Technical Assistance to Plotter-Racks to Develop a Modular Chiller using the R-290

First Deliverable: Report of Assessment and Analysis

Task1: Assessment of similar products and cases in Europe and U.S. using propane as a refrigerant fluid for modular chillers in centralized refrigeration systems, including the safety strategies for each product and analyse the performance of equipment compared to: HCFC (R-22), HFC (R-404A, R-134a, R-410A).

By

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Report Submitted to

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In partial fulfilment of the duties for the TOR "Expert on modular chiller, based on R-290, for commercial refrigeration equipment"

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1 Introduction

Propane, a naturally occurring substance, is produced as a by-product from oil refineries. It is currently used in many applications as a fuel source; but has also been recently extended for use in domestic refrigerators and freezers and small commercial refrigeration and freezing application. Figure 1 depicts the molecular structure of propane which is a sustainable and green refrigerant since it has significantly lower global warming potential (GWP) of only 3, zero ozone depletion potential (ODP), and results in superior efficiency over baseline refrigerants. The main challenge when using propane as a refrigerant is its high degree of flammability. As such, it is critical that proper health and safety measures are followed during the design, manufacturing, and installation of propane containing systems to minimize the deflagration hazards and maintain peak performance over its lifetime. The terms “propane”, “HC-290”, and “R-290” are used interchangeably to describe the refrigerant propane used in vapor compression in systems.

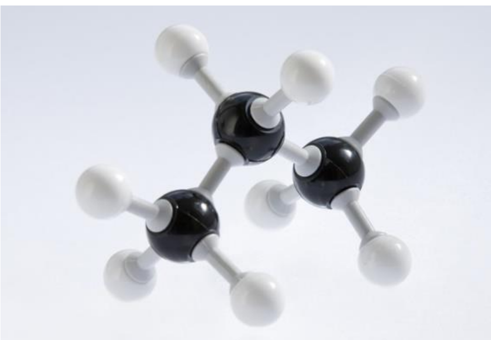

Figure 1: Propane Molecule

R-290 has a similar vapor pressure performance to that of HCFC-22 (R-22) as shown in Figure 2; especially below freezing conditions. Overall, it tends to have smaller vapor pressure at the same saturation temperature compared with R-22. On the other hand, R-290 is shown to have a consistent 15% loss in volumetric capacity compared to R-22 as shown in Figure 3. Furthermore, ideal thermodynamic vapor compression cycle simulation shows similar energy efficiency to R-22. R-290 is largely compatible with materials commonly used in the construction of refrigeration and air conditioning equipment. It is widely available and relatively inexpensive. It is typically stored and transported in steel cylinders. R-290 used in vapor compression systems should comply with the required purity and moisture contents as per the AHRI standard 700[1] are:

- 99.5% by weight Minimal nominal composition
- 2% by weight maximum impurities (C_3 and C_4 saturated hydrocarbons are only allowed)
- 1.5% by volume at 25°C maximum air and non-condensable gases
- 10 mg/kg moisture content

[1] http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_700-2016_with_Addendum_1.pdf

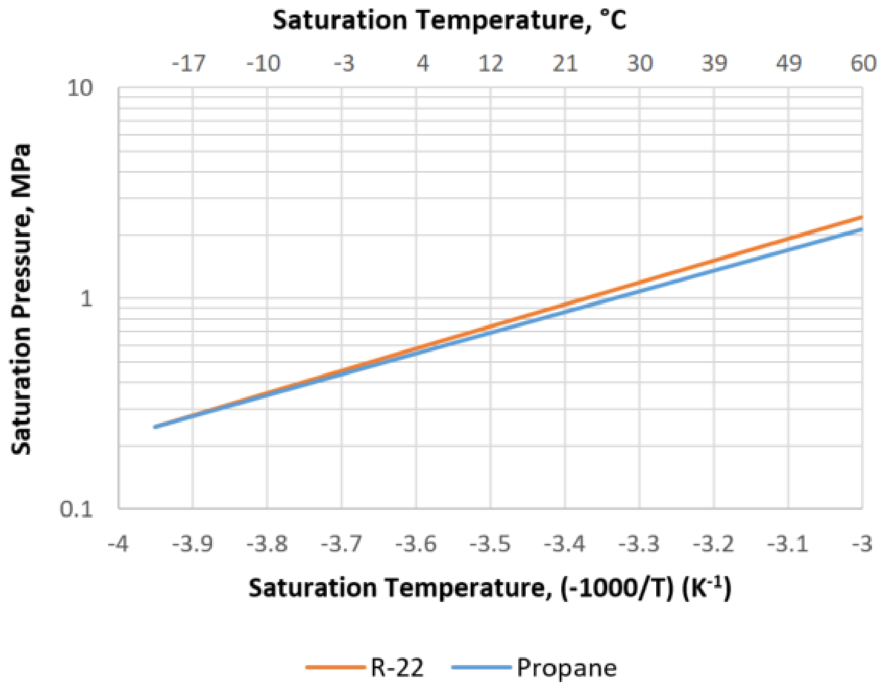

Figure 2: Saturation Pressure - R-22 versus Propane

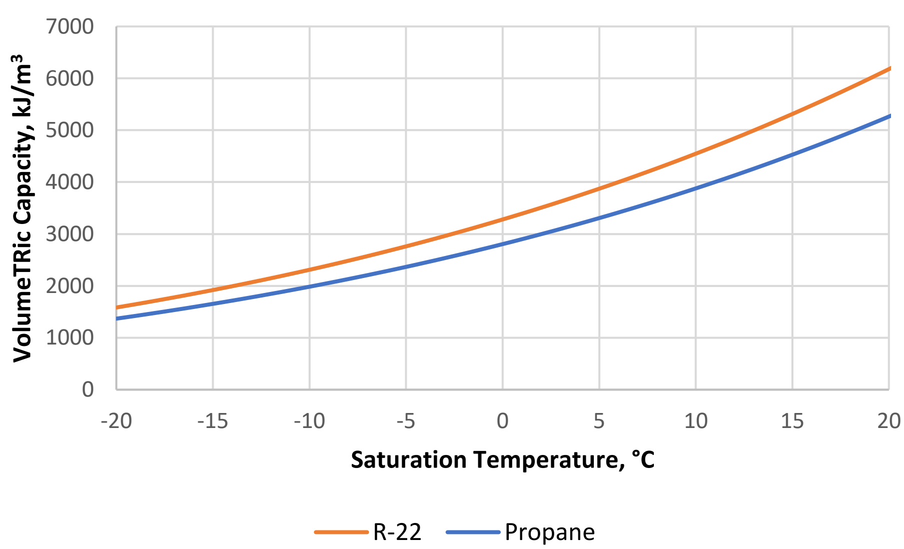

Figure 3: Volumetric Capacity: R-22 versus Propane

Additional comparison between R-290 and R-22 properties is illustrated in Table 1.

Table 1: Comparison between R-290 and R-22 design properties

Refrigerant	Propane (R-290)	HCFC-22 (R-22)
ODP	0	0.06
GWP	3	1760
Boiling point @ 1 bar	-42°C	-41°C
Critical Temperature	97°C	96°C
Critical Pressure	4.25 MPa	4.99 MPa
Safety Class[2,3]	A3	A1
Lower Flammability Limit (LFL)	2.1% by volume[4]	NA
Upper Explosive Limit (UEL)	9.5% by volume[4]	NA
Autoignition temperature	450°C[4]	NA
Minimum ignition energy (MIE)	0.25[5]	NA
Lubricants	Mineral oil, Alkybenzene, Polyolester (POE), and others	Mineral oil, Alkybenzene

2 R-290 Refrigeration Chiller Design Requirements

R-290 refrigerant chillers should be designed under the following assumptions:

- System is operating in a normal situation;
- System will not be working in an explosive atmosphere;
- System is gas-tight and sealed;
- Commissioning will be performed by experienced, qualified and trained engineers/technicians;
- Risk associated with potential leaks is acknowledged and managed: Explosions may result from a spark produced by an electrical device

The R-290 refrigeration chiller is comprised of conventional and specifically designed components. In general, the heat exchangers, flow accessories[6], and sensors[7] are like those used in conventional chillers. However, the mass control devices such as the compressors and expansion valves need to be properly sized and selected to operate with R-290.

2.1 Design Practices

In general, R-290 chillers should be designed to:

- Minimize charge
- Minimize leakage
    - No mechanical joints

[2] ANSI/ASHRAE Standard 34-2016, Designation and Safety Classification of Refrigerants, 2016, with Addenda, American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 25 West 43rd Street, 4th Floor, New York, New York 10036 U.S.A., 1791 Tullie Circle N.E., Atlanta, GA 30329, U.S.A.
[3] ISO 817:2014, Refrigerants -- Designation and safety classification, 2014, ISO.
[4] http://www.refrigerants.com/pdf/SDS%20R290%20Propane.pdf
[5] https://www.jraia.or.jp/english/side/presentation3.pdf
[6] Such as filter driers, sight glasses, check valves, safety valves, shut-off valves and solenoid valves
[7] Such as pressure switches and thermistors

    - Leak check before charging
- Manage risks associated with potential refrigerant leaks
    - Leak detection and control system
    - Ability to pump down the propane charge into a liquid receiver when leak detection is activated
    - Ability to shut off the electrical supply to the chiller when sufficient charge is within the liquid receiver
    - Ability to ventilate the compressor enclosure using EU ATEX[8] – certified ventilation fan
- Compressors:
    - Electric components fitted to the compressor rated at IP54 standard or better
    - Motor winding thermistor housed and wired separately from other electrical components
    - Clearly marked "Attention Fire Hazard"
- Electrical components:
    - Inherently safe
    - Limited risk of spark build-up through adequate earth bonds
- Pressure relief valves: In the case of abnormal operation or in the event of pressure built-up in the system, the abnormally high-pressure gas should be relieved to the low-pressure side of the equipment. Upon further pressure increase, the gas should be relieved using pressure relief-valves to the ambient.
    - Fitted on each refrigerant circuit
    - Mounted close to, but above the liquid receivers
    - If air cooled condensers, should be located above the highest point of each condenser bank circuit, and should be easily accessible and clearly visible from a safe distance
    - Discharge port on the valve must be directed to a safe place, away from any source of ignition – preferably in an upward direction, to prevent pooling
    - Should be able to provide visual alert to the operators in the case of refrigerant release
- Framework:
    - Completely enclose all system pipework and components containing propane
- Labelling:
    - Include refrigerant type and class (flammability)
    - If sold in EU – declaration of conformity with relevant regulations and standards

2.2 Operation Practices

Safe operation of R-290 refrigeration equipment requires that the end user inform the local authority of the location of propane chiller installation, along with the system's relevant health and safety information. It is important to conduct planned maintenance to keep the system working under safe, efficient, and reliable conditions. This requires experienced trained technicians that are certified to work with R-290. And finally, it is recommended to have regular leak checking; once per quarter with record-keeping

[8] Atmosphères Explosibles directive (http://ec.europa.eu/growth/sectors/mechanical-engineering/atex_en)

3 Market Analysis

3.1 Propane Market in USA

The propane market in USA is limited greatly by the EPA SNAP regulation limits, ASHRAE Standard 15, and UL 60335-2-89. The resulting allowable equipment are only small commercial self-contained units with a maximum charge of 150 gm of propane charge. So far, EPA SNAP has not approved the use of R-290 for supermarket refrigeration systems.[9]

Budzar Industries Inc. ((https://www.budzar.com/propane-chillers/) provides customized propane chiller solutions that can be used when authorities having jurisdictions allow. The cooling capacities start at 5 TR (17.6 kW) and the systems employ either reciprocating or screw compressors. These chillers employ stainless steel plate heat exchanger, galvanized steel frame, gas detector and alarm system.

In 2013, Hussmann has provided self-contained display unit to H-E-B supermarket in old Austin, Texas airport site. [10] Furthermore, True Manufacturing has adopted the use of hydrocarbon refrigerants in its product lines including the use of Propane for commercial reach-in and self-contained display cases. [11]

3.2 Propane Market in Europe

The European market has been more focused on establishing reliable alternative refrigerants due to the mandated F-gas regulations. There are several companies that have developed chillers for supermarket refrigeration applications including:

- SRS Frigadon (http://www.srs-frigadon.com/chillers/)
- Futron Eco Cooling Systems (http://futron-gmbh.de/multichiller-en.html; -10°C – 10°C)
- Euroklimat (http://euroklimat.it/scheda-prodotto.php?cat=3)
- Tecno Freddo (http://www.aerrecoldtech.it/listit2catalogoeng/perseo-series/81.html)
- Frigopol (http://www.frigopol.com/en/referenzen/fluessigkeitskuehlsatz-28-127-mit-natuerlichem-kaeltemittel-propan/, http://www.frigopol.com/wp-content/uploads/MA-041-01-Fluessigkeitskuehler-luft-R290-englisch.pdf) [12]
- Felzer (http://felzer.lv/storage/Leaflets/Felzer_R290_v201710_ENG.pdf)
- Teko (https://teko-gmbh.com/en/products/rack-units/ransta/) (company is no longer working with propane)

On the other hand, there are several other companies that focused their product development for propane chillers for comfort cooling applications; including:

- Cool-Therm (https://www.cooltherm.co.uk/propane-chillers)
- Bundgaard Refrigeration (http://www.bundgaardref.com/portfolio/awc1s/)
- Hitema (http://www.hitema.com/standard-products/propane)
- Geoclima https://www.geoclima.com/v-range/

[9] https://www.epa.gov/snap/substitutes-typical-supermarket-systems
[10] http://www.hussmann.com/en/Press%20Releases/Hussmann_H-E-B_Propane_072513.pdf
[11] https://www.truemfg.com/AboutUs/Natural-Refrigerant
[12] http://www.eurammon.com/sites/default/files/attachments/09_eurammon_symposium_2017_herunter_dujardin_f3.pdf

- York (JCI, chiller in Denmark)[13]

And finally, there are some speciality companies that have developed propane chillers for marine and transport applications such as Heinen & Hopman (https://heinenhopman.com/en/merchant/carrier/carrier-air-conditioning/propane-chiller/)

3.3 Safety Features and Performance Characteristics from Relevant OEM

Based on the information provided above, the OEMs were further surveyed to understand the applicable safety features employed in their systems along with the performance characteristics of the various designs when available. Table 2 below summarises the safety features and performance characteristics for the different systems.

Table 2: R-290 systems' safety features and performance characteristics from relevant OEMs

OEM	System type	Safety features	Performance characteristics
SRS Frigadon	Air to water/ brine	Compliant to the following Standards: • EC 98/37/CE machinery • EC low voltage directive 73/23/EEC • EC machinery directive 91/368/EEC of 20th June 1991 • Elinstallationsreglerna SS 4364000, Starkströmsföreskrifterna, ELSÄK-FS 2004:1 • EN 378-2 Specification for refrigerating systems and heat pumps • IEC 60079-15 Electrical Apparatus for Explosive Gas Atmospheres • PED pressure equipment directive 97/23/EEC • Svensk Kylnorm, last update from date of issue • Svenska Elektrotekniska Normer, Svensk Standard SS-EN 60 204-1, of 21 May 2007 • Tryckbärande anordningar AFS 1999:4	R-290, @32°C ambient and water supply/return 6°/12°C: 132 kW, EER = 2.72 R-290, @32°C ambient and water supply/return 6°/12°C: 198 kW, EER = 2.73 R-1270, @32°C ambient and water supply/return -6°/-2°C: 110.4 kW, EER = 2.12 R-1270, @32°C ambient and water supply/return -2°/-6°C: 165.6 kW, EER = 2.12
Futron Eco Cooling Systems	Water to water/ brine	Flammable refrigerant detector Ex-rated ventilation system Gas-tight enclosure All fittings are brazed to avoid leakage	NA Cold generator from -10 to 10°C
Euroklimat	Air to water/ brine	R-290 leak detector with built-in alarm level and LED status indicator ATEX certified compressor, EC fan, electrical cabinet resistant to refrigerant leakage ingress Safety interlock system to avoid water/brine freeze	R-290, @46°C ambient and water supply/return -8°/-4°C: 61 kW, EER = 2.0 R-290, @46°C ambient and water supply/return -8°/-4°C: 130 kW, EER = 1.7

[13] http://hydrocarbons21.com/news/view/2782 accessed May 28th, 2018

OEM	System type	Safety features	Performance characteristics
Tecno Freddo	Air to water/ brine	Special gas detector for flammable gases;[14] pressure switches; pressure relief valves, extraction fan ATEX certified compressor, EC fan, Microchannel HX to minimize charge	@ ambient of 30°C[15] -4/-8°C (Brine chiller) Cooling capacity: 22 – 200 kW EER: 2.5 to 2.7
Frigopol	Water to water/ brine and Air to water/ brine	Gas detection system Isolating machine room from electric cabinet Dedicated exhaust air stream depending on installation location Blow-out pipe for safety relief valves	Chiller Range from 20 to 250 kW Temperatures: Brine or water -10°C to +15°C Heat rejection water 30°C to 60°C 1 or 2 ref. circuits
Frigopol and Alpiq	Air to water/ brine	Gas detection system Isolating machine room from electric cabinet	Capacity from 40 to 350kW for Glycol from +6°C to -15°C
Felzer	Water to water/ brine and Air to water/ brine	Refrigerant leak detector in the unit to detect the leakage ATEX sensors, switches and other critical equipment to prevent sparks Fan (ATEX on indoor) for ventilation of the leaked gas from the unit to the duct Safety valve piping to evacuate refrigerant in case of overpressure	NA for medium temperature refrigeration, see http://felzer.lv/storage/Leaflets/Felzer_R290_v201710_ENG.pdf for further details.

4 Case Studies for Performance Comparisons

In this section, we introduce several case studies where propane is used as a replacement refrigerant for the incumbent technology either based on drop-in or when complete equipment changeover was made.

4.1 Low-Lift Chiller Application[16]

Two Waitrose stores are compared. The stores have similar size and load and employ a system chiller that provide chilled water as the condenser medium for the in-store propane integral cases. As such, the chillers are low-lift. One of the stores had the R-134a chillers retrofitted to use R-1234ze(E) while the other store employed propane as the refrigerant for the low-lift chillers. The comparisons revealed that the R-1234ze(E) chillers consumed 22% less energy than the propane chillers.

[14] http://www.aerrecoldtech.it/uploads/Documentazione_ENG/R290%20AIR%20COOLED%20WATER%20CHILLER-%20General%20Description.pdf

[15] http://www.aerrecoldtech.it/uploads/Documentazione_ENG/R290%20AIR%20COOLED%20WATER%20CHILLER%20-%20Technical%20data.pdf

[16] Low-GWP Alternatives in Commercial Refrigeration: Propane, CO2 and HFO Case Studies", United Nations Environment Programme, 2014, Publication job number: DTI-1666PA, page 27

4.2 Low Temperature Refrigeration Application (High Lift Application)[17]

Hwang et al. 2005 studied a low temperature refrigeration application in a controlled experimental setup to evaluate the performance of propane, R-404A, and R-410A. the studied system had a capacity of 4 kW and the evaporating temperature was set at -29°C. An adjustable speed scroll compressor, that was originally designed for R-404A, was used to maintain the target cooling capacity when evaluating the different refrigerants. Table 3 summarizes the experimentally evaluated performance using the Compressor that was originally designed for R-404A.

Table 3: Performance as experimentally measured

		R-290	R-404A	R-410A
Full load performance	Capacity, kW	3.7	3.7	3.9
	COP, -	0.88	0.784	0.8
	$COP/COP_{R\text{-}290}$	1	0.89	0.91
Part load	Capacity, kW	4.7	4.9	4.9
	COP, -	1.31	1.24	1.27
	$COP/COP_{R\text{-}290}$	1	0.95	0.97

* adapted from [17]: Table 9 for full load and Table 14 for part load

Table 4 shows the performance when the compressor efficiency is normalized across refrigerants. This case assumes that with proper compressor designs, the compressor isentropic efficiency can be similar for the different refrigerants. It is important to note that the R-290 and R-404A compressor isentropic efficiency obtained from the experimental results were almost identical; hence there was not impact for the normalization; on the other hand, the R-410A isentropic efficiency was much lower; hence there was larger potential for improvement.

Table 4: Performance after normalizing the compressor efficiency

$COP/COP_{R\text{-}290}$	R-404A/R-290	R-410A/R-290
Full load performance	0.9	1
Part load	0.95	0.99

* adapted from [17]: Table 12 for full load and Table 15 for part load

Furthermore, when considering the equipment cost, it was assumed that R-290 would result in a 10% cost premium over HFC refrigerants due to safety requirements. Hence, if the equipment can be designed at the same cost, the 10% cost premium may be used to employ brushless DC motors on condensers and fans and achieve higher efficiency of the HFC refrigerant systems. The result of this

17 http://www.icarhma.org/APP_CONTENT/icarhma/files/MEMBERS/Green%20Report%20Report%20Final%20Lowtemp11-05.pdf

study is shown in Table 5. Finally, when considering the impact of secondary loop and the parasitic power required to pump the glycol, the final performance comparison is shown in Table 6.

Table 5: Simulated results based on equal first cost and compressor efficiency

COP/COP_{R-290}	R-404A	R-410A
Full load performance	0.97	1.08
Part load	1.03	1.07

Table 6: Simulated results based on the secondary loop for the R-290 system and equal compressor efficiency

COP/COP_{R-290}	R-404A	R-410A
Full load performance	0.97	1.08
Part load	1.05	1.11

4.3 Comparisons Propane Versus HCFC-22 in Milk Processing Facilities[18]

This case study focused on milk cooling chiller applications, with chilled water produced at 2°C. in the first installation the HCFC-22 used 440 kW/day, while the HC-290 system consumed only 287 kW/day, resulting in a net electricity savings of 35%. In the second installation a net savings of 38% was achieved. However, further installation throughout Indonesia showed energy savings ranging from 13% to 37% depending on the baseline and location of the unit.

4.4 Other examples of HC refrigerant retrofits in existing large systems[19]

In this study, Taylor and Ong devised a conversion procedure to retrofit existing equipment with HC. This included:

- Introduction of concept
- Equipment diagnosis survey and report
- Safety audit
  - In open rooftop installation leak detectors were not required as determined by the Singapore Civil Defence Force (SCDF)
  - Safety survey was performed to ensure adequate ventilation, no exposed electrical or fire source in the system vicinity, added proper warning signs and control of access by public, and all electrical components and panel were adequately sealed
- Pre-retrofit repairs and servicing
- Pre-retrofit system and energy consumption monitoring
- Fitting of safety devices

[18] ARYADI SUWONO, 2008, "Conversion of Various HCFC-22 Systems to Hydrocarbon" Natural Refrigerants Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs, Proklima International, Published by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 1st edition: Eschborn, July 2008

[19] LADAS TAYLOR and JACKSON ONG, 2008, "Application of Hydrocarbon Refrigerants in Existing Large Systems" Natural Refrigerants Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs, Proklima International, Published by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 1st edition: Eschborn, July 2008

- Gas leak sensors when the refrigerant charge within the enclosed area fall between the LFL and UEL,
- Detection devices are connected to ventilation fans and alarms

- System conversion (charge optimization included; usually start with R-290 charge = 29.7% of the baseline charge)
- Post retrofit system and energy consumption monitoring
- Conversion report
- Regular service and maintenance – unless client opts for in-house personnel to be trained

A summary of the refrigerant retrofits and conversion performed through the program conducted by Taylor and Ong is shown in Table 7.

Table 7: Refrigerant retrofit summary

System description	Capacity	Savings post conversion from HCFC-22 to HC-290
1. Singapore		
China Classic Pte Ltd (a subsidiary of Far East Organisation).	Five York air-cooled chillers, model: YDAJ98MU7-50PA ~ 700 kW	16.1%
Far East Square Shopping Mall	York 200 TR Water-cooled Recip Chiller	16%
Defence Science & Technology Agency	Carrier 1 hp Air-cooled split unit	16%
Dapenso Building using	Carrier 21 TR Water-cooled Packaged Unit	32%
Watson's Stores using	Daikin Air-cooled Split Unit	24%
The Moomba Restaurant, Boat Quay using	McQuay 8 hp Air-cooled split unit	16%
2. Malaysia		
7-eleven Stores Kuala Lumpur	Topaire Air-cooled Split Unit	24%
Flairis Kota Tinggi	Water-cooled Packaged Unit	19%
Nichicon Bangi recorded	Topaire Water-cooled Packaged Unit	20%
Sumiden Electronics Shah Alam	Topaire Air-cooled Split Unit	22%
Hosiden Electronics Bangi	Air-cooled Split Unit	25%
Alps Electric Nilai	Dunham-Bush Water-cooled Packaged Unit	17%
Panasonic AVC Network Shah Alam	Air-cooled Split Unit	19%
Venture Tebrau I Johor	Dunhan-Bush 65 TR Water-cooled Packaged	47%
Panasonic Communication Senai Johor	National 20 hp Water-cooled Packaged	20%

System description	Capacity	Savings post conversion from HCFC-22 to HC-290
Celestica Electronics Tampoi Johor	Topaires 3 x 80 TR Water-cooled Packaged	24%
Menara Ansar Johor	Carrier 23 TR Water-cooled Packaged	13%
Bangunan PharmaCARE KL	Topaires 26 TR Air-cooled Packaged	23%
Sumitomo Electronics Tebrau II Johor	York 32 TR Water-cooled Packaged	21%
Taiko Electronics Senai Johor	York 21 TR Water-cooled Packaged	20%
GG Circuits Industries Tampoi Johor	Carrier 35 TR Water-cooled Packaged	14.0%
YKJ Industries Kulai Johor	Acson 4 TR Air-cooled Split Unit	27.0%
Tru-Tech Electronics Ulu Tiram Johor	York 20 TR Air-cooled Packaged	19.0%
Matsushita Electric Company Shah Alam	Carrier 35 TR Water-cooled Packaged	15.0%
Menara AmFinance KL	York 21 TR Water-cooled Packaged	16.0%
Li Tat Mfg Masai Johor	York 17 TR Air-cooled Ducted Type Split Unit	29.0%
OYL HQ (R&D Lab)	new 3 TR split units	27.0%
UiTM Shah Alam Campus	Hitachi screw chiller	19.7%
Damansara Realty	Carrier 10 TR Packaged units	32.0%
Pantai Medical Centre Bangsar	York 80 TR Heat Recovery Unit	24.0%
Pantai Medical Centre Bangsar	York Air-cooled Chiller Packaged	18.0%
Lam Wah Ee Hospital Penag	Carrier Water-cooled Packaged	20.0%
Elecan SemiConductor Penang	Air-cooled Packaged	14.8%
Comfort Engineering Puchong	Carrier Air-cooled Packaged	18.5%
Cekap Rea Johor	National Air-cooled Split Unit	16.7%
3. Thailand		
Carrier HQ Building	Carrier 150 TR recip chiller	14%
Two 7-11 stores	split unit and walk-in-freezer	20%
4. Indonesia - Jakarta		
Alfamart 649 stores in Jakarta	air-cooled split units	25%
ITC Mangga Dua	208 TR Carrier recip chillers recorded	35%
JW Marriott Hotel	132 TR York recip chillers	25%
Supermal Karawaci	60 TR Hitachi screw AHU	30%
Mulia Hotel	Copematic 5 TR semi-hermetic comp	13%
Sol Elite Marabella Hotel	1.5 TR Sanyo split unit recorded	24%

System description	Capacity	Savings post conversion from HCFC-22 to HC-290
Maspion Plaza	150 TR York recip chiller recorded 15%	15%
Kondominium Simpruk Teras	10 TR Fair pckg unit	22%
Mal Kelapa Gading	200 TR Carrier recip chillers	28%
Darmawangsa Square	2 TR General split unit	24%
Siloam Gleneagles Hospital	1 TR Mitsubishi split unit	45%
Yayasan Pendidikan Permai	1 TR Gree split unit	22%
5. Indonesia - Bali		
Maya Ubud Resort & Spa		41%
Sahid Jaya Hotel		51%
Ritz Carlton Hotel		28%
Kartika Plaza Beach Hotel		55%
6. Indonesia - Lombok		
Sahid Jaya Hotel		72%
Oberoi Hotel		18%
Novotel Hotel		39%
Lombok Raya Hotel		27%
Sheraton Senggigi Hotel		53%
Senggigi Beach Hotel		36%
Jayakarta Hotel		25%
Intan Lombok Hotel		21%
Holiday Inn Hotel		20%
7. Philippines		
Gaisano Country Mall	50 TR Hitachi Screw Type Compressor	16%
Park Square One (Ayala Mall)	7.5 TR Frascold Semihermetic Reciprocating Compressor	12%
Delsa Chemicals Office	5 TR Maneurop Hermetic Reciprocating Compressor	14%
McDonalds Restaurant	7.5 TR Maneurop Scroll Type Compressor	12%
Legenda Hotel	2 TR Matsushita Rotary Type Compressor	19%
Federal Express (Fedex)	7 TR Copeland Hermetic Reciprocating Compressor	21%
Iglesia ni Cristo Church	3 TR Copeland Scroll Type Compressor	15%
INARP Research Inc.	2 TR Matsushita Rotary Compressor	12%
Building Care Corporation	5 TR Copeland Hermetic Reciprocating Compressor	20%
Mandarin Restaurant	40 TR Century Screw Type Compressor	17%

4.5 Packaged Air-Cooled Chiller

In this comparison between 2 different original equipment manufacturers (OEMs) supplying air-cooled chillers with R-22 and R-290 is provided. The Climatecool R-22 chillers[20] have a large range of capacities from 25 to 185 kW. On the other hand, Cool-therm R-290 chillers[21] are available with either reciprocating or screw type compressors and have capacities ranging from 20 to 755 kW. The performance of both OEM equipment range is summarized in Table 8 below.

Table 8: Summary of the performance comparison between Climatecool R-22 chillers and Cool-therm R-290 chillers when rated at 35°C ambient and water supply/return of 6/12 °C

OEM	Climatecool	Cool-therm	
Compressor technology	Reciprocating	Reciprocating	Screw
Capacity range, kW	25 to 185	20.48 – 616.24	144.8 – 755.2
EER range, W/W	2.94 to 3.04	2.67 – 3.11	2.87 – 3.34

4.6 Packaged Air-Cooled Chiller[22]

Based on data provided by Geoclima srl and Cool-therm[22]; 5 chillers operating with R-290, R-134a, and R-1234ze(E) were compared. The chillers are rated at an ambient temperature of 35°C with water supply/return temperatures of 6/12 °C. The R-290 EER is the lower than R-134a, which is lower than that of R-1234ze(E). However, the seasonal efficiency for the R-290 is similar to that of R-134a. The R-134a and R1234ze(E) chillers operating with magnetic bearing compressors "Turbocor" have significantly higher efficiency than R-290. This performance of the 5 chillers along with the indicative cost is summarized in below.

Table 9: Performance and cost comparison for 417 kW cooling capacity chillers

Refrigerant	R-290	R-134a		R-1234ze(E)	
Compressor type	Screw	Screw	'Turbocor'†	Screw	'Turbocor'†
Power including fans (kW)	152	147	121	121	118
Energy efficiency ratio (EER)	2.74	2.84	3.43	3.27	3.53
Seasonal EER (SEER)	4.6	4.57	5.09	5.15	5.26
Approximate modulation	20-100%	20-100%	0-100%	20-100%	0-100%
Refrigerant charge (kg)	44	82	79	159	76
Refrigerant GWP	3	1,300[23]	1,300[23]	1[23]	1[23]
Length (m)	4.5	4.51	4.51	4.51	4.51
Width (m)	2.25	2.25	2.25	2.25	2.25
Height (m)	2.54	2.54	2.53	2.54	2.54
Weight (kg)	4,498	4,583	3,026	4,629	3,241
Indicative relative capital cost	100%	72%	98%	93%	127%

[20] http://www.sureintl.com/pdf-files/modular_air_cooled_chiller.pdf
[21] https://www.cooltherm.co.uk/uploads/files/R290_docs/CT_Air_Cooled_R290_Chillers.pdf
[22] https://www.cooltherm.co.uk/uploads/files/R290_docs/CIBSE_Propane_R290_CPD.pdf
[23] http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf

†'Turbocor' is a brand name for Magnetic bearing compressor technology

5 Material compatibility[24]

R-290 is compatible with most elastomer and plastic refrigeration materials used as O-rings, valve-seats, gaskets, etc. (e.g. Neoprenes, Vitons, Nitriles, Nylon, HNBR, PTFE), not compatible with PMMAs, EPDM, natural rubbers, and silicone rubbers

Material[25]		R-600a	R-290	R-1270	R-22
Acrylonitrile butadiene styrene	ABS	A	S	S	NR
Cellulose acetate Butyrate	CAB	*	A	S	*
Epoxy	EP	E	E	S	S
Ethyltetrafluoethylene	ETFE	*	S	*	A
Polyamide	PA	*	S	S	S
Polycarbonate	PC	NR	A	S	S
Polyethylene	PE	S	S	A	A
Polyethylene terephthalate	PETP	S	S	*	S
Polyoxymethylene Polyformaldehyde	POM	S	S	S	A
Polypropylene	PP	S	S	S	A
Polyphenylene-oxide	PPO	A	NR	*	*
Polyphenylene-sulfide	PPS	S	S	A	A
Polystyrene	PS	S	S	S	NR
Polyurethane	PUR	S	A	S	*
Polyvinyl chloride	PVC	A	S	A	A
Polyvinyl fluoride	PVF	S	S	S	A
Polysulfone	PSU	S	S	S	NR
Unsaturated polyester	UP	*	S	*	S
Polytetrafluoroethylene	PTFE	S	S	S	A
Polychlorotrifluoroethylene	PCTFE	S	S	S	A, sw
Nitrile Rubber	NBR	S	NR	S	NR
Butyl (isobutene-isoprene) rubber	IIR	S	NR	NR	A, sw
Chloroprene (Neoprene Rubber)	CR	NR	NR	NR	A, sw
Silicone Rubber	VMQ	NR	NR	NR	NR

S: satisfactory; NR: not recommended; A: acceptable; sw: strong swelling; *: no data available

R-290 is compatible with mineral oils (MO), however, they are more soluble than HCFCs and thus may affect the viscosity. Therefore, it is recommended to go with a higher viscosity oil. Oils with silicone and

[24] JÓSE M. CORBERÁN, 2008, "Use of Hydrocarbons as Working Fluids in Heat Pumps and Refrigeration Equipment", Natural Refrigerants Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs, Proklima International, Published by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 1st edition: Eschborn, July 2008

[25] https://us.misumi-ec.com/pdf/tech/mold/p1737.pdf

silicate additives are not compatible. Table 10 below summarizes the oil compatibility for the different refrigerants.

Table 10: Lubricant - Oil Compatibility

Lubricant	HCs	HFCs	R-22
Mineral oil (MO)	Compatible†	Limited compatibility	Compatible
Alkyl benzene (AB)	Compatible†	Compatible	
Mineral oil (MO) + Alkyl benzene (AB)	Compatible	Limited compatibility	
Poly alpha olefin (PAO)	Compatible	Limited	
Polyol ester (POE)	compatible†	Compatible	
Poly vinyl ether	Not compatible	Compatible	
Poly alkylene glycol (PAG)	Limited compatibility‡	Compatible	
Hydro treated mineral oil	Not compatible		

† denote lubricant possibly requiring basic viscosity correction.

‡ denote lubricant that is especially critical with moisture.

6 General Guidelines for Safe Design, Manufacturing and Installation of Hydrocarbon Refrigeration Equipment[26]

Safety is a critical issue to consider during the design, manufacturing, and installation of hydrocarbon (HC) based refrigeration equipment. The system must be leak-tight and sufficiently robust over its lifetime. This can be mainly achieved by limiting mechanical connections. Furthermore, components' safety must be guaranteed while in contact with flammable/explosive atmosphere. Finally, appropriate ventilation and protective systems must be used to manage risk in the event of catastrophic refrigerant leakage.

Technician safety must be ensured by eliminating sources of ignition during installation, servicing and maintenance. This is achieved by developing safe working plans and providing adequate safety training on topics including the awareness of potential flammability/explosion.

6.1 R-290 Refrigerant Classification

According to the ASHRAE 34-2016[2] and ISO 817-2014[3] R-290 is classified as a highly flammable refrigerant. Figure 4 shows the ASHRAE-34 refrigerant safety classification. In this case, A3 denotes a lower toxicity (Occupational Exposure Limit (OEL) > 400 ppm) and higher flammability refrigerant (Burns at explosive speed with high heat of combustion)

[26] Proklima 2010, "Guidelines for the safe use of hydrocarbon refrigerants: A handbook for engineers, technicians, trainers and policy-makers - For a climate-friendly cooling", Published by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 1st edition: Eschborn, September 2010

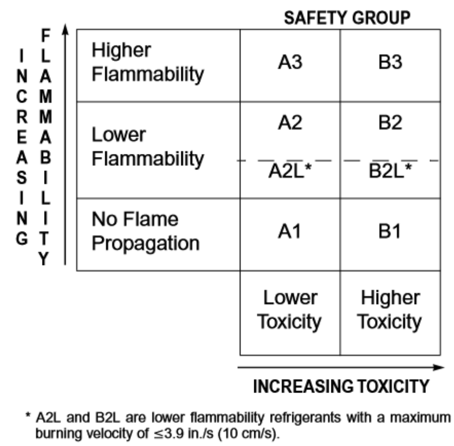

Figure 4: Refrigerant safety group classification[2]

The Practical limit (PL) or the Refrigerant Concentration Limit (RCL) are intended to reduce the risks of acute toxicity, asphyxiation, and flammability hazards in normally occupied, enclosed spaces. They are calculated as the minimum of

- Acute toxicity exposure limit (ATEL)
- Oxygen deprivation limit (ODL)
- 20% of the lower flammability limit (LFL)

In the case of R-290, the RCL is equal to 0.0095 kg/m^3 and is based on the LFL.[2]

For R-290 to form a deflagration or explosion risk, the fire/explosion triangle must be satisfied. Figure 5 shows a generic fire/explosion triangle for HC refrigerants; it requires the availability of fuel (R-290), oxidizer (air), and source of ignition (SOI). In the case of R-290, the triangle requires air, sparks with energy greater than 0.25 mJ, open flames, or hot surfaces with temperatures higher than 450°C. Fire/Explosion triangle

Figure 5: fire/explosion triangle for generic HC refrigerants

6.2 Applicable International Safety Standards

International safety standards concerning HC refrigerants in commercial refrigeration are summarized in Table 11 below:

Table 11: Description of relevant safety standards when operating with HCs

Standard	Title	Application	HC size limit
ISO 5149:2014[27]	Mechanical refrigerating systems used for cooling and heating – safety requirements	All refrigeration, air conditioning and heat pumps; domestic, commercial, industrial	Variable, depending upon application
IEC 60335-2-89:2010[28]	Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant condensing unit or compressor	Any refrigeration appliances used for commercial situations	Up to 150 g
IEC 60079-15:2017[29]†	Electrical Apparatus for Explosive Gas Atmospheres		

† email correspondence with Chris Jennings (SRS-Frigadon). This and additional standards are also listed in Jűrgensen 2008[30]

6.3 Production and Manufacturing Facilities

In a production and manufacturing facility of propane refrigeration chiller, the flammable refrigerant may be present in one of the following areas:

- Refrigerant storage (cylinders or bulk tank)
- Refrigerant pumping and control of supply
- Refrigerant charging areas
- Appliance repair and refrigerant recovery area
- Refrigerant supply distribution pipework
- Other work area (leak checking, electrical safety testing, operation/performance testing, final assembly, packaging areas)

Figure 6 below depicts a typical production process. The process can involve areas where flammable refrigerant is not present such as the component assembly, and strength and tightness test section, and the evacuation section. Once the assembled parts are successfully evacuated, the charging process may begin, and the system becomes filled with flammable refrigerant. In Figure 6 below, the charged system is indicated by green coloured boxes and the areas of the manufacturing facility that require special safety consideration is highlighted in grey.

[27] ISO 5149:2014, "Refrigerating systems and heat pumps – Safety and environmental requirements" (parts 1-4)
[28] EC 60335-2-89:2010/AMD2:2015 Amendment 2 - Household and similar electrical appliances - Safety - Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor
[29] IEC 60079-15:2017 Explosive atmospheres - Part 15: Equipment protection by type of protection "n" https://webstore.iec.ch/publication/33074
[30] HEINZ JÜRGENSEN, 2008, "Propane as an Alternative to R22 for Small Refrigeration Systems at High Ambient Temperatures" Natural Refrigerants Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs, Proklima International, Published by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 1st edition: Eschborn, July 2008

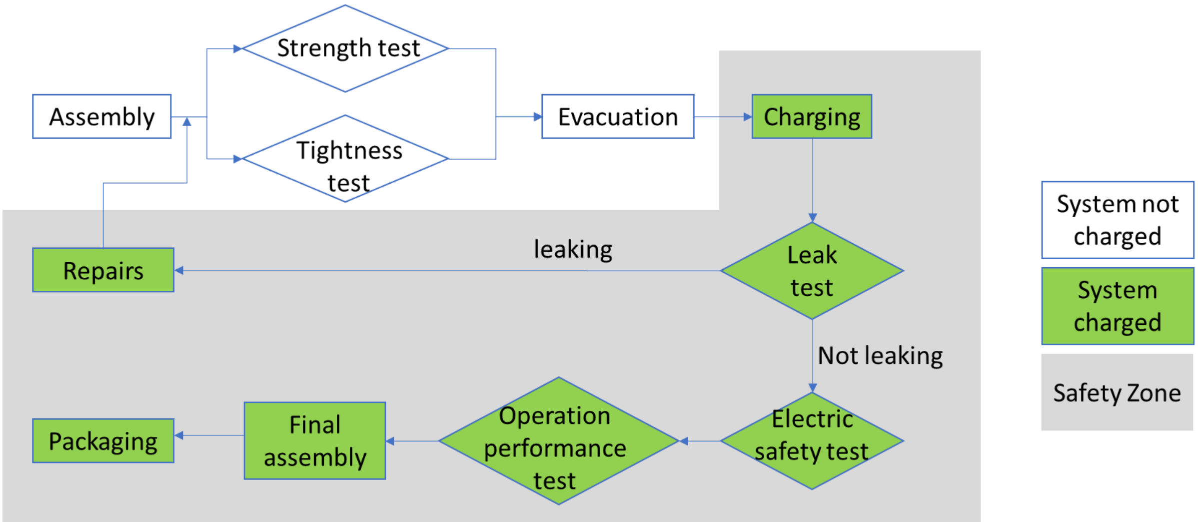

Figure 6: Assembly process

6.4 Refrigerant supply

Refrigerant can be supplied from bulk tanks (1 – 2 tonnes) or cylinders which may be located externally to the production area or within charging machines. Tanks and/or cylinders require inspection and maintenance that is mostly arranged by the refrigerant supplier.

Refrigerant is transferred between the tanks/cylinders and the charging area using transfer pumps that are safely housed. Refrigerant transfer also requires the use of other instrumentation such as the pressure regulating valves, pressure relief valves, shut-off valves, pressure gauges, and refrigerant detection sensors, etc. A summary of the standard safety features for bulk tanks, cylinder enclosures, and pump rooms is provided in *Table 12* below.

The preferred pipework between the pumping room and the charging station are welded stainless steel pipes to provide needed robustness and avoid leakage. It is important to regularly test this pipework for strength and tightness.

Table 12: Safety features for bulk tanks, cylinder enclosures and pump rooms

Safety feature	Bulk tank	Cylinder cage	Cylinder room	pump room
Minimum safe distance to surrounding occupancy	Yes	Yes	Yes	Yes
Area is fenced, locked, and restricted for authorized personnel only	Yes	Yes	Yes	Yes
Warning signs on entrance		Yes		
Bund wall to contain accidental spill	Yes	Yes	Yes	Yes
Easy access for deliveries and fire/emergency response	Yes	Yes	Yes	Yes

Safety feature	Bulk tank	Cylinder cage	Cylinder room	pump room
Gas detection system and associated alarms	Yes	Yes, if indoors	Yes	Yes
Emergency stop buttons	Yes	Yes	Yes	Yes
Vessels must have pressure relief devices	Yes	Yes	Yes	Yes
Liquid level indication on the vessel	Yes			
Warning signs, flammable gas/hazardous area signage on vessel and surrounding area	Yes	Yes	Yes	Yes
No potential sources of ignition within the area	Yes	Yes	Yes	Yes
No combustible materials in the immediate area	Yes	Yes	Yes	Yes
Above-ground and below-ground pipework is protected against accidental damage and corrosion	Yes	Yes	Yes	Yes
Use an excess-flow valve on the vessel outlet	Yes			
No drains or sunken areas	Yes	Yes	Yes	Yes
Ventilation gaps to the outside			Yes	Yes
Ventilation duct system			Yes	Yes
Explosion relief			Yes	Yes
Fire extinguisher			Yes	Yes
Sprinkler system			Yes	Yes
Anti-static flooring			Yes	Yes
Warning signs, flammable gas/hazardous area signage on vessel and surrounding area			Yes	Yes
No potential sources of ignition within the area			Yes	Yes

6.5 Safety Guidelines for the Manufacturing facility

In general, manufacturing facilities for R-290 or other flammable refrigerant equipment should consider the following safety features:

- Inverted hood and associated ventilation system at the charging stations and potential leak locations
- Gas detection

- Emergency stop buttons
- Audible and visual alarm signal
- Warning signs
- Associated emergency management control system

Additional attention is required in the following areas along the production line:

6.5.1 Charging machines

Charging machines that are specific for HC should be used when handling HC refrigerants. There are 3 types of charging machines:

- Fed from remote location
- Fed from a cylinder with immediately located next to machine
- Fed from a cylinder held internally

These charging machines include gas detector to initiate internal exhaust ventilation in the case of inadvertent release. The ventilation rate depends on the amount of refrigerant present in the charging machine and the associated safety features incorporated to prevent further refrigerant supply.

For the case of the remote cylinder that is positioned in the immediate area, an enclosed area or bund wall should be used with additional gas detectors and floor-level ventilation system.

It is important to consider proper connectors to minimize the refrigerant release or air ingress during the charging process. Charging should be made over an inverted ventilated hood that catches any refrigerant spill (when the refrigerant is heavier than air, as with R-290).

Gas detectors should be placed where any significant release may be sensed. At the event of abnormally high concentration, the supply of refrigerant to the charging machine should be terminated and the ventilation rate increased.

6.5.2 Maintenance and repair shop

In the case of appliance repair during production; the refrigerant should be recovered/vented, and the equipment should be appropriately evacuated. This can be done by any of the following procedures:

- Recover the refrigerant using appropriate refrigerant recovery machine, flush the system with nitrogen, and then evacuate with a vacuum pump
- Vent the refrigerant to the exhaust ventilation duct, flush with nitrogen, and then evacuate with a vacuum pump
- Employ equipment that recovers, evacuates, and exhausts automatically
- Use combined venting and evacuation devices (e.g. compressed air driven venturi pump)

6.5.3 Other work areas

Other work areas impacted by the flammable refrigerant include:

- **Leak checking area**: a small release of previously undetected leak may be occurring
- **Electrical safety testing area**: a small release of previously undetected leak may be occurring

- **Operation/performance testing area**: a small release previously undetected leak may be occurring, or temporary release may occur when dummy condensing unit or evaporator unit are connected to or disconnected from the manufactured appliance using quick connector
- **Final assembly area** (where the assembly of the appliance is completed): a small release of previously undetected leak may be occurring
- **Packaging area** (where appliance is wrapped and boxed): a small release of previously undetected leak may be occurring

6.6 Creating a Safe Factory Environment

The following subsystems allow a factory to operate in a safe and autonomous manner with managed risks to minimize the impact on personnel, facility, and production.

6.6.1 Gas detection

Gas sensors should be appropriately located to ensure that refrigerant release will be identified. The number and location of the sensors is based on thorough understanding of potential release points. Infrared and catalytic type sensors are the most suitable. Sensors must be regularly recalibrated to ensure that the system is constantly active. It is also recommended to keep spare sensors available.

6.6.2 Ventilation system

In any refrigerant charging facility, ventilation is required. However, in the case of flammable refrigerants, ventilation becomes an even more important safety factor and requires the use of explosion proof fans/blowers. The system should be designed to be fire-safe, with hoods, grilles, ductwork, and fans operating as follows:

- In work areas, inverted hoods collect any released refrigerant
- Discharge should be positioned out of the building in a way that any exhaust can't get back to the building or occupied spaces
- Fans are normally dual speed: low level for normal operation and high level for emergency operation when the refrigerant concentration above the threshold is triggered
- Fan motors and blades must be rated for use in hazardous areas
- Back-up fans are usually recommended
- Differential pressure sensors across the fans should be employed to ensure that they are working; in case of failure, the refrigerant supplier should be terminated
- Duct and grill materials should be fire rated

6.6.3 Warning alarms

To increase the level of awareness during working hours, in the case of accidental refrigerant release, warning indicators should be carefully laid out throughout the plant to inform the workers, managers, and first responders accordingly. These indicators should provide both audible and visual alarms. There should be 2 levels of alarms indicating the severity of the refrigerant release/spill event.

6.6.4 Control system

An emergency control system should be employed to ensure seamless interlock between gas detectors, differential pressure sensors, pressure sensors, manual emergency buttons, etc. and the refrigerant pumping, ventilation operation, and warning alarms.

Some of the relevant safety controls guidance for the system are highlighted below:

- Run with uninterruptible power supply to ensure continuous operation of the entire system during electricity outage.
- Designed in fail-safe mode, i.e. in the case of failure, all refrigerant supplies will be shut-off (using normally closed valves and contactors).

6.6.5 Markings and signage

Marking and signage should be posted at all critical positions to ensure that personnel are aware of potential hazards and interference with the equipment safety. Signs and warnings may include:

- Flammable gas
- Read the instructions before using
- Hazardous area
- Authorised personnel access only, etc.

6.6.6 Instructions and procedures

To ensure safe working environment, it is important to develop a clear set of instructions and working procedures acknowledging the nature of hazards involved in the manufacturing/assembly process. This material should cover:

- Correct operation of all production equipment
- Correct operation of all safety-related equipment
- Mechanics and logic of safety system
- Emergency procedures
- Reporting structures and procedures
- Safe handling of flammable gases
- Correct and safe working procedures
- Maintenance procedures
- Prohibited actions

6.7 Creating a Safe Workshop and Repair Areas

To ensure safe working environment, workshop and repair areas should be carefully designed with a focus on minimizing risk and ensuring proper workflow. Workshop and repair areas normally will service or recondition equipment which may include refrigerant recovery, leak testing, and performance evaluation.

6.7.1 Area layout

The workshop and repair areas are usually divided into discrete sub-areas

- Refrigerant handling
- Hot and electrical work

The refrigerant handling area is classified as hazardous. This area should be clearly marked, particularly at entrances, with notices indicating the presence of HC refrigerant. To provide additional safety during accidental leak, a 0.5 – 1.0 m high bund wall can be used to surround the charging area. The entire working area should be identified on the floor with visible yellow lines as shown in Figure 7 below. In addition, warning notices indicating "Highly Flammable", and "Authorized Personnel Only", warning symbol "Flammable Gas", and prohibition sign "No Smoking or Open Naked Flames" should be placed clearly at the entrance of the working zones. Also, a dry powder fire extinguisher should be available within each area and the refrigerant cylinders should preferably be stored outside, and/or kept in dedicated flammable gas cage.

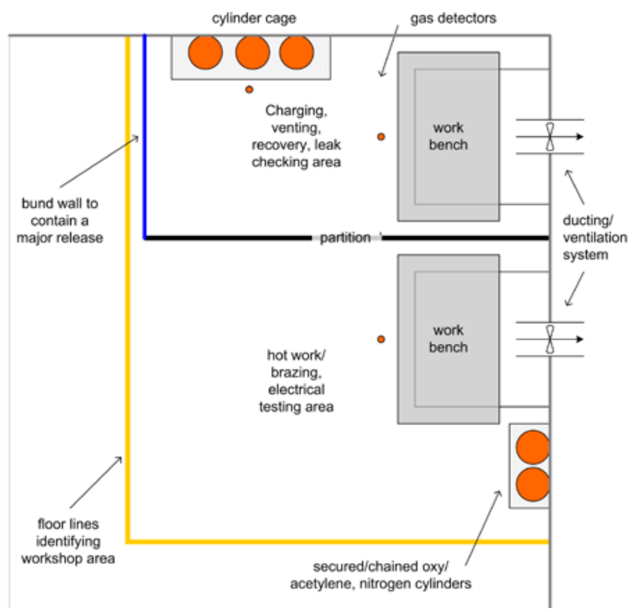

Figure 7: Suggested layout for workshop/repair area[26]

6.7.2 Workshop safety system

The safety system relies primarily on gas detection, alarms, refrigerant flow control, and ventilation equipment. When HC gas detectors detect concentrations greater than 20% of the LFL, the system should:

- Enable alarms: audible and visible
- Engage shut-off devices, and
- Increase mechanical ventilation

In addition, best practices for gas detectors should include the following:

- Located at ground level and where a release may possibly occur
- Placed down wind of natural and forced ventilation drafts to ensure their effectiveness
- Cover an area of no more than 30 m^2
- Calibrated at regular intervals, as recommended by the manufacturer
- Protected from foreign material and substances that may affect its performance and protected against mechanical damage.

The mechanical ventilation system should be installed in all areas where HC refrigerants are being used. Two stages of ventilation are required:

Stage 1 - To maintain the refrigerant/air concentrations less than 1000 ppm for HC refrigerants
Stage 2 - To remove dangerously high concentrations of refrigerant as quickly as possible to reduce the risk of fire or explosion

The same ventilation system best practices mentioned in section 6.6.2 are applicable here.

6.7.3 Working practices

In general, same rules discussed in section 6.6.6 should be followed. Furthermore, a strong focus on the risk of open flames should be mentioned due to the proximity between the refrigerant handling zone and the hot work zone.

6.7.4 Protective equipment for workshop areas

In typical HC workshop/repair areas the following protective equipment and documentation are recommended:

- Service equipment
  - ✓ Electronic leak detector (suitable for HCs)
  - ✓ Soapy water (or leak detection spray cans)
  - ✓ Refrigerant cylinders (R290, R600a, etc,)
  - ✓ Refrigerant recovery cylinder
  - ✓ Nitrogen (oxygen-free, dry nitrogen) cylinder
  - ✓ Vacuum pump and vacuum gauge
  - ✓ Refrigerant recovery machine (suitable for use with HCs)
  - ✓ Venting hose
  - ✓ Scales/electronic balance
  - ✓ Gauge manifolds and hoses
  - ✓ Hand tools including adjustable spanners, pliers, valve keys, etc
- Documentation
  - ✓ Flammable gas stickers
  - ✓ R290, R600a, etc, refrigerant stickers
  - ✓ Flammable gas signs
  - ✓ "Do not enter" or equivalent signs
  - ✓ Comparators for R290, R600a, etc
- Protective equipment
  - ✓ Fire extinguisher
  - ✓ Gloves
  - ✓ Goggles

7 Equipment Design and Development[26]

7.1 Safe design of equipment operating with flammable refrigerant

The concept of integrated safety provides the best approach to handle the hazards of designing equipment operating with flammable refrigerants. This concept relies on ignition prevention and techniques for protection against potential ignition in the case of flammability hazard. This process relies on:

- preventing the formation of flammable atmospheres,
- preventing the ignition of any flammable atmospheres that might occur, and
- limiting the range of flames and pressures to a minimum in the case of ignition

this can be summarized as shown in Figure 8 below.

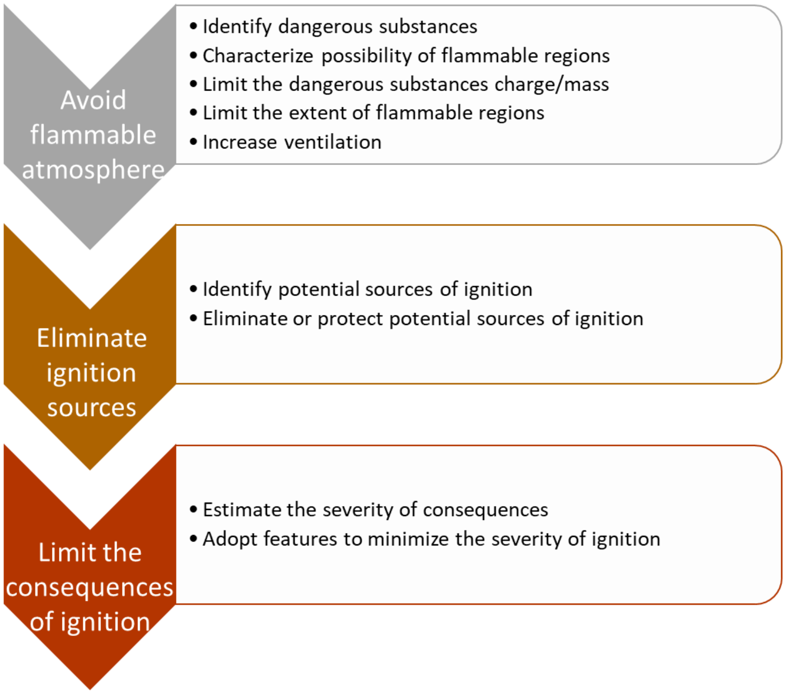

Figure 8: Integrated safety design practices

7.1.1 Avoiding flammable atmosphere

A flammable atmosphere is present whenever the refrigerant-air mixture is between the LFL (lower flammability limit) and the UEL (upper explosive limit). As such, it is important to understand the refrigerant/air mixture distribution upon accidental release and evaluate the potential that it will be within the LFL and UEL bounds. It is important to identify the parts of the equipment where flammable atmosphere is present. Each region should be assigned a probability for the presence of a flammable mixture and the extent and persistence of that flammable mixture.

To maintain safe design, the amount of flammable mixture should be kept at the minimum possible otherwise it is important to provide the following risk management measures:

- contain flammable material
- prevent further release or the spread of the flammable mixture
- ensure that the contents of containers and pipes are clearly identifiable, and
- adopt other practical measures, such as detection of potentially flammable atmospheres, generating proper alarm procedures and initiating appropriate ventilation.

7.1.2 Eliminating potential sources of ignition

Ignition can be caused when a spark with a high energy source (value to depend on the refrigerant), or when a hot surface (temperature depends on refrigerants, for R-290 it is 450°C) are in direct contact with the flammable mixture (refrigerant-air mixture between LFL and UEL). As such, designers should carefully consider potential sources of ignition could, particularly electrical or mechanical equipment. Appropriate protection may be applied to electrical and mechanical equipment in the case of ignition potential of flammable gas is identified.

7.1.3 Limiting the severity of consequences of an ignition event

If potential sources of ignition persist, the impact of ignition should be studied:

- maximum pressure development,
- extent of any flames, and
- radiated heat

These are usually conducted using computational fluid dynamic (CFD) simulation or experimental methods. After the severity is carefully studied, the system designer should use possible methods to protect against overpressure and flame spread. These include venting, suppression, containment and isolation.

7.2 Steps of Integrated Safety Design Principles

Step 1: Refrigerant leakage

- Avoid or minimise leakage
- reduce the charge size of the system
- reduce the amount that may be released into a particular area
- use ventilation, gas detection and associated controls

Step 2: Identify all the potential sources of ignition

- remove or ensure they are shielded from flammable refrigerant mixture in the event of a leak

Step 3: Understand the severity associated with potential ignition

- ensure that all housings or enclosures have venting, or
- eliminate the possibility of refrigerant entering them, and
- use marking and instructions to raise the awareness of those who may encounter the system and refrigerant

In addition, possible operating faults should be carefully analysed to prevent dangerous situations and any anticipated misuse.

7.3 Avoiding Leaks

Refrigerant leakage can be avoided by:

- Appropriate system design and layout
- Selection of appropriate components
- Suitable installation and tightness testing/leak checking practices
- Regular maintenance and system checks
- Servicing by competent technicians, using proper equipment

7.3.1 Best practices for leak reduction

To minimize the leaks, several principles may be applied; including:

- Designing the system as more than one independent refrigerant circuit
    - In the event of a major leak, only the refrigerant within one circuit is released. This would result in cost and space implication

- Using automatic shut-off valves to isolate parts with large refrigerant charge within the refrigeration circuit (e.g., receiver, condenser, etc) when a leak is detected
- Designing systems with fewer pipe joints and seals
- Ensuring good material compatibility within the refrigeration system (particularly valve seals, O-rings, etc); and consider the full range of operating temperatures and pressures that the materials will be subjected to, as this can also affect the compatibility
- Minimising components and joints known that are prone to leakage

For further information, additional practical tools for aiding the reduction of emissions of refrigerants is provided by the Real Zero project[31] of the Institute of Refrigeration, and further guidance can be found within the Code of Practice on Minimisation of Refrigerant Emissions[32].

7.3.2 Piping design consideration

The design and installation of pipework in the case of HC equipment should consider the following:

- Protect against impact, weathering, external corrosion, and galvanic corrosion at the junction of dissimilar metals
- Ensure proper brazing at all joints
- Avoid residual stresses in bends or joints
- Avoid water condensation between the tubes and insulation
- Trade-off between mechanical strength and lack of susceptibility to vibration and work hardening, and external corrosion in the selection of tube/pipe material should be considered (e.g. steel vs. copper)
- Provide adequate support for pipes based on tube diameter, number of joints, weight and spacing distance
- Avoid pipe routing in areas where it may be walked on or used as support beams. When unavoidable, protective covers and warning labels should be provided
- Design pipe runs to allow for expansion and contraction
- Minimise the effects of vibration
- Prevent liquid hammer during the design of pipe routing and the selection of valve types. If quick-acting valves are required in long lines, means of suppressing pulsation must be provided
- Minimise mechanical joints, especially flare joints. Welding or brazing are the preferred joining methods
- Use continuous piping without vibration eliminators or flexible connectors for compressor connections, providing that excessive vibration or stresses will not be transmitted to the rest of the system. If vibration eliminators or flexible connectors must be installed in strict accordance to manufacturers' instructions to avoid catastrophic leakage

7.3.3 Design considerations for system components

Relevant design considerations for major system components are described below.

- Heat Exchanger:
    - Protected against possible mechanical damage
    - Protected against freezing if they contain water

[31] https://www.ior.org.uk/careers/refrigerant-containment
[32] https://www.thenbs.com/PublicationIndex/documents/details?Pub=IR&DocID=296290

    - Defrost controls should be designed and adjusted to avoid any unnecessary defrost operations, to minimise thermal stresses and avoid surface temperatures exceeding autoignition temperature
    - Ensure complete defrost in for lower temperature air coolers and drip trays during every defrost cycle
    - In the event of risk of refrigerant leakage into heat transfer fluid, means of heat transfer fluid sampling must be provided
- Compressors should be installed on anti-vibration mountings
- Access must be provided for leak testing of compressors, evaporators, condensers and associated components
- Valves
    - Sufficient valves must be provided to ensure that servicing and maintenance result in insignificant loss of refrigerant
    - Avoid unsafe pressures in isolated circuit sections containing liquid refrigerant
    - Valves with bellows or a diaphragm are more preferential over spindle seal
    - Valves with O-ring spindle seals are more preferential over valves with spindle packing glands; except in the case of elastomeric material is not available
    - Valves should be fitted with their seal caps
    - Safety valve venting should be vented to the low-pressure side of the refrigeration circuit or piped far from any source of ignition
        - Low-pressure side safety valve should be vented to atmosphere
        - High-pressure side must not be protected by a bursting disc venting to atmosphere
    - Dual relief valves are preferred as they allow quick change over at the mandatory service intervals
    - An indicating device should be fitted to the outlets of valves to visually evaluate previous discharge to atmosphere during maintenance

7.3.4 Indirect or secondary systems

It is important to prevent potential leaks of flammable HC refrigerant to the service areas served by the secondary heat transfer fluid. This may happen in the case of refrigerant leakage through the evaporator or condenser wall into the secondary circuit. Such accidental release may be prevented by implementing at least one of the following techniques:

- Use an automatic air/refrigerant separator, within the secondary circuit on the outlet pipe from the evaporator or the condenser
- Use a double wall heat exchanger
- Ensure that the pressure of the secondary circuit is greater than the pressure of the primary circuit
- Use a double indirect system

In any system with refrigerant charge exceeding 25 kg; the presence of refrigerant in any associated circuit containing a heat transfer fluid should be detected and monitored.

7.4 Refrigerant Charge Limit

The refrigerant charge limit for commercial refrigeration system may be controlled by 2 major international standards: ISO 5149 and IEC 60335-2-89. The ISO 5149 standard applies for all types of equipment while the IEC 60335-2-89 focus primarily on self-contained equipment.

The allowable refrigerant charge depends on the maximum (M_{max}) and allowable (M_{al}) charge prescribed in the corresponding standards. The M_{max} is a function of the equipment, location, and occupancy, the M_{al} is a function of room size and refrigerant release location. Furthermore, M_{max} and M_{al} depends on the LFL, summarized in Table 13 below for relevant HCs.

Table 13: Flammable and practical limits of relevant HC refrigerants

Value	R600a	R290	R1270
LFL, kg/m^3	0.043	0.038	0.043
LFL, %	1.8	2.1	2.5
PL/RCL, kg/m^3	0.01	0.0095	0.01
Density of vapour, kg/m^3	2.48	1.86	1.77

Occupancy categories

- Category A: general occupancy that is not restricted to public. Under this category, refrigerant leakage is not allowed to exceed the practical limit
- Category B: supervised occupancy with some personnel restriction, some occupant may be aware of potential hazard
- Category C: general occupancy – occupancy with authorised access only

Table 14 provides a summary of the allowable and maximum refrigerant charge for the different configuration of non-comfort equipment based on ISO 5149 for installations above ground. Below ground installation have M_{max} of 1 kg and M_{al} of PL x VRm for direct systems and 1 kg for indirect systems.

Table 14: Summary of M_{max} and M_{al} according to ISO 5149 for non-comfort equipment

Occupancy type	System type	M_{al}, kg	M_{max}, kg
Category A	Direct	PL × VRm	1.5
Category A	Indirect	5	5
Category B	Direct	PL × VRm	2.5
Category B	Indirect	10	10
Category c	Direct	PL × VRm	10 or 25*
Category c	Indirect	No limit	No limit

VRm is the room volume

* 25 kg if compressor and liquid receiver are in an unoccupied machinery room or in the open air

Furthermore, to ensure adequate ventilation and minimise the risk of developing a flammable atmosphere, the following air flow is required especially in tight and enclosed areas.

$V_{min} = 0.004*M/LFL$

Where V_{min} is the minimum required air flow in m^3/s, M it the refrigerant charge in kg, and LFL is the lower flammability limit in kg/m^3 as defined in Table 13.

7.4.1 Refrigerant charge minimization

To minimize the refrigerant charge, system components should be designed to minimize internal volume. Below are some additional specific requirements for the different components:

- Compressors:
    - Use one with smallest internal volume (e.g. use rotary, scroll, and hermetic reciprocating instead of semi-hermetic reciprocating and screw compressors)
    - Select a compressor with smallest suction chamber
    - Use oil with low refrigerant solubility
        - PAG, AB, and PAO are better than mineral and POE
- Evaporators and condensers
    - Use smaller diameter tubes and compensate the tube length to maintain same heat transfer area
    - Use of variable fin density as needed to maximize the airside heat transfer without the need to increase the tube length
    - Consider the use of enhanced tubing to minimise the tube length
    - Use microchannel heat exchanger when available
    - Plate-type evaporators and condensers are preferred over tube-shell and shell and tubes due to the potential charge reduction
- Liquid, delivery, suction, and discharge lines
    - Refrigerant charge in interconnecting pipes have significant variation between different systems
    - Optimised piping design can reduce the charge by 15-40%
    - The low viscosity of HC allows for smaller pipe diameters
- Liquid receivers and suction accumulators
    - Liquid receivers require significant amount of charge. Their use should be limited to only cases where a wide range of operating conditions exist, or for pump-down cycles
        - A carefully designed larger condenser may be used alternatively
        - If its use is unavoidable, it may be sized to accommodate the maximum and minimum variation in liquid level. Vertically mounted are more preferred over horizontally mounted
    - Suction accumulators allow for proper operation over a wide range of operating conditions
        - Not much refrigerant charge as they contain superheated vapour
        - Reductions in charge may be obtained by optimising the geometry

7.5 Sources of Ignition and Methods of Avoiding Them

Sources of ignition (SOI) associated with the equipment may ignite a flammable mixture upon the release of a flammable refrigerant to the atmosphere. Potential SOI include:[33]

[33] Other SOI include: hot gases, hot particles, mechanically generated sparks, electrical apparatus, static electricity, lightning, radio frequency electromagnetic waves (from 10^4 Hz to 3×10^{12} Hz), other electromagnetic waves (from

- A spark with energy > 0.25 mJ
- An open flame
- A hot surface > 450°C

Below are discussions on precautions that should be taken to avoid ignition such as in the case of hot surfaces, electrical sparks/sources of ignition, and fan assemblies.

7.5.1 Hot surfaces

During the design phase, it should be ensured that the temperatures of any surfaces with potential exposure to the leaked refrigerant do not exceed the auto-ignition temperature of the refrigerant, reduced by 100 K; this equates to about 350°C for R-290. If the maximum surface temperature of a device under uncontrolled conditions is not stated by the manufacturer; then the temperature should be experimentally evaluated as specified in IEC 60335-1, IEC 60335-2-89 and IEC 60204-1.

Maximum surface temperature measurement is done by:

- Continuous temperature measurement using thermocouples fixed on the exposed surface of the device
- Preventing protective devices other than self-resetting thermal motor-protectors for motor-compressors from operating, except those which are terminated by a non-self-resetting protective device or by an intentionally weak part becoming permanently open-circuited
- Preventing the operation of the thermal motor protectors for motor-compressors when steady conditions are established
- Allowing automatic termination of defrosting using available control device; when used to stop the defrosting at a given temperature or pressure
- Avoiding sealing compound flow out during the test

7.5.2 Electrical sources of ignition

Careful positioning and selection of electrical components can prevent potential hazards. Leaked refrigerant should not flow or stagnate around electrical components. According to the relevant safety standards (ISO 5149, IEC 60335-2-89) electrical components that could act as source of ignition must further comply with IEC 60079-15:2017[29] and IEC 60079-14:2013[34]. Finally, the component should not be in an area where a potentially flammable mixture of refrigerant and air would accumulate.

In addition, care should be taken to ensure that electrical terminals, including capacitor terminals are adequately tightened and secured against loosening and that adequate insulation is provided to avoid live parts shorting together. Similarly, electric motors must be of brushless design. Whilst it is standard practice to earth all parts of an assembly (including housing and ancillary parts), it is critical to ensure that this is carried out comprehensively for equipment using flammable refrigerants.

3×10^{11} Hz to 3×10^{15} Hz), ionizing radiation, ultrasonic vibration, adiabatic compression, shock waves, exothermic reactions

[34] IEC 60079-14:2013 Explosive atmospheres - Part 14: Electrical installations design, selection and erection https://webstore.iec.ch/publication/628

7.5.3 Fan assemblies

Fan assemblies may be an additional SOI due to sparks created from fan blades friction with its housing. This SOI can be avoided by maintaining a minimum clearance distance between the blade and the housing.

- The fan construction must be of rigid design
    - The casing
    - Supporting structures
    - Guards, protective devices and other external parts
- Materials pairing for the casing and fan blades
    - plastic materials for both pair is normally acceptable
    - plastic materials and any metal pair is normally acceptable
    - aluminium and aluminium or other metallic pairs are normally acceptable
    - stainless steel pairs must not be used
    - steel alloy and brass pairs must not be used
    - If (non-aluminium) metallic pairs are used, chrome content should be less than 15% (to avoid sparking),
- rotational speed should be less than 40 m/s, and additional considerations are necessary if the shaft power is greater than 5.5 kW
- Paint containing aluminium or iron oxides must not be used because of the risk of sparks
- The fan must be fitted to avoid excessive vibration
- All metallic parts must be earthed
- The most important criterion is the clearance distance between the fan blades and the casing, which shall be at least 1% of the diameter and no less than 2 mm

7.6 System Installation Best Practices

This section presents some guidance based on ISO 5149 and IEC 60335-2-89 including:

- Outdoor installations
- Machinery rooms
- Piping
- Safety valves
- Gas detection
- Additional system safety concepts

7.6.1 Outdoor installations

Outdoor installation should be protected against potential mechanical damage and provide adequate means for risk management in the event of refrigerant leakage.

- Refrigerant-containing and critical parts of the equipment must be protected from mechanical damage
- Equipment housing should be robust and resistant to weather and other forms of damage
- Equipment should be positioned at a safe distance from items that may be negatively affected by a release of refrigerant
- Ensure free ventilation all around the equipment, and avoid permanent or temporary blockages
- The area should be free of combustible materials

- Due consideration should be given to drains and lower terrains, in case escaped refrigerants could pass through them and accumulate
- Careful consideration should be given to the positioning of the equipment with regards to opening to other buildings, duct inlets, vents, etc

When accessible by members of the public additional criteria should be considered:

- The charge of individual refrigerant circuits should not exceed the values specified Table 14
- The equipment housing should prevent or inhibit interference from others
- Avoid proximity to areas where people may congregate

For equipment located in an area accessible by authorised personnel only, the following criteria should be considered:

- Access to the area should be controlled
- The controlled area should have a radius of between 2 m to 5 m away from the equipment, depending upon the charge size and the design of the equipment

The minimum "safe" distance, d (m) may be approximated as

$$d = C_w \times \sqrt{\frac{M_c}{\pi \times h_{enc} \times LFL}}$$

where M_c is the refrigerant charge per individual circuit (kg) and h_{enc} is the height (m) of the enclosure or fence surrounding the system. Note that fence should be located within the "safe" distance. When no fencing is present, the height of the unit housing may be used for the calculation. The constant C_w depends on the local airflow conditions:

- Sheltered location, such as besides or between buildings, $C_w \approx 0.5$,
- Exposed location, such as on a roof, $C_w \approx 0.25$.

7.6.2 Machinery rooms

Machine room installations usually require adherence with local and national regulations. When HC equipment are located within machinery room, additional requirements are imposed. These largely relate to potential flammable mixture and the required measures to avoid potential ignition. In general:

- In the case of potentially reaching the LFL, the installation should comply with the requirements for hazardous areas
- Avoid sources of ignition inside the machinery rooms
- Combustion equipment such as boilers are considered SOIs; as such they can't be co-located within the same machinery room as an HC refrigerating system
- piping and ducting passing through walls, ceilings and floors must be tightly sealed to avoid refrigerant leakage spill over to other enclosed or occupied areas
- Eliminate air intakes for any equipment from within the machinery room
- Precautions must be taken to prevent leaked refrigerant that is denser than air entering into drainage systems
- Voids in the machinery room floor should be avoided, or designed so that heavier than air refrigerant could not accumulate in these spaces in the event of a leak

Employ proper safety control measures in the machinery room to enable proper risk management during flammable refrigerant release. This includes: flammable refrigerant detection, alarms, electrical interlock, and ventilation fan.

Additional features for the machinery room considering HC refrigerants include:

- Direct access to outdoors when the refrigerant concentration higher than 20% of the LFL is detected
    - If not possible, then it should be through a dedicated vestibule equipped with self-closing, tight-fitting doors
- To improve dispersion and minimise the severity of the ignition event, ensure that a large open wall area is available; ideally at least 50% of the area of one of the walls should be open, and preferably close to 100%
    - Open area may be fencing, grilles, etc, but should not pose any resistance to the free-flow of air
- If there is any less than 25% of the total (four walls plus ceiling) area that is not open, then some explosion relief must be provided if the refrigerant charge would result in flammable concentration reaching the LFL. This would ensure that in case of deflagration or explosion, a controlled failure will occur preventing severe damage to the building
    - This explosion relief may be in the form of a frangible wall or roof, which should have very low mass and weak fixings, and should require a force of less than around 20 kPa to open
- The access to the machinery room should be permitted for suitably trained, authorised persons only

7.7 Case study: development of an R-290 enclosure for supermarket refrigeration

This is the design of the Futron chiller, it is based on a special ventilated enclosure comprising the entire refrigerating system which provides cooling to a secondary heat transfer circuit.

The refrigeration system is a self-contained system within a gas-tight enclosure. It can be positioned outside the property to satisfy most of the essential elements of the relevant regulations. As such, it is possible to use non-Ex-rated components and optimise the system cost.

- All components are located within the enclosure and connected via brazing to exclude the possibility of leakage
- A leak-proof pan is used at the bottom of the enclosure to avoid refrigerant dispersion since R-290 is denser than air
- At least one gas sensor is positioned close to the bottom of the enclosure, when activated it isolates the electricity supply from all electric components within the unit except for an Ex-rated fan that is immediately activated to exhaust any released refrigerant to ambient

8 Conclusions

R-290 has a similar vapor pressure performance to that of R-22; especially below freezing conditions. R-290 results in roughly 15% loss in volumetric capacity compared with R-22. Furthermore, ideal thermodynamic vapor compression cycle simulation shows similar energy efficiency to R-22. R-290 is largely compatible with materials commonly used in the construction of refrigeration and air conditioning equipment. It is widely available and relatively inexpensive.

In general, the following should be considered during the design of propane equipment:

- Minimize charge
- Minimize leakage
- Manage risks associated with potential refrigerant leaks
- Employ specially designed compressors for propane
- Use inherently safe electrical components
- Employ pressure relief valves: the first from the high side discharging to the low-pressure side and then from the low-pressure side discharging to ambient
- enclose all system pipework and components containing propane inside a sturdy framework to avoid damage during transport and operation
- Employ Labelling to include refrigerant type and class (flammability)

Currently, the propane chiller refrigeration market is very limited; in the US only one company offer custom made units (Budzar Industries Inc.), in Europe however, there are 6 companies offering propane chiller solutions for the refrigeration applications:

- SRS Frigadon
- Futron Eco Cooling Systems
- Euroklimat
- Tecno Freddo
- Frigopol
- Felzer

These manufacturers have different designs and different refrigerant safety management techniques; but in general, the refrigerant safety management in include:

- R-290 leak detector with built-in alarm level and LED status indicator
- ATEX-rated ventilation system
- Gas-tight enclosure
- All fittings are brazed to avoid leakage
- ATEX certified compressor, EC fan, electrical cabinet resistant to refrigerant leakage ingress
- ATEX sensors, switches and other critical equipment to prevent sparks
- Microchannel HX to minimize charge
- Isolating machine room from electric cabinet
- Dedicated exhaust air stream depending on installation location
- Blow-out pipe for safety relief valves
- Safety valve piping to evacuate refrigerant in case of overpressure

Several studies were presented in section 4 discussing the performance comparison of propane against HCFC and HFC refrigerants:

- For low-lift applications, propane was 24% less efficient than R-2134ze(E)
- For high-lift (low temperature refrigeration applications), propane was better than R-410A and R-404A; but when accounting for potential losses associated with secondary coolant and the impact of compressor redesign, R-410A became the best option
- For milk-processing facilities, propane retrofits provided 13 to 37% efficiency boost over R-22 depending on the ambient conditions
- For a large scale retrofit study in South-East Asia, propane resulted in energy savings ranging from 12 to 51% compared with R-22
- For AC chiller applications, propane had similar or better performance to R-22, but lower performance compared with R-134a and R-1234ze(E)

The detailed guidelines for safe design, manufacturing and installation of hydrocarbon refrigeration equipment were presented including:

- Applicable international safety standards
- Production and manufacturing facilities
- Refrigerant supply
- Safety Guidelines for the manufacturing facility
- Creating a safe factory environment
- Creating a safe workshop and repair areas

And finally, the integrated safety design practice for hydrocarbon equipment was presented along with a case study for the development of a propane refrigeration chiller for supermarket application.

This work illustrates that propane chillers for supermarket refrigeration has a strong potential for energy savings and long-term sustainability. The high flammability associated with propane as a refrigerant can be successfully mitigated through proper design and operation according to the presented guidelines.

9 Additional Resources:

https://www.feta.co.uk/uploaded_images/files/BRA%20Guide%20to%20Flammable%20Refrigerants%20-%20Issue%201%20-%20Oct%2012.pdf

http://www.emersonclimate.com/en-US/Resources/Refrigerants/Pages/propane-refrigerant.aspx

http://www.linde-gas.com/en/products_and_supply/refrigerants/natural_refrigerants/r290_propane/index.html

http://hydrocarbons21.com/articles/6238/broadening_hydrocarbon_horizons_commercial_refrigeration_technology_and_heat_pumps

http://hydrocarbons21.com/products/view/emerson_copeland_scroll_compressors_propane_r290