2002

Quantitative Risk Assessment Of Flammable Refrigerants In Room Air Conditioners

D. Colbourne
Calor Gas Ltd

T. J. Ritter
Calor Gas Ltd

R1-5

QUANTITATIVE RISK ASSESSMENT OF FLAMMABLE REFRIGERANTS IN ROOM AIR CONDITIONERS

Daniel Colbourne*, Terry J. Ritter
Calor Gas Ltd, Athena Drive, Tachbrook Park, Warwick, UK.
*Author for correspondence, Tel: +44 1926 330088, Fax: +44 1926 318612, E-mail: dcolbour@calorgas.co.uk

ABSTRACT

A number of safety standards and guidelines specify requirements for air-conditioning equipment that use flammable refrigerants. It is important that safety and technical requirements are based on sound scientific judgement in terms of the likelihood of potential risks occurring. This paper develops the risk assessment strategy by considering the following factors in detail, all of which may influence the possibility of ignition risk: mass of refrigerant, room size, typical ignition sources, leakage from refrigerant systems, failure unit components, building ventilation rates, build-up and decay of flammable concentrations and servicing. A risk model is developed using fault tree analysis, which incorporates these parameters to determine their effect on the risk of ignition occurring after a leak from an installed split type air conditioning system. Results are presented for normal operation as well as for servicing.

NOMENCLATURE

AC	room volume air changes (s^{-1})
A_f	floor area of room (m^2)
$\overline{C}$	mean concentration in air (kg.m^{-3})
C_h	concentration at height h_C (kg.m^{-3})
$\overline{C}_i$	mean initial concentration (kg.m^{-3})
h	installation height of unit, height of release (m)
h_C	height of concentration, C_h (m)
h_{eff}	effective height of the leak (m)
LFL	lower flammability limit of refrigerant (kg.m^{-3})
M	refrigerant mass charge (kg)
N_{SOI}	no. of 'live' ignition source events per day (-)
t	time following the development of the flammable concentration (s)
$\dot{V}_a$	volume flow of air (m^3.s^{-1})
ΔP	imposed pressure across building (Pa)
Δt_{FC}	duration of flammable concentration (s)
Δt_{SOI}	duration of a 'live' ignition source (s)
Φ_{FV-t}	the frequency of a flammable-volume resulting from a leak (-)
Φ_{ign}	the probability of ignition (-)
Φ_{leak}	the probability of a leak (-)
Φ_{recog}	proportion untrained who recognise flammable refrigerant (-)
Φ_{refuse}	proportion of untrained who refuse to work (-)
Φ_{serv}	frequency of "competent" servicing (-)
Φ_{SOI}	the frequency of a source of ignition in the environment (-)
Φ_{train}	proportion trained in handling flammable refrigerants (-)

INTRODUCTION

The objective of this work is to present a comprehensive risk assessment of the use of flammable refrigerants in air conditioning equipment, based on two different charge size calculation approaches. The purpose is to establish whether either of the approaches will contribute to an unacceptably high ignition risk probability. The quantified risk assessment (QRA) is conducted using a comprehensive risk model developed specifically for this purpose. The risks relate to indoor ignition only, and for the purposes of this publication, outdoor releases are not evaluated. The two charge size calculation methods are: (i) unaided dispersion of released refrigerant (Kataoka *et al*, 2000):

$$M = 2.5 \cdot (LFL)^{1.25} \cdot h \cdot \sqrt{A_f} \quad (1)$$

ii) Dispersion of released refrigerant aided by unit airflow (Colbourne and Butler, 2000):

$$M = 0.25 \cdot (LFL) \cdot A_f \cdot 2.2 \quad (2)$$

The refrigerant mass according to eqn. (2) is only permitted when the air handler provides a minimum airflow, $\dot{V}_a = M / (225 \cdot LFL)$. Consequences of ignition have not been accounted for, but are currently being studied as part of an ongoing investigation. Risk frequencies are calculated according the variety of scenarios, including indoor units installed at low level (0.6m), medium level (1.2m) and high level (1.8m)m representing floor, window and wall units respectively. For each situation, both normal operation and servicing situations were evaluated. It was assumed that fixed equipment would not be put in storage whilst it is charged with refrigerant. Whilst the methodology can be applied to any refrigerant whose properties are known, the analysis presented here has been limited to R290 (propane)

RISK CALCULATION METHODOLOGY

The general approach to risk assessment in this study is that of fault-tree analysis. Data for ignition sources, flammable volumes, failure scenarios, etc., have been collated in order to determine their respective frequencies. These frequencies are evaluated in a fault-tree, providing overall risk for the sceanrio in question. The probability of ignition is based on three fundamental factors: i) presence of a potential source of ignition, ii) occurrence of a leak, and iii) flammable-volume resulting from that leak. The probability of ignition is found from the formula (eqn. 3)

$$\Phi_{ign} = \Phi_{SOI} \cdot \Phi_{leak} \cdot \Phi_{\Gamma} \tag{3}$$

The frequency of the source of ignition is dependent upon the types of electrical equipment and flame-producing devices within the environment, as well as their location and density within a specific room. Leak probabilities are generally based on empirical data, with the frequency of a flammable atmosphere being a function of the size of the leak and other environmental conditions. For each of the calculation methods, the ignition source frequency, indoor leaks, unit component failure and flammable volume frequency are calculated. Each frequency is estimated according to the nature of the installation in terms of location and operating mode. The various components that contribute to the frequencies are listed in Table 1.

Table 1: Components for overall ignition risk frequency calculation

Charge size	Ignition source location	Activity	Leak type	Failure of unit components	Flammable volume source
Eqn (1) Eqn (2)	Gen. occupied space Kitchen Office	Normal operation (on) Normal operation (off) Servicing (trained) Servicing (untrained)	Small Medium Catas-trophic	Fan motors Airflow/duct blockage Control circuit	Small (plume) Medium (plume) Catastrophic (plume) Catastrophic (cloud)

IGNITION SOURCES

Items that could be considered as potential sources of ignition have been identified for each location. Valid sources of ignition must meet the following criteria: minimum ignition energy: 20mJ and/or minimum surface temperature: 460°C. The frequency of the ignition source is obtained from the average time an ignition source and flammable concentration is present per day, divided by the time in one day, eqn. (4).

$$\Phi_{SOI} = \frac{(\Delta t_{SOI} + \Delta t_{FC}) \cdot N_{SOI}}{86400} \tag{4}$$

Most ignition sources are assumed 'live' for 5 seconds (e.g. light switch, cigarette lighter, etc), but other such as gas hobs will be continuous for a duration typical of their usage. The local positioning of the ignition source has also been accounted for, in terms of its height with respect to the height of the unit and the type of release. For example, a denser-than-air refrigerant release from a floor unit will not be ignited from a wall-switch. Further, 'small' and 'medium' leak plumes disperse rapidly and are therefore only subject to ignition from the corresponding top, middle or lowest third of the room height. For most occupied spaces, the number of ignition sources is considered finite in relation to the room size; a large kitchen will not necessarily have twice as many cookers and kettles within it, as it doubles in floor area. The exception to this is office space, where the number of ignition sources (e.g. PCs) will increase proportionally with increasing floor space. It should also be noted that ignition sources within the appliance itself are not considered because safety standards already ensure they be eliminated.

Due to space limitations, it is not possible to provide an in-depth discussion of the various individual ignition sources, but those that are considered applicable are listed here. Ignition sources in general occupied spaces: TV on/off, video on/off, games console on/off, hi-fi on/off, light switches, plug switches, cigarette lighting. In an office space: PC on/off, light switches, light bulbs (starter), plug switches, cigarette lighting. In a kitchen: gas hob, electric hob on/off, gas oven, electric oven on/off, cooker extract unit, gas boiler pilot, microwave, refrigerator, kettle on/off, washing machine, drying machine, light switches. All data is based on UK practice.

Ignition sources for servicing depend on the competency of the technician. If a service person is trained in the use of flammable refrigerant handling, the probability of him using potential sources of ignition are greatly reduced, albeit not eliminated. There will also be situations where they must use a source of ignition to carry out the work, e.g. brazing. To determine what the frequency of ignition sources apply, a typical service pattern has been assumed, based on the data provided in Goetzler *et al* (1998). The duration of the visit taken is for 2.5 hours, with a visit occurring 0.1 times per year. Goetzler also estimates that 15% of service calls require brazing activities. It is assumed that a trained service engineer will not smoke when handling flammable refrigerants. Potential ignition sources for a trained technician arise from the brazing torch and torch sparker. For an untrained person they are additionally those arising recovery machine, vacuum pump, refrigerant detector (electrical), refrigerant detector (halide) and cigarette lighting. In order to establish the circumstances where trained and untrained service technicians are likely to work on equipment containing flammable refrigerants, a basic methodology has been devised. In the UK, it is estimated that 0.9 service technicians have received training for flammable refrigerant, 0.6 of these have a familiarity with them since a large proportion of domestic refrigerators already use R600a. 0.4 of the untrained technicians are likely to refuse working on the refrigerant due to legal implications. Using eqn. (5), it is estimated that Φ_{serv} = 0.924 of units will be serviced by 'competent' service people and 0.076 will be serviced by those not considered competent.

$$\Phi_{serv} = \Phi_{trained} + (1 - \Phi_{trained}) \cdot \Phi_{recog} \cdot \Phi_{refuse} \tag{5}$$

In summary, the frequency of sources of ignition considered here are detailed in Table 2 and are compared against the values used in other published QRAs for comparative purposes.

Table 2: Estimated ignition source frequencies and comparisons with other QRAs

Location	This study	HSE, 2000	Van Gerwen, 1995	Goetzler, 1998
Kitchen	1.09×10^{-1}	-	-	-
General occupied space	2.49×10^{-2}	1.0×10^{-4} per m^2	8×10^{-3}, 2×10^{-3}	1.0×10^{-4}
Office (per m^2)	1.41×10^{-4}	-	-	-
Servicing - trained	7.43×10^{-4}	-	-	5×10^{-4} 1.5×10^{-7}
- untrained	5.23×10^{-4}			1.4×10^{-5}

LEAKAGE DATA

For refrigerant leakage, some useful data has been made available (Ayers, 2000), which provide a good indication of historical and future leakage values. For one-year period (Nov 1999 – Oct 2000) refrigerant leaks have been monitored at 410 supermarket installations throughout the UK that range in age from one to ten years. Leakage quantities, locations and frequencies were measured. The instrumentation took samples every 30 minutes and the sampling points were located throughout each installation at high-risk positions (15 sampling modules each with 10+ sampling points) so that any refrigerant release from most locations would be observed. The size of the leaks was categorised as 'small', 'medium' and 'catastrophic' leaks. It should be noted that all measurements apply only to systems that are operating continuously, since none of these installations completely shut down. Out of the 108 million samples, 1,533,239 leak events were measured; 1,435,473 were 'small', 86,882 were 'medium' and 10,884 were 'catastrophic'. 28.1% of the leaks were from components normally located indoors (e.g. expansion device, evaporator coils, etc) giving an indoor leak frequency of 'small' leaks of 3.74×10^{-3}, 0.23×10^{-3} for 'medium' leaks and 28.1×10^{-6} for 'catastrophic' leaks. Data on installations of various ages has been considered, so the leak frequencies can be scaled up or down depending upon the age of the equipment considered.

Leakage from equipment in off-cycle

A system during standstill (i.e. compressor switched off) has a lower probability of having a catastrophic leakage since many of the mechanisms that cause leakage are not present, such as pressure changes, temperature changes and vibration. A recent report by AEA Technology (Guyoncourt & Fennell, 2000) considered mechanical and corrosion failure modes, of which very few were found to have the potential to cause a failure that could result in a gas release within the period required for a catastrophic leak. However, it was found that a combination of fatigue and stress corrosion cracking (SCC) under severe environmental conditions proceeds to a rapid failure. It was considered that stresses due to vibration from the compressor and thermal stresses generated during on and off periods could lead to fatigue failures in badly designed pipe-work or in cases where the tubing or unions have manufacturing defects. Failures would usually occur during the working period when the vibration stresses are highest, thus reducing the likelihood of it occurring in off-cycle. However, relaxation of a compressive thermal stress component after shut-down of the system could expose a pre-existing fatigue crack to a static tensile stress already present in the copper causing a sudden rupture of the pre-existing fatigue crack.

The pre-requisites for SCC of phosphorous deoxidised copper (refrigeration pipe) are: a corrodent, (particularly ammonia), presence of water on the surface and tensile stress. Tensile stresses of sufficient magnitude may be present in the copper and water vapour will condense on the tube surface in the region of the expansion valve and the evaporator. Ammonia could be generated for example by the bacterial decomposition of urine or other organic materials. Thus, the probability of a SCC failure can be evaluated. Taking into consideration all the factors necessary to cause such a failure, a frequency of 1×10^{-9} has been estimated, which is comparable to the historical figure of 3.0×10^{-8} advised by the Liquefied Petroleum Gas Association (LPGA, 2001) on catastrophic leaks from a LPG storage tank. This is considered to be an analogous situation since it is a static vessel that has a fixed holding charge and is only subject to minor internal pressure variation according to ambient conditions. Since these vessels are located outside they are normally subject to more rigorous conditions than those within a human occupied space.

Leakage during servicing

It is probable that the leakage rate in servicing is going to be greater than for normal operation since the service technician could be intentionally breaking in to the refrigerant containing circuit. With reference to Goetzler, the leak frequency leading to a significant release during servicing is recommended as 1.0×10^{-3}, which is assumed "catastrophic". In addition, the frequency of service calls requiring refrigerant handling is 0.15 to be applied to the total servicing risk. Taking the proportion of indoor leaks, the respective proportions are calculated. It is assumed that the probability of small and medium leaks is the same order of difference higher (about 10 times) when servicing than during normal operation: 2.90×10^{-2} for 'small', 1.79×10^{-3} for 'medium' and 2.18×10^{-4} for 'catastrophic' leaks.

It is also assumed that a leak could occur either whilst the unit is operating (e.g. during charging) or whilst switched off. On this basis, a 50% probability has been applied to account for the unit operating whilst a leak occurs, and similarly, a 50% probability of a leak occurring whilst not operating. 0.25 of refrigerant handling activities is conducted inside since systems are generally recovered and charged from the condensing unit. Also accounted for is the possibility of a release from a refrigerant cylinder. Experiments from liquid off-take cylinders indicate that approximately 0.15 kg/s are released when the valve is fully open, whilst it takes approximately 5 seconds for the service technician to correct this occurrence. This is considered constant regardless of the unit charge size.

FLAMMABLE VOLUMES FROM REFRIGERANT RELEASE

Since reliable data is available on leaks, the flammable volume-time (FV-t) – the duration that a volume of refrigerant within its flammable range exists for - can be used to determine the frequency that a flammable concentration will occur. For a particular release scenario, it is essential to be able to define the FV-t, since the simultaneous occurrence of a flammable cloud with a 'live' ignition source will leak to ignition. Each of the three leak categories described earlier were considered, and the FV-t estimated under according to leak type, mass flow, location of release, room volume, air movement and ventilation considerations. All releases have been assumed vapour releases since much of the data is only available for this situation. The method for determining the FV-t of a release will be different according to the type of the release. The frequency of the flammable concentration, Φ_{FV-t}, is found from the total available room volume and the duration of the release (eqn. 6).

$$\Phi_{FV-t} = \frac{FV-t}{(31557600 \cdot \Phi_{leak}) \cdot A_f \cdot h_C} \tag{6}$$

Flammable volume-time of leak plumes

In the case of a plume, the FV-t of the plume was estimated based on the geometry of the release. Low, medium and catastrophic leak data was used to estimate nominal release characteristics from a circular hole in pipework using conventional steady flow equations. The approach described by Cleaver *et al* (1994) was used to determine the magnitude of the flammable volumes generated from jets. The FV-t is then calculated from integrating the volume within the plume that corresponds to the region between the flammable limits of the refrigerant over the total release time. The FV-t of a plume is generally small, in the order of 0.5 – 1.5 m^3.s for a 'small' leak and 15 – 35 m^3.s for a 'medium' leak, of 1kg.

Catastrophic leaks

There are three different situations where a flammable cloud occurs following a catastrophic release: (i) a cloud from a release of mass according to equation (1); (ii) a release mass according to equation (2) with minimum airflow in equation (3); (iii) a release mass according to equation (2) with no airflow. Equation (1) was derived on a constant FV-t basis, so all releases under situation (i) are 900 m^3.s. A basic cloud-decay model, validated against data from previous experiments (Colbourne and Butler, 2000) was used for case (ii), and the output from this corresponded closely with the results of CFD modelling described by Kataoka *et al* (2000). For example, a 1kg release from 2m produced a FV-t of 120m^3.s. The approach used to derive equation (1) is used to calculate the initial size of the flammable volume for case (iii). Eqn. (7) is used to estimate the height of the 'flammable pool' following a catastrophic leak, when $C_h = LFL$.

$$M_r = A_f \cdot \left[\left(C_h \cdot h_{eff} - \frac{C_h \cdot h_{eff}^3}{3 \cdot h_{eff}^2} \right) - \left(C_h \cdot h_C - \frac{C_h \cdot h_C^3}{3 \cdot h_C^2} \right) \right] \tag{7}$$

The effective leak height, h_{eff}, is a function of the floor area and the leak height according to eqn. (8).

$$h_{eff} = \exp\left(\ln (h) - 0.37 \cdot \ln (A_f / 7) \right) \tag{8}$$

The flammable-volume is the product $(h_C \cdot A_f)$. Given that infiltration invariably exists, the flammable volume time is approximated using the decay equation over the flammable volume for the prescribed infiltration rate. The use of experimental data from an earlier set of experiments (Colbourne and Butler, 2000) was used to validate the use of eqn. (9).

$$\overline{C}(t) = \overline{C}_i \cdot \exp\left(- AC \cdot t \right) \tag{9}$$

The FV-t is therefore the product $(h_C \cdot A_f \cdot t)$**,** where t is the time that $LFL \leq \overline{C}(t) \leq UFL$. As an example, for a 1kg release for a floor unit the FV-t range from 120,000 m^3.s for AC = 0.25 h^{-1}, to 4,000m^3.s for AC = 5 h^{-1}. A catastrophic release from a wall unit range from 8,000 m^3.s for AC = 0.25 h^{-1}, to 300m^3.s for AC = 5 h^{-1}.

Failure of unit components

The use of certain unit components may contribute to an increased FV-t, since their failure may result in a lack of sufficient airflow in case (iii) above. These are:

- *Fan motors.* Frequency of fan motor failures depends on a wide range of factors including working environment, type of motor and so on. Generally, precise data is not readily available. Data provided by one manufacturer states a fan/fan motor failure rate of two in 1000 per year.
- *Air flow.* Filters and air ducts tend to get blocked which reduces airflow rate and therefore the effectiveness of the airflow. There is no data available to show the proportion of volume flow rate degradation with increased blocking of filters, which would be a function of time, dependent on the environment that the equipment is working. However, data has been found in Davies and Pearson (1999) for appliance flue blocking. This gives a value of 13% of flues blocked per annum, which is considered conservative for air conditioning equipment, but was employed here in absence of more specific data.
- *Control circuit.* There is no available data on the failure of control circuits, but discussion with engineers involved in refrigeration controls indicate that a figure of 5% failure per year is reasonable.

Ventilation effect

The effects of ventilation are significant to the creation and dispersion of a flammable concentration of leaked refrigerant. More-importantly, they contribute to the flammable volume-time of a refrigerant release. On this basis it is important to determine statistical data on airflow rates for buildings. All buildings have a degree of air leakage, which equates to an internal airflow through the building, which should be taken into account when evaluating the presence of flammable clouds and the subsequent dispersion of refrigerant. Statistical data on building leakage at an imposed pressure is available from certain sources. A collation of leakage data at an imposed pressure of 50 Pa (Orme *et al*, 1998) has been used to determine the typical variation in room air changes under a range of conditions. Within the UK, 3% of buildings have AC = 0-4 h^{-1} at 50Pa, 29% have AC = 5-9 h^{-1}, 28% have AC = 10-14 h^{-1}, 13% have AC = 15-19 h^{-1} and 2% have AC = 25-30 h^{-1}. To convert the air change rate due to the imposed pressure of 50 Pa to an air change rate based on real conditions, eqn. (10) was used.

$$AC = AC(50) \cdot (\Delta P / 50)^n \tag{10}$$

Where the index n is generally 0.6 – 1.0 depending on the structure, and, ΔP is based on air pressure calculations for the conditions in question. Using the general approach for calculation of stack and wind-pressure (BS 5925), the variation in pressure across a building fabric for the range of yearly conditions was evaluated. The result is the proportion of time that occupancies have a specific air change rate due to natural ventilation. Based on UK data for a two-storey building in an urban area, the frequencies for infiltration rates - or proportion of time such air change rates are present – are: 0.086 for $0 \le AC \le 0.5$, 0.225 for $0.5 \le AC \le 1.0$, 0.432 for $1.0 \le AC \le 2$, 0.241 for $2 \le AC \le 5$, 0.016 for $5 \le AC \le 10$. These frequencies were be used in the estimations of FV-t in eqn. (9), created from catastrophic refrigerant releases as described above.

RESULTS

The results of the calculations for ignition frequencies are presented here. Firstly, it is useful to note the primary elements of the risk calculation; the sum of which provides the total overall risk. These primary elements are the ignition risks due to leakage, flammable volume and ignition under the conditions stated. Table 3 lists this data for a wall unit containing 1kg of R290 in an office space of 48m^2 according to eqn. (2), with a 12 hour/day operating cycle.

Table 3: Example of primary elements of total risk

Element	Normal operation	Servicing
Small leak plume	4.63×10^{-14}	4.50×10^{-12}
Medium leak plume	2.66×10^{-13}	1.27×10^{-10}
Catastrophic leak plume	1.99×10^{-12}	1.93×10^{-10}
Catastrophic leak, unit on, floor	4.10×10^{-11}	4.52×10^{-09}
Catastrophic leak, unit off, floor	6.15×10^{-15}	4.52×10^{-09}
Catastrophic leak, unit on, safety controls fail	3.17×10^{-12}	5.97×10^{-10}
Catastrophic leak, unit off, safety controls fail	3.60×10^{-15}	4.52×10^{-09}
Leak from cylinder	-	4.99×10^{-09}
Overall Risk	4.65×10^{-11}	2.17×10^{-08}

In this example, the risks associated with small and medium sized leaks are negligible during normal operation. The effect of the plume resulting from a catastrophic leak makes a slight contribution, but the primary cause of the risk of ignition is the development of a floor-level flammable cloud when the unit is operating normally, and when the unit's components fail. With the servicing scenario the situation is similar, where a catastrophic leak occurs and the unit is either on, off or off with the safety controls failed. Thus, the majority of the factors that contribute to the overall ignition risk of this equipment are primarily flammable

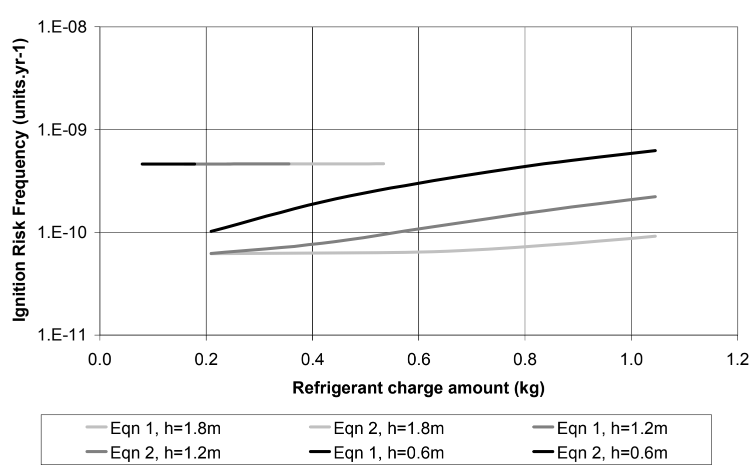

Fig. 1: Results for units installed at different heights

clouds at floor level and the effects of failure of safety critical controls. The difference in elemental risk is consistent across the range of charge size and installation scenarios investigated and compared.

Normal operation

The first set of results were generated from the risk model under "normal operation" mode, using refrigerant charges corresponding to eqn. (1) and (2) for floor areas ranging from $10m^2$ to $50m^2$. Figure 1 provides the results for units installed at heights 0.6m (floor), 1.2m (window) and 1.8m (wall). Since eqn (1) was developed specifically to maintain a constant FV-t, the ignition risk frequency remains constant regardless of installation height or charge amount. Conversely, charge sizes based on eqn (2) show a gradual increase with increase in both charge amount and reduction of installation height. As observed in other work, the flammable volume of a release increases in relation to room size due to loss of effectiveness in mixing, when the release is unaided. Thus, the increase in risk is due to the influence of component failure (i.e. loss of forced airflow). A release of a fixed mass from low level also results in less effective dispersion, again producing a greater FV-t with lower installation heights. However, due to the influence of aided dispersion when airflow is adequate, the FV-t is significantly reduced, ensuing lower overall risk than that provided by use of eqn. (1). The constant risk level of eqn. (1) is exceeded for larger (M >0.8 kg) floor-based units designed to eqn. (2), due to the combination of large charges and poor dispersion when forced airflow fails. Results in Fig. 1 are for an office space. Ignition within a general occupied space ranges from a similar value in a large room ($50m^2$) to a ten-fold increase in a smaller room. Similarly, the risk within a kitchen is approximately three times greater in large areas, increased to around 30 times greater when the room is much smaller. These differences are approximately proportional to the ignition source frequency within the room in question.

Servicing

Generally the rating of the risk levels according to the design clauses, follow that of the normal operation scenario. The exception is that of equation (2), which indicates a low risk level for small floor areas rising to the risk level of the other clauses. The reason for this is that where the generation of high concentrations due to high charge sizes can occur, the safety system cannot necessarily be activated

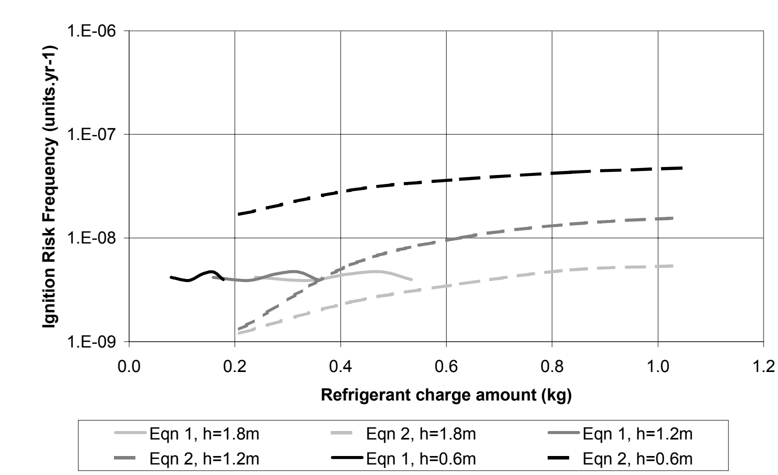

Figure 2: Results for servicing different units

Note about assumptions

Despite the objective of QRA being to present realistic predictions, lack of appropriate data necessitated certain assumptions. Assumed data or conditions were always worse case, and include:

- Leak frequencies were from supermarket installations are higher than small hermetic units.
- All catastrophic leaks are assumed 3½ minutes, whilst data shows most occur over a longer period, thus developing lower concentrations.
- Leaks assumed to be vapour only when most are mixed phase, reducing FV-t.
- Assumed that infiltration dilutes the leak rather than also mixing which would also reduce FV-t.
- Effect of mixing due to thermal convection currents and human movement was neglected.
- Although tests show up to 35% of refrigerant is retained in a system after a catastrophic leak, it is neglected.

CONCLUSION

In this study, a methodology for calculating the risks associated with the use of flammable refrigerants in air conditioning equipment is described and the results of the model are presented, which are based on UK conditions. In particular, the risk assessment has been used to determine the effect of design and construction of equipment according to the two approaches detailed as eqn. (1) and eqn. (2). No particular situation resulted in a significantly higher risk, although the use of eqn. (2) produces an escalation in risk towards higher charge sizes, whereas the risk when using eqn (1) is constant. This is to the detriment of very low charge sizes relative to the dimensions of the room. It should be noted that the presented frequencies are based on in-use and servicing modes, and that additional risks are present during manufacture, installation and decommissioning.

In order to put the calculated risks into context, it is useful to compare them against other measures of "accepted" risk. Firstly, the UK Health and Safety Executive provide recommended values for risk (HSE, 2000). An intolerable risk of injury to individuals (not at work) is $1x10^{-5}$, and a negligible risk is $1x10^{-6}$. Another measure of risk is that of well-known events. For example, death by lightning strike is $7x10^{-7}$, death by a bee sting is $4x10^{-7}$ and death from an aeroplane crash is $1x10^{-7}$. In addition, there are existing fire risks from other household appliances. Based on statistical data on UK fires (Collier and Watson, 1997) the following frequencies are for fires from appliances in-use: refrigerators - $1.13x10^{-5}$; gas cookers - $8.71x10^{-4}$; electric cookers - $8.25x10^{-4}$; gas central heating - $4.03x10^{-5}$; electric central heating - $1.01x10^{-4}$; washing machine - $1.63x10^{-4}$; television - $2.65x10^{-5}$. The lowest reported risks are for gas water heating ($4.56x10^{-6}$) and audio/visual equipment ($8.08x10^{-6}$). Whilst the fire risk associated with the audio/visual is probably due to electrical faults, a release of flammable gas is the usual cause of a fire from a heating appliance. In comparison, the maximum calculated ignition (only) risk for air conditioning equipment using flammable refrigerants is in the order of $3x10^{-8}$ when installed in a small kitchen and $8x10^{-7}$ when being serviced.

REFERENCES

Ayers, J. Parasense study on refrigerant leaks. Parasense Ltd, Gloucester, UK, November 2000.

BS 5925: 1991 Code of Practice for principles and designing for natural ventilation. BSI, London, UK, 1991.

Cleaver, R. P., Marshall, M. R., Linden, P. F. The build-up of concentration within a single enclosed volume flowing a release of natural gas. J. Hazardous Materials, No. 36, pp. 209-226, Elsevier, 1994.

Colbourne, D. Butler, D. J. G. Dispersion of flammable refrigerants from split air-conditioners. Proc. IIR 4th Gustav-Lorentzen Conf., Purdue, USA, 2000.

Collier, P., Watson, L. Fire Statistics United Kingdom 1997. Home Office Statistical Bulletin, Research Development and Statistics Directorate, London, UK, November 1998.

Davies, P., Pearson, J. Gas In relations to other domestic risks. Business Strategy Group Research project for the Health and Safety Executive, Final Report. UK, August 1999.

Goetzler, W., Bendixen, L., Bartholomew, P. Risk assessment of HFC-32 and HFC-32/134a (30/70 wt. %) in split system residential heat pumps. Final Report DOE/CE/23810-92 for ARTI, Arthur D. Little, USA, April 1998.

Guyoncourt D. M. M., Fennell, P. H. Potential catastrophic failures of refrigerant systems. Report no. XYZ, AEA Technology, Didcot, UK, November 2000.

Health & Safety Commission. Gas safety review: options for change. Health Safety Executive, London, UK, 1999.

Kataoka, O., Yoshizawa, M., Hirakawa, T. Allowable charge calculation method for flammable refrigerants. Proc. Int. Refrigeration Conf., Purdue, USA, 2000.

LPGA, 2001. Data reported from Roberts, A. F. Methods for estimating harmful consequences of fires and explosions following a release of LPG. IR/F/FR/80/10, November 1980.

Orme, M., Liddament, M. W., Wilson, A. Numerical data for air infiltration and natural ventilation calculations. Air Infiltration and Ventilation Centre, Coventry, UK, 1998.

van Gerwen, R.J.M, Jansen, C.M.A. Risk Assessment of the Use of Flammable Refrigerants. Final Report of TNO Institute of Environmental and Energy Technology, Apeldoorn, 1995.