ALTERNATIVE REFRIGERANTS FOR CENTRALIZED AIR CONDITIONING SYSTEMS

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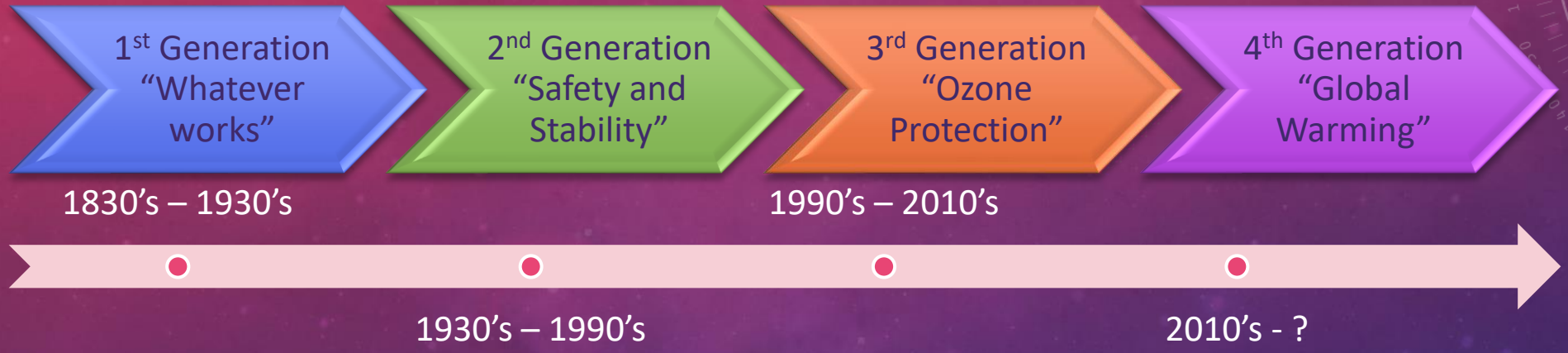
HISTORY OF HVAC&R REFRIGERANTS



1st Generation "Whatever works"	2nd Generation "Safety and Stability"	3rd Generation "Ozone Protection"	4th Generation "Global Warming"
Limited applications – Industry Poor Safety and cost	Enabled Innovation	Preserved 2nd gen. innovations, safety, stability and efficiency	Limited optimal choices Safety and design challenges

• NH_3
• CO_2
• Hydrocarbons
• H_2O
• SO_2
• Methyl Chloride (R-40)
	• NH3
	• CFCs: R-11, R-12
	• HCFCs: R-22, R-502
		• NH_3
		• HCFCs: R-22, R-123
		• HFCs:
		  • R-134a
		  • R-410A
		  • R-404A
		  • Other blends
			• NH_3
			• Low GWP HFCs, HFOs, and HCFOs: R-1234yf, R-1234ze(E), R-1233zd(E), R-32, and their blends
			• Renewed interest in natural refrigerants: CO_2, Hydrocarbons

GWP OF COMMON REFRIGERANTS

NEW REQUIRED PROPERTIES FOR REFRIGERANT GAS

- Boiling point between –40°F and 32°F (-40°C and 0°C)
- ***Nonflammable*?**
- Considerably less toxic (nontoxic)
- Chemical stability (inside a refrigeration machine, but breaks down to harmless products if released into the atmosphere)
- Nice if pungent odor for leak detection
- Nice if inexpensive (more difficult to achieve)
- Cannot contain chlorine, bromine, or iodine, all of which deplete ozone
- Must have short atmospheric lifetime to minimize GWP

4TH GENERATION REFRIGERATION

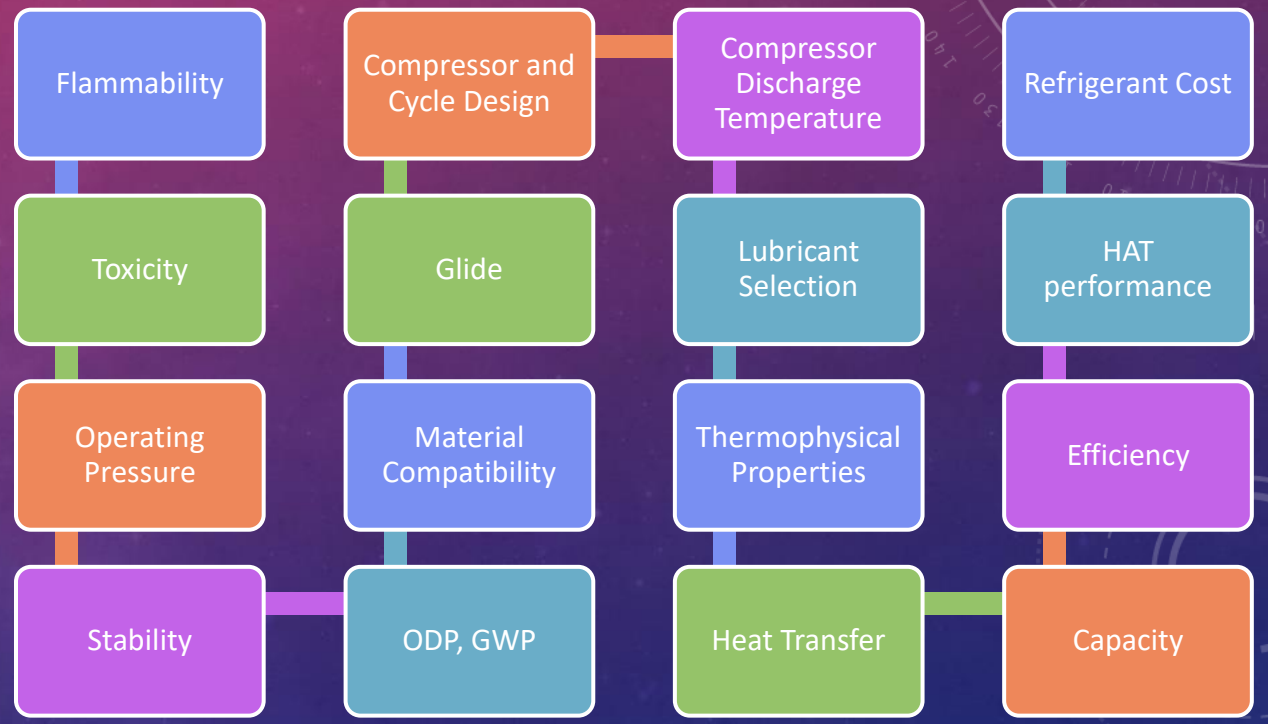
- React with Common Atmospheric Species to shorten life span
- Couple of Chemistry Approaches
  - Increase the number of Hydrogens
  - Include oxygen or others
  - Reduce chemical stability – add bromine or Iodine
  - Unsaturation's (double or triple bonds; i.e. using Olefins)
- Best Approach
  - Unsaturation and Hydrogen (HFO, HCFO, HCO, HBFO)
- Problem : Flammability Increases

THE ISSUE IS NOT “NATURAL FLUIDS” VERSUS “SYNTHETIC FLUIDS” (FLUOROCHEMICALS)

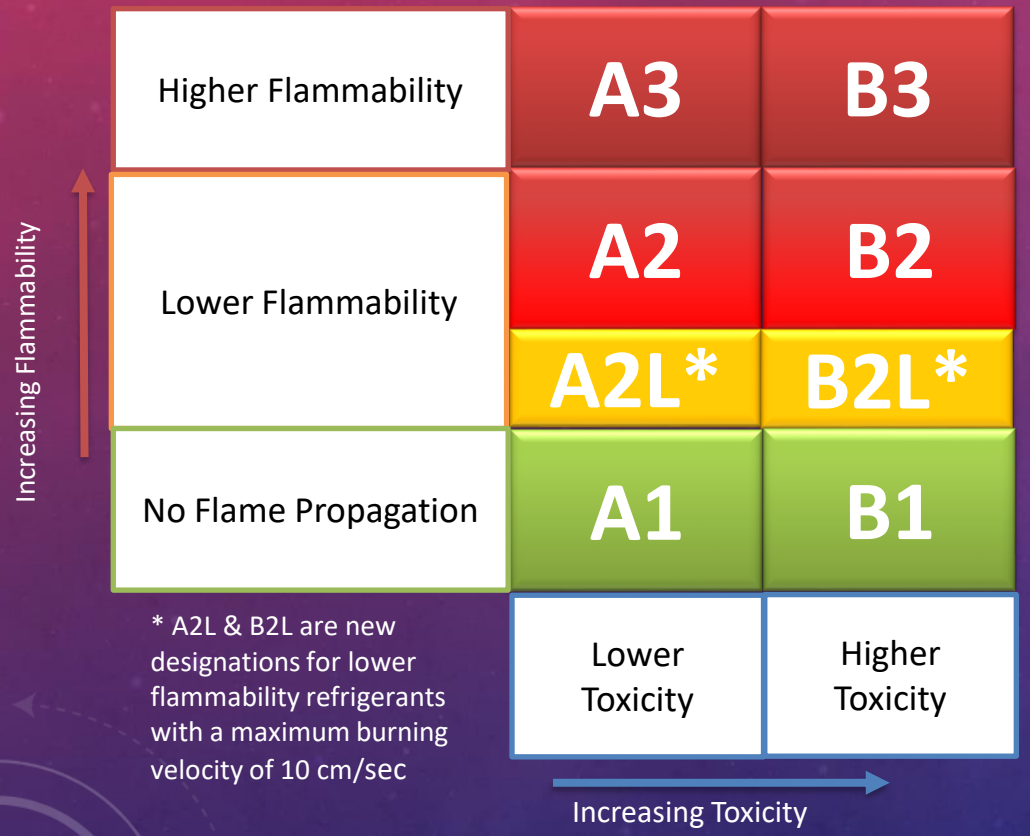
More important are environmental stewardship and delivering cooling or heating with the smallest possible life-cycle climate impact, regardless of technology being used.

REFRIGERANT SELECTION: A TRADE-OFF

- Environmental performance (~0 ODP and reduced GWP)
- Safety for consumers (flammability and toxicity)
- Energy efficiency (reduced indirect CO_2 emissions, especially at high ambient operations)
- Intellectual property considerations
- Transition costs (industry and consumers)
- Product sustainability



SAFETY STANDARDS; ASHRAE STD 34 / ISO 817

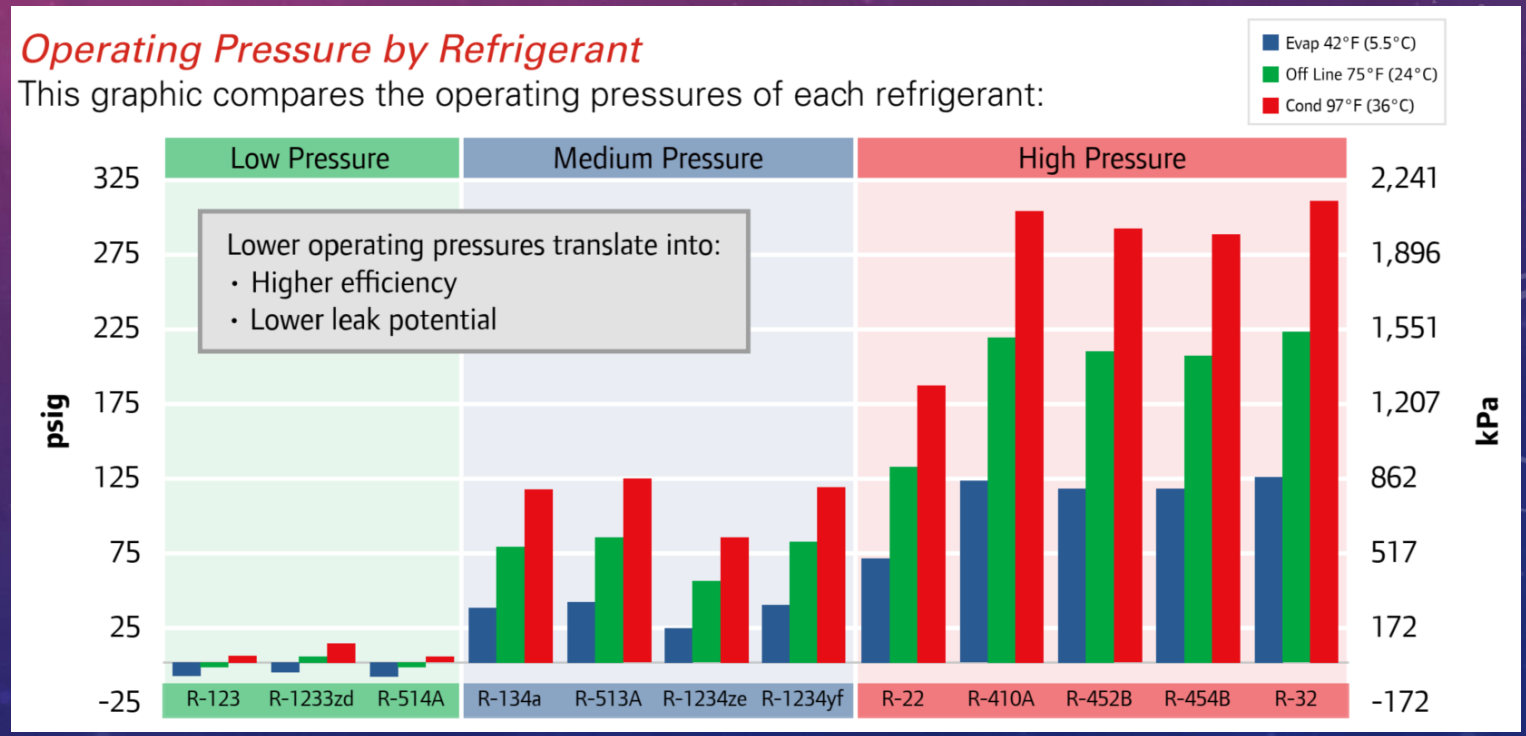


* A2L & B2L are new designations for lower flammability refrigerants with a maximum burning velocity of 10 cm/sec

- Safety Classification depends on flammability and toxicity
- Toxicity depends on the Occupational Exposure Limit (OEL)
  - > 400 ppm is class A
  - < 400 ppm is class B
- Flammability depends on lower flammability limit (LFL) determination, flame velocity determination, and heat of combustion
  - 1 Nonflammable
  - 2L Feeble, slow flame, slow low-pressure rise
  - 2 Burns faster, low heat of combustion
  - 3 Burns at explosive speed, high heat of combustion

REFRIGERANT SELECTION BY COMPRESSOR TECHNOLOGIES

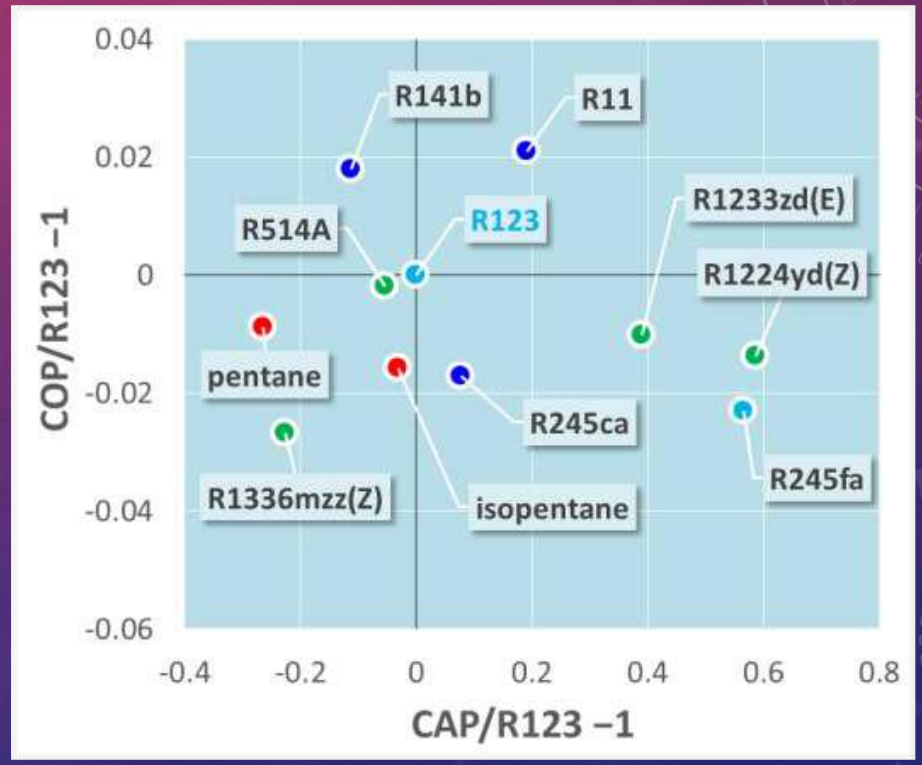
- Centrifugal – low and medium pressure Refrigerants (R123, R134a) ➔ greater than 1000 TR (3,500 kW)
- Screws – medium and some high pressure (R134a, R22-past) ➔ (500 – 5000 TR)
- Scrolls & Reciprocating – high pressure mostly (R22, R410A, R407C)
  - Scrolls: 2 – 2000 TR
  - Reciprocating: ~ 1 – 100 TR



Source: Trane API Refrigerant Brochure

LOW PRESSURE R-123 ALTERNATIVES

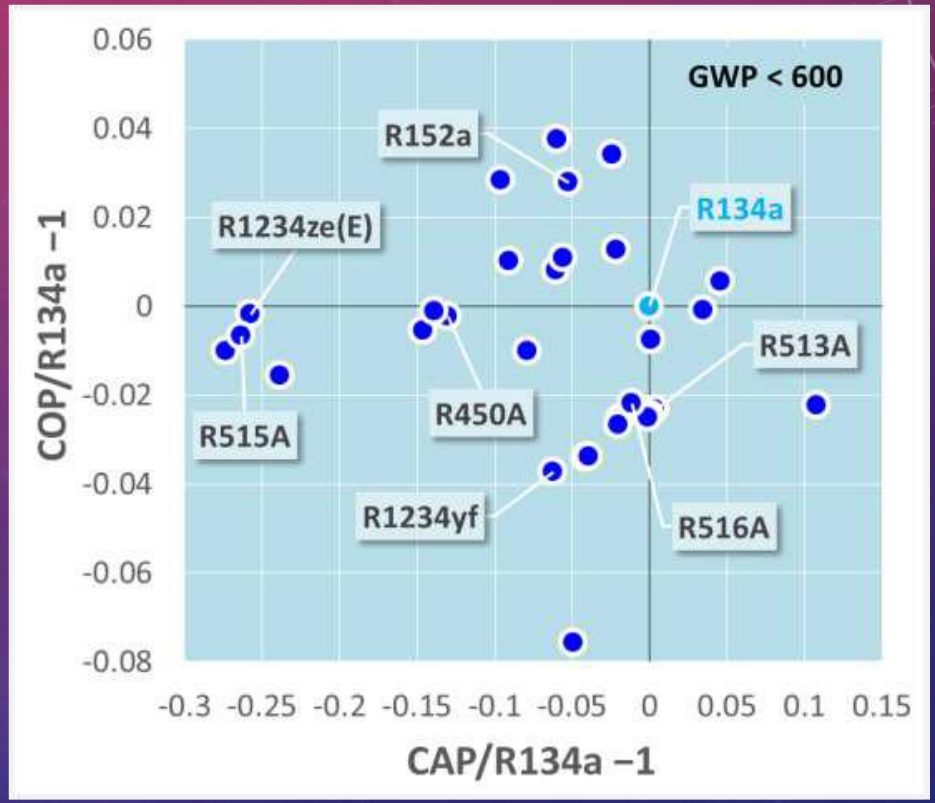
- Flammability
  - Nonflammable: GWP 400-600
  - Flammable: GWP <150
- Good efficiency
- Near design compatible alternatives available
- Varying glide



Source: Seminar 56 Low GWP Alternative Refrigerants and Their Applications, Part 2, 2017 Winter Conference, Las Vegas, NV
Steve Kujak, “Insights into the Next Generation HVAC&R Refrigerant Future”

MEDIUM PRESSURE R-134A ALTERNATIVES

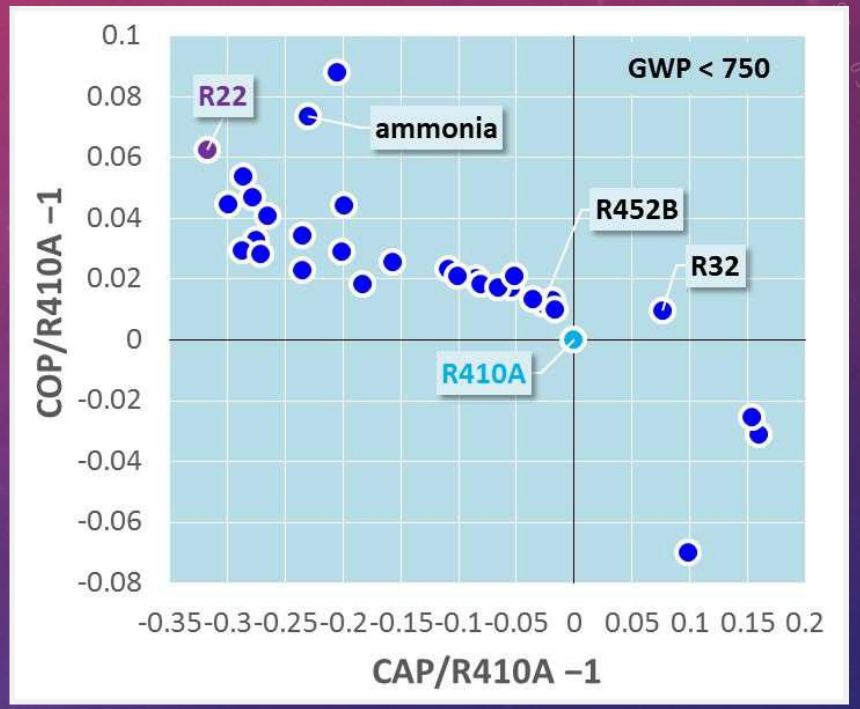
- Low GWP available today
  - R-1233zd(E)
  - R-1224yd
  - R-514A
  - R-1234ze(E)
- Most nonflammable
- Good Efficiency
- No Glide
- Compatible with existing designs



Source: Seminar 56 Low GWP Alternative Refrigerants and Their Applications, Part 2, 2017 Winter Conference, Las Vegas, NV
Steve Kujak, "Insights into the Next Generation HVAC&R Refrigerant Future"

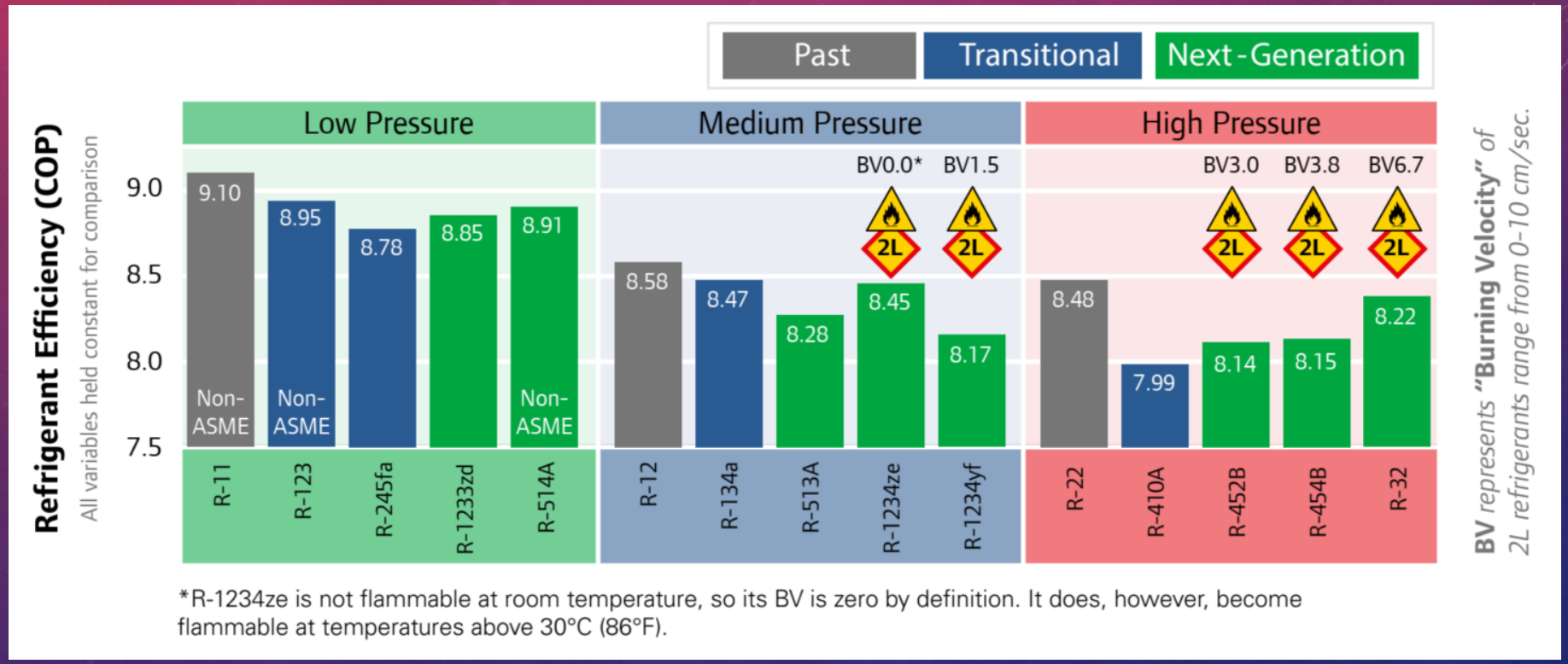
HIGH PRESSURE R-410A ALTERNATIVES

- GWP: 460 – 675
- **Flammable** (except for the new R-466A)
- Higher efficiency
- Near design compatible alternatives available
- Varying glide



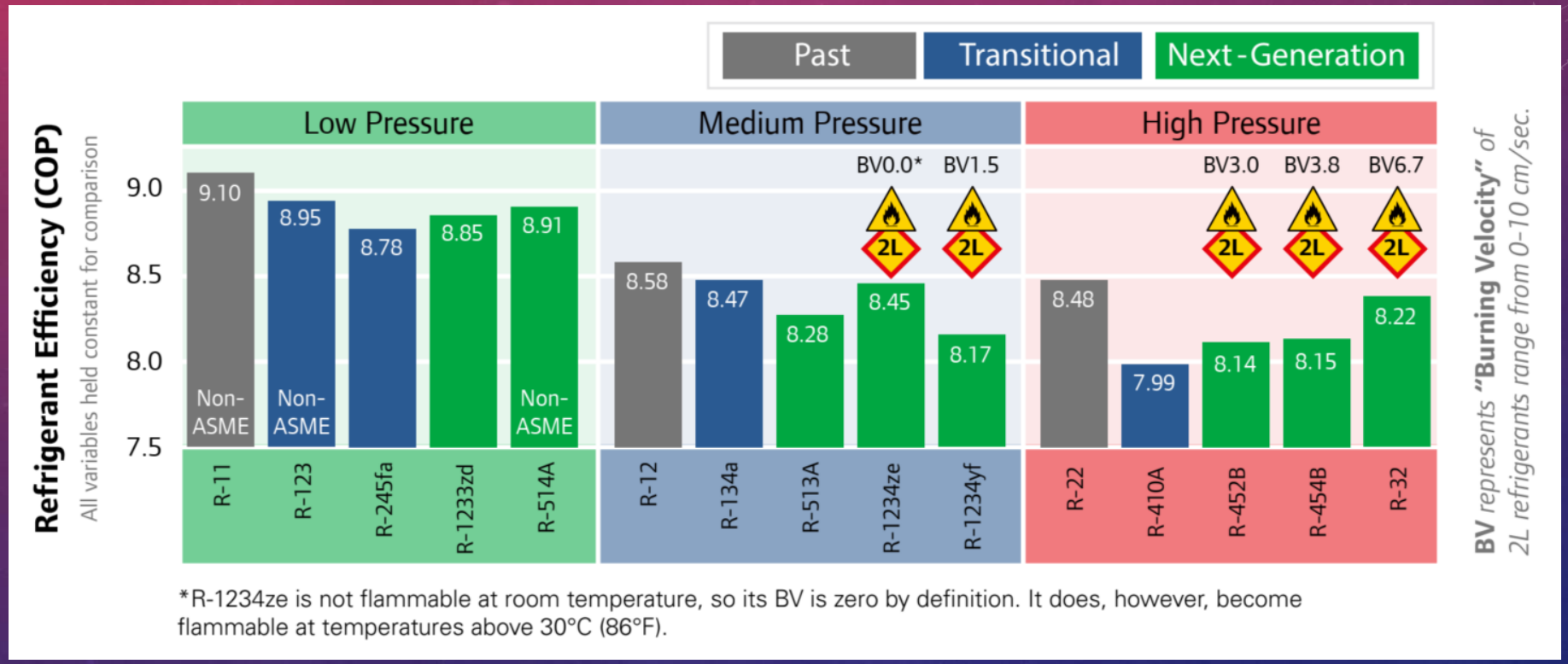
Source: Seminar 56 Low GWP Alternative Refrigerants and Their Applications, Part 2, 2017 Winter Conference, Las Vegas, NV
Steve Kujak, "Insights into the Next Generation HVAC&R Refrigerant Future"

ENVIRONMENTAL IMPACT



Source: Trane API Refrigerant Brochure

ENVIRONMENTAL IMPACT



Source: Trane API Refrigerant Brochure

EXPERIMENTAL ANALYSIS – PACKAGED ROOFTOP AC SYSTEMS

R-22 ALTERNATIVE REFRIGERANTS

Refrigerant	Manufacturer	ASHRAE Safety Class	GWP (AR5)
R-22[a]	-	A1	1,760
ARM-20a[b] (R-457A)	Arkema	A2L	139
ARM-20b[b]	Arkema	A2L	251
L-20a (R-444B)[b]	Honeywell	A2L	295
DR-7(R-454A)[b]	Chemours	A2L	238

[a] Sources: IPCC AR5, 2013

[b] GWP values for refrigerant blends not included in IPCC reports are calculated as a weighted average using manufacturer-supplied compositions.

R-410A ALTERNATIVE REFRIGERANTS

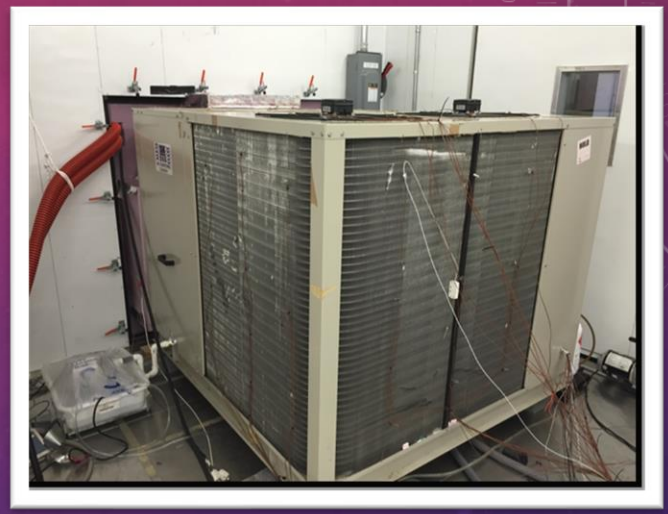
Refrigerant	Manufacturer	ASHRAE Safety Class	GWP (AR5)
R-410A[a]	-	A1	1924
L41-Z (R-447B)[b]	Honeywell	A2L	715
DR-55[b] (R-452B)	Chemours	A2L	676
ARM-71a[b]	Arkema	A2L	461
R-32[a]	Daikin	A2L	677

[a] Sources: IPCC AR5, 2013

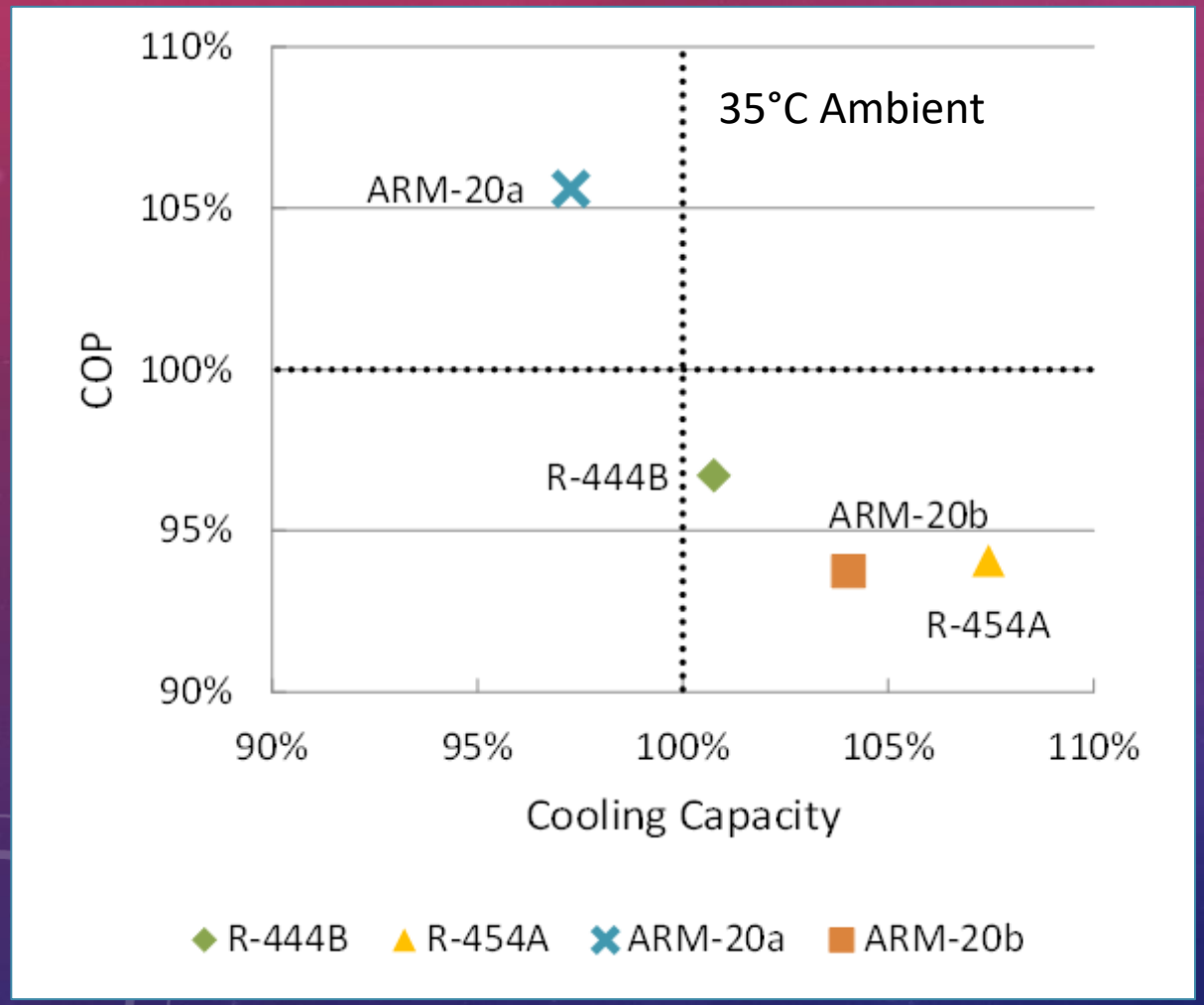
[b] GWP values for refrigerant blends not included in IPCC reports are calculated as a weighted average using manufacturer-supplied compositions.

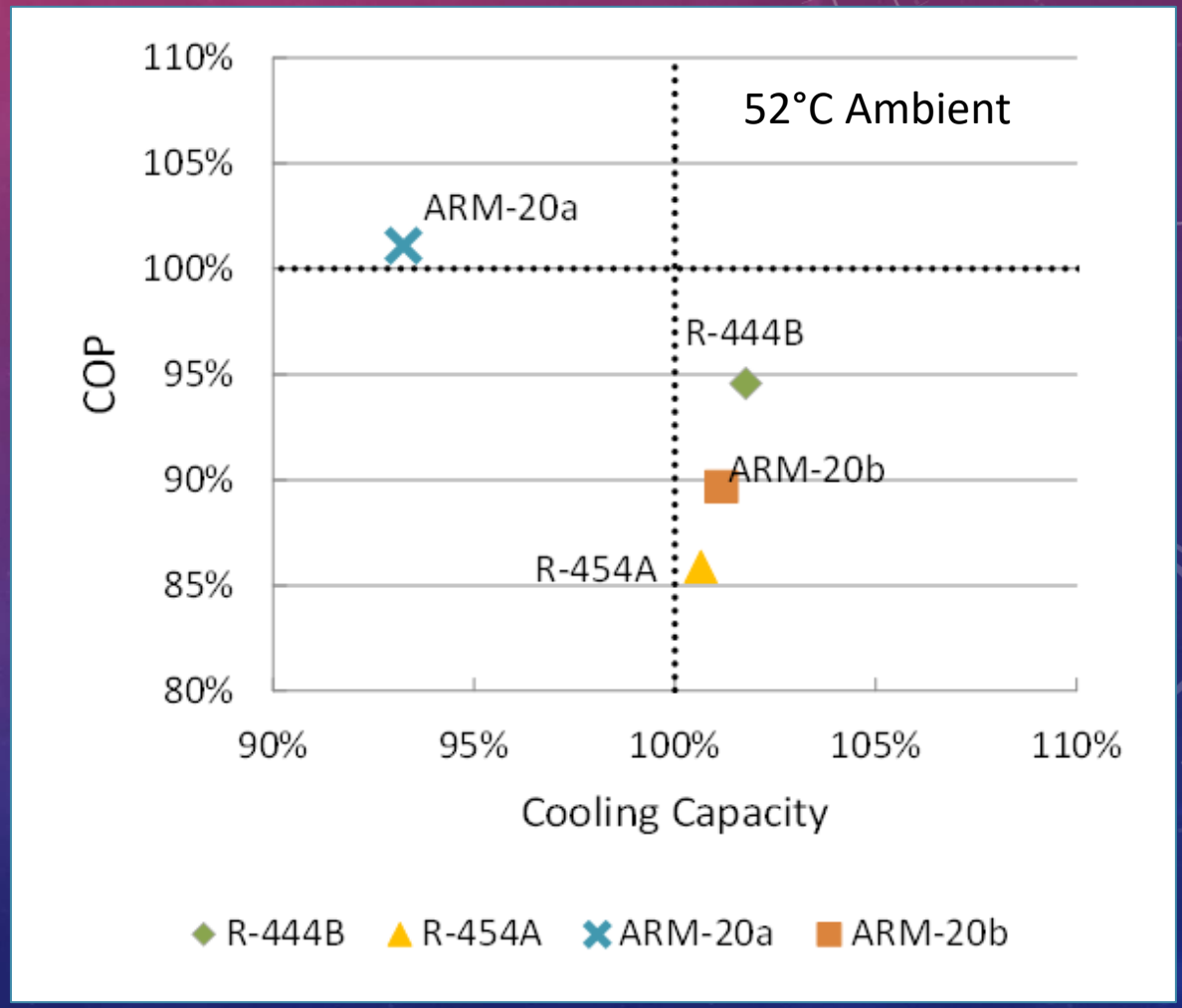
PACKAGED AC UNITS

- R-22 Unit (SKM PACL-51095Y)
  - 380/415V, 3 Ph, 50 Hz
  - Capacity*(T1) = 92.8 kBtu/h (27.2 kW)
  - EER = N/A
- R-410A Unit (Petra PPH4 115)
  - 460V, 3 Ph, 60 Hz
  - Capacity*(T1) = 132 kBtu/h (~ 38.68 kW)
  - EER* = 10.66 (COP ~ 3.12)

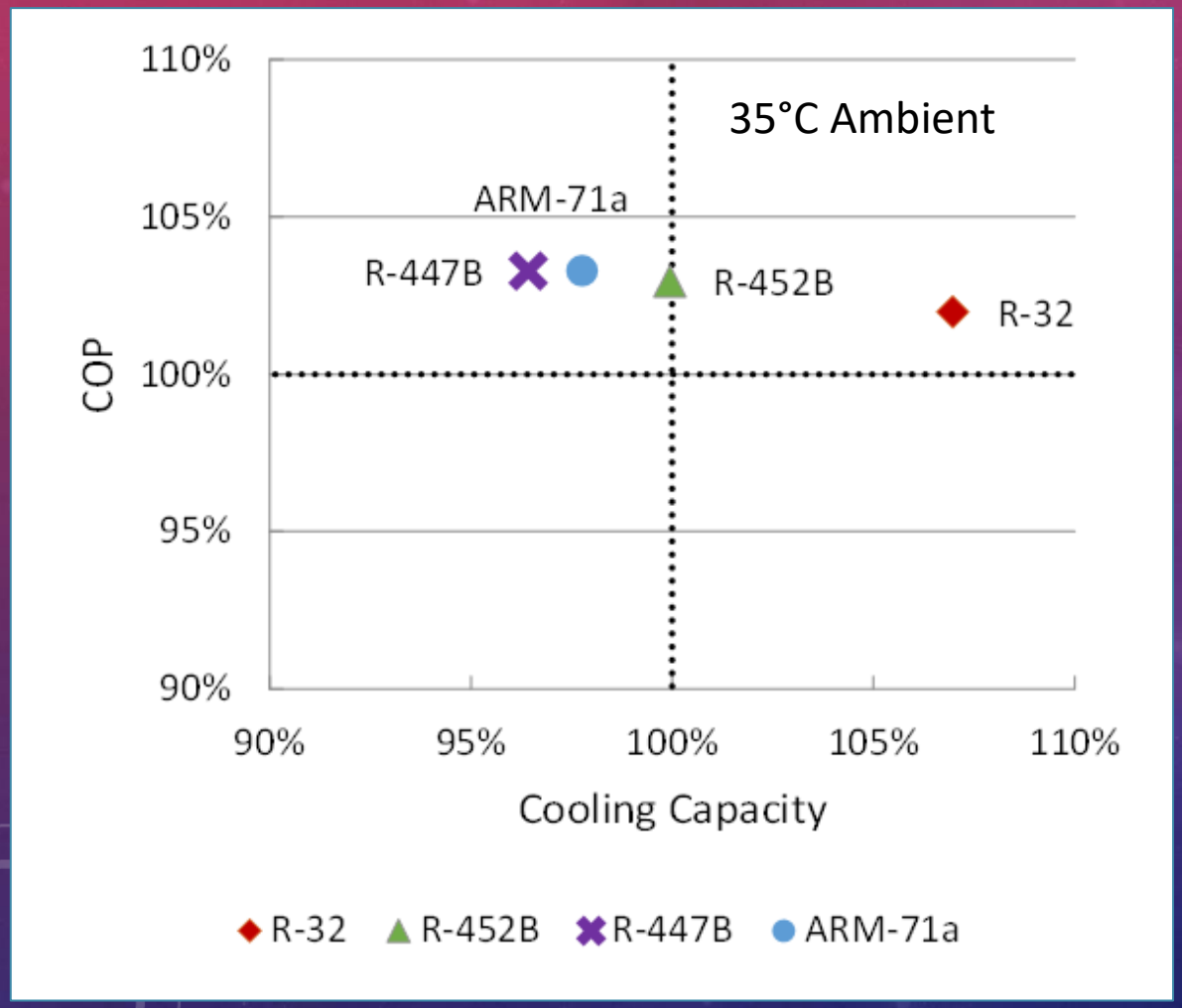


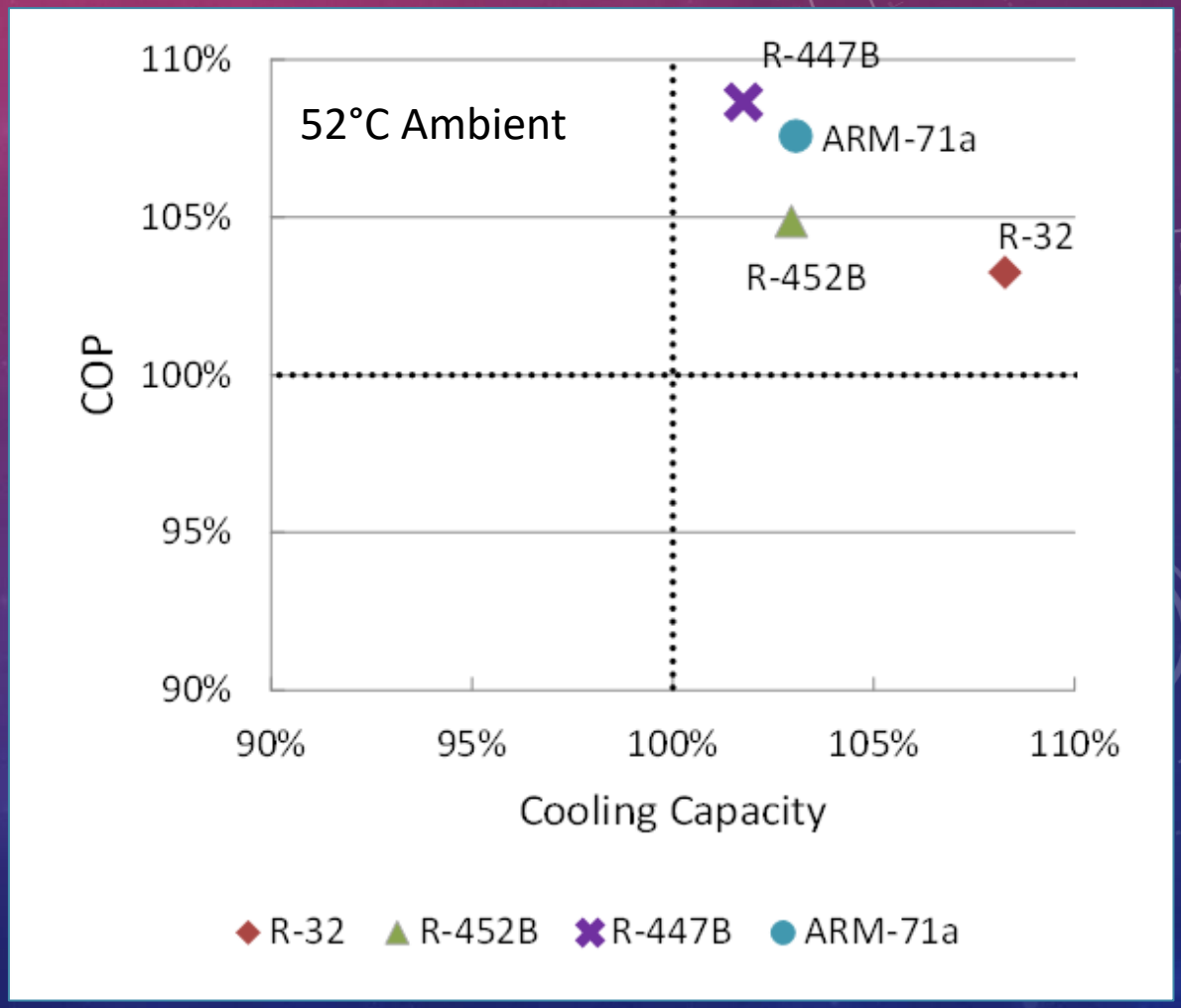
PERFORMANCE RELATIVE TO R-22





PERFORMANCE RELATIVE TO R-410A





THANK YOU!

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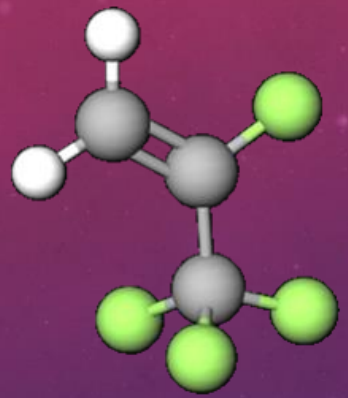
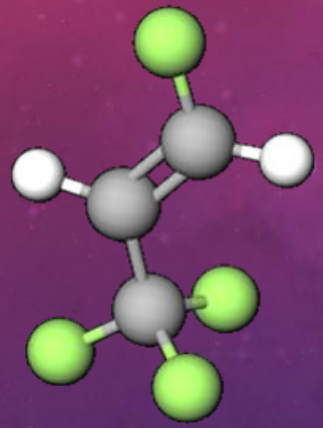
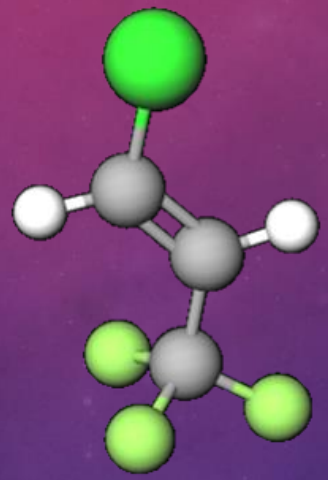
REPRESENTATIVE ALTERNATIVE LOW GWP REFRIGERANT MOLECULES



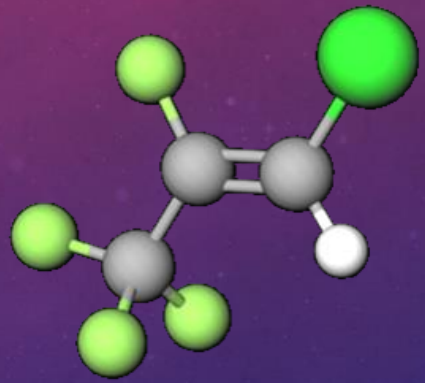
R-1234yf –A2L



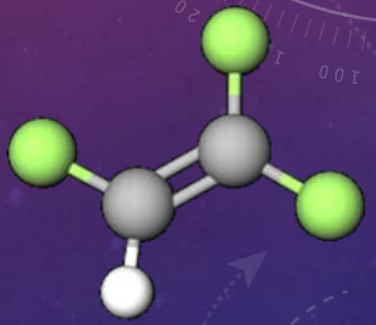
R-1234ze(E)- A2L



R-1233zd(E) – A1



R-1224yd(Z)- A1



R-1123

Refrigerant for HVAC

This table compares various properties of both current and next-generation refrigerants. The efficiencies and capacity changes shown are based on the theoretical properties of the refrigerant alone, with all design variables held constant for objective comparison.

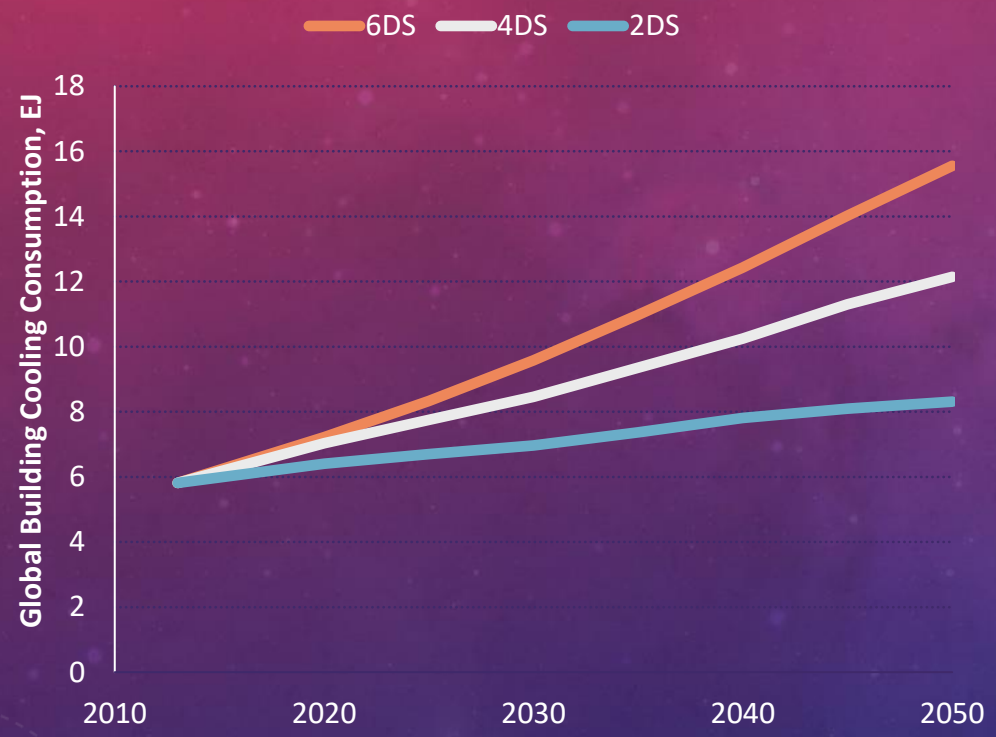
		Low Pressure			Medium Pressure				High Pressure			
		R-123	R-1233zd	R-514A	R-134a	R-513A	R-1234ze[3]	R-1234yf	R-22	R-410A	R-452B	R-32[4]
Flammability	ASHRAE Class	Non (1)	Non (1)	Non (1)	Non (1)	Non (1)	Slight (2L)	Slight (2L)	Non (1)	Non (1)	Slight (2L)	Slight (2L)
	BV (cm/s)	n/a	n/a	n/a	n/a	n/a	0.0	1.5	n/a	n/a	3.0	6.7
Toxicity[1]	ASHRAE Class	Higher (B)	Lower (A)	Higher (B)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)	Lower (A)
	OEL	50	800	320	1000	650	800	500	1000	1000	870	1000
Efficiency (COP)		8.95	8.85	8.91	8.47	8.28	8.45	8.17	8.48	7.99	8.14	8.22
Capacity Change		baseline	~35% gain	~5% loss	baseline	similar	~25% loss	~5% loss	-	baseline	~2% loss	~9% gain
GWP[2]		79	1	2	1300	573	1	1	1760	1924	675	677
Atmospheric Life		1.3 years	26 days	22 days	13.4 years	5.9 years	16 days	11 days	11.9 years	17 years	5.5 years	5.2 years

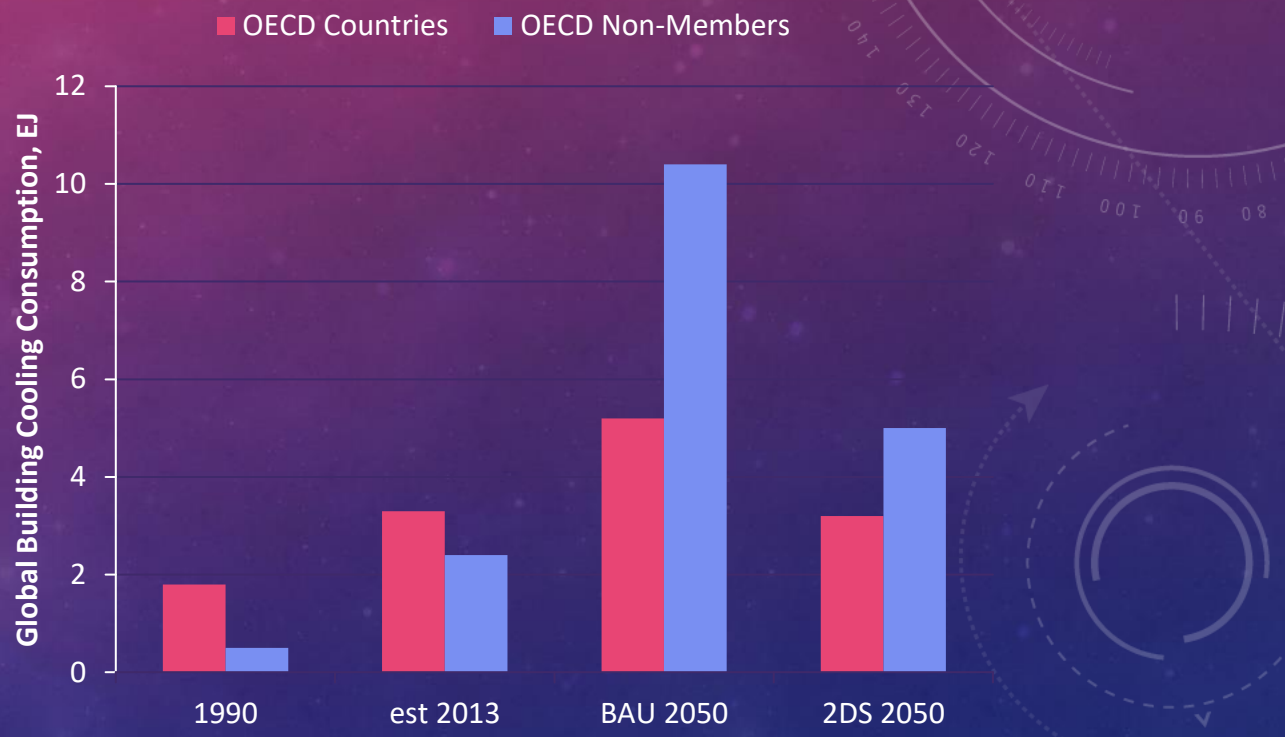
[1]None of the refrigerants shown in the table are considered "toxic" or "highly toxic" as defined by the IFC, UFC, NFPA 1 or OSHA regulations.
[2]GWP values reported are per the Fifth Assessment Report (AR5) of the IPCC (Intergovernmental Panel on Climate Change).
[3]R-1234ze is not flammable at room temperature, so its BV is zero by definition. It does, however, become flammable at temperatures above 30°C (86°F).
[4]R-32 is an existing refrigerant but never used alone in the past due to its flammability.

Source: Trane API Refrigerant Brochure

CHALLENGES AND OPPORTUNITIES

GLOBAL COOLING DEMAND

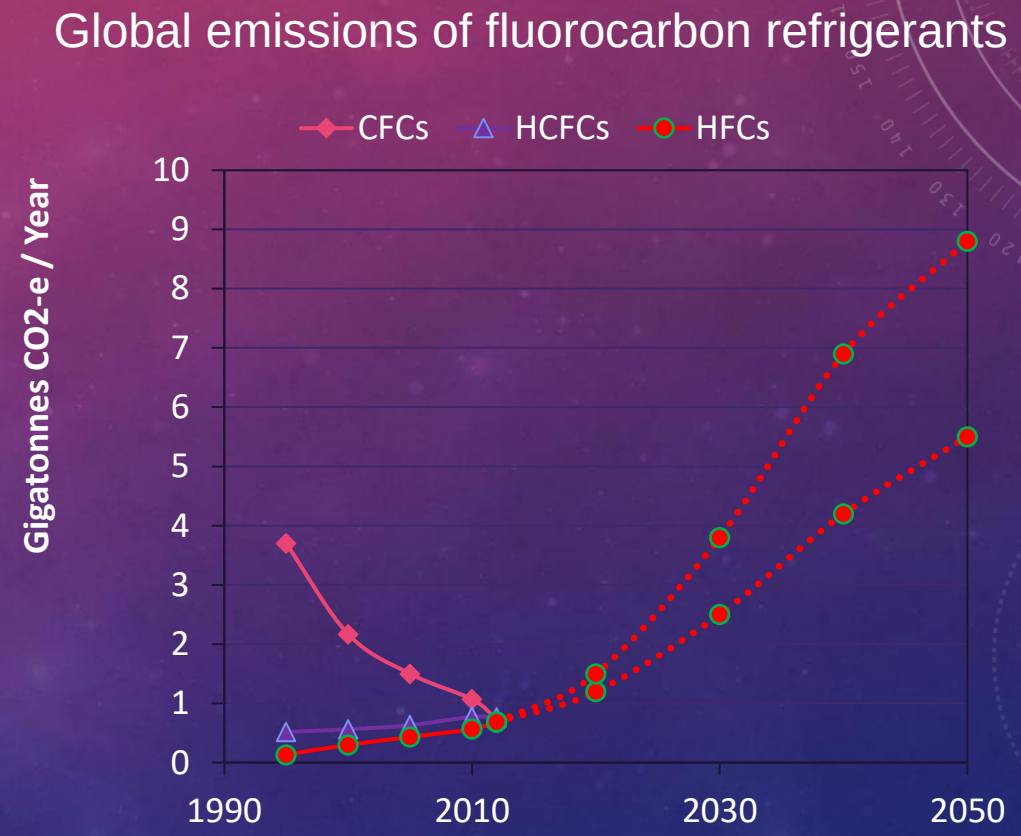




http://www.iea.org/Textbase/nppdf/stud/16/ETP2016.pdf

CHALLENGES AND OPPORTUNITIES

- Kigali Amendment to the Montreal Protocol
  - Transition from HCFC to HFC
  - Staring HFC phase-down in developing world
  - Potential for Leapfrogging
- More challenging task
  - Several alternatives (no clear silver bullet yet)
  - Safety, efficiency, and capacity tradeoff



http://www.esrl.noaa.gov/csd/assessments/ozone/2014/assessment_for_decision-makers.pdf
http://www.atmos-chem-phys.net/14/4563/2014/acp-14-4563-2014.pdf

TEST CONDITIONS

Test condition	Outdoor	Indoor		
	DBT	DBT	WBT	RH
	°C	°C	°C	%
AHRI A/ AHRI‡	35.0	26.7	19.4	50.9
T3‡	46	29	19	39.0
Hot‡	52	29	19	39.0
Extreme‡	55	29	19	39.0