Accepted Manuscript

Title: An investigation of refrigerant leakage in commercial refrigeration

Author: Christina Francis, Graeme Maidment, Gareth Davies

PII: S0140-7007(16)30338-3
DOI: http://dx.doi.org/doi: 10.1016/j.ijrefrig.2016.10.009
Reference: JIJR 3452

To appear in: *International Journal of Refrigeration*

Received date: 15-4-2016
Revised date: 1-10-2016
Accepted date: 9-10-2016

AN INVESTIGATION OF REFRIGERANT LEAKAGE IN COMMERCIAL REFRIGERATION

Christina FRANCIS, Graeme MAIDMENT, Gareth DAVIES
London South Bank University, 103 Borough Road, London, SE1 0AA,
Email:francic8@lsbu.ac.uk

Highlights

- Comprehensive analysis of a large number of F-gas leakage records was conducted.
- A methodology of categorizing refrigerant leakage incidents is summarized.
- Common locations and system components prone to leakage are identified.
- Long term solutions to control refrigerant leakage are discussed.

ABSTRACT

Given that refrigerant demand is set to rapidly increase, long term solutions for leakage prevention are required to effect change in the industry. This paper presents the results of a project which investigated refrigerant leakage within two of the UK's major supermarket chains. Leakage data from 1,464 maintenance records were analysed. The analysis categorized the type, location of each leak and volume of refrigerant replaced during repair. Over 82% of the recorded leaks were from R404A refrigeration systems, and mainly consisted of *pipe or joint failures* or a *leaking seal/gland/core* located in the compressor pack and the high pressure liquid line. It is recommended that the industry focuses on improving design, installation and maintenance of pipework and valves, at the components that most often develop faults to minimize refrigerant leakage.

KEYWORDS
Refrigerant, leakage, F-gas emissions, supermarkets

1. INTRODUCTION

A study by Gschrey *et al.* (2011) indicated that the contribution of fluorinated gases (F-gases) to global warming will increase from approximately 1.3% (2004) to 7.9% (2050) of projected total anthropogenic CO_2 emissions in a business-as-usual scenario. Gschrey *et al*. highlighted that additional efforts are required from both developed and developing countries in order to achieve significant reductions in F-gas emissions. Many refrigerants used in RACHP (refrigeration, air conditioning and heat pump) systems are F-gases (Bauer *et al.*, 2015). Leakage of refrigerant gases from these systems impacts the environment in two ways (Koronaki *et al*., 2012). Firstly there is a direct effect due to the global warming potential (GWP) of the leaked gas, and secondly, there is an indirect effect due to the decreased efficiency of the refrigeration system (due to the loss of charge) which leads to increased energy consumption (Grace *et al.*, 2005). In particular, emissions of hydrofluorocarbons (HFCs) refrigerants have been increasing mainly due to their widespread use as replacements for chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs) (Montzka *et al*., 2014). This is in addition to the rapidly increasing demand for RACHP systems in emerging economies (Davis and Gertler, 2015).

Commercial refrigeration is considered to be one of the applications that contribute most to global warming (Mota-Babiloni *et al.*, 2015a). The growth in the commercial refrigeration sub-sector is of concern, since it is reported to have the highest CO_2-equivalent emissions for the whole RACHP industry equivalent to 40% of total annual refrigerant emissions (UNEP, 2014), despite it being responsible for only 22% of worldwide refrigerant consumption (Devotta *et al.*, 2005). Leakage in commercial refrigeration systems varies greatly from one system to another (Coulomb, 2008). Annual leak rate can be an average of 11% (Koronaki *et al.*, 2012) and up to 30% in some cases (Beshr *et al.*, 2015). Refrigerant leakage can also have a significant financial impact for the user depending on how quickly the leak is found and repaired (ETSU, 1997 and Koronaki *et al*., 2012).

The design of the refrigeration system is a crucial decision from both an economic and environmental viewpoint (Söğüt, 2015). Although, numerous investigations have been carried out in order to reduce CO_2 emissions, these efforts have not yet been sufficient to reduce climate change to sustainable levels (Mota-Babiloni *et al.*, 2015b). Design options tend to include using alternative refrigerants and improving the efficiency of the system (Beshr *et al.*, 2015). However, designs for leak tight systems remain fundamental for reducing refrigerant leakage and associated costs. To date, limited results from comprehensive analyses of F-gas leakage and/or maintenance records have been published and used to inform design. Leak tight design and installation requires practical knowledge and understanding of the locations and system components where leaks are most commonly found in refrigeration systems.

This paper investigates and presents a detailed study of refrigerant leakage based on a total of 1,464 F-gas service records compiled from two major supermarket chains and builds on some preliminary results reported by Cowan *et al.* (2015). In section 2, the current article provides some background information on regulations and the results of other leakage studies on commercial systems. The methodology used in the present study is described in section 3, and in section 4 the results of the analysis are reported and discussed. In section 5, long term solutions for leak control are highlighted and section 6 outlines the main conclusions of the study.

2. STRATEGIES TO CONTROL REFRIGERANT LEAKAGE

The commercial refrigeration sector comprises the equipment, technologies, and services used to store and dispense frozen and fresh foods at appropriate temperatures (Devotta *et al.,* 2005). The sector includes: a) stand-alone systems; b) condensing unit systems; and c) full supermarket systems. Stand-alone systems are self-contained whereby the components are integrated. Condensing unit systems are small commercial systems with compressors and condensers located external to the sales area, but with the evaporators located in display cases in the sales area, or in a cold room for food storage. Full supermarket systems can be either (i) centralized; or (ii) distributed, systems. Centralized systems generally have a central plant in a remote location with a series of compressors and condenser(s) circulating liquid refrigerant or secondary heat transfer fluid to display cabinets and cold storage rooms in other parts of the building. In contrast, distributed systems use multiple smaller compressor/condenser units which are located in close proximity to the display cases. According to UNEP (2014), 93% of emissions from this sector arise from system types b) and c). This is partly due to the volume of the refrigerant bank in these systems, and partly due to the long lengths of distribution pipework and the number of joints needed, which both increase the risk of leakage.

Since 2006, the F-gas regulations (Regulation (EC) No 842/2006) along with other strategies have been applied in Europe with the aim of minimizing the emissions of fluorinated gases (F-gases), including HFCs. The regulations have been recently revised, and it is anticipated that there will be a global phase down of HFC refrigerants to more climate friendly alternatives through the aid of the revised Regulation (EU) No 517/2014 (European Commission, 2016) and amendment to the Montreal Protocol (Deol *et al.*, 2015). Likewise, the US Environmental Protection Agency (US EPA) (2015a) published a regulation on acceptable and unacceptable substitute refrigerants under the SNAP (Significant New Alternatives Policy) program.

The F-gas regulations have led to several successful initiatives, such as the REAL Zero (Refrigerant Emissions and Leakage - Zero) project developed in the UK. This was aimed at reducing refrigerant leakage in industrial and commercial refrigeration systems (REAL, 2016). Since then several “REAL” branded projects have evolved offering multi-lingual training guides and e-learning tools on refrigerant leakage and safe handling of alternative refrigerants (REAL, 2016). In the US, a similar programme is administrated under the GreenChill Partnership with food retailers (US EPA, 2015b).

A number of certification schemes have also been developed to ensure maintenance personnel are competent in the safe handling of RACHP systems such as the ISO 5149, EU No. 517/2014 Regulation and EN 13313 (Coulomb *et al*., 2015). Of particular note, the Dutch STEK (Stichting Emissiepreventie Koudetechniek: Foundation for the Prevention of Emissions in Refrigeration) certification program is credited with reducing emissions from 20% to 3.5% on average since its inception (EFCTC, 2011). However most of these qualification schemes are not mandatory worldwide (Coulomb *et al.*, 2015) and RACHP systems are reported to continue to leak. In fact, all refrigeration systems have the potential to leak, because pressures in the system are usually many times higher than atmospheric (Tassou and Grace, 2005). Refrigerant loss has been attributed to a range of factors (Tassou and Grace, 2005 and Koronaki *et al.*, 2012), for example:

a) Gradual leakage through components over long periods of time before the leak is detected
b) Catastrophic or physical damage resulting in large refrigerant losses over a short period of time
c) Operation of pressure relief devices
d) Small losses during routine maintenance, repair and/or recovery of refrigerant

A number of authors have reported on the reasons why refrigeration systems continue to leak. Following an extensive survey of professionals, ETSU (1997) identified the 6 most common leakage sites as flare joints, shaft seals, other mechanical joints, signal lines/small bore lines, valves/glands, and vibration (chaffing). Birndt *et al.* (2001) have summarized the results of the research project “Tightness of Refrigeration Systems”, which was conducted in two states in Germany and involved leak tests of selected commercial refrigeration systems, focussing particularly on supermarkets. It was found that 14.4% of the identified leaks (i.e. 15 out of 104) accounted for 85% by weight of the refrigerant loss. Of the 104 identified leaks, 18 occurred in the cycle components and 86 in the assembly joints. Meurer and Nicoletti (2005) also reviewed the same survey and further highlighted that 22% of all measurable leaks were from flared joints, which were responsible for 50% of the refrigerant losses. Overall 96% of the total refrigerant loss was through field assembled joints. Rhiemeier *et al.* (2009) compiled a comparative assessment of similar studies on refrigerant leakage undertaken in other parts of Europe and the US. A few of these studies are reviewed later in section 4 of this paper. Whilst the results of these studies were fairly detailed, they were based on relatively small samples.

The current paper examines the extent and reasons why leakage occurs in supermarket refrigeration systems, based on a survey of 1,464 service records from two major UK supermarket chains. It describes the methodology used in developing a refrigerant leakage analysis tool to examine the most common locations/system components where leakage/faults were found. It builds on some preliminary results reported in Cowan *et al.*, (2015). It also highlights some of the common practices used within the refrigeration industry for service maintenance or leakage repair.

3. METHODOLOGY

3.1 Data Profile

Collection of refrigerant usage log data was undertaken from 2010 onwards, across multiple sites from two of the UK’s major supermarket chains identified as Company A and Company B. The records for Company A involved supermarkets with a typical sales floor area of 2,787 m^2, with each store operating with 5 or less centralized refrigeration pack systems, and a total refrigerant charge estimated at 500 kg. The packs were installed in internal plant rooms, with roof-mounted condensers feeding shop-floor cabinets, freezers, and cold stores. Approximately 20% of service technician call-outs involved adding/removing refrigerant. In contrast, Company B records covered over 300 stores with a typical floor area of 3,716– 4,645 m^2. Each store consisted of up to 20 refrigeration systems including central refrigeration packs, condensing units, and integral systems with a total accumulative charge of over 1,000 kg. The refrigeration systems were mostly centralized direct expansion systems with roof-mounted compressor packs feeding several different types of evaporators. For Company B, less than 5% of the records were related to service technician call-outs that involved adding/removing refrigerant.

The reason for the disparity shown between the technician call-outs for Company A and Company B is unknown. However, the retrieved data were recorded in two different formats, each unique to the culture of the particular organization. Company A provided detailed paper-based maintenance records and work orders, whereas Company B provided a simplified summary report of refrigerant usage in an electronic data log spreadsheet. The different formats of the data presented some difficulties in ensuring consistency of the data analysis. Therefore, a structured methodology was developed for categorizing the fault types and fault locations, down to the individual component level.

3.2 Data Analysis

A strategy was developed to standardize the data within a set of 25 predetermined data input fields, which consisted of questions with a range of possible answers. Microsoft Excel software was used to tabulate the results of the analysis. The structured approach used for the analysis included critical information about the leak/fault incident report (e.g. previous (related) incidents, call out initiator, response time, leak detection method, number of leaks detected, repair actions, and system downtime), as well as more basic information about the nature of the faults and the quantities of refrigerant added.

The locations of the faults were categorized using a simplified schematic of a typical refrigeration system found in a supermarket as outlined in Fig. 1. The refrigeration system typically comprised a roof-mounted or service room-located multi-compressor pack including either an integral or remote condenser, with evaporators remotely located in the sales/display cabinet area and connected by long pipe runs. System boundaries were created to define distinct regions for the typical supermarket refrigeration system. The system boundaries consisted of 6 main regions referred to as system level fault locations, and listed as: Compressor Pack; High Pressure (HP) Gas Pipe; Remote Condenser; HP Liquid Line; Evaporator; and Low Pressure (LP) Suction Lines.

In the Excel spreadsheet analysis, each region or "system level-fault location" can be selected from a drop-down list menu. The selected "system level-fault location" then allows a variety of corresponding sub-components to be selected via the "component level-fault location" drop-down list menu. An option has been provided for updating the drop-down list with additional components, as necessary. To deal with the large number of reasons recorded for faults, similar faults were often grouped as a single category. Each fault category could also be selected from a drop-down list menu. This process facilitated comparison between the fault types and locations. In some cases, relatively little information about the fault was provided. However, a minimum set of data input fields were required for adequate analysis, which allowed data to be consolidated and compared from different sources. The minimum data input fields needed for the analysis were specified as:

- Refrigerant Type
- Fault Category
- Fault Location- System Level AND/OR –Component Level
- Net Refrigerant Added

The structure of the data analysis ensured standardization and compatibility for all users of the Excel leakage analysis tool. In addition, it is considered that the research methodology should enable the study to be readily replicated by other researchers.

3.3 General Assumptions

A number of general assumptions were made for analysis of the service records:

1) All fault repairs on a leaking valve were attributed as *leaking seal/gland/core*, if not otherwise indicated.
2) Incident reports labelled as *pipe or joint failure* were assumed to represent a leak in a pipe; however the recorded data on the pipe or joint failure was sometimes incomplete. In most cases of this type, the fault location at the system and component level was known, but in some cases the fault category had not been clearly specified in the report. For example, where the incident report stated that the "Service Technician found and repaired leak on discharge pipework," it was assumed that the discharge pipework was located within the compressor pack and the fault location at the system and component levels could then be indicated. However, in this example the report did not specify whether the leak was due to a *fracture/rupture/crack* or due to a *leaking flange/union/joint*. Therefore, the fault category was simply recorded as *pipe or joint failure*.
3) If a pressure relief valve (PRV) had been blown and fixed, it was designated in the *fracture/rupture/crack* fault category.
4) Faults categorized as mechanical components were those which directly related to repairs or replacements of the main mechanical components of a RACHP system such as the compressor pack, evaporator, thermal expansion valve and condenser.

5) Faults categorized as ancillary components included devices such as fans and pumps.
6) Transducers, switches, and gauges were grouped together in the analysis as *monitor/control hardware.*

4. RESULTS

This section presents the results and information from a total of 1,464 faults compiled from two data sources, with approximately 46% of the data from Company A and 54% from Company B. For companies A and B combined, an estimated 36,000 kg of net refrigerant was added to the two supermarket refrigeration systems. The majority (82%) of the refrigeration systems in companies A and B used R404A refrigerant. The remainder used R134a and R410A refrigerants. Approximately 31% of the records were considered incomplete, since some critical information was not included. In cases where the fault category was unknown, it was recorded in the Excel spreadsheet as *other/not stated*. In cases where the fault location at the system and/or component level was not known, it was designated as "unspecified" in the Excel spreadsheet.

It was also observed that no leak was found, or another fault was identified in 17% of the total records. However, these refrigeration systems were still topped-up with refrigerant without providing any other explanation. These refrigerant additions accounted for 10% of the total refrigerant added by weight. The current analysis aims to review and analyze **all** faults identified within the incident reports where refrigerant was added, in an effort to determine common practices used within the industry. The results from the analysis should help to improve good practice guidelines, as well as identifying problematic leakage prone components.

4.1 Common Fault Types of Refrigeration Systems

The common fault types found in the supermarket refrigeration systems were grouped into 18 categories and the percentage number of faults for each category was compared for companies A and B. It was anticipated that the frequencies of some fault categories should decrease over time due to increased maintenance; however no clear evidence of this was apparent within the time period of this study. However, this could have been due to reduced reliability as a result of aging of the system. The percentage of total refrigerant mass added as a result of each fault was determined, which revealed that although the frequency with which the fault occurs is of course important, attention should also be given to the average amount of refrigerant required to be added to the system each time the fault occurs. Therefore, the refrigerant addition per incident by fault category was also determined from the records for companies A and B.

4.1.1 Refrigeration system fault types

A comparison of the frequencies of particular fault types for the two companies is shown in Fig. 2. Fig. 2 indicates that both companies recorded the same eight top faults in each case, with *pipe or joint failure* accounting for an overall average of 27% of the combined data, (i.e. 29.65% and 23.54% of the number of faults within Company A and Company B, respectively). This is followed by *leaking seal/gland/core* of valves, whereby Company A and Company B accounted for 26.25% and 16.03%, respectively. Almost 17% of the faults for Company A and 40% of faults for Company B were not identified in the leakage data. These faults were recorded as *other/not stated* where faults were not specified or stated as "refrigerant shortage" or "cause not known."

If the *other/not stated* faults are excluded, and the contribution of the identifiable faults are compared, the top two faults account for over 66% of the reported identifiable faults (i.e. *pipe or joint failure* at 37% and *leaking seal/gland/core* at 29%). The *Miscellaneous* category in Fig. 2 refers to a small number of faults which are not listed in the other categories. *Miscellaneous* faults included *electrical/ electronic hardware*, *dirt/corrosion/blockage*, *moisture issue*, *loose item/cap/seal*, *vibration*, *physical damage* (*3rd party)*, and *missing cap/seal*.

4.1.2 Refrigeration system fault types and refrigerant added

The two most commonly occurring faults by mass (i.e. *pipe or joint failure* at 28% and *leaking seal/gland/core* at 26%), are also responsible for over 53% of the total refrigerant mass added on average for both companies (see Fig. 3) and over 73% of the refrigerant mass added if the *other/not stated* fault contributions are excluded. However, it is considered that the *other/not stated* faults' contribution to the total refrigerant mass added (i.e. 27%) should be included, as this represents the addition of significant quantities of refrigerant, although the fault was either not known or not reported. This suggests that significant refrigerant leakage occurred, on a number of occasions, where the problem was not subsequently identified and therefore, may not have been completely rectified. However, further investigation is required to verify this. In terms of the remaining leakage fault categories, the *fracture/rupture/crack* fault was responsible for 8% of the refrigerant mass added, while less than 11% of the total refrigerant mass added was due to the other identifiable fault categories.

Interestingly, *pipe or joint failure* and *leaking seal/gland/core*, which were the two most frequently occurring types of faults, were not the top faults when considering the amount by mass of refrigerant added per incident. Fig. 4, which shows the refrigerant additions by mass per incident for the identifiable faults, indicates that *physical damage caused by a third party* and *fracture/rupture/crack* were responsible for the highest addition of refrigerant mass (at an average of 30 kg per incident).

In the case of *third party damage* to refrigeration systems, although this occurred in less than 0.3% of reported incidents, this was responsible for the greatest refrigerant leakage per incident (i.e. up to 37 kg per incident as shown in Fig. 4). This concurred with a German leak tightness study cited by Bostock (2007) which also reported that catastrophic losses accounted for a very large proportion of the total refrigerant losses. Faults identified as *fracture/rupture/cracks* required refrigerant mass additions of on average approximately 32 kg per incident, which accounted for the second largest leakage quantity per incident.

The *leaking seal/gland/core* faults for the present study which refer to leaks from valves and *pipe or joint failure* faults were responsible for refrigerant mass additions per incident of on average 30 kg and 26 kg, respectively (see Fig. 4 for details). These results were similar to those of the study presented by Colbourne (2004), as cited by Rhiemeier *et al.*, (2009) whereby pipework (mechanical joints) and valves (general) accounted for 50.3% of the total quantity of leaked refrigerant. Therefore, as expected, these types of leaks were both frequent and had a high leakage rate.

In contrast, the faults of *loose item/cap/seal* and *vibration* indicated a low frequency of less than 0.5%, which accounted for a total of 0.45% of refrigerant mass leaked in the data sample considered here. This differed from the results of a US study presented by Hoglund (2006) in which mechanical wear (i.e. loose-fitting, damaged, or worn gaskets, worn packing, missing gaskets, and missing caps) and vibration were more prevalent, and resulted in 86% of the mass of the refrigerant leaked (as cited by Rhiemeier *et al.*, 2009). Despite the low frequency and relatively low overall contribution to the total refrigerant mass leakage for *loose item/cap/seal* and *vibration* found in this study, in instances where they occurred, these faults resulted in significant leakage mass per incident, of 26 kg and 16 kg, respectively (see Fig. 4 for details). The difference in the results between the present study and Hoglund's study may be due to the different methods of categorization used. For example, *loose fittings* in Hoglund's report included Schrader caps, rotalock valves, service port caps etc., which have been included in the *leaking seal/gland/core* fault category in the present report. If the *leaking seal/gland/core* contribution is included with the *loose item/cap/seal* and *vibration*, then the total refrigerant mass addition increases to 26% of the total for the present study, although this is still much lower than that reported by Hoglund (2006).

4.2 Fault Location in RACHP Systems

Fig. 5 categorizes the fault locations at the system level (i.e. 6 main regions and unspecified location) and indicates that in 611 of the 1,464 faults reported, the record failed to clearly identify the fault location at the system level. The highest number of faults (471) for which a location was identified, were concentrated in the compressor pack followed by the high pressure (HP) liquid line and evaporator. This same trend was observed in the analysis of the total refrigerant mass added for each system level, resulting from a fault in a specified location. The lowest number of faults and mass of refrigerant added (i.e. 2 and 26 kg) were reported for the HP gas pipeline.

Information on the manufacturers/suppliers of the refrigeration systems for Company A and B were not provided to the authors in the study. Hence it was difficult to determine whether there was a correlation between the fault location/category and the supplier. However, it should be noted that the results recorded for the fault locations at system level were consistent with those reported in the US study presented by Hoglund (2006), as cited by Rhiemeier *et al.* (2009), whereby the mechanical service room, which houses the compressor, experienced the largest refrigerant mass losses (56%). Hoglund also highlighted that display cases, condensers, and store piping provided many refrigerant leakage reduction opportunities. Display cases, condensers, and store piping are accounted for in the evaporators, remote condenser and HP liquid line system level boundaries in the present study, respectively. Similarly, the US EPA (2011) indicated that 39% of sources of leakage for a regional supermarket chain in the US were located within the compressor pack which agrees with the present study.

The high number of faults in the compressor pack relative to other system components is of particular concern. It is likely that the faults within the compressor pack can be attributed to the continuous vibration and significant fluctuations in temperature and pressure during the on/off cycling of the compressor. It is possible that the design of the compressor pack could be improved, making it more resilient to leakage at the relevant locations. However, further investigation is required to identify the root causes of the faults at these locations.

4.3 Impact of Individual Stores

Fig. 6 shows the distribution of leaks per store for 257 stores and illustrates that a small number of stores leak a large amount of refrigerant. Therefore, it is considered that standardization of best practices of leakage control measures across multiple chain stores would be advantageous.

5. LONG TERM SOLUTIONS FOR LEAKAGE CONTROL

Long-term joint venture relationships between the equipment owners and their service organisations to undertake proactive maintenance is a reasonably effective leakage control strategy. One supermarket company in the UK, has demonstrated over a 14-year period that through employing best practices, refrigerant leakage rates were effectively reduced from 54% to 8% (Cowan *et al.*, 2015). Similarly, there has been good progress in reducing refrigerant emissions, as a result of the contribution of regulatory, fiscal, and voluntary agreements and initiatives, as well as through technological developments (Cowan *et al.*, 2014).

Zieger *et al.* (2014) suggested that developing countries have the chance to leapfrog the adoption of high GWP HFCs and switch from their current predominantly HCFC refrigerants to new climate-friendly substances and technologies, both in the short and medium term. Several alternative refrigerants have been proposed however the adoption of these new refrigerants has not been mainstream due to issues such as flammability and relative under performance (Mota-Babiloni *et al.*, 2015b). Leakage minimization will therefore continue to be an essential strategy in reducing overall emissions in the RACHP sector. Hence, the achievements made in controlling refrigerant leakage in industrial countries such as the Dutch STEK and REAL projects should be instrumental and immediately applicable in driving change in other countries. Moreover, leakage prevention is important with all refrigerants for a range of reasons discussed earlier. The likelihood of refrigerant loss in refrigeration systems is inevitable; therefore other long term solutions are required in the industry to effect change.

In addition to good housekeeping practices in reducing refrigerant leakage, manufacturers of RACHP systems and equipment installers also have a role to play in leakage prevention. Analysis of this type, along with further investigation into the problematic components identified in the study as prone to leakage is recommended. It is considered that the findings can be used to influence and modify common practices in equipment design, installation and maintenance within the industry. This is also being encouraged by recent legislation such as the EU F-gas regulations.

6. CONCLUSIONS

To ensure a sustainable future, the adoption of climate friendly (low GWP) alternative refrigerants will be essential for the RACHP industry. However, the benefits of continuous refrigerant leak control measures can be realised worldwide and is effective immediately. Similarly, given that refrigerant demand is set to increase, manufacturers, equipment installers and service technicians also have a role to play in providing a long term solution for leakage prevention to effect change in the industry. This paper presents the results of a refrigerant leakage analysis for two of the UK's major supermarket chains. The analysis was aimed at providing a better understanding of common leaking components and exploring ways to reduce these faults. The investigation showed that the most common faults are *pipe or joint failure* and *leaking seal/gland/core,* which agreed with the findings from previous studies. These faults were predominantly found within the compressor pack and HP liquid line. It is recommended that further research into developing leak tight design, installation and maintenance of refrigeration system components that frequently develop faults should be conducted. In contrast, third party physical damage to refrigeration systems is responsible for the greatest leak per incident, although in terms of number of incidents, it is relatively rare. The current research also illustrated that it is common practice to recharge refrigeration systems without identifying leaks or faulty components. Ten percent of the total refrigerant added by weight was used to recharge refrigeration systems without explanation. In several such incidents, it was reported that no leak was found, or another fault was identified. It is important that ongoing leak checks are recorded accurately, so that other technicians can follow-up appropriately on measures from previous checks.

REFERENCES

Bauer, C., Treyer, K., Heck, T. and Hirschberg, S. (2015) Greenhouse Gas Emissions from Energy Systems, Comparison, and Overview, in: *Reference Module in Earth Systems and Environmental Sciences*. [Online]. DOI: 10.1016/B978-0-12-409548-9.09276-9 [Accessed 25 June 2016].

Beshr, M., Aute, V., Sharma, V., Abdelaziz, O., Fricke, B. and Radermacher, R. (2015) A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerants, *International Journal of Refrigeration*, 56, pp. 154–164. [Online]. DOI:10.1016/j.ijrefrig.2015.03.025 [Accessed 05 June 2016].

Birndt, R., Riedel, R. and Schenk, J. (2001) *Tightness of commercial refrigeration system.* Research project commissioned by the FORSCHUNGSRAT KÄLTETECHNIK (Research Council for Refrigeration Technology), ILK Dresden, Germany, [Online]. Available from: http://www.fluorocarbons.org/uploads/Modules/Library/tightness-commercial-refrigeration.pdf [Accessed 05 March 2016].

Bostock, D. (2007) Designing to minimise the risk of refrigerant leakage, in: *Proceedings of the Institute of Refrigeration (IOR) Annual Conference on Carbon Footprint*: One Step Beyond., London, 29th November, 2007. London: IOR, pp.1-11.

Coulomb, D. (2008) Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment, *Trends in Food Science & Technology*, 19 (8), pp. 413–417. [Online]. DOI:10.1016/j.tifs.2008.03.006 [Accessed 05 June 2016]

Coulomb, D., Colombo, I. and Boubacar, S. (2015) *28th IIR informatory note on refrigeration technologies: qualification and certification of refrigeration technicians*. Paris: International Institute of Refrigeration.

Cowan, D., Chaer, I., Lundquist, P., Maidment, G., and Coulomb, D. (2014) *24th informatory note on refrigeration technologies: containment of refrigerants within refrigeration, air conditioning and heat pump systems*, Paris: International Institute of Refrigeration. [Online]. Available from: http://www.cni-instaladores.com/volcado/Mailing/Note_24_EN.pdf [Accessed 05 March 2016]

Cowan, D., Maidment, G., Churchyard, B. and Bonner, J. (2015) Maintenance and long term operation of supermarkets and minimizing refrigerant leakage, in: Evans, J.A. and Foster, A. M. (eds.) *Sustainable Retail Refrigeration*. West Sussex: John Wiley & Sons, Ltd., pp. 229–262.

Davis L. W. and Gertler P. J. (2015) Contribution of air conditioning adoption to future energy use under global warming, in: *Proceedings of the National Academy of Science of the United States of America*, 112 (19), pp.5962–5967. [Online]. DOI: 10.1073/pnas.1423558112 [Accessed 05 March 2016]

Deol, B., Andersen, S. O., Chaturvedi, V., Jaiswal, A. and Dilley, S. M. (2015) *Amending the Montreal Protocol - summary of amendment proposals and discussion of key components to phasing fown HFCs* (Draft Discussion Paper). National Resources Defense Council. [Online]. Available from:

http://conf.montreal-protocol.org/meeting/mop/mop-27/pubs/Observer%20Publications/AmendingtheMontrealProtocol.pdf [Accessed 4 March 2016]

Devotta, S., Sicars, S., Agarwal, R., Anderson, J., Bivens, D., Colbourne, D., Hundy, G., König, H., Lundqvist, P., McInerney, E., Nekså, P. and El-Talouny, A. (2005) Refrigeration in Calvo, E. and Elgizouli, S. *IPCC/TEAP special report: safeguarding the ozone layer and the global climate system: issues related to hydrofluorocarbons and perfluorocarbons.* Nairobi: Intergovernmental Panel on Climate Change and Montreal Protocol's Technology and Economic Assessment Panel (IPCC/TEAP). [Online]. Available from: http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf [Accessed 5 March 2016]

EFCTC- European Fluorocarbons Technical Committee (2011) *The Dutch model: A reduction of emissions from over 20% to 3.5% on average*. STEK (Stichting Emissiepreventie Koudetechniek). [Online]. Available from: http://www.fluorocarbons.org/uploads/documents/figaroo/Case_Study_The_Netherlands_4938.pdf [Accessed 3 March 2016].

ETSU, (1997) *Good practice guide 178, cutting the cost of refrigerant leakage.* Oxfordshire: Energy Technology Support Unit (ETSU), Harwell.

European Commission (2016) EU legislation to control F-gases, *Climate Action*. [Online]. Available from:http://ec.europa.eu/clima/policies/f-gas/legislation/index_en.htm [Accessed 3 March, 2016]

Grace, I., Datta, D. and Tassou, S. (2005) Sensitivity of refrigeration system performance to charge levels and parameters for on-line leak detection, *Applied Thermal Engineering*, 25(4), pp. 557-566. [Online]. DOI: 10.1016/j.applthermaleng.2004.07.008 [Accessed 5 March 2016]

Gschrey, B., Schwarz, W., Elsner, C. and Engelhardt, R. (2011) High increase of global F-gas emissions until 2050, *Greenhouse Gas Measurement and Management*, 1 (2), pp. 85–92. [Online]. DOI:10.1080/20430779.2011.579352 [Accessed 04 June 2016].

Koronaki, I. P., Cowan, D., Maidment, G., Beerman, K., Schreurs, M., Kaar, K., Chaer, I., Gontarz, G., Christodoulaki, R. I. and Cazauran, X. (2012) Refrigerant emissions and leakage prevention across Europe - results from the RealSkillsEurope project, *Energy*, 45 (1), pp 71-80. [Online]. DOI:10.1016/j.energy.2012.05.040 [Accessed 04 March 2016]

Meurer, C. and Nicoletti A. (2005) Advances in supermarket refrigeration leak reduction, in: *European Conference on Technological Innovations in Air Conditioning and Refrigeration Industry*, Milan, June 18, 2005. [Online]. Available from: http://www.centrogalileo.it/nuovapa/Articoli%20tecnici/INGLESE%20CONVEGNO/XI%20Convegno%20English/1%20SESSIONE/Meurer-Nicoletti%20SOLVAY%20ingl.pdf [Accessed 5 March 2016]

Montzka, S. A., McFarland, M., Andersen, S. O., Miller, B. R., Fahey, D. W., Hall, B. D., Hu, L., Siso, C. and Elkins, J. W. (2014) Recent trends in global emissions of hydrochlorofluorocarbons and hydrofluorocarbons: reflecting on the 2007 adjustments to the Montreal Protocol, *The Journal of Physical Chemistry*, 119 (19) pp.4439-4449. [Online]. DOI: 10.1021/jp5097376 [Accessed 05 March 2016]

Mota-Babiloni, A., Navarro-Esbrí, J., Barragán-Cervera, Á., Molés, F., Peris, B. and Verdú, G. (2015a) Commercial refrigeration – An overview of current status, *International Journal of Refrigeration*, 57, pp. 186–196. [Online]. DOI:10.1016/j.ijrefrig.2015.04.013 [Accessed 25 June 2016].

Mota-Babiloni, A., Navarro-Esbrí, J., Barragán-Cervera, Á., Molés, F. and Peris, B. (2015b) Analysis based on EU Regulation No 517/2014 of new HFC/HFO mixtures as alternatives of high GWP refrigerants in refrigeration and HVAC systems, *International Journal of Refrigeration*, 52, pp. 21–31. [Online]. DOI:10.1016/j.ijrefrig.2014.12.021[Accessed 25 June 2016].

REAL-Refrigerant Emissions and Leakage Skills for Europe (2016), *REAL alternatives.* [Online]. Available from: http://www.realskillseurope.eu/home [Accessed 28 June 2016]

Rhiemeier, J., Harnisch J., Ters C., Kaufield, M. and Leisewitz, A. (2009) *Comparative assessment of the climate relevance of supermarket refrigeration systems and equipment*. Environmental Research of the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety. Research Report 206 44 300 UBA-FB 001180/e. Dessau-Roßlau: Federal Environment Agency. [Online]. Available from: http://www.epa.gov/sites/production/files/documents/ubastudy_supermarkets.pdf [Accessed 5 March 2016].

Söğüt, M. Z. (2015) Investigation of environmental effects based on exergetic irreversibility for Display Cases' Units in Commercial Cooling, *International Journal of Green Energy*, 12, pp. 15–22. DOI:10.1080/15435075.2014.889002 [Accessed 25 June 2016].

Tassou, S. A. and Grace, I. N. (2005) Fault diagnosis and refrigerant leak detection in vapour compression refrigeration systems, *International Journal of Refrigeration*, 28 (5), pp.680-688. [Online]. DOI: 10.1016/j.ijrefrig.2004.12.007 [Accessed 4 March 2016]

UNEP (2014) *Low-GWP alternatives in commercial refrigeration: propane, CO_2 and HFO case studies.* Paris: United Nations Environment Programme (UNEP) Division of Technology, Industry and Economics (DTIE) and Climate and air coalition to reduce short-lived climate pollutants (CCAC). [Online]. Available from: http://www.ccacoalition.org/en/resources/low-gwp-alternatives-commercial-refrigeration-propane-co2-and-hfo-case-studies [Accessed 28 June 2016].

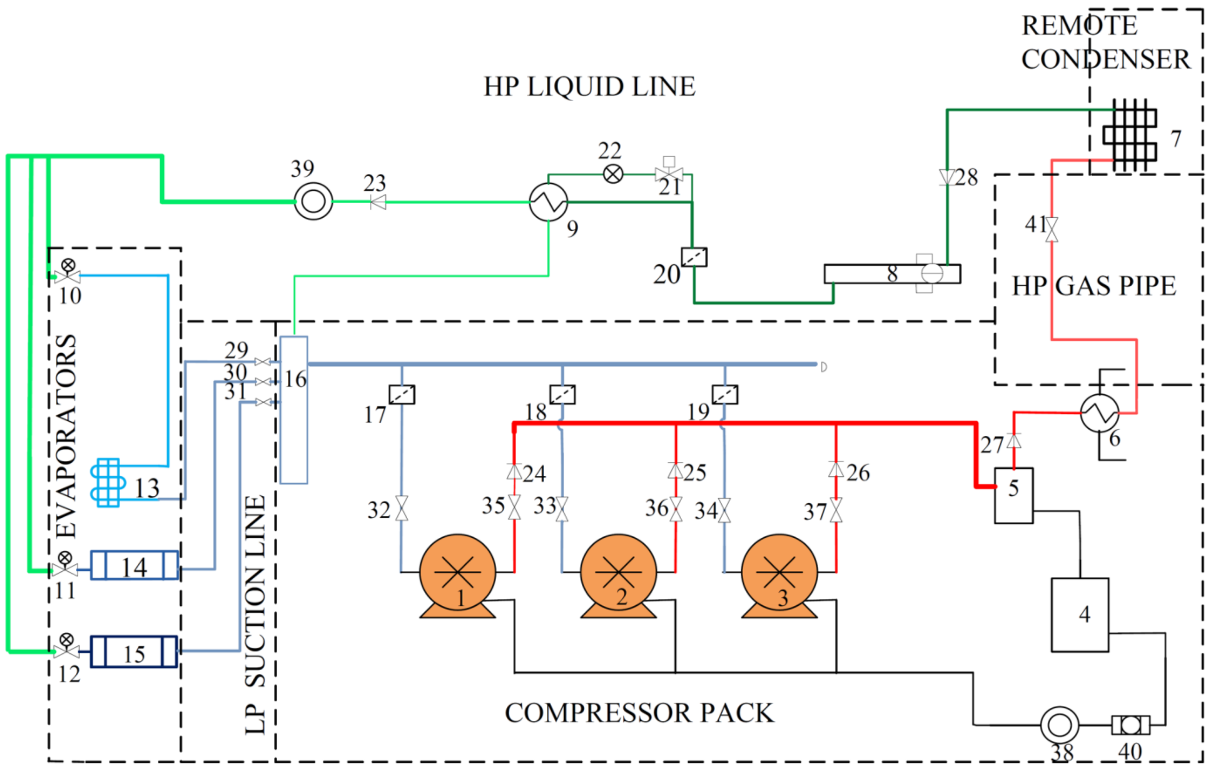
US EPA - Environmental Protection Agency (2011) *GreenChill best practices commercial refrigeration leak prevention and repairs*.(No. EPA 430-B-11-001). US Environmental Protection Agency GreenChill Advanced Refrigeration Partnership. [Online]. Available from: http://www2.epa.gov/sites/production/files/documents/GChill_LeakTightEquipInstall.pdf [Accessed 05 March 2016].

US EPA - Environmental Protection Agency (2015a) *Protection of stratospheric ozone: change of listing status for certain substitutes under the significant new alternatives policy program; final rule* (Federal Register No. Vol. 80 No. 138). United States Government Publishing Office. [Online]. Available from: https://www.gpo.gov/fdsys/pkg/FR-2015-07-20/pdf/2015-17066.pdf [Accessed 4 March 2016]

US EPA - Environmental Protection Agency (2015b.) *Factsheet - prioritizing leak tightness during commercial refrigeration equipment installation.* [Online]. Available from: http://www.epa.gov/greenchill/fact-sheet-prioritizing-leak-tightness-during-commercial-refrigeration-equipment [Accessed 4 March 2016].

Zeiger, B., Gschrey, B. and Schwarz, W. (2014) *Alternatives to HCFCs/HFCs in developing countries with a focus on high ambient temperatures*. Frankfurt: Öko-Recherche.[Online]. Available from: http://ec.europa.eu/clima/policies/f-gas/legislation/docs/alternatives_high_gwp_en.pdf [Accessed 5 March 2016].

Fig. 1 - Refrigeration system schematic partitioned to show potential leakage points



1-3.Compressor	13. Evaporator-Low Temp. Chiller	23-28. Non-Return Valve
4.Oil Reservoir	14. Evaporator-Med. Temp. Chiller	29-31. Evaporator Pressure Regulators
5.Oil Separator	15. Evaporator-Cold Store	32-34. Compressor Suction Valve
6.Desuperheater	16. Suction Header	35-37. Compressor Discharge Valve
7.Condenser	17-19. Suction Filter	38-39. Sight Glass
8.Liquid Receiver	20. Liquid Line Filter Drier	40. In-Line Filter
9.Liquid Subcooler	21. Solenoid Valve	41. Shut Off Valve
10-12.Thermal Expansion Valve	22. Thermal Expansion Valve	

Fig. 2 - Comparison of refrigeration system fault types for two companies

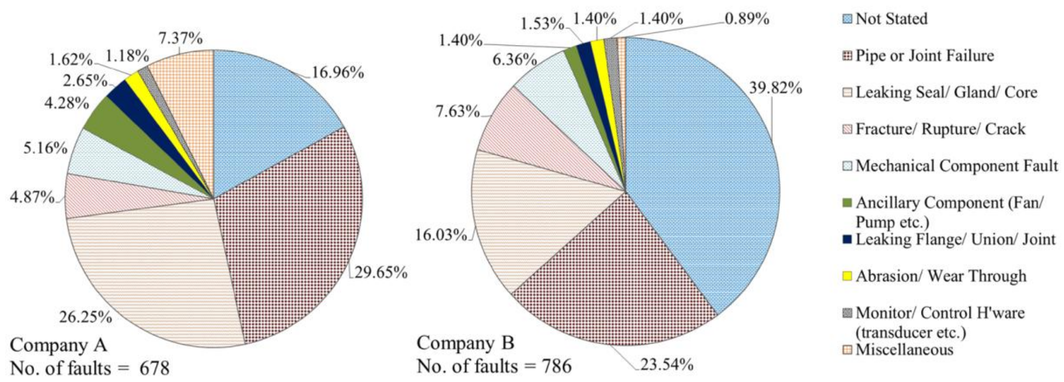


Fig. 3 - Percent of total refrigerant added by mass (in response to a particular fault category) for both companies (total refrigerant added = 35, 808.18 kg)

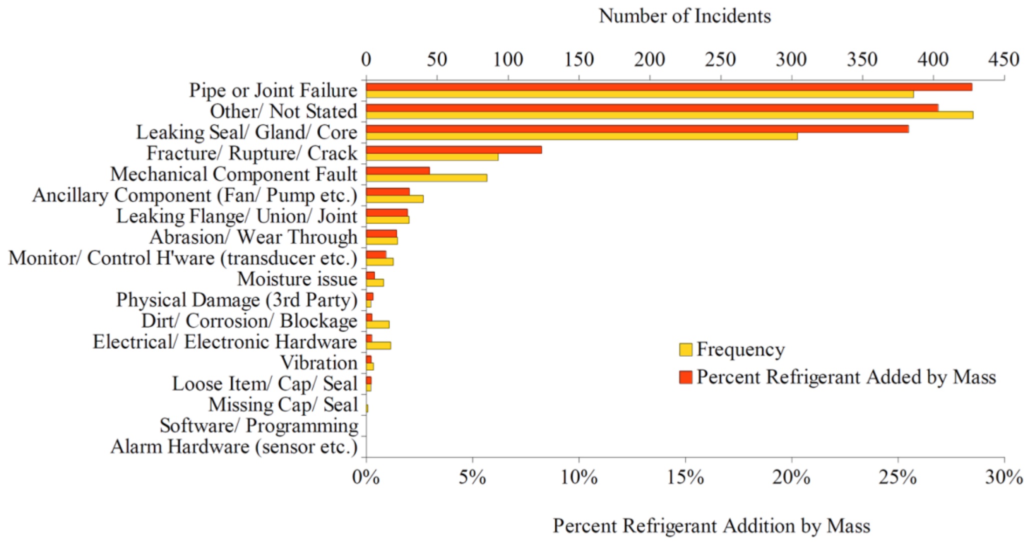


Fig. 4 - Refrigerant addition per incident (by fault category) (kg) for both companies ("other/ not stated" faults not included)

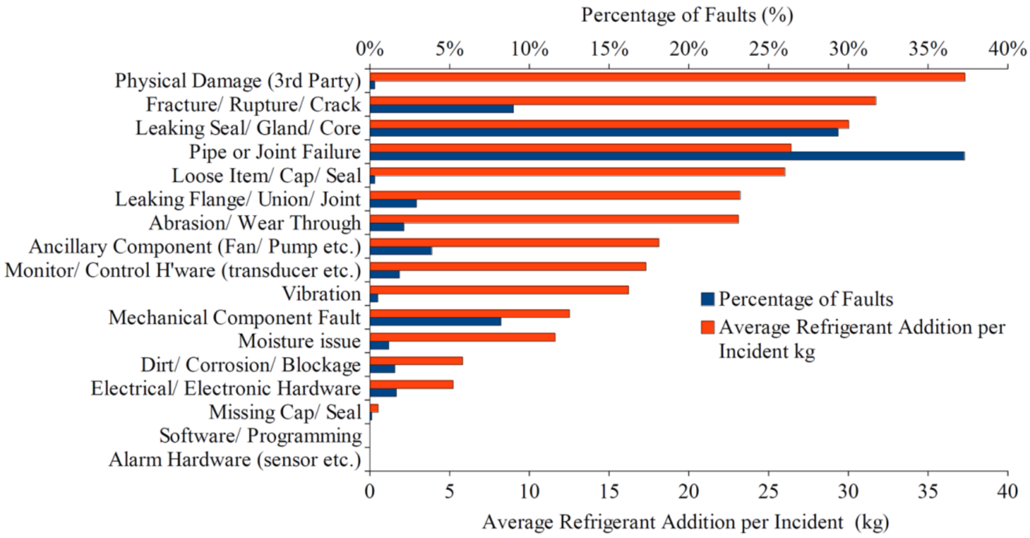


Fig. 5 - Frequency of faults and total refrigerant added at system level fault location for both companies

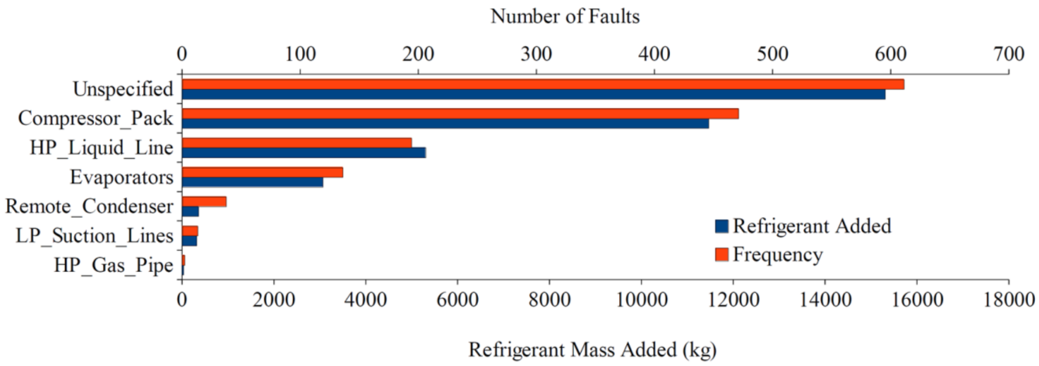


Fig. 6 - Recorded leakage and frequency of leakage for a range of stores