

AN UPDATE ON LOW-GWP REFRIGERANTS: Options and Challenges

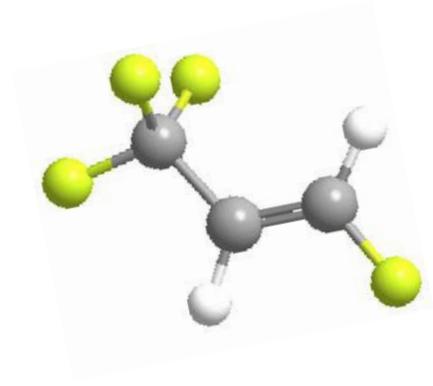
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Acknowledgement:

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Outline



- **50th anniversary (1971 to 2021); what changed?**
- **Evolution of refrigerant applications**
- **Low-GWP refrigerant options**
- **Concluding comments**

50th anniversary of establishment of SAREK (1971 to 2021) What changed?

Year 1971 issues

Power generation

- Plenty of coal but proven oil reserves for 30 years only

Year 2021 issues

By-products of power generation

- CO₂ emissions (fossil fuel) → 2015 Paris Agreement
- Nuclear waste and safety (nuclear power plants)
- Ecological impacts (hydroelectric dams)



Industrial revolution (1760~1840)

- Improved productivity through inventions and new production methods

Watt's steam engine; iron production; textile industry ...

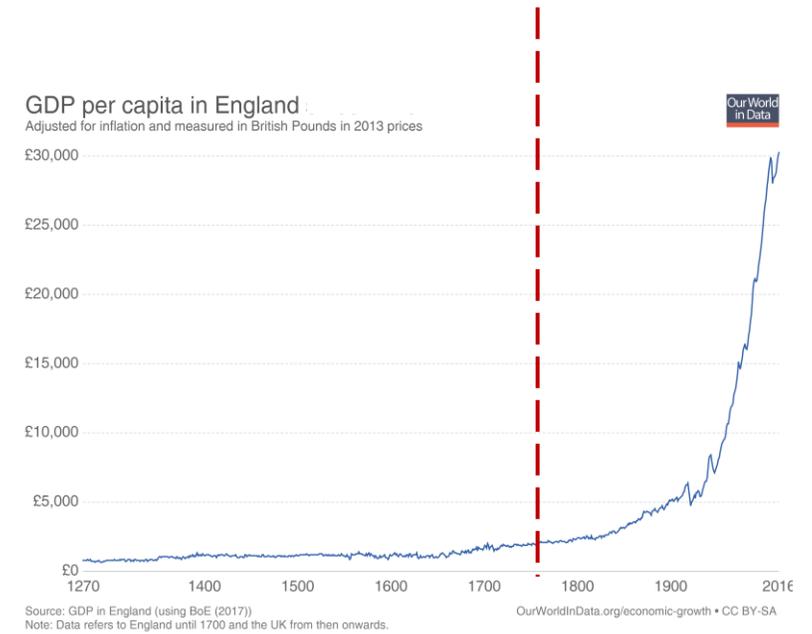
- 2015 Paris Agreement

Hold global warming to well below **2 °C** and pursue to limit global warming to **1.5 °C** relative to pre-industrial levels.

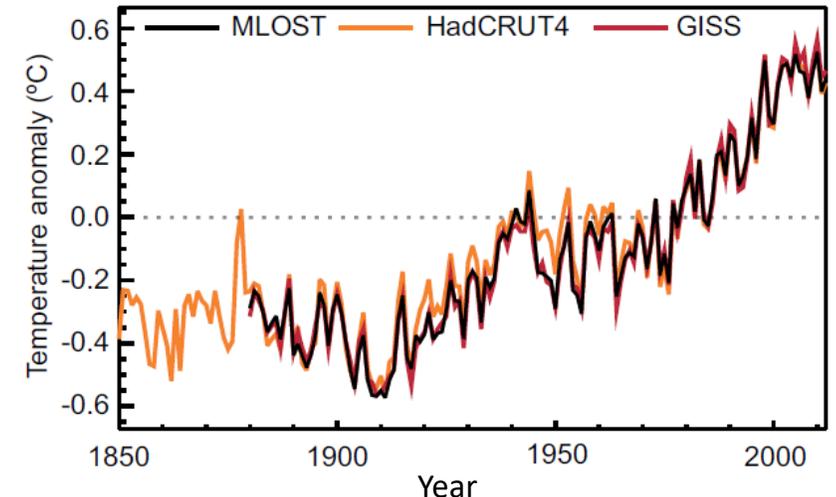
UN (2015)

Average global temperatures reached **1 °C** above pre-industrial levels in 2015 for the first time. Cléménçon (2016)

The Earth is within **1 °C** of the “**2 °C** limit”.



OurWorldInData (2021)



Annual global mean surface temperature relative to 1961 – 1990 average (three databases shown), Myhre, G. et al. (2013)

Use of refrigeration has environmental consequences

○ 7.8 % of global GHG emissions are attributed to the refrigeration sector

Direct emission contribute 37 %



- Low-GWP refrigerants
- Improved containment
- Lower refrigerant charge
- End-of-life recovery



○ Kigali Amendment to the Montreal Protocol

Over 80 % cut in production & consumption of HFCs by 2047



Bring weighted GWP across all sectors to ≈ 300

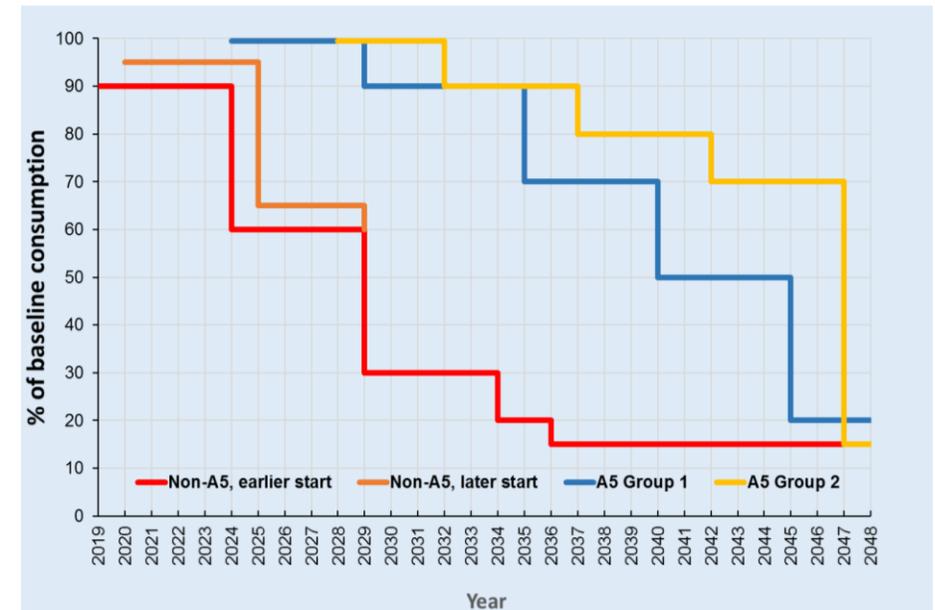


Reduce future global warming due to HFC
from **0.3 °C to 0.5 °C** to less than **0.1 °C**

Indirect emissions contribute 63 %



- Increase of efficiency
- Automated fault detection



Refrigerant safety classification

ANSI/ASHRAE Std. 34-2019: Designation and Safety Classification of Refrigerants

ISO 817:2014: Refrigerants – Designation and safety classification

Flammability classification

Class 1: No Flame Propagation (ASTM E681 test)

Class 2L: Lower Flammability

LFL > 0.10 kg/m³ (ISO 817: 3.5 % by volume)

Heat of combustion < 19000 kJ/kg

Burning velocity ≤ 10 cm/s

Class 2: Flammable

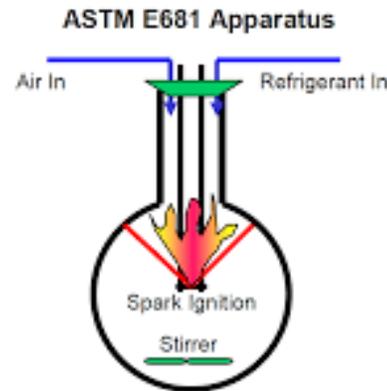
LFL > 0.10 kg/m³ (ISO 817: 3.5 % by volume)

Heat of combustion < 19000 kJ/kg

Class 3: Higher Flammability

LFL ≤ 0.10 kg/m³ or

Heat of combustion ≥ 19000 kJ/kg



F L A M M A B I L I T Y	SAFETY GROUP		
	Higher Flammability	A3	B3
	Flammable	A2	B2
	Lower Flammability	A2L	B2L
No Flame Propagation	A1	B1	
	Lower Toxicity	Higher Toxicity	

→ INCREASING TOXICITY

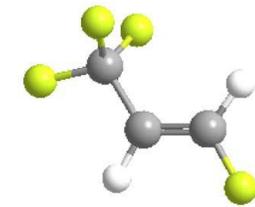
Toxicity classification

Class A: Lower toxicity; OEL ≥ 400 ppm (v/v)

Class B: Higher toxicity; OEL < 400 ppm (v/v)

Evolution of refrigerant applications

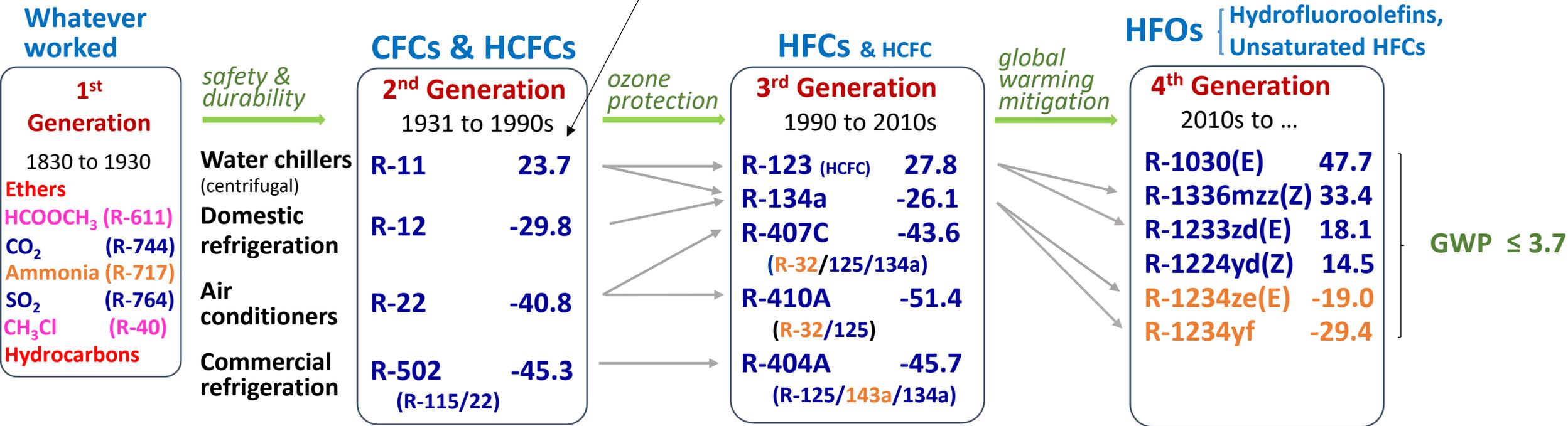
■	No flame propagation	1
■	Lower flammability	2L
■	Flammable	2
■	Higher flammability	3



HFO-1234ze(E)

└─── # of fluorine atoms
└─── # of hydrogen atoms +1
└─── # of carbon atoms -1
└─── # C=C double bonds

Normal bubble point (°C)



Evolution of refrigerant applications

■	No flame propagation	1
■	Lower flammability	2L
■	Flammable	2
■	Higher flammability	3

Natural fluids

Whatever worked

1st Generation

1830 – 1930

Ethers
 HCOOCH_3 (R-611)
 CO_2 (R-744)
 Ammonia (R-717)
 SO_2 (R-764)
 CH_3Cl (R-40)
 Hydrocarbons

safety & durability

Water chillers (centrifugal)
 Domestic refrigeration
 Air conditioners
 Commercial refrigeration

CFCs & HCFCs

2nd Generation

1931 to 1990s

R-11	23.7
R-12	-29.8
R-22	-40.8
R-502 (R-115/22)	-45.3

ozone protection

HFCs & HCFC

3rd Generation

1990 to 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C (R-32/125/134a)	-43.6
R-410A (R-32/125)	-51.4
R-404A (R-125/143a/134a)	-45.7

global warming mitigation

Fluorinated single-compound options

HFOs & HFCs

4th Generation

2010s to ...

R-1030(E)	47.7
R-1336mzz(Z)	33.4
R-1233zd(E)	18.1
R-1224yd(Z)	14.5
R-1234ze(E)	-19.0
R-1234yf	-29.4
R-152a	-24.0
R-32	-51.7

GWP ≤ 3.7

GWP = 138

GWP = 677

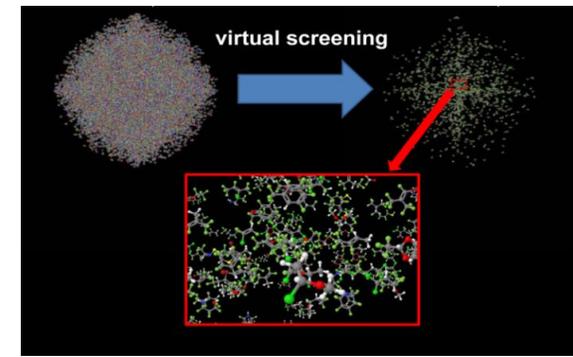
NIST Database screening for R-410A substitutes

PubChem database

- Component atoms: C, H, N, O, S, F, Cl, Br
- Maximum number of atoms: 18

Molecule count

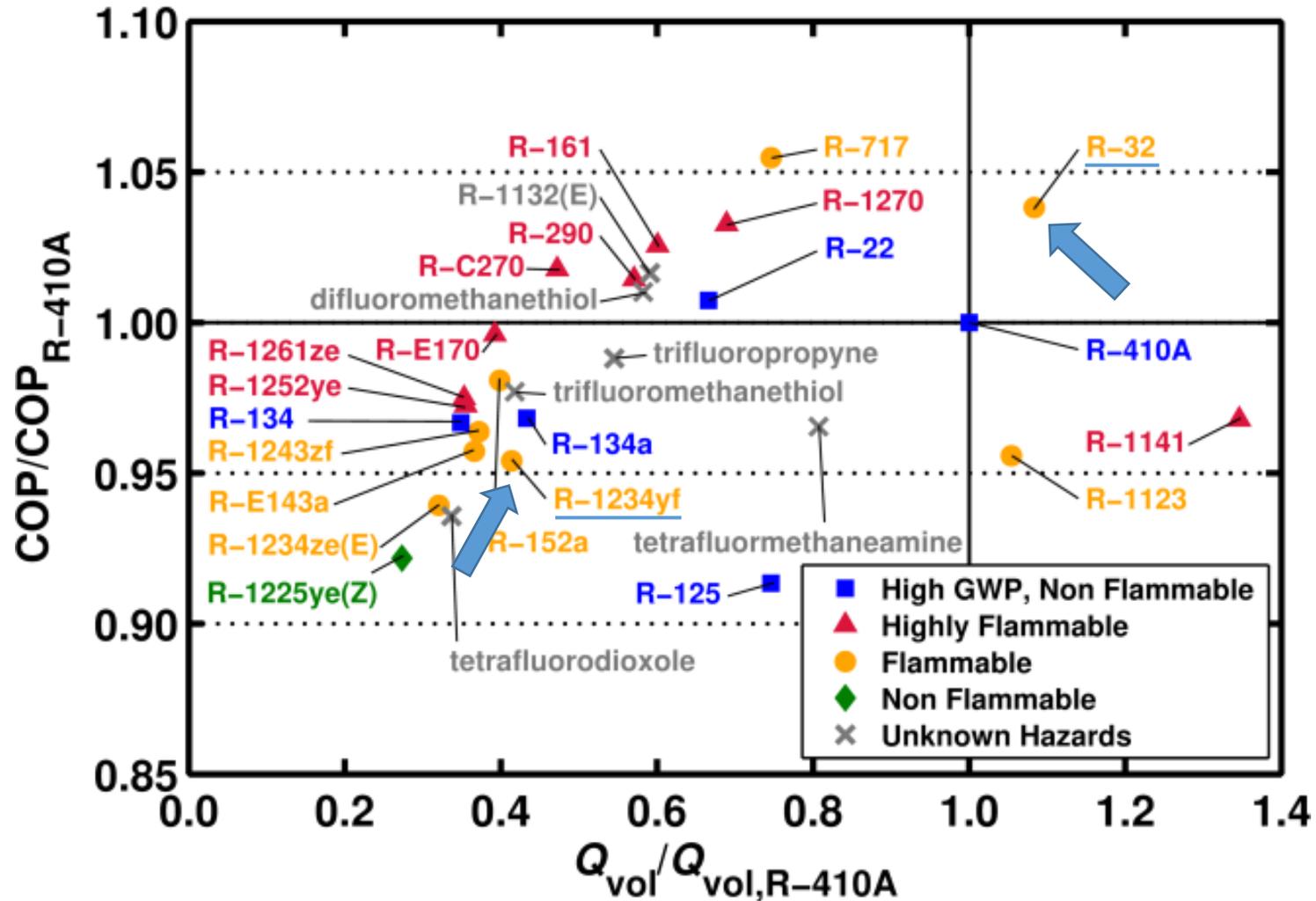
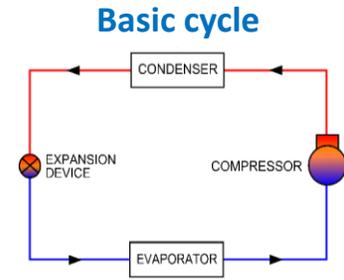
60 000 000



Nonmetallic					
				H	
B	C	N	O	F	Noble gases
	Si	P	S	Cl	
		As	Se	Br	
			Te	I	
				At	
Metals					

COP and Q_{vol}

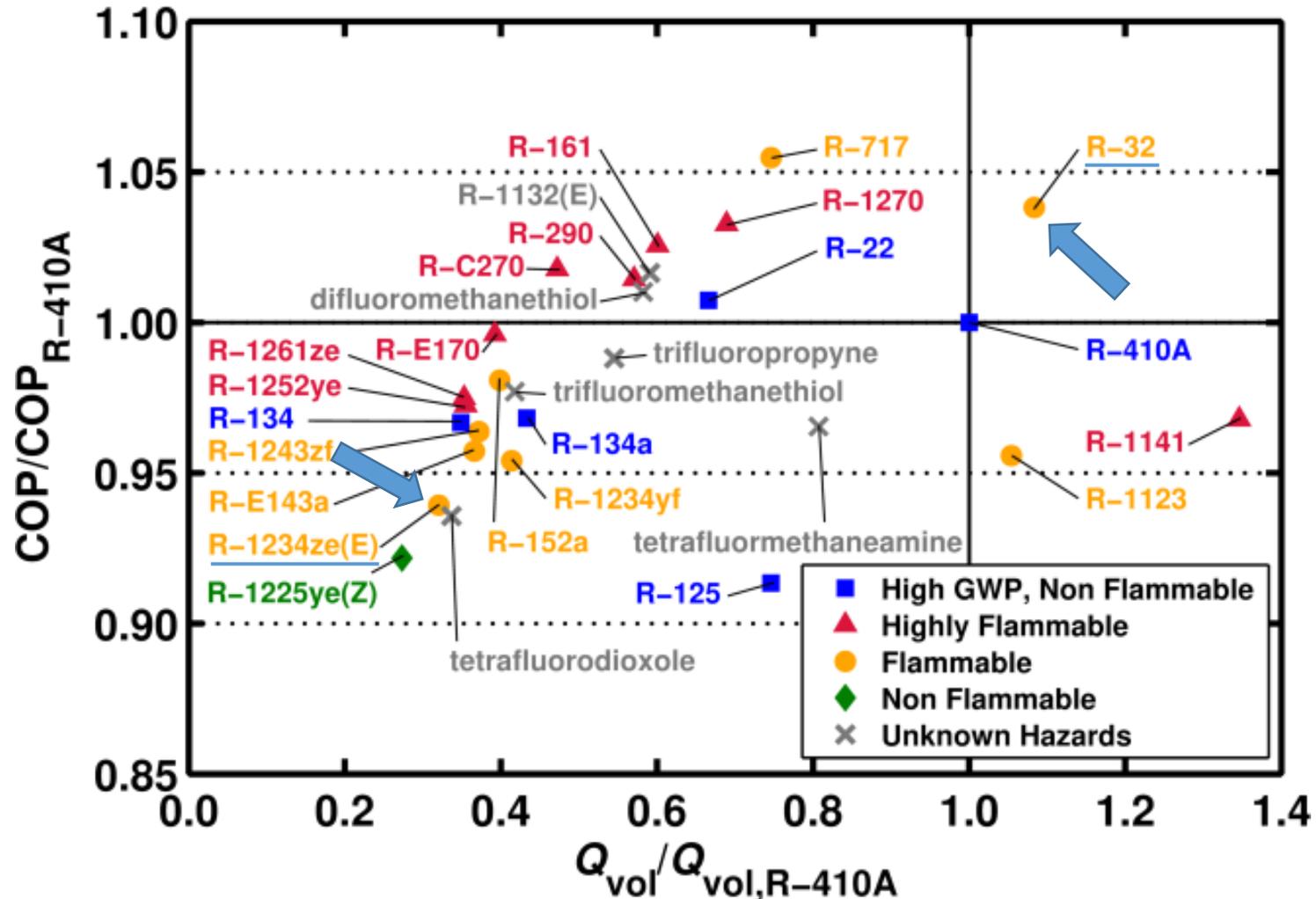
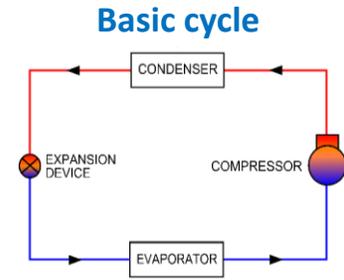
Air conditioning



Capacity boosters: R-41, R-1132a, R-170, R-744

COP and Q_{vol}

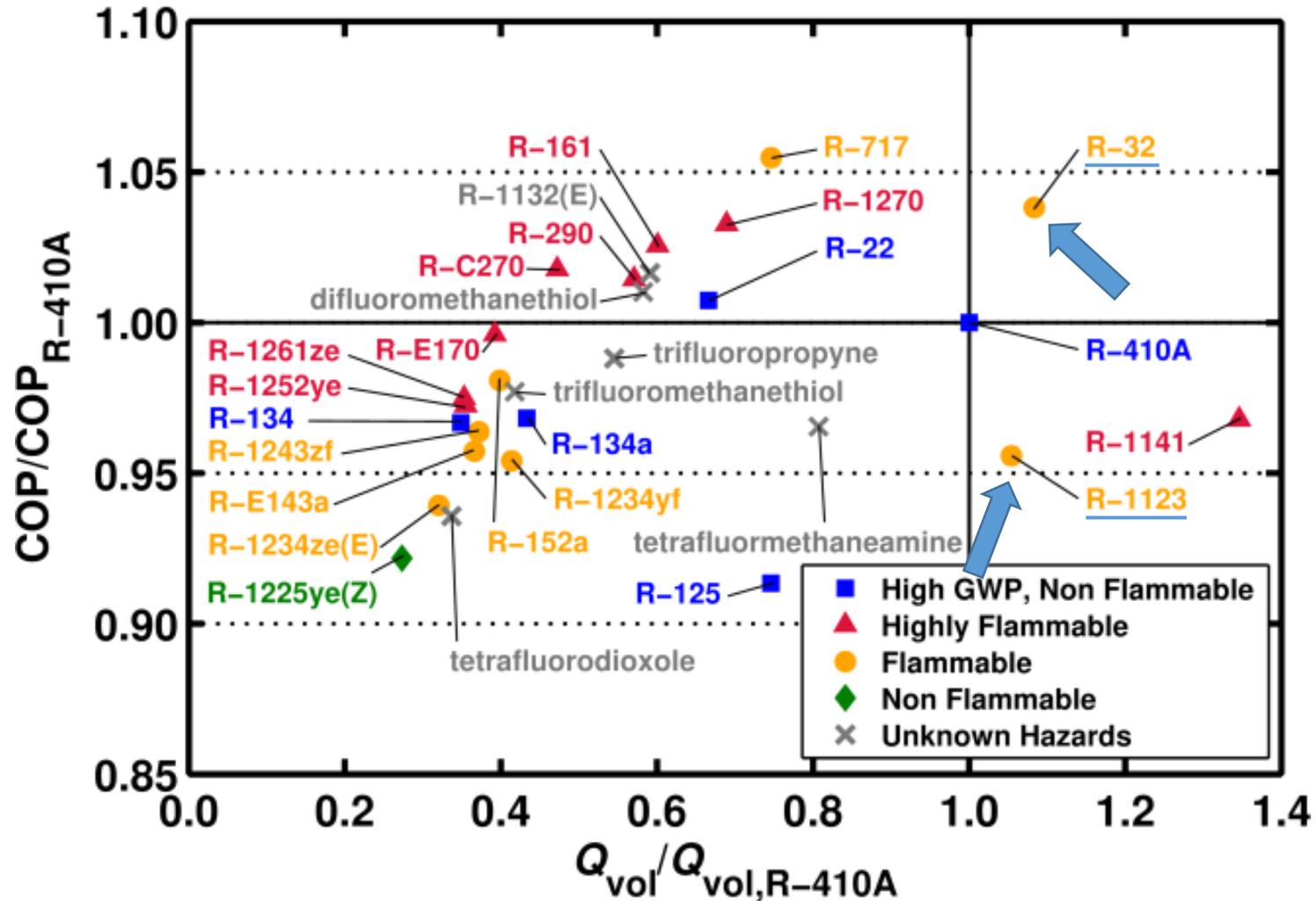
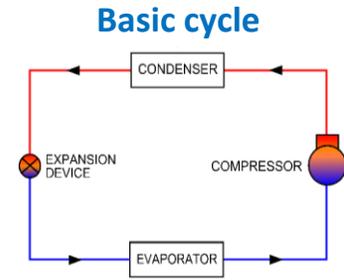
Air conditioning



Capacity boosters: R-41, R-1132a, R-170, R-744

COP and Q_{vol}

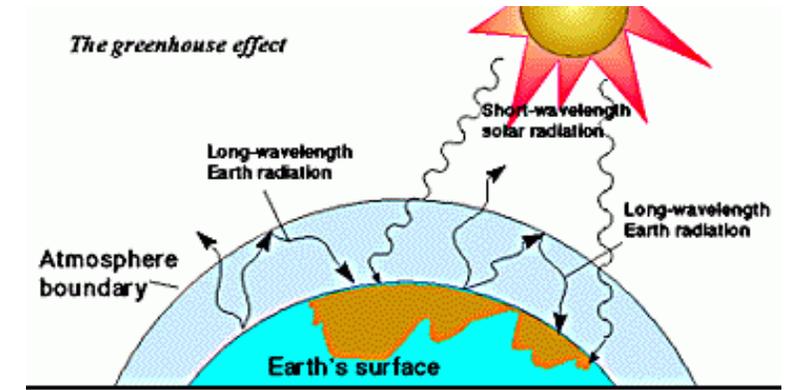
Air conditioning



Capacity boosters: R-41, R-1132a, R-170, R-744

Global Warming Potential (GWP)

**GWP = Time-integrated global mean radiative forcing
referenced to that of CO₂ (100 years horizon)**



- **Ability to trap Earth's infrared radiation [radiative efficiency, RE (W·m⁻²·ppb⁻¹)]**

$$RE_{\text{CFC, HCFC, HFC}} = 0.10 \text{ to } 0.32$$

$$RE_{\text{HFO}} = 0.01 \text{ to } 0.07$$

HFOs have a lower RE by one order of magnitude.

- **Atmospheric lifetime, LT (years)**

$$LT_{\text{CFC}} = \text{up to } 1020$$

$$LT_{\text{HCFC}} = \text{up to } 17$$

$$LT_{\text{HFC}} = \text{typically } 5 \text{ to } 29 \text{ (up to } 242)$$

$$LT_{\text{HFO}} < 0.06$$

HFOs have a shorter LT by up to three orders of magnitude.

$$GWP_{\text{CFC}} = 4660 \text{ to } 13900$$

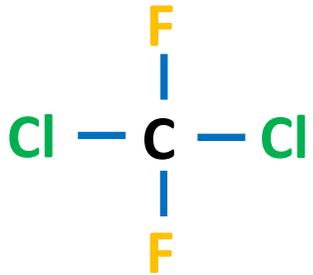
$$GWP_{\text{HCFC}} = 79 \text{ to } 1980$$

$$GWP_{\text{HFC}} = 4 \text{ to } 12400$$

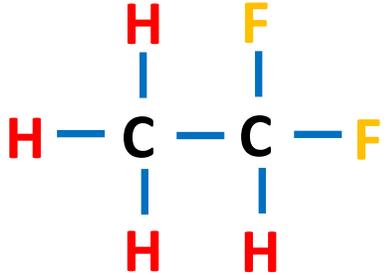
$$GWP_{\text{HFO}} \leq 16$$

$$GWP_{\text{HC}} \leq 1$$

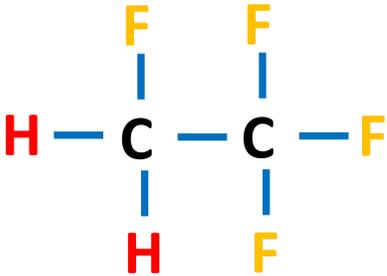
Trade-off between GWP and flammability



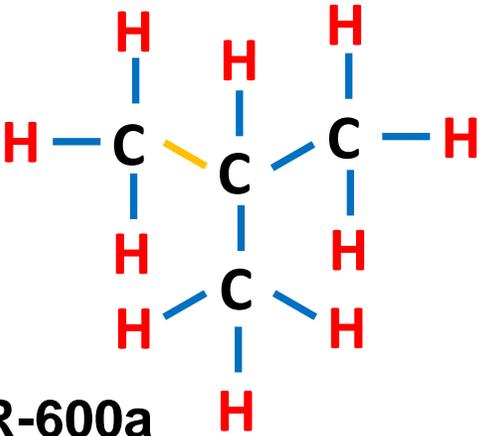
R-12
GWP = 10200; Safety: A1



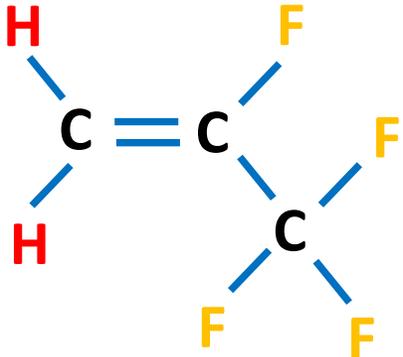
R-152a
GWP = 138; Safety: A2



R-134a
GWP = 1300; Safety: A1



R-600a
GWP < 1; Safety: A3



R-1234yf
GWP < 1; Safety: A2L

Both **H** and **C = C** shorten atmospheric life (GWP ↓) and increase flammability.

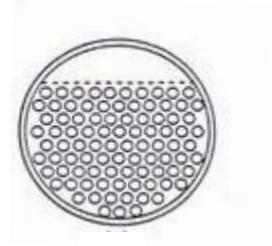
Cycle simulations with CYCLE_D-HX

Input data

- Inlet and outlet temperatures of heat sink and heat source
- Compressor efficiency

Water-to-refrigerants hxs

- $\Delta T_{hx, evaporator}$ and $\Delta T_{hx, condenser}$ the same for each fluid
- Zero pressure drop



Air-to-refrigerant hxs

- Optimization of the number of parallel refrigerant circuits to maximize COP

The same for all refrigerants

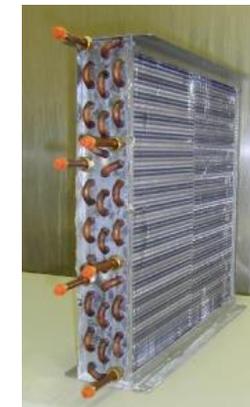
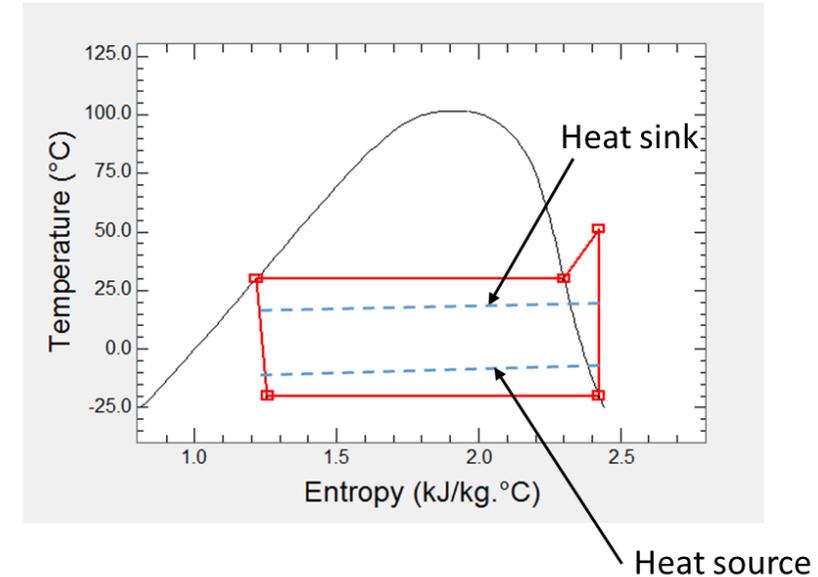
- $\Delta T_{hx} = \frac{Q_{hx}}{UA_{hx}}$

$$UA_{hx} = \frac{1}{\underbrace{[R_{air} + R_{tube}]}_{\text{The same for all refrigerants}} + R_r}$$

The same for all refrigerants

Calculated for each refrigerant

- Pressure drop simulated in relation to the value for the reference fluid

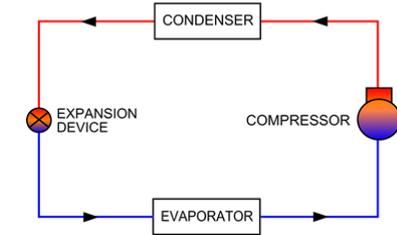


Low-GWP refrigerant options

Centrifugal water chillers (water cooled)



■	No flame propagation	1
■	Lower flammability	2L
■	Flammable	2
■	Higher flammability	3



AHRI Std. 550/590 test conditions

HFCs & HCFC

Low-GWP options

3rd Generation

1990 – 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C	-43.6
(R-32/125/134a)	
R-410A	-51.4
(R-32/125)	
R-404A	-45.7
(R-125/143a/134a)	

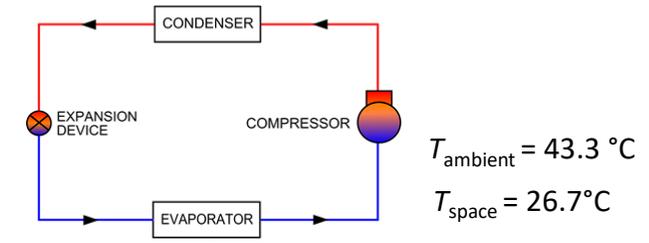
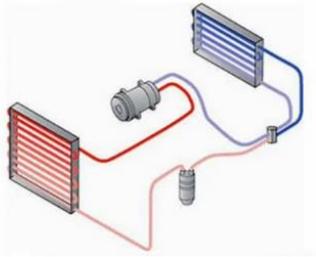
4th Generation

2010s –

	NBP (°C)	Safety	GWP	Composition (mass)	$\frac{COP}{COP_{ref}}$	$\frac{Q_v}{Q_{v,ref}}$
R-514A	29.0	B1	2*	R-1336mzz(Z)/1130(E) (74.7/25.3)	≈1.0	≈1.0 ^{&}
R-1233zd(E)	18.1	A1	3.7*		0.99	1.37
R-1224yd(Z)	14.5	A1	<1 [#]		0.97	1.55
R-515B	-19.0	A1	299	R-1234ze(E)/227ea (91.1/8.9)	0.99	0.73
R-1234ze(E)	-19.0	A2L	<1		0.99	0.74
R-513A	-29.2	A1	573	R-1234yf/134a (56/44)	0.97	1.01
R-1234yf	-29.4	A2L	<1		0.96	0.94
R-516A	-29.4	A2L	131	R-1234yf/134a/152a (77.5/8.5/14)	0.97	0.99

Low-GWP refrigerant options

Automotive air conditioner



HFCs & HCFC

Low-GWP options

3rd Generation

1990 – 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C	-43.6
(R-32/125/134a)	
R-410A	-51.4
(R-32/125)	
R-404A	-45.7
(R-125/143a/134a)	

4th Generation

2010s –

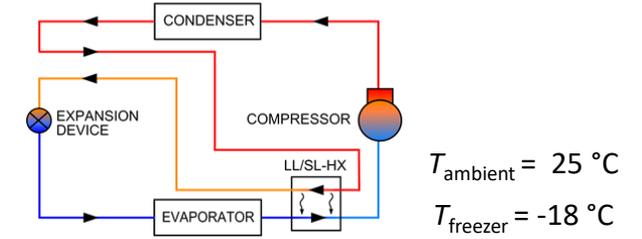
	NBP (°C)	Safety	GWP	Composition (mass)	$\frac{COP}{COP_{ref}}$	$\frac{Q_v}{Q_{v,ref}}$	Glide (°C)
R-744 (CO₂)	-78.0	A1	1				
R-444A	-34.3	A2L	1	R-32/ 152a /1234ze(E) (21/5/83)	0.98	1.01	10.0
R-1234yf	-29.4	A2L	<1		0.91	0.91	
R-516A	-29.4	A2L	131	R-1234yf/ 134a / 152a (77.5/8.5/14.0)	0.96	0.96	
R-152a	-29.2	A2	138		1.07	0.98	
R-513A	-29.2	A1	573	R-1234yf/ 134a (56/44)	0.95	1.00	
R-450A	-23.4	A1	547	R-134a/ 1234ze(E) (42/58)	0.98	0.86	0.6
R-1234ze(E)	-19.0	A2L	<1		0.97	0.73	
R-515B	-19.0	A1	299	R-1234ze(E)/ 227ea (91.1/8.9)	0.96	0.72	

Glide at normal bubble point

Transition to R-1234yf is dominant for MAC systems.

Low-GWP refrigerant options

Domestic refrigerator



HFCs & HCFC

Low-GWP options

3rd Generation
1990 – 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C	-43.6
(R-32/125/134a)	
R-410A	-51.4
(R-32/125)	
R-404A	-45.7
(R-125/143a/134a)	

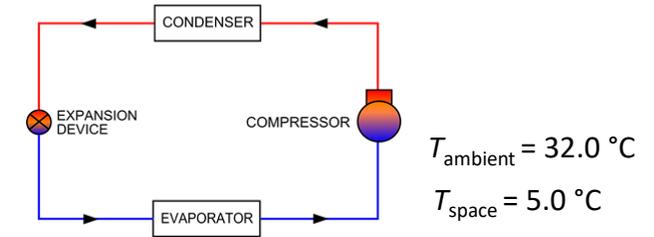
4th Generation
2010s –

	NBP (°C)	Safety	GWP	Composition (mass)	$\frac{COP}{COP_{ref}}$	$\frac{Q_v}{Q_{v,ref}}$	Glide (°C)
R-744 (CO₂)	-78.0	A1	1				
R-444A	-34.3	A2L	1	R-32/152a/1234ze(E) (21/5/83)	0.98	0.95	10.0
R-1234yf	-29.4	A2L	<1		0.96	1.07	
R-516A	-29.4	A2L	131	R-1234yf/134a/152a (77.5/8.5/14.0)	0.98	1.06	
R-152a	-29.2	A2	138		1.06	0.90	
R-513A	-29.2	A1	573	R-1234yf/134a (56/44)	0.98	1.10	
R-450A	-23.4	A1	547	R-134a/1234ze(E) (42/58)	0.99	0.84	0.6
R-1234ze(E)	-19.0	A2L	<1		0.97	0.69	
R-515B	-19.0	A1	299	R-1234ze(E)/227ea (91.1/8.9)	0.96	0.67	
R-600a	-11.7	A3	<1*		1.01	0.49	

Transition to R-600a has occurred in the E.U.

Low-GWP refrigerant options

Commercial refrigeration; reach-in cooler, $T_{\text{space}} = 5\text{ }^{\circ}\text{C}$



HFCs & HCFC

Low-GWP options

3rd Generation

1990 – 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C	-43.6
(R-32/125/134a)	
R-410A	-51.4
(R-32/125)	
R-404A	-45.7
(R-125/143a/134a)	

4th Generation

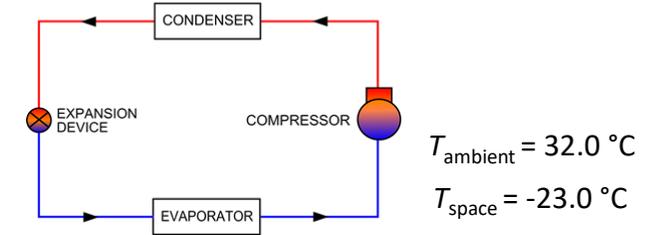
2010s –

	NBP ($^{\circ}\text{C}$)	Safety	GWP	Composition (mass)	$\frac{\text{COP}}{\text{COP}_{\text{ref}}}$	$\frac{Q_v}{Q_{v\text{ref}}}$	Glide ($^{\circ}\text{C}$)
R-744 (CO₂)	-78.0	A1	1				
R-290	-42.3	A1	<1*		1.05	1.49	
R-444A	-34.3	A2L	89	R-32/152a/1234ze(E) (12/5/83)	0.95	1.00	10.0
R-1234yf	-29.4	A2L	<1		0.94	0.96	
R-516A	-29.4	A2L	131	R-1234yf/134a/152a (77.5/8.5/14.0)	0.98	1.01	
R-152a	-29.2	A2	138		1.04	0.95	
R-513A	-29.2	A1	573	R-1234yf/134a (56/44)	0.97	1.04	
R-450A	-23.4	A1	547	R-134a/1234ze(E) (42/58)	0.98	0.86	0.6
R-1234ze(E)	-19.0	A2L	<1		0.97	0.72	
R-515B	-19.0	A1	299	R-1234ze(E)/227ea (91.1/8.9)	0.98	0.71	

Low-GWP refrigerant options

Commercial refrigeration; low-temp walk-in freezer, $T_{space} = -23\text{ °C}$

■	No flame propagation	1
■	Lower flammability	2L
■	Flammable	2
■	Higher flammability	3



HFCs & HCFC

Low-GWP options

3rd Generation

1990 – 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C	-43.6
(R-32/125/134a)	
R-410A	-51.4
(R-32/125)	
R-404A	-45.7
(R-125/143a/134a)	

4th Generation

2010s –

	NBP (°C)	Safety	GWP	Composition (mass)	$\frac{COP}{COP_{ref}}$	$\frac{Q_v}{Q_{v,ref}}$	Glide (°C)
R-455A	-51.6	A2L	147	R-744/32/1234yf (3.0/21.5/75.5)	1.02	0.90	12.5
R-454C [#]	-46.0	A2L	146	R-32/1234yf (21.5/78.5)	1.03	0.82	8.2
R-452A	-47.0	A1	1945	R-32/125/1234yf (11/59/30)	0.99	0.96	3.8
R-449A [#]	-46.0	A1	1282	R-32/125/1234yf/134a (24.3/24.7/25.3/25.7)	1.07	0.96	6.1
R-448A	-45.9	A1	1273	R-32/125/1234yf/134a/1234ze(E)	1.07	0.97	6.1
R-457A	-42.7	A2L	139	R-32/1234yf/152a (18/70/12)	1.06	0.76	7.2
R-744 (CO ₂)	-78.0	A1	1				
R-290 ^{@,&}	-42.0	A1	<1*		1.11	0.87	

[#] Other blends are available in this series

[@] Small refrigerant charge equipment

[&] Applications with secondary fluid

R-744 options: cascade system (R-1234ze(E)/R-744, R-717/R-744); supermarket system (booster system)

Transport refrigeration:

R-404A -> R-452A -> ?

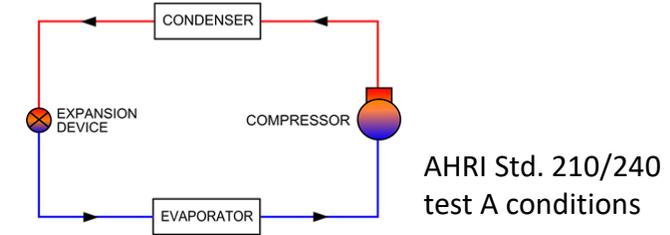
R-134a -> R-513A -> ?

Low-GWP refrigerant options

Space air conditioner (residential, small commercial)



■	No flame propagation	1
■	Lower flammability	2L
■	Flammable	2
■	Higher flammability	3



HFCs & HCFC

3rd Generation

1990 – 2010s

R-123 (HCFC)	27.8
R-134a	-26.1
R-407C	-43.6
(R-32/125/134a)	
R-410A	-51.4
(R-32/125)	
R-404A	-45.7
(R-125/143a/134a)	

Low-GWP options

4th Generation

2010s –

	NBP (°C)	Safety	GWP	Composition (mass)	$\frac{COP}{COP_{ref}}$	$\frac{Q_v}{Q_{v,ref}}$	Glide (°C)
R-32	-51.7	A2L	677		1.05	1.10	
R-452B	-51.0	A2L	676	R-32/125/1234yf (67/7/26)	1.02	0.98	0.7
R-454B	-50.9	A2L	467	R-32/1234yf (68.9/31.1)	1.02	0.97	0.9
R-466A	-51.7	A1	697	R-32/125/CF ₃ I (49/11.5/39.5)	1.01	1.07	0.7
R-744 (CO₂)	-78.0	A1	1				
R-290 @,&	-42.0	A3	<1*		1.03	0.58	
R-717 &	-33.0	A2L	<1		1.13	0.78	

@ Small refrigerant charge equipment
& Applications with secondary fluid

Any new single-compound fluids for AC?

■	No flame propagation	1
■	Lower flammability	2L
■	Flammable	2
■	Higher flammability	3

New entries to ASHRAE Std. 34 since 2017

		NBP (°C)	Safety	GWP
•	R-1224yd(Z) <chem>CF3CF=CHCL</chem>	14.5	A1	1
•	R-1336mzz(E) <chem>CF3CH=CHCF3</chem>	7.4	A1	16*
•	R-13I1 <chem>CF3I</chem>	- 21.9	A1	1
•	R-1132a <chem>CF2=CH2</chem>	- 86.7	A2	1

Low-pressure applications

Can be used as a component of non-flammable blends. Challenge: reactivity

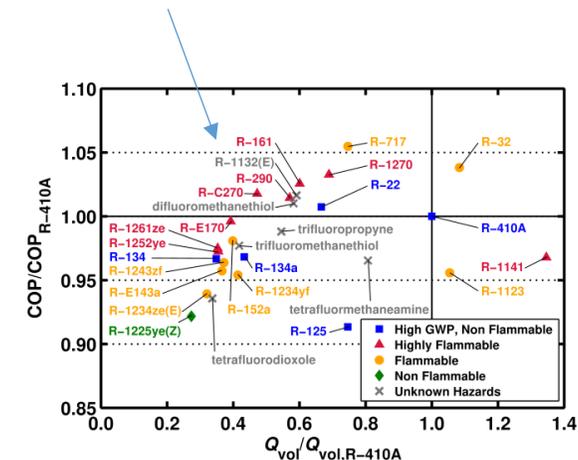
New toxicity data
Ultra-low temp. applications

New fluid of interest

		NBP (°C)	Safety	GWP
•	R-1132(E) <chem>CHF=CHF</chem>	-53.0	not assigned, likely flammable	?

Limited property data: Akasaka et al. (2020) & Perera et al. (2020)

Note: $NBP_{R-410A} = -51.4 \text{ °C}$



Concluding comments



○ Availability of low-GWP refrigerants varies between applications

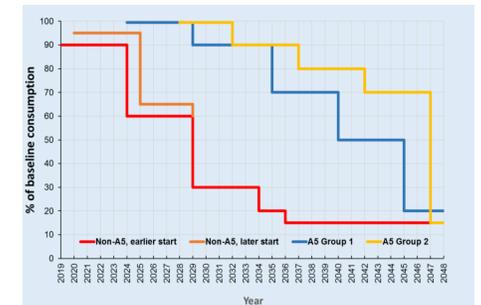
- Low-pressure applications: good availability; low GWP, nonflammable
- Medium- and high-pressure applications: replacement fluids are at least mildly flammable
- No direct HFO replacement for R-410A and R-404A
- Transition to 2L refrigerants in most applications
- Increased market share of natural refrigerants
- Increased market fragmentation

○ Trade off between **GWP** ↓ and **flammability** ↑

○ Prospects for finding new viable refrigerants are minimal

○ We will have to use refrigerants judiciously, which includes:

- Selection of refrigerant recognizing environmental and safety considerations
- High-efficiency, leak-free equipment
- Improved refrigerant handling practices (equipment commissioning, servicing, and decommissioning)



Thank you for your attention.

Relevant publications

- AGC, 2017. AMOLEA® 1224yd, Technical information. ASAHI Glas Co: 1-18. <https://www.agc-chemicals.com/file.jsp?id=30728> (accessed 2021-06-02)
- Akasaka, R.; Fukuda, S.; Sakoda, N.; Higashi, Y., 2020. pvT Property measurement and development of an equation of state for new refrigerant HFO1132(E), Proceedings of the 2020 JSRAE Annual Conference, Tsu-city, Japan
- Allgood, C., Johnston, P., Kim, S., Kujak, S., Yana Motta, S., Rydkin, I., 2021. Roundtable: A Conversation on Refrigerants, ASHRAE J 2021, 63 (3), 30-37
- ASHRAE 2019. ANSI/ASHRAE Standard 34-2019, Designation and Safety Classification of Refrigerants, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA
- AHRI, 2017. 210/240-2017 Standard for Performance Rating of Unitary A/C and Air Source Heat Pump Equipment. Air Conditioning, Heating and Refrigeration Institute, Arlington, VA.
- AHRI, 2020. AHRI Standard 550/590, Standard for Performance Rating of Water Chilling and Heat Pump Water-Heating Packages using the Vapor Compression Cycle, Air Conditioning, Heating and Refrigeration Institute, Arlington, VA.
- Brignoli, R., Brown, J.S., Skye, H., Domanski, P.A., 2017. Refrigerant Performance Evaluation Including Effects of Transport Properties and Optimized Heat Exchangers, Int. J. Refrig., 80: 52-65, doi.org/10.1016/j.ijrefrig.2017.05.014
- Brown, J.S., 2012. Introduction to alternatives for high-GWP HFC refrigerants. Proc. of ASHRAE/NIST Refrigerants Conf., Gaithersburg, MD
- Brown, J.S., Brignoli, R., Domanski, P.A., Yoon, Y.J., 2021. CYCLE_D-HX: NIST Vapor Compression Cycle Model Accounting for Refrigerant Thermodynamic and Transport Properties, Version 2.0. National Institute of Standards and Technology, Gaithersburg, MD. doi.org/10.18434/M32231
- Calm, J.M., 2008. The next generation of refrigerants – Historical review, considerations and outlook, Int. J. Refrig., 31:1123-1133. doi:10.1016/j.ijrefrig.2008.01.013
- Calm, J.M., 2012. Refrigerant Transitions ...Again. ASHRAE/NIST Refrigerants Conference, Gaithersburg, MD
- Cléménçon, R., 2016. The two sides of the Paris climate agreement: Dismal failure or historic breakthrough? J. Environment & Development, 25(1) 3-24.
- Domanski, P.A., Brignoli, R., Brown, J.S., Kazakov, A.F., McLinden, M.O., 2017. Low-GWP Refrigerants for Medium and High-Pressure Applications, Int. J. Refrig., 84:198-209, doi:10.1016/j.ijrefrig.2017.08.01
- ISO, 2014. International Standard ISO 817:2014, Refrigerants—designation and safety classification. International Organization for Standardization, Geneva, Switzerland
- IIR ,2017. The Impact of the refrigeration sector on climate change, 35th Informatory Note on refrigeration Technologies. Paris, France, <https://iifir.org/en/fridoc/the-impact-of-the-refrigeration-sector-on-climate-change-141135> (accessed 2021-06-02)
- Kujak, S., Schultz, K., 2020. Less than 150 GWP options to replace R-452A for transport refrigeration. 6th IIR Int. Conf. on Sustainability and the Cold Chain. Nantes, France. doi.org/10.18462/iir.iccc.2020.292229
- Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O., 2018. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology. Standard Reference Data Program, Gaithersburg, MD
- McCain, W.C., Macko, J., 1999. Toxicity review for iodotrifluoromethane (CF₃I). Proceedings of the Halon Options Technical Working Conference, Albuquerque, NM
- McLinden, M. O., Brown, J. S., Kazakov, A. F., Brignoli, R., Domanski, P. A., 2017. Limited options for low-global-warming-potential refrigerants. Nature Communications, 8:14476. doi:10.1038/ncomms14476
- Myhre, G. et al., 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- OurWorldInData, 2021. Oxford Univ., <https://ourworldindata.org/about> (accessed 2021-05-28)
- Perera, U. A.; Miyazaki, T.; Sakoda, N.; Higashi, Y., 2020. Determination of saturation pressure and critical pressure for new refrigerant HFO1132(E), Proceedings of the 2020 JSRAE Annual Conference, Tsu-city, Japan
- UN, 2015. Paris Agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf (retrieved 2021,5,31)
- UNEP, 2019. Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer. Ozone Secretariat United Nations Environment Programme 2019 https://ozone.unep.org/sites/default/files/2019-07/MP_Handbook_2019.pdf
- UNEP, 2019. Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee 2018 Assessment Report. https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf
- WMO, 2018. Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58. World Meteorological Organization, Geneva, Switzerland