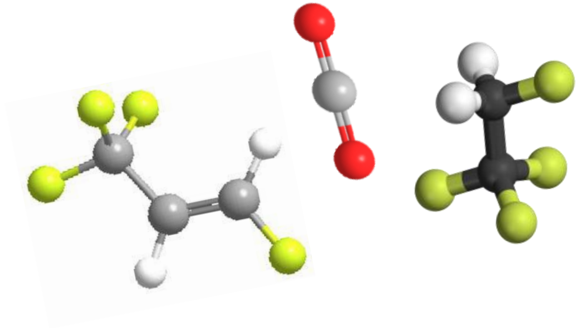
From the Beginnings of Artificial Cold to Climate-Friendly Fluids; Evolution of Refrigerants Application



NIST

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Acknowledgement

M.O. McLinden, A. Kazakov, G. Linteris, I. Bell

J. S. Brown, R. Brignoli, J. Heo

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Background

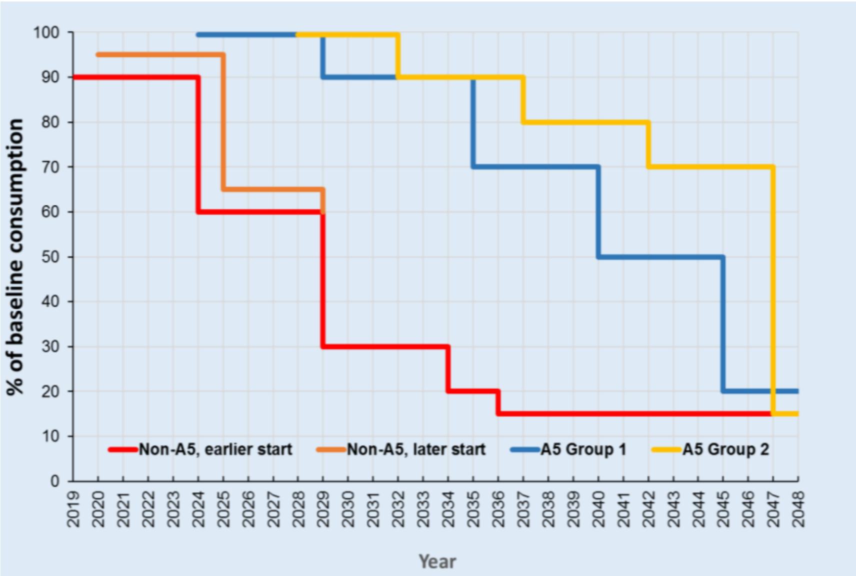
- **Refrigeration is used everywhere**

  Food industry, air conditioning, cryogenics, medicine and health products, energy, etc.

- **Use of refrigeration will increase, particularly in developing countries**

- **Use of refrigeration has environmental consequences**
  - Current refrigerants (HFCs) are greenhouse gases; need for low-GWP refrigerants
  - Emissions of CO_2 from fossil fuel power plants; need for high efficiency
  - Kigali amendment to the Montreal Protocol (2016); production & consumption of HFCs to be cut by more than 80 % over the next 30 years.

    Weighed GWP across all sectors ≈ 300



Industrial revolution (1760~1840)

GDP per capita in England since 1270

Adjusted for inflation and measured in British Pounds in 2013 prices

Source: GDP in England (using BoE (2017))

Note: Data refers to England until 1700 and the UK from then onwards.

OurWorldInData.org/economic-growth • CC BY-SA

OurWorldInData (2018)

- Improved productivity through inventions and new production methods
  (Watt’s steam engine; iron production; textile industry)
- Sustained growth of income and population
- The most important event since the domestication of animals and plants (10 000 years ago)

Beginnings of artificial cold

1755 – apparatus to make ice by evaporation of water at reduced pressure; W. Cullen
1824 – genesis of thermodynamics; Carnot
1834 – refrigeration machine using compression of a liquefiable gas; Perkins
1834 – demonstration of the Peltier effect

  – reliable compressor; Harrison
  – absorption machine; F. Carre
  – air cycle machine; Gorrie
  – machine relying on evaporation of water (R-718) at reduced pressure; E. Carre
  – refrigerants: ethyl ether, methyl ether (R-E170), petrol ether + naphtha (chemogene),
  CO_2 (R-744), ammonia (R-717), SO_2 (R-764), methyl chloride (R-40)

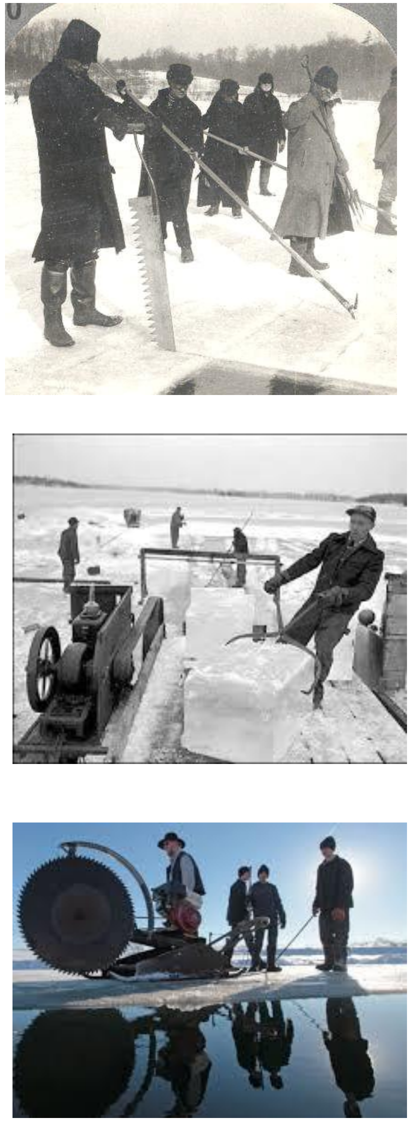
1876 – ammonia compressors by Linde; application of thermodynamics

Main applications: ice making, transport of meat by sea, and brewing

1890 -> 1900 – collapse of ice harvesting
1918 – dominant refrigerants: ammonia, CO_2, SO_2
1920s – introduction of HCs
1931 – introduction of CFC refrigerants

Thevenot, R. (1979)

Ice harvesting



Application of refrigerants

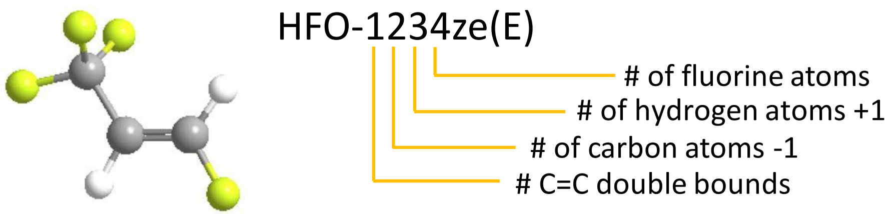
🟦 No flame propagation
🟧 Lower flammability
🟥 Higher flammability

Natural fluids

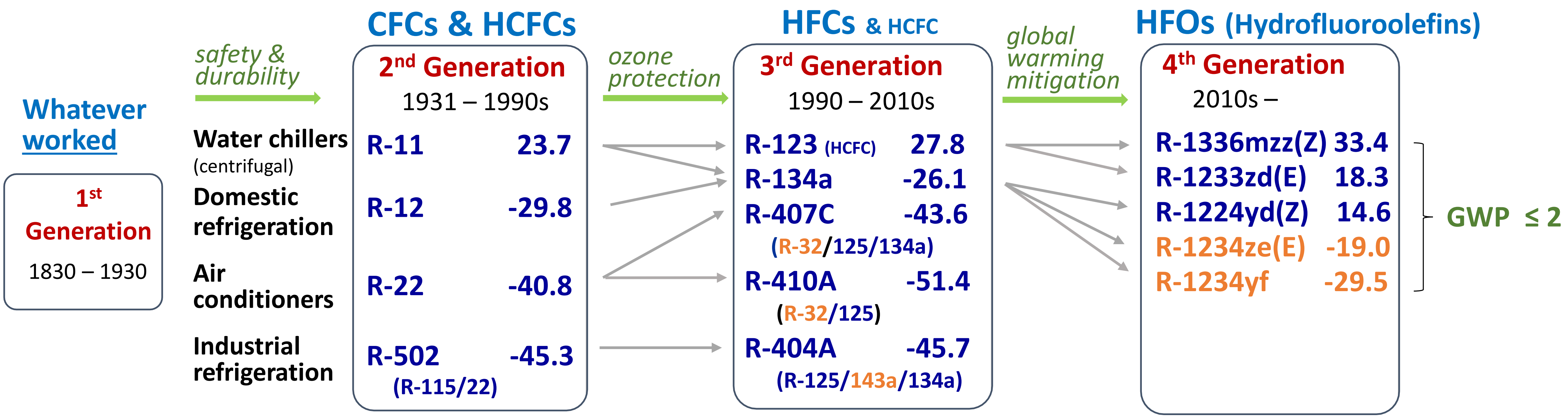
H_2O	100.0	R-717	-33.3	R-600a	- 11.7
CO_2	-78.4			R-290	- 42.1
air	-194.2			R-1270	- 47.7

Ammonia

Normal boiling point (°C)



Fluorinated fluids



Whatever worked

1st Generation
1830 – 1930

safety & durability

CFCs & HCFCs

2nd Generation
1931 – 1990s

Water chillers (centrifugal)	R-11	23.7
Domestic refrigeration	R-12	-29.8
Air conditioners	R-22	-40.8
Industrial refrigeration	R-502 (R-115/22)	-45.3

ozone protection

HFCs & HCFC

3rd Generation
1990 – 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

HFOs (Hydrofluoroolefins)

4th Generation
2010s –

R-1336mzz(Z)	33.4
R-1233zd(E)	18.3
R-1224yd(Z)	14.6
R-1234ze(E)	-19.0
R-1234yf	-29.5

GWP ≤ 2

Calm (2008), Calm (2012), Myhre, G. et al. (2013)

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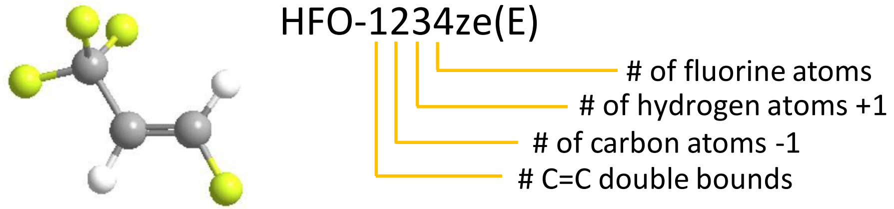
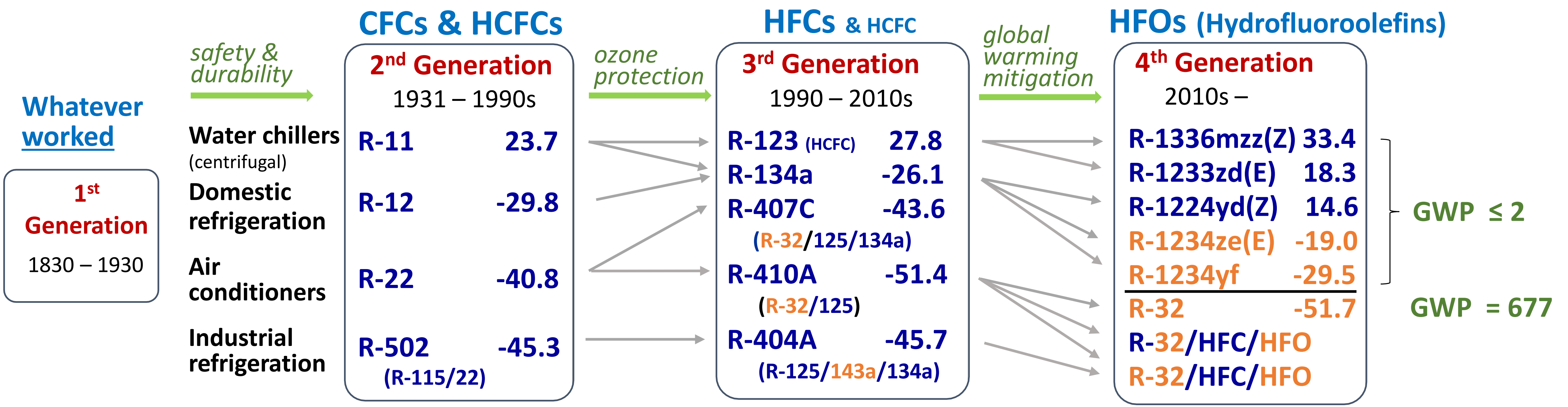


HFO-1234ze(E)

# of fluorine atoms
# of hydrogen atoms +1
# of carbon atoms -1
C=C double bounds

Fluorinated fluids



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Domestic refrigeration
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R-32	-51.7
R-32/HFC/HFO	
R-32/HFC/HFO	

GWP ≤ 2

GWP = 677

Calm (2008), Calm (2012), Myhre, G. et al. (2013)

NIST search for low-GWP fluids (2012 – 2017)

Objective: Identify molecules that might be good replacements for R-410A and R-22

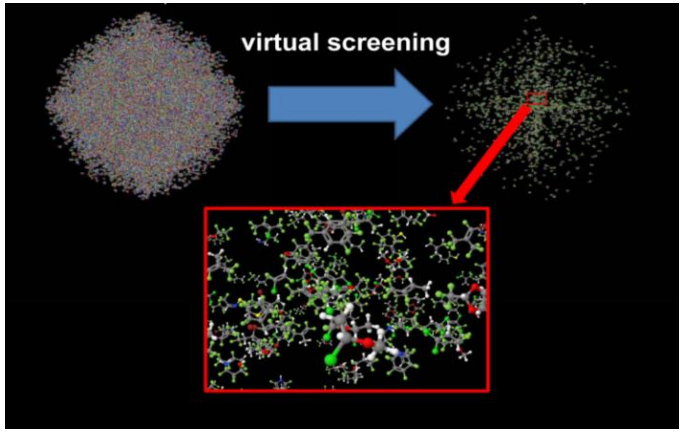
Air-conditioning and refrigeration applications
- positive displacement compressors
- forced-convection air-to-refrigerant heat exchangers

Approach: Perform screening using comprehensive database

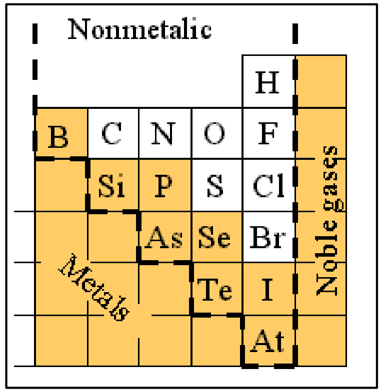
(PubChem lists over 60 million unique chemical structures)

Important attributes/filters:

- Performance: COP, volumetric capacity (Q_{vol})
- Environmental: ODP, GWP
- Safety: toxicity, flammability
- Materials: stability, compatibility (lubricant, seals, metals, etc.)
- Cost



NIST search for low-GWP fluids (cont.)



PubChem database

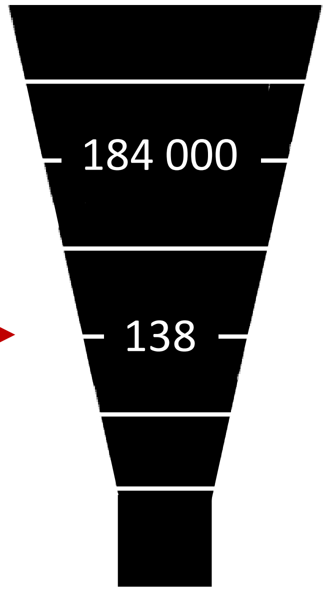
- Component atoms: C, H, N, O, S, F, Cl, Br
- Maximum number of atoms: 18
- $GWP_{100} < 1000$
- Critical temperature: 46 °C < T_{crit} < 146 °C
- Toxicity (MSDS, RCL, TLV, $=CF_2$)
- Stability

Evaluated manually

- Volumetric capacity > 0.33 $Q_{vol,R\text{-}410A}$
  (Basic cycle simulations)

Molecule count

60 000 000



21

15 - at least mildly flammable
6 - unknown hazards

- 21 (primary interest) + 3 (commercial interest) + 3 (low T_{crit}) → 27 fluids
- New toxicity data on R-1132a; 27 + 1 (low T_{crit}) → 28 fluids

Performed detailed simulations with optimized heat exchangers for 24 fluids

Air conditioning (McLinden et al., 2017)

Refrigeration and heating (Domanski et al., 2017)

28 candidate fluids

Basic cycle; air conditioning;
optimized heat exchangers

21 fluids of primary interest:

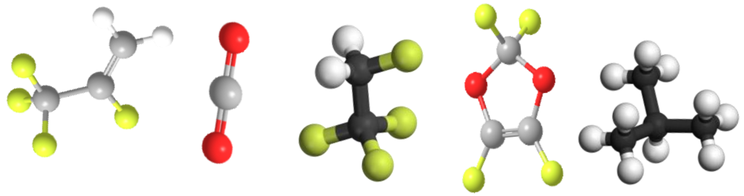
$46\ °C < T_{cr} < 146\ °C$

$Q_{vol} > 0.33\ Q_{vol,R\text{-}410A}$

15 - at least mildly flammable
6 - unknown hazards

7 additional fluids:

- ● subcritical operation; 3 fluids
  [R-134, R-1123, R-1225ye(Z)]
- ● supercritical or near-critical operation; 4 fluids
  [R-170, R-41, R-1132a, R-744]

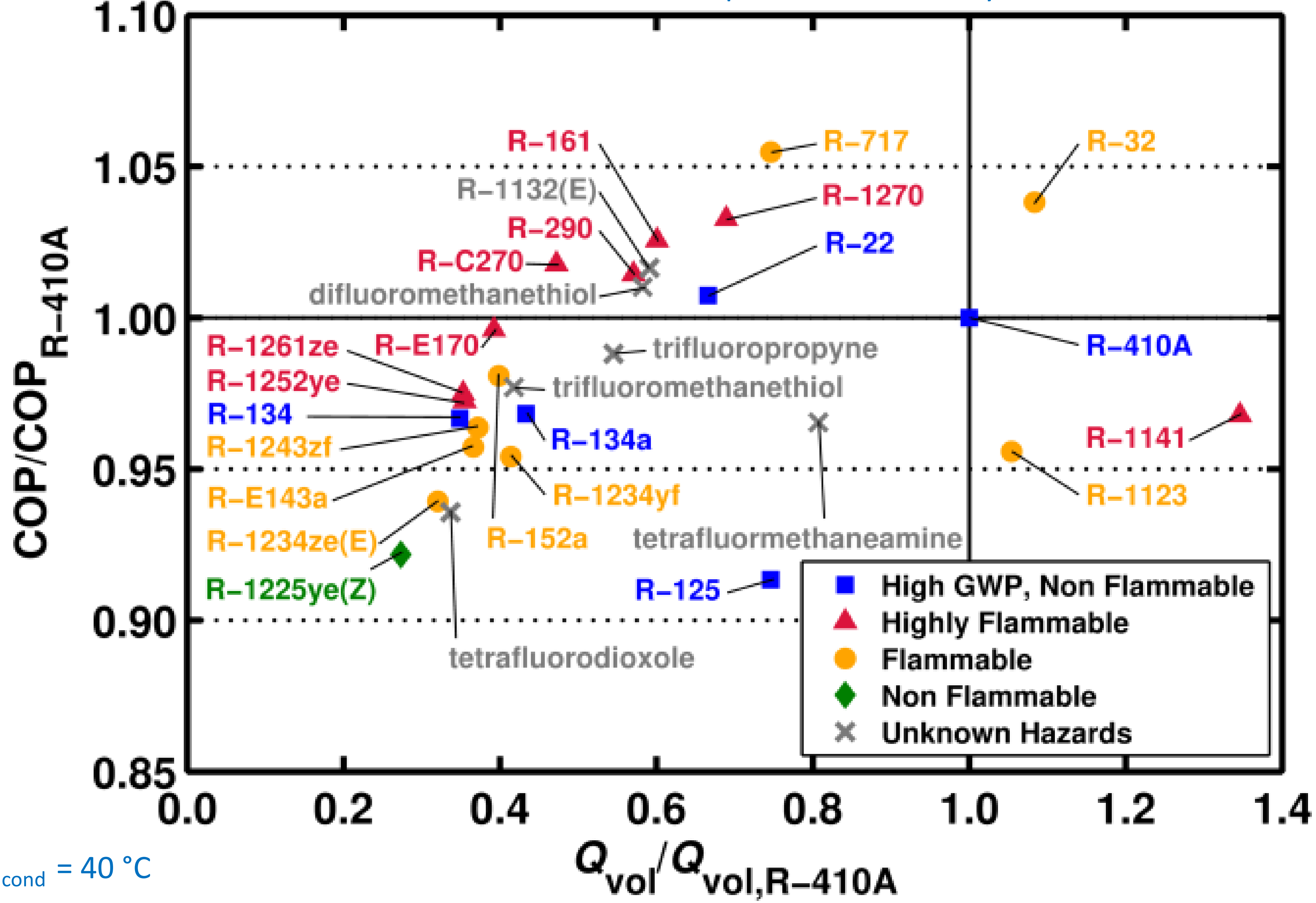


				GWP	T_{cr} (K)	$\frac{COP}{COP_{R410A}}$	$\frac{Q_{vol}}{Q_{vol,\ R410A}}$
Hydrocarbons and dimethylether							
ethane	$CH_3\text{-}CH_3$	●	R-170	6	305.3		
propene (propylene)	$CH_2\text{=}CH\text{-}CH_3$		R-1270	2	364.2	1.033	0.689
propane	$CH_3\text{-}CH_2\text{-}CH_3$		R-290	3	369.9	1.014	0.571
methoxymethane (dimethylether)	$CH_3\text{-}O\text{-}CH_3$		R-E170	1	400.4	0.996	0.392
cyclopropane	$\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}$		R-C270	86	398.3	1.018	0.472
Fluorinated alkanes (HFCs)							
fluoromethane	CH_3F	●	R-41	116	317.3		
difluoromethane	CH_2F_2		R-32	677	351.3	1.038	1.084
fluoroethane	$CH_2F\text{-}CH_3$		R-161	4	375.3	1.026	0.601
1,1-difluoroethane	$CHF_2\text{-}CH_3$		R-152a	138	386.4	0.981	0.399
1,1,2,2-tetrafluoroethane	$CHF_2\text{-}CHF_2$	●	R-134	1120	391.8	0.967	0.348
Fluorinated alkenes (HFOs) and alkynes							
1-1-difluoroethene	$CF_2\text{=}CH_2$	●	R-1132a	<1	324.2		
fluoroethene	$CHF\text{=}CH_2$		R-1141	<1	327.1	0.968	1.346
1,1,2-trifluoroethene	$CF_2\text{=}CHF$	●	R-1123	3	343.0	0.956	1.054
3,3,3-trifluoroprop-1-yne	CF3-C≡CH		n.a.	1.4	363.3	0.988	0.545
2,3,3,3-tetrafluoroprop-1-ene	$CH_2\text{=}CF\text{-}CF_3$		R-1234yf	<1	367.9	0.954	0.414
(E)-1,2-difluoroethene	$CHF\text{=}CHF$		R-1132(E)	1	370.5	1.016	0.591
3,3,3-trifluoroprop-1-ene	$CH_2\text{=}CH\text{-}CF_3$		R-1243zf	<1	376.9	0.964	0.372
1,2-difluoroprop-1-ene‡	$CHF\text{=}CF\text{-}CH_3$		R-1252ye‡	2	380.7	0.973	0.355
(E)-1,3,3,3-tetrafluoroprop-1-ene	$CHF\text{=}CH\text{-}CF_3$		R-1234ze(E)	<1	382.5	0.939	0.320
(Z)-1,2,3,3,3-pentafluoro-1-propene	$CHF\text{=}CF\text{-}CF_3$	●	R-1225ye(Z)	<1	384.0	0.922	0.273
1-fluoroprop-1-ene‡	$CHF\text{=}CH\text{-}CH_3$		R-1261ze‡	1	390.7	0.975	0.353
Fluorinated oxygenates							
trifluoro(methoxy)methane	$CF_3\text{-}O\text{-}CH_3$		R-E143a	523	377.9	0.957	0.366
2,2,4,5-tetrafluoro-1,3-dioxole	$\text{-}O\text{-}CF_2\text{-}O\text{-}CF\text{=}CF\text{-}$		n.a.	1	400.0	0.936	0.337
Fluorinated nitrogen and sulfur compounds							
N,N,1,1-tetrafluormethanamine	$CHF_2\text{-}NF_2$		n.a.	20	341.6	0.965	0.807
difluoromethanethiol	$CHF_2\text{-}SH$		n.a.	1	373.0	1.010	0.582
trifluoromethanethiol	$CF_3\text{-}SH$		n.a.	1	376.2	0.977	0.418
Inorganic compounds							
carbon dioxide	CO_2	●	R-744	1.00	304.1		
ammonia	NH_3		R-717	<1	405.4	1.055	0.746

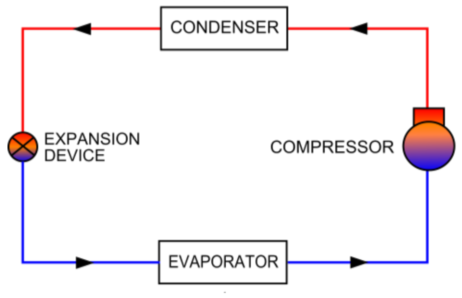
COP and Q_{vol}

Air conditioning

Simulations with optimized hx circuitry



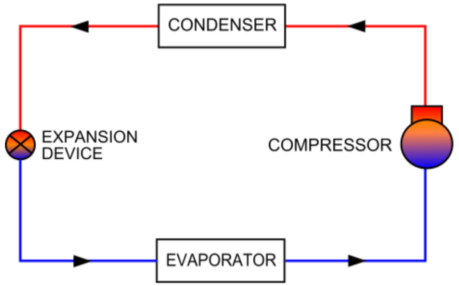
Basic cycle



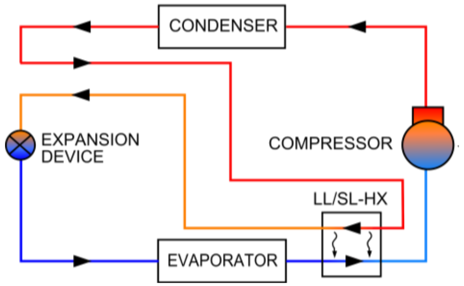
R-410A: $T_{sat,evap}$ = 10 °C; $T_{sat,cond}$ = 40 °C

COP and Q_{vol}; air conditioning

Basic cycle



Cycle with LL/SL-HX



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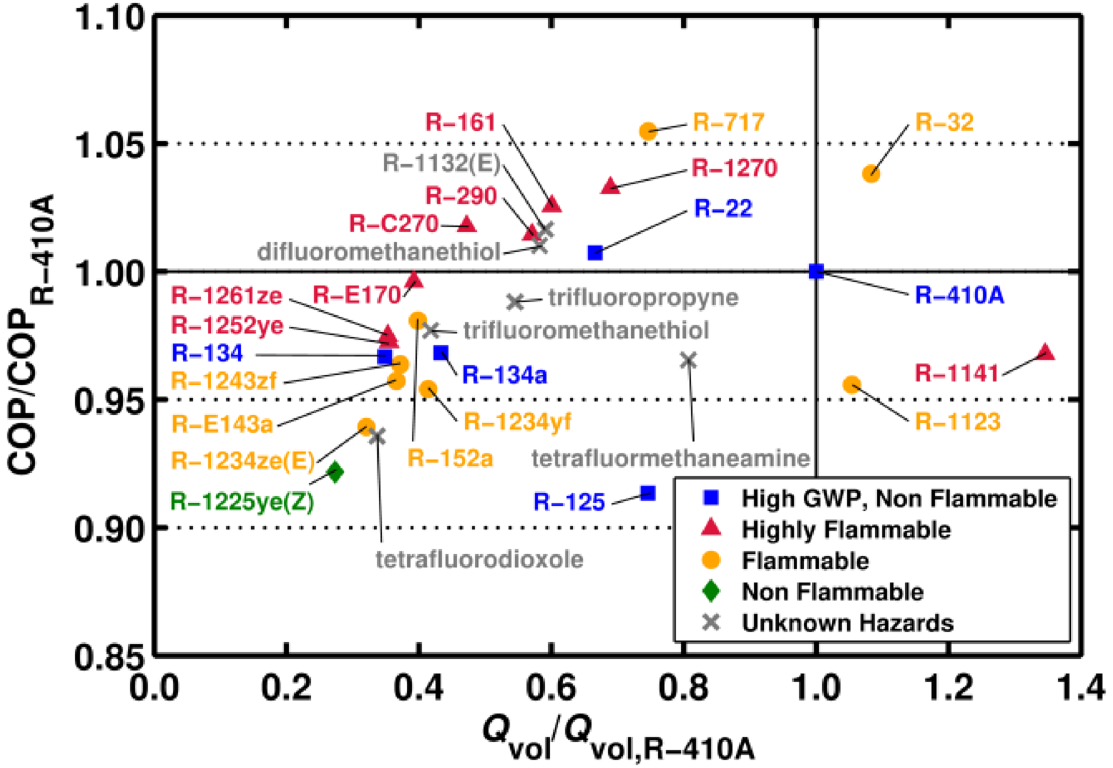

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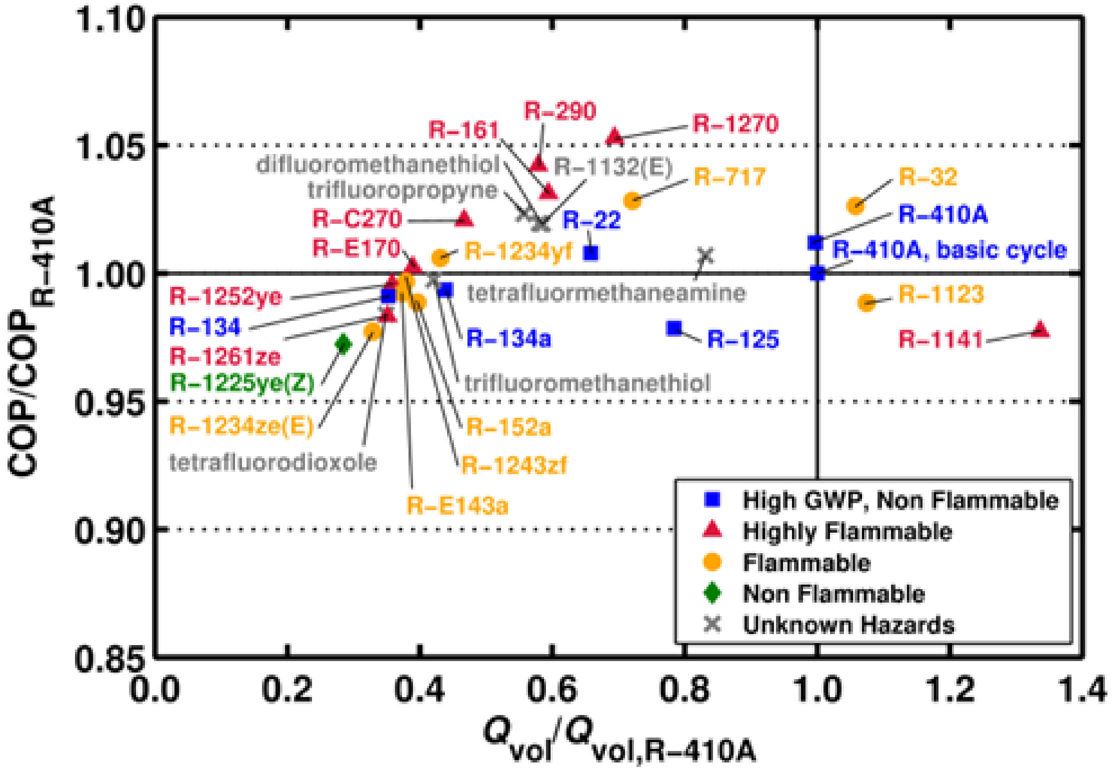
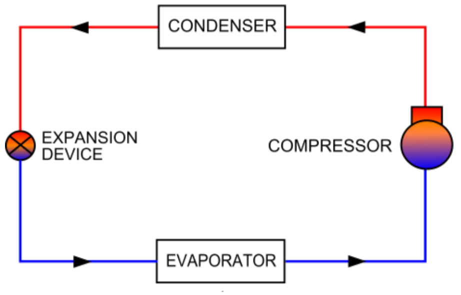
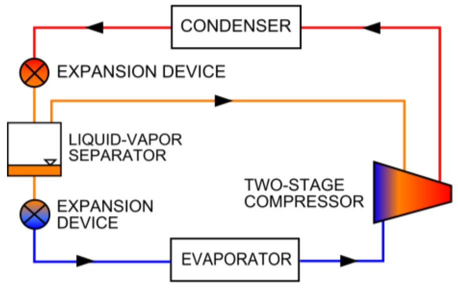


COP and Q_{vol}; air conditioning

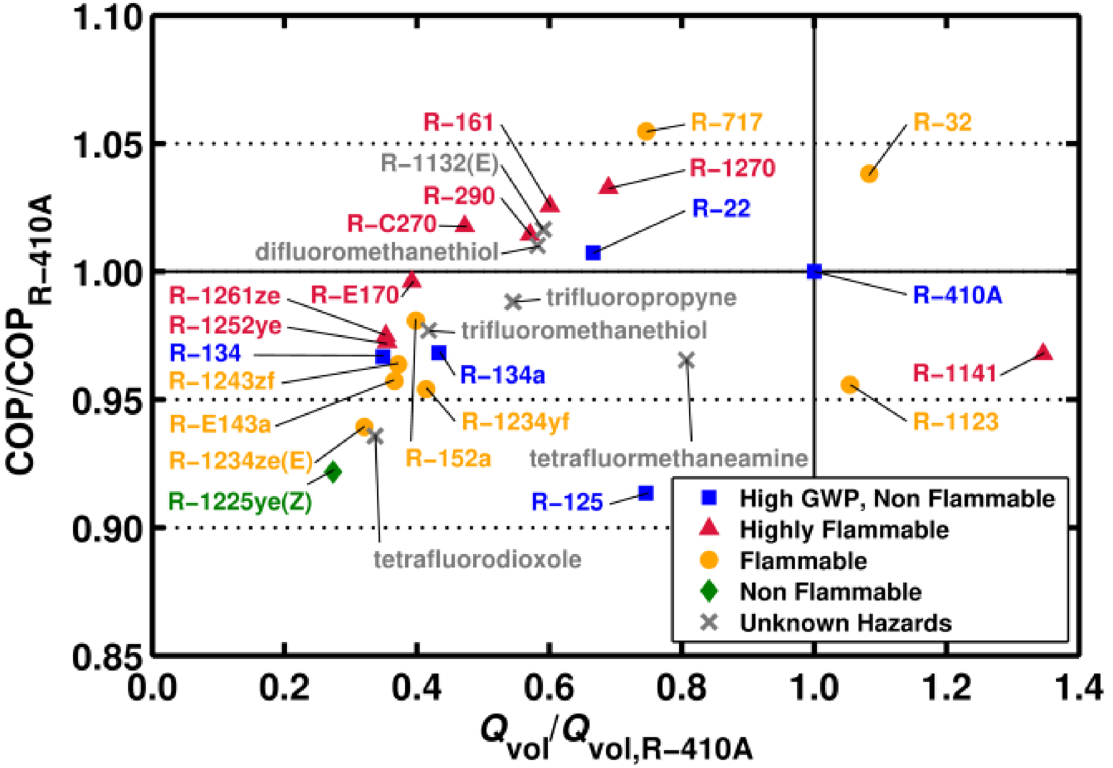
Basic cycle



Economizer cycle



Simulations with optimized hx circuitry



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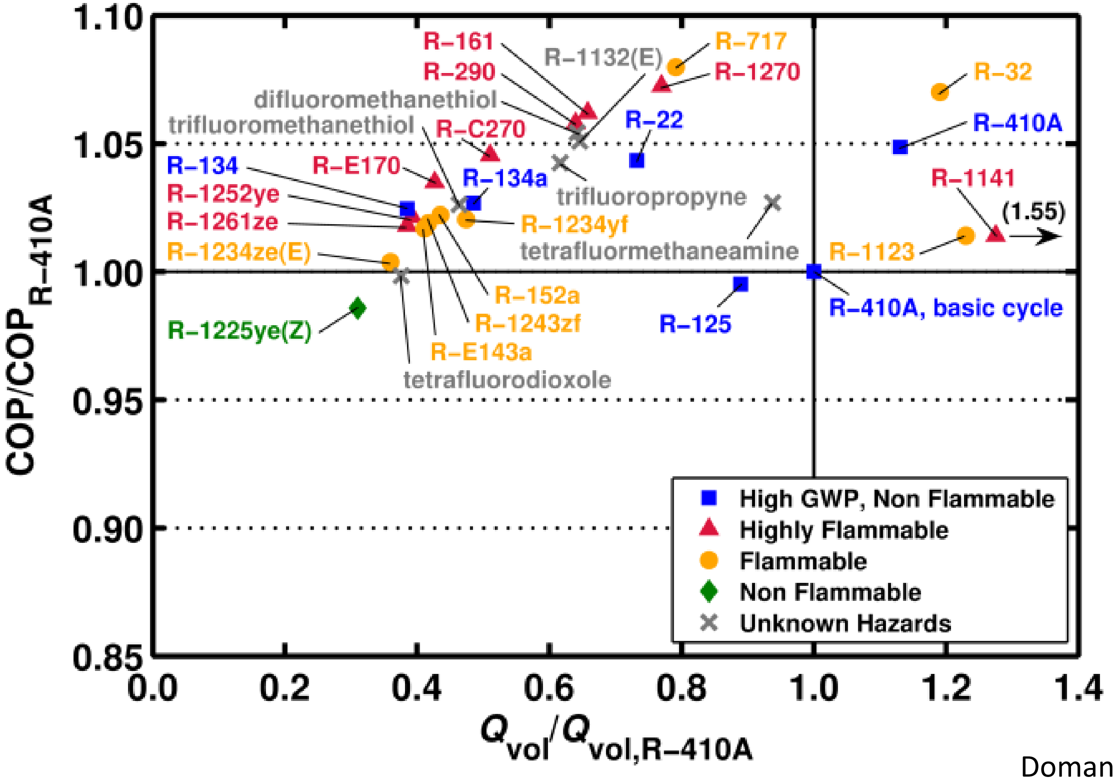
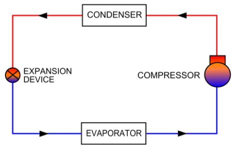
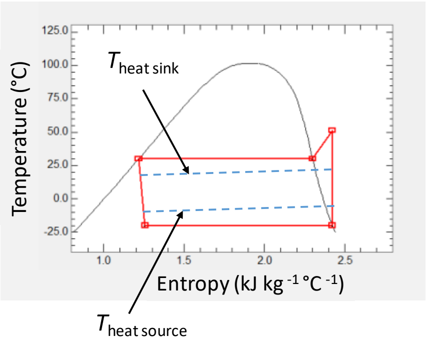


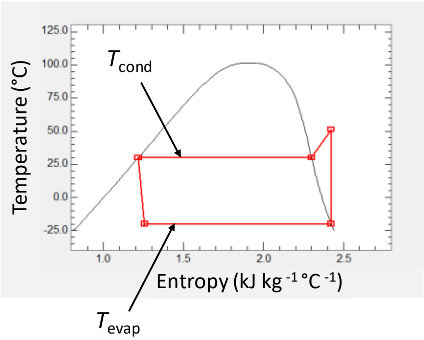
Domanski (1995)

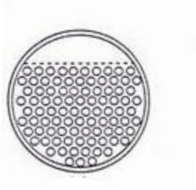
COP and Q_{vol}; air conditioning

Basic cycle









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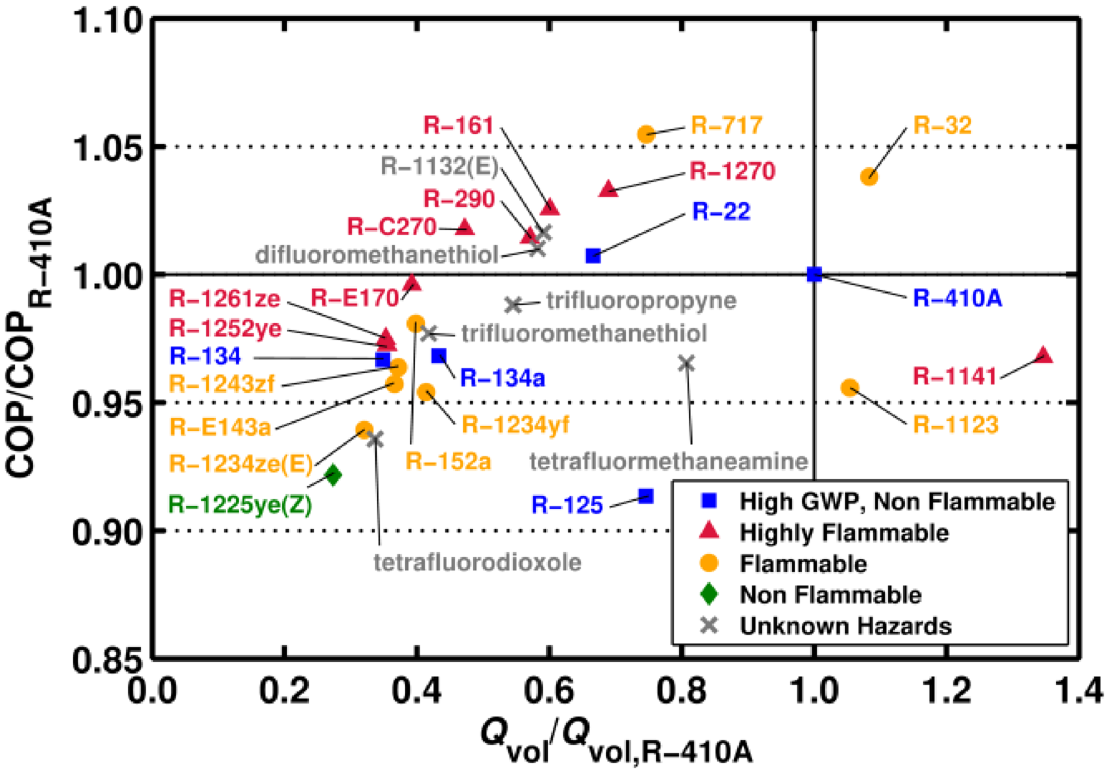
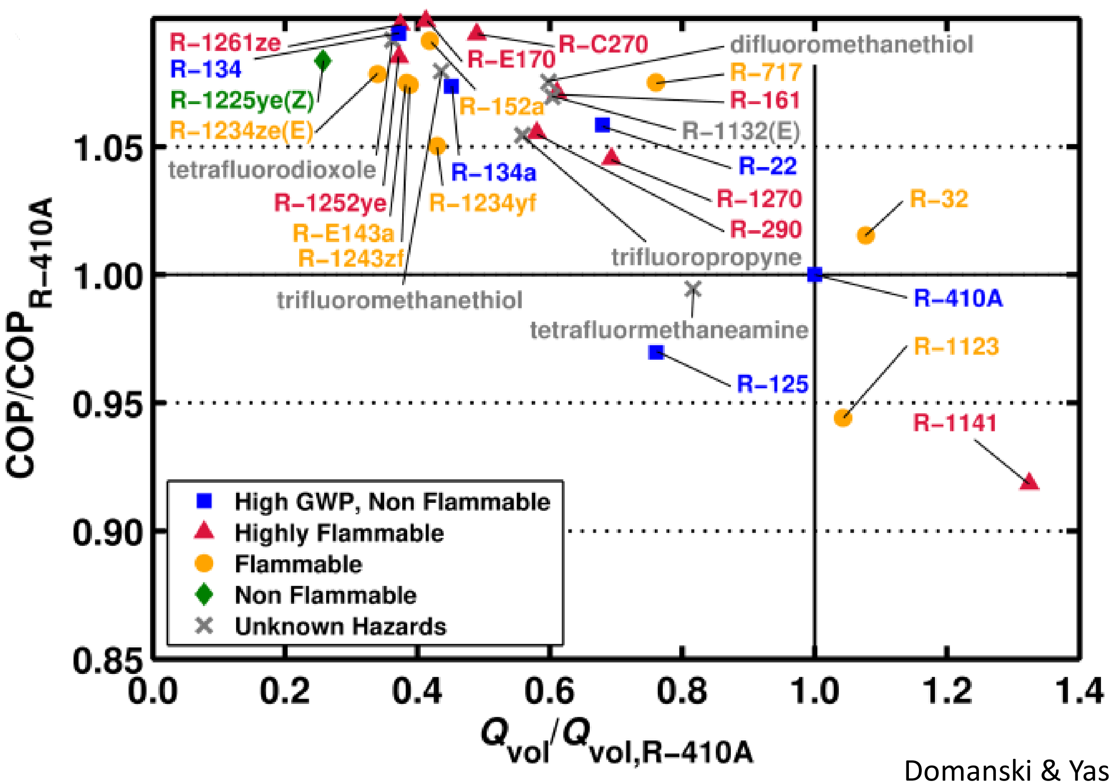


Ideal cycle simulations



Domanski & Yashar (2006)

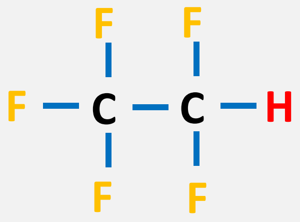
Why there are no low-GWP fluids that are nonflammable and have high Q_{vol}?

Trade-off between low GWP and flammability

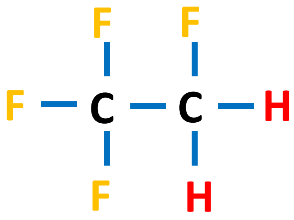
GWP can be lowered by:

○ **Replacing F or Cl with H.**
It shortens the atmospheric life but leads to flammability.

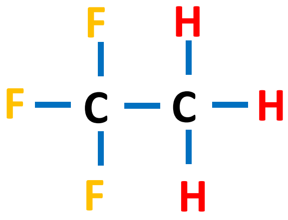
○ **Adding a C=C double bond.**
Contributes to the reaction with oxygen.



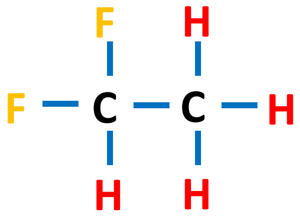
R-125
GWP = 3170; T_{cr} = 66.0 °C
Class: 1



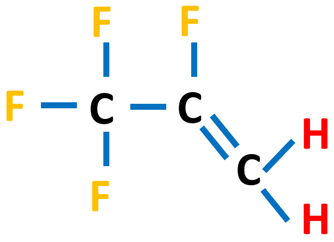
R-134a
GWP = 1300; T_{cr} = 101.1 °C
Class: 1



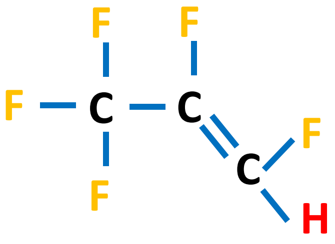
R-143a
GWP = 4800; T_{cr} = 72.7 °C
Class: 2L



R-152a
GWP = 138; T_{cr} = 113.3 °C
Class: 2



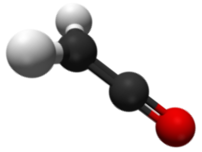
R-1234yf
GWP = < 1; T_{cr} = 94.7 °C
Class: 2L

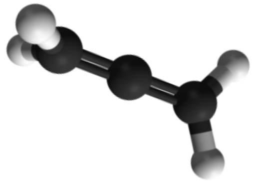


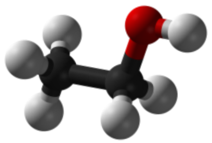
R-1225ye(Z)
GWP < 1; T_{cr} = 110.9 °C
Class: 1

Is it all ?
Why some other fluids did not make it ?

- Peroxides [-O-O-]: unstable, one dropped
- Alkynes [-C≡C-]: ≡ generally less stable than =, one retained
- Ketenes [>C=C=O]: generally very reactive, three dropped
- Allenes [>C=C=C<]: very reactive
- Alcohols [-OH]: high T_{cr}
- = CF_2 group: high reactivity often associated with toxic effects; some exceptions
- = OF group: not stable, may lead to hydrofluoric acid

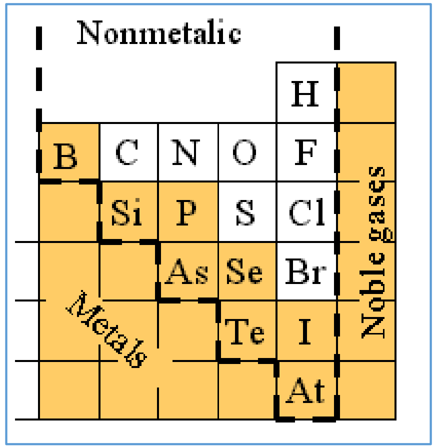






How reliable was the screening process?

Did we miss good fluids?



- PubChem database is complete (?)

  PubChem lists 30 three-carbon HFOs out of 31 possible. It is unlikely that the missing molecule would posses significantly different properties than those already listed.

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

  Additional screening of a different database with 2000 industrial fluids yielded small molecules with the above eight elements only.

- $GWP_{100} < 1000$ (?)

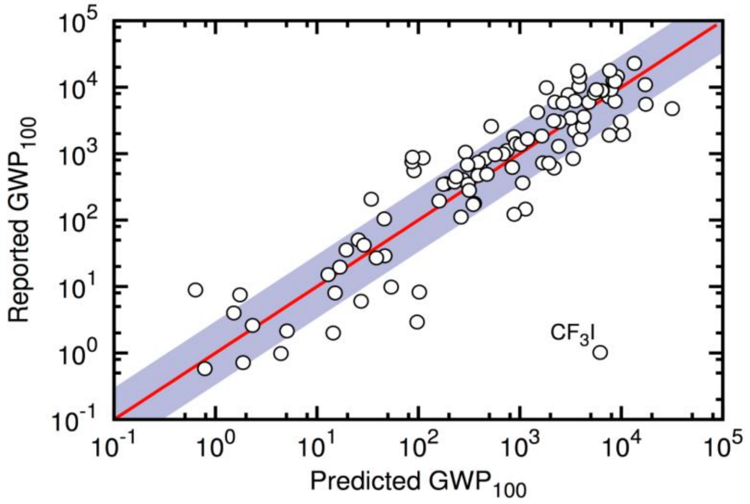
- Critical temperature: 46 °C < T_{cr} < 146 °C (?)

  Estimated with standard deviation of 16.5 K (4.5 %). $T_{cr, R\text{-}410A}$=71.3 °C

- Stability and toxicity (?)

  Published data, which may be erroneous. E.g., toxicity of R-1132a

  Unstable fluid may be stabilized and used in the system. E.g., R-1123, R-13I1 (CF_3I)



RMS deviation: factor of 3

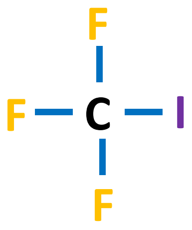
CF_3I - ASHRAE Standard 34 proposed addenda ‘t’ and ‘s’

Addendum ‘t’

R-13I1
Chemical name = trifluoroiodomethane
Chemical formula **CF_3I**
OEL = 500 ppm v/v
Safety Group = A1
GPW = 0.4

Addendum ‘s’

R-466A
Composition (mass %) = R-32/125/13I1 (49/11.5/39.5)
OEL = 860 ppm v/v
Safety Group = A1
GWP = 733



CF_3I

○ ODP = 0.008

○ Good thermodynamic properties

○ Fire suppression properties

○ **Toxicity** of **CF_3I** was studied in the 1990s (McCain and Macko, 1999). **CF_3I** is SNAP-approved fire suppressing agent replacing halon 1301 (total flooding) and halon 1211 (streaming), with restrictions to unoccupied and non-residential uses, respectively.

○ R-1234yf/**CF_3I** (70/30) was studied in the 2000s for automotive ACs, within the Cooperative Research Program CRP150 (SAE). Dropped over concerns related to the **non-zero ODP** and **reactivity** of **CF_3I**. (Brown, 2012)

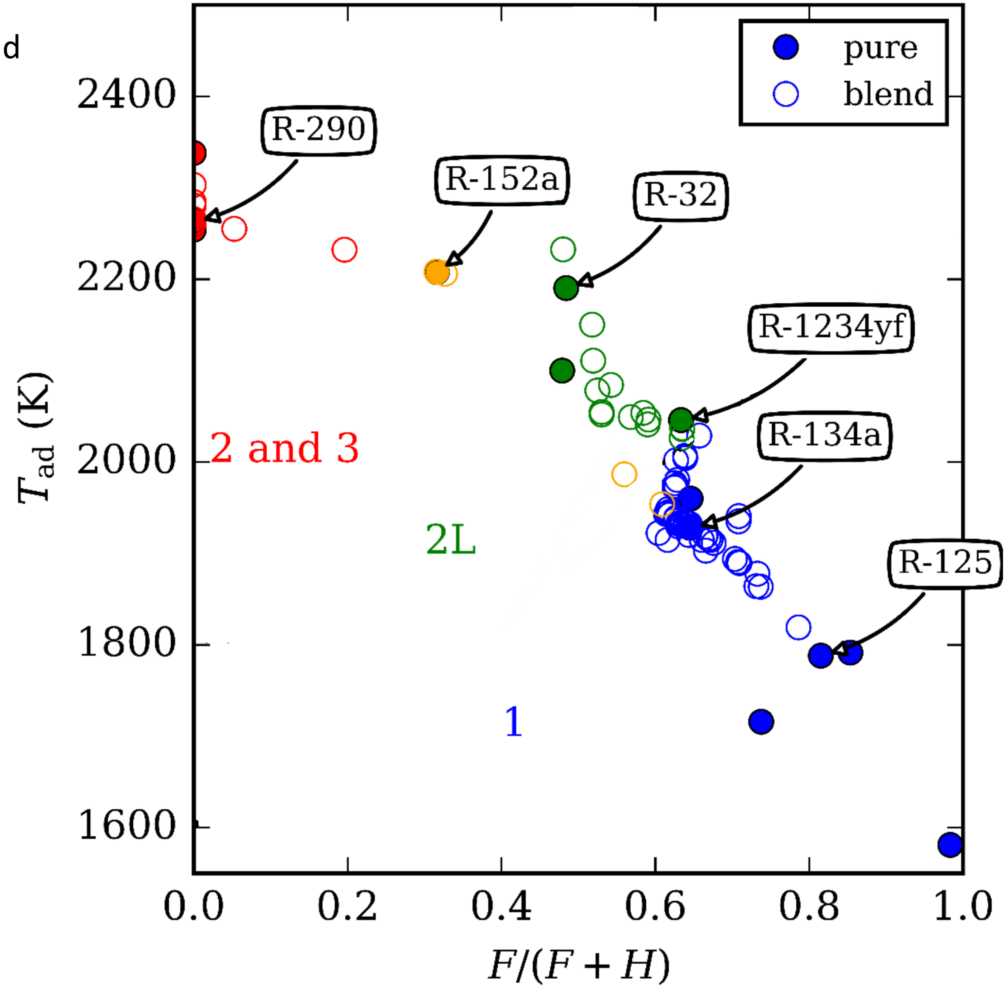
CF_3I is expected to see future application as a component of <u>nonflammable</u> blends.

Application challenge: reactivity

Normalized Flammability Index $\overline{\Pi}$

Novel empirical flammability estimate

- Uses $F/(F+H)$ in reactants and adiabatic flame temperature T_{ad}
- Effects of humidity are included
- Based on the ASHRAE Std. 34 experimental database of refrigerant flammability



Initial temperature = 60 °C; mole fraction of H_2O in air = 0.014

Linteris et al. (2017)

Normalized Flammability Index $\bar{\Pi}$

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- ○ Effects of humidity are included
- ○ Based on the ASHRAE Std. 34 experimental database of refrigerant flammability

Flammability index

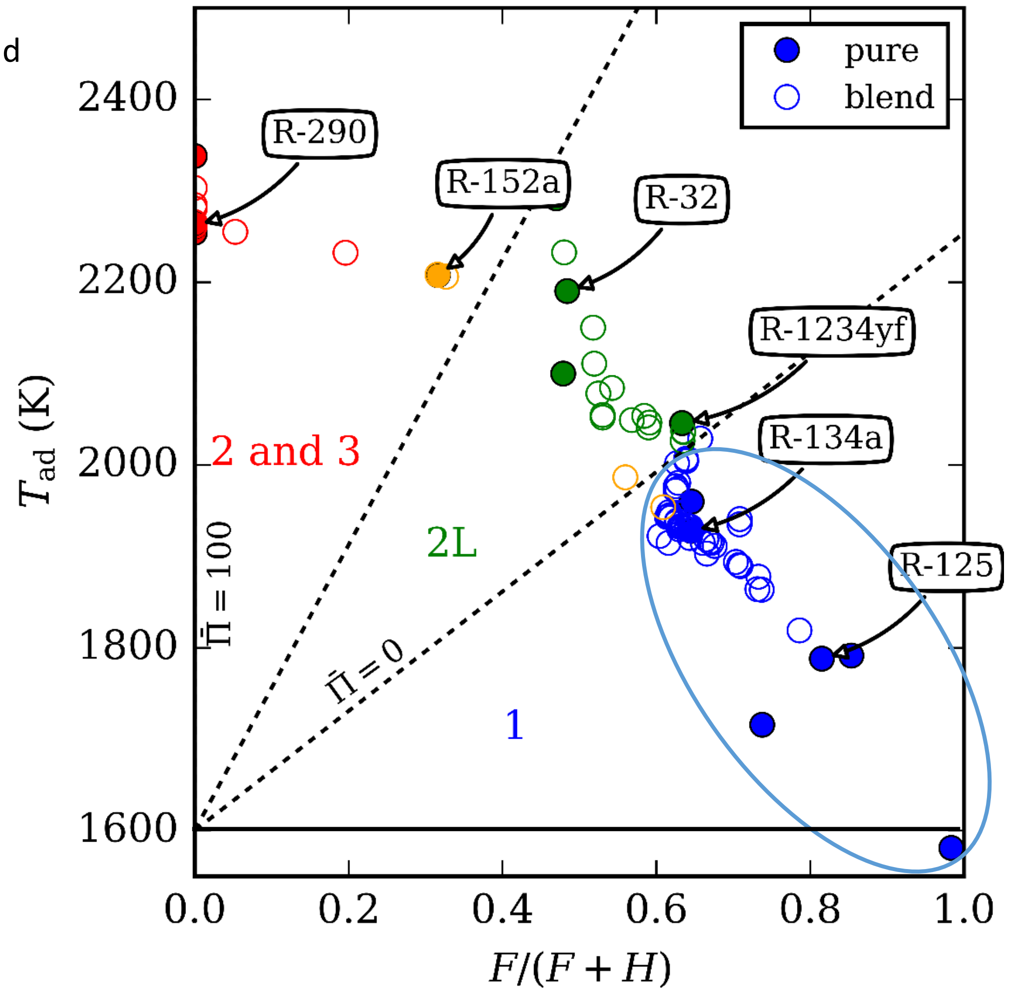
$$\Pi = \mathrm{arctan2}\left(\frac{T_{ad} - 1600}{2500 - 1600}, \frac{F}{F + H}\right) \cdot \left(\frac{180}{\pi}\right)$$

$\Pi_{1,2L} = 36$; flammability boundary between classes 1 and 2L

Normalized flammability index

$$\bar{\Pi} = \frac{\Pi - \Pi_{1,2L}}{90 - \Pi_{1,2L}} \cdot 100$$

$\bar{\Pi} < 0$ No flame propagation



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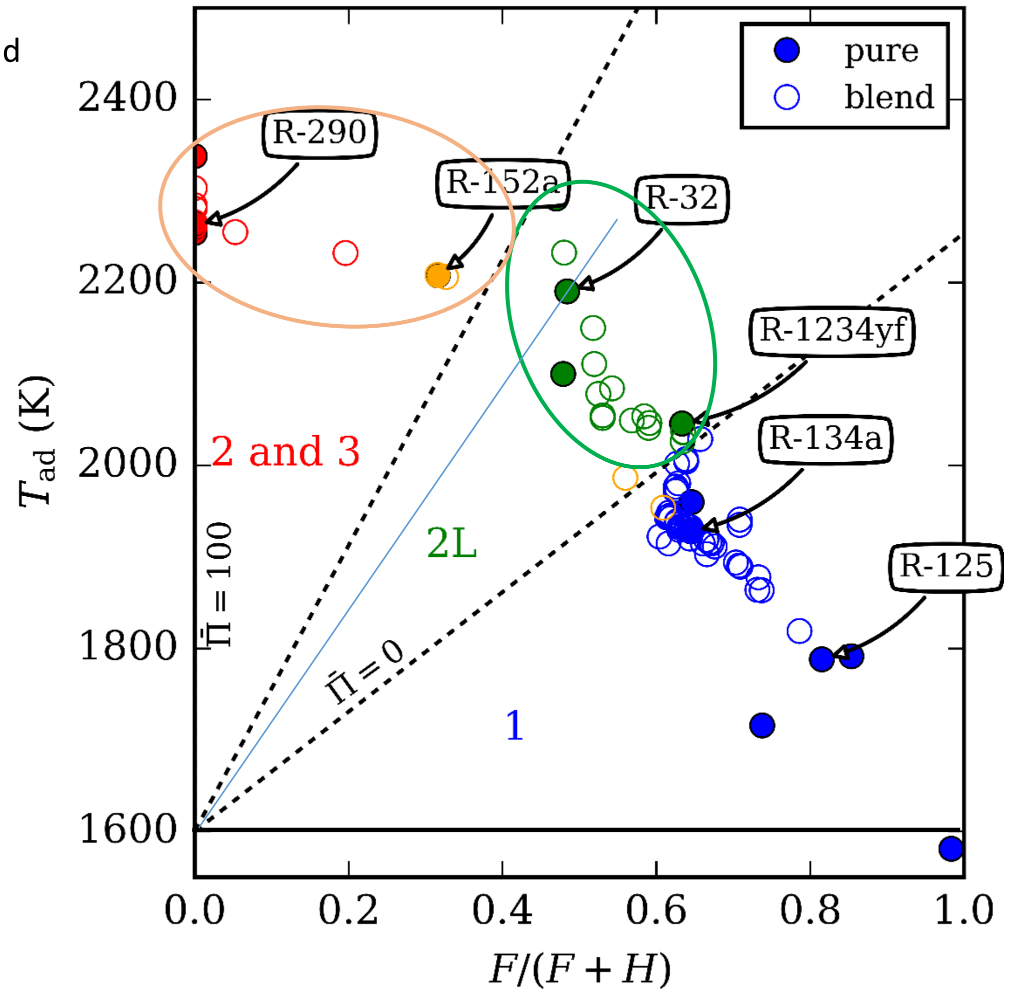
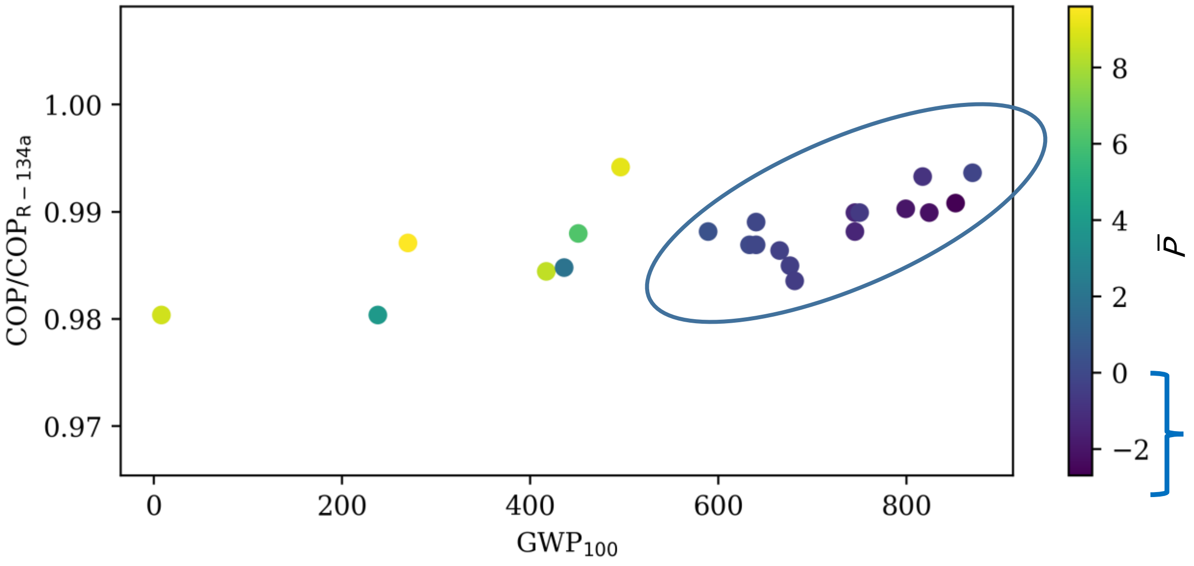


Linteris et al. (2017)

Initial temperature = 60 °C; mole fraction of H_2O in air = 0.014

Search for nonflammable replacements for R-134a

- ○ Comprehensive evaluation binary, ternary and four-component blends (13 compounds considered)
- ○ Selection criteria:
  - Minimize flammability
  - Minimize GWP
  - Maximize COP
  - Match volumetric capacity to that of R-134a



Bell et al. (2019)

Blend components	Composition (molar)	GWP	$\frac{\mathrm{COP}}{\mathrm{COP}_{\mathrm{R-134a}}}$	$\frac{Q}{Q_{\mathrm{R-134a}}}$	$\overline{\Pi}$
R-152a/1234yf	0.08/0.92	8	0.980	0.957	7.7
R-134a/1234yf	0.20/0.80	238	0.980	0.996	2.8
R-134a/152a/1234yf	0.20/0.16/0.64	270	0.987	0.984	8.7
R-152a/1234yf/134	0.16/0.48/0.36	417	0.984	0.900	7.5
R-134a/1234yf	0.36/0.64	436	0.985	1.018	1.0
R-134a/1234yf/1243zf	0.36/0.44/0.20	451	0.988	1.004	5.2
R-134a/152a/1234yf	0.36/0.20/0.44	496	0.994	0.994	8.3
R-134a/1234yf	0.44/0.56	537	0.987	1.025	-0.1
R-134a/1234yf	0.468/0.532 †	573	0.988	1.027	-0.4
R-134a/1234yf/134	0.48/0.48/0.04	633	0.987	0.975	-1.1
R-134a/1234yf/1234ze(E)	0.52/0.32/0.16	640	0.987	0.989	-1.2
R-134a/1234yf	0.52/0.48	640	0.989	1.029	-1.2
R-134a/1234yf/134	0.4/0.44/0.16	665	0.986	0.958	-1.3
R-134a/125/1234yf	0.44/0.04/0.52	676	0.985	1.049	-1.5
R-134a/227ea/1234yf	0.40/0.04/0.56	681	0.984	1.007	-1.5
R-134a/1234ze(E)	0.60/0.40	745	0.988	0.908	-2.4
R-134a/1234yf	0.60/0.40	745	0.990	1.031	-2.4
R-134a/1234ze(E)/1243zf	0.60/0.36/0.04	750	0.990	0.966	-1.5
R-134a/1234yf/1234ze(E)	0.64/0.2/0.16	799	0.990	0.986	-3.0
R-134a/152a/1234yf	0.64/0.04/0.32	817	0.993	1.023	-1.8
R-134a/1234yf/134	0.52/0.32/0.16	824	0.990	0.966	-3.2
R-134a/1234ze(E)	0.68/0.32	852	0.991	0.929	-3.7
R-134a/1234yf/1243zf	0.68/0.2/0.12	870	0.994	1.020	-1.1

† R-513A

Low-GWP refrigerant options

🟦 No flame propagation
🟧 Lower flammability
🟥 Higher flammability

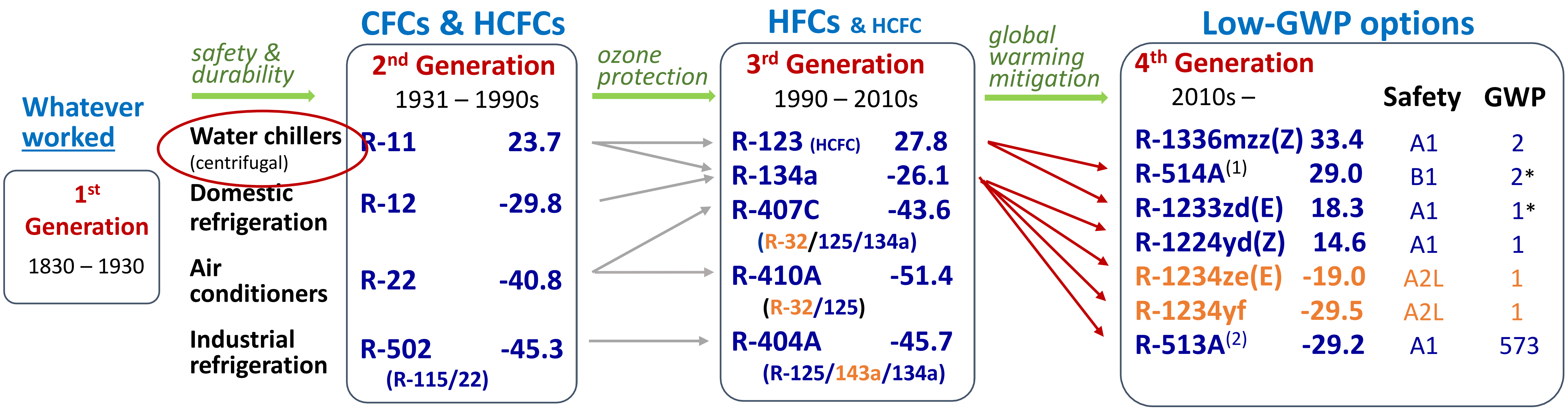
Natural fluids

H_2O	100.0	R-717	-33.3	R-600a	- 11.7
CO_2	-78.4			R-290	- 42.1
air	-194.2			R-1270	- 47.7

Ammonia

Normal boiling point (°C)

Fluorinated fluids



Whatever worked

1st Generation
1830 – 1930

safety & durability

Water chillers (centrifugal)
Domestic refrigeration
Air conditioners
Industrial refrigeration

CFCs & HCFCs

2nd Generation
1931 – 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 – 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

Low-GWP options

4th Generation
2010s –

		Safety	GWP
R-1336mzz(Z)	33.4	A1	2
R-514A[(1)]	29.0	B1	2*
R-1233zd(E)	18.3	A1	1*
R-1224yd(Z)	14.6	A1	1
R-1234ze(E)	-19.0	A2L	1
R-1234yf	-29.5	A2L	1
R-513A[(2)]	-29.2	A1	573

Calm (2008), Calm (2012), Myhre, G. et al. (2013)

* Source other than IPCC AR5

(1) R-1336mzz(Z)/1130(E) (74.7/25.3)

(2) R-1234yf/134a (56/44)

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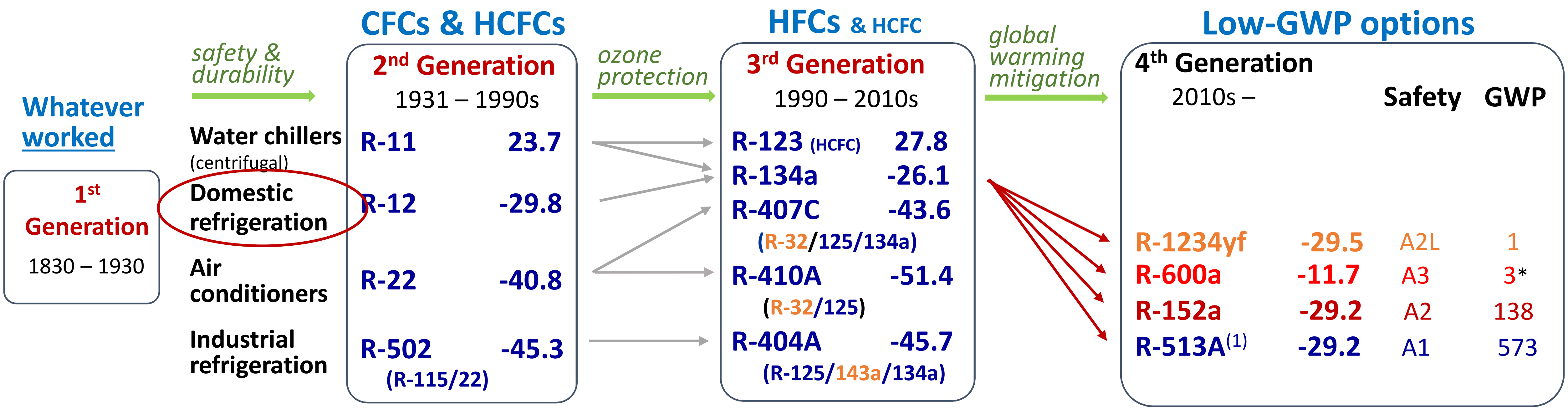
H_2O	100.0	R-717	-33.3	R-600a	- 11.7
CO_2	-78.4			R-290	- 42.1
air	-194.2			R-1270	- 47.7

Ammonia

Normal boiling point (°C)

Fluorinated fluids



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global warming mitigation

Low-GWP options

4th Generation
2010s –

		Safety	GWP
R-1234yf	-29.5	A2L	1
R-600a	-11.7	A3	3*
R-152a	-29.2	A2	138
R-513A(1)	-29.2	A1	573

Calm (2008), Calm (2012), Myhre, G. et al. (2013)

* Source other than IPCC AR5

(1)R-1234yf/134a (56/44)

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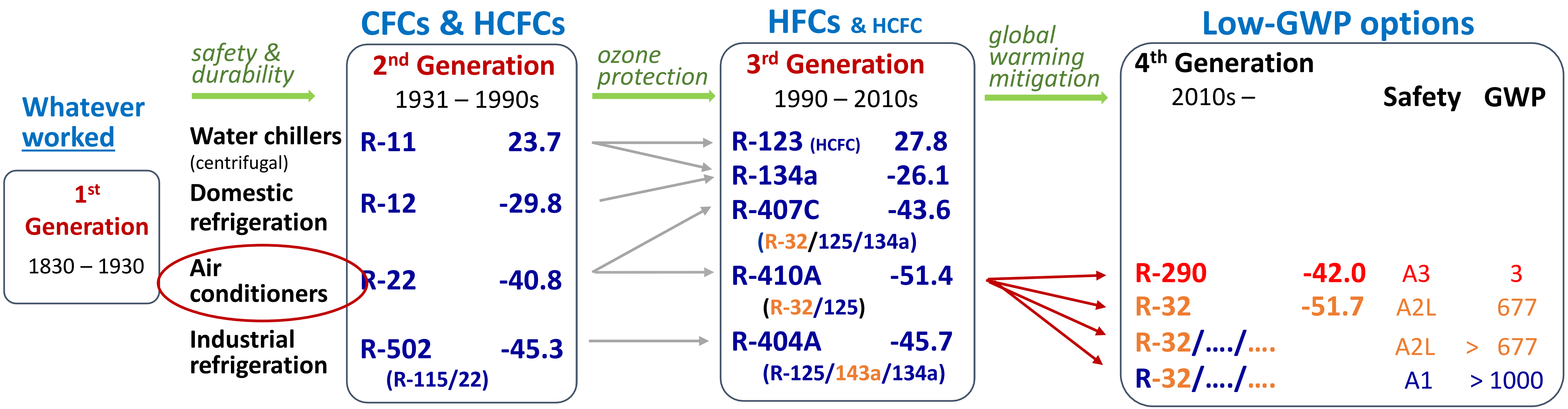

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global warming mitigation

Low-GWP options

4th Generation
2010s –

		Safety	GWP
R-290	**-42.0**	A3	3
R-32	**-51.7**	A2L	677
R-32/..../....		A2L	> 677
R-32/..../....		A1	> 1000

Calm (2008), Calm (2012), Myhre, G. et al. (2013)

Low-GWP refrigerant options

- 🟦 No flame propagation
- 🟧 Lower flammability
- 🟥 Higher flammability

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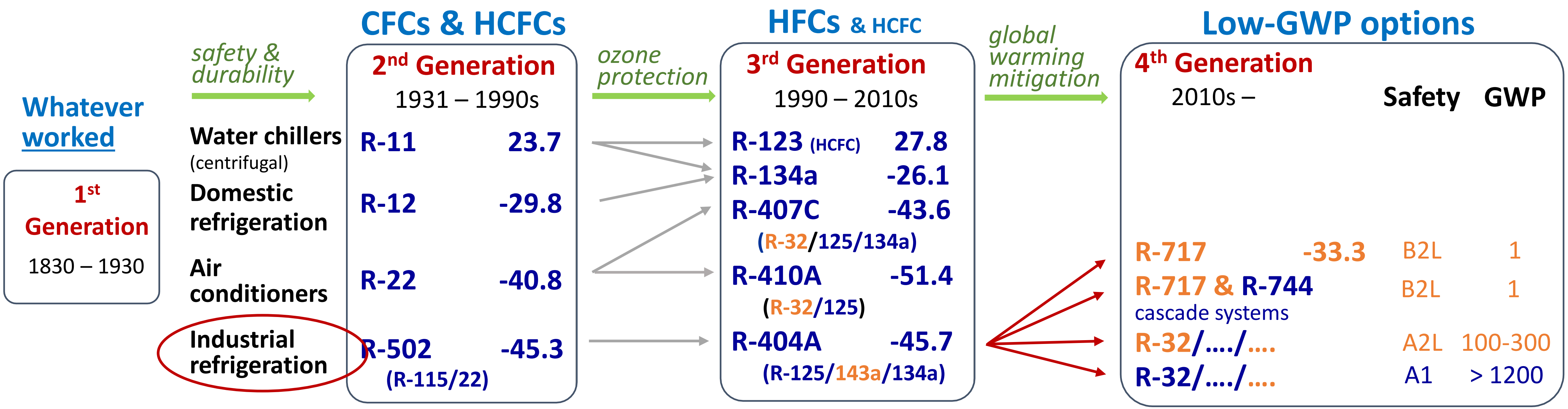
Ammonia

Normal boiling point (°C)

Fluorinated fluids



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global warming mitigation

Low-GWP options

4th Generation
2010s –

		Safety	GWP
R-717	-33.3	B2L	1
R-717 & R-744 cascade systems		B2L	1
R-32/..../....		A2L	100-300
R-32/..../....		A1	> 1200

Calm (2008), Calm (2012), Myhre, G. et al. (2013)

Cooling technologies

sorted by primary energy input

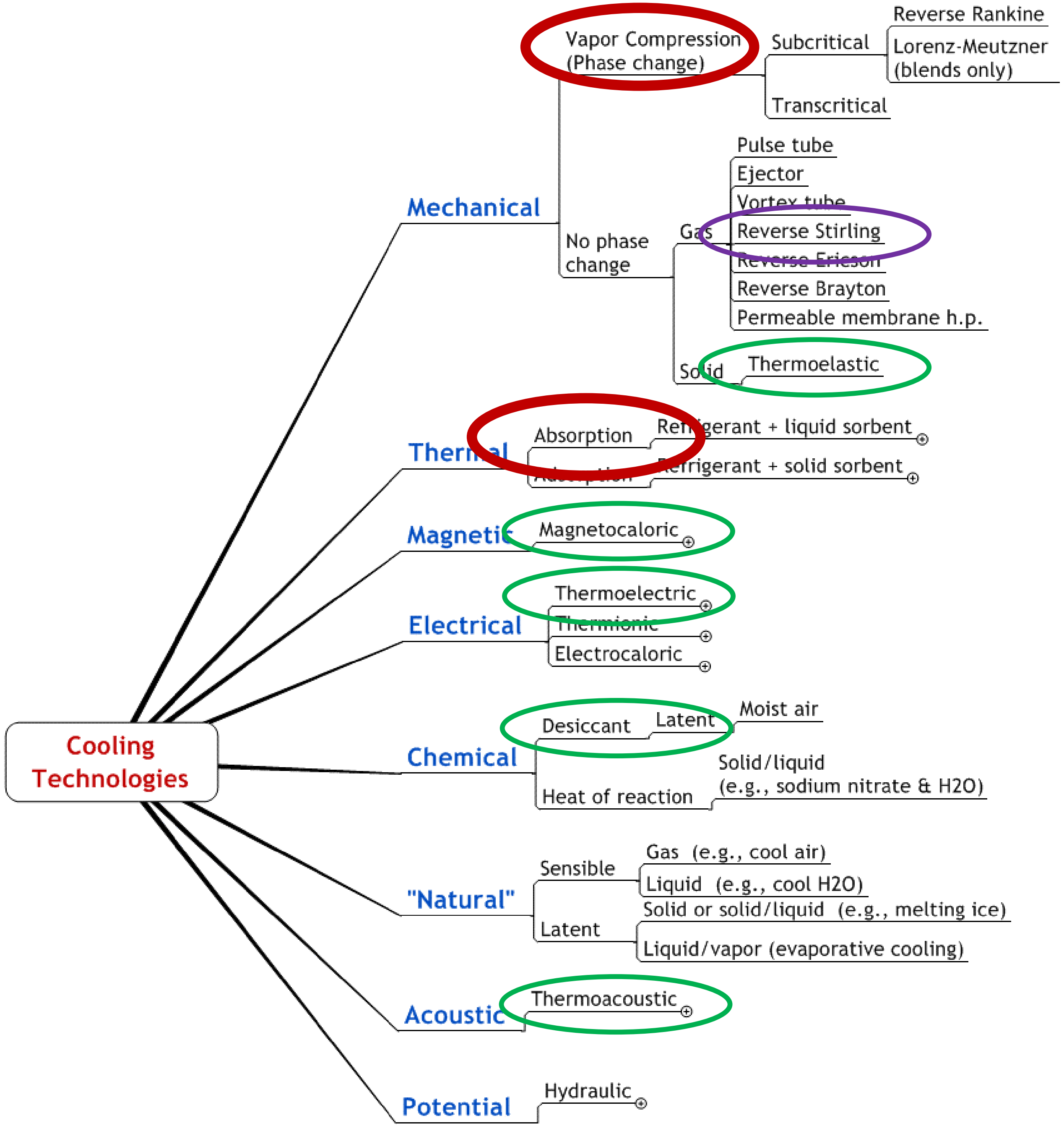
Acceptance criteria

- Coefficient of Performance
- Environmental
- Safety
- Cost
- Reliability
- Serviceability
- Physical size, weight

Best prospects for competing with vapor compression

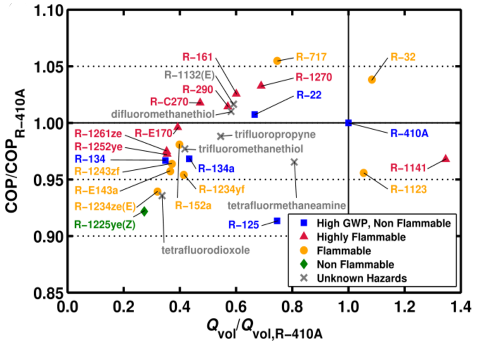
🟢 Space conditioning

🟣 Food refrigeration



- Cooling Technologies
  - Mechanical
    - Vapor Compression (Phase change)
      - Subcritical
        - Reverse Rankine
        - Lorenz-Meutzner (blends only)
      - Transcritical
    - No phase change
      - Gas
        - Pulse tube
        - Ejector
        - Vortex tube
        - Reverse Stirling
        - Reverse Ericson
        - Reverse Brayton
        - Permeable membrane h.p.
      - Solid
        - Thermoelastic
  - Thermal
    - Absorption
      - Refrigerant + liquid sorbent
    - Adsorption
      - Refrigerant + solid sorbent
  - Magnetic
    - Magnetocaloric
  - Electrical
    - Thermoelectric
    - Thermionic
    - Electrocaloric
  - Chemical
    - Desiccant
      - Latent
        - Moist air
    - Heat of reaction
      - Solid/liquid (e.g., sodium nitrate & H2O)
  - "Natural"
    - Sensible
      - Gas (e.g., cool air)
      - Liquid (e.g., cool H2O)
    - Latent
      - Solid or solid/liquid (e.g., melting ice)
      - Liquid/vapor (evaporative cooling)
  - Acoustic
    - Thermoacoustic
  - Potential
    - Hydraulic

Concluding comments



- Availability of low-GWP refrigerants varies between applications
  - Good availability of low-pressure fluids (low GWP, nonflammable)
  - No direct HFO replacement candidate for R-22 or R-410A

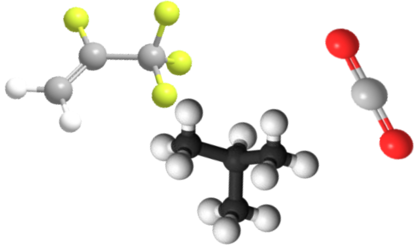
    Single-component medium- and high-pressure replacement fluids are at least mildly flammable

- Prospects for finding new viable refrigerants are minimal.

  New equipment will have to be designed using the fluids we know already and their blends.

- Trade off between GWP ↓ and flammability ↑

Concluding comments



- Alternative cooling technologies?

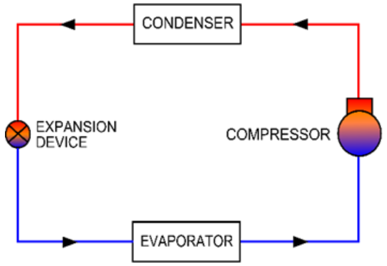
Alternative technologies will gain entry in niche applications

but

will need significant development effort and material breakthroughs to be competitive and enter the main stream.

Ice harvesting

Vapor compression



?

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

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

Thank you for your attention.

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