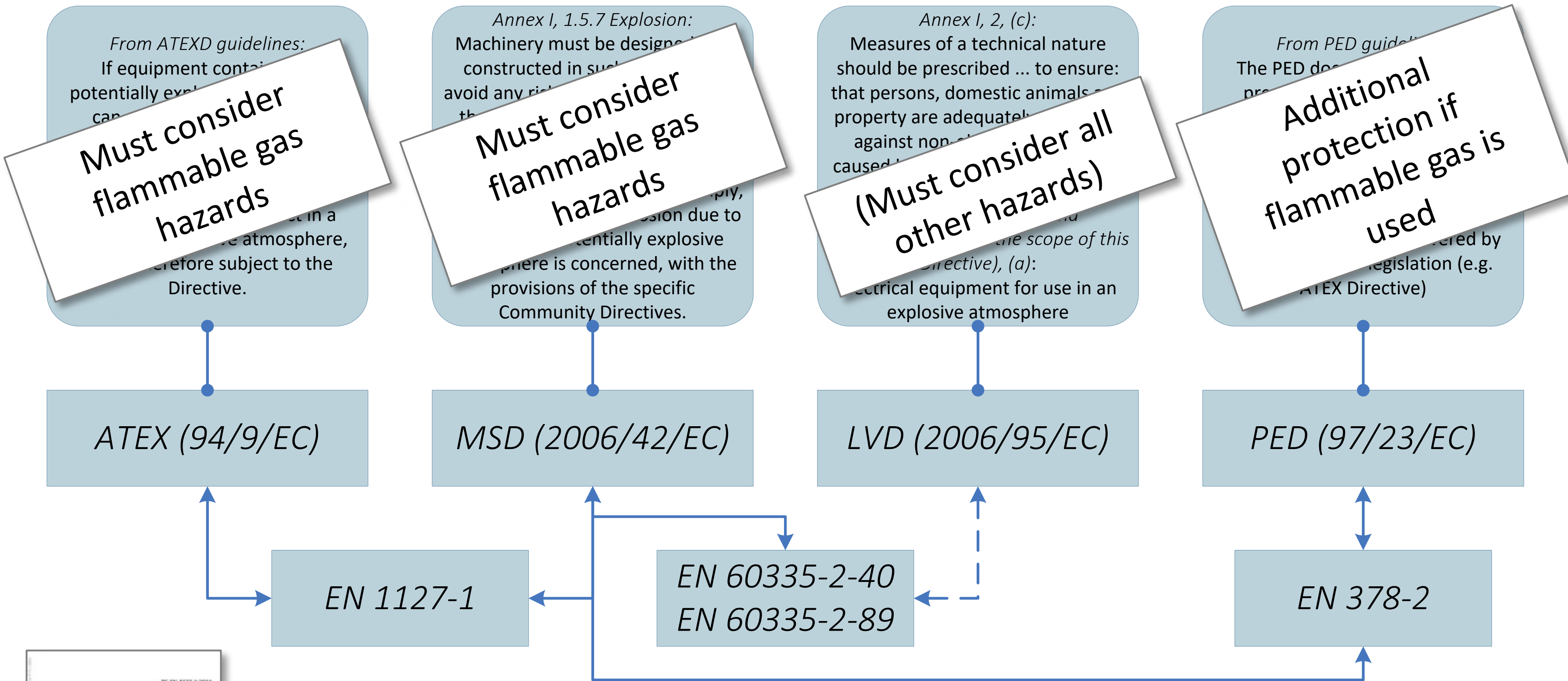
Household and similar electrical appliances — Safety —

Part 1: General requirements

ICS 97.030

BSI British Standards

Directives on use of flammable gas



How to do the flammability risk assessment

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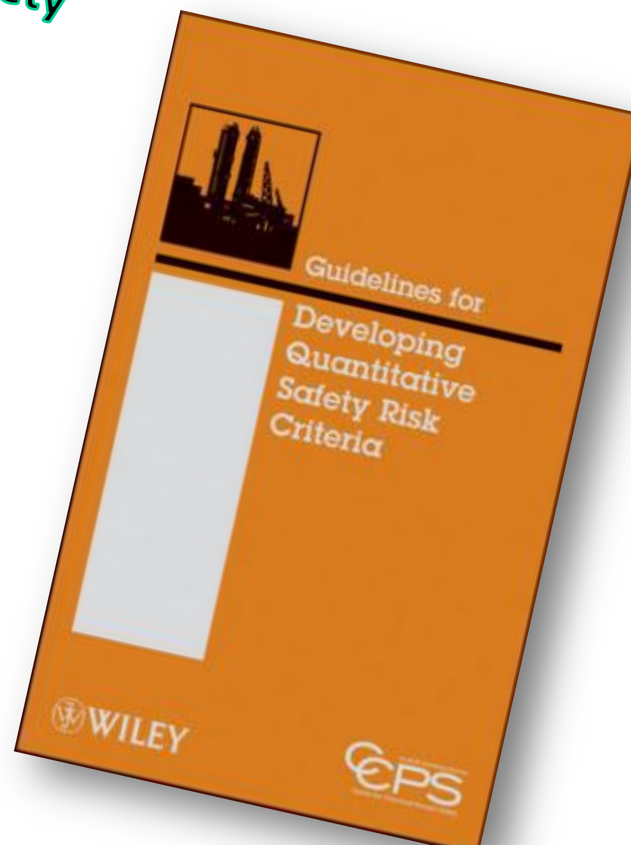
Constructive guidance

Preferences, values and expectations of society

Approach to reaching decisions on risk

Handling uncertainty

Criteria for reaching decisions and tolerability limits

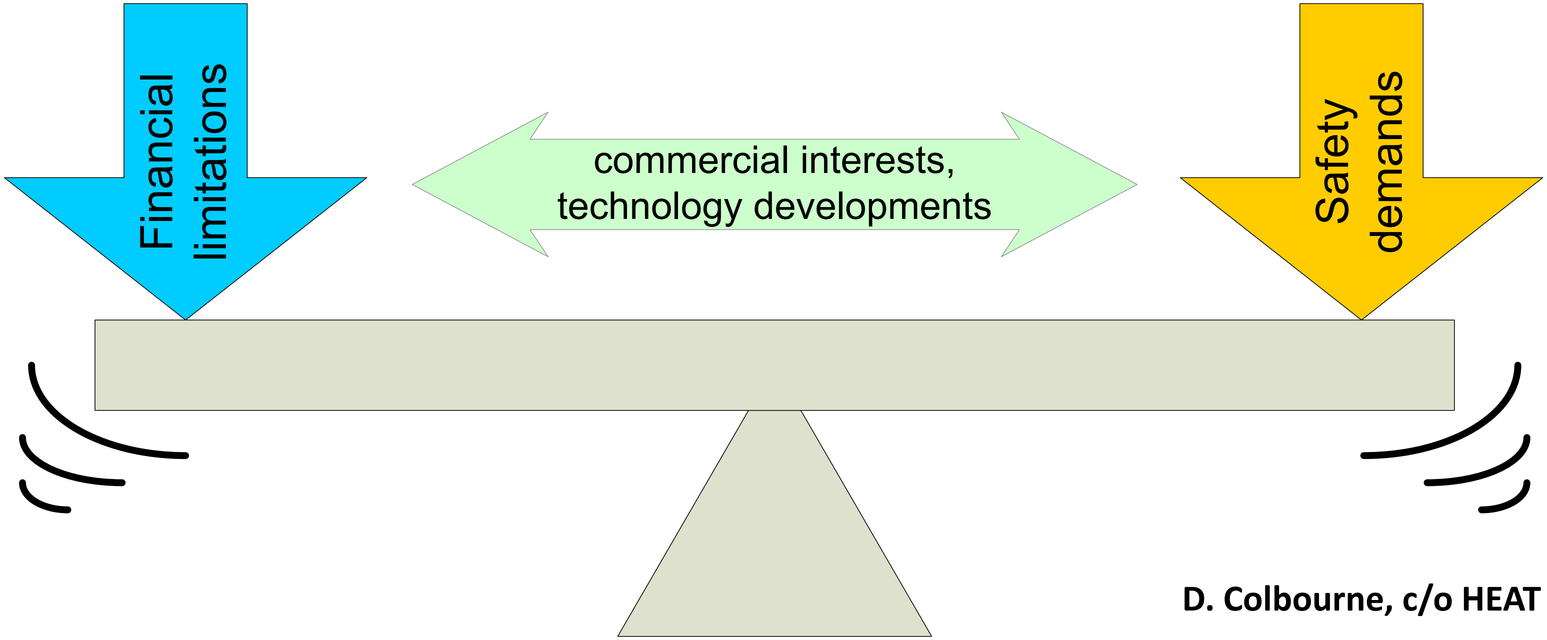


Practical approach

General principles… "In order to achieve an acceptable level of safety…"

Realistically, this is an arbitrary criterion

- Typically qualitative "feel" of people writing standards
- Balance between preferred safety demands and financial limitations
- Strongly affected by manufacturer/contractor liability issues, lawyers, technology and commercial interests



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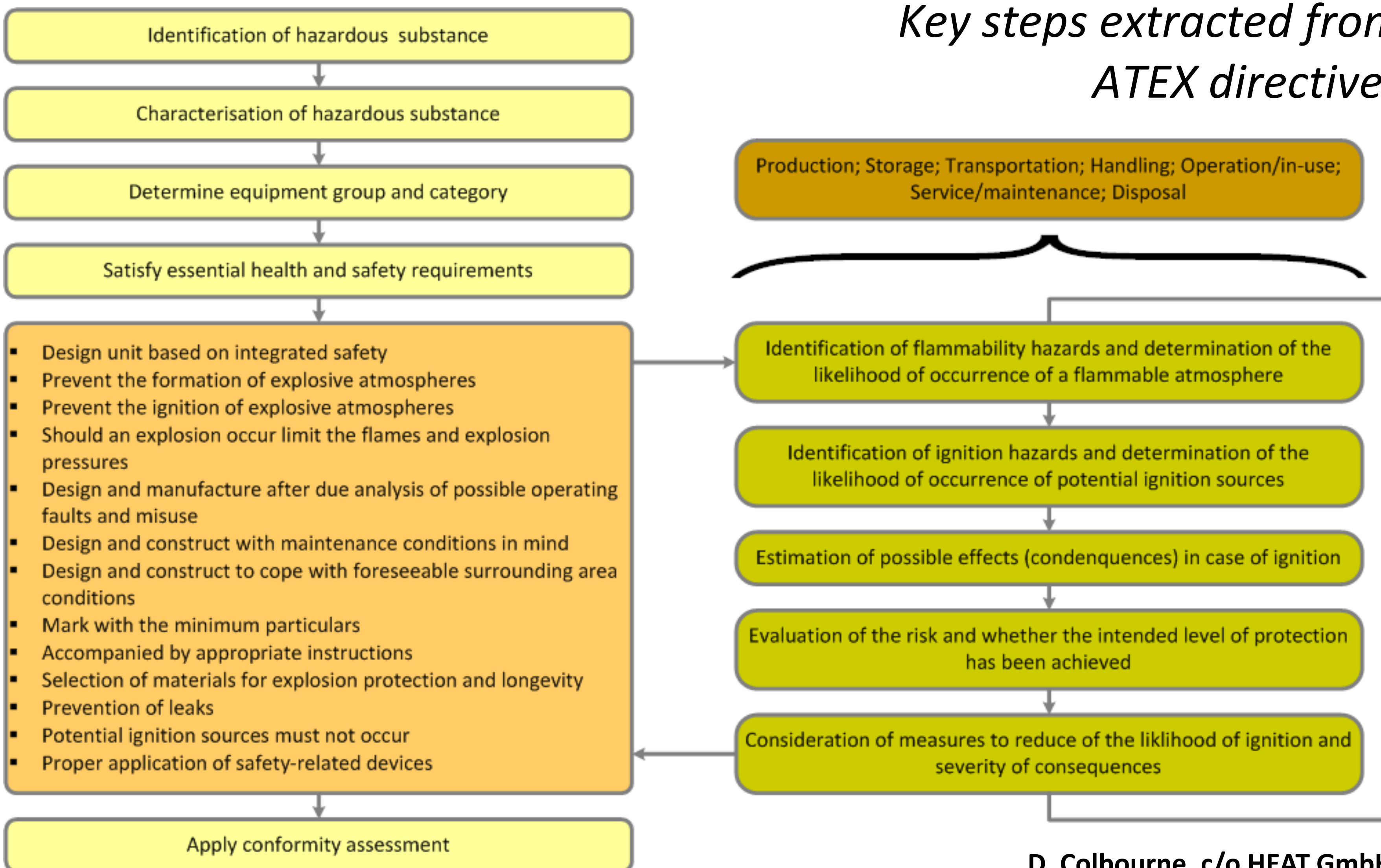
Risk assessment under ATEX

Key steps extracted from ATEX directives



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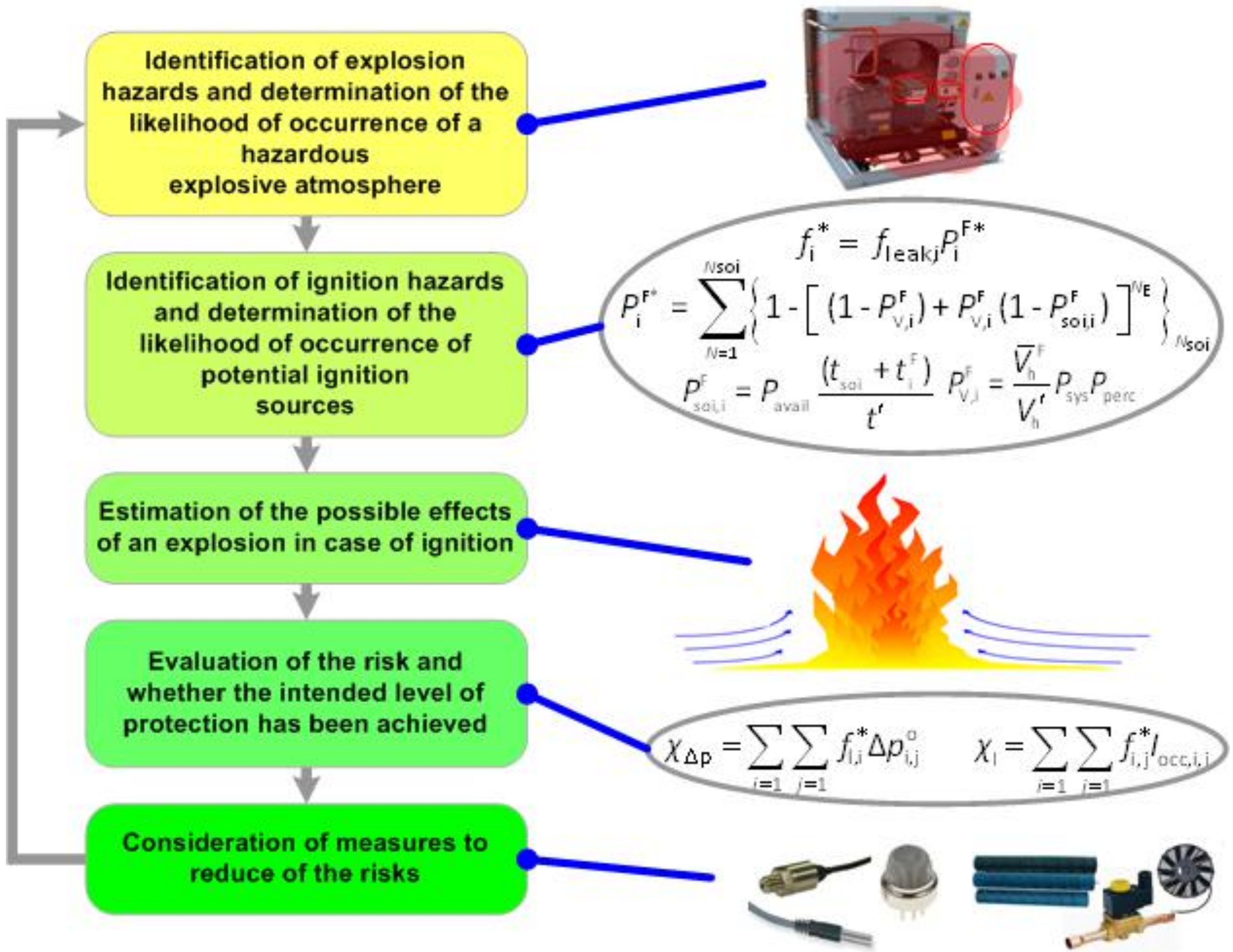
Specifically for flammable refrigerants



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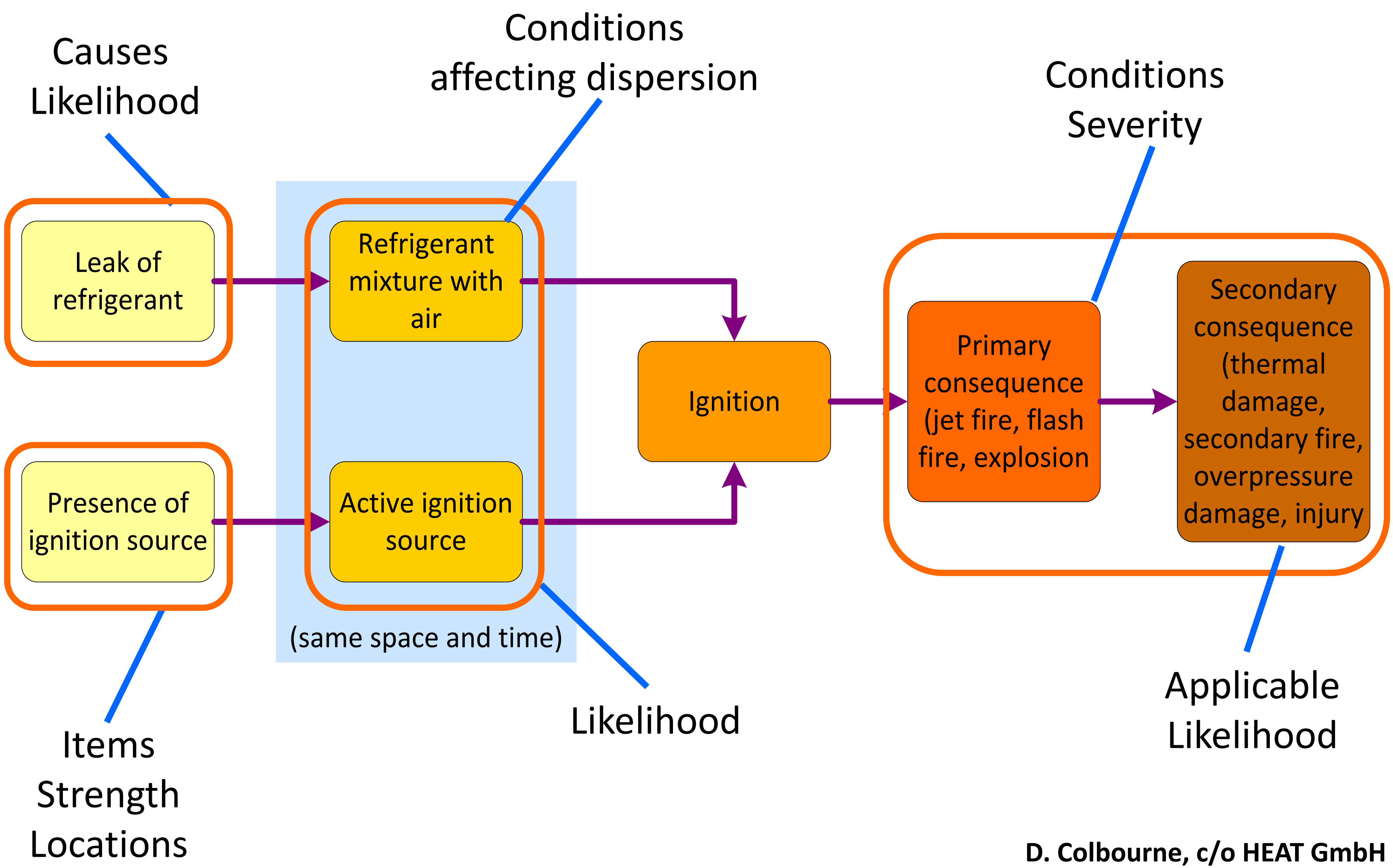
Risk processes



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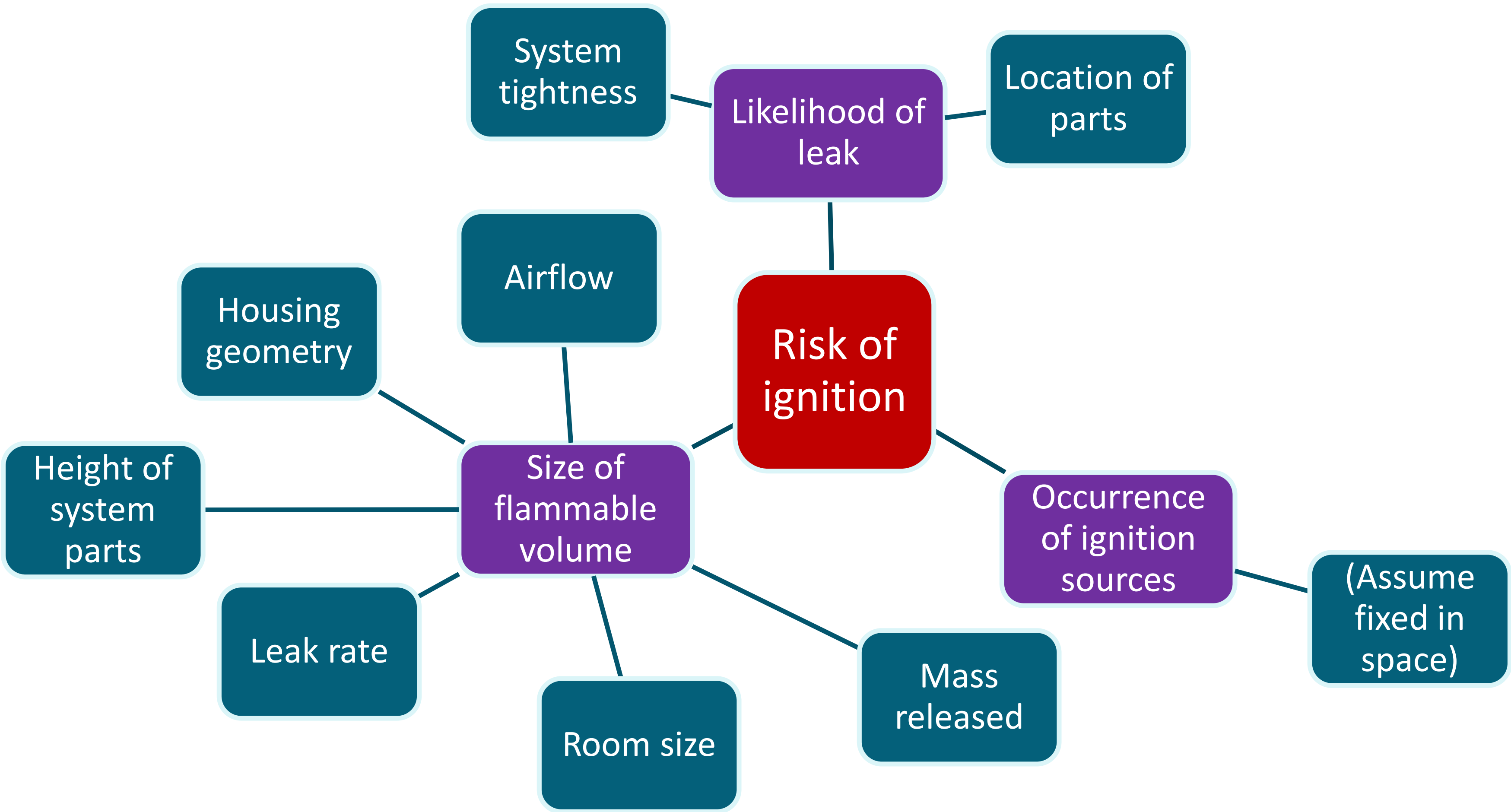
Flammable risk map



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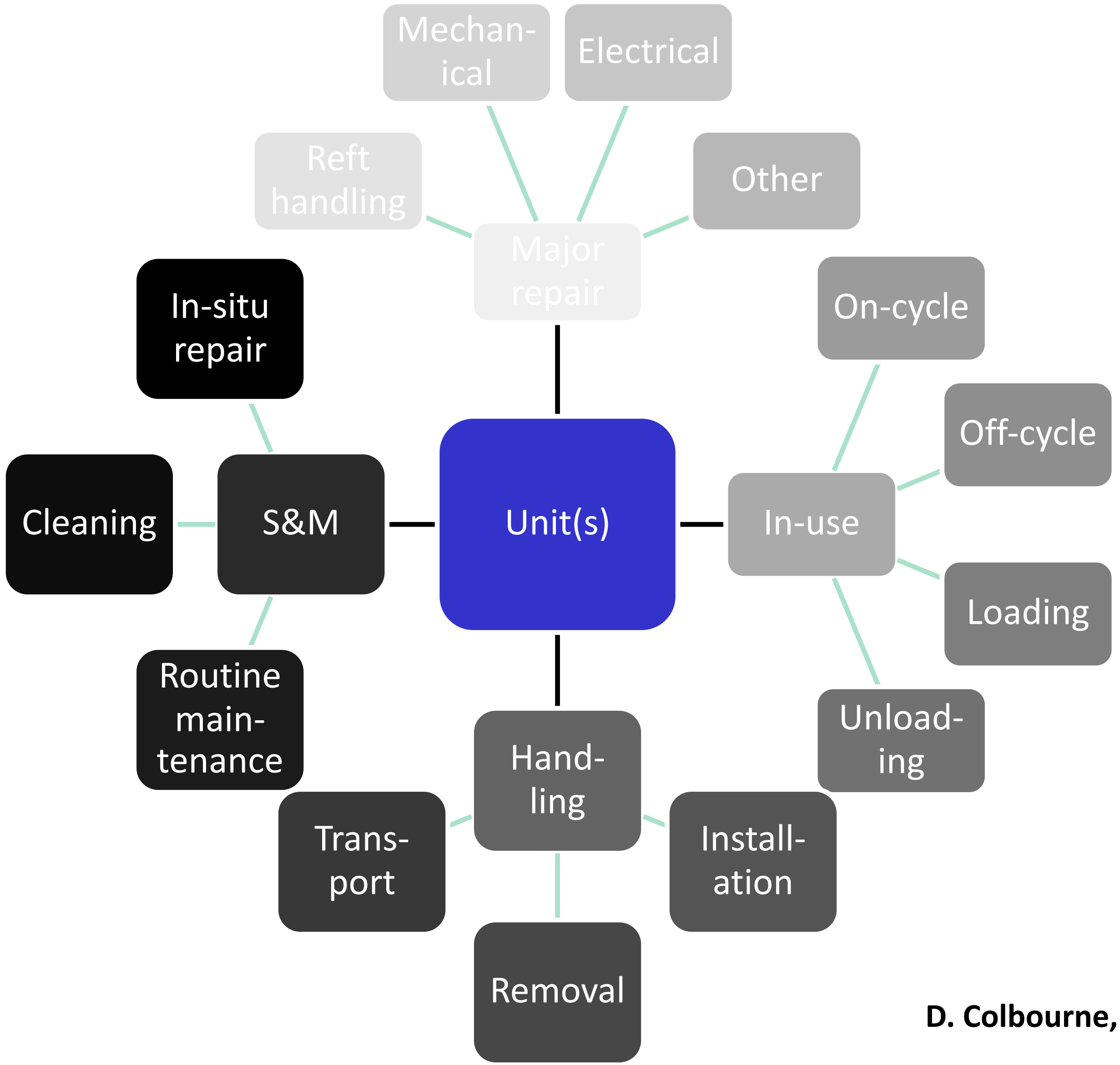
Map of actions/activities



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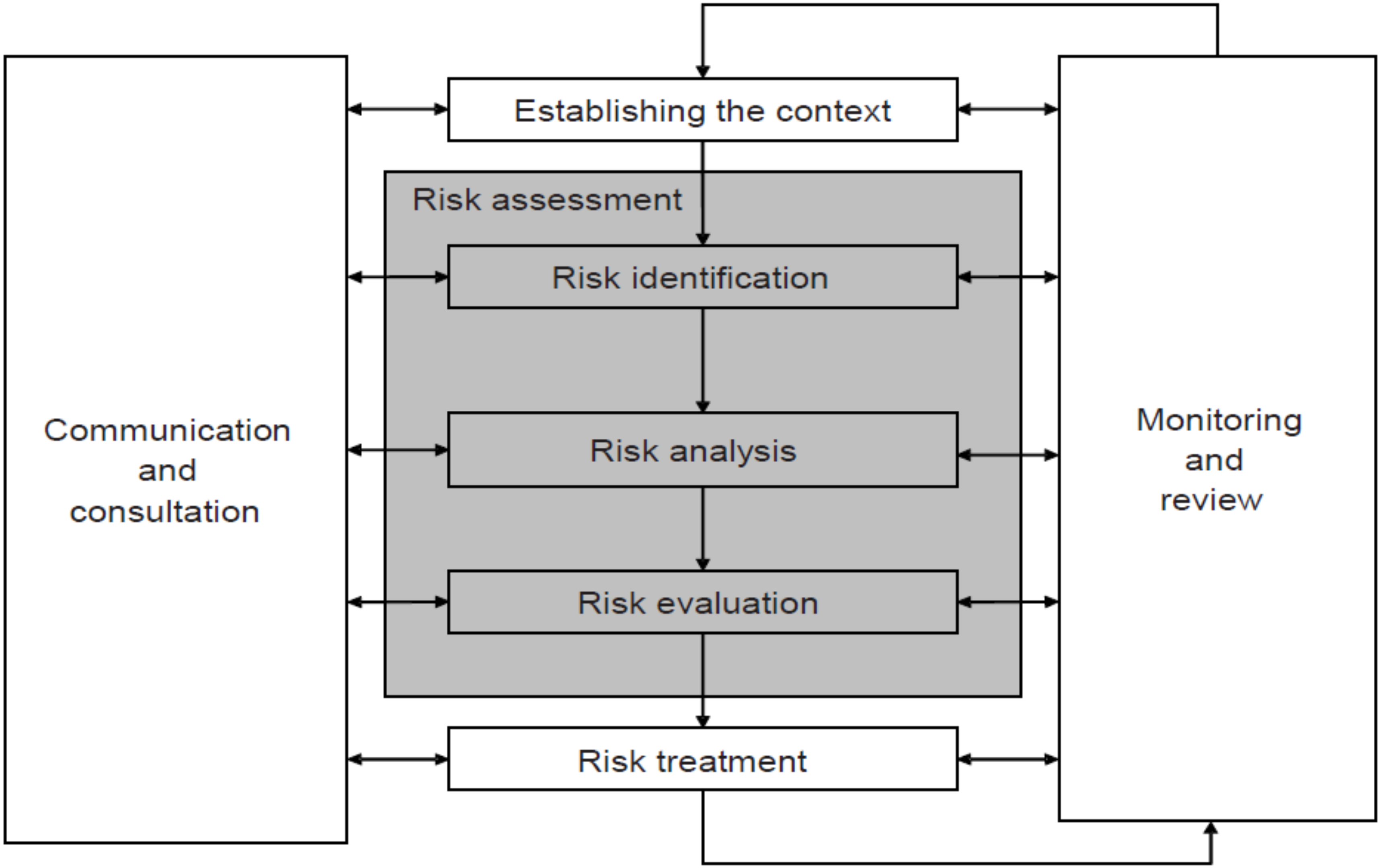
Overview of risk assessment sequence



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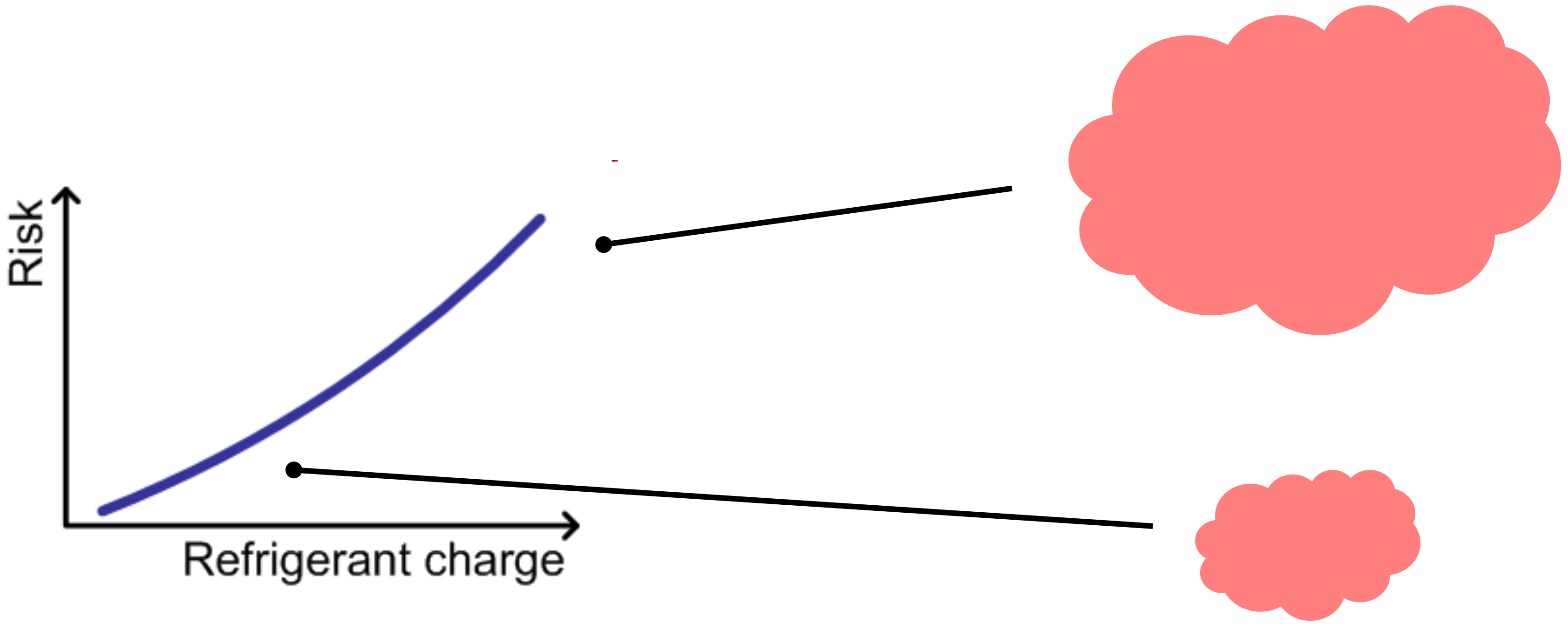
Charge amount

Basic relationship between refrigerant charge and risk…

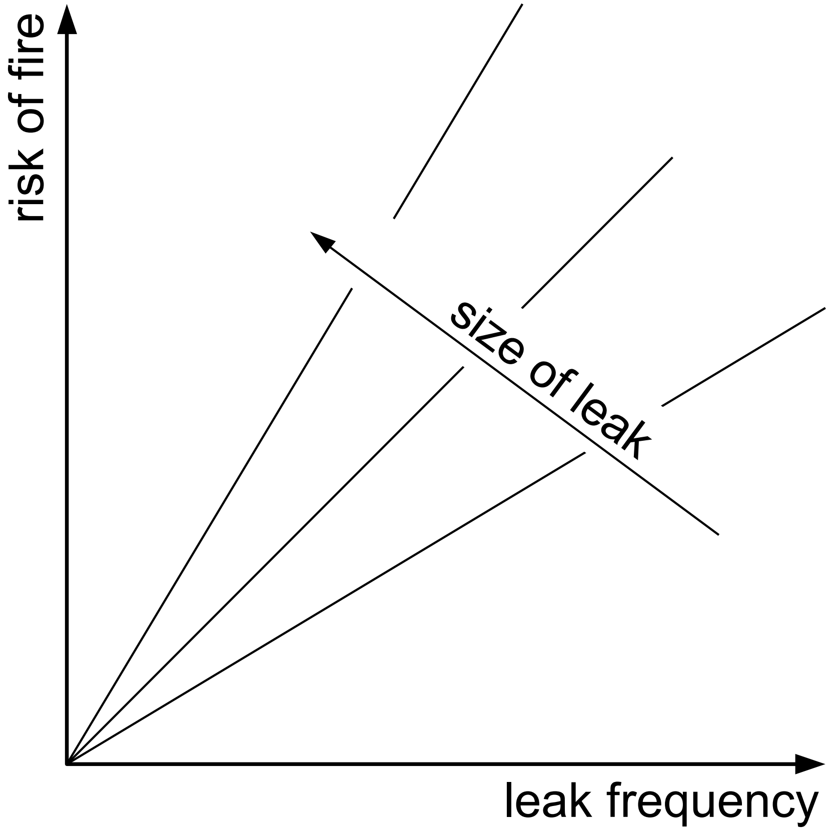


Do what you can to reduce charge – if practicable!

Leakage

General effect of leak frequency and size of leak on risk

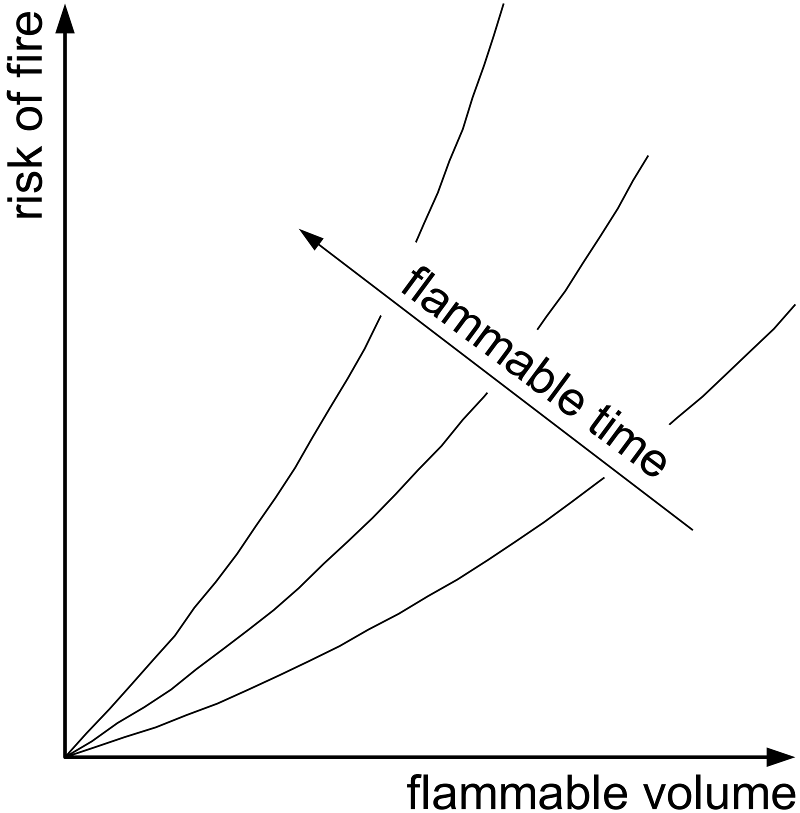
- Higher leak frequency produces high risk of ignition
- Larger leak size (higher mass flow) increases risk of ignition

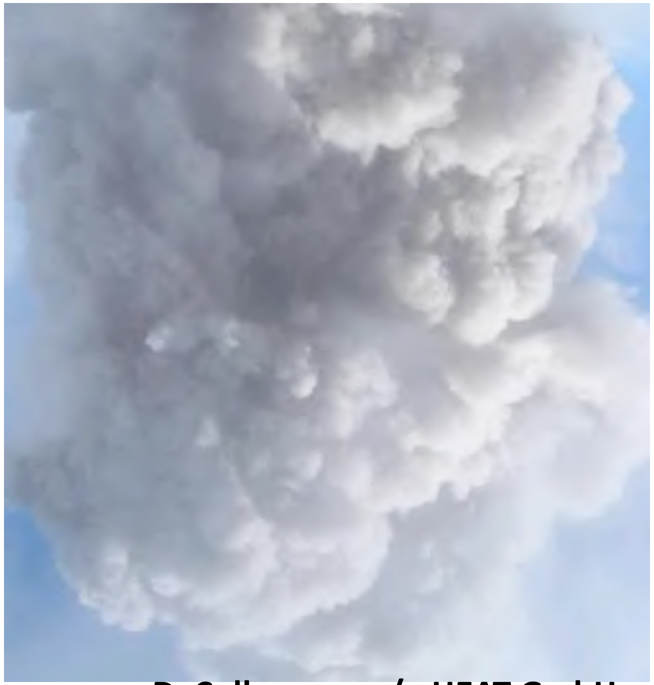


Dispersion of refrigerant

General effect of size and duration of flammable volume on risk

- Larger flammable volume produces higher risk
- Longer flammable time gives higher risk





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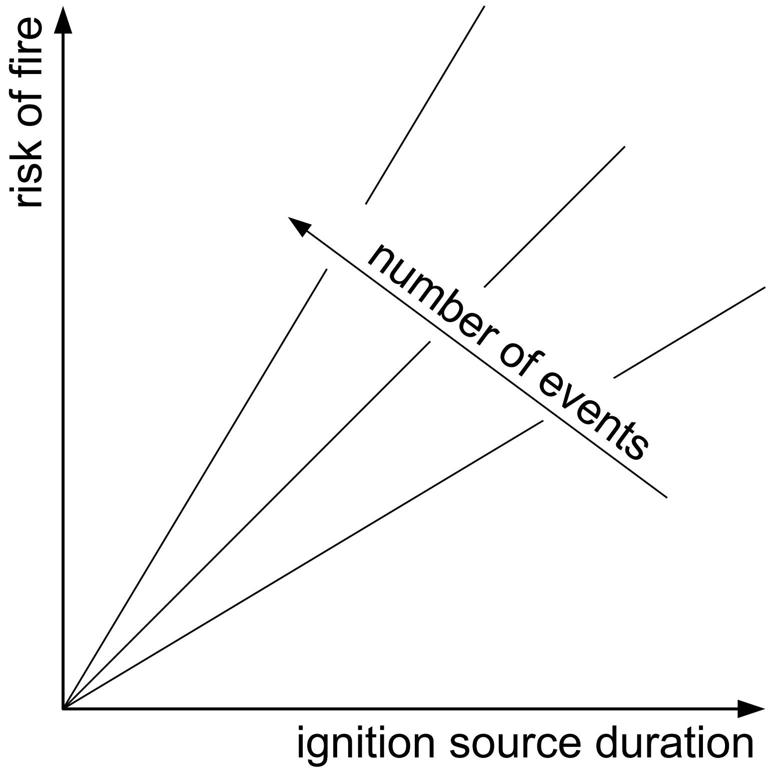
Source of ignition

General effect of duration and number of “active” events of source of ignition on risk

- Longer “active” duration of SOI produces higher risk
- Greater number of “active” SOI events gives higher risk



Implications of flammability characteristics…

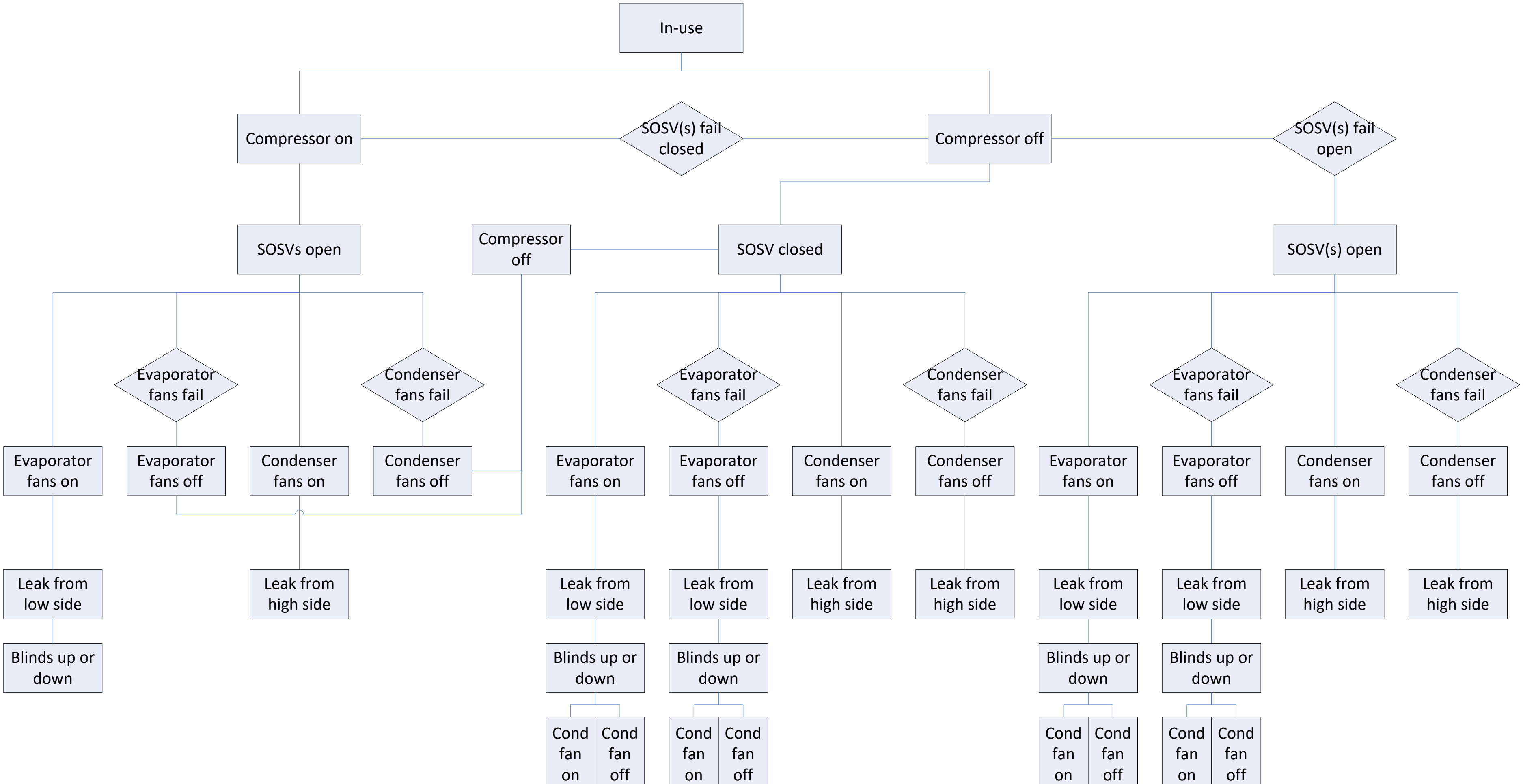
Level of flammability risk broadly related to flammability characteristics

Refrigerant	R1234yf	R32	R152a	R600a	R1270	R290	Impact (for lower value)
ISO 817 class	A2L	A2L	A2	A3	A3	A3	
AIT (°C)	405	648	455	460	455	470	Easier to ignite with hot surface
MIE (mJ)	780	29	0.9	0.7	0.28	0.35	Easier to ignite with spark
BV (cm/s)	1.5	6.7	23	38	45	46	Faster flame, bigger overpress
LFL (% vol)	6.2	14.4	4.8	1.8	1.8	2.1	Reaches flamm conc sooner
UFL (% vol)	12.0	29.3	17.3	8.4	11	9.8	More difficult ignite in system
HOC (MJ/kg)	10.7	9.5	16.3	50	45.8	46.3	Gives out more energy

All possible failure scenarios

For 'in-use' activity phase

Typically 98 – 99.9% of the product lifetime



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Activity phases

General activity phases

- Production
- Transfer
- Storage
- Transport
- Installation
- In-use
- Servicing/ maintain
- Decommis sioning

Risk analysis/semi-quantitative risk assessment

consequence	cost						
severe	> €1m cost	V	D	C	B	A	A
	€100k - €1m cost	IV	E	D	C	B	A
	€10k - €100k cost	III	F	E	D	C	B
	€0 - €10k cost	II	G	F	E	D	C
minor	€0 cost	I	G	G	F	E	D
			I	II	III	IV	V
			$<1^{-5}$/y	1^{-5}/y to 1^{-2}/y	1^{-2}/y to 1^{-1}/y	1^{-1}/y to 1/y	>1/y
			very unlikely	frequency			very likely

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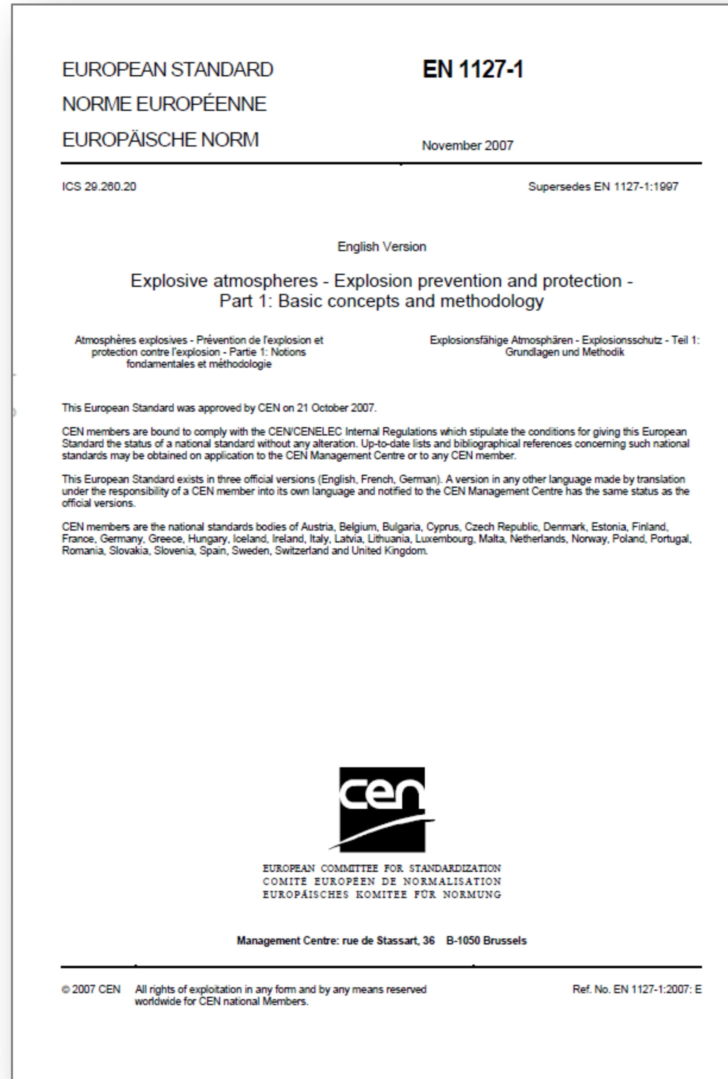
EN 1127-1

“Explosive atmospheres – explosion prevention and protection Part 1 basic concepts and methodology”

- Broadly applies to any situation involving flammable gases (including refrigerants)
- Harmonised to both ATEX and machinery directives
- Straight-forwards, procedural and clear

Most recent version is 2019



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1127-1

November 2007

ICS 29.260.20

Supersedes EN 1127-1:1997

English Version

Explosive atmospheres - Explosion prevention and protection - Part 1: Basic concepts and methodology

Atmosphères explosives - Prévention de l'explosion et protection contre l'explosion - Partie 1: Notions fondamentales et méthodologie

Explosionsfähige Atmosphären - Explosionsschutz - Teil 1: Grundlagen und Methodik

This European Standard was approved by CEN on 21 October 2007.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the CEN Management Centre has the same status as the official versions.

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Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 1127-1:2007: E

EN 1127-1

1 Scope

This European Standard specifies methods for the identification and assessment of hazardous situations leading to explosion and the design and construction measures appropriate for the required safety. This is achieved by:

— risk assessment;

— risk reduction.

The safety of equipment, protective systems and components can be achieved by eliminating hazards and/or limiting the risk, i.e. by:

a) appropriate design (without using safeguarding);

b) safeguarding;

c) information for use;

d) any other preventive measures.

Measures in accordance with a) (prevention) and b) (protection) against explosions are dealt with in Clause 6, measures according to c) against explosions are dealt with in Clause 7. Measures in accordance with d) are not specified in this European Standard. They are dealt with in EN ISO 12100:2010, Clause 6.

The preventive and protective measures described in this European Standard will not provide the required level of safety unless the equipment, protective systems and components are operated within their intended use and are installed and maintained according to the relevant codes of practice or requirements.

This standard specifies general design and construction methods to help designers and manufacturers in achieving explosion safety in the design of equipment, protective systems and components.

This European Standard is applicable to any equipment, protective systems and components intended to be used in potentially explosive atmospheres, under atmospheric conditions. These atmospheres can arise from flammable materials processed, used or released by the equipment, protective systems and components or from materials in the vicinity of the equipment, protective systems and components and/or from the materials of construction of the equipment, protective systems and components.

This European Standard is applicable to equipment, protective systems and components at all stages of its use.

This European Standard is only applicable to equipment group II which is intended for use in other places than underground parts of mines and those parts of surface installations of such mines endangered by firedamp and/or flammable dust.

This European Standard is not applicable to:

1) medical devices intended for use in a medical environment;

2) equipment, protective systems and components where the explosion hazard results exclusively from the presence of explosive substances or unstable chemical substances;

3) equipment, protective systems and components where the explosion can occur by reaction of substances with other oxidizers than atmospheric oxygen or by other hazardous reactions or by other than atmospheric conditions;

4) equipment intended for use in domestic and non-commercial environments where potentially explosive atmospheres may only rarely be created, solely as a result of the accidental leakage of fuel gas;

5) personal protective equipment covered by Directive 89/686/EEC;

6) seagoing vessels and mobile offshore units together with equipment on board such vessels or units;

7) means of transport, i.e. vehicles and their trailers intended solely for transporting passengers by air or by road, rail or water networks, as well as means of transport insofar as such means are designed for transporting goods by air, by public road or rail networks or by water; vehicles intended for use in a potentially explosive atmosphere shall not be excluded;

8) the design and construction of systems containing desired, controlled combustion processes, unless they can act as ignition sources in potentially explosive atmospheres.

EN 1127-1

4 Risk assessment

4.1 General

This risk assessment shall be carried out for each individual situation in accordance with EN ISO 12100 and/or EN 15198, unless other standards can be identified as being more appropriate to the situation:

a) Identification of explosion hazards and determination of the likelihood of occurrence of a hazardous explosive atmosphere (see 4.2);

b) Identification of ignition hazards and determination of the likelihood of occurrence of potential ignition sources (see 4.3);

c) estimation of the possible effects of an explosion in case of ignition (see 4.4);

d) evaluation of the risk and whether the intended level of protection has been achieved;

NOTE The intended level of protection is defined by at least legal requirements and, if necessary, additional requirements specified by the user.

e) consideration of measures to reduce of the risks (see Clause 6).

A comprehensive approach shall be taken, especially for complicated equipment, protective systems and components, plants comprising individual units and, above all, for extended plants. This risk assessment shall take into account the ignition and explosion hazard from:

1) the equipment, protective systems and components themselves;

2) the interaction between the equipment, protective systems and components and the substances being handled;

3) the particular industrial process performed in the equipment, protective systems and components;

4) the surroundings of the equipment, protective systems and components and possible interaction with neighbouring processes.

EN 1127-1

Safety standards – ignition sources

Sources of ignition on unit – systematic evaluation (EN 1127-1)

Type	Examples for RACHP equipment
Hot surfaces	Defrost heaters, compressor, friction on fan motor shaft
Flames and hot gases (including hot particles)	None
Mechanically generated sparks	Fan blade impacts
Electrical apparatus	Condenser fan motor, fan speed controller, gas sensor controller, circuit breaker, mains contactor, compressor relay, compressor start relay
Stray electric currents	Possible short circuits
Static electricity	Fan blades
Lightning	None
Radio frequency (RF) electromagnetic waves from 10^4 Hz to 3×10^{11} Hz	None
Electromagnetic waves from 3×10^{11} Hz to 3×10^{15} Hz (microwave, infrared)	None
Ionising radiation	None
Ultrasonics	None
Adiabatic compression and shock waves	Compressor (internal)?
Exothermic reactions	None

EN 1127-1

Consequences of ignition

Consequences of ignition

Once the refrigerant has leaked from the system and has formed a flammable mixture, it is important to understand the possible consequences if it is ignited

- Useful to evaluate the risk
- Useful to identify means to mitigate severe consequences

To examine

- Different types of consequences
- Factors that affect severity of consequences
- Typical consequences expected when using HCs in cooling systems

Consequences of ignition

Consequences of ignition have two categories…

Primary consequence

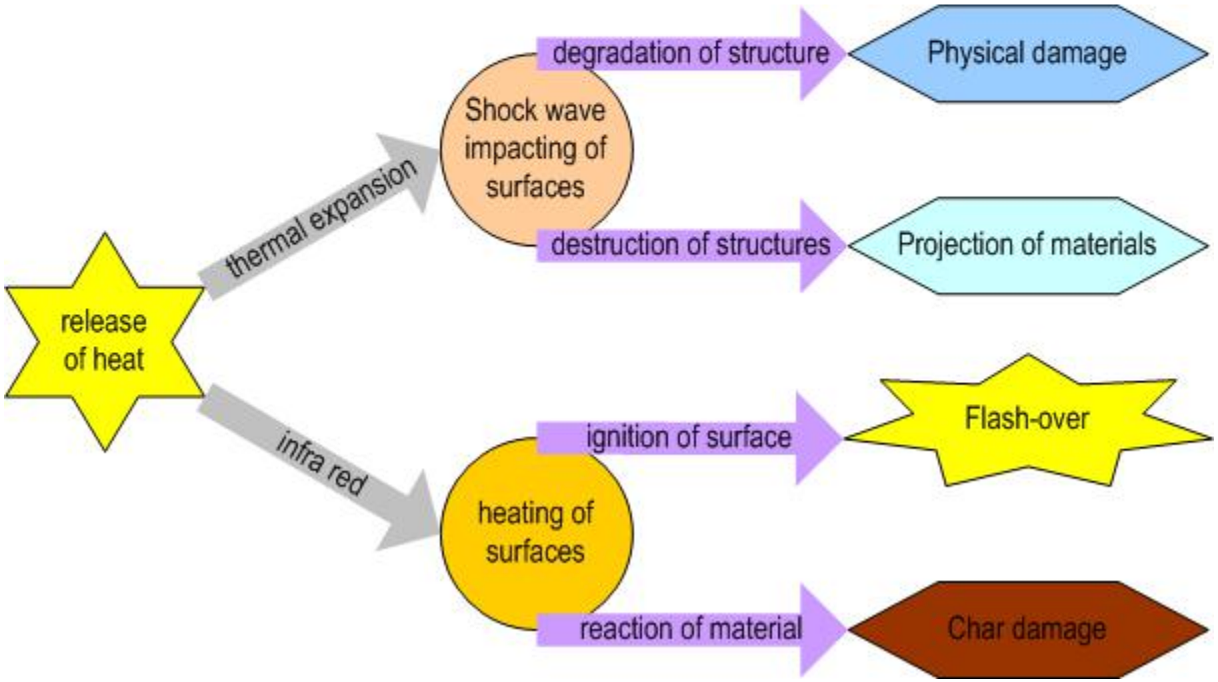
- The events that occurs as a direct result of ignition

Secondary consequence

- The events that are caused by the primary consequence

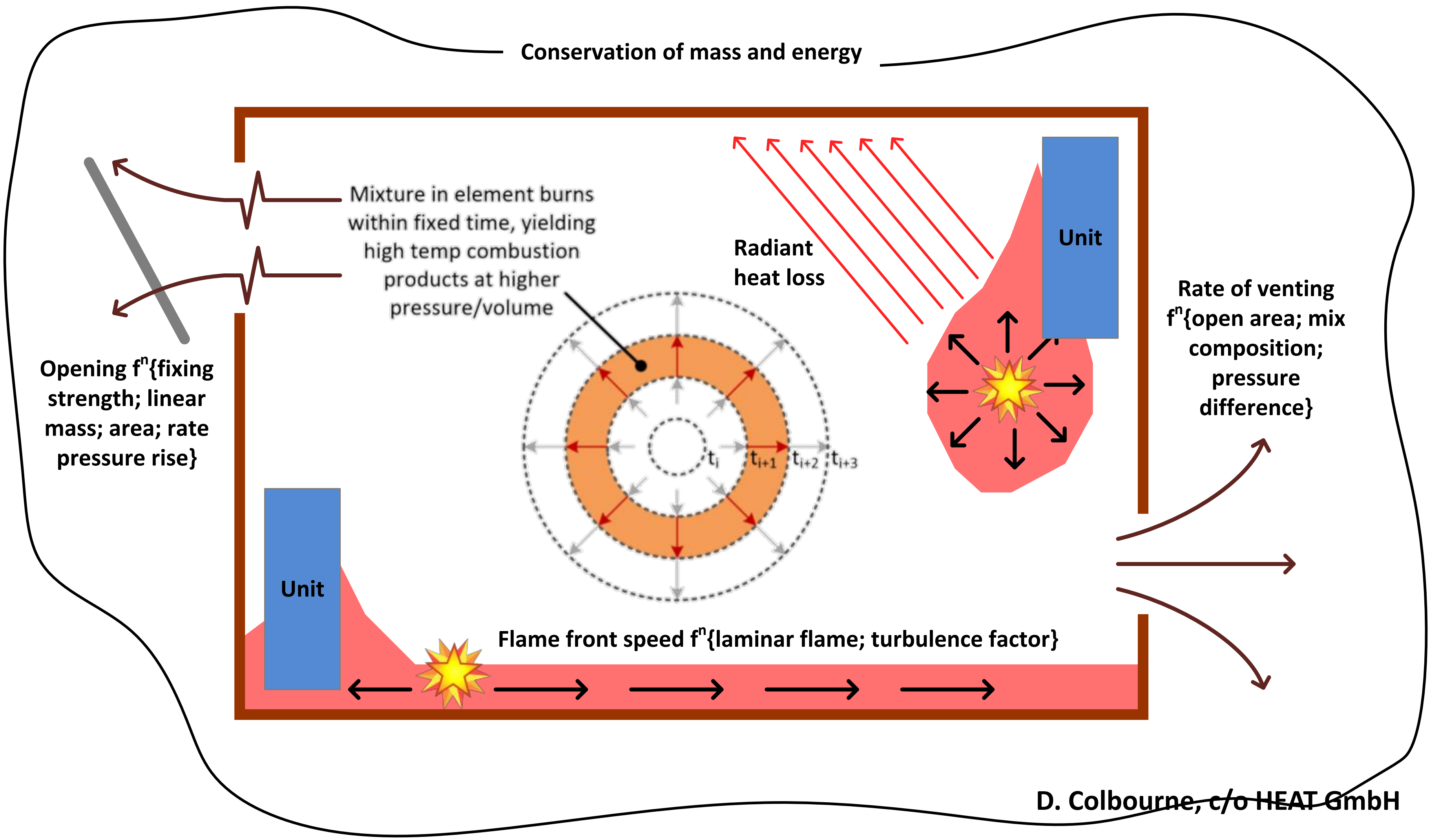
Represents the transfer of energy

Normally concerned with end result, i.e., secondary consequence



Modelling approach

Finite element model for expanding front of combustion products



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Consequences of ignition

Severity of overpressures

To structures,

3 – 7 kPa	Shattering of glass windows, occasional frame failure
7 – 14 kPa	Corrugated steel or aluminium connection failure and buckling, plaster walls cracking, wood walls splintering
14 – 20 kPa	Shattering of concrete or cinder block wall panels
20 – 28 kPa	Collapse of self-framing steel panel building
34 kPa	Snapping of wooden utility poles
55 kPa	Shearing and flexure failure of brick wall panel
34 – 69 kPa	Shattering of laminated car safety glass

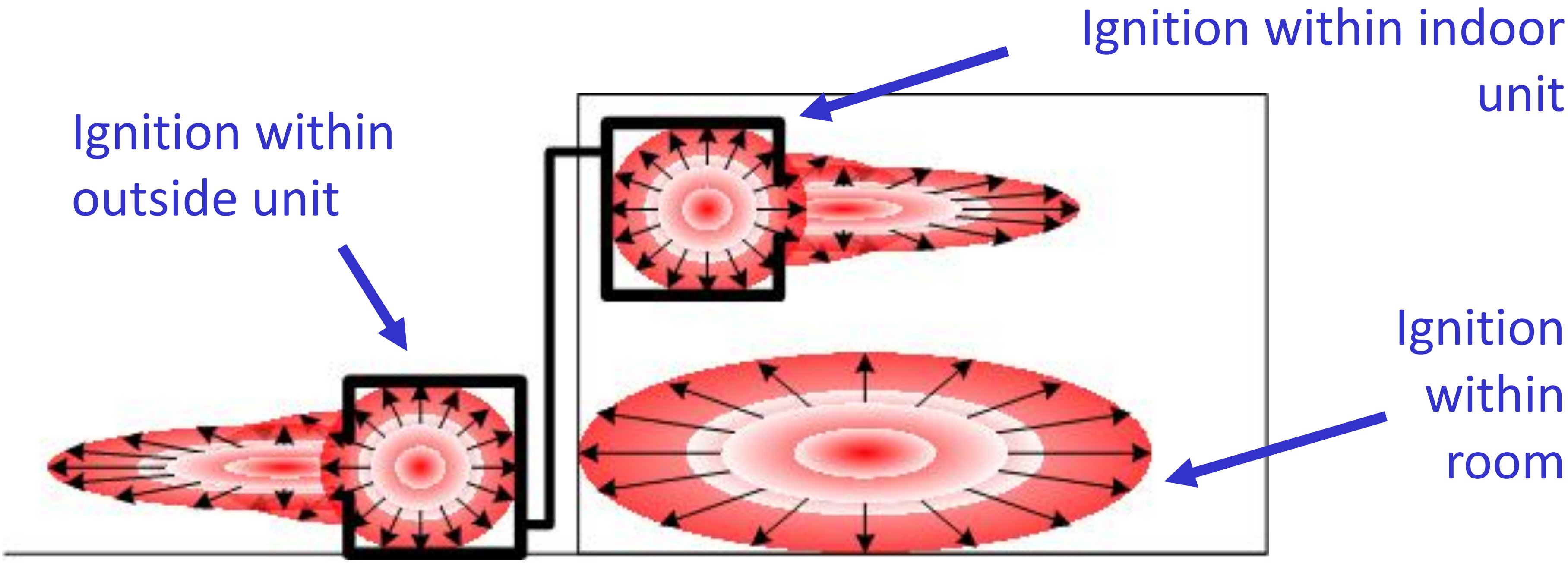
To persons

4 kPa	Threshold for injury from flying glass
10 kPa	Threshold for multiple skin laceration from flying glass
20 kPa	10% probability for eardrum rupture, overpressure will hurl person to ground
70 kPa	Threshold for lung haemorrhage
190 kPa	1% mortality

Consequences of ignition

Should consider overpressure in three situations

- Ignition of flammable mixture within room
- Ignition of flammable mixture within indoor unit
- Ignition of flammable mixture within outdoor unit



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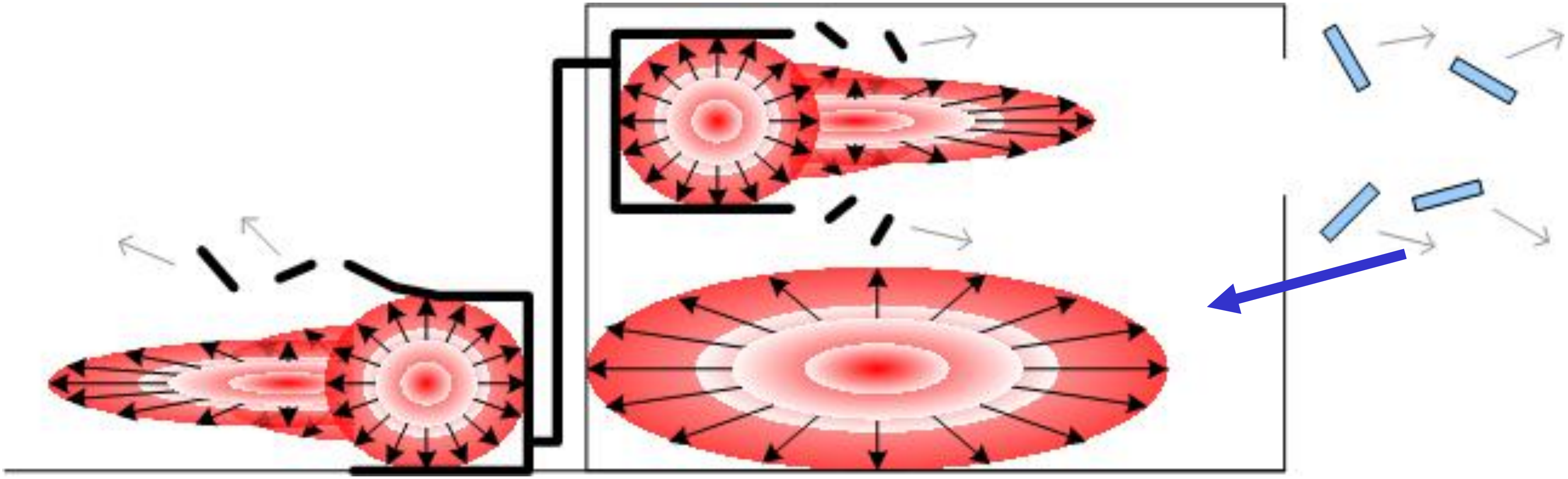
Consequences of ignition

In fact, the generated pressure normally exceeds the strength of buildings, enclosures, etc

- Enclosure housing may be forced open
- Windows, doors or walls may be broken

Results in the release of excess volume and therefore reduces overpressure



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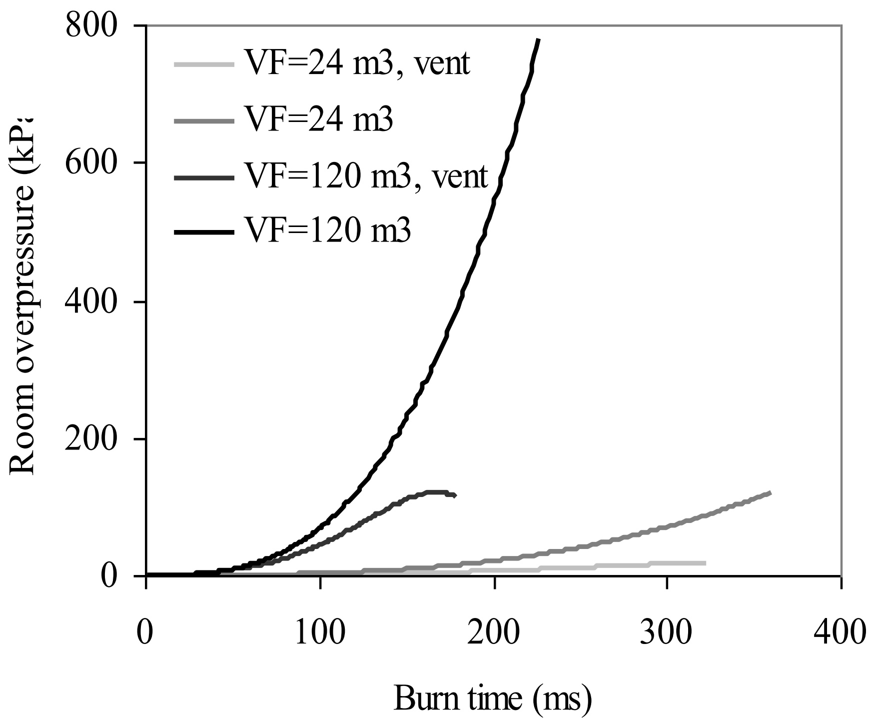
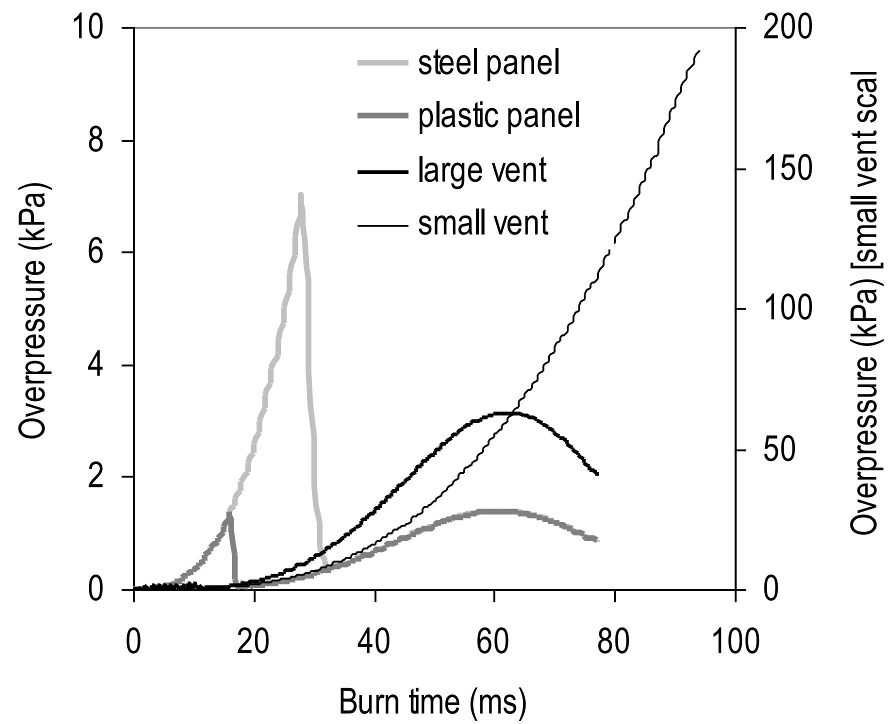
Consequences of ignition

Example calculations for relatively empty space

- Maximum overpressure very sensitive to particular conditions
- Graphs show influence of vent holes and vent panels



Completely full of flammable mixture, partially full



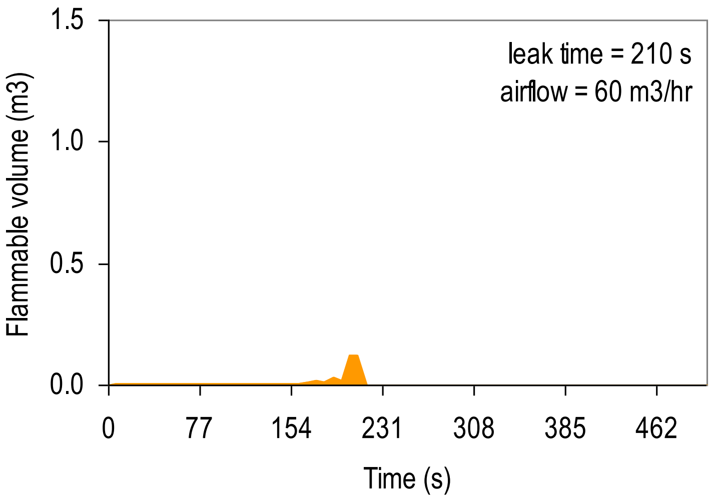
Compressor compartment with open vent holes, with vented panels

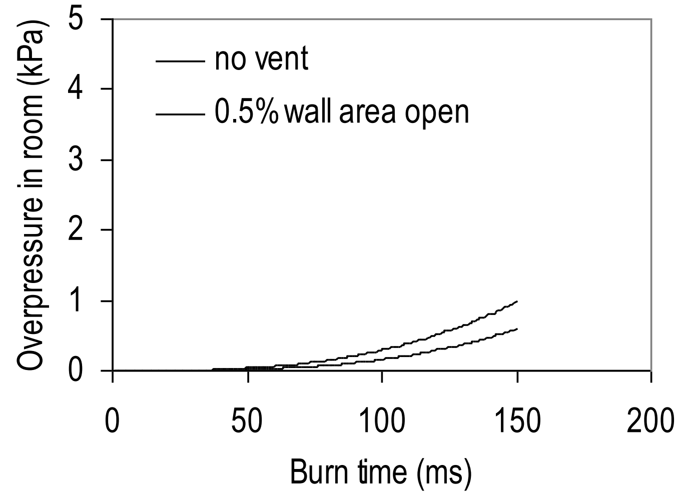
Note: “burn time” = time for entire mixture to combust

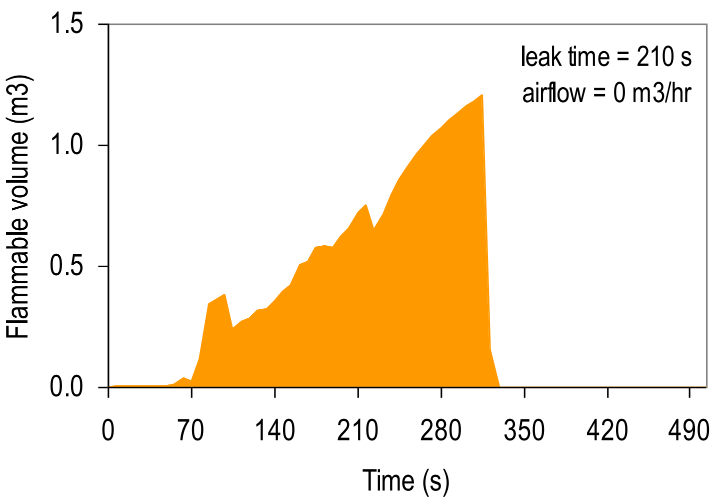
Consequences of ignition

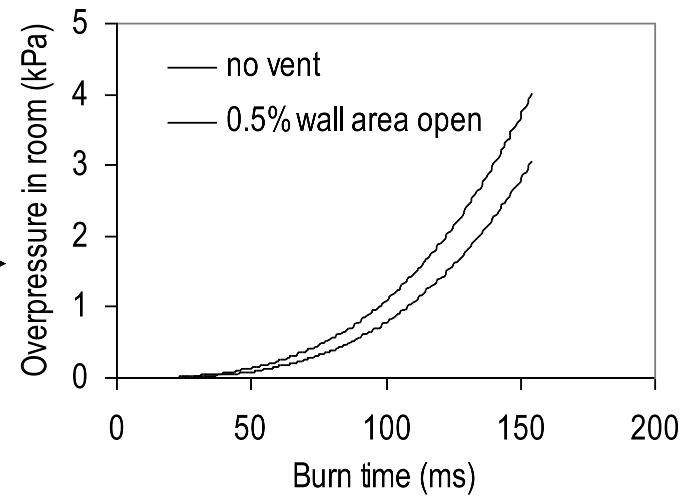
Example calculations

- To give an impression of the effects on overpressure





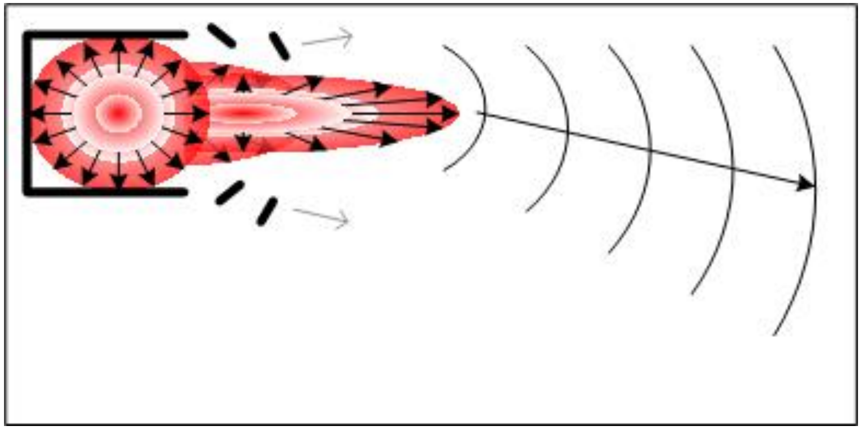


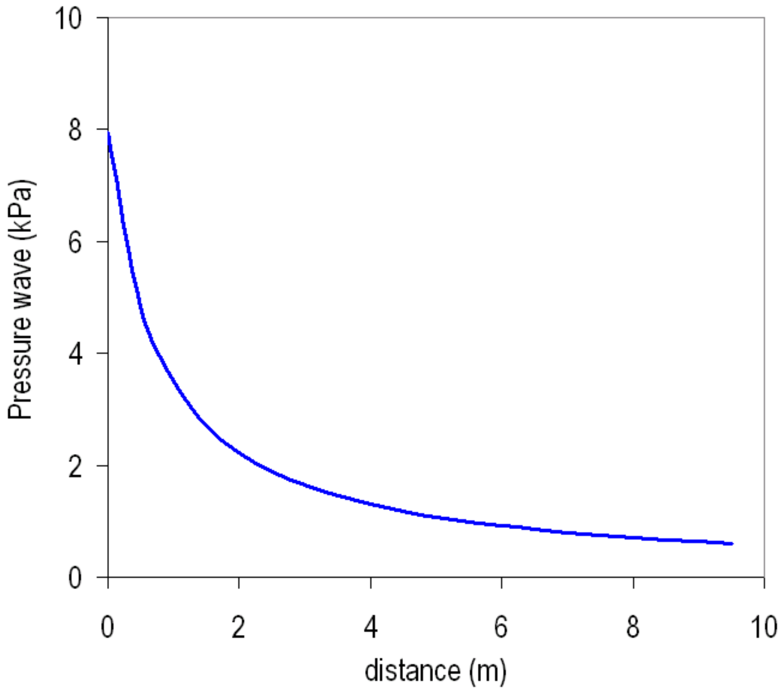


Consequences of ignition

If there is overpressure within an enclosure that escapes, a shock-wave will travel outwards

- Exponential decay away from source
- Mainly a function of source overpressure only
- Within enclosed spaces, shockwave will be reflected (but dampened)
- May also damage building structure





Consequences of ignition

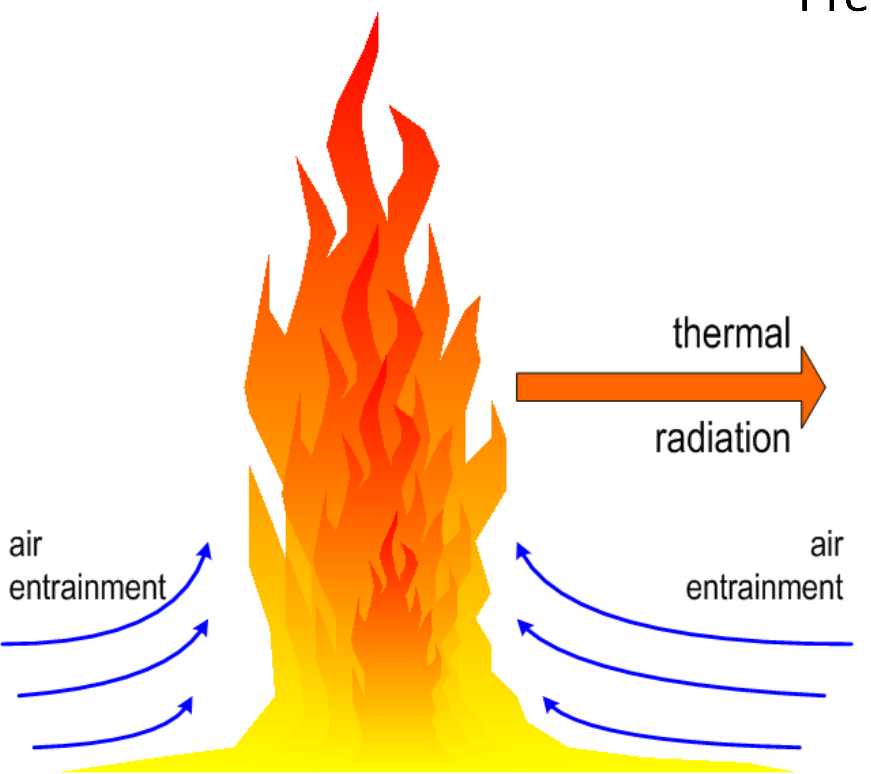
Ignition of an unconfined flammable volume results in burning

- Flame radiates infra-red to surroundings

The "dose" of thermal radiation is a function of

- Incident factor, distance to occupant, heat of combustion, mass of flammable mixture, burn time

Presence of combustible materials nearby affect likelihood of secondary fire



Thermal dose ($s(kW/m^2)^{4/3}$)	Effect
115	pain threshold
150	flashover (secondary fire)
1050	1% fatality
6500	99% fatality

Consequences of ignition

Harm Caused	Thermal Dose (TDU), $(kW/m^2)^{4/3}s$
Escape impeded	290
1-5% Fatality offshore	1000
50% Fatality offshore with radiation only to the front or back (i.e. from a fireball).	1000
50% Fatality offshore	2000
100% Fatality offshore	3500

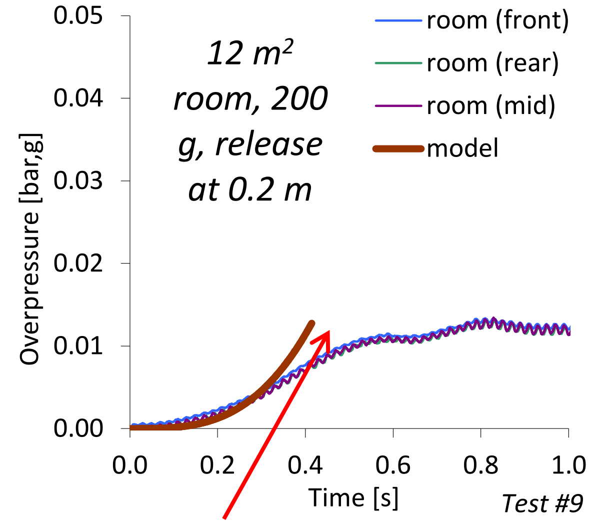
Type	Size	Duration	Radiated Surface Emissive Heat Flux (kW/m^2)	Hazard
Pool fire (open)	Medium	Long	50 – 150	Radiation, smoke, engulfment
Pool fire (severe or confined)	Medium	Long	100 – 230	Radiation, smoke
Jet fire (open)	Medium	Medium/Long	50 – 250	Radiation, smoke
Jet fire (confined)	Medium	Medium/Long	100 – 300	Radiation, smoke
Flash fire	Large	Short	170	Engulfment
Fireball	Large	Short	270 (HID SRAG)	Radiation

Validation

Using experimental data for

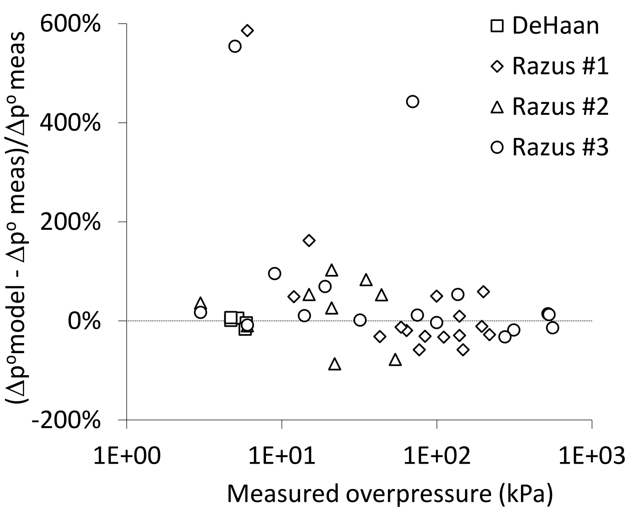
- Partially filled, partially confined gas explosions
- Specific ignition tests involving AC&R equipment in confined spaces
- Also initial (positive) cross-check against recent testing

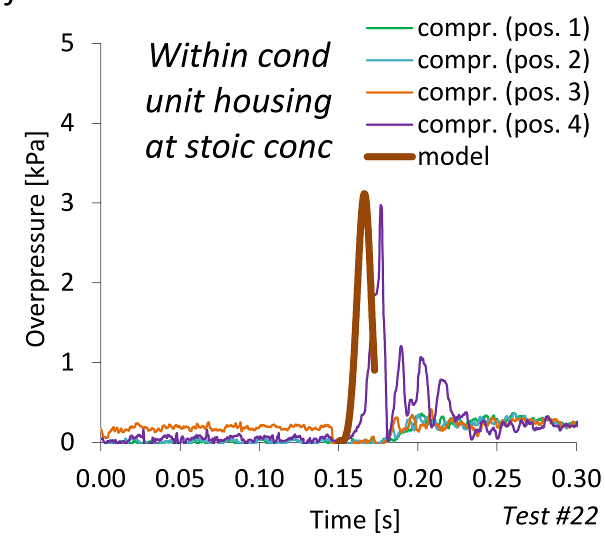
In general not bad; at times overestimates

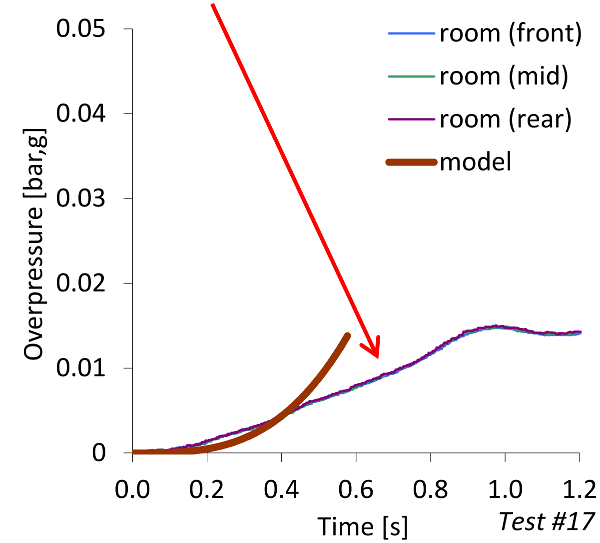


Difference due to rectangular room shape and non-stoichiometric conc

Various cases; 5 m^3 to 100 m^3, 20% to 100% filled with flam mix, confined and unconfined





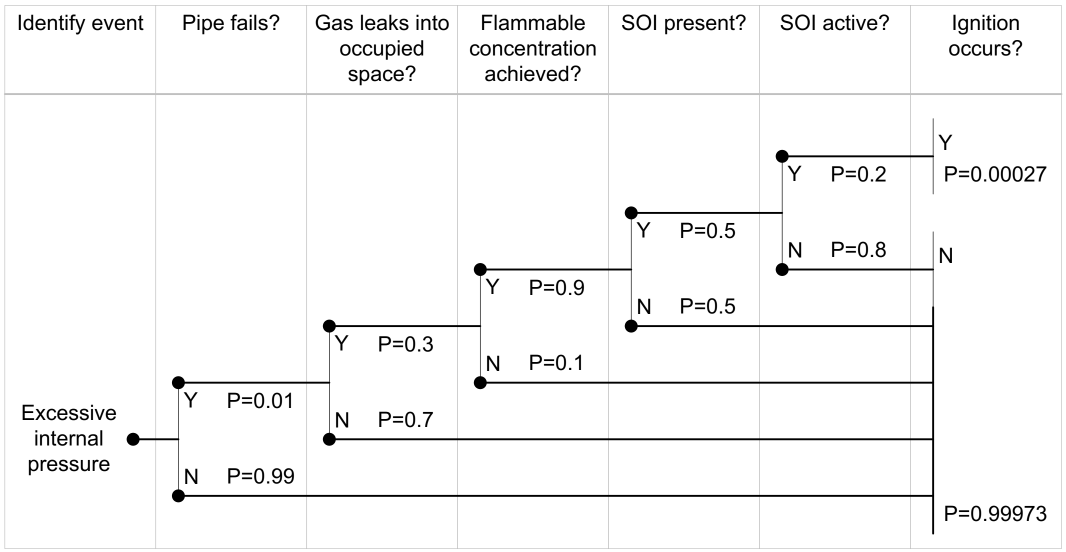


Risk analysis

- Tools
- Uncertainties

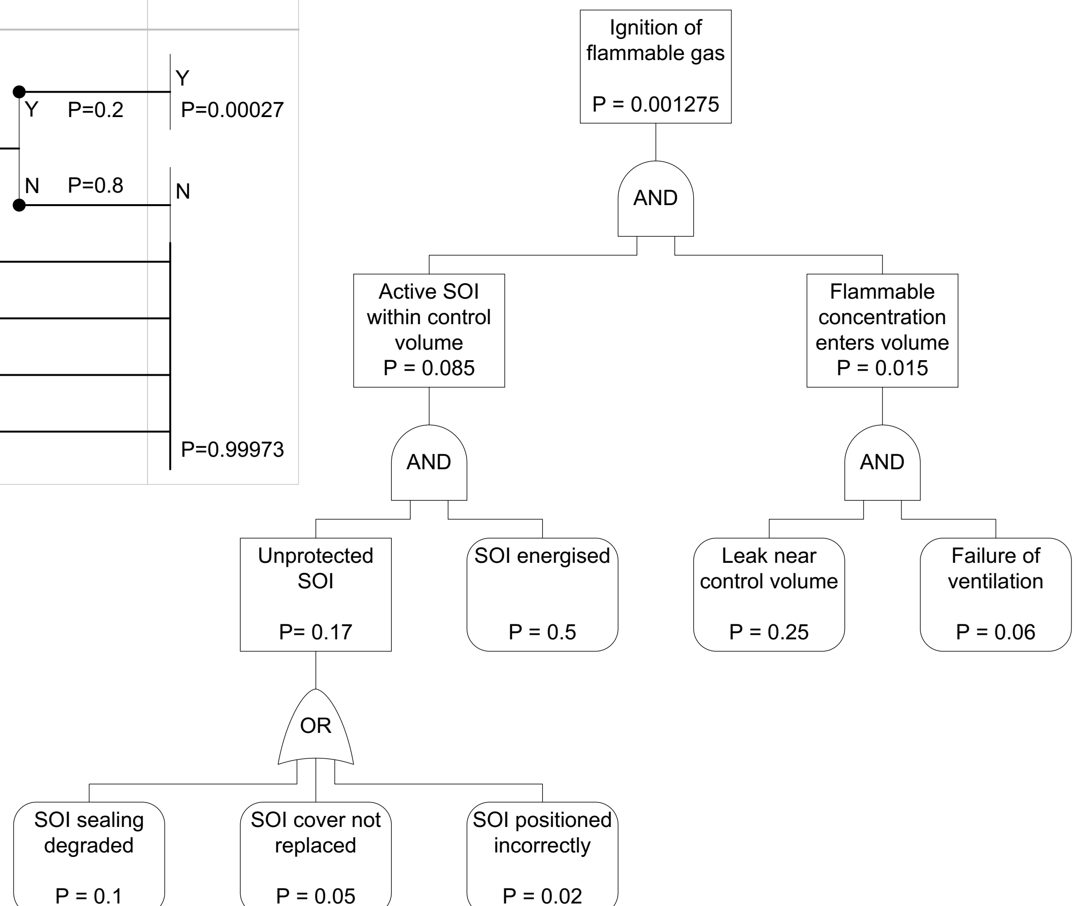
Risk analysis/risk assessment

Quantitative methods



Event tree analysis (ETA) ↑

Fault tree analysis (FTA) →



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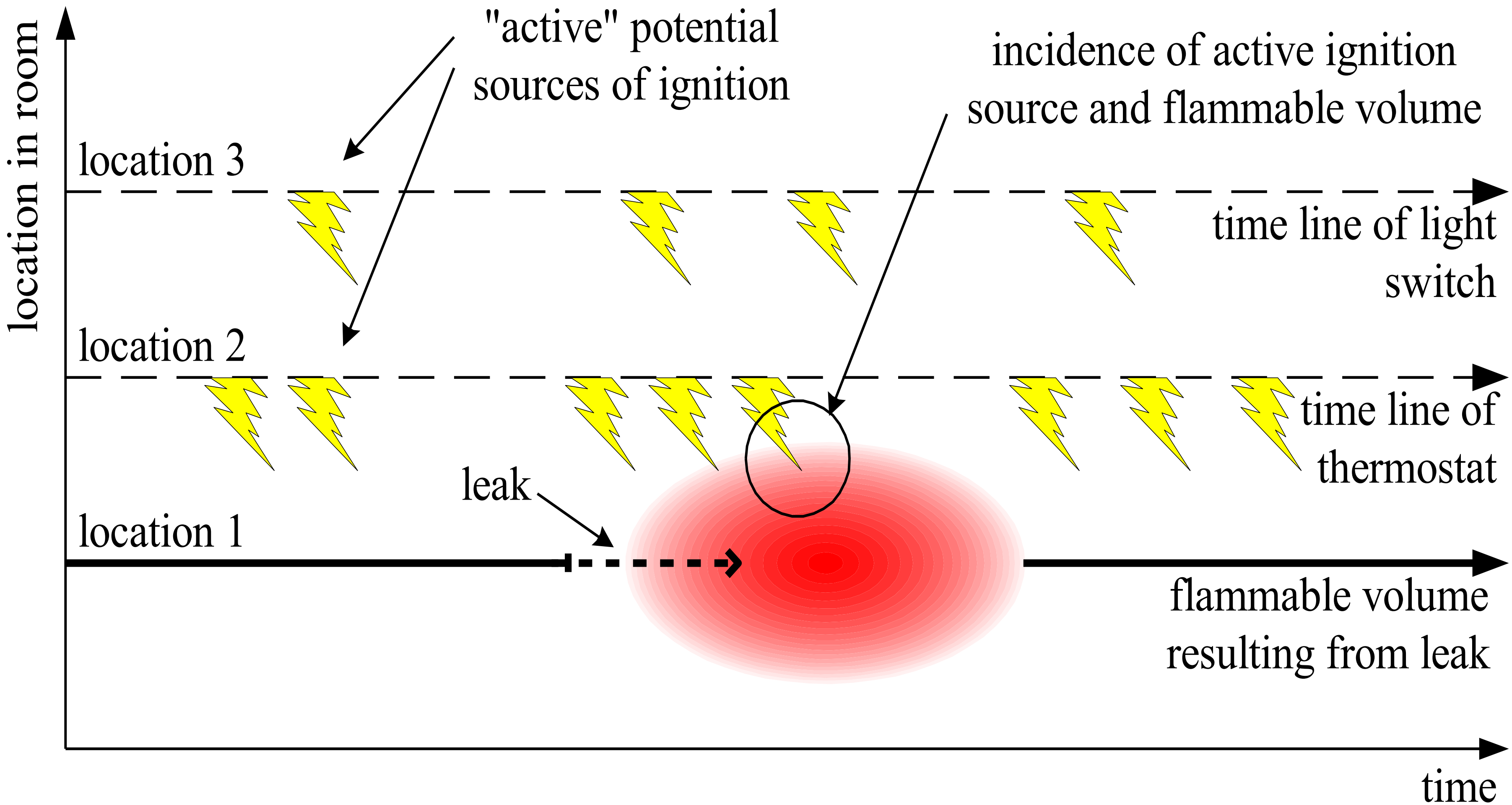
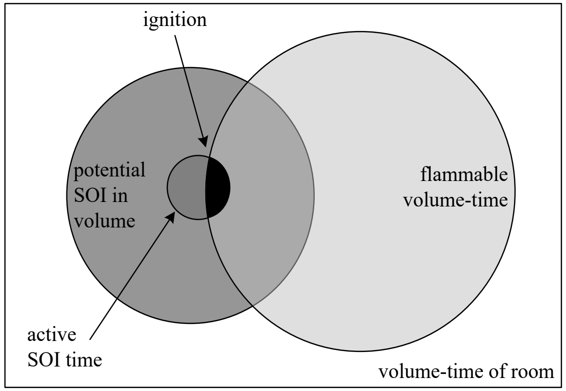
Incidence of events

Coincidence of events required for ignition



Basic probability formulae



Ignition frequency: $f^* = f_{leak} \, P_{FV}$

Probability of flammable mixture being present: $P_{FV} = \dfrac{V_F}{V_{cv}} P_{prc}$

Probability of ignition source being active: $P_{soi} = \dfrac{P_{av}(t_{soi} + t_F)}{t_{ref}}$

Probability of ignition source being active within flammable mixture:

$$P_{ign} = \sum_{N=1}^{N_{soi}} \{1 - [(1 - P_{FV}) + P_{FV}(1 - P_{soi})]^{N_E}\}$$

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Input data

Parameter	Sources
Leak frequency, f_{leak}	From leak size study
Volume of flammable mixture, V_F	From models
Percolation probability, P_{prc}	From literature; usually about 0.5
Size of control volume, V_{cv}	From local geometry
Availability of SOI, P_{av}	Dependent upon individual items
Time that SOI is active, t_{soi}	Dependent upon individual items
Time that mixture is flammable, t_F	From models or measurements
Reference time, t_{ref}	Selected as appropriate
Number of SOIs, N_{soi}	According to the equipment
Number of SOI events, N_E	Estimated from equipment function

Uncertainties

QRA is a "best guess" estimation ONLY

- Useful to consider the uncertainties associated with each element
- If you assume "worse case" for everything, ignition probability = 1 !!!

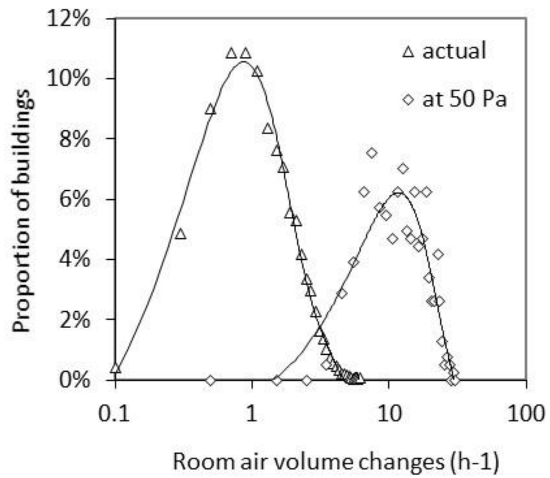
Very useful for comparing different situations and judging effects from risk mitigation measures

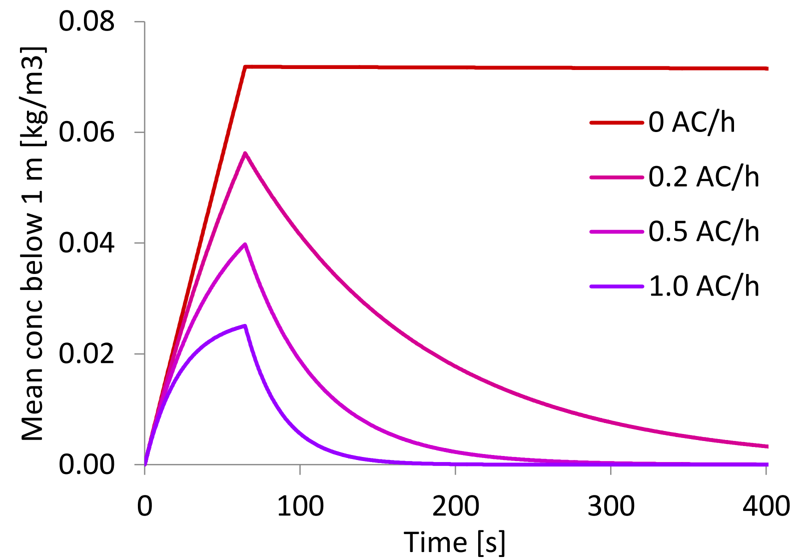
For example, HP is designed to be 'perfect', but faults arise which compromise safety

Uncertainties – infiltration

Infiltration/air change rates

- Various literature provides details of air change rates
- From the literature, lowest value seems to be in the order of 0.3 air changes per hour





- Simple mixing model shows even ½ AC/h drastically reduces concentration beneath release height when release rate is relatively low, compared to 0 AC/h

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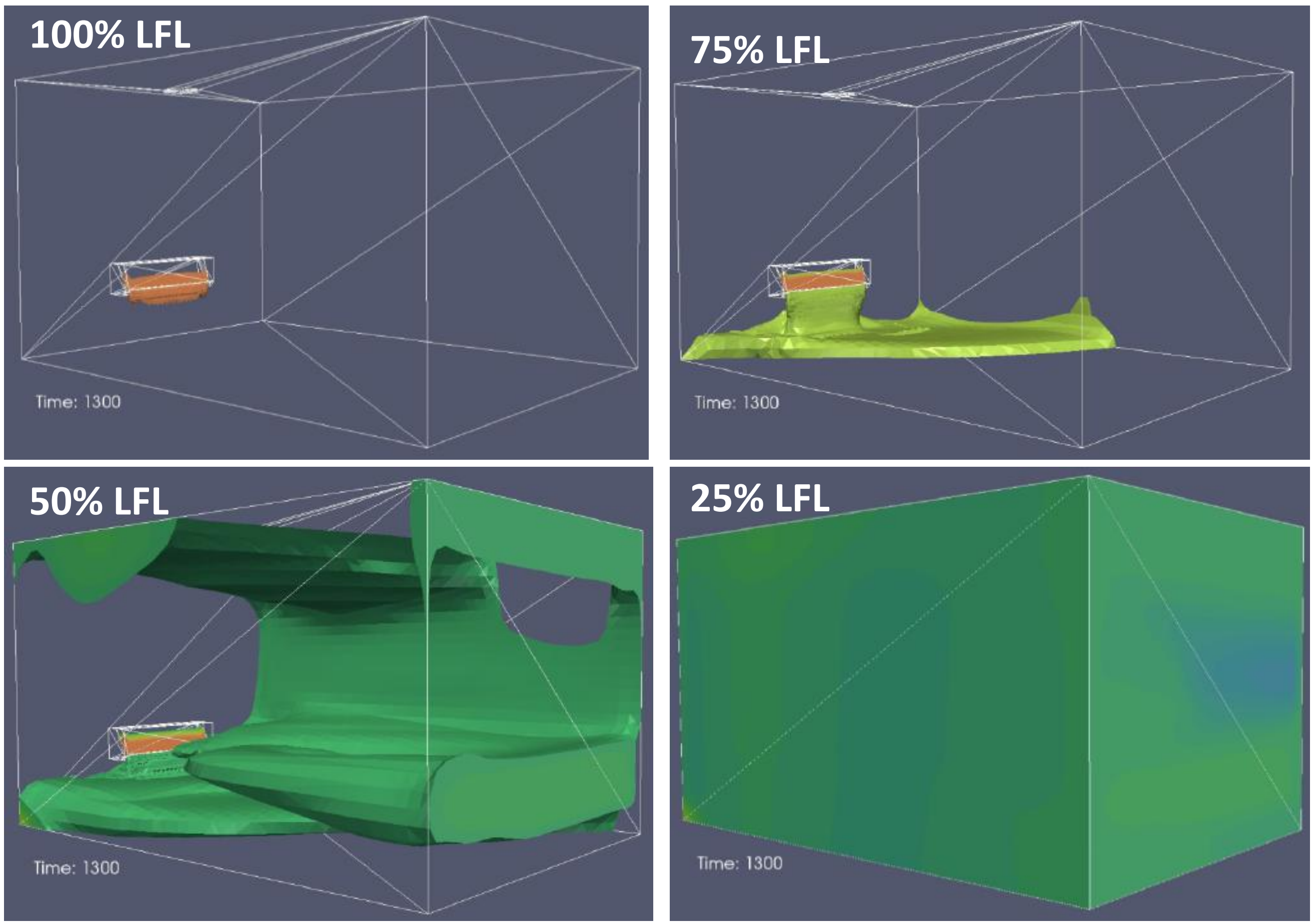
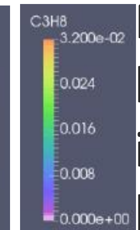
Uncertainties – effect of thermal sources

Effect of thermal gradients: two thermal walls





Relatively small heat source results in entire space becoming well mixed/almost homogenous

- And no more flammable region across floor
- Shear (differential) velocity up to about 0.13 m/s

Convection due to heat flux from one heating wall (+15 W/m^2 = 170 W total) and one cooling (-15 W/m^2) for thermal balance; release 450 g of R290 at 15 g/min

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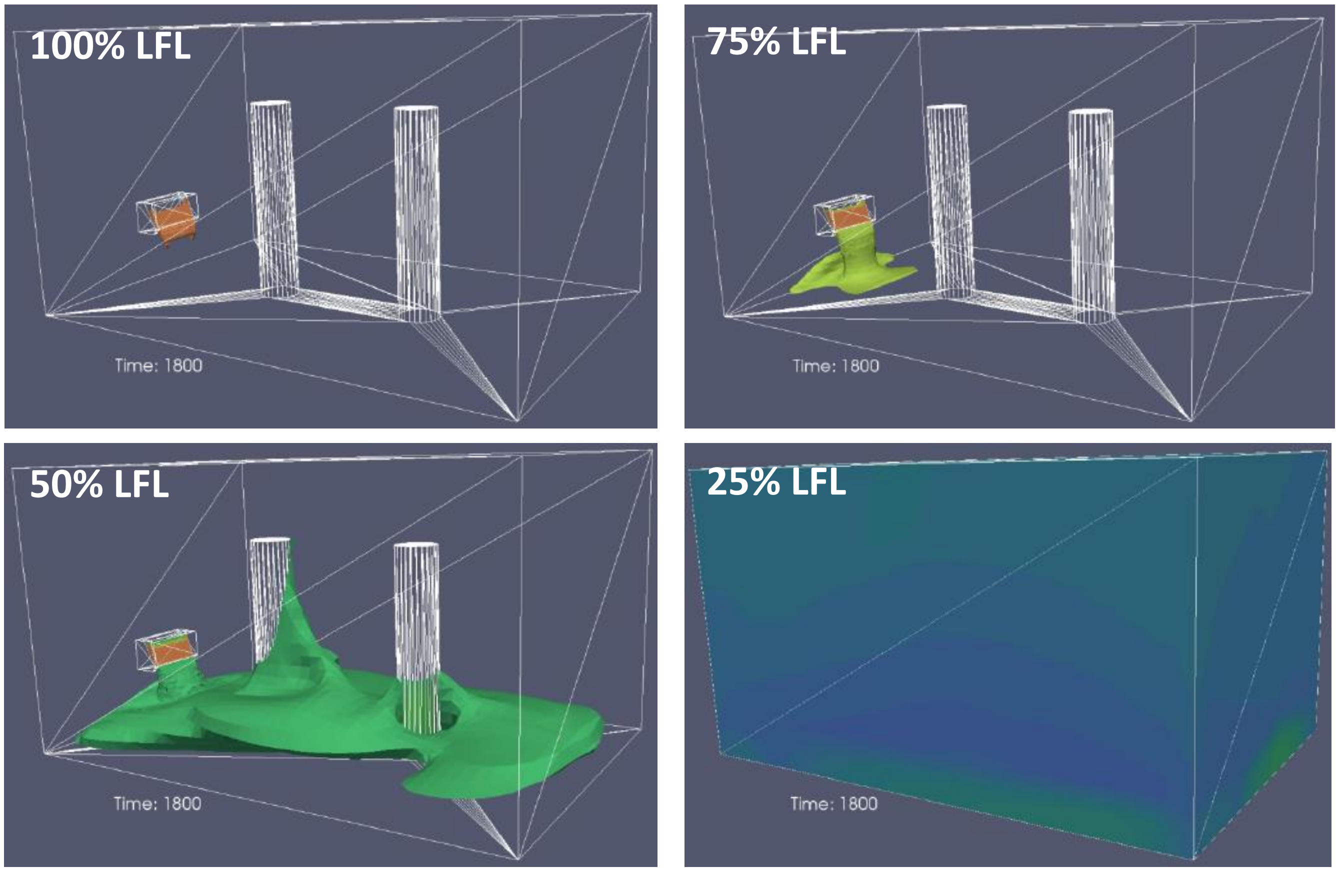
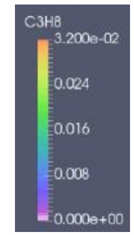
Uncertainties – effect of thermal sources

Effect of thermal gradients: two thermal persons





- Relatively small heat source results in entire space becoming well mixed/almost homogenous
- And no more flammable region across floor

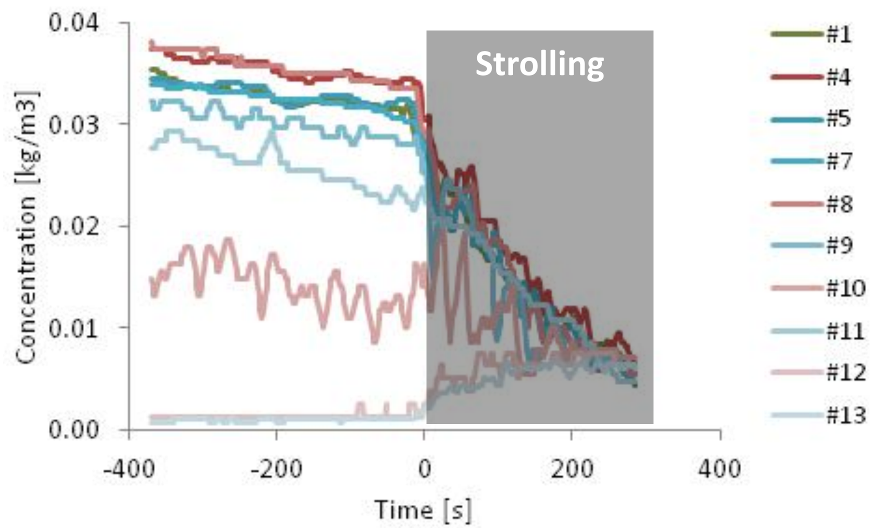
Convection due to heat flux from two persons (+100 W each = 200 W total) and cooling (-2.6 W/m^2) at each vertical wall for thermal balance; release 450 g of R290 at 15 g/min

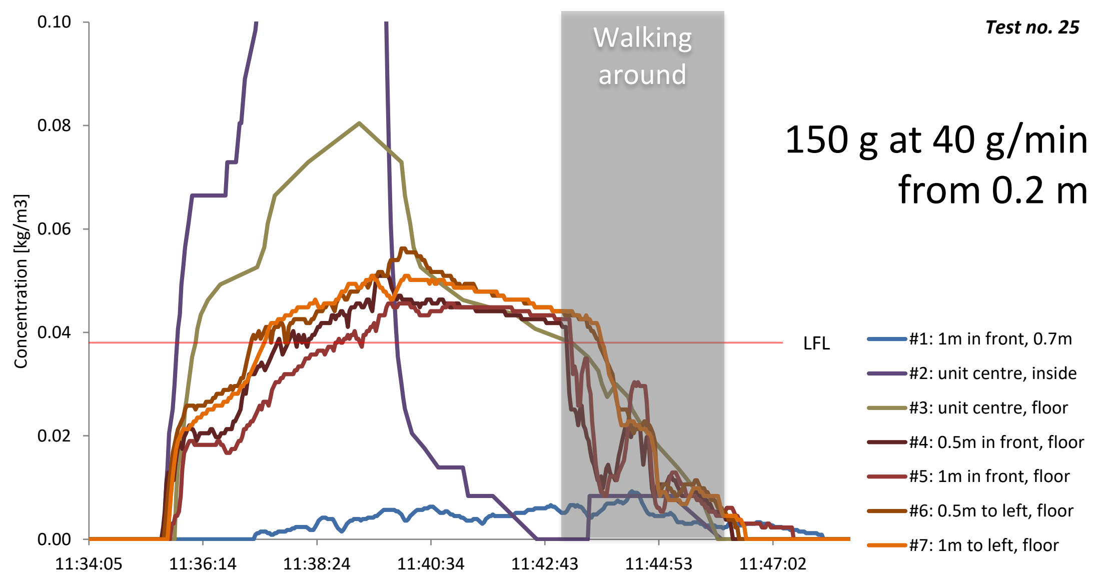
Uncertainties – movement of personnel

Personnel

- Movement of personnel helps to dilute release
- Measurements show effect of gentle strolling following a release
- After approx. two to three minutes almost fully dilutes layer

300 g at 50 g/min from 1 m





Risk analysis

- Examples
- Lifetime risk values

Risk analysis – example of Heat Pump (HP)

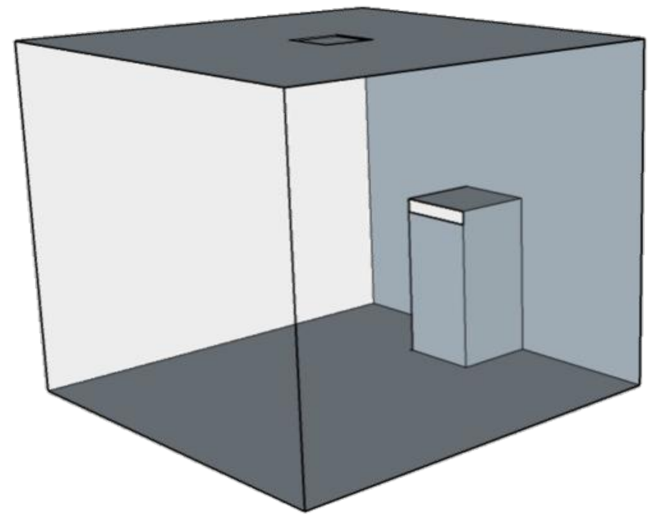
Water-to-water HP in an enclosure in a 3 m × 3 m × 2.5 m high room

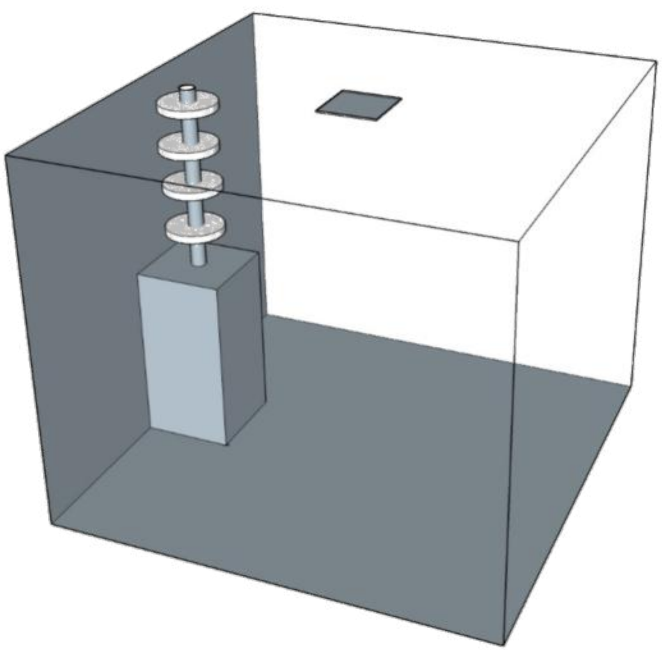
Enclosure 0.6 m × 0.6 m × 1.2 m high

Small opening at the top

Room has no openings, no ventilation, etc.

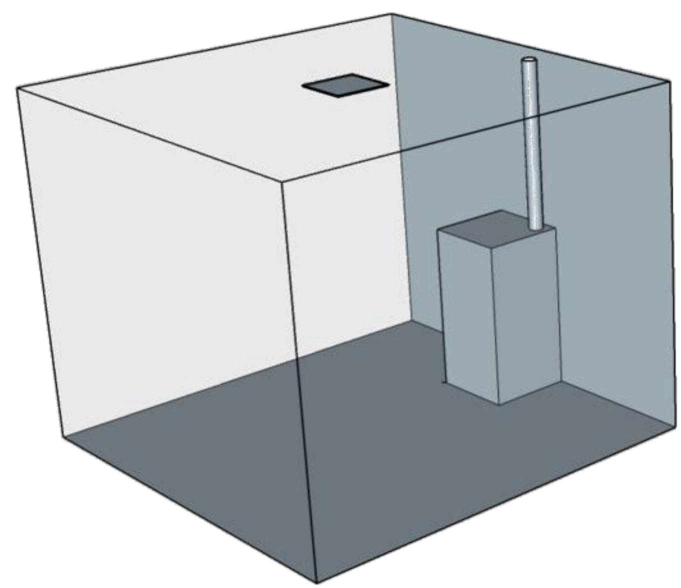
Release of 60 g/min from system, about 1.0 kg





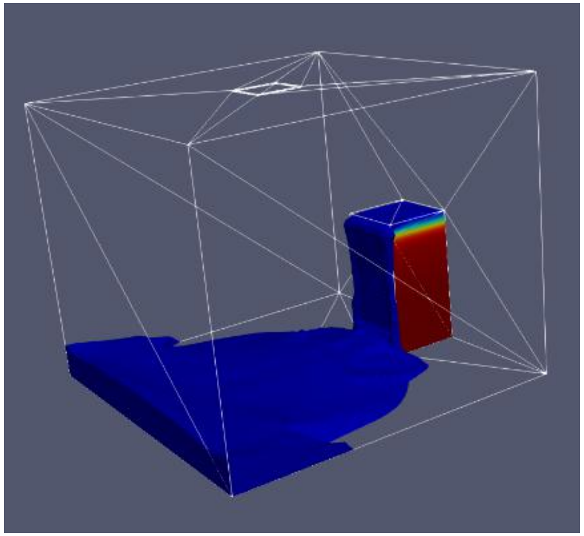
Consider three different designs (for example)

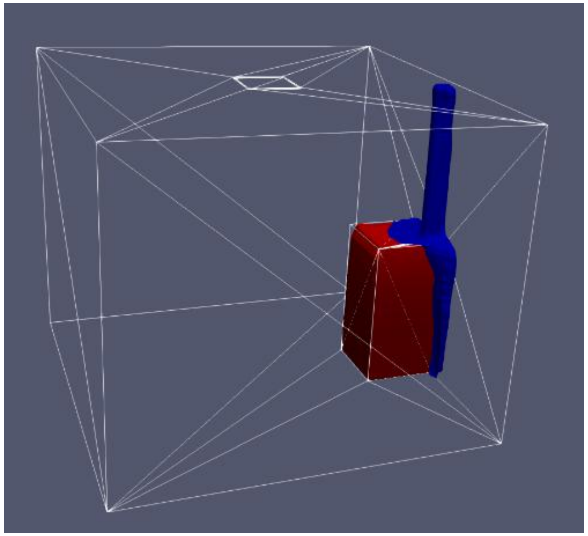
- Open at top
- With plain stack
- With “finned” stack

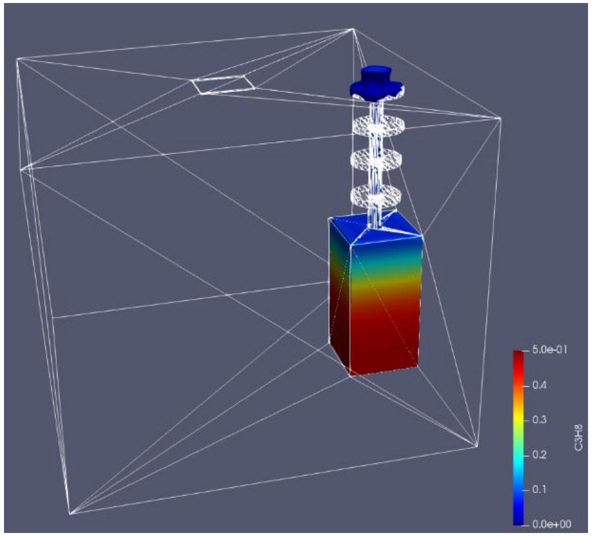


Risk analysis – example of HP

Results of CFD simulation







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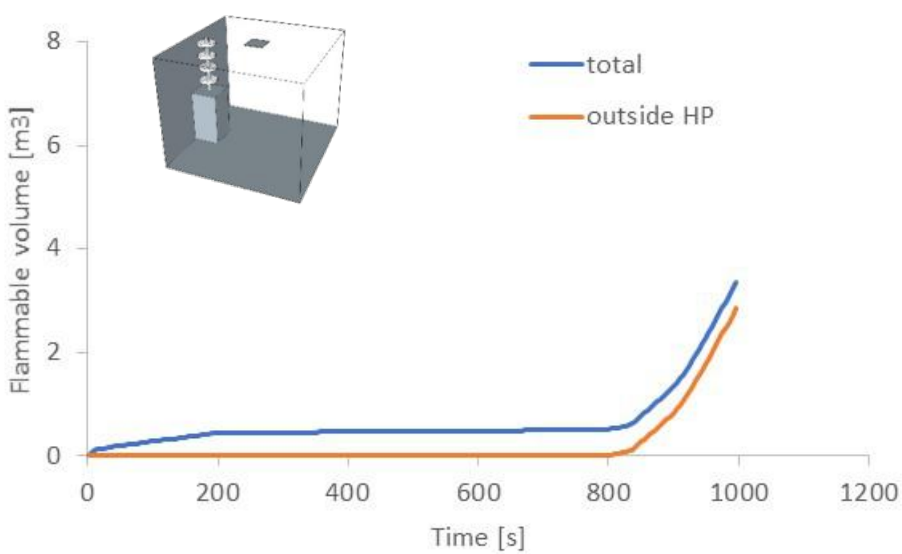
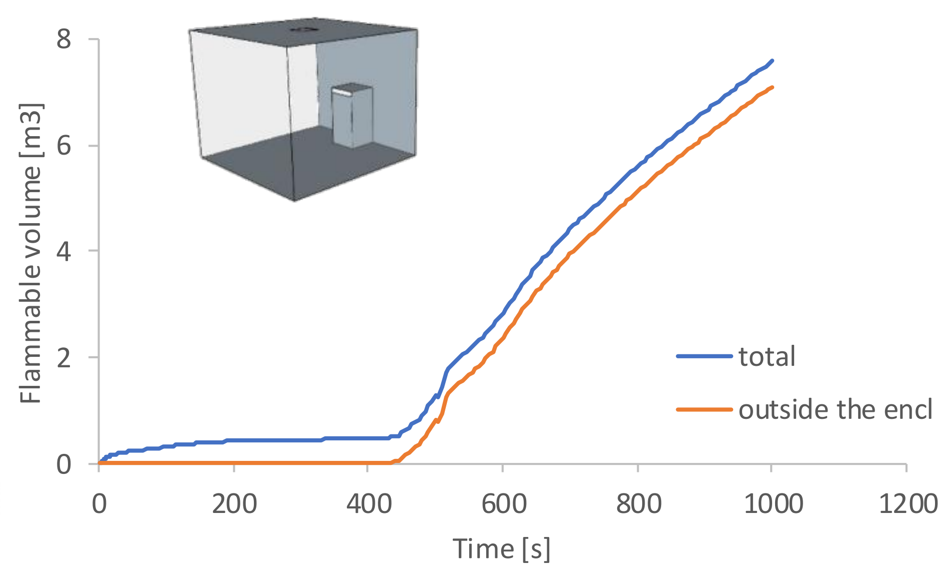
Risk analysis – example of HP

Comparison of calculated flammable volumes arising from leak inside HP

- Total FV (i.e. inside and outside enclosure)
- FV only outside the enclosure

Gives idea of effectiveness of different designs for mitigation





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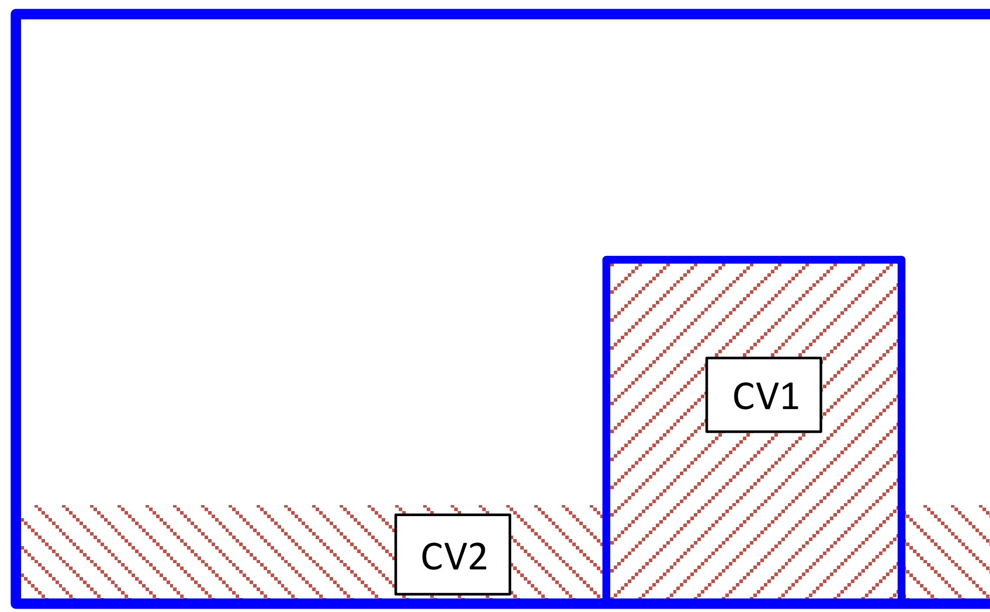
Risk analysis – example of HP

Control volumes: each volume/region where a flammable mixture can form should be assigned as a "control volume"

- Used to determine frequency of ignition
- Calculate severity of consequences

"control volume" vs "zone" (in ATEX)

- "control volume" is a fixed size
- "zone" depends upon result of calculation (input values, etc)



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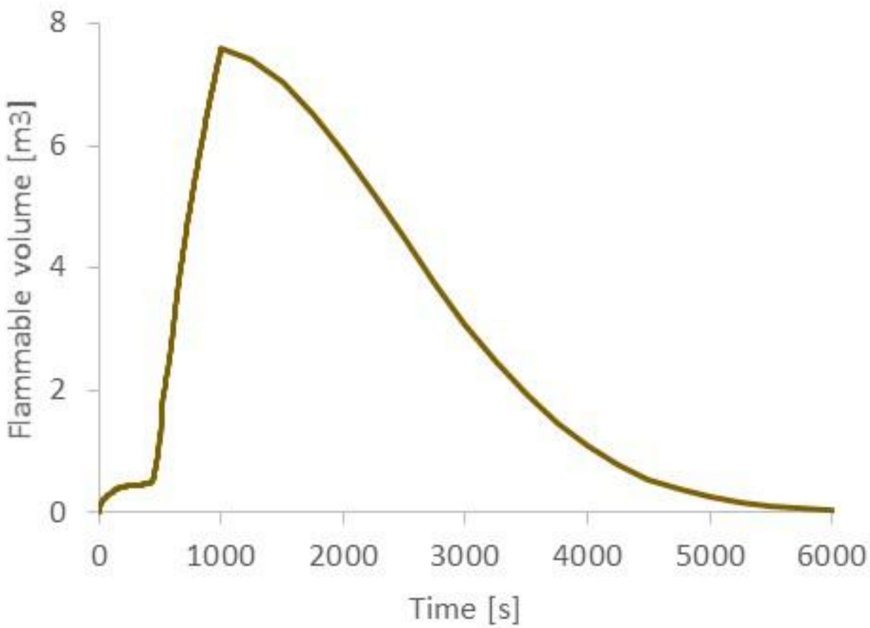
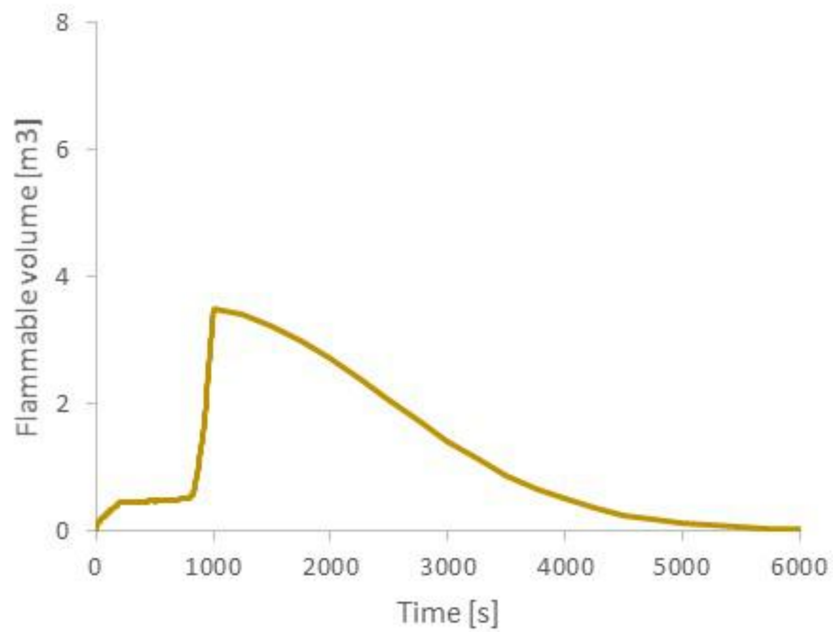
Risk analysis – example of HP

Quantify flammable volume

- From CFD or similar methods



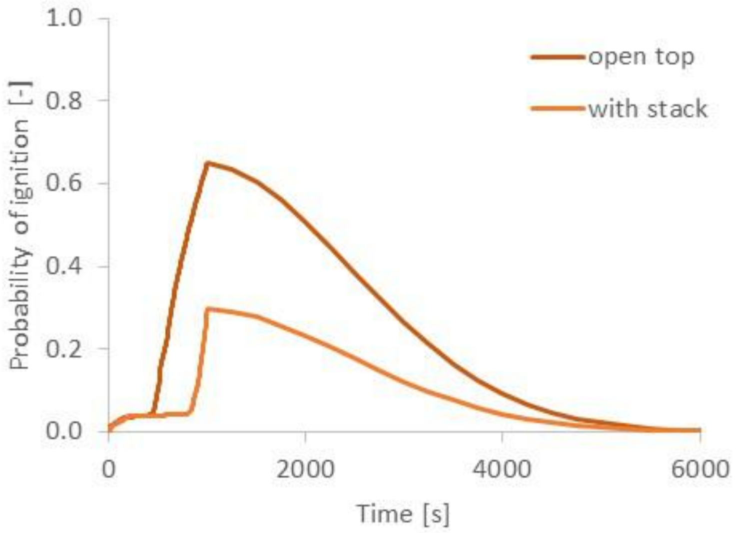


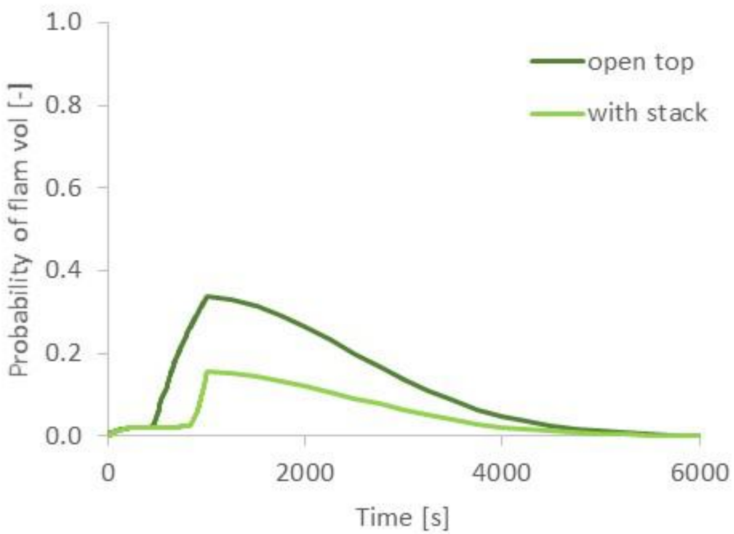
Risk analysis – example of HP

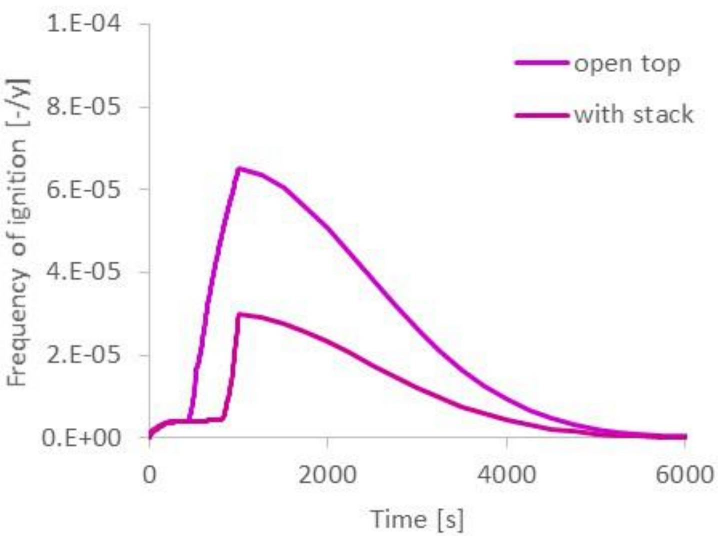
Calculate:

- probability of flammable volume
- probability of ignition
- Frequency of ignition

Can use average for representative value







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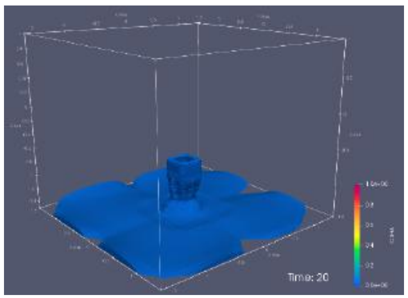
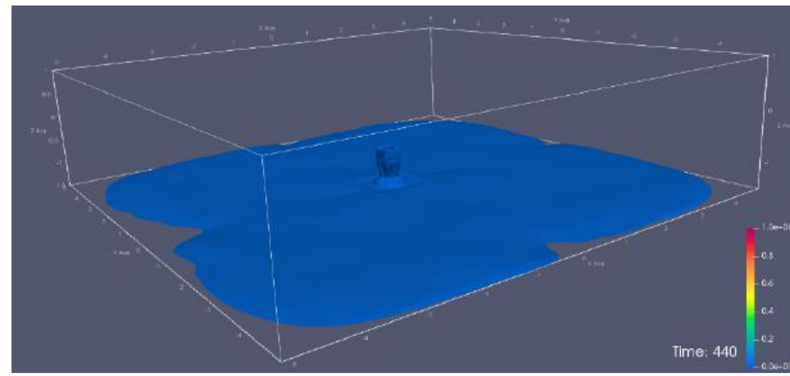
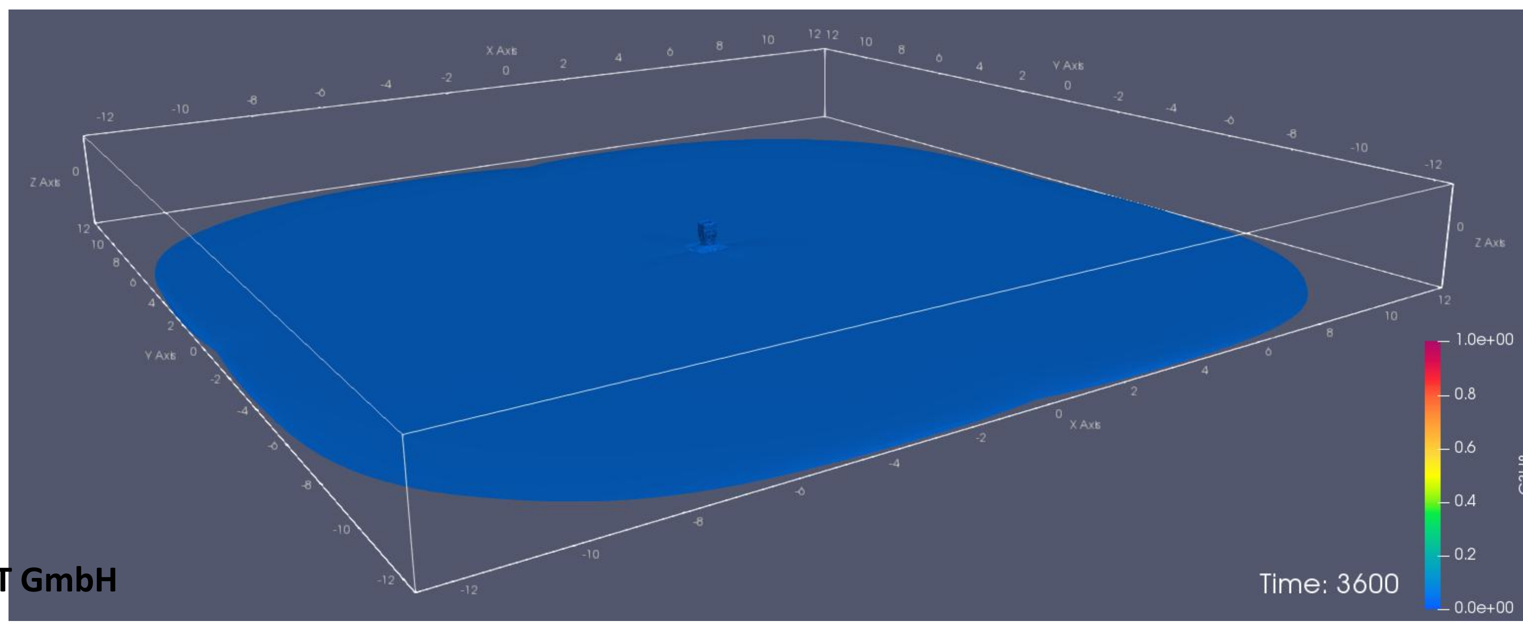
Risk analysis – example of HP

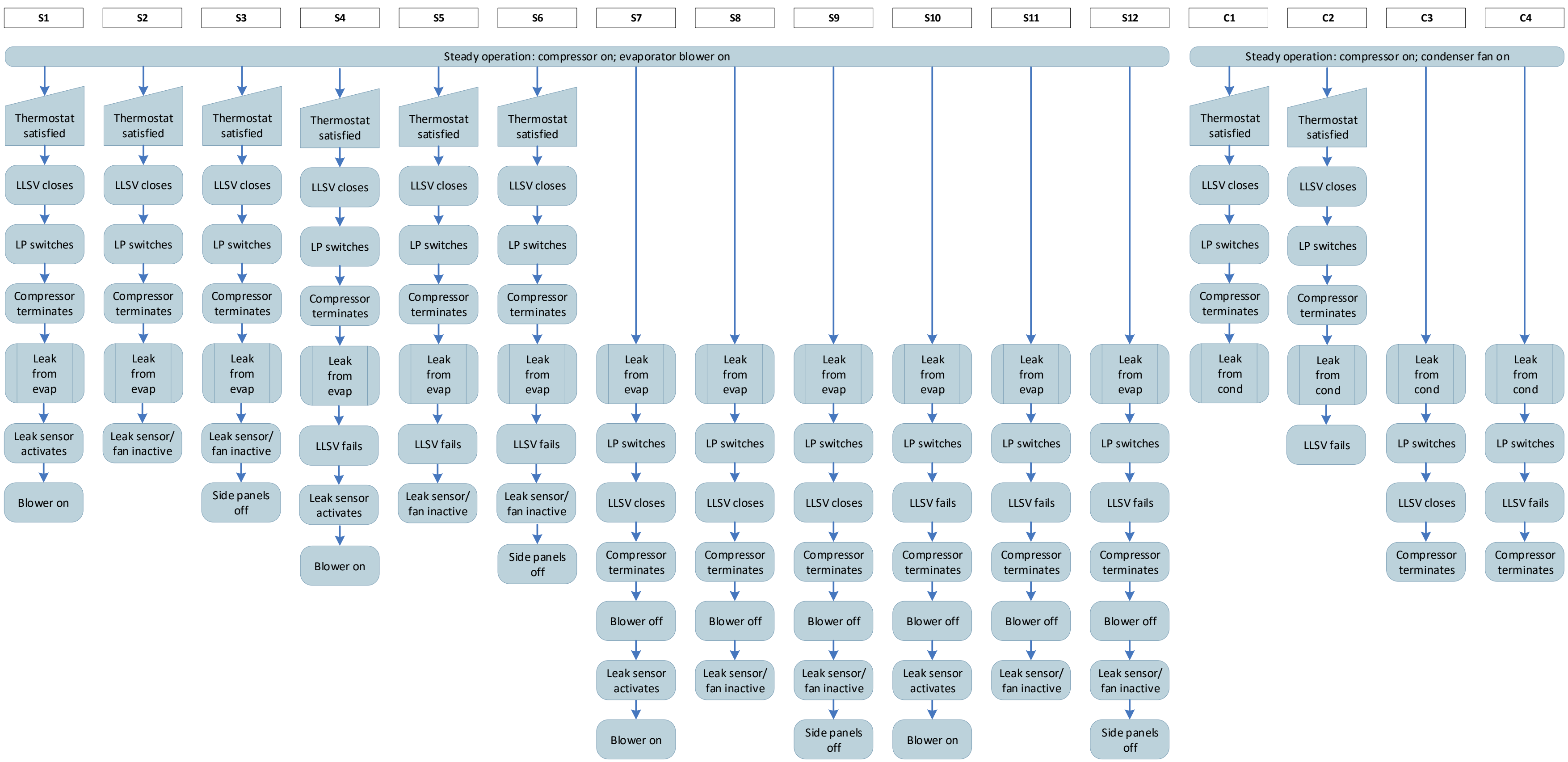
Note: any flammable mixture will likely spread across the space floor; thus, any control volume should represent the entire available space area







Event chain



	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	C1	C2	C3	C4
Release mass	100 g	100 g	100 g	1000 g	1000 g	1000 g	500 g → 100 g	500 g → 100 g	500 g → 250 g	500 g → 250 g	500 g → 250 g	500 g → 250 g	1000 g	1000 g	500 g → 250 g	500 g → 400 g
Blower	On	Off	Off	On	Off	Off	On → off → on	On → off	On → off → on	On → off	On → off	On → off	Off	Off	On → Off	On → off
Pot flamm mix																

To analyse all possible operating modes/conditions

- Also possible to assign probability to each strand

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Probability of failure on demand

Failure rates / failure on demand

For example, HP is designed to be ‘perfect’, but faults arise which compromise safety

- Lack of enclosure tightness
- Enclosure panel not being replaced correctly
- Broken leak detection (gas sensor, system parameter, ultrasonic)
- Electrical components

All should be accounted for

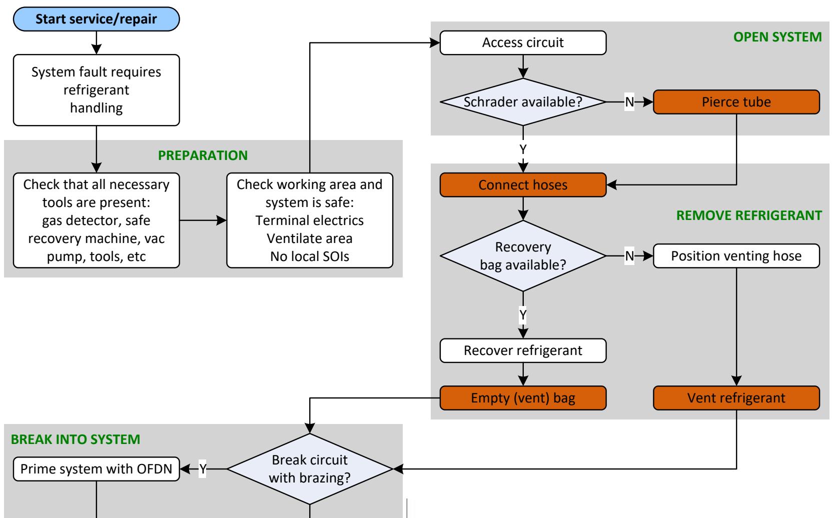
Use calc for Probability of FOD (SIL in accordance with EN 61508)

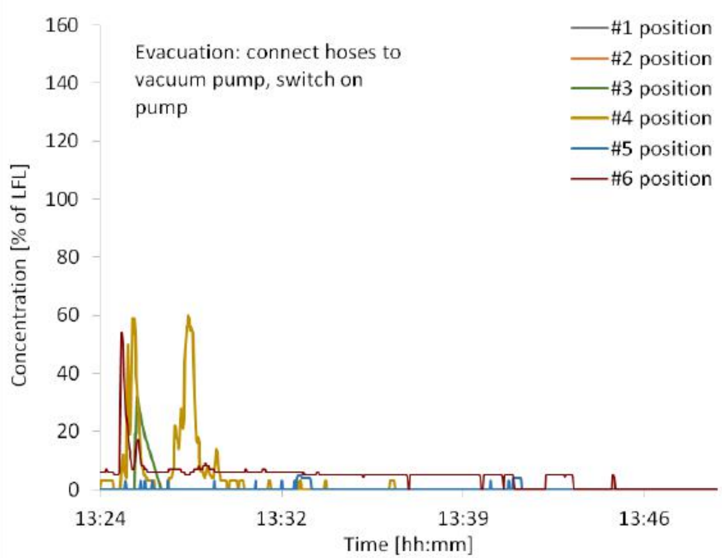
e.g., https://www.pepperl-fuchs.com/great_britain/en/32909.htm or use Markov models

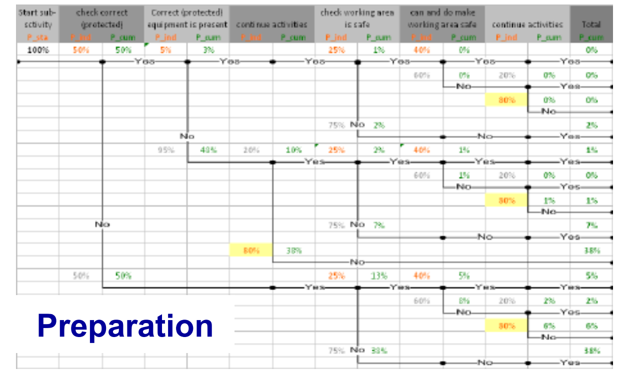
- Frequency of (i) detected and (ii) undetected and dangerous failure
- Interval between functional checks
- Mean time to repair

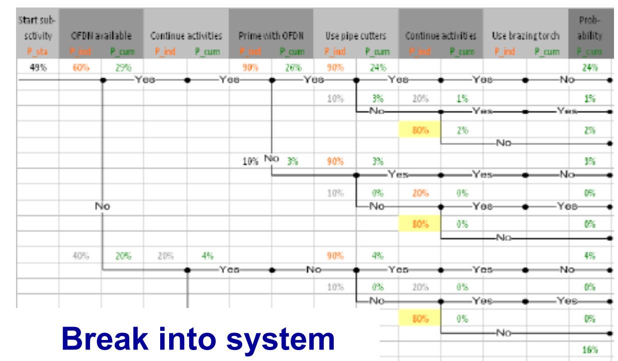
Considering service and maintenance

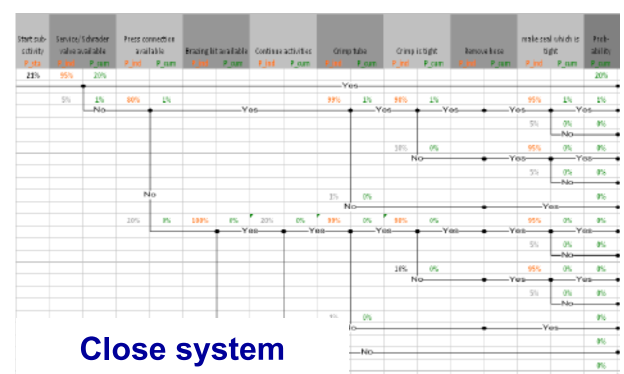
Typically greatest risk over product lifetime











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Ignition frequencies for in-use

Wall unit	Basic	Advanced measures
Charge size	340 g	580 g
Measures	None	Tightness
Ignition frequency	3×10^{-8} / y	8×10^{-9} / y

Note: calcs from internal project

Window unit	Basic	Advanced measures
Charge size	200 g	580 g
Measures	None	Tightness, airflow,
Ignition frequency	5×10^{-7} / y	3×10^{-9} / y

Floor unit	Basic	Advanced measures
Charge size	150 g	580 g
Measures	None	Tightness, airflow, SOSVs
Ignition frequency	5×10^{-6} / y	4×10^{-9} / y

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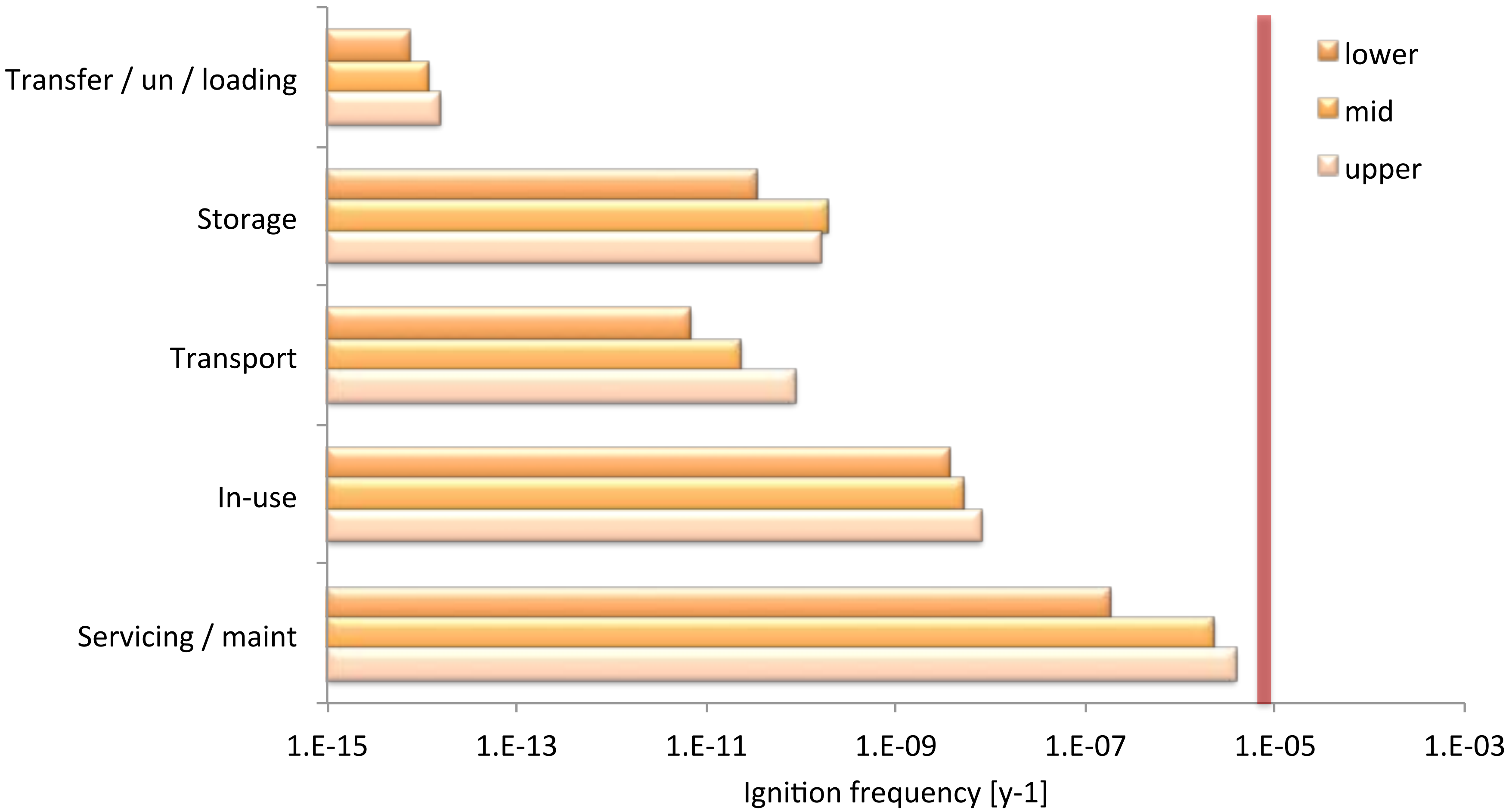
Lifetime risk values



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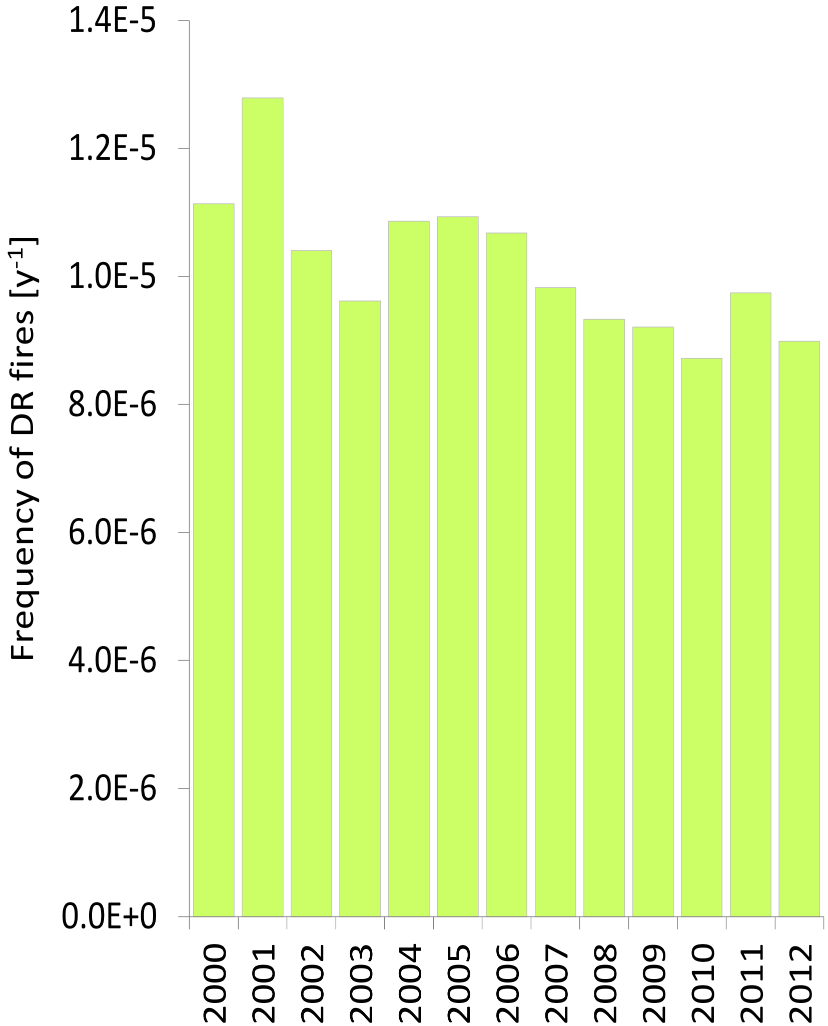
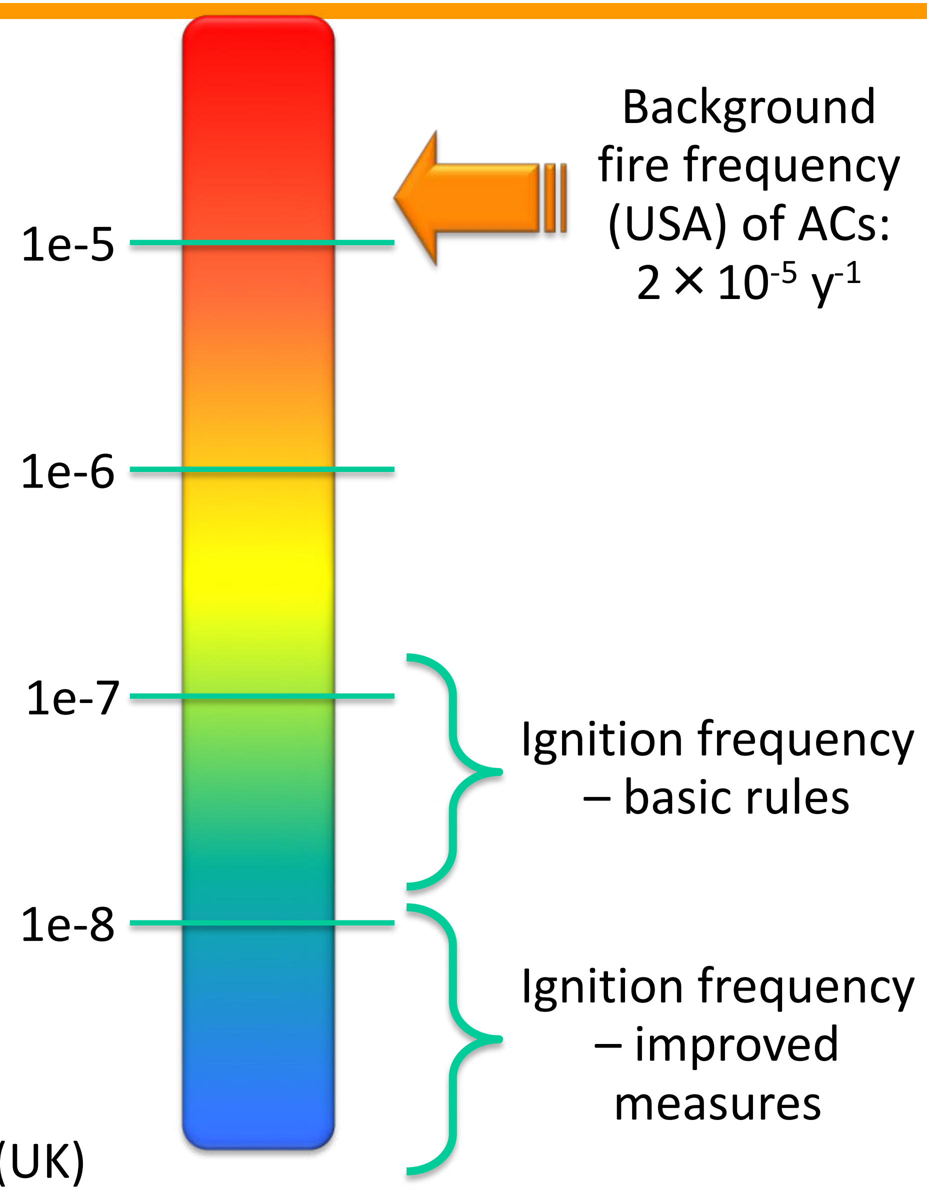
Gauging against a baseline



Frequency of fires from domestic fridges (UK)



Final remarks

- Legislation in Europe demands products are “safe”
  - Inferred through compliance with relevant directives
  - Robust means of demonstrating level of safety through risk assessment
  - (Applies to all hazards, not just flammability)
- Application of a standard – harmonised or not – is just one option for complying with legislation
  - Can be considered as a sort of safety net
- This type of approach common in many countries
- Risk assessment supported by
  - Different techniques (fault tree, event tree, SWIFT, HAZOP, LOPA, etc)
  - Reliability/failure data
  - Experiments and measurements
- Examples units using R290 have additional flammability risk 1/100th – 1/10,000th of reference baseline risks

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