Recommended leak hole size and mass flow rates by system and application characteristics

lifefront

Public report

for the project LIFE FRONT

LIFE FRONT (Flammable Refrigerants Options for Natural Technologies) is an EU project aiming to remove barriers posed by standards for flammable refrigerants in refrigeration, heating and cooling applications

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LIST OF ABBREVIATIONS

C_D	Coefficient of Discharge
DN	Nominal diameter
GHG	Green House Gas
GWP	Global Warming Potential
HC	Hydrocarbon
HFC	Hydrofluorocarbon
LFL	Lower Flammability Limit
LIFE FRONT Project	Flammable Refrigerant Options for Natural Technologies – Improved standards & product design for their safe use (FRONT)
RAC	Refrigeration and Air conditioning
RACHP	Refrigeration, Air conditioning, and Heat Pump
UFL	Upper Flammability Limit

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In the effort to reduce greenhouse gas emissions, natural refrigerants provide an important environmentally friendly alternative for the refrigeration, air conditioning and heat pump (RACHP) sector regarding energy-efficiency and global warming potential. A review of relevant safety standards and a market survey under the LIFE FRONT project showed that the primary barriers to flammable refrigerants in safety standards are mainly related to refrigerant charge size limits, which reduce the ability of systems to provide the envisaged cooling capacity.

The LIFE FRONT project seeks to determine appropriate safety requirements and measures for RACHP appliances using flammable refrigerants. This report first outlines the background of current charge size limits of various standards. It also provides a brief overview of available studies on leakages t and their main results.

Under the LIFE FRONT project, a realistic assumption of risk parameters, based on frequency of leaks, leak hole sizes and mass flow rates, and a fundamental approach to leak time measurements is developed. During a field study data was collected on leak hole sizes, types and causes in RACHP appliances. In another part of this FRONT project laboratory measurements of gas concentrations arising from refrigerant releases from different parts of RACHP systems are being carried out. The results are also expected to improve the effectiveness of measures to reduce refrigerant releases and to further improve leak detection processes. Results of both the field survey and the laboratory tests are summarised in two public databases: one on leak hole sizes and one on leak simulation/concentration measurements; and in the reports published under the FRONT project.

Results from collected data showed a clear trend: the vast majority of the leak holes reported from the field are very small relative to the pipe size (i.e. more than 80% are less than 0.02 mm^2). The identified leak hole sizes so far led to leak rates of 0-50 g/min of vapour based on typical conditions for R290. Based on these results a framework is proposed for a rational approach to the determination of assumed leak rates. The proposed framework considers various factors and operating conditions of a RACHP system (see Annex).

INTRODUCTION

LIFE FRONT is a demonstration project funded under the LIFE programme of the European Union (Climate Change Mitigation 2016 priority area). It aims to remove the barriers posed by standards for flammable refrigerants in refrigeration, air conditioning and heat pump (RACHP) applications. For promoting the use of flammable refrigerants in RACHP appliances, current RACHP safety standards need to be revised.

A thorough overview of relevant RACHP standards, as well as a compilation of barriers posed by these standards to the use of flammable hydrocarbon refrigerants is available in the following report, also published under the LIFE FRONT project: *Impact of standards on hydrocarbon refrigerants in Europe*[1]. The report is available for download from the project website at *lifefront.eu.*

The replacement of hydrofluorocarbons (HFCs) with low GWP environmentally friendly refrigerants is essential for the reduction of greenhouse gas (GHG) emissions from RACHP equipment. Due to their favourable thermophysical properties, hydrocarbons (HCs) are important alternatives.

As HCs are flammable, it is essential to understand the details of their ignition risk. Major contributing factors to an ignition risk are the likelihood or frequency of a leak, the amount and persistence of the resulting flammable mixture and the occurrence of ignition sources. A fundamental aspect of reducing the flammability risk for RACHP systems is to avoid sources of ignition in potentially flammable zones on and around the equipment. Identification of critical zones requires an assumption of a certain mass flow of refrigerant leak and an understanding of the dispersion and dilution of that refrigerant. The size of the flammable mixture results from the leak hole size which dictates the release mass flow, leak hole orientation and location, the mass of refrigerant released, airflow, room size, housing geometry and the height of the system parts. Therefore, it is important to analyse the release mass flow rate and its corresponding leak hole size to determine the allowable mass of refrigerant charge to minimise the possibility of ignition.

Figure 1 provides an example of the sort of relationship between leak hole size and the extent of "zone 2" (i.e., region where protected electrical components need to be applied, as defined in EN 60079-10-1) and the minimum room area necessary to avoid a flammable concentration developing across the room floor (under quiescent conditions). The larger the leak hole size, the greater the R290 mass flow into the space and the higher propensity for developing a flammable concentration. As a consequence, larger leak holes mean that more potential ignition sources within the room need to be protected – thus incurring more cost – and the maximum cooling capacity of the RACHP system diminishes, eventually demanding a larger number of smaller systems (again, incurring higher cost). Thus, an appropriate and reasonable assumption for the leak hole size is critical for the cost-effective deployment of RACHP systems using HCs.

[1] http://lifefront.eu/downloads/

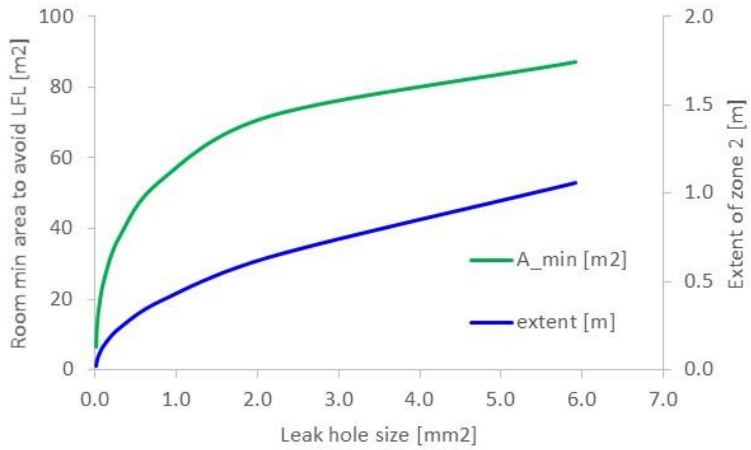

Figure 1 Example relationship between leak hole size, extent of potentially flammable zone and minimum room area to avoid floor concentrations at and above LFL

The LIFE FRONT project seeks to determine appropriate safety requirements and measures for RACHP appliances using flammable HC refrigerants. This report addresses the basis for a realistic assumption of leak hole sizes based on frequency of leaks and mass flow rates. A risk assessment for the use of flammable refrigerants and the selection of reasonable risk parameters need to be considered as input for safety standards, determining among others the allowable refrigerant charge sizes and system design characteristics.

As barriers posed by relevant standards for promoting the use of natural refrigerants mainly exist for appliances with some or all of the refrigerating circuit located indoors, these are the focus of this report.

1 FUNDAMENTALS

1.1 Ignition considerations

The frequency of ignition can be expressed as the number of occurrences of an event per unit time, for a piece of equipment under a given application environment. For flammable refrigerants, the occurrence of an ignition is based on the coincidence of three fundamental events:

- Occurrence of a leak;
- Development of a flammable-refrigerant/air mixture at a specific location;
- Existence of an active source of ignition within the flammable mixture.

All three events have their individual probabilities and the frequency of ignition can be expressed as the product of these events under different conditions. The frequency of leaks is related to the construction and operational characteristics of the system. The potential volume of a flammable mixture in the event of a leak and its duration (persistence) is influenced by many parameters including refrigerant charge size, leak time and local airflow conditions. The latter arises from natural ventilation (infiltration), convection caused by thermal sources, evaporator and condenser fans, mechanical ventilation of the room, etc. For a given set of conditions, the flammable volume is also dictated by the refrigerant itself; flammability characteristics vary among refrigerants due to differences in flammability limit, minimum ignition energy and burning velocity. Table 1 shows some of the flammability characteristics of refrigerants commonly used.

Table 1 Common refrigerant flammability characteristics [3][2]

Refrigerant	R1234yf	R1234ze	R32	R143a	R717	R152a	R600a	R1270	R290
Class	A2L	A2L	A2L	A2L	B2L	A2	A3	A3	A3
NBP (°C)	-29.4	-18.9	-51.7	-47.0	-33.3	-25.0	-11.7	-47.6	-42.1
AIT (°C)	405	368	648	750	630	455	460	455	470
MIE (mJ)	780	not known	29	27	45	0.9	0.7	0.28	0.35
BV (cm/s)	1.5	1.2	6.7	7.1	7.2	23	38	45	46
LFL (% vol)	6.2	6.5	14.4	8.2	16.7	4.8	1.8	1.8	2.1
UFL (% vol)	12.0	12.7	29.3	17.9	30.4	17.3	8.4	11	9.8
HOC (MJ/kg)	10.7	10.1	9.5	10.3	18.6	16.3	50	45.8	46.3
ρ_v, STP (kg/m^3)	4.66	4.66	2.13	3.44	0.70	2.70	2.51	2.35	1.80

Note: LFL= lower flammability limit, UFL=upper flammability limit, MIE=minimum ignition energy [3], AIT=Auto ignition temperature, BV= burning velocity, NBP=Normal boiling point, HOC=Heat of combustion, ρv STP= density at standard temperature and pressure

1.2 Current assumed leak rates

Various elements of current safety standards such as ISO 5149, IEC 60335-2-24/89/40, EN 378, IEC-40 etc. are built upon assumed leak times or leak mass flow rates of the (flammable) refrigerant used. These assumed leak times or rates are important to the development of a critical refrigerant concentrations (upper/ lower flammability levels) and the resulting maximum charge size (or releasable charge) allowed in the system. The assumed leak mass flow rate serves as a fundamental element for the risk assessment and safety requirements must therefore be selected on a robust basis.

RACHP system standards like EN 378, EN 60335-2-89and EN 60335-2-40 tend to specify a mass flow rate or a leak time (used to determine mass flow rate) directly. For instance, within EN 60335-2-89: 2010, leak rate is based on 80% of the charged mass over 10 min or 1 hour, irrespective of the refrigerant type and/or saturation pressure.[4] Within EN 60335-2-40: 2019, 100% of the charged mass is assumed to leak over four minutes or – for A2L refrigerants in enhanced tightness refrigeration systems (ETRS) – it is fixed at 10 kg/h (167 g/minute). When being used to determine ventilation rates and area classification on the equipment itself, EN 378: 2016 states 60 g/min for systems with DN< 50 mm and 180 g/min for systems with larger pipes, again irrespective of the type of refrigerant or expected operating conditions and pressures. Yet, EN 378: 2016 has an implicit assumption of total system charge

[2] ISO 5149-1, ISO 817, Refprop 9.1

[3] Minimum Ignition Energy: the minimum energy that is required to ignite a mixture of a specified flammable material with air or oxygen at standard conditions

[4] Determination of leak mass flow under IEC 60335-2-89: 2019 no includes a method to determine mass flow according to refrigerant type and operating conditions, specifically for the so-called "surrounding concentration test" in order to evaluate whether flammable concentrations develop around the appliance in the event of a leak.

leaking in four minutes for system assigned as for "human comfort"; for a 1.5 kg system charge this would correspond to 375 g/min, which is considerably higher than 60 g/min – such a difference makes no sense and is illogical. Whilst ISO 5149: 2014 uses the same assumption for "human comfort" systems, it broadly bypasses the matter for addressing ignition sources and instead states that "Refrigerating systems using A2, A3, B2 or B3 refrigerants shall be constructed in a way that any leaked refrigerant will not flow or stagnate and cause a fire or explosion hazard in areas in the vicinity of the system where electrical components, which could be a source of ignition and could function under normal conditions or in the event of a leak are fitted." There is no guidance in terms of assumed leak rate in order to assist in determining where leaked refrigerant will flow to or stagnate in areas in the vicinity of the system.[5]

A comparison of the assumed leak mass flow rates is shown in Figure 2. It can be seen that for some standards there is a linear increase in mass flow rate with a greater charge size, whereas in other cases there is a fixed mass flow rate regardless of the system charge. For two systems with essentially identical conditions, there could be a difference by a factor of 10 for the assumed mass flow rates between different standards with an absence of supporting evidence for justification.

The comparison of different leak rates across the current standards shows vastly different values. Such variation is rather counter-intuitive and defies any logical reasoning. Each refrigerant circuit handled by the various standards listed is treated differently, despite the high possibility that any circuit that falls under one standard could be identical, with respect to design and construction, location and subject to the same external forces and conditions as one that falls under another standard. Similarly, there is an inconsistency with respect to determination and impact of charge amount.

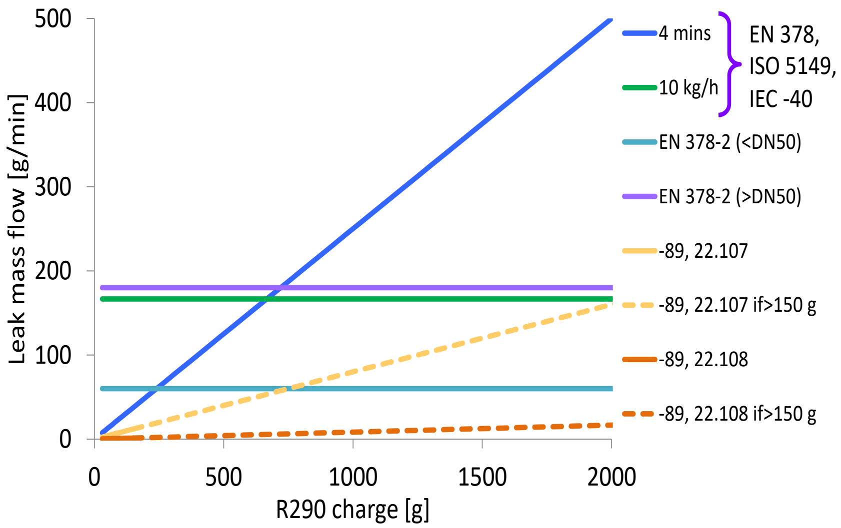

Figure 2 Assumed leak mass flow rate across various standards
(Dashed lines are values in IEC 60335-2-89 extrapolated to charge sizes above 150g)*

Measurements on real systems show significant deviation from these values mentioned above.

For example, Figure 3 shows the behaviour of an RACHP system containing 400 g of R290 (propane) with a 5 mm^2 instantaneous leak hole will empty within about four minutes (to a pressure of around 1/10th bar, gauge). The average mass flow rate is generally about one-third of the calculated choked mass flow (based on starting conditions) due to the rapid internal depressurisation as the release proceeds. For systems with larger charge sizes, the deviation from choked flow at starting conditions is

[5] Note also that the text in the standard ignores the fact that 2L refrigerants can be ignited by ignition sources!

less pronounced due to the relatively longer sustained back pressure. In this respect the important parameters related to degree of uniformity of leak mass flow rate are the ratio of hole size to system charge (and to some extent, the proportion of the system surface area available for high heat flux.

Figure 4 also provides an example of about 600 g of R290 being released through a 0.8 mm2 orifice. Whilst the initial mass flow is marginally higher that in Figure 3 despite the hole being about six times larger, the leak duration is about five times longer. Moreover, the shape of the leak profile is rather different.

These two examples indicate the differences in how system construction characteristics and conditions can influence the leakage mass flow rates.

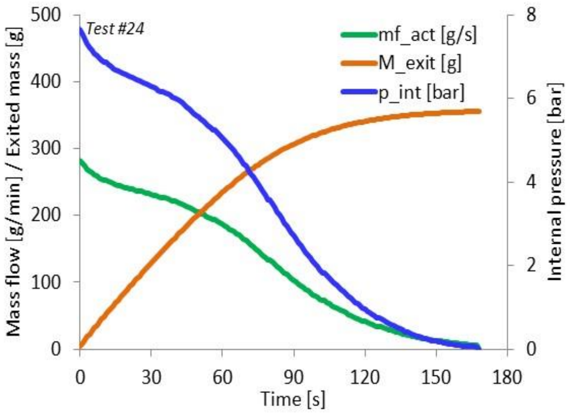

Figure 3 R290 being released from an AHU through a 5 mm2 orifice

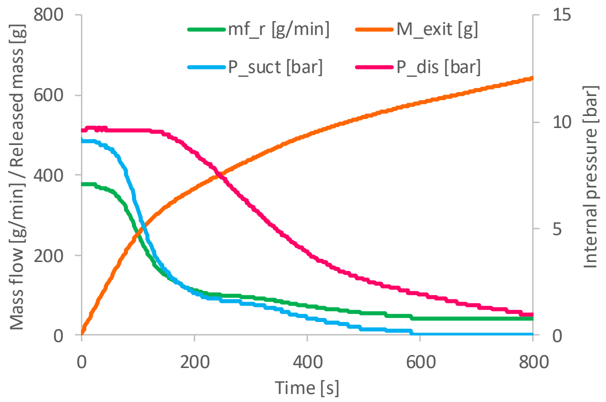

Figure 4 R290 being released from a split AC IDU through a 0.8 mm2 orifice

By comparison, the standard which addresses determination and classification of potentially flammable areas, IEC 60079-10-1, contains a different approach where the practitioner is expected to determine release mass flow based on knowledge of expected hole size and fluid properties. Figure 5 shows calculated vapour only mass flow rates for hole sizes as suggested by IEC 60079-10-1, assuming R290 at a saturated vapour pressure corresponding to 45°C.

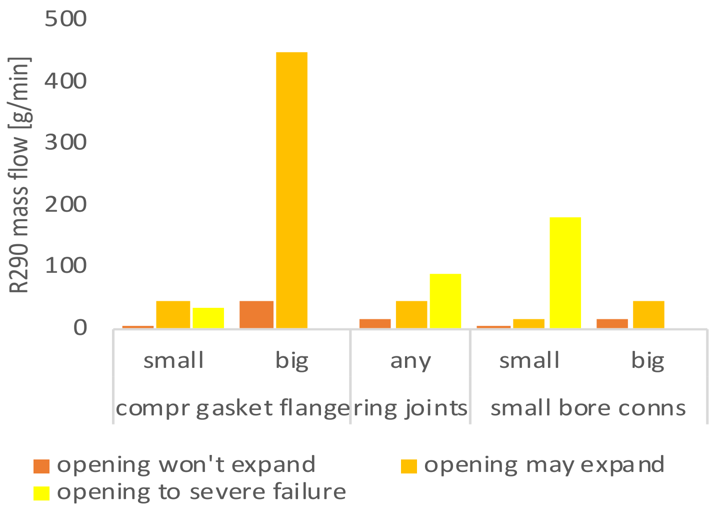

Figure 5 Vapour mass flow rates determined for R290 (propane) using holes sizes in Table B1. of 60079-10-1: 2015

The mass flow rates specified by RACHP standards tend to be substantially greater than those arising from the suggested hole sizes in IEC 60079-10-1 (if low side parts of the refrigeration system were assumed, mass flow rates would be half to two-third of these 'high side' values) except for the case of a leak from an expanding compression gasket flange (which are seldom used in small to medium RACHP systems). These mass flow rates are fixed leak rates and are independent of the quantity of refrigerant therein; there could be tens of thousands of kilograms. However, several RACHP standards are a function of system charge, but there is little evidence from studies that system charge dictates leak hole size and thus mass flow rates (although as mentioned above greater mass in liquid phase will delay the decline in back pressure under certain conditions) but its influence is minor compared to many of the other variables highlighted here.

1.3 Four-minute-leak-time fallacy

The assumed leakage mass flow rate is perhaps the most critical of all parameters affecting the determination of charge limits. Historically (since about 2000), the assumption used was that the entire charge is released within four minutes. This was reportedly based on measurements according to a test described in IEC 60335-2-24 to determine the mass flow rate for a domestic refrigerator leak simulation test (ordinarily using R600a as refrigerant). It was found to take four minutes to pass 150 g of R744 refrigerant through a specified capillary tube. Hence the four-minute leak time was chosen as the basis for the assumption of allowable refrigerant charges. However, the release time for different refrigerant types varies widely due to the difference in their thermodynamic properties which invalidates such a broad-brush approach. Figure 6 compares the choked flow mass flux of R744 and selected flammable refrigerants.

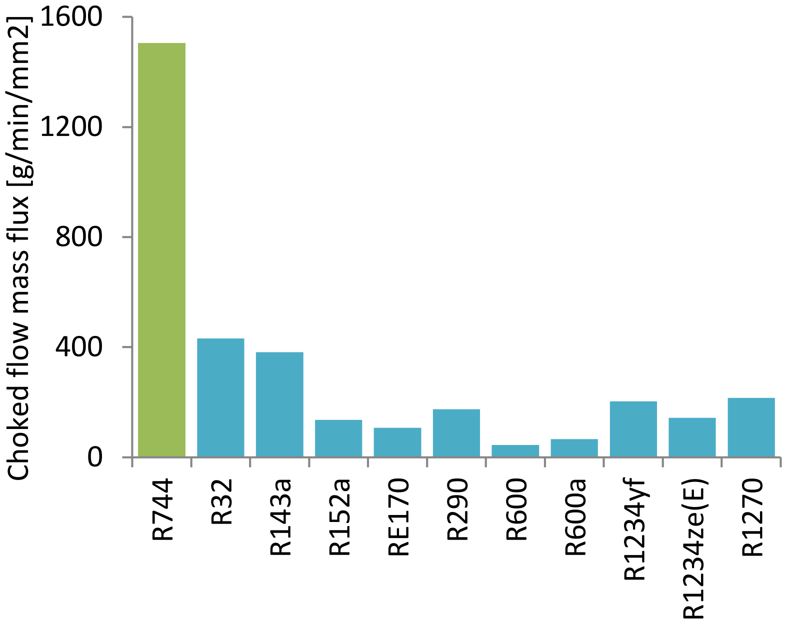

Figure 6 Comparison of mass flux at choked flow at saturated vapour pressure corresponding to 25°C for various flammable refrigerants and R744

R744 exhibits a mass flux of about 15 times higher than that of R290 and over 40 times higher than R600a. This implies that R290 and R600a would take substantially more time to leak out, as inferred in IEC 60335-2-24, stating that 80% of the refrigerant charge may be released over one hour. Critically, the leak mass flow rate or leak time is rather sensitive to the refrigerant type as well as to internal conditions of the refrigeration cycle (such as saturated vapour pressure). These parameters also depend on the leak mechanism and the leak hole size. Therefore, the assumption of a single fixed leak time (e.g. four minute leak time) to cover all refrigerants, circuit design and operating conditions is far from appropriate, especially given the strong dependency of the time to develop a flammable concentration and thus maximum charge. Thus, the leak time or mass flow rate must be carefully considered with respect to the refrigerant type, design and construction of RACHP system as well as empirical leak data [1].

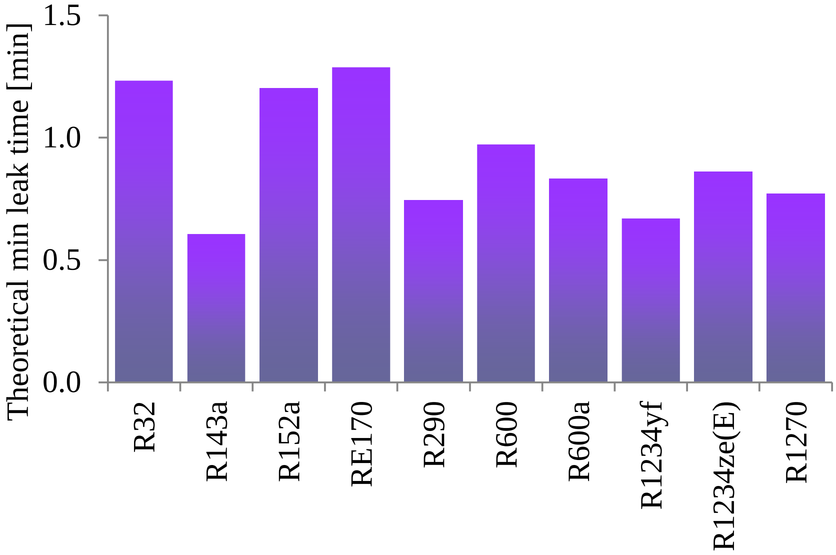

Figure 7 Comparison of theoretical minimum leak time for various flammable refrigerants in RACs

Conversely, if a worse case leak rate were to be applied then values corresponding to charge mass divided by compressor mass flow rate could be adopted as shown in Figure 7. Here the leak time ranges from ½ to 1 ½ minutes and there is a wide variation amongst different refrigerants. Critically, leak time or leak mass flow rate is rather sensitive to the refrigerant type as well as internal conditions (i.e. saturation temperature). They are also contingent upon the leak mechanism and the leak hole size.

1.4 Leak hole causes and development

Different types of leaks are mainly classified based on their formation and underlying causes. Most common leak types include the forced rupture leak (caused by a mechanical impact from external objects), pitting, crevice and galvanic corrosion occurring due to the presence of chloride or dissimilar metals, fatigue, fretting and various types of jointing faults. The miscellaneous faults such as electrical/electronic hardware, loose item/cap, vibration contribute least to the refrigerant leakage. The physical damage caused by a third party and fracture or rupture were also responsible for the highest addition of refrigerant mass [2]. Table 2 shows various types of leaks, their possible causes and likelihood of occurrence during compressor on- and off-mode.

Table 2 Types of leaks and underlying causes

Types of leak	Causes	Development rate	Occurrence in off-mode	Occurrence in on-mode
Forced rupture damage	Mechanical impact from external object	Instant	Possible	Possible
Pitting, crevice, galvanic corrosion	Presence of chloride, dissimilar metals	Gradual	Possible	Possible
Microbiologically-induced corrosion	Presence of microorganisms	Gradual	Possible	Possible
Ant-nest corrosion	Presence of moisture, oxygen and corrosive media (organic acid)	Rapid	Possible	Possible
Erosion- Corrosion	High velocity flow, containing particulates	Gradual	Possible	Possible
Stress-corrosion cracking	Strain and tensile stresses within pipe, pressure/temperature variations, presence of ammonia or water	Gradual	Improbable	Possible
Fatigue cracking	Excessive work hardening due to vibration	Gradual, Instant	Improbable	Possible
Electrical short circuit	Non insulated power supply cable in contact with pipe creating an electric arc	Instant	Improbable	Possible
Pressure-rupture, burst	Excessive internal pressure	Instant	Improbable	Possible
Thermal fatigue	Thermal stratification, cycling stripping	Gradual, Instant	Improbable	Possible

Types of leak	Causes	Development rate	Occurrence in off-mode	Occurrence in on-mode
Loosening of fitting	Vibration, poor connections/joints. Damaged threads due to overtightening of ferule, cracked flare, flare not holding the nut	Gradual	Improbable	Possible
Fretting	Repetitive rubbing of surfaces	Gradual	Improbable	Possible
Liquid hammer	Pressure wave from instantaneous value closing	Instant	Improbable	Possible

The frequency of a given leak hole size is believed to be broadly independent of the refrigerant charge size and can be described as a function of the following factors:

- Length of pipe and surface area
- Pipe wall thickness
- Number of joints/connections
- Type of joint/connection
- Number and type of components (valves, filter/driers, etc.)
- Type of compressor
- Degree of vibration control
- Severity of external weathering
- Vulnerability to external mechanical impact

In principle, it should be possible to correlate these various characteristics with the size and extent of leak holes in a probabilistic approach.

1.5 Leak hole size

Different systems show different types of leak hole sizes, from very small "pinhole" leaks to holes leading to so-called "catastrophic" leaks. It is known that many systems have 'pinhole' leaks (with mass flow rate in the order of grams per months) and that these represent the majority of all system leaks. Large or catastrophic leaks are reported where refrigerant pipes are sheared or completely split, and the refrigerant can potentially leak at rates in the order of kilograms per minute. The probability of occurrence of catastrophic leaks is extremely low. If safety requirements are developed assuming the more realistic case of pinhole leaks, it is likely that only minimal changes to the equipment design are required to accommodate flammable refrigerants, compared to those for non-flammable refrigerants. Whereas if catastrophic leaks are used as the basis for developing safety requirements, then the equipment will potentially be over-engineered at excessive costs with the probability of occurrence of such a leak being extremely minimal. It may be deemed excessively disproportionate to substantially increase the cost of all systems, on the basis that one system in a million exhibits an instantaneous catastrophic leak once per year (and even then, other conditions may be present, such as infiltration, personnel movement, thermal current, etc., which generally disperse high concentrations rapidly).

Calculated risk assessments are required in order to define assumed leak hole sizes (and mass flow rates) warranting the safe operation of the equipment with affordable safety measures. The flammability and safety of a system is impacted by the various elements related to leak characteristics. The most important characteristic is the frequency of leaks, particularly the frequency of leaks of a given hole size. As empirical data is scarce, approximations and assumptions are normally used for the assessment of leak hole characteristics. Further, the location of leaks and the mechanism of leak development (from corrosion, mechanical impact etc.) also need to be considered to understand the rate of leak hole development.

Ideally, assumed hole sizes and mass flow rates should be based on empirical data and assumptions. The LIFE FRONT Project aims at gathering such empirical data, and, based on such data, in a second step providing input data for use in quantitative risk assessments that may also lead to recommendations on allowable charge sizes.

1.6 System pressure and operating state

Leak rate/time depends on the state of refrigerant within the indoor part of the system, which in turn depends on the operating state of the system (cooling/off/heating). Therefore, the system operating pressure (corresponding to refrigerant saturation temperature) needs to be taken into account (as shown in Figure 8). Note that the cooling condition can be neglected in this example since the higher pressure during "off" condition will be present at some time (since the unit will never be on cooling 100% of time).

The difference between mass flux at 45°C and 15°C is a factor of 2.5 to 3.5, depending upon the refrigerant is shown in Figure 9, thus highlighting the need to base mass flow rates of the anticipated operating conditions.

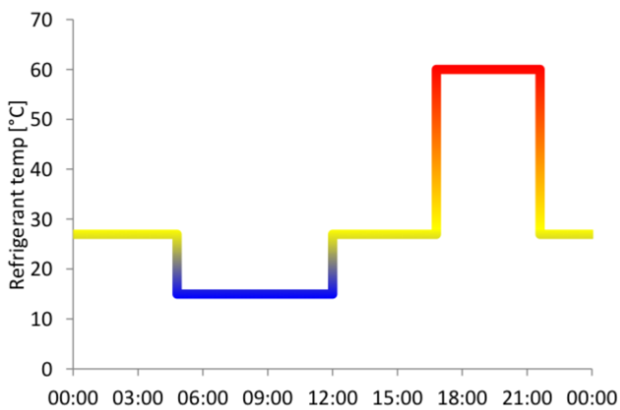

Figure 8 Example of the variation in a reversible system's (for instance) saturation temperature (and thus pressure) during different operating modes. The assumed leak rate should be based on the highest of these values

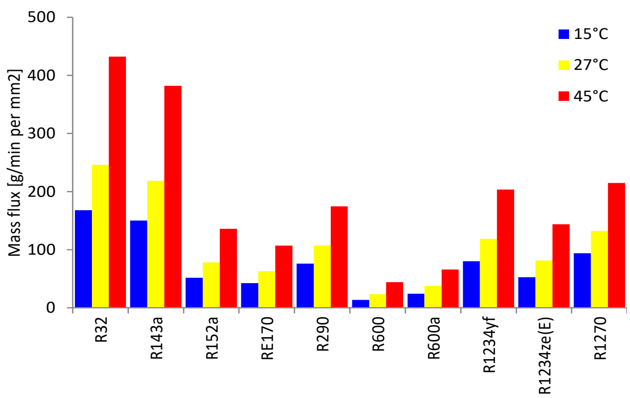

Figure 9 Effect of saturated refrigerant temperature (and corresponding pressure) on leak mass flux for various flammable refrigerants

1.7 Characterising impact of leak mass flow rate

The assumed refrigerant leakage mass flow rate is one of the most critical parameters affecting the development of a flammable concentration and thus the determination of refrigerant charge size limits.

Practical mass flow rates from real systems have been presented previously (e.g., Colbourne et al, 2013; Colbourne and Suen, 2016) along with approximation of actual potential leak rates based on leak hole sizes from field surveys. Applying those leak hole sizes to the critical mass flux of the various flammable refrigerants, the "expected" maximum leak rate is in the order of 5 to 10 g/min – a factor of about 100 times lower than if the fastest leak times would be used. Adoption of these expected leak rates would lead to maximum charge limits in the order of two to five times greater than those currently permitted.

Examples of the influence of leak mass flow rate and released mass on developed flammable concentrations (at the time of cessation of the release) when the fan is off are given in Figure 10 for an air conditioner indoor unit positioned at 0.5 m, 1.0 m and 1.5 m height. For these measurements a release was initiated and concentration was measured at sampling points at multiple heights at the centre of the room. Floor level sampling points were monitored and the flow terminated and released mass recorded once they approached the LFL of R290. Data in Figure 10 shows that as mass flow rate diminishes more refrigerant accumulates in the space between the horizontal plane of the IDU and the floor, allowing a greater mass of refrigerant to be released before LFL is exceeded across the floor. For the IDUs at higher positions, there is a more clearly defined homogenous layer extending some distance above the floor, before rapidly transitioning to much lower concentrations closer to the IDU height. Also, for the higher IDU the release mass flow rate becomes as important as the installation height in determining maximum charge. Figure 11 compiles the data for all three IDU heights and mass flow rates. As the IDU is installed at higher levels, a greater charge can be released without reaching LFL at the floor and it benefits more from a longer release time.

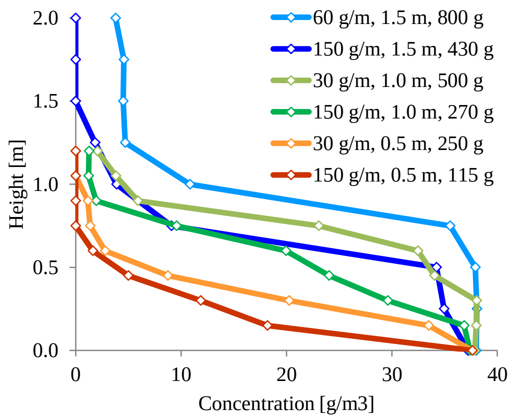

Figure 10 Effect of various release mass flow rates for IDU at 0.5 m, 1.0 m and 1.5 m

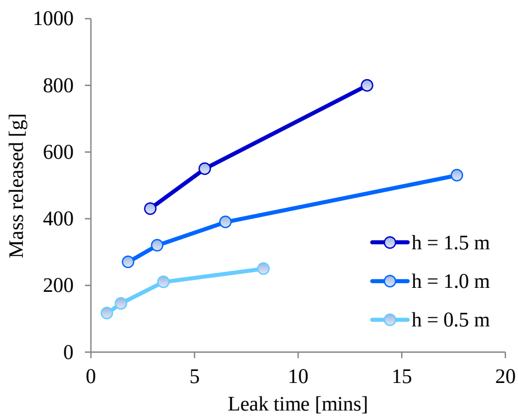

Figure 11 Effect of release time and IDU height on released mass upon reaching LFL at floor

1.8 Variable release rate

Hitherto, there has been an assumption that leak holes occur instantaneously, thus leading to an immediate and constant mass flow rate of a given size. Thus, tests involving concentration measurements prescribed within safety standards as well as other studies (e.g., Colbourne and Suen, 2003; Kataoka et al, 2000, Li, 2014; Zhang et. al., 2013) employ a constant release mass flow rate. This assumption is unlikely to represent a "realistic" leak scenario, i.e., which may increase over time due to gradual enlargement of orifice size or which may diminish over time as system charge is depleted. On one hand, leak holes take time to develop; as the orifice area increases over time so will the mass flow (assuming a steady back pressure). Corrosion leaks evolve in the order of weeks, months or years (inferring that system charge will have been depleted at extremely small rates – <1 g/min – that do not pose safety concerns) whereas leaks due to fatigue cracking can develop in minutes. Figure 12 illustrates an example case for advancing leak rate from severe fatigue cracking, based on a system with 1000 g R290 at 25°C and a compressor rotating at 2900 rpm, using a simple model based on Fleck (1984).

On the other hand, as a leak progresses, boiling of the liquid refrigerant depresses the backpressure so that mass flow declines (Colbourne and Liu, 2012). An example of decaying leak rate due to an instantaneous 5 mm2 hole at the condenser outlet on an R410A window AC is shown in Figure 13, where the system had been off for 24 hours and also moments after the system had been continuously operating. In the former, a gradual decrease can be noted. In the latter case, the hot compressor imposes a higher saturated vapour pressure but prevents significant absorption of refrigerant in the oil, resulting in a higher initial flow rate and also a much steeper decay. The time for a large hole to develop can be faster than the time for refrigerant charge to deplete with such a large hole – so it is reasonable to assume an instantaneous hole in parts of the system that are vulnerable to fatigue cracking. Depending on the particular circumstances, the variation in mass flow over time will consist of an increase as the hole size develops and eventually a decay as the system pressure declines, with a middle period of steady mass flow release for which the duration depends upon hole size, refrigerant amount and pressure.

Overall, two general cases may be identified. For "small and medium" leaks, it is reasonable to assume a fairly constant leak rate where the middle period accounts for the majority of the mass leaked. For "large" leaks, the decay period (e.g., as in Figure 13) is dominant as the leak hole must have developed due to mechanisms that cause near-instantaneous holes (such as external impact or fatigue cracking). Such flow rate profiles may lead to different maximum concentrations following a release of a certain mass.

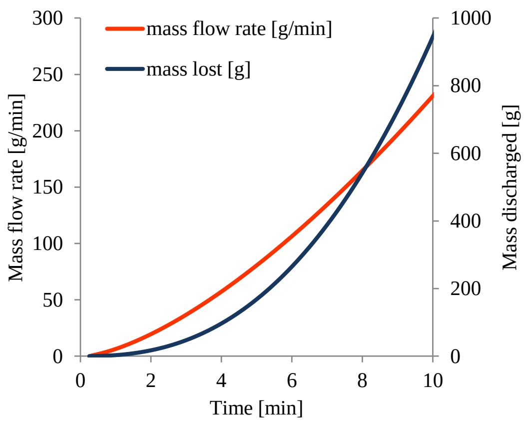

Figure 12 : Approximated leak mass flow rate of R290 at the initial period of fatigue crack in pipe

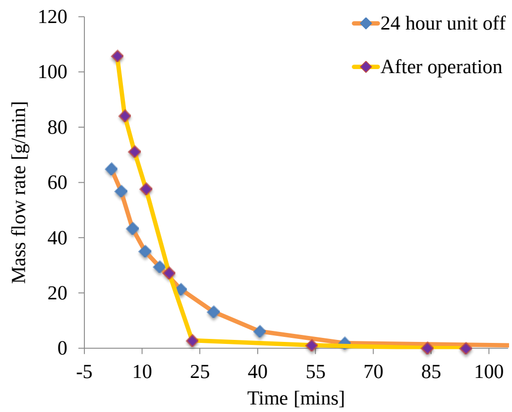

Figure 13 Measured instantaneous release mass flow rates from a window AC

Concentration measurements within a room were made in order to assess the impact of these leak development scenarios. Figure 14 and Figure 15 show floor concentrations with IDU fan off, arising from a rising release profile (broadly mimicking that in Figure 12) and a decaying release profile (as in Figure

13), respectively. Figure 16 is a reference case using a constant flow rate. All tests involved a 300 g release of R290 over ten minutes from IDU right hand return bends at a height of 1.0 m. Whilst the test in Figure 16 used a constant 30 g/min, the variable mass flow tests used six increments of 50 g at mass flow rates ranging between 10 g/min and 100 g/min in 15 g/min graduations.

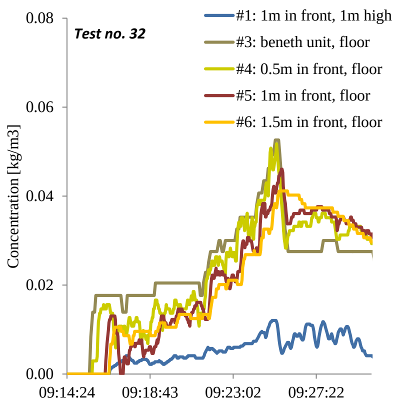

Figure 14 Rising release rate averaging 30 g/min for 10 mins

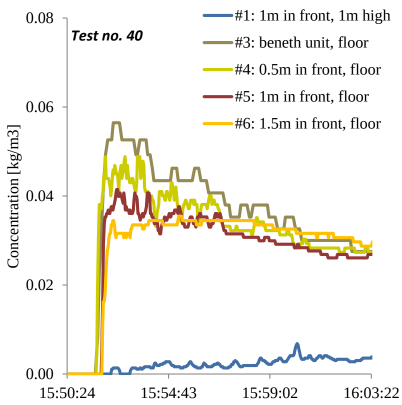

Figure 15 Decaying release rate averaging 30 g/min for 10 mins

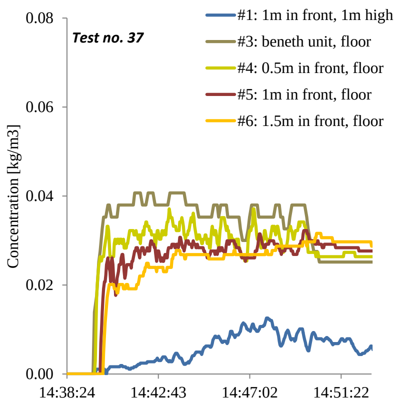

Figure 16 Constant release rate of 30 g/min for 10 mins

Results show substantially differing concentration profiles. Rising leak rate shows gradual concentration rise until maximum value. Decaying leak produces a significant initial "jump" moments after the start of the release, which for most sampling points represents the peak concentrations for the entire test. With both the variable leak rates, average floor concentration changes significantly over the test duration, compared to a relatively minor change with the fixed leak rate. Overall, the two variable rate cases produce a substantially higher maximum concentration than the fixed leak rate, although whilst the peak maximum is about the same for both yet the average maximum value for the decaying release rate is 10% lower than that of the rising release rate. This is due to the short period where the mass flow rate is several times higher than the constant 30 g/min case. Particularly for the decaying leak, the initially high leak rate seems to dominate the subsequent floor concentration. Concentration at 1 m above floor level supports this, as it is significantly lower than in the other two cases, where the higher mass flow occurring latterly seems to shunt more of the mixture from the floor upwards.

1.9 Release phase

Most experimental studies reporting on this subject have used vapour only releases. Primarily this is because the experimental procedure is much easier and mass flow can be controlled more consistently. Furthermore – at least for smaller RACHP system, "real" simulated leaks (i.e. from systems) have found that even if a release is created from a liquid or two-phase pipe, there is usually intermittent or cyclic "spitting" of liquid for the first tenth of the release duration and is then followed by continuous vapour only.

A number of tests were carried out in order to determine any significant difference between vapour only and two-phase release, where R290 was released at 100 g/min at the right-hand return bends of an IDU positioned 1 m above the floor when IDU fan is off. Sampling points were located on the floor at 1 m increments away from the IDU. Refrigerant cylinder was cooled to about 0°C, the supply hose insulated and then cooled with liquid R290 to avoid pre-boiling of the liquid at the start of the test. It is estimated that the vapour fraction of the two-phase release during the test was 0.25.

Example results for averaged floor concentration are shown in Figure 17. Whilst the vapour release tends to create a faster rate of concentration rise initially, concentration development for the two-phase release tends to be more gradual and the final concentration is also marginally lower. This more gradual rise is likely due to the delay caused by the vaporisation of the liquid droplets.

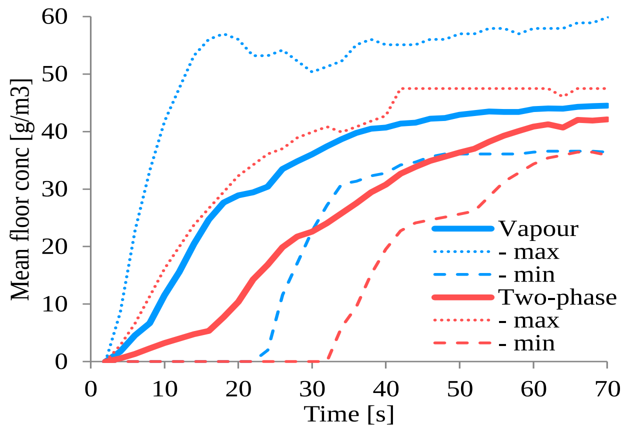

Figure 17 Comparison of average, maximum and minimum floor concentrations for vapour and two-phase release of 100 g/min from IDU at 1.0 m

The average maximum concentration after a 120 g release is approximately 10% higher for the vapour-only release (as shown in Figure 18). In addition, the variation across floor concentrations is substantially wider for vapour releases (±11 g/m3) than for the two-phase release (±6 g/m3). Overall two-phase releases seem to lead to more homogenous distribution, which is probably due to the additional convection generated by the flashing liquid and additional thermal gradients.

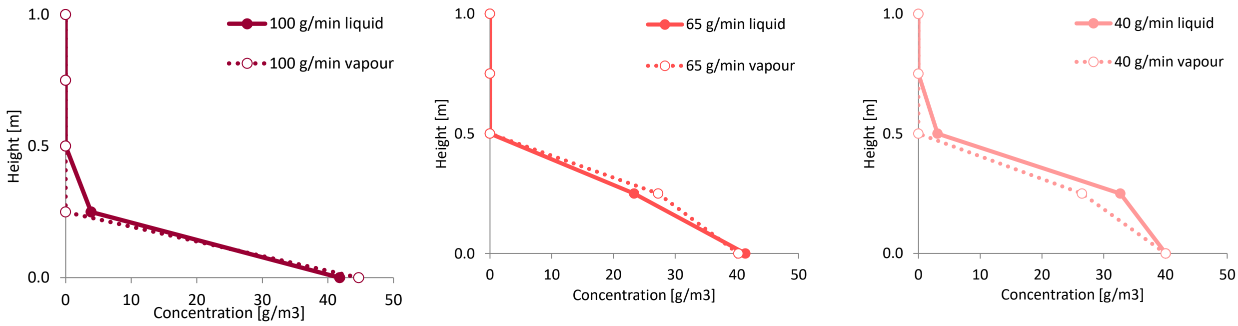

Figure 18 Comparison of concentrations from two-phase ("liquid") and vapour only releases

Therefore, based on these tests, it is concluded that vapour-only releases represent the most severe outcome in terms of maximum concentrations.

2 LEAK CAUSES, FREQUENCY AND HOLE SIZE FROM VARIOUS INDUSTRIES

There is some literature that reports on leak hole sizes, both in the process industry in general and to some extent within the RACHP sector. To provide a first insight into "realistic" hole sizes, these studies are mentioned here.

2.1 Leak frequency and hole size from outside RACHP industry

Various studies on leak hole size and leak frequency were conducted in industrial pipelines especially in the oil and gas sector. The EGIG pipeline leak study (2001) was performed based on an extensive leak database to provide a realistic picture of the frequencies and probabilities of incidents over nine major European gas transmission companies during 1970-2001. The overall incident frequency with an unintentional gas release over the period 1970-2001 was reported to be 0.44 incidents per year per 1,000 km of pipeline. External interference seems to be the main cause of gas pipelines for gas leakages. The overall ignition probability is low: according to the EGIG database, gas has ignited in 4% of all incidents during the period. The ignition probability differs significantly per diameter and type of leak, with an ignition probability of 9.5% for small pipeline (<= 16 inch) with a rupture and 25% for a large pipeline (>16 inch). Most of the incidents are reported to be caused either by external interference, corrosion, material failure, ground movement or other unknown causes [6].

The UK Health and Safety Executive (HSE) hydrocarbon release database (HCRD) provides the source of leak frequencies for offshore quantitative risk assessment (QRA). The most recent publication of this database (HSE 2002) contained 2,071 leaks, although there is a database available on the HSE internet site, which is regularly updated and contains about 4,400 leaks at present. Despite having a high-quality database, several problems emerged from using it for offshore QRA. The main problem is that when QRAs use unmodified HSE leak frequencies, the risk results tend to be much higher than actual experience, although comprehensive validation of this is difficult. Among the available frequencies for 89 separate types and diameters only 27 have more than 20 leaks and 18 have no leaks at all. Also, the statistics give hole size distribution for seven-hole size groups (<10 mm, 10<25 mm, 25<50 mm, 50<75 mm, 75<100 mm, >100 mm and not applicable) [7].

Figure 19 shows the number of leaks per year from 1992-2010 as a varying pattern with the majority of the leaks reported to be minor.

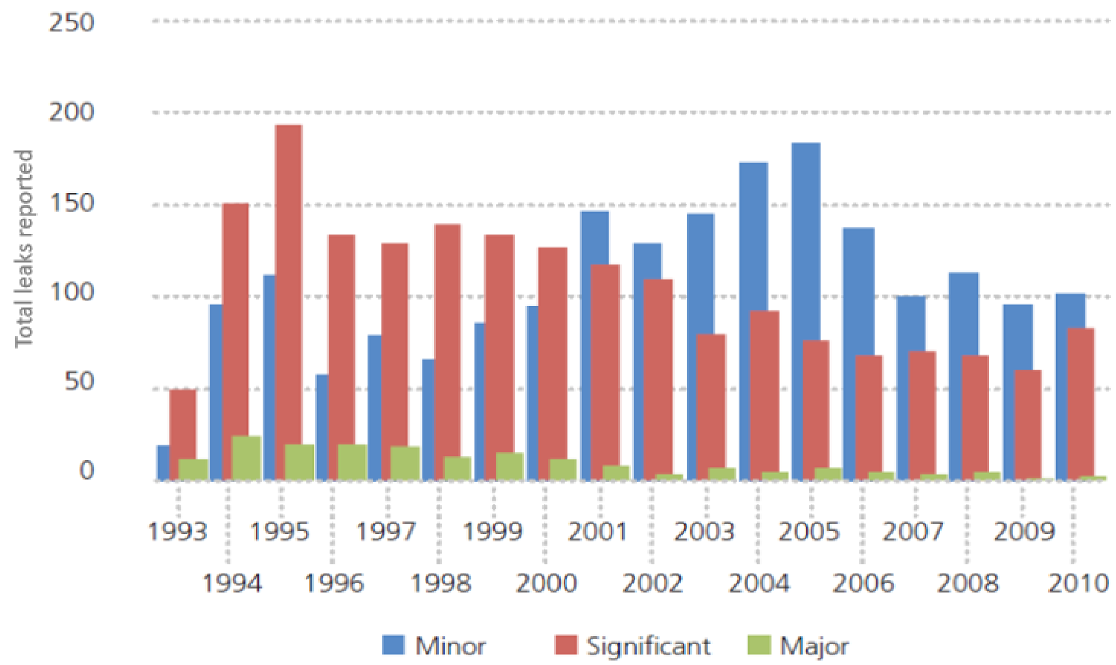

Figure 19 Total leaks reported in the HSE Leak release database (Source: Hydrocarbon release reporting and statistics, HSE 2012)

The leak frequencies from the HCRD data were estimated by grouping the data into different types and sizes of equipment and then fitting an analytical leak frequency function to the data. Thus, a smooth variation of leak frequency was obtained with equipment and hole size and the leak frequencies were further split into different leak scenarios. Moreover, to provide more compatibility the whole database is divided into two scenarios of full pressure leaks and zero pressure leaks[6]. The generated leak frequency from piping is high compared to other equipment (heat exchangers, pressure vessels, compressors etc.) in the study.

Although the database is based on large oil and gas industries, which uses an infinite reservoir compared to the relatively small and finite charges used in RACHP industries, these two databases provide a statistical evaluation on the leak hole size, providing a more realistic picture of the frequencies and ignition probabilities of leak incidents. The database is also extensive in considering the large amount of data collected and provides useful information about trends of leaks developed over the decades.

2.2 Leak hole size and mass flow rates from the RACHP sector

Various studies have been conducted to analyse the leak causes and effects on refrigeration systems and to ensure the tightness of the systems.

One study based on supermarket refrigeration systems in UK analysed 1,464 samples to estimate the major leak causes and refrigerant loss patterns. Most common faults were found to be pipe or joint failure and leaking seal/gland/core. These faults were predominantly found within the compressor pack

[6] Full pressure leaks: leaks beginning at normal operating pressure, until controlled by ESD and blowdown with a small probability of ESD/blowdown failure. Zero pressure leak: The scenario includes all leaks where the pressure inside the leaking equipment is virtually zero (0.01 bar or less) because of a zero normal operating pressure of the equipment or depressurization for maintenance.

and high pressure liquid lines. 22% of the leaks were from flared joints which were responsible for 50% of the refrigerant loss. 96% of the refrigerant loss was through field assembly joints. It was also found that third-party physical damages (mechanical impact during handling) to the refrigeration system is responsible for the greatest leak per incident, although in terms of number of incidents it is relatively rare [2].

Another research project commissioned by the Research Council for Refrigeration Technology (Germany) in 2001 measured the leak tightness of supermarket refrigeration systems, including compound and decentralised systems with refrigerant charges from 60 to 360 kg. Out of the 104 measured samples more than half of the leaks were in the range of 0.5 to 30 g/a and 14% in the range of 1,001 to 10,000 g/a which contributes to up to 85% refrigerant loss in the system. It was also observed that the largest leak rates (>1000 g/a) were displayed by the flanged joints. The refrigeration system with the smallest refrigerant charge clearly displayed high specific leak rates. The results lead to recommend a careful assembly of separable connections, especially the flanged joints, with high sealing reliability [8].

Two studies from Japan measured leak sizes from RACHP systems. One of these studies (JARECO, 2013) surveyed thousands of refrigeration and air conditioning systems (ranging from 1 kg to 170 kg of HFC) and measured their leak flow rates over a fixed time. The average leak rate across the entire dataset was equivalent to 0.16 g/min, assuming vapour only leaks with standard flow equations, corresponding to a leak hole size of 0.002 to 0.005 mm^2, depending on the refrigeration and saturation temperature being used. The largest leak rate observed was just under 3 g/min, corresponding to a leak hole size of 0.04 to 0.07 mm^2 [9].

Another study from Japan (JSRAE, 2014) carried out an assessment of maximum leak hole sizes in multi-split air conditioning systems by removing leaky units for measuring. The mass flow rate of vapour and liquid refrigerant was measured in the removed units. The largest leak measured from indoor units had about 6 g/min of R32 vapour at 10°C and 67 g/min of liquid at 63°C; equating to a hole size of 0.045 mm^2 using standard flow conditions. For outdoor units the largest leak gave 58 g/min of R32 vapour and 660 g/min of liquid at the same temperature, equating to a hole of 0.45 mm^2. It is reasonable to expect outdoor units to have larger holes due to greater vibrations and more aggressive environmental conditions [10].

In order to estimate the mass flow rates of R290 from the leak hole sizes determined by the Japanese studies, measurements were conducted under various scenarios. The average R290 mass flow was measured through various engineered leak orifices (0.2 mm, 0.5 mm, 1.0 mm, 1.5 mm and 2.5 mm diameter) with several commercial refrigeration systems and air conditioners. R290 charges of approximately 600 g, 800 g, 900 g, 1,000 g and 1,100 g were used in different systems. Leaks were created at various positions in the circuits, including discharge pipes, condenser inlets, condenser outlet, liquid line, evaporator inlet, evaporator outlet and suction lines both during compressor on and off cycles.

During the compressor off cycle, the measured average mass flux (from the beginning of an instantaneous leak up to a pressure of 0.2 bar) ranged from 30-60 g/min per mm^2 of hole area. During the compressor operating condition (evaporating temperature between -20 to +15 °C) the average mass flux from the evaporator side ranged from 20-40 g/min per mm^2 and 80-120 g/min per mm^2 for the condenser side. The mass flux rate was largely affected by the local liquid fraction at the leakage part of the system.

Based on the identified maximum leak hole sizes from the two aforementioned Japanese studies and the range of release mass fluxes from the real systems, 'maximum realistic leak flow rates' are established. The evaluated maximum leak rate from the evaporator is considered to range from 5 g/min to 30 g/min and similarly 10 g/min to 60 g/min for condenser sides. The average leak mass flow rates established for different operating modes based on hole sizes are summarised in Table 3.

Table 3 Average leak mass flow rate for different operating modes based on max hole size using R290[7]

Compr. operating mode	**Hole size source**	**Evaporator side**		**Condenser side**	
		Low mass flux (30 g/min per mm²)	**High mass flux (60 g/min per mm²)**	**Low mass flux (80 g/min per mm²)**	**High mass flux (120 g/min per mm²)**
Off	JSRAE (IDU;0.05 mm²)	1	3	1	3
	JSRAE (ODU;0.45 mm²)	14	27	14	27
	JARECO (max;0.07 mm²)	2	4	2	4
On	JSRAE (IDU;0.05 mm²)	1	2	4	5
	JSRAE (ODU;0.45 mm²)	9	18	36	54
	JARECO (max;0.07 mm²)	1	3	6	8

Whilst these leak rates can yield concentrations significantly higher than LFL surrounding an appliance when using 150 g of R290, since there are millions of products using charge amounts close to 150 g of R290 without any report of incidents, it is arguably unreasonable to employ leak mass flow rates that are orders of magnitude greater than those that are necessary to approach the LFL. There is a significant discontinuity between the proposed leak rates and current values referred to within the various RACHP standards. Using 150 g of R290, the mass flow rate of the simulated leaks shows that the concentration at all positions surrounding the appliance exceeds 50% of LFL and 100% of LFL.

An affirmation with real leak data is required to provide a more rational estimation of leak mass flow rates. This calls for the establishment of a real leak database from the RACHP sector, to analyse leakage characteristics and in a second step to improve relevant safety standards as it is the objective of the EU FRONT project.

[7] Experimental leak rates encompass pressure decay over time, release of refrigerant first in two phase states and then vapour only, specific positions of leak holes in the refrigerant circuit, heat transfer into the system from the surrounding etc.

3 DATA GATHERING

A database of leak hole sizes and frequency of occurrence of leaks is required. Hole size and thus leak mass flow rates vary widely with the type of leak, system operation mode, state of refrigerant and the system configuration. Basic steady flow models are insufficient to accurately estimate the mass flow rate from a given leak hole size due to the dynamic effect of system behaviour. Laboratory tests were set up to measure leak mass flow rates and concentration developments for the different types of appliances. Anecdotal information available and the limited published data both indicate that the leak hole scenario is extremely rare. Recommendations for the choice of leak sizes to determine allowable charge sizes were developed based on the results gathered from the dataset.

3.1 Methodology

In order to develop a representative database on leak hole sizes in existing RACHP systems and corresponding mass flow rates, extensive field data covering a wide range of equipment types, applications and location of systems is required. Within the FRONT project database leak hole sizes are gathered by analysing respective equipment samples from different manufacturers. Samples include air conditioners, heat pumps and commercial refrigeration appliances. Almost all samples gathered show very small leaks. This trend, that larger leaks only occur in exceptional cases, was confirmed by the long experience of industry partners involved, all of them being equipment manufacturers.

For each leakage sample the following parameters– as far as possible – are documented:

- Type of equipment
- Installation date/age of leak
- Nominal capacity
- Function (cooling, heating, reversible etc.)
- Refrigerant type
- Refrigerant charge
- Location/component of leak
- Position of the leak
- Estimated leak cause
- Compressor type
- Sealing
- Factory leak test
- And, if available: Total length of piping, type and number of joints in the system, number of line components, pipe diameter/component nominal diameter, information on condenser and evaporator, surface treatments etc.

In addition, visual observation and photographs are collected.

The analysis of leak samples is done by the manufacturer technicians or by HEAT, using either analogue volume flow meters or digital mass flow meters. The temperature, pressure at the flow meter and the observed flow rate are measured for the analysis of leak characteristic. Flow rates are measured with a reference gas (such as air, nitrogen, R290, etc. according to availability at the location) and at a pressure above what is necessary to achieve standard choked flow. The leak mass flow rate of the samples from heat pumps was measured directly at the leakage points. Figure 20 shows images of the leakage samples measured.

Figure 20 Tested leak samples (RACHP samples)

Figure 21 shows some examples of how the leak measurements were made.

Figure 21 Tested leak samples (RACHP samples)

Once the flow rate through the leak hole has been recorded, the standard flow equation for choked flow was used to drive the hole area:

$$A_o = \frac{\dot{m}}{C_d\sqrt{k\rho_o(p_o - p_{atm})\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} \tag{1}$$

Where:

$\dot{m}$ = mass flow of vapour through leak hole [kg/s]

C_d = discharge coefficient [-];

k = ratio of specific heats of refrigerant vapour at relevant temperature indicated above [-]

ρ_0 = density of refrigerant vapour at the specified saturation temperature [kg/m3];

p_0 = saturated vapour pressure of refrigerant at the specified saturation temperature [Pa];

p_{atm} = atmospheric pressure [101325 Pa].

Further, a statistical analysis was performed to understand the proportion of data samples that would be required to provide a robust larger database. With the currently available leak size data and applying the adequate rules of statistics, it is estimated that with a minimum of 385 data points it will be possible to establish a robust dataset with a 95% confidence interval and a 5% margin of error. To account for this error, the chosen leak hole sizes can be adjusted upwards to cover any uncertainty.

3.2 Results from collected data

Up to May 2019, some 250 leakage data from various RACHP systems including heat pumps, air conditioners and refrigeration equipment were collected. Most of the measured samples had very small hole sizes providing smaller leak flow rates. The majority of the holes in the samples were so small that the output didn't reach the lowest flow rate indicator (0.4 litres per minute for the analogue flow meters and 0.2 g/min for the digital flow meters); in these cases, half of the lowest increment value was taken as the flow rate. Nevertheless, the lowest value on the measuring scales are well below the leak flow rate necessary to form a flammable mixture under almost all circumstances. Therefore, the precise reading is not considered important.

Most of the analysed leak points of the AC models (cooling only) were located at the condenser coil of the system and at the return bends in the indoor units. The estimated causes are corrosion, condenser fin forming pits and mechanical impact from external objects.

A probability distribution of the measured leak hole size and mass flow rates is shown in

Figure 22 and Figure 23 respectively. More than 80% of the samples showed leak hole sizes varying from 0 to 0.02 mm2. The remaining leaks measured a hole size from 0.02 to 0.4 mm2. The largest hole size measured was 0.36 mm2. The distribution is comparable for the leak samples from the three different equipment types (AC, HP and refrigeration equipment).

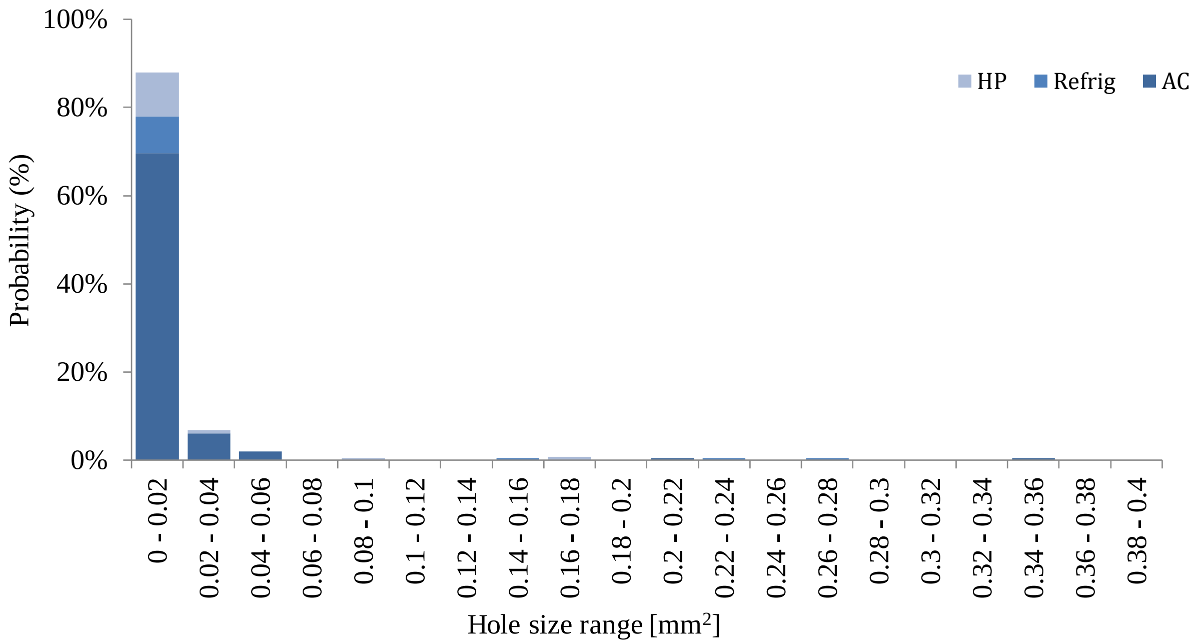

Figure 22 Leak hole size distribution (250 data points analysed), May 2019

The leak flow rate probability distribution chart in Figure 23 shows a similar pattern, where the mass flow was determined from the holes sizes using R290 and normalised conditions (saturated vapour pressure corresponding to 35°C) for consistency. The majority (85%) of the leaks have a flow rate between 0 – 10 g/min and the remaining have a flow rate ranging from 10 – 50 g/min. For holes that were not influenced by technician intervention, the largest leak mass flow rate was measured to be 48.3 g/min, corresponding to a leak hole area of 0.36 mm^2.

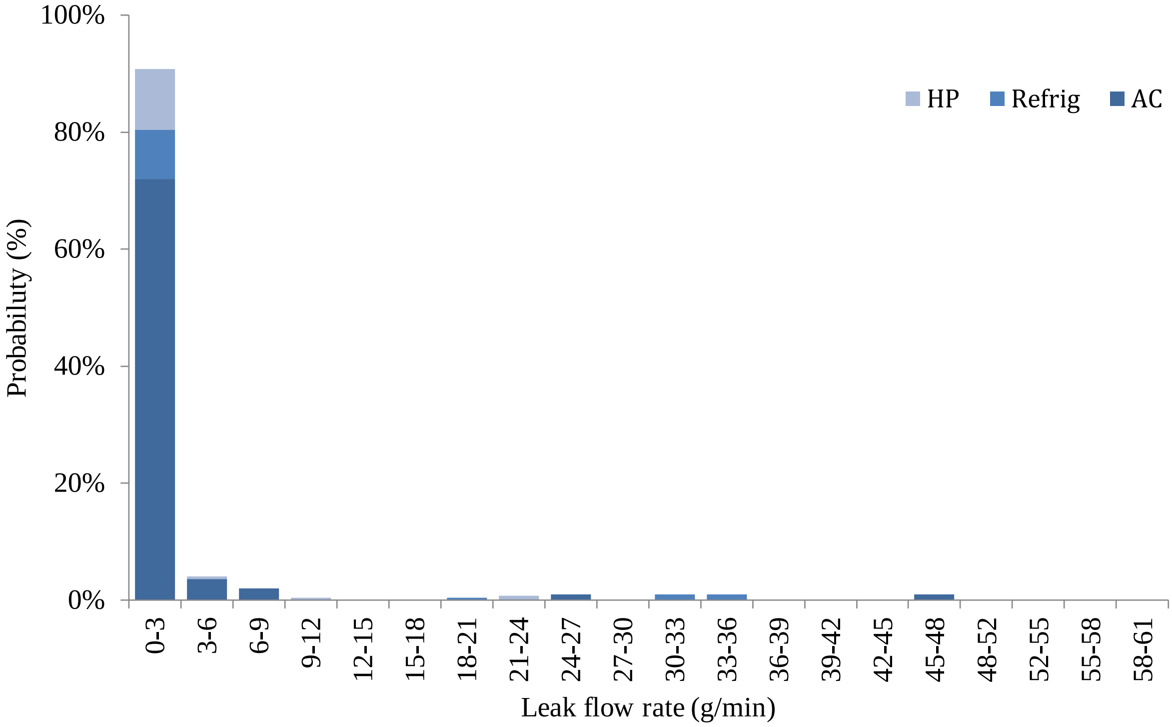

Figure 23 Leak mass flow rate distribution based on R290 vapour under standard conditions (250 data points analysed), May 2019

Further tests and leak measurements are underway to measure the leak parameters from different manufacturers and system types on various systems models. The goal is to extend the database, further analyse, and to improve RACHP safety standards. A final update of this report will be provided at the end of the project (early 2020).

3.3 Coefficient of discharge

The effective area for outflow of a leak is smaller than the hole area, mainly because fluid is flowing towards the hole from all directions and needs to be "bent" to be parallel to the hole axis (there is also a minor contribution from friction). The ratio of the effective area: actual area is known as the coefficient of discharge (C_D). The value of C_D depends on several factors, including the Reynolds number and the geometry of the hole and of the internal approach towards it. In practice, the range is ~0.6-0.99.

Hole areas were not measured directly, but calculated from equation 1, with the assumption that C_D= 0.6, thus maximising the estimated hole area.

3.4 Filtering for human intervention

Across the collected leak hole samples, the majority are evidently due to "natural" leakage (i.e., typical mechanisms as identified in Table 2), whereas a small fraction of the leak holes were clearly augmented by human intervention. Two examples include repeated re-brazing of a heat exchanger return bend and intervention of pipe-cutters. For instance, whenever a technician gains access to a system one or more of several methods may be applied, such as pipe-cutting, decoupling mechanical connections, use of brazing torches or indeed dropping objects on pipes. Across these causes of leaks, there are arguments to include or discount the respective leak hole samples from the analysis. Therefore, both classes have been included in the analysis, although with the results presented separately.

3.5 Extension to all leaks

It was mentioned previously that the flow meters used have a lower measurement range and that the majority of the leaks evaluated were in fact below this lower range. Therefore, these data should also be viewed within the context of an entire market sector. To this end, data from leakage studies (for the purposes of evaluate warming impacts) were used, and presently from DECC (2014). This study found that 8.97% of non-domestic and 10.00% of domestic heat pumps exhibited leaks per year. The UNEP (2018) RTOC report states annual leak rate for stationary air conditioning to be between 2 – 10% per year and commercial refrigeration between 15 – 30% (although this does include centralised systems). Thus, for the types of RACHP systems from where the leak samples were taken, it is reasonable to assume an annual leak rate of at least 5% of the overall population.

According to the partners' data, the samples used represent about 0.05% of the products placed in the market in the period of the study. Thus, it may be estimated that – for the types of equipment within this project – leak holes greater than 0.1 mm^2 have a leak frequency of 0.00002 per year.

3.6 Confidence levels

A statistical analysis has been carried out on the data-set, as it currently stands, using the non-parametric approach. Based on the 251 (leak) elements in the sample, an upper percentile of 0.95 (95%) and upper confidence limit (UCLs) of 0.95, 0.99 and 0.999 the rank of the upper confidence bound is 245, 247 and 249, respectively. Conservatively (by assuming C_D = 0.6 throughout), we can say with:

- 95% confidence that the 95th percentile of the population of holes will not exceed 0.17 mm^2.
- 99% confidence that the 95th percentile of the population of holes will not exceed 0.23 mm^2.
- 99.9% confidence that the 95th percentile of the population of holes will not exceed 0,36 mm^2.

4 CONCLUSION

Data collection on leak hole sizes turned out to be more challenging and time consuming than expected (due to availability of samples, servicing structures and confidentiality concerns). In response to a limited amount of data available at the start of the laboratory tests for concentration development, not only release rates corresponding to the leak hole sizes identified in the field test were chosen, but instead a wider range of assumed leak rates was used in the testing and simulations, for instance, various increments up to 150g/min. This approach was used to ensure that larger leaks that might eventually be identified at a later stage of the project would be as well covered by the laboratory tests and simulations.

With the 251 data points on leakages gathered by June 2019 a clear trend is evident: the vast majority of the leak holes reported from the field are very small relative to the pipe size, i.e., about 84% are less than 0.02 mm^2. With this clear trend, verifiable conclusions can already be made based on the current data bank, although the number of samples is not extensive. If the results were much more scattered or the step change in occurrences at around 0.02 mm^2 was less distinct then there would be an obvious need to gather more results to make verifiable conclusions. The identified leak hole sizes so far lead to leak rates of 0 to 50g/min based on typical conditions for R290. These data differ from those used in the RACHP safety standards.

Based on the results so far, a formula was developed to determine the assumed leak hole sizes, as explained in Annex. This method identifies a leak hole size based on an assumed frequency. The formula proposes a leak rate based on leak hole size and leak mechanisms. The determination of maximum charge sizes should be based on various system and refrigerant parameters. It depends on the leak time or leak mass flow rates varying for the different refrigerants, operating conditions and hole sizes.

Adopting a single leak time of four minutes cannot be justified as refrigerants differ in properties and likely leak mechanisms of the leak release.

First results from the LIFE FRONT project have already been implemented in an output of the standardisation processes: based on the results so far, a formula to determine the assumed leak rate for commercial refrigeration appliances was introduced within the now published international standard IEC 60335-2-89 in Annex CC.2; this was finally approved on 10th May 2019. The outputs from this project are also being proposed as the basis of text for charge size calculations and leak simulation tests for the revision of EN 378 and IEC 60335-2-40.

The LIFE FRONT leakage databank does not only provide information on leak hole sizes and resulting mass flow, but also gives valuable information on causes of leaks and other parameters. The leak flowrate can be linked to the leak cause. This is especially important for manufacturers to address the underlying causes for leakages and to develop appropriate mitigation measures. It should be considered for charge size limits for each type of product and different refrigerants. Respective tests implemented within the LIFE FRONT project are designed to demonstrate that the mitigation measures or safety methodology proposed are efficient to avoid that a flammable mixture is created in the surrounding of the appliance.

A scientific approach needs to be included into the safety standards that will lead to appropriate requirements in terms of construction, testing methods and safety devices.

Two public databanks, one on leak hole sizes and one on concentration measurements show the results gathered from the field data and laboratory work. Both databanks are available on the EU FRONT project website at www.lifefront.eu. For confidentiality reasons all data are anonymised.

5 REFERENCES

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6 ANNEX

6.1 Development of quantification methods – Proposed Framework

For each refrigerant specific leak rates should be applied as each of them is characterised by different properties. Only then the existing standards can be adapted to allow the use of more reasonable maximum charge sizes in the system. To address this gap, a framework for the leak hole size/time measurement is proposed here, offering a rational approach towards determining the assumed leak rates.

Within the EU LIFE FRONT project lab tests on RACHP equipment were performed to analyse the refrigerant leak mass flow rates (and subsequently to measure the respective concentrations). Different hole sizes were measured from the high and low-pressure side of the system and further for the indoor and outdoor parts of the system. A leak meter/mass flow meter was used for leak flow measurements.

A mathematical function with the leak frequency parameters may be used to estimate the frequency of leak holes occurring in a system. At a fixed leak frequency, systems with longer piping (and fixed outer diameter and joint types) are expected to have larger leak holes. Figure 24 shows the probability of occurrence of a leak increasing with the pipe length.

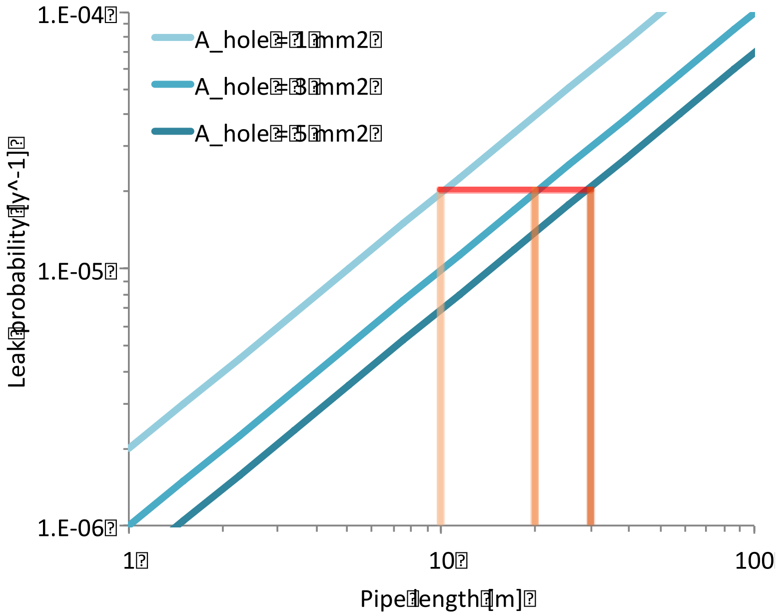

Figure 24 Leak probability with length of piping

On a probabilistic basis, a system with longer piping and more joints or connections is expected to have a greater number of bigger hole sizes compared to a system with a shorter pipe length. Also, a system with poorer joints and less vibration control mechanisms is expected to have larger holes. When assuming the leak rate/time all factors influencing the leak hole frequency shall be considered instead of just referring to the arbitrary four-minute leak time (as outlined under 2.2).

The new approach for the determination of assumed hole sizes involves discretising the system into relevant sections with different characteristics. The system characteristics and conditions can be used to determine the leak hole size of each section. The leak hole size can be thus evaluated by using a formula in the structure of equation 1 below.

$$f_{leak}(d) = \frac{a \times b \times d^n}{m\,ln(D_o) - p}\left(c \times L_{pipe} + s \times N_{cpnt}\right) \qquad [1]$$

Where:

f_{leak} *= frequency of leak hole of a given size (range) (y-1)*

d = leak hole diameter (m)

a, b, c, d, m, p, s *= constants for location of parts, vibration control and impact protection and type of joints or connections (-)*

n *= an index (-)*

L_{pipe}*= length of piping (accounted for number of joints or connections) (m)*

D_o*= Pipe outer diameter (m)*

N_{cpnt} *= number of line components*

This methodology takes into account various factors that affect the frequency and size of a leak hole, like the length of piping, number of components, vibration and impact control of the system and others. Longer piping and a higher number of line components are expected to be associated with larger holes. On the other hand, systems with thicker pipes and better vibration and impact control are expected to give fewer/smaller holes and thereby lower leak mass flow rates.

As the number of line components is irrespective of the pipe length and is relevant only for very short piping it can be neglected. Hence equation (1) can be simplified and rearranged for the determination of leak hole sizes based on the leak frequency as shown in equation (2).

$$d = \left(\frac{a \times b \times c \times L_{pipe}}{f_{leak} \times D_0}\right)^{0.5} \; ; d \leq D_0 \qquad [2]$$

Where:

d *= leak hole diameter (m)*

f_{leak} *= frequency of leak hole of a given size (range) (y-1)*

a, b, c *= constants for location of parts, vibration control and impact protection and type of joints or connections*

L_{pipe} *= length of piping (accounted for number of joints or connections) (m)*

D_0 *= Pipe outer diameter (m)*

The evaluated leak hole size can be further used to obtain the mass flow rate based on maximum anticipated local conditions for relevant sections of the system. The mass flow rate can be calculated by using the following equation (3).

$$\dot{m} = C_d \pi * \left(\frac{d}{2}\right)^2 \sqrt{k\rho_0 (P_0 - P_{atm}) \left(\frac{2}{(k+1)}\right)^{\frac{k+1}{k-1}}} \qquad [3]$$

Where:

$\dot{m}$ = mass flow rate (kg/s)

d = leak hole size (m)

k = ratio of specific heat (C_p/c_v)

ρ_0 density of refrigerant (kg/m^3)

P_0 = system internal pressure (Pa)

P_{atm} = atmospheric pressure (Pa)

The output from the field data and lab tests are sound data on 1) leak sizes and 2) concentrations of mixtures which will then provide the basis for corresponding changes in the unit construction leading to a reduced flammability risk from the system. The results are also expected to improve the effectiveness of measures to reduce release amount and to further improve leak detection processes.

The proposed framework offers a rational approach to the determination of assumed leak rates as it considers various factors and operating conditions of a RACHP system. By adaptation of reasonable performance indicators, the methodology described implies a much more realistic approach than the arbitrary assumption of 4 minutes leak rates.

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