Workshop on Hydrocarbon Refrigerant Safety

Quantitative Risk Assessment on RACHP equipment

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Königstein, Germany

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1. Introduction
2. Legislation and specifics for flammable refrigerants
3. Consequences of ignition
4. Risk analysis
5. Examples
6. Final remarks
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.)
Risk = frequency of hazardous event × consequence severity
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
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

ATEX

LVD

MSD

PED

All demand risk assessment

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Relevant standards
## Tools for risk assessment

<table>
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<th>Structured or semi-structured interviews</th>
<th>Cause-and-effect analysis</th>
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<td>Primary hazard analysis</td>
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<td>Hazard and operability studies (HAZOP)</td>
<td>Bow tie analysis</td>
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<td>Hazard Analysis &amp; Critical Control Points (HACCP)</td>
<td>Reliability centred maintenance</td>
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<td>Environmental risk assessment</td>
<td>Sneak circuit analysis</td>
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<td>Structure “What if?” (SWIFT)</td>
<td>Markov analysis</td>
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<td>Scenario analysis</td>
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<td>Business impact analysis</td>
<td>Bayesian statistics and Bayes Nets</td>
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<td>Root cause analysis</td>
<td>FN curves</td>
</tr>
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<td>Failure mode effect analysis</td>
<td>Risk indices</td>
</tr>
<tr>
<td>Fault tree analysis</td>
<td>Consequence/probability matrix</td>
</tr>
<tr>
<td>Event tree analysis</td>
<td>Cost/benefit analysis</td>
</tr>
<tr>
<td>Cause and consequence analysis</td>
<td>Multi-criteria decision analysis (MCDA)</td>
</tr>
</tbody>
</table>
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
Directives on use of flammable gas

**From ATEXD guidelines:**
- If equipment contains potentially explosive gas, the equipment can be installed in a potentially explosive atmosphere, provided it is subject to the Directive.

**Must consider flammable gas hazards**

**ATEX (94/9/EC)**
- **EN 1127-1**

**Annex I, 1.5.7 Explosion:**
- Machinery must be designed and constructed in such a way as to avoid any risk of explosion due to the presence of an explosive atmosphere. The scope of this Directive, (a): Additional protection if flammable gas is used

**MSD (2006/42/EC)**
- **EN 60335-2-40**
- **EN 60335-2-89**

**LVD (2006/95/EC)**

**PED (97/23/EC)**
- **EN 378-2**

How to do the flammability risk assessment

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Constructive guidance

Preferences, values and expectations of society

Handling uncertainty

Approach to reaching decisions on risk

Criteria for reaching decisions and tolerability limits
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
Risk assessment under ATEX

Key steps extracted from ATEX directives

- Identification of hazardous substance
- Characterisation of hazardous substance
- Determine equipment group and category
- Satisfy essential health and safety requirements

- Design unit based on integrated safety
- Prevent the formation of explosive atmospheres
- Prevent the ignition of explosive atmospheres
- Should an explosion occur limit the flames and explosion pressures
- Design and manufacture after due analysis of possible operating faults and misuse
- Design and construct with maintenance conditions in mind
- Design and construct to cope with foreseeable surrounding area conditions
- Mark with the minimum particulars
- Accompanied by appropriate instructions
- Selection of materials for explosion protection and longevity
- Prevention of leaks
- Potential ignition sources must not occur
- Proper application of safety-related devices

Apply conformity assessment

Production; Storage; Transportation; Handling; Operation/in-use; Service/maintenance; Disposal

Identification of flammability hazards and determination of the likelihood of occurrence of a flammable atmosphere

Identification of ignition hazards and determination of the likelihood of occurrence of potential ignition sources

Estimation of possible effects (consequences) in case of ignition

Evaluation of the risk and whether the intended level of protection has been achieved

Consideration of measures to reduce the likelihood of ignition and severity of consequences

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Specifically for flammable refrigerants

- Identification of explosion hazards and determination of the likelihood of occurrence of a hazardous explosive atmosphere
- Identification of ignition hazards and determination of the likelihood of occurrence of potential ignition sources
- Estimation of the possible effects of an explosion in case of ignition
- Evaluation of the risk and whether the intended level of protection has been achieved
- Consideration of measures to reduce the risks

\[ P_i^{F*} = \sum_{N=1}^{N_{soi}} \left( 1 - \left[ (1 - P_{V,i}^F) + P_{V,i}^F (1 - P_{so,i}^F) \right]^{1/t} \right) \]

\[ P_{soi,i}^F = P_{avail} \frac{t_{soi} + t_i^F}{t^F} \]

\[ P_{V,i}^F = \frac{V_h^F}{V_h} P_{sys} P_{perc} \]

\[ \chi_{\Delta p} = \sum_{i=1}^{N_{soi}} \sum_{j=1}^{N_{soi}} f_{i,j}^* \Delta p_{i,j}^0 \]

\[ \chi = \sum_{i=1}^{N_{soi}} \sum_{j=1}^{N_{soi}} f_{i,j}^* l_{occ,i,j} \]

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Risk processes

- Causes
  - Leak of refrigerant
  - Presence of ignition source

- Likelihood

- Conditions affecting dispersion
  - Refrigerant mixture with air
  - Active ignition source

- Ignition

- Conditions Severity
  - Primary consequence (jet fire, flash fire, explosion)
  - Secondary consequence (thermal damage, secondary fire, overpressure damage, injury)

- Applicable Likelihood

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Map of actions/activities

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Charge amount

Basic relationship between refrigerant charge and risk...

Do what you can to reduce charge – if practicable!

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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
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

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

For ‘in-use’ activity phase

Typically 98 – 99.9% of the product lifetime

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Activity phases

- Production
- Transfer
- Storage
- Transport
- Installation
- In-use
- Servicing/maintain
- Decommissioning
Risk analysis/semi-quantitative risk assessment

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“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
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 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.
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.
5 Possible ignition sources .................................................................................................................
5.1 Hot surfaces ................................................................................................................................
5.2 Flames and hot gases (including hot particles) ..............................................................................
5.3 Mechanically generated sparks ....................................................................................................
5.4 Electrical apparatus ....................................................................................................................
5.5 Stray electric currents, cathodic corrosion protection .................................................................
5.6 Static electricity ..........................................................................................................................
5.7 Lightning ......................................................................................................................................
5.8 Radio frequency (RF) electromagnetic waves from $10^4$ Hz to $3 \times 10^{11}$ Hz ..................
5.9 Electromagnetic waves from $3 \times 10^{11}$ Hz to $3 \times 10^{15}$ Hz ..................................................
5.10 Ionizing radiation .......................................................................................................................}
5.11 Ultrasonics ...................................................................................................................................
5.12 Adiabatic compression and shock waves .....................................................................................
5.13 Exothermic reactions, including self-ignition of dusts ...............................................................
## Safety standards – ignition sources

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

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

6.1 Fundamental principles

6.2 Avoidance or reduction of the amount of explosive atmosphere

6.2.1 Process parameters

6.2.2 Design and construction of equipment, protective systems and components

6.3 Hazardous areas

6.4 Requirements for the design and construction of equipment, protective systems and components by avoidance of effective ignition sources
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 occur 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

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Modelling approach

Finite element model for expanding front of combustion products

Conservation of mass and energy

Opening f₀ {fixing strength; linear mass; area; rate pressure rise}

Mixture in element burns within fixed time, yielding high temp combustion products at higher pressure/volume

Radiant heat loss

Rate of venting f₀ {open area; mix composition; pressure difference}

Flame front speed f₀ {laminar flame; turbulence factor}

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## Consequences of ignition

### Severity of overpressures

<table>
<thead>
<tr>
<th>Overpressure (kPa)</th>
<th>Effects to Structures</th>
<th>Overpressure (kPa)</th>
<th>Effects to Persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 – 7 kPa</td>
<td>Shattering of glass windows, occasional frame failure</td>
<td>4 kPa</td>
<td>Threshold for injury from flying glass</td>
</tr>
<tr>
<td>7 – 14 kPa</td>
<td>Corrugated steel or aluminium connection failure and buckling, plaster walls cracking, wood walls splintering</td>
<td>10 kPa</td>
<td>Threshold for multiple skin laceration from flying glass</td>
</tr>
<tr>
<td>14 – 20 kPa</td>
<td>Shattering of concrete or cinder block wall panels</td>
<td>20 kPa</td>
<td>10% probability for eardrum rupture, overpressure will hurl person to ground</td>
</tr>
<tr>
<td>20 – 28 kPa</td>
<td>Collapse of self-framing steel panel building</td>
<td>70 kPa</td>
<td>Threshold for lung haemorrhage</td>
</tr>
<tr>
<td>34 kPa</td>
<td>Snapping of wooden utility poles</td>
<td>190 kPa</td>
<td>1% mortality</td>
</tr>
<tr>
<td>55 kPa</td>
<td>Shearing and flexure failure of brick wall panel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34 – 69 kPa</td>
<td>Shattering of laminated car safety glass</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
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
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

![Graph 1: Room overpressure vs. Burn time]
- Completely full of flammable mixture, partially full

![Graph 2: Overpressure vs. Burn time]
- 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

```
leak time = 210 s
airflow = 60 m3/hr
```

```
leak time = 210 s
airflow = 0 m3/hr
```
If there is overpressure within an enclosure that escapes, a shockwave 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

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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

<table>
<thead>
<tr>
<th>Thermal dose (s(kW/m^2)^{4/3})</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>pain threshold</td>
</tr>
<tr>
<td>150</td>
<td>flashover (secondary fire)</td>
</tr>
<tr>
<td>1050</td>
<td>1% fatality</td>
</tr>
<tr>
<td>6500</td>
<td>99% fatality</td>
</tr>
</tbody>
</table>
## Consequences of ignition

<table>
<thead>
<tr>
<th>Harm Caused</th>
<th>Thermal Dose (TDU), (kW/m²)⁴/³ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escape impeded</td>
<td>290</td>
</tr>
<tr>
<td>1-5% Fatality offshore</td>
<td>1000</td>
</tr>
<tr>
<td>50% Fatality offshore with radiation only to the front or back (i.e. from a fireball)</td>
<td>1000</td>
</tr>
<tr>
<td>50% Fatality offshore</td>
<td>2000</td>
</tr>
<tr>
<td>100% Fatality offshore</td>
<td>3500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Duration</th>
<th>Radiated Surface Emissive Heat Flux (kW/m²)</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pool fire (open)</td>
<td>Medium</td>
<td>Long</td>
<td>50 – 150</td>
<td>Radiation, smoke, engulfment</td>
</tr>
<tr>
<td>Pool fire (severe or confined)</td>
<td>Medium</td>
<td>Long</td>
<td>100 – 230</td>
<td>Radiation, smoke</td>
</tr>
<tr>
<td>Jet fire (open)</td>
<td>Medium</td>
<td>Medium/Long</td>
<td>50 – 250</td>
<td>Radiation, smoke</td>
</tr>
<tr>
<td>Jet fire (confined)</td>
<td>Medium</td>
<td>Medium/Long</td>
<td>100 – 300</td>
<td>Radiation, smoke</td>
</tr>
<tr>
<td>Flash fire</td>
<td>Large</td>
<td>Short</td>
<td>170</td>
<td>Engulfment</td>
</tr>
<tr>
<td>Fireball</td>
<td>Large</td>
<td>Short</td>
<td>270 (HID SRAG)</td>
<td>Radiation</td>
</tr>
</tbody>
</table>
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

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

Within cond unit housing at stoic conc

Difference due to rectangular room shape and non-stoichiometric conc
Risk analysis

- Tools
- Uncertainties
**Risk analysis/risk assessment**

**Quantitative methods**

<table>
<thead>
<tr>
<th>Identify event</th>
<th>Pipe fails?</th>
<th>Gas leaks into occupied space?</th>
<th>Flammable concentration achieved?</th>
<th>SOI present?</th>
<th>SOI active?</th>
<th>Ignition occurs?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excessive internal pressure</td>
<td>Y P=0.3 N P=0.7</td>
<td>Y P=0.9 N P=0.1</td>
<td>Y P=0.2 N P=0.8</td>
<td>Y P=0.00027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y P=0.01 N P=0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Event tree analysis (ETA) ↑**

**Fault tree analysis (FTA) →**

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Incidence of events

Coincidence of events required for ignition

"active" potential sources of ignition

incidence of active ignition source and flammable volume

location 1

location 2

location 3

leak

flammable volume resulting from leak

time line of thermostat

time line of light switch

time line of thermostat

time

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Basic probability formulae

Ignition frequency: \( f^* = f_{\text{leak}} P_{FV} \)

Probability of flammable mixture being present: \( P_{FV} = \frac{V_F}{V_{cv}} P_{prc} \)

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

Probability of ignition source being active within flammable mixture:

\[
P_{ign} = \sum_{N=1}^{N_{soi}} \left\{ 1 - \left[ (1 - P_{FV}) + P_{FV}(1 - P_{soi}) \right]^{N_E} \right\}
\]
## Input data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leak frequency, $f_{\text{leak}}$</td>
<td>From leak size study</td>
</tr>
<tr>
<td>Volume of flammable mixture, $V_F$</td>
<td>From models</td>
</tr>
<tr>
<td>Percolation probability, $P_{\text{prc}}$</td>
<td>From literature; usually about 0.5</td>
</tr>
<tr>
<td>Size of control volume, $V_{cv}$</td>
<td>From local geometry</td>
</tr>
<tr>
<td>Availability of SOI, $P_{\text{av}}$</td>
<td>Dependent upon individual items</td>
</tr>
<tr>
<td>Time that SOI is active, $t_{\text{soi}}$</td>
<td>Dependent upon individual items</td>
</tr>
<tr>
<td>Time that mixture is flammable, $t_F$</td>
<td>From models or measurements</td>
</tr>
<tr>
<td>Reference time, $t_{\text{ref}}$</td>
<td>Selected as appropriate</td>
</tr>
<tr>
<td>Number of SOIs, $N_{\text{soi}}$</td>
<td>According to the equipment</td>
</tr>
<tr>
<td>Number of SOI events, $N_E$</td>
<td>Estimated from equipment function</td>
</tr>
</tbody>
</table>
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
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
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/m² = 170 W total) and one cooling (-15 W/m²) 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/m²) 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

150 g at 40 g/min from 0.2 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
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
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)
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
Note: any flammable mixture will likely spread across the space floor; thus, any control volume should represent the entire available space area
To analyse all possible operating modes/conditions

- Also possible to assign probability to each strand
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

1. Start service/repair
   - System fault requires refrigerant handling

2. Preparation
   - Check that all necessary tools are present: gas detector, safe recovery machine, vac pump, tools, etc
   - Check working area and system is safe: Terminal electrics Ventilate area No local SOIs

3. Break into system
   - Prime system with OFDN
   - Break circuit with brazing?

4. Evacuation
   - Connect hoses to vacuum pump, switch on pump

5. Break into system

6. Close system

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## Ignition frequencies for in-use

<table>
<thead>
<tr>
<th></th>
<th>Basic</th>
<th>Advanced measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wall unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge size</td>
<td>340 g</td>
<td>580 g</td>
</tr>
<tr>
<td>Measures</td>
<td>None</td>
<td>Tightness</td>
</tr>
<tr>
<td>Ignition frequency</td>
<td>3×10⁻⁸ / y</td>
<td>8×10⁻⁹ / y</td>
</tr>
<tr>
<td><strong>Window unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge size</td>
<td>200 g</td>
<td>580 g</td>
</tr>
<tr>
<td>Measures</td>
<td>None</td>
<td>Tightness, airflow,</td>
</tr>
<tr>
<td>Ignition frequency</td>
<td>5×10⁻⁷ / y</td>
<td>3×10⁻⁹ / y</td>
</tr>
<tr>
<td><strong>Floor unit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge size</td>
<td>150 g</td>
<td>580 g</td>
</tr>
<tr>
<td>Measures</td>
<td>None</td>
<td>Tightness, airflow,</td>
</tr>
<tr>
<td>Ignition frequency</td>
<td>5×10⁻⁶ / y</td>
<td>4×10⁻⁹ / y</td>
</tr>
</tbody>
</table>

Note: calcs from internal project

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Gauging against a baseline

Background fire frequency (USA) of ACs: $2 \times 10^{-5} \, \text{y}^{-1}$

Ignition frequency – basic rules

Ignition frequency – improved measures

Frequency of DR fires [y$^{-1}$]

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