HERRICK CONFERENCES 2024
COMPRESSORS | REFRIGERATION | BUILDINGS
JULY 15 - 18, 2024 • WEST LAFAYETTE, INDIANA

Safe Use of Hydrocarbons in HVAC&R Applications

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PURDUE UNIVERSITY | Ray W. Herrick Laboratories

Acknowledgements

Thank you the following

Dr. Daniel Colbourne, Re-Phridge

Laure Meljac, NIBE

Dr. Andy Pearson, Star Refrigeration

Marek Zgliczynski, Nidec

Dr. Ingo Seliger, Viessmann

Asbjorn Vonsild, Vonsild Consulting

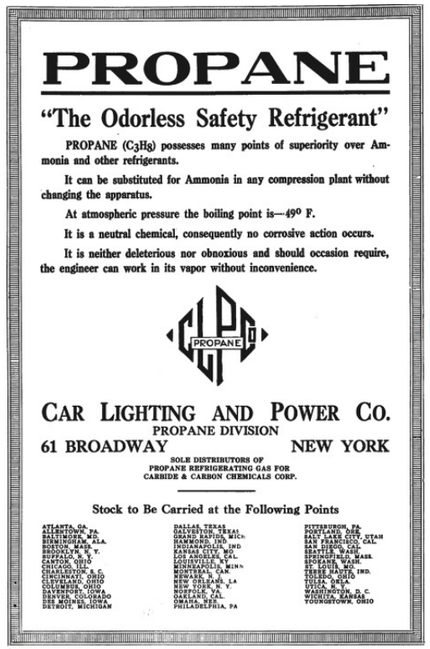
Denise Ball, Matthew Irons, Eric Winandy Copeland

for helping me with this presentation

Contents

- Safety Standards in HVAC&R
- Compressor Risk Analysis
- Safety Measures for Components
- Examples of Heat Pump Units with Propane (Europe)

Hydrocarbons Return Over The Years Driven By Their Low Impact On Environment



PROPANE

"The Odorless Safety Refrigerant"

PROPANE (C_3H_8) possesses many points of superiority over Ammonia and other refrigerants.

It can be substituted for Ammonia in any compression plant without changing the apparatus.

At atmospheric pressure the boiling point is—49° F.

It is a neutral chemical, consequently no corrosive action occurs.

It is neither deleterious nor obnoxious and should occasion require, the engineer can work in its vapor without inconvenience.

CAR LIGHTING AND POWER CO.
PROPANE DIVISION
61 BROADWAY NEW YORK

SOLE DISTRIBUTORS OF
PROPANE REFRIGERATING GAS FOR
CARBIDE & CARBON CHEMICALS CORP.

Stock to Be Carried at the Following Points

Advertisement for propane appearing in the December 1922 issue of Ice and Refrigeration magazine.

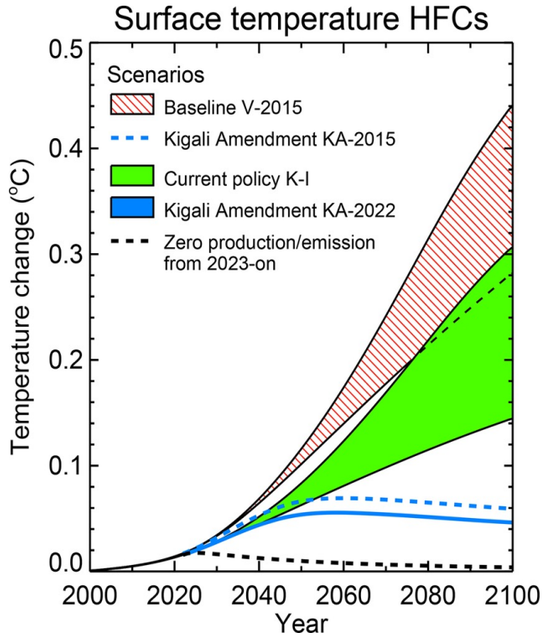
R-290 marketed as "safe refrigerant" in 1920s

- First vapour compression system ever built was in 1834 with diethyl ether
- *H. D. Edwards, Proc. American Soc. Refrig. Eng. (1922):*
- *"…First applications with propane recorded in 1911..*

…hydrocarbon are the best for use in household and small units where operation for long periods without attention is essential"… "is inflammable and open flames should not be permitted where its vapors collect"

- Early 1990s, following Montreal Protocol European manufacturers of refrigerators introduced isobutane (R-600a)
  - It's estimated more than 800 million in the field - UNEP 2022

- Kigali amendment to MP (2016) global phasing-down harmful HFCs
- **Hydrocarbons are considered a future-proof refrigerants for this transition phase**



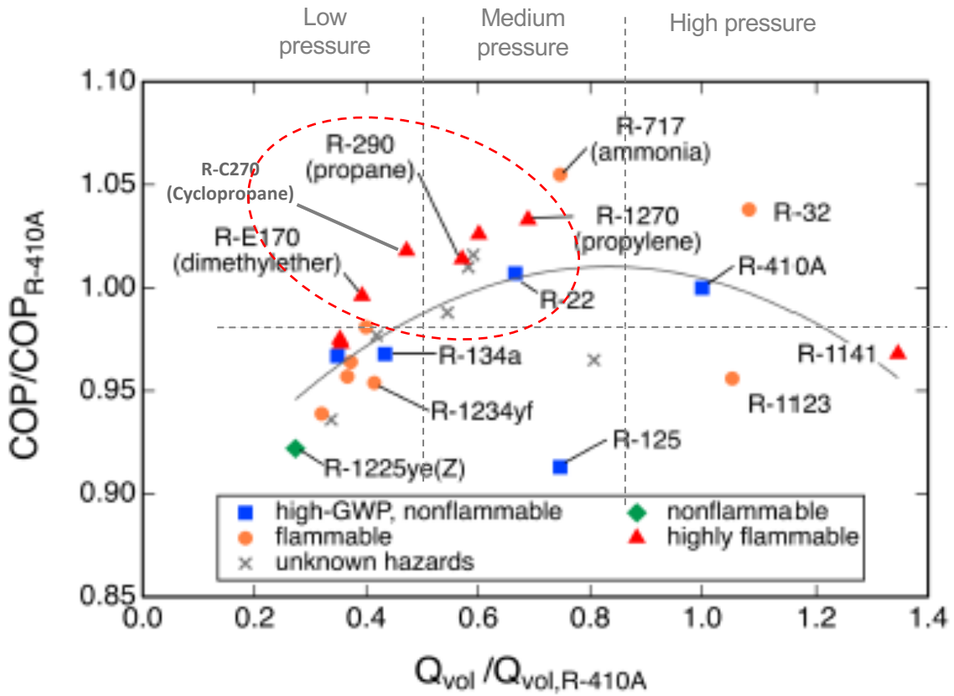
Expected temp. rise:

0.06 vs. 0.4 K by 2100

Guus J. M. Velders et al., Atmos. Chem. & Phys., 2022

Strict Adherence to Rules is Fundamental for the Success of Hydrocarbons

- In the search for sustainability, appropriate thermodynamic properties are required
- But safety issues cannot be set aside when considering these alternatives



Source : Mc Linden IIR.ICR.2019

Hydrocarbons (HCs) Demonstrate Good Performance

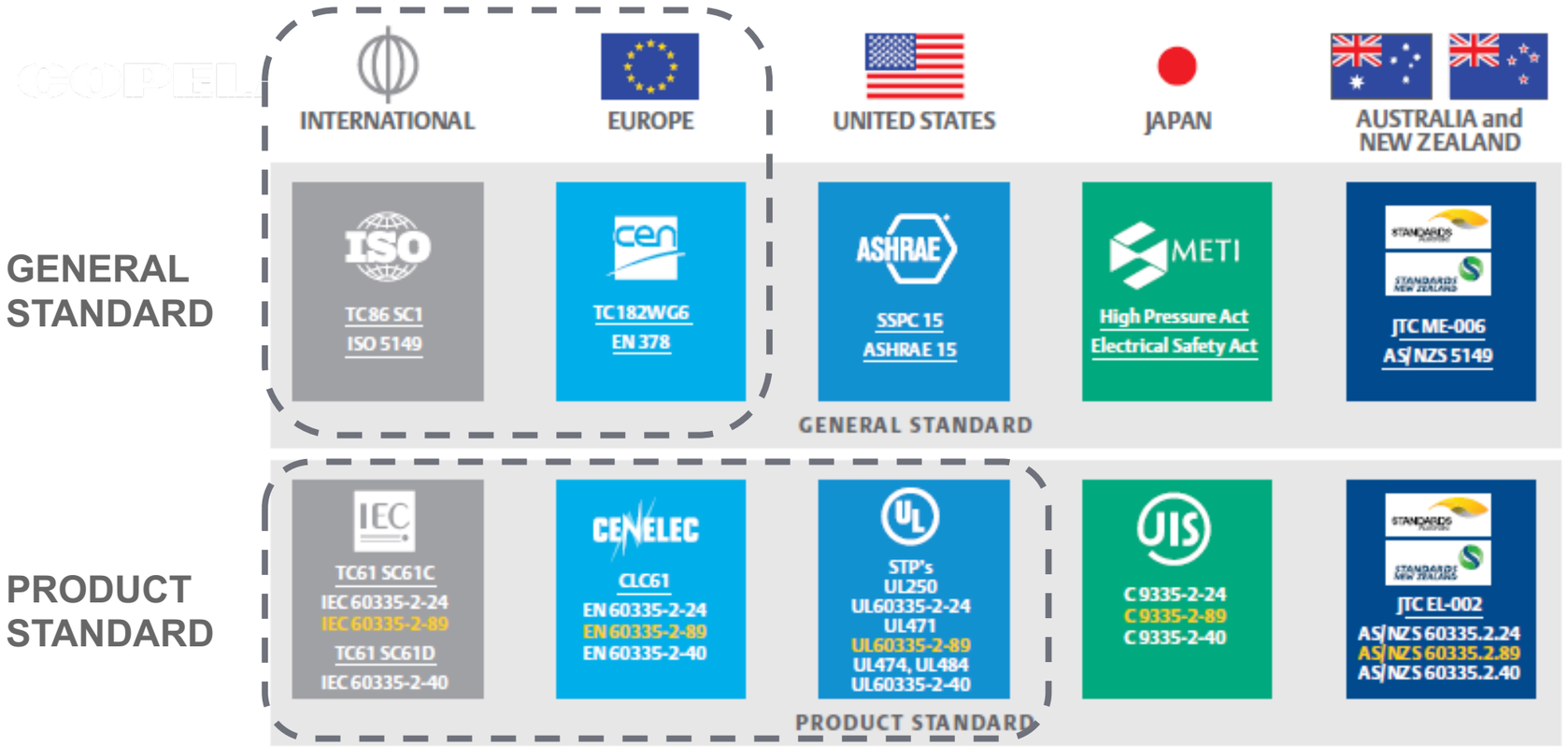
Most Common HCs Used as Refrigerants

Refrigerant	GWP_{100}	Lower - Upper Flamability limit [vol%]	Burning Velocity [cm/s]	Heat of Combustion [MJ/kg]	Minimum Ignition Energy [mJ]	Auto-ignition temperature [°C/°F]
R-E170 Dimethyl ether	<1	**3 - 26**	**54**	**28.8**	**0.32**	235 / 455
R-170 Ethane	0.4	**3.1 - 12**	**47**	**47.5**	**0.26**	515 / 959
R-290 propane	0.02	**2.1 - 9.5**	**45**	**46.3**	**0.25**	470 / 878
R-600a Isobutane	0.006	**1.8 - 9.6**	**37**	**45.6**	**0.25**	460 / 860
R-1270 propylene	0.02	**2.7 - 11.1**	**48**	**45.8**	**0.26**	455 / 851
R-32	**677**	**14.4 - 29.3**	**6.7**	**9.5**	**15**	**648 / 1198**
A3 vs. R32		**18%**	**7 time**	**5 time**	**2%**	**-221 K**

Severity Level Can be High if Safety is Not Properly Addressed

Overview of HVAC&R Standards

- Flammability safety is addressed through industry guidance, standards, norms and codes
- Safety standards provide guidelines on safest way to use refrigerants and reduce risk
- Act as traffic light for use flammable refrigerants, if standard permits, sector can adopt



GENERAL STANDARD

PRODUCT STANDARD

Mitigation in Safety Standard:

- **Limit charge**
- **Minimize leakage**
- No flammable concentration
- **No ignition source**
- People competence

Hydrocarbons Charges Limits in ISO5149 & EN378

Split System | Chiller

Access Category	Location Class			
	All Refrigerating system Indoor (I)	Compressor & Receiver in unoccupied space (II)	All refrig. system outdoor or in machinery room (III)	Ventilated enclosure (IV)
Public Access	C2 <= 1.5 kg		5 kg	130 x LFL (R290: 4.94 kg)
	C3 <= 1.5 kg*			
Supervised Access	C2 <= 1.5 kg		10 kg	
	C3 <= 2.5 kg*			
Authorized Access Only	C2 <= 1.5 kg		No limit **	
	C3 <= 10 kg*	C3 <= 25 kg*		

(*) below ground or above w/o emergency exit

* For underground, charge limited to 1 kg

** machinery room only access c

Human comfort

C2 $M \leq 2.5\,(LFL)^{1.25}\,x\,A^{0.5}\,x\,h_0$

C3 $M \leq \mathbf{0.2}\boldsymbol{x}LFL\text{x}A\text{x}2.2$

LFL : lower flammability limit

A: room area, h_0: height

Examples

Hospitals, theatres, supermarkets, schools, hotels, dwellings, restaurants

Professional offices, laboratories, places for general manufacturing and where people work

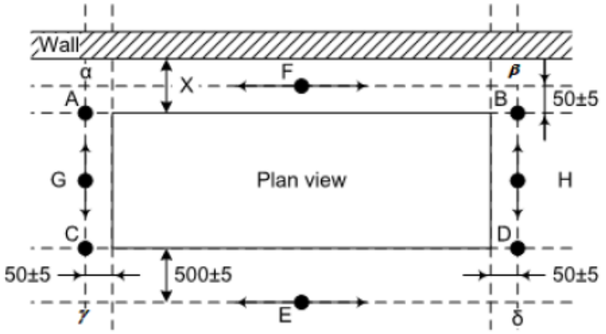
Manufacturing facilities, cold stores, non-public areas in supermarkets

Refrigerating systems in location class I and II and for public access shall be **Sealed System** (**Hermetically**)

Product Standards Allows Use of Hydrocarbons in Commercial Refrigeration

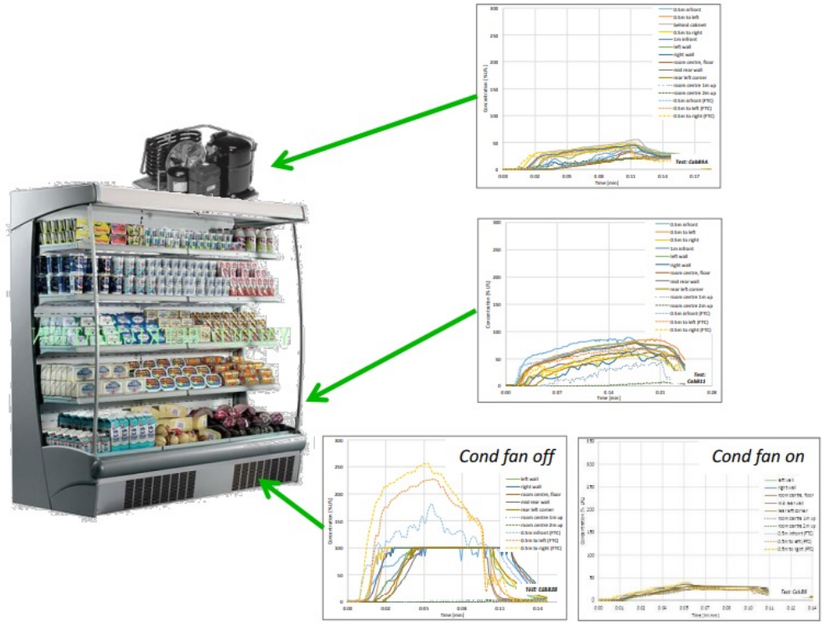
Standards	Scope	Limit for Hydrocarbons
IEC 60335-2-75:2018	Commercial dispensing appliances and vending machines	150 g
IEC 60335-2-118:2021	Professional ice cream makers	Under revision to include 150 g
IEC 60335-2-89:2019*	Commercial appliances	13 x LFL [494 g for R290]

(*) UL 60335-2-89:2021, limiting charge to 8xLFL [304 g of R290] for appliances with doors, drawers



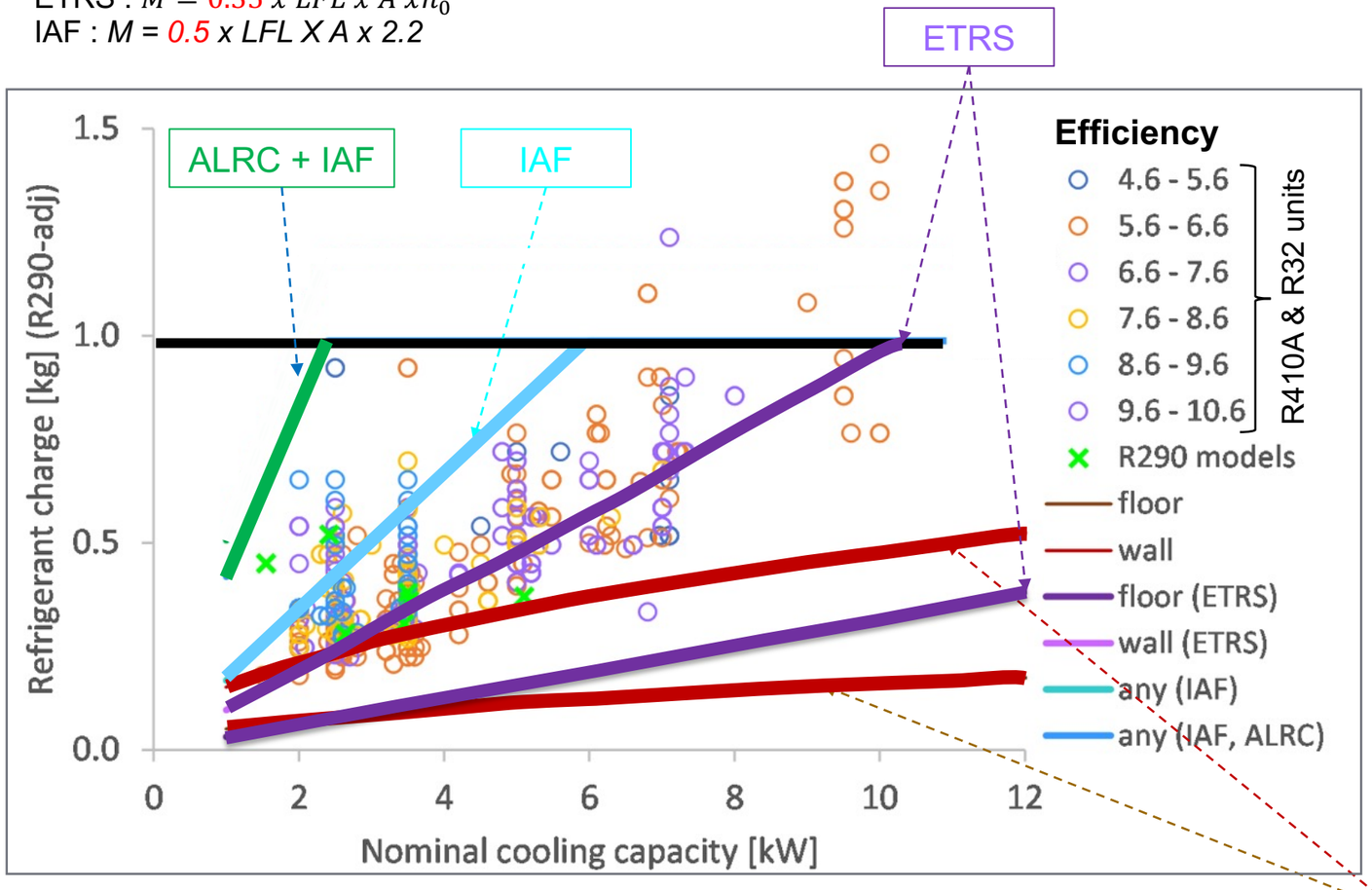
Additional requirement when charge exceeds 150g

- Room size restriction
- Sealed system
- Tubing protected from potential damage
- Limitation of vibrations and resonance in piping
- Surrounding concentration not exceeding 50 % of LFL



New IEC 60335-2-40:2022 Allows Use of Hydrocarbons in Split A/C Indoor Units

Standard System : $M = 2.5\ (LFL)^{1.25}\ A^{0.5}\ h_0$
ETRS : $M = 0.35\ x\ LFL\ x\ A\ x h_0$
IAF : *M = 0.5 x LFL X A x 2.2*



R410A and R32 charge limits converted to R290 (liquid density ratio) - Source D. Colbourne

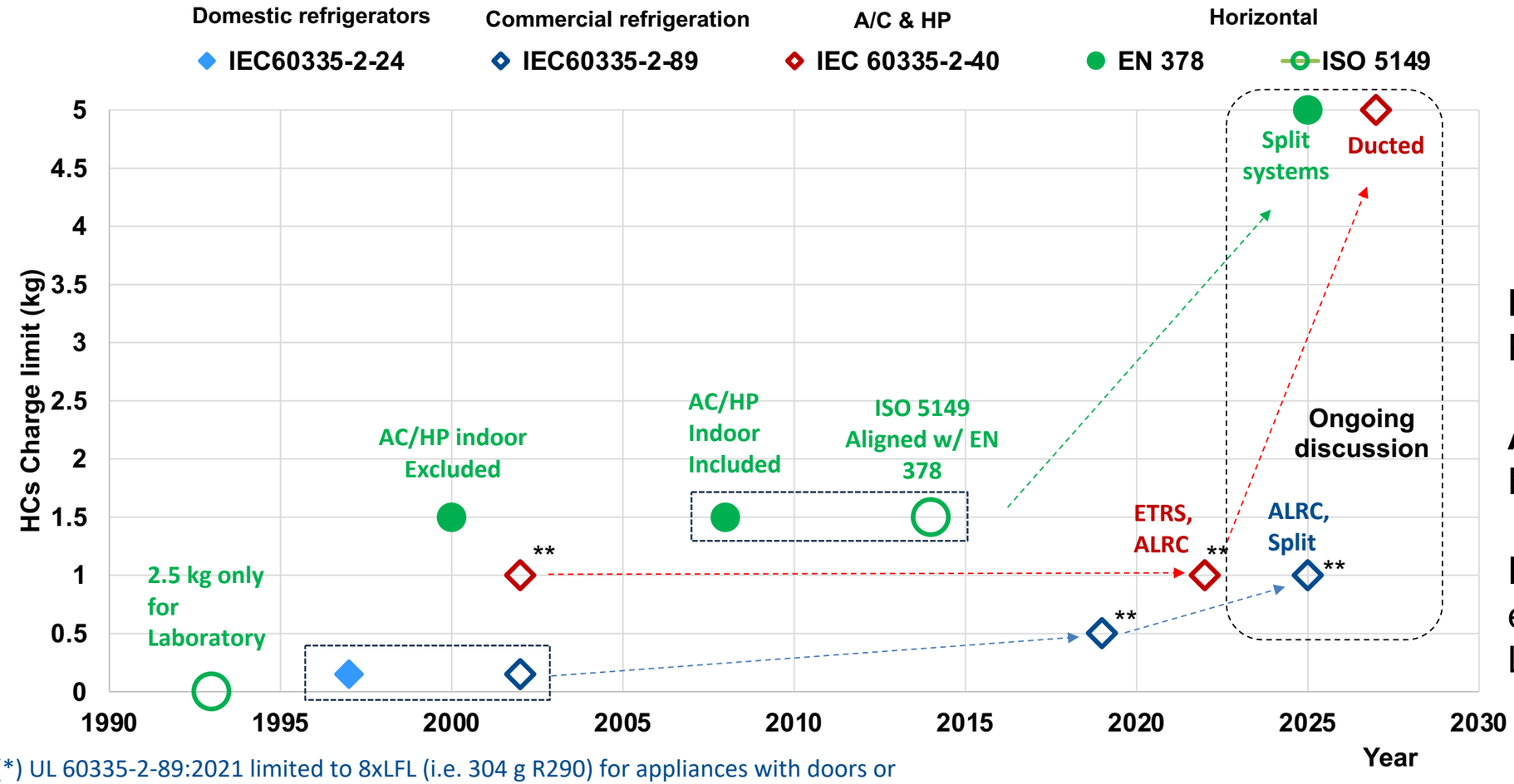
New Measures in IEC 60335-2-40:2022

- ETRS: Enhanced Tightness Refrigerating System, robust design with lower leak rate
- IAF: Integrated Air Flow, dilution of flammable leaks
- ALRC: Active Limited Releasable Charge, measure limiting the leaks (i.e. shut off valve actuated by a leak detector)

- Outdoor unit with secondary fluid and indoor in ventilated enclosure limited to 4.94 kg (~11 lb.)
- Beyond, ISO 5149 is the reference

Previous IEC 60335-2-40: 2018 standard, limiting hydrocarbons

Milestones in Application of Hydrocarbons in HVAC&R Standards for Indoor Space



(*) UL 60335-2-89:2021 limited to 8xLFL (i.e. 304 g R290) for appliances with doors or

(**) limit for R290

ETRS: Enhanced Tightness Refrigerating System

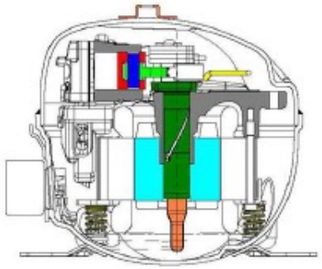
ALRC: Active Limited Releasable Charge

Indoor unit in ventilated enclosure limited to 130 x LFL (*i.e. 4.94 kg for R-290*)

Standards continue to evolve, and very likely the limits will increase

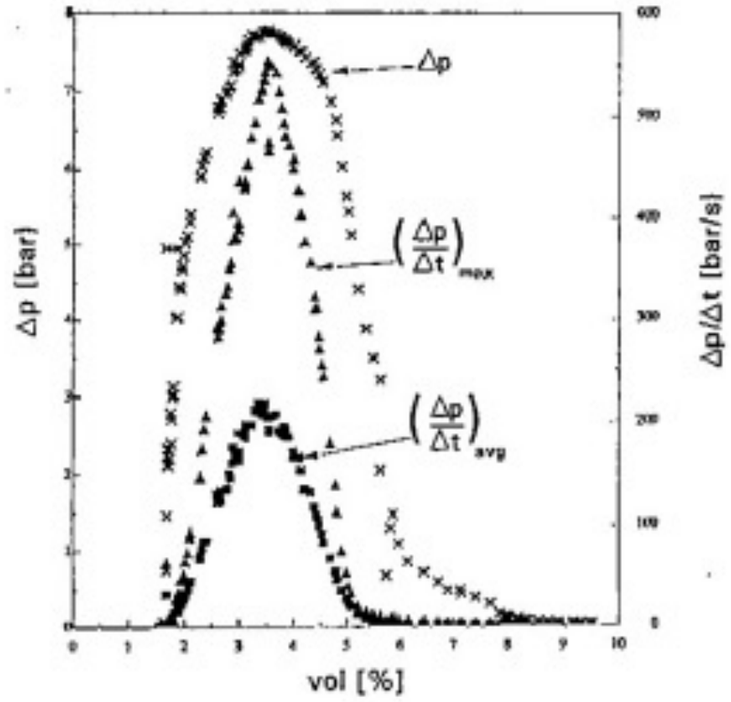
Risk Assessment on Domestic Compressor

Source: M. Zgliczynski and P. Sansalvadore : Purdue conf. 1994



Pioneering risk assessment made by Aspera in 1994, before the standards adopt flammable refrigerants

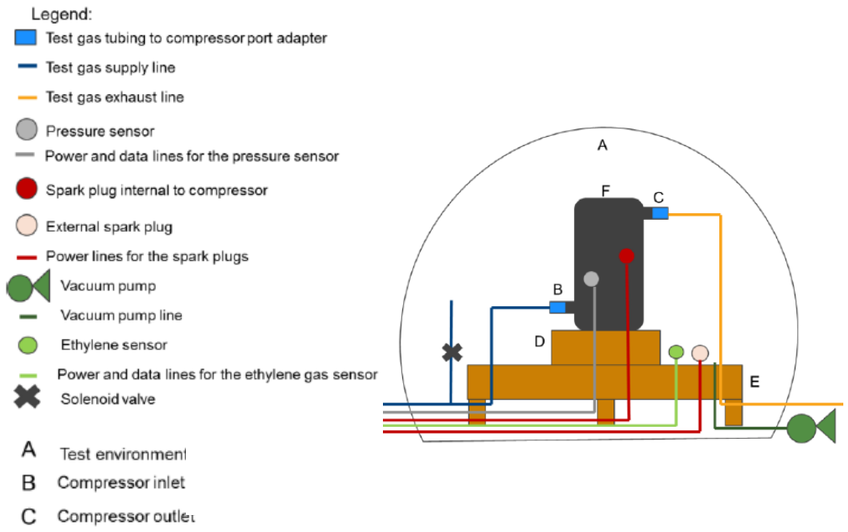
- Experimental explosion tests with R600a/Air mixture
- Experiment shows maximum pressure occurs at stoichiometric mixture (3.5 % v/v)
- Pressure rise up
  - from ambient pressure to ~ 8 bar (116 psi) (ratio ~ 8),
  - from 6 bar (87 psi) to 32 bar (464 psi) (ratio ~ 5.4)
- No mechanical failure observed
- Risk seems to be reasonably low in event of ignition

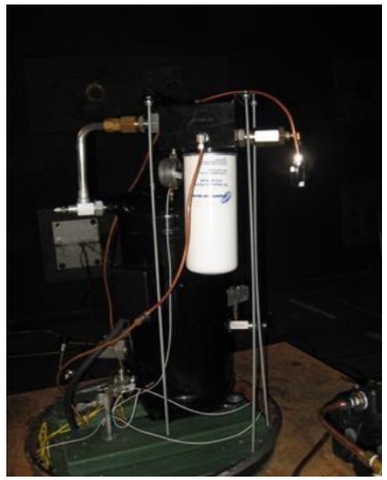


Explosion Assessment of Hydrocarbons in Scroll

Scope

- Artificially create explosion in lower-chamber
- Does explosion propagate to upper-chamber with motor ON and OFF? *Yes,*
- Does enclosure prevent igniting surrounding flammable atmosphere? *Yes,*
- Does enclosure withstand the explosion pressure without bursting? *Yes,*
- Check mechanical damage to the mechanisms *No damage found*
- Measure internal pressures





compressor setup for test

Motor state	R-290		R-1150	
	OFF	ON	OFF	ON
Average peak pressure lower-chamber [bar]	11.0	4.0	5.8	4.9
Average peak pressure upper-chambler [bar]	-	28.1	14.5	8.5
Average pressure rise rate lower-chamber [bar/s]	494	-	703	476
Flammable speed [cm/s]	45		71.0	

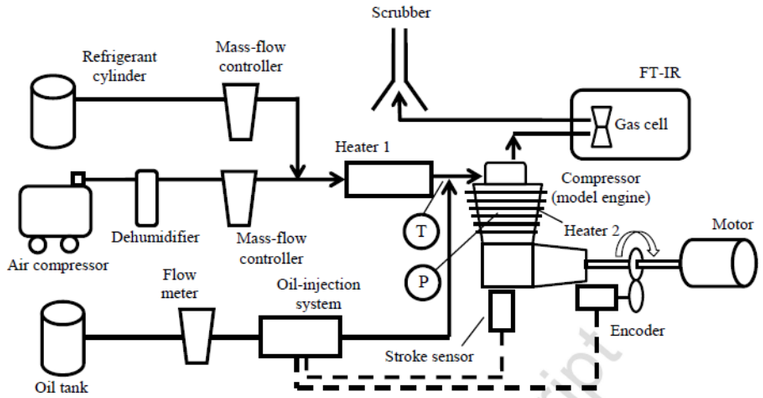
10 flammable mixtures tests for each condition state

Scroll compressor shell designed for much greater pressures

IEC 60335-2-34 : 39 bar lower / 91 bar Upper

Risk Assessment During Incorrect Pump-Down (Dieseling)

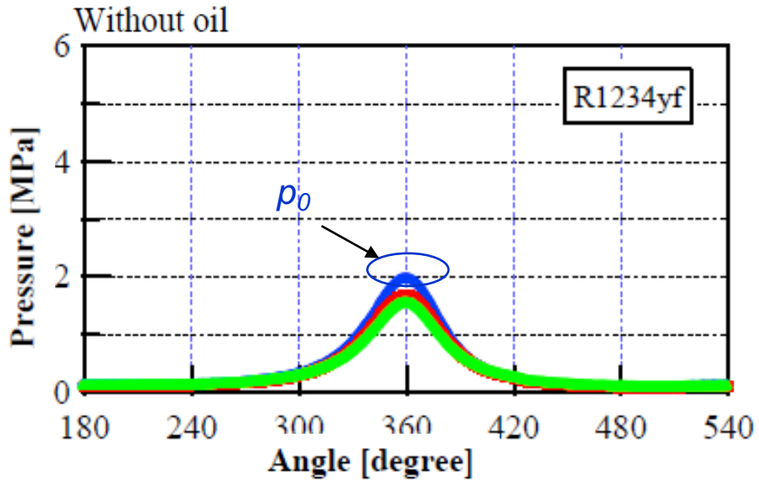
Source : Higashi et al. (IIR.GL.2018, ICR 2015)

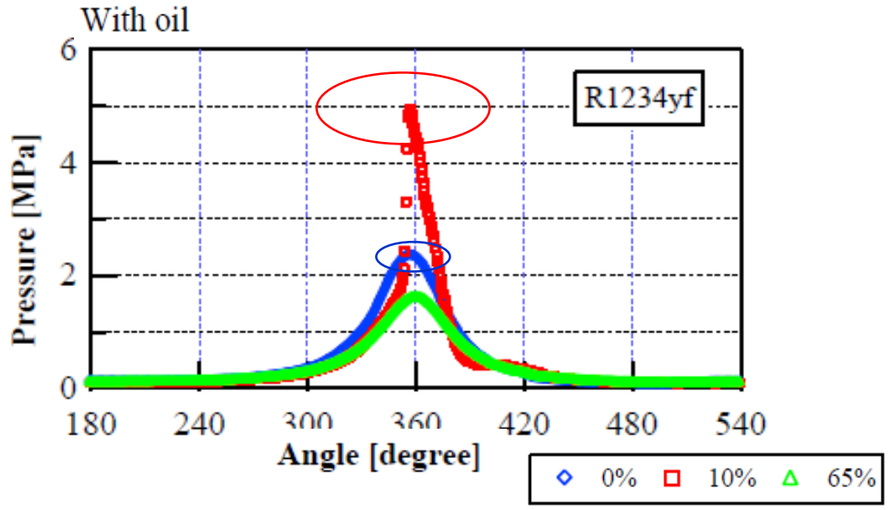


4-stroke Engine compression ratio 16

- Inlet temperature 260°C
- Volumetric compression ratio 16

No combustion with **only** refrigerant/air mixture

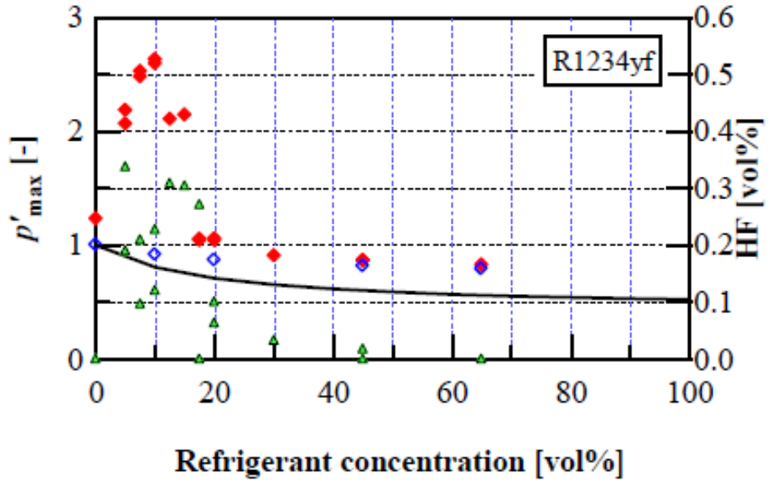


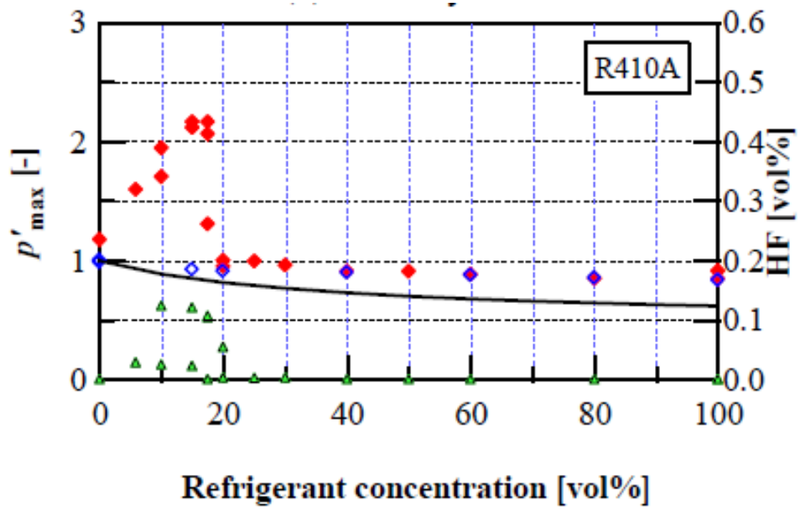


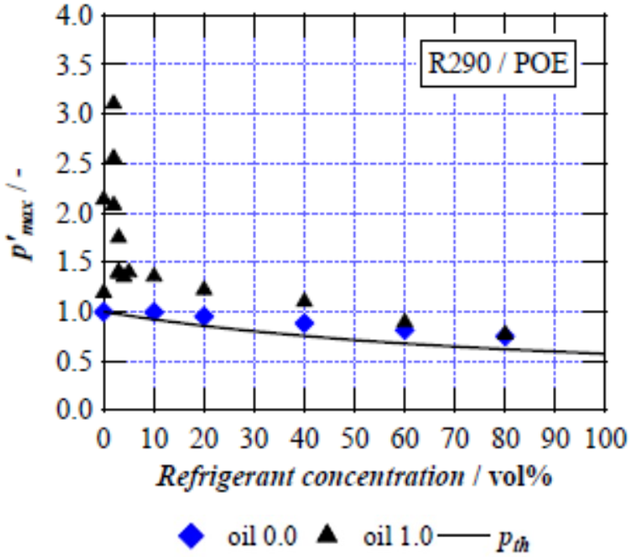
- Pressure **rise** with air/oil mixture (~ 2.4 MPa – 348 psi)
- Pressure **peak** with air/oil/refrigerant (10%) more than 2 times (5.0 MPa – 725 psi)

Risk Assessment During Incorrect Pump-Down (Dieseling)

Source : Higashi et al. (IIR.GL.2018, ICR 2015)







$p'_{max} = \frac{p_{max}}{p_0}$, p_0 max pressure with only air

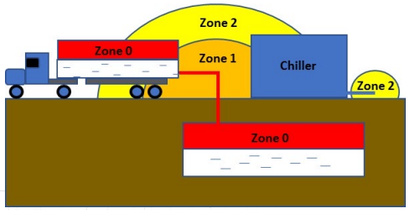
◆ w/ oil ◇ w/o oil —— p_{th} ▲ HF (hydrogen fluoride)

- Pressure peak resulting from combustion of air/lubricant is moderate unless refrigerant is added
- Tendency for combustion to occur at low concentrations of refrigerant
- Flammability range with R290 is narrower than fluorocarbons range (2 % vol.)
- No significant difference in pressure rise between flammable and non-flammables

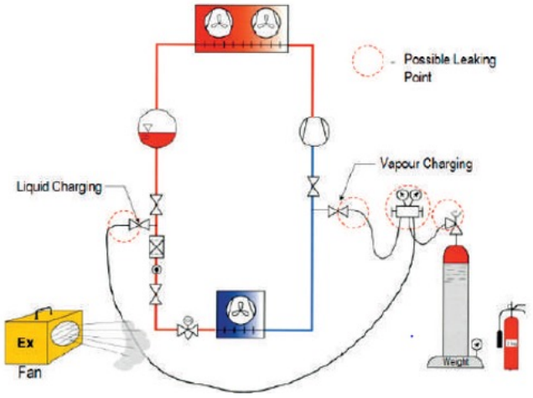
Components Requirement For Flammables Refrigerants

www.asercom.org/wp-content/uploads/2023/04/En_Components-for-Flammable-Refrigerants.pdf

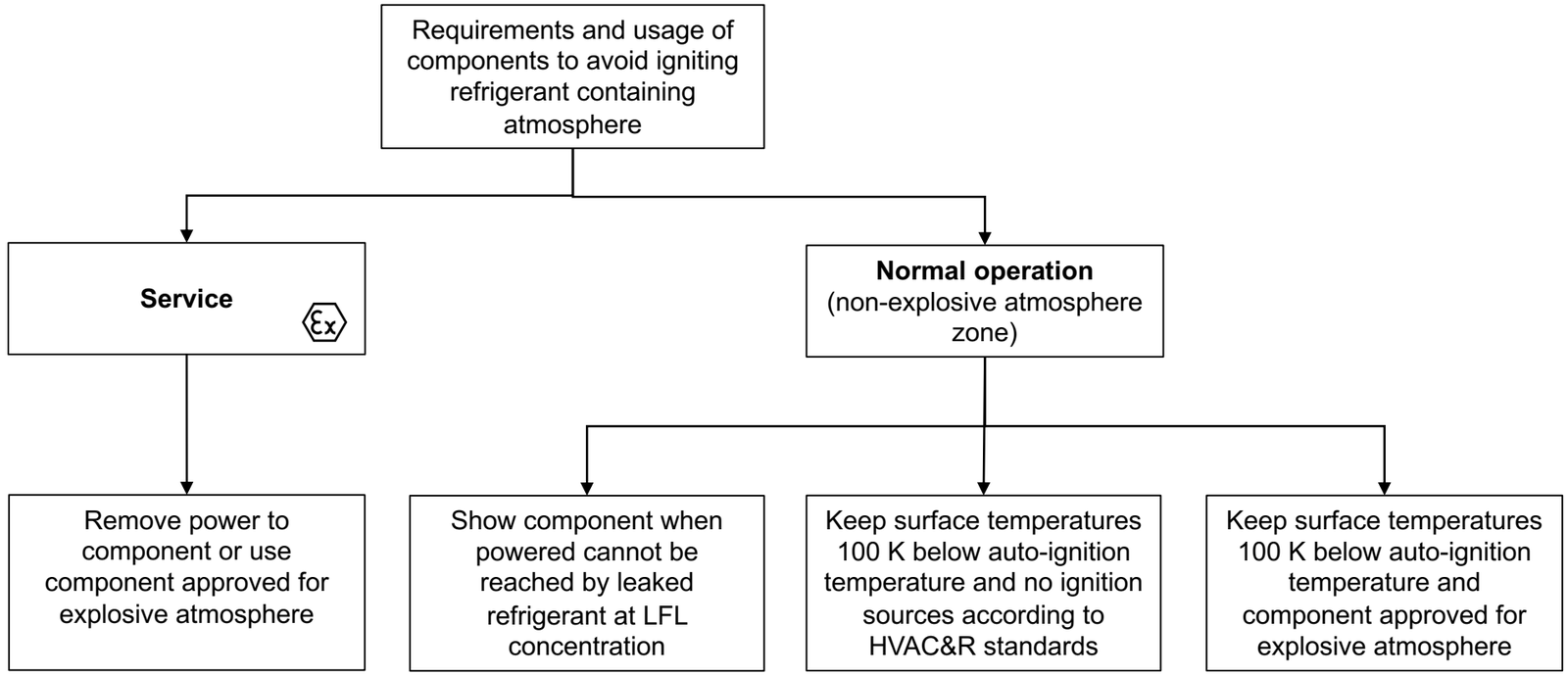
Explosive Atmosphere



Explosive atmosphere approval is required when refrigerating system is installed in an ATEX zone (e.g. petrochemical)



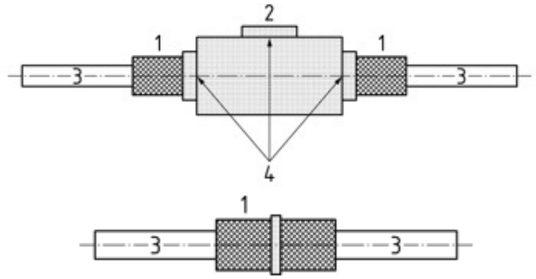
During service, maintenance,… an explosive environment may be generated



Generally, HVAC&R standards are more stringent than ATEX standard

Tightness Requirement for Components & Joints

- HVAC standards require for HCs indoor units **Sealed system**
- **Sealed System** use only sealed components and sealed pipes joints
- ISO 14903 is reference standard for tightness of components and joints



1 joint
2 component body
3 pipe
4 component body joint

		R290 Tightness level [g/a]	Harshness test (pressure-temp, vibration, freeze, Material)	Sealed test (hydrostatic, fatigue)
Components	with Body having only brazing or welding joints	≤ 1.0	Yes**	Not required
	with Body having other permanent body joints (compression, press, ..)	≤ 1.4*	Yes	Yes
Pipings	with brazed or welding joints	1.0	Yes**	Not required
	with other permanent joints (compression, press, …)		Yes	Yes

(*) component with internal volume > 1 liter
(**) : Only pressue and vibration Tests when different base material

Data at 10 bar and 20 °C

Durability & Leak Rate of Field-Made Joints

ASHRAE Research Project Report 1808-RP 2019

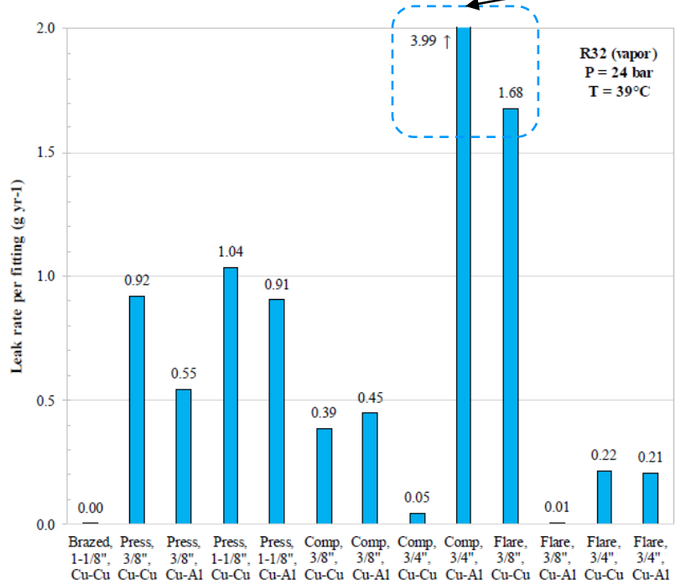



Fitting Type	Brazed	Press	Compression	Flare
Dimensions (pcs)	1-1/8" (25)	3/8" , 1-1/8" (100)	3/8" , 3/4" (100)	3/8" , 3/4" (100)
Failure after assy	12%	1%	22%	56%
Failure rate after repair	12%	1%	8%	4%
PT Cycling Failures (40 pcs*)	0%	0%	8%	3%
FT cycling failures (40 pcs*)	0%	0%	8%	15%
Vibration failures (20 pcs*)	1 OF 5	0%	30%	30%
Sequential failures (4 pcs - 3/8 ")	N.A	0	1	1

freeze-thaw (FT) cycling, pressure/temperature cycling (PT)
Sequential test = Vibration + PT + FT

Average leak rate after all tests (excluding the failed)

One single set with unusual large leak



- **Technician expertise** has significant effect on brazed and flare fittings
- Press fittings show lowest assembly failure rate and highest durability
- Compression and Flares fittings exhibit high level of failure (assembly, testing)

Protection Types From IEC 60079 ATEX Standards

- Leaks in HVAC&R is **similar** to ATEX **Zone 2** for gases IIA (typical propane)
- HVAC&R standards recommend Equipment Protection Levels (EPLs) for zone 2
- Other options are also allowed, details differ from one standard to another

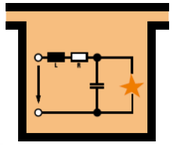
Zone	EPLs
0	Ga'
1	'Ga' or 'Gb'
2	'Ga' or 'Gb' or 'Gc'

Typical Equipment Protections used in HVAC&R from IEC 60079-XX

(XX)	Code	Description	Method of protection
0	-	General Requirement	Includes basic test (Thermal endurance, impact, drop, IP protection, electrostatic…)
1	d	Flameproof equipment	Explosion containment
7	e	Increased safety	Avoid of ignition source
11	i	Intrinsic safety	Energy Limitation
15	n	Non-sparking (nC, nR)	Exclusion
18	m	Molded encapsulation	Exclusion

Non-metallic

Electrical connections



Electronic

Relay

Solenoid coil

Assessment & Measures Applied on Compressor

Tightness measures (ISO 14903)

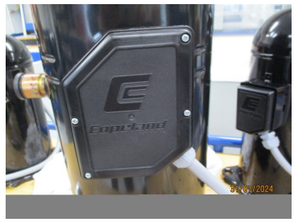
- Hermetical shell
- Only brazed fittings
- Increased requirement for pressure strength, welding and materials for flammable (EU pressure equipment directive)
- Individual Leak tightness test

Protection from electrical sparks (IEC 60079)

- Live parts not source of ignition (increased safety)

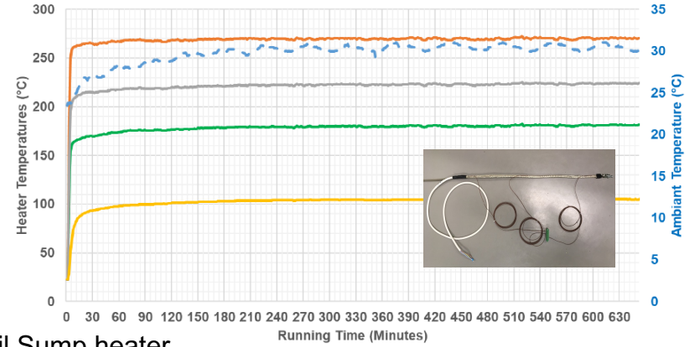
- Switches and Relay protected (nC)

- Non-metallic material with no risk due to electrostatic charges



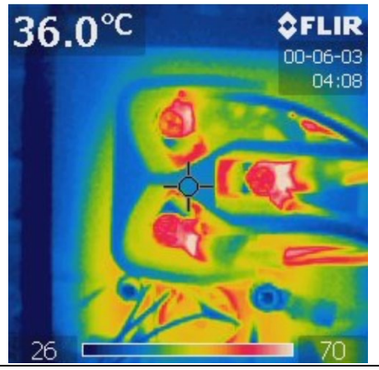
Protection from high surface temperature (IEC 60335)

- Surface temperature in normal and abnormal limited to 370°C



Oil Sump heater

Electrical connectors



Safety Measures for Flow & Control Components

				Safety Measures
Mechanical Products	 Moisture indicator	 Filter	 TXV	Demonstrate tightness (ISO 14903)
Electro-Mechanical Components non ATEX	 Pressure switch	 Solenoid valve	 EEV	 FS controller	Demonstrate tightness (ISO 14903) No source Ignition (e.g. IEC 60335-2-40)
Electronic-Mechanical Components ATEX certified	 Presssure transmitter	 EEV	 Pressure switche	Demonstrate tightness (ISO 14903) ATEX Certified (IEC60079)

R290 Indoor HP installed in Ventilated Enclosure

- Introduced early 1980s, typically exhaust indoor air to water
- Hydraulic space heating & domestic hot water

Basic Safety Measures (IEC 60335-2-40 reference)

- Refrigerating circuit built in an enclosure at -20 Pa or more
- Hermetically sealed system and no ignition sources inside enclosure
- Permanent ventilation in the enclosure to remove all leaked charge in less than 4 min or 4 kg/h leak rate for ETRS
- Secondary fluid Heat exchanger shall not release refrigerant into indoor :
  - **No risk of freezing the condenser as there is no active defrost operation**
  - **Gas separator in the enclosure**

NIBE Indoor HP (2022)
Nominal heating capacity 7 kW (23 k BTU/h)
R290 charge 420g (0.9 lb.)

R290 Outdoor Monobloc HP for Household

- Air to Water HP
- Hydraulic space heating & domestic hot water.

Basic Safety measures (IEC 60335-2-40 reference)

- Refrigerant circuit placed outdoor
- Hermetically sealed system and factory tightness checked
- No ignition sources inside the enclosure
- Leaked refrigerant into the secondary fluid is separated in a gas separator and vented outdoor
- Maintenance on refrigerant systems shall be made by HCs qualified personnel

Air to Water HP Outdoor Monobloc (Viessmann)
Heating capacity (A7/W35) : 5 to 18 kW (18 k to 61 k BTU/h)
R290 Charge 1.4 kg (3.1 lb)

“SKILLSAFE - EU Project” Developing EU Guideline

- Joint Industry Expert Group (JIEG) for developing safety guideline across EU for R290 outdoor monobloc
- Provide essential information for best practices during life cycle, on training and certification
- Draft will be published early 2025
- Will expand later to indoor HPs and other systems

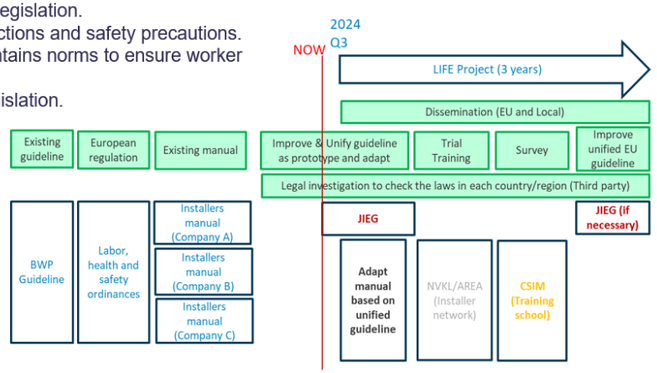
Training and certification

Transport and Logistic | Product information | Installation & Commissioning | Operation/service and Maintenance | Disposal

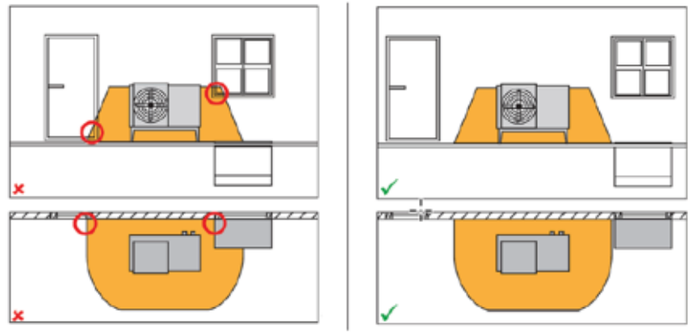
Current Situation:
- The guidelines across Europe are fragmented.
- Existing guidelines include national industry guidelines, manufacturing manuals, and European health and safety legislation.
- Installer manuals provide installation instructions and safety precautions.
- European Health and Safety legislation contains norms to ensure worker safety.
- National guidelines incorporate national legislation.

To overcome this fragmentation, the JIEG's aim is to develop and implement a uniform safety guideline across the EU and will work on:
1. **Data and information collection**
2. **Development of uniform guidelines**

The project consortium will then continue with the following tasks:
3. **Pilot site testing**
4. **Risk assessment and finalisation**



Outdoor installation guidance



Bundesverband wärmepumpe guideline

Interest of Hydrocarbons in Steam Raising High Temperature Heat Pumps

- Growing interest in higher temperature heat pump applications,

  e.g. steam generation heat pumps 140 - 160 °C (284 - 320 F)

- Pentane (R-601) one of most promising working fluids under investigation for industrial stream generation heat pumps (Tcritical = 196.5 °C)
- Heating COP is about 10% better than n-butane (R-600) under similar conditions
- **Low volumetric cooling capacity and sub-atmospheric pressure at room temperature are challenges to address**

Conclusion

- Measures introduced into safety standards over the years have made it possible to increase the charge limits of highly flammable refrigerants
- Further research is still needed to enable standards using increased charges
- System tightness is one key requirement
- Very limited risk from dieseling and explosion from ambient pressure
- Components shall be designed for use with flammable gases
- Guidelines and training is an important part of the puzzle for the success of hydrocarbons in HVAC&R

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Thank You For Your Attention