New Developments in Lower GWP Refrigerants (MENA)

ASHRAE Professional Development
New Developments in Lower GWP Refrigerants (MENA)

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Clean Energy Air and Water Technologies FZE
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Course ID: 920017564
Learning Objectives

Alternative Lower Global Warming Potential (GWP) Refrigerants are widely sought as sustainable solutions for Heating Ventilation Air Conditioning and Refrigeration (HVAC&R) applications. At the end of this course; participants will be able to

• Understand the transition landscape
• Describe the proposed refrigerants and how they can be used in different HVAC&R applications
• Understand the challenges and opportunities associated with the different types of refrigerants
• Differentiate between different related standards and codes
Outline/Agenda

- Background Information
- Proposed Alternatives for Different Applications—Theoretical and Empirical Analyses
- Related Standards and Codes of Systems and Substances
- Challenges and Opportunities
- Systems Perspective—Energy Efficiency with New Refrigerants
Defining the Refrigerants

• A refrigerant is a substance or mixture of substances, used for either providing cooling (usually air conditioning or refrigeration) or heating (heat pumps), while usually undergoing liquid-to-vapor or vapor-to-liquid phase transition respectively

• Refrigerants are all around you
  • Sometimes referred to “natural” refrigerants
  • Most refrigerants are engineered to provide the required safety and efficiency for specific applications at an adequate cost

• One of the most commonly used refrigerants is that used by your body to keep you cool! You drink it everyday
  • R718 or water
History of HVAC&R Refrigerants

1st Generation
“Whatever works”
1830’s – 1930’s

- NH₃
- CO₂
- Hydrocarbons
- H₂O
- SO₂
- Methyl Chloride (R-40)

2nd Generation
“Safety and Stability”
1930’s – 1990’s

- NH₃
- CFCs: R-11, R-12
- HCFCs: R-22, R-502

3rd Generation
“Ozone Protection”
1990’s – 2010’s

- NH₃
- HCFCs: R-22, R-123
- HFCs:
  - R-134a
  - R-410A
  - R-404A
  - Other blends

4th Generation
“Global Warming”
2010’s - ?

- NH₃
- Low GWP HFCs, HFOs, and HCFOs: R-1234yf, R-1234ze(E), R-1233zd(E), R-32, and their blends
- Renewed interest in natural refrigerants: CO₂, Hydrocarbons

Limited optimal choices
Safety and design challenges

Limited applications – industry
Poor safety and cost

Enabled innovation
Preserved 2nd gen. innovations, safety, stability and efficiency
Regulatory Landscape—Growing Pressure on HFCs

• Global: phase-down of HFCs through the Kigali amendments to the Montreal Protocol

• Japan: Kyoto Protocol—METI/NEDO promoting development and use of fluids with low GWP. Extensive risk assessment study for use of Class 2L flammable refrigerants (5 years).

• EU: F-gas regulations. Regulations on stationary refrigerants starting in 2020, now 2015!

• Australia: Australian Carbon Trading Scheme proposed high carbon tax, starting (including HFCs). Currently under debate.

• U.S.: EPA rulemaking/SNAP
Phasing Down HFCs

- Based on equivalents CO₂ emissions (mass * GWP)
- No ban on specific refrigerants
- The higher the GWP and the larger mass used, the higher its impact would be on the collective country quota and thus pressure for phase-down
- Focus of phase-down:
  - Reduce GWP of refrigerant used
  - Reduce refrigerant charge size
  - Reduce leakages
  - Recover, recycle and reclaim refrigerants

$190 in USA
$113 in India!

$190 in USA
$70 in India!
Kigali Amendment Proposals

• Adopted by the 28th Meeting of Parties to the Montreal Protocol on October 15th 2016 in Kigali, Rwanda. It includes the following:
  • Agreement in principle by all 197 member countries to focus on reduction of HFC use to reduce net warming by 0.5°C
  • Adds HFCs to the list of substances controlled under the Montreal Protocol.
  • Phase-down HFCs under the Montreal Protocol as their use is increasing rapidly as substitutes for ozone-depleting substances.
  • Four major, separate phase-out timelines; several exceptions.
  • Obviously some clean-up work and final ratifications are necessary and in process
Kigali’s Impact

• Phase-down, not a phase-out, of HFCs
• Avoids over 80 billion metric tons of carbon dioxide equivalent cumulatively through 2050
• According to UNEP:
  • HFC phase-down is expected to avoid up to 0.5 degree Celsius of global temperature rise by 2100
  • Continue to protect the ozone layer

Kigali’s HFC Phase-Down Schedule

A2 exceptions: Belarus, Russian Federation, Kazakhstan, Tajikistan, Uzbekistan
• 25% HCFC component of baseline
• 5% reduction in 2020
• 35% reduction in 2025

A5 exceptions (Group 2): GCC, India, Iran, Iraq, Pakistan

Technology review in 2022 and every 5 years

Technology review 4–5 years before 2028 to consider the compliance deferral of 2 years from the freeze of 2028 of A5 Group 2 to address growth

Source: Kujak, S., “Flammability and New Refrigerant Options”, *ASHRAE Journal* May 2017
Technology Pull

• A2 countries have already stopped production of HCFCs and are limiting its use
  • HFC market is very mature
  • Alternative refrigerants are already being extensively evaluated

• These development in developing countries would be available to A5 countries via “international pull-through”
  • Potential for leapfrogging from HCFC to alternative lower GWP refrigerants

• Additional regulations and rules in developments for A2 countries such as leak reduction, technician training, and refrigerant recovery could be considered by A5 countries
Kigali’s Ratifications

<table>
<thead>
<tr>
<th>Country</th>
<th>Country</th>
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</tr>
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<td>Australia</td>
<td>Ecuador</td>
<td>Luxembourg</td>
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<td>Grenada</td>
<td>Niger</td>
<td>Trinidad and Tobago</td>
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<td>Ireland</td>
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<td>Côte d'Ivoire</td>
<td>Lao People's Democratic Republic</td>
<td>Palau</td>
<td>United Kingdom of Great Britain and Northern Ireland</td>
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<td>Czech Republic</td>
<td>Latvia</td>
<td>Panama</td>
<td>Uruguay</td>
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<td>Democratic People's Republic of Korea</td>
<td>Lithuania</td>
<td>Portugal</td>
<td>Vanuatu</td>
</tr>
</tbody>
</table>

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
  - Unsaturations (double or triple bonds; i.e. using olefins)
- Best approach
  - Unsaturation and hydrogen (HFO, HCFO, HCO, HBFO)
- Problem: flammability increases
Representative Alternative Low GWP Refrigerant Molecules

R-1234yf – A2L

R-1234ze(E) – A2L

R-1233zd(E) – A1

R-1224yd(Z) – A1

R-1123
# Olefin Molecules Proposed as Refrigerants

<table>
<thead>
<tr>
<th>Designation</th>
<th>ASHRAE Designation</th>
<th>Chemical</th>
<th>BP °C</th>
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<tbody>
<tr>
<td>HO-1150</td>
<td>R-1150</td>
<td>Ethene</td>
<td>–104°C</td>
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<tr>
<td>HO-1270</td>
<td>R-1270</td>
<td>Propene</td>
<td>–48°C</td>
</tr>
<tr>
<td>HFO-1234yf</td>
<td>R-1234yf</td>
<td>1,1,1,2-tetrafluoropropene</td>
<td>–29.4°C</td>
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<tr>
<td>HFO-1234ze</td>
<td>R-1234ze</td>
<td>1,1,1,3-tetrafluoropropene</td>
<td>–19°C</td>
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<tr>
<td>HFO-1336mzz(Z)</td>
<td>R-1336mzz(Z)</td>
<td>1,1,1,4,4,4-hexafluoro-2-butane</td>
<td>33.4°C</td>
</tr>
<tr>
<td>HFO-1233zd(E)</td>
<td>R-1233zd(E)</td>
<td>t-1-chloro-3,3,3-trifluoropropene</td>
<td>19°C</td>
</tr>
<tr>
<td>HCO-1130(E)</td>
<td>R-1130 (E)</td>
<td>t-dichloroethene</td>
<td>47.7°C</td>
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<tr>
<td>HFO-1123</td>
<td>Trifluoroethene*</td>
<td>Trifluoroethylene</td>
<td>–56°C</td>
</tr>
<tr>
<td>HCFO-1224yd</td>
<td>Chlorotetrafluoro-propene*</td>
<td>1-chloro-2,3,3,3-tetrafluoropropene</td>
<td>16°C</td>
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<tr>
<td>HFO-1132a</td>
<td>Difluoroethene*</td>
<td>1,1-difluoroethylene (vinylidenefluoride)</td>
<td>–86.7°C</td>
</tr>
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</table>
Refrigerant Selection: A Trade-Off

- Environmental performance (~0 ODP and reduced GWP)
- Safety for consumers (flammability and toxicity)
- Energy efficiency (reduced indirect CO₂ emissions, especially at high ambient operations)
- Intellectual property considerations
- Transition costs (industry and consumers)
- Product sustainability
HFO-1234yf—Low-GWP Option to Replace R-134a

- HFO-1234yf is the first in a growing family of olefin molecules
- Met timing mandated by European MAC Directive to replace R-134a
- Excellent environmental properties
  - Very low GWP of 1, zero ODP, good LCCP
  - Atmospheric chemistry determined and published
- Low toxicity: Acute and chronic toxicity superior to R-134a
- System performance very similar to R-134a
  - Excellent COP and capacity, no glide
  - Thermally stable and compatible with R-134a components
  - Potential for direct substitution of R-134a
HFO-1234yf Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>R-134a</th>
<th>R-1234yf</th>
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<tbody>
<tr>
<td>Boiling Point</td>
<td>–26°C</td>
<td>–29°C</td>
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<tr>
<td>Molecular weight</td>
<td>102</td>
<td>114</td>
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<tr>
<td>Formula</td>
<td>CF₃CH₂F</td>
<td>CF₃CF=CH₂</td>
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<tr>
<td>GWP</td>
<td>1300</td>
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Vapor Pressure, MPa vs Temperature, °C
HFO Development Trend as per ASHRAE Standard 34

<table>
<thead>
<tr>
<th>First HFO Molecule in Standard 34</th>
<th>2008 – HFO-1234yf</th>
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<tr>
<td>First HFO Blend in Standard 34</td>
<td>2012 – Class 2L</td>
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<tr>
<td>First Non Flammable HFO Blend</td>
<td>2013</td>
</tr>
<tr>
<td>HFO Status as of Mid 2017</td>
<td></td>
</tr>
<tr>
<td>(Includes refrigerants proposed,</td>
<td></td>
</tr>
<tr>
<td>but not necessarily listed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 8 distinct molecules</td>
</tr>
<tr>
<td></td>
<td>• 37 refrigerant blends (21 flammable, 16 non-flammable)</td>
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Proposed Alternatives for Different Applications

Theoretical and Empirical Analyses
R-22/R-407C Alternatives

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<tr>
<th>Refrigerant</th>
<th>GWP(_{100,\text{years}}), AR5</th>
<th>ODP</th>
<th>Standard 34 Designation</th>
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<tr>
<td>R-22</td>
<td>1760</td>
<td>0.06</td>
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<td>R-407C</td>
<td>1624</td>
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<tr>
<td>DR-93</td>
<td>1147</td>
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<td>A1</td>
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<td>N-20b</td>
<td>904</td>
<td>0</td>
<td>A1</td>
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<td>R-449B</td>
<td>1296</td>
<td>0</td>
<td>A1</td>
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<td>ARM-20b</td>
<td>251</td>
<td>0</td>
<td>A2L</td>
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<tr>
<td>DR-3</td>
<td>146</td>
<td>0</td>
<td>A2L</td>
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<tr>
<td>R-444B</td>
<td>295</td>
<td>0</td>
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Relative Performance Compared with Baseline Refrigerant: R-22
### R-404A Alternatives

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<th>GWP&lt;sub&gt;100years&lt;/sub&gt;</th>
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<tr>
<td>R-404A</td>
<td>3943</td>
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<td>0</td>
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<td>ARM-35</td>
<td>2019</td>
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<td>0</td>
<td>A1</td>
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<td>R-452A</td>
<td>1945</td>
<td>0</td>
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<td>R-448A</td>
<td>1273</td>
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<td>146</td>
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<td>ARM-32a</td>
<td>1445</td>
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<td>DR-33</td>
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<td>N-40a</td>
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<td>A1</td>
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# R-404A Alternatives

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<th>AR5</th>
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<tr>
<td>N-40b</td>
<td>1222</td>
<td>0</td>
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<td>ARM-30a</td>
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<td>ARM-31a</td>
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<td>D-2Y65</td>
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<td>DR-7</td>
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<td>L-40</td>
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<td>R-32</td>
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<td>R-32/R-134a</td>
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<td>R-290</td>
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Relative Performance Compared with Baseline Refrigerant: R-404A
# R-134a Alternatives

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<tr>
<td>R-134a</td>
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<td>AC5X</td>
<td>568</td>
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<td>A1</td>
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<td>ARM-41a</td>
<td>860</td>
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<td>A1</td>
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<td>D-4Y</td>
<td>521</td>
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<td>A1</td>
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<td>N-13a,N-13b</td>
<td>547</td>
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<td>573</td>
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<td>ARM-42a</td>
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<td>R-1234yf,R-1234ze</td>
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<td>R-600a, R-290/R-600a</td>
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Relative Performance Compared with Baseline Refrigerant: R-134a
# R-410A Alternatives

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<td>HPR1D</td>
<td>407</td>
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<td>L-41a, L-41b</td>
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<td>A2L</td>
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<td>R-32</td>
<td>677</td>
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<td>R-32/R-134a</td>
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<td>R-32/R-152a</td>
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Relative Performance Compared with Baseline Refrigerant: R-410A
Market Fragmentation

- R-134a
  - Refrigerators: HCs and R-1234yf
  - MAC: R-1234yf
  - Chillers/refrigeration: R-513A, R-1234ze(E), R-1234yf
- R-404A/R407C
  - Transport: R-452A and CO$_2$
  - Stationary: R-448A, R-449A/B, transcritical CO$_2$, cascaded cycles
- R-410A
  - Small charge: HCs and R-32
  - Splits: R-32 and R-452B
Related Standards and Codes of Systems and Substances
Standards

ASHRAE Industry Consensus Standards

• ASHRAE Standard 34—Safety classification
• ASHRAE Standard 15—Application rules, large equipment
• ASHRAE Standard 15.2—Residential and light commercial AC and HP

General Standards

• ISO 817—Safety classification
• ISO 5149—Application rules
• European Norms (EN) EN378—Design guide for AC, heat pump, and refrigeration equipment, with required safety
Standards

**ASHRAE Product Standards**
- Underwriter’s Laboratories standards for certification of specific equipment uses:
  - UL 471—Commercial refrigeration and freezers,
  - UL 484—Room air conditioners,
  - UL 250—Domestic refrigerators, and
  - More for other equipment types

**Product Standards**
- EC and IEC product and equipment standards, which have precedence in many venues:
  - EN/IEC 60335-2-89—Commercial refrigeration and freezing,
  - EN/IEC 60335-2-40—Electrical AC and heat pumps,
  - EN/IEC-60335-2-24—Domestic refrigerators, and
  - more for other equipment types
ASHRAE Standard 34

• A listing of refrigerants that have been reviewed and evaluated for safety.

• An evergreen document subject to continuous maintenance.

• New refrigerants can be added to this standard after a new refrigerant application is submitted to and reviewed by the Standing Standards Process Committee that oversees this standard—SSPC34.

• As necessary, new refrigerant safety classification rules can be added.
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

* A2L and B2L are lower flammability refrigerants with a maximum burning velocity of ≤3.9 in./s (10 cm/s).

**FIGURE 6.1.4** Refrigerant safety group classification.
ASHRAE Standard 15

- Safety classification information developed and published in ASHRAE Standard 34 is, in turn, used in ASHRAE Standard 15
- ASHRAE Standard 15 is an application standard. It gives basic rules for how and where a refrigerant can be used, based on the safety classification developed by ASHRAE Standard 34 for that refrigerant
- Building code agencies, government agencies, architects, and designers use the application guidelines that are developed by ASHRAE Standard 15
ASHRAE Standard 15—Purpose and Scope

• Purpose: Specifies safe design, construction, installation, and operation of refrigeration systems

• Scope: Establishes safeguards for life, limb, health, and property and prescribes safety requirements

• Applies to:
  • Design, construction, test, installation, operation, and inspection of mechanical and absorption refrigeration systems, including heat-pump systems used in stationary applications;
  • Modifications, including replacement of parts or components if they are not identical in function and capacity; and
  • Refrigerant substitutions with a different designation
# Standards and their Impact on Flammable Refrigerant Charge Limit

<table>
<thead>
<tr>
<th>Standard</th>
<th>Title</th>
<th>Application</th>
<th>Factors that dictate allowable charge limit</th>
<th>Flammable Ref. Charge Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 60335-2-24 ANSI/UL 60335-2-24 (6th)</td>
<td>Particular requirements for refrigerating appliances, ice-cream appliances and ice-makers</td>
<td>Domestic refrigeration</td>
<td></td>
<td>Up to 150g of flammable refrigerant per circuit</td>
</tr>
<tr>
<td>IEC 60335-2-89 ANSI/UL 60335-2-89 (1st)</td>
<td>Particular requirements for commercial refrigerating appliances with an incorporated or remote condensing unit or compressor</td>
<td>Any refrigeration appliances used in commercial situations</td>
<td>Minimum room size, leak detection sensors, fan circulation</td>
<td>Current: Up to 150g of flammable refrigerant per circuit Future: A2L ~1.2 kg A3 ~ 0.5 kg</td>
</tr>
<tr>
<td>IEC 60335-2-40 (6th)</td>
<td>Particular requirements for electrical heat pumps, air conditioners and dehumidifiers</td>
<td>Any air conditioning and heat pump applications</td>
<td>Minimum room size, LFL, lowest release height, maximum releasable charge, leak detection sensors, ventilation</td>
<td>A2L ~ 80 kg A3 ~ 1 kg</td>
</tr>
<tr>
<td>ISO 5149</td>
<td>Mechanical refrigeration systems used for cooling and heating - safety requirement</td>
<td>Any refrigeration, air conditioning and heat pumps: domestic, commercial and industrial</td>
<td>Varies by access category and location classification</td>
<td>Current: A2L ~ 39 x LFL A3 ~ 1.5 kg Future: A2L ~ 60-80 kg A3 ~ 1.5 kg</td>
</tr>
</tbody>
</table>
Safety Standards and Building Codes—US Example

ASHRAE 34 - 2016

SNAP Approval

ASHRAE 15 - 2019

Model Codes (ICC/IAPMO)

2018 Uniform Mechanical Code
SAFE USE OF REFRIGERANTS
Assessing Risks when Using Flammable Refrigerants

• Evaluate and quantify the hazards

• Make reasonable assumptions and ask relevant questions
  • For example: What is the probability of a leak occurring?
  • If a leak or loss of refrigerant does occur, what is the probability that it might ignite?
  • If an ignition occurs, what are the consequences?
  • What leak scenarios can be imagined and quantified?
Flammability—Controlling and Designing for Key Factors

• Fuel air mixture:
  • Select refrigerant with higher concentration (LFL) to minimize the chance of having a “combustible cloud”

• Ignition sources
  • Restrict or enclose
  • Select refrigerants requiring highest minimum ignition energy

• Severity of event
  • Design application to handle pressure rise (venting)
  • Design refrigerant to minimize potential secondary issues
  • Select refrigerants with lowest possible burning velocity
Considerations for Using Flammable Refrigerants

• Determine if the refrigerant might be used in a space occupied by humans
  • Residential? Factory? Business (e.g., supermarket)?

• Is the space used for working or as a living space for ordinary citizens, some of whom may have limited or impaired mobility?

• Limit the amount of refrigerant per machine, based on the risk posed by the particular refrigerant, and/or the size of the room that contains the machine
Considerations for Using Flammable Refrigerants

• Depending on the amount of flammable refrigerant being used, there may be requirements for overpressure relief venting to the outside of the building or requirements for direct mechanical venting of escaped gas by use of fans. For larger systems, the requirements may include limiting the equipment that contains hazardous refrigerants to specially designed and access-controlled machine rooms or even machine placement outside of the building altogether.

• These measures are already used for such refrigerants as propane, ammonia, HCFC-123, and hydrocarbons, as used in chiller systems per ASHRAE Standard 15 and ISO 5149. These same safety measures are being reviewed and extended to fit the new Class 2L lower-risk, flammable refrigerants.
How Does One Use a Flammable Refrigerant?

• Apply the rules in relevant standards
  • ASHRAE Standard 15—primarily for commercial and industrial applications
  • ASHRAE Standard 15.2P—domestic and light commercial AC equipment in the United States
    • This standard is under development

• IEC/UL standards for specific applications
  • Standards are being updated and harmonized globally
  • IEC/UL/60335–x-xx
Information Available for Users, Designers, and Installers on Low-GWP Refrigerants

(See also the references at the end of these charts for links to manufacturer safety information.)
Safety Information Available Now: Material Safety Data Sheets

• Manufacturers are legally responsible for providing safety information about products they make and sell (safety data sheets [SDS]/material safety data sheets [MSDS]). These are on manufacturer web sites and searchable.

• Third-party regulatory bodies also provide safety limits and usage guidelines (e.g., UL in the United States).

• Some consideration had already been given to using flammable refrigerant gases (propane, butane, isobutane, etc.), particularly for domestic refrigerators and other small systems; more detailed in European ISO, EN, and EC standards.
Refrigerant MSDS and Safe-Handling Instructions

- Search online for MSDS for the product(s) of interest
- Search terms: “Refrigerant Safety”, “Refrigerant Handling”, “Product_Name” Safe Handling
Rigorous Refrigerant Safety are Required

• Use leak monitors but now not just on large systems.
• Use oxygen monitors in enclosed spaces or low areas like basements.
• Be sure that pressure relief devices and any overpressure vents exhaust to the outside of the building.
• Use active mechanical venting if equipment is indoors.
New Rules Apply for Flammable Refrigerants

- Determine the flammability of the refrigerant being used.
- Do not use flammable refrigerants in equipment not designed for or rated for flammable refrigerants.
- Use vacuum pumps and recovery machines rated for use with flammable refrigerants, with non-sparking switches and non-sparking motors.
- Be aware of charge size limitations, as prescribed by safety codes and regulations.
Be Aware of Common Hazards

• Do not smoke or allow others to smoke if flammable refrigerants are being used, transferred, charged, or recovered.

• Be alert for any potential ignition source—heaters, sparking motors or switches, static electricity, etc.

• When brazing, or welding, be sure all refrigerant has first been evacuated from the system.

• Not a new concern but much more important with flammable refrigerants
Challenges and Opportunities
Global Cooling Demand

Green House Gas Emissions

- Stationary A/C account for ~700 MMTCO2e annually
  - 74% Indirect emissions from electricity generation
  - Direct emissions: 7% HFC and 19% HCFC

<table>
<thead>
<tr>
<th>Residential</th>
<th>Status</th>
<th>2012 Global Annual Sales (US$B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room &amp; portable</td>
<td>🟢</td>
<td>$3.4</td>
</tr>
<tr>
<td>Ducted split &amp; single-package</td>
<td>𝐷الة</td>
<td>$3.3</td>
</tr>
<tr>
<td>Ductless split system</td>
<td>🟢</td>
<td>$48.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Commercial</th>
<th>Status</th>
<th>2012 Global Annual Sales (US$B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaged terminal</td>
<td>🟢</td>
<td>$0.2</td>
</tr>
<tr>
<td>Packaged rooftop unit</td>
<td>𝐷الة</td>
<td>$4.6</td>
</tr>
<tr>
<td>Ductless (VRF/VRV)</td>
<td>🟢</td>
<td>$10.7</td>
</tr>
<tr>
<td>Scroll / recip. chiller</td>
<td>𝐷الة</td>
<td></td>
</tr>
<tr>
<td>Screw chiller</td>
<td>🟢</td>
<td>$8.3 (All chillers)</td>
</tr>
<tr>
<td>Centrifugal chiller</td>
<td>🟢</td>
<td></td>
</tr>
</tbody>
</table>

Green signifies that equipment operates using refrigerants with GWP as low as 10 or less.
Blue signifies that equipment operates using refrigerants with GWP as low as 700 or less.

Commercially available in some global markets; Product under development; Tested in Lab.
Cost Implications of New Refrigerants

• Global cost-effectiveness is key to the transition to sustainable A/C

• Since the 1970s, U.S. manufacturers have steadily reduced the inflation-adjusted cost of residential central-ducted A/C systems while maintaining or improving performance, even while transitioning away from ODS to today’s HFC refrigerants

• Performance improvements and charge minimization efforts supporting transition towards low-GWP can offset upfront cost increased through life-cycle energy savings
HAT Performance—Experimental Assessment
Split Units: 5.28 kW Capacity

- Unit designed for high ambient performance up to 55°C
- Rated Capacity at ISO T1 (~AHRI A) = 5.28 kW (18 kBtu)
- COP: R-22 unit = 2.78 (EER ~ 9.5); R-410A unit = R-410A unit
  - COP = 3.37 (EER ~ 11.5)
- R-22 unit
  - COP = 2.78 (EER ~ 9.5)
Performance Relative to Baseline at 55°C
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 Baseline at 52°C

R-22 Baseline

- R-444B
- R-454A
- ARM-20a
- ARM-20b

R-410A Baseline

- R-447B
- R-452B
- R-32
- ARM-71a
## Low-GWP AREP Phase II HAT Matrix

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Equipment Type</th>
<th>Baseline Refrigerant</th>
<th>Refrigerants Tested</th>
<th>Test type</th>
<th>Test Standard</th>
<th>AREP Report No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3-ton air source, split</td>
<td>R-410A</td>
<td>R-32</td>
<td>soft-opt.</td>
<td>AHRI Standard 210/240</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>3-ton air source, split</td>
<td>R-410A</td>
<td>ARM-71a, DR-5A, HPR2A, L-41-1, L-41-2</td>
<td>drop-in</td>
<td>AHRI Standard 210/240</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>3-ton air source, split</td>
<td>R-410A</td>
<td>R-32, DR-5A, L-41-2</td>
<td>drop-in</td>
<td>AHRI Standard 210/240</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>5-ton air source, RTU</td>
<td>R-410A</td>
<td>R-32, ARM-71a, DR-5A, DR-55, HPR2A, L-41-2</td>
<td>drop-in</td>
<td>AHRI Standard 210/240</td>
<td>47 &amp; 53</td>
</tr>
<tr>
<td>5</td>
<td>6-ton air source, RTU</td>
<td>R-410A</td>
<td>R-32</td>
<td>soft-opt.</td>
<td>AHRI Standard 340/360</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>4-ton air source, RTU</td>
<td>R-410A</td>
<td>R-32, DR-5A, DR-55</td>
<td>soft-opt.</td>
<td>AHRI Standard 210/240</td>
<td>56</td>
</tr>
<tr>
<td>7</td>
<td>2.5-ton air source, RTU</td>
<td>R-22, R410A</td>
<td>R-32</td>
<td>soft-opt.</td>
<td>AHRI Standard 210/240</td>
<td>57</td>
</tr>
<tr>
<td>8</td>
<td>1.5-ton air source, mini-split</td>
<td>R-410A</td>
<td>R-32, ARM-71a, DR-55, HPR2A, L-41-2</td>
<td>soft-opt.</td>
<td>AHRI Standard 210/240</td>
<td>62</td>
</tr>
<tr>
<td>9</td>
<td>1.5-ton air source, mini-split</td>
<td>R-22</td>
<td>N-20b, DR-3, ARM-20b, L-20a, DR-93, R-290</td>
<td>soft-opt.</td>
<td>AHRI Standard 210/240</td>
<td>62</td>
</tr>
<tr>
<td>10</td>
<td>2-ton air-to-water chiller</td>
<td>R-410A</td>
<td>R-32, DR-5A, L-41-1, L-41-2</td>
<td>drop-in</td>
<td>Tester defined conditions</td>
<td>46</td>
</tr>
<tr>
<td>11</td>
<td>split system commercial ice machine</td>
<td>R404A</td>
<td>ARM-20b, N-40c</td>
<td>drop-in</td>
<td>AHRI Standard 810 and 29</td>
<td>45</td>
</tr>
</tbody>
</table>

AC at High Ambient Conditions
Summary

• Large global pull towards sustainable refrigerant use by governments, industry, and end users

• Several new molecules in new risk classes have been developed or proposed and are being evaluated

• Some “old refrigerants” (hydrocarbons, CO$_2$, ammonia) are also being considered or reconsidered for various applications but with new regulations for their use on a wider basis

• The risk and hazard evaluations of using flammable refrigerants in applications where they have not been used before or using 2L refrigerants is still a work in progress. Liability and public safety concerns are powerful forces that must be settled.
Summary (continued)

• Using small charge amounts (150 gm) is one strategy to enable use of flammable refrigerants, such charges are used in domestic refrigerators

• Limited amounts of Class 2L (300 gm to 500 gm) refrigerants are being used in small room AC units in Asia

• Around the world, safety standards for the use of flammable refrigerants are still being finalized. This is work in progress
  • ASHRAE Standard 15, ASHRAE Standard 15.2 for domestic AC
  • EN378, IEC 60335-2-NN, ISO 817, and ISO 5149 internationally
  • Building codes in the United States and internationally must be updated, and this is expected to occur 2020 to 2023
Setting the Stage for New Refrigerants

• Non-flammable alternatives limits for different baselines
  • R-123: <10 GWP available
  • R-134a: 400 to 600 GWP
  • R-404A: 1200–1400 GWP
• R-410A: all 2L class
• Need to work with flammability as a new design variable
• Harness additional opportunities from zeotropic mixtures
• Don’t fear product fragmentation by refrigerants—we are at the age of customized industry (3-D printing)
Although every effort has been made to ensure that the information in this report is correct, neither the author nor ASHRAE assumes, and hereby disclaim any liability to users of this information for any loss, damage, or injury caused by errors or omissions, whether such errors or omissions result from negligence, accident, changing regulations, or any other cause.
Questions?

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Managing Director, Clean Energy Air and Water Technologies FZE

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- Healthcare Facility Design Professional (HFDP)
- Certified HVAC Designer (CHD)
- Operations and Performance Management Professional (OPMP)
The presentation has ended. The following charts are for your information going forward. References and links to internet-based information are provided to enable the user to find updated information going forward as the regulatory environment solidifies.

Background Information
References


• ASHRAE. 2007. ASHRAE Standard 97-2007, Sealed glass tube method to test the chemical stability for materials for use within refrigeration systems. Atlanta: ASHRAE.


References


References


References


References

References


• Goetzler, W, Guernsey, M., Young, J., Fuhrman, J, Abdelaziz, O., 2016, The Future of Air Conditioning for Buildings,
References


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