U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

Research & Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants

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Prepared by Navigant Consulting, Inc.

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Preface

The U.S. Department of Energy's (DOE) Building Technology Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy, engaged Navigant Consulting, Inc., (Navigant) to develop this research and development (R&D) opportunities report for next-generation low global warming potential refrigerants. The initiatives identified in this report are Navigant's recommendations to BTO for pursuing in an effort to accelerate the widespread adoption of low-global warming potential (GWP) refrigerants in residential and commercial equipment. Inclusion in this report does not guarantee funding; each initiative must be evaluated in the context of all potential activities that BTO could undertake to achieve its goals.

BTO also manages the residential appliance and commercial equipment standards program; however these activities are separate from DOE's technology R&D funding programs. As part of the standards program, many of the appliances and equipment types covered by this report have ongoing test procedure and standards rulemakings. To maintain the separation between the emerging technologies activities and the appliances standards activities, and to prevent undesirable interaction between the two, this report does not cover test procedures for residential and commercial equipment, energy efficiency descriptors, or efficiency standards levels.

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List of Acronyms

A/C	Air Conditioning
AHRI	Air-Conditioning, Heating, & Refrigeration Institute
AHRTI	Air Conditioning, Heating, and Refrigeration Technology Institute
AREP	Alternative Refrigeration Evaluation Program
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BTO	Building Technologies Office
CFC	Chlorofluorocarbons
CO2	Carbon Dioxide
DOE	Department of Energy
DX	Direct Exchange
EPA	Environmental Protection Agency
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefins
HVAC&R	Heating, Ventilation, Air Conditioning, and Refrigeration
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
LCCP	Life-Cycle Climate Performance
MVAC	Mobile Vehicle Air Conditioning
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
ODP	Ozone Depletion Potential
ORNL	Oak Ridge National Laboratory
R&D	Research & Development
SNAP	Significant New Alternatives Program
UL	Underwriters Laboratories
UMCP	University of Maryland College Park

Executive Summary

Refrigerants are used in a wide variety of heating, ventilation, air conditioning, and refrigeration (HVAC&R) equipment. The current generation of refrigerants, hydrofluorocarbons (HFCs), have zero ozone depletion potential; however, when released to the atmosphere, they have significant global warming potential (GWP). The growing international emphasis on global warming mitigation has stimulated interest in a new generation of low-GWP refrigerants.

In 2014, the United States, Canada and Mexico proposed an amendment to the Montreal Protocol to reduce production and consumption of HFCs by 85% during the period 2016–2035 for Non-A5 (developed) countries.[1] In addition, the European F-gas legislation was issued in 2014, which will reduce HFC consumption by 79% over the period 2016–2030.[2]

The Building Technologies Office (BTO) within the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy has a critical stake in supporting the development, evaluation, and widespread implementation of low-GWP refrigerants. Part of BTO's strategy is to develop and implement technology roadmaps that drive market transformations, and more specifically, to develop innovations in key technology areas such as working fluids.[3] Within this context, BTO has a strong interest in ensuring that next-generation low-GWP refrigerants can maintain or improve the energy efficiency performance of HVAC&R equipment.

DOE retained Navigant Consulting Inc. (hereafter, "Navigant") to identify and highlight high-priority R&D activities that DOE could support to help accelerate the transition to next-generation low-GWP refrigerants in HVAC&R equipment. This R&D roadmap covers the following equipment types:

- Residential refrigeration
- Self-contained commercial refrigeration
- Supermarket refrigeration
- Residential and commercial direct-expansion air conditioning
- Chillers

Navigant began this effort by conducting background research to assess the current state of the industry. We then hosted a stakeholder workshop at Navigant's office in May 2014 to solicit ideas from industry stakeholders about activities that DOE could support to accelerate the transition to next-generation refrigerants. Finally, we condensed the full set of initiatives and evaluated them using a defined set of criteria. Based on this evaluation, we identified the highest-priority initiatives for recommendation. We also solicited feedback on the draft report from industry stakeholders and incorporated the feedback into this final report.

This report recommends a set of initiatives that would have either a direct effect on maintaining or improving energy efficiency while switching to next-generation low-GWP refrigerants, or an

[1] http://www.epa.gov/ozone/downloads/HFC_Amendment_2014_Summary.pdf
[2] http://ec.europa.eu/clima/policies/f-gas/index_en.htm
[3] Building Technologies Program Multi-Year Work Plan, 2011-2015. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf.

indirect or enabling effect. Table ES 1 and Table ES 2 show the highest-priority recommended initiatives described in this report. The report also highlights several initiatives that did not score as highly—due to having a poor fit with the BTO mission—but that garnered high levels of stakeholder support during the workshop. These are shown in Table ES 3.

Table ES 1: High-Priority Initiatives with Direct Impacts on Energy Efficiency

ID No.	Initiative/Activity	Category
1	Expand NIST modeling research to identify and explore theoretical properties of new low-GWP blends, particularly azeotropes.	Modeling and Evaluation Tools
2	Characterize the heat transfer and thermodynamic properties and efficiency performance of new refrigerants and blends.	New Refrigerant Development
10	Develop techniques for detecting and dramatically reducing refrigerant leakage in currently installed systems.	Equipment Development
12	Use modeling tools to perform system-level evaluations of newly identified fluids for specific applications.	Modeling and Evaluation Tools
11	Investigate techniques for improving temperature control and operational efficiency of secondary loops in installed supermarket refrigeration systems.	Equipment Development
13	Improve LCCP models by conducting studies to better understand differences in average annual versus peak season performance in large systems.	Modeling and Evaluation Tools

Table ES 2: High-Priority Initiatives with Indirect Impacts on Energy Efficiency

ID No.	Initiative/Activity	Category
4	Create a public repository for risk assessments, performance characteristics, material compatibility data, and fire incidents for alternative refrigerants.	Industry Collaboration
6	Develop prototype systems that demonstrate leak detection with high-reliability, inexpensive sensors.	Equipment Development
7	Characterize materials compatibility and stability of new refrigerants and blends.	New Refrigerant Development
14	Explore additional A1 refrigerants or blends as drop-in options for servicing existing equipment.	New Refrigerant Development

Table ES 3: Low-Scoring Initiatives with High Stakeholder Support

ID No.	Initiative/Activity	Category
3	Improve flammability test methods and prediction tools for blended compounds.	Safety Risks
5	Conduct flammability risk assessments on additional A2L, A3, and B2L fluids for a wider range of applications.	Safety Risks
8	Investigate alternative system architectures that would inherently mitigate flammability risks with A2L and A3 fluids.	Safety Risks

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1 Introduction

1.1 Background

Refrigerants are used in a wide variety of HVAC&R equipment. The first generation of refrigerants included substances such as hydrocarbons, ammonia, and carbon dioxide. The second generation of refrigerants included chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which became widely used because they were efficient, non-flammable, and non-toxic. In the 1980s, CFCs and HCFCs were determined to play a major role in depleting the stratospheric ozone layer. Beginning in the 1990s, the industry phased out CFCs and HCFCs in favor of a third generation of refrigerants: hydrofluorocarbons (HFCs). HFCs have zero ozone depletion potential; however, when released to the atmosphere, they have significant global warming potential (GWP)[4]. The growing international emphasis on global warming mitigation has stimulated interest in a fourth generation of low-GWP refrigerants.

In 2014, the United States, Canada and Mexico proposed an amendment to the Montreal Protocol to reduce production and consumption of HFCs by 85% during the period 2016–2035, for Non-A5 (developed) countries. Under the proposal, A5 (developing) countries would reduce HFC production and consumption by 85% during the later period 2025–2045.[5]

In addition, the European F-gas legislation was issued in 2014.[6] Under the F-gas regulations, HFC consumption will be reduced by 79% over the period 2016–2030, a more aggressive timeline than the North American Montreal Protocol proposal. The F-gas regulations also include application-specific bans covering new equipment as well as service and maintenance.

Figure 1.1 shows the phasedown schedules from the North American Montreal Protocol proposal and the European F-gas regulations.

[4] Global Warming Potential is a relative measure that describes the amount of heat trapped by a particular gas, when released into the atmosphere, compared to the amount of heat trapped by an equivalent mass of carbon dioxide gas. In this report, we refer to GWP values calculated over a 100-year time interval. The GWP value of carbon dioxide is defined as 1. For example, a GWP value of 500 for a particular gas indicates that the gas would trap 500 times more heat than the equivalent mass of carbon dioxide over a 100-year time period.

[5] http://www.epa.gov/ozone/downloads/HFC_Amendment_2014_Summary.pdf

[6] http://ec.europa.eu/clima/policies/f-gas/index_en.htm

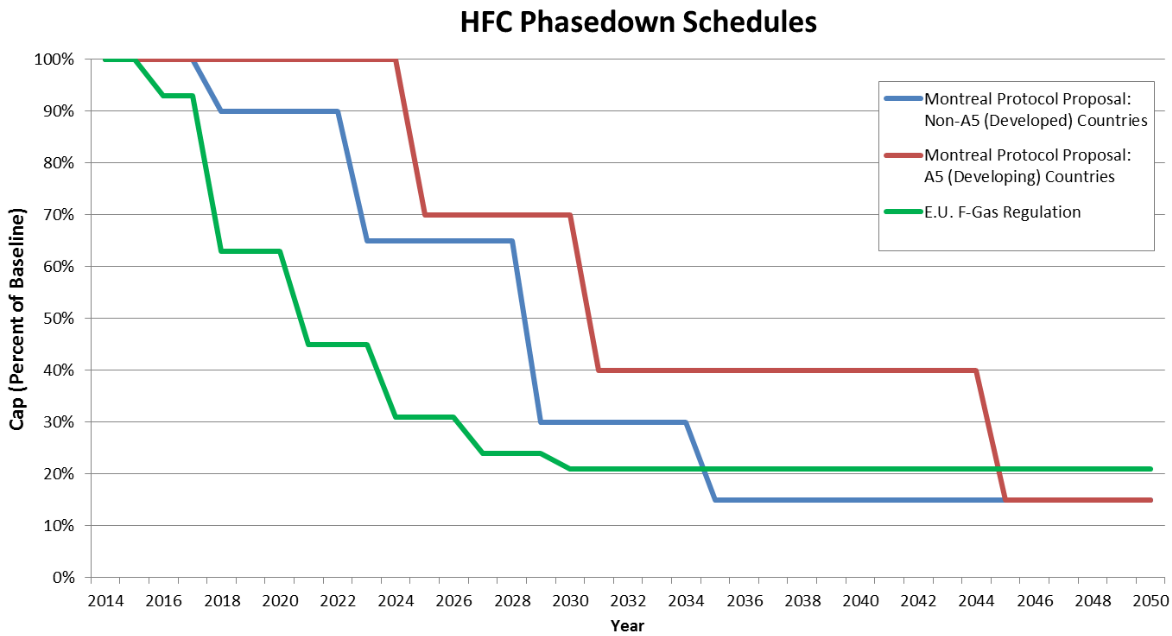
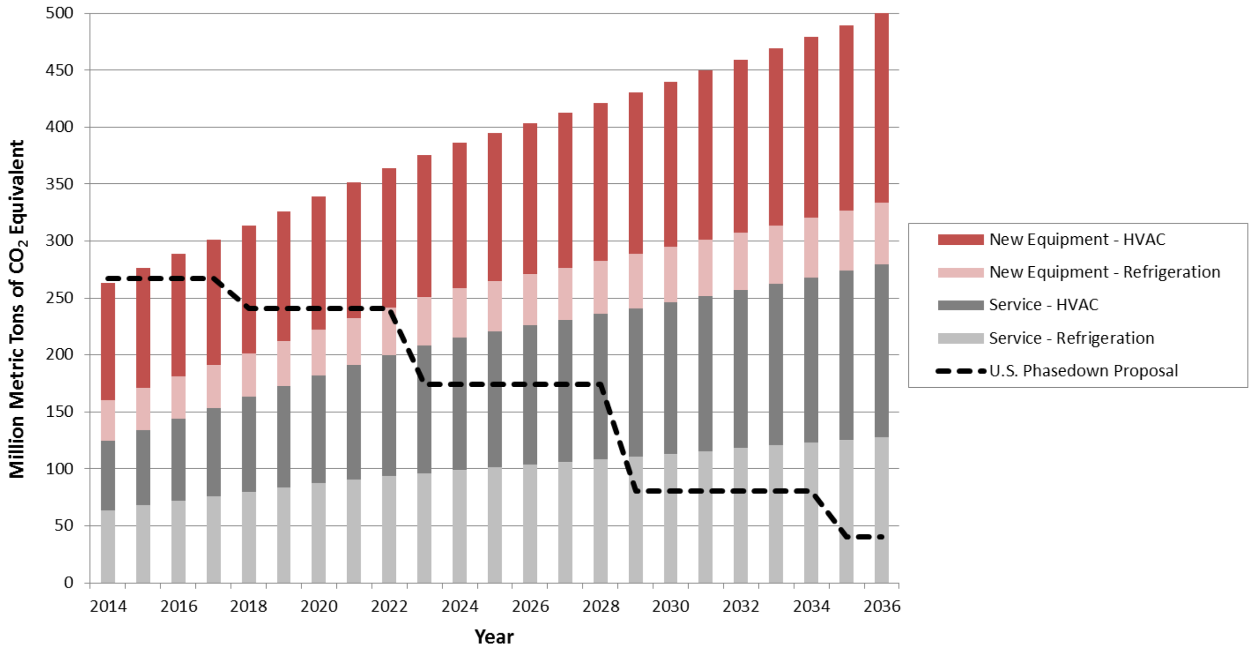


Figure 1.1: HFC phasedown schedules for North American Montreal Protocol proposal and European F-gas regulation

In the U.S., reducing the nation's HFC consumption by 85 percent would require an enormous deviation from business-as-usual activity in the HVAC&R industry. Figure 1.2 shows the estimated domestic consumption of HFCs, weighted by GWP, in a business-as-usual scenario during the period 2014–2036. These estimates were derived from shipment information and equipment characteristics from the U.S. Environmental Protection Agency's (EPA) Vintaging Model[7], a tool for estimating the annual consumption and emissions of refrigerants and other industrial chemicals across a wide range of industries. The HFC consumption model indicates that new equipment accounts for just under half of total annual HFC consumption, whereas servicing of installed equipment accounts for just over half.

[7]Godwin, David S; Van Pelt, Marian Martin; Peterson, Katrin. "Modeling Emissions of High Global Warming Potential Gases." Available online at http://www.epa.gov/ttn/chief/conference/ei12/green/godwin.pdf.



Source: Navigant HFC Consumption Model

Figure 1.2: Projected GWP-weighted HFC consumption for domestic HVAC&R applications under business-as-usual scenario

The difference between the business-as-usual scenario and the proposed phase-down commitment demonstrates the significant challenge to implementing a phase-down of this magnitude. Achieving the proposed phase-down target becomes progressively more difficult each year. Compounding this challenge are numerous technical barriers to finding suitable alternatives to current HFC refrigerants, as discussed more fully throughout this report.

1.2 DOE Building Technologies Office Mission and Goals

The BTO has a critical stake in supporting the development, evaluation, and widespread implementation of low-GWP refrigerants. The mission of the BTO is as follows:

> *Develop and promote efficient, affordable, and environmentally friendly technologies, systems, and practices for our nation's residential and commercial buildings that will foster economic prosperity, lower greenhouse gas emissions, and increase national energy security, while providing the energy-related services and performance expected from our buildings.*[8]

[8] Building Technologies Program Multi-Year Work Plan, 2011-2015. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf.

The BTO Multi-Year Work Plan for 2011–2015[9] articulates BTO's mission and program goals as follows:

- Promote efficiency
- Promote affordability (cost reduction)
- Promote "environmentally friendliness"
- Lower greenhouse gas emissions
- Conduct R&D to advance innovative technologies
- Conduct R&D for integrated buildings approaches
- Accelerate adoption of new products on the market
- Increase private sector collaboration in developing new technologies
- Develop innovations in HVAC
- Develop innovations in working fluids

Part of BTO's strategy is to develop and implement technology roadmaps that drive market transformations, and more specifically, to develop innovations in key technology areas such as working fluids. Within this context, the BTO has a strong interest in ensuring that next-generation low-GWP refrigerants maintain or improve upon the current energy efficiency performance of HVAC&R equipment.

1.3 Objective of This Roadmap

The objective of this roadmap is to identify and highlight high-priority R&D activities that DOE could support to help accelerate the transition to next-generation low-GWP refrigerants in HVAC&R equipment.

DOE retained Navigant Consulting Inc. (hereafter, "Navigant") to develop this report as a follow-on to a similar report written in 2011.[10] This report reflects the current state of the industry in 2014. Numerous advances have been made since the 2011 report, as described throughout this report.

This report focuses primarily on reducing HFC *consumption*. Numerous other reports on this topic focus on HFC *emissions*, which occur when HFC fluids evaporate during leakage events or due to improper disposal at a product's end of life. However, HFC phase-down targets such as the Montreal Protocol proposal and the F-gas regulations place mandatory limits on the total annual GWP-weighted HFC *consumption*.

In addition, this report does not focus extensively on the energy efficiency performance of HVAC&R equipment. The alternative refrigerants discussed in this report may have either higher or lower energy efficiency performance than the HFCs they would replace, depending on the specific application. In some cases, switching to low-GWP refrigerants may require engineering design changes in order to maintain current efficiency levels. This roadmap

[9] Ibid.
[10] 2011 report available at: http://www1.eere.energy.gov/buildings/pdfs/next_generation_refrigerants_roadmap.pdf.

primarily addresses the challenges associated with the development and implementation of next-general refrigerants within the overall context of maintaining or improving energy efficiency.

1.4 Technology and Market Scope

This R&D roadmap covers the following equipment types:

- Residential refrigeration
- Self-contained commercial refrigeration
- Supermarket refrigeration
- Residential and commercial direct-expansion air conditioning (A/C)
- Chillers

Foam-blowing applications fall outside the scope of this roadmap. Many foam blowing applications already use low GWP fluids such as cyclopentane or HFO-1233zd, so little or no additional R&D is required to commercialize them more widely. Not-in-kind cooling technologies (i.e. non-vapor-compression cooling technologies such as thermoelectric, magnetic refrigeration, etc.) also fall outside the scope of this roadmap. These technologies are covered in a separate BTO report titled Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies.[11]

[11] Available at: http://energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf.

2 Report Approach

Figure 2.1 summarizes the approach used to identify and prioritize the R&D initiatives recommended in this report. The approach used for this report is similar to the approach used for other recent BTO reports and technology roadmaps for topic areas including water heating technologies, geothermal heat pumps, and building-integrated solar technologies.[12] The following sections provide additional details about each stage of the process.

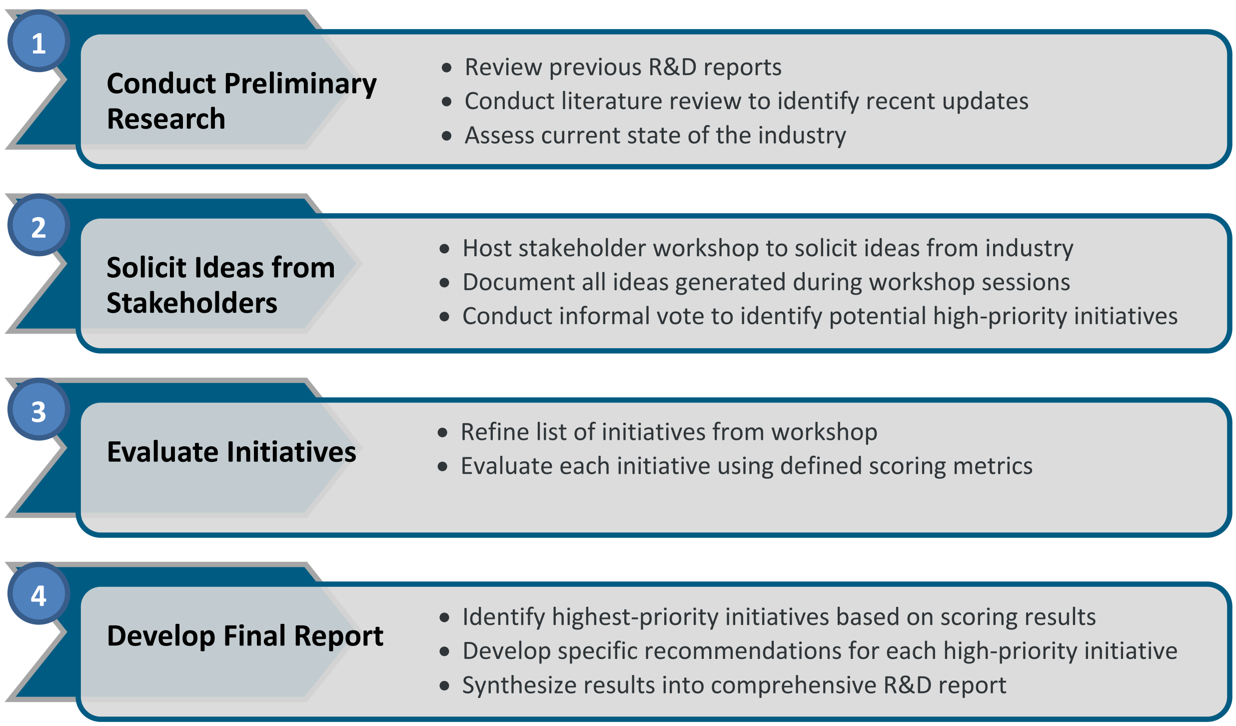


Figure 2.1: Report development process

2.1 Stage 1: Conduct Preliminary Research

We conducted a preliminary assessment of next-generation refrigerants currently on the market. We reviewed any major changes in legislation or regulations, R&D initiatives, and new product deployments that have occurred since the 2011 report. The information gathered during this stage provided a comprehensive overview of the current state of the market.

2.2 Stage 2: Solicit Ideas from Stakeholders

We invited key industry stakeholders to a workshop at Navigant's Washington, D.C office on May 29, 2014. The attendees included representatives from equipment manufacturers, refrigerant manufacturers, industry trade groups, academia, national research laboratories, and key government agencies. During this day-long event, participants provided updates on low-GWP

[12] BTO publications available at: http://www1.eere.energy.gov/library/default.aspx?page=2.

refrigerant activities conducted by their organizations and identified the most critical challenges and barriers facing the industry. Stakeholders suggested 54 possible initiatives that DOE could support to help accelerate the transition to next-generation refrigerants. At the end of the workshop session, participants were asked to cast votes to identify the highest-priority initiatives from their own perspective. Appendix A provides the summary report from the workshop.

2.3 Stage 3: Evaluate Initiatives

Following the workshop, we refined the list of identified initiatives by combining overlapping ideas into a set of unique initiatives. For any ideas that were too broad in scope, we tailored the wording to represent a specific actionable initiative that maintains the spirit of the initial idea. We then screened and evaluated each of the refined initiatives using the methodology illustrated in Figure 2.2 and described further below.

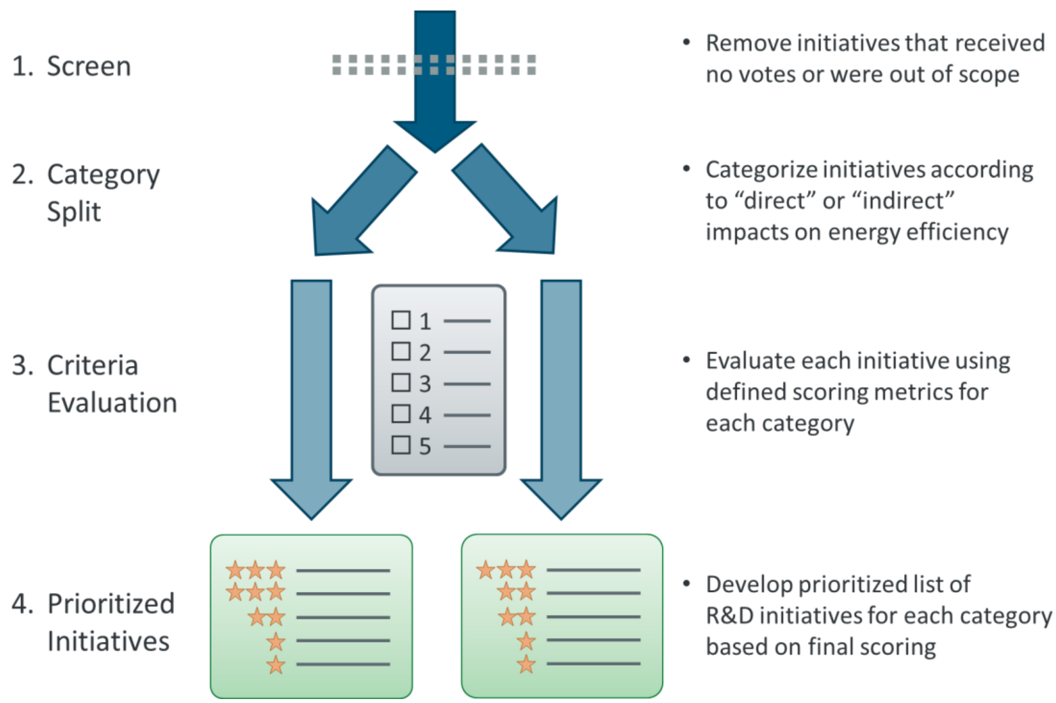


Figure 2.2: Initiative prioritization methodology

» Step 1: Screen Initiatives

First, the list of initiatives was screened to remove from further consideration those initiatives that did not receive any stakeholder support (i.e. “votes”) at the end of the workshop session. We reviewed the list of screened-out initiatives to confirm that none of them represented key topics of discussion during the workshop sessions despite not having received any votes at the end. Second, the remaining list of initiatives was filtered to remove any initiatives that were outside the scope of consideration for this report; i.e., initiatives that were policy-related or those that were unrelated to research, development, or deployment activities that BTO could support.

» **Step 2: Split into Categories**

Next, the initiatives were split into two categories according to whether the initiative could have a direct impact on energy efficiency, or whether it could have an indirect or enabling impact. We included this split in recognition of BTO's focus on supporting R&D initiatives that improve energy efficiency in building equipment. Many of the initiatives articulated during the workshop do not directly relate to energy efficiency, and without full context may seem out of scope for BTO consideration. However, such initiatives may enable the use of certain low-GWP refrigerants that would maintain or improve current energy efficiency levels or prevent a decrease in energy efficiency that would occur with other less favorable alternatives. Splitting the initiatives into these two categories helps highlight those initiatives that are directly related to energy efficiency, versus those that are not directly related but which are still worthy of consideration for BTO support.

An example of an initiative with a direct impact on energy efficiency would be modeling the thermodynamic properties of new refrigerants. An example of an initiative with an indirect impact on energy efficiency would be performing a safety risk assessment on a flammable refrigerant that has similar performance characteristics as a non-flammable refrigerant currently in use. A safety assessment is not directly related to energy efficiency; however, by performing the risk assessment, the flammable refrigerant could be approved for use in a new application whose energy efficiency would be maintained or improved as a result of using the flammable refrigerant.

» **Step 3: Assign Scores for Each Metric**

After categorizing the initiatives, we then evaluated each initiative using the following set of scoring criteria:

- **Fit with BTO mission** – How closely does the initiative align with BTO's goals, objectives, and capabilities?
- **Criticality of DOE involvement** – How critical is DOE involvement to the likely success of the initiative?
- **Level of stakeholder support** – How strongly did industry stakeholders support and prioritize the initiative during the workshop sessions?

We scored each of the metrics on a scale from one to five. We also assigned a weighting factor to each criterion to reflect its relative importance. Table 2.1 provides the scoring rubric and the weightings for the three criteria. Appendix B provides the finalized scores for each of the initiatives.

Table 2.1: Initiative Scoring Criteria

Metric	1	2	3	4	5	Weight
Fit with BTO Mission	Weak fit with BTO mission and goals defined in Multi-Year Work Plan	(Weak to moderate fit)	Moderate fit with BTO mission and goals defined in Multi-Year Work Plan	(Moderate to strong fit)	Strong fit with BTO mission and goals defined in Multi-Year Work Plan	**40%**
Criticality of DOE Involvement	No DOE involvement required. Low risk activity.	Initiative would benefit from DOE involvement, but may not be required.	Initiative requires DOE involvement to start, but may not require DOE's continued interaction.	Initiative requires DOE involvement, and requires DOE's continued interaction.	Initiative may have originated with DOE. Initiative will not start or be carried on without strong DOE involvement. High risk activity.	**30%**
Level of Stakeholder Support	1 vote	2-3 votes	4-5 votes	6-7 votes	8 or more votes	**30%**

» Step 4: Prioritize Initiatives

We evaluated each of the 31 refined initiatives using the process described above. We drafted detailed discussions of the top initiatives for each category (direct and indirect) and highlighted the barriers that stakeholders identified as the most significant. For each high-priority initiative, we provided a brief description of the objectives and tasks that would be associated with each initiative.

2.4 Stage 4: Develop Final Report

Based on the results of the evaluation, Navigant developed detailed descriptions of each initiative as a starting point for BTO to use in supporting the transition to next-generation low-GWP refrigerants. After prioritizing the initiatives and developing this R&D report, we presented a draft of the document to DOE for internal review. We also circulated a draft among stakeholders and industry experts who volunteered to provide external peer review. We then incorporated feedback from all of these reviews into this final report.

3 Market Overview

This section provides an overview of the current state of the HVAC&R industry with respect to the transition to next-generation low-GWP refrigerants. The status updates provided in this section reflect progress that has been made as of the publishing date of this report.

3.1 Current Low-GWP Refrigerant Options

Since the 1990s, HVAC&R equipment has predominantly used high-GWP HFC refrigerants. In response to global HFC phase-down targets and proposals, the industry has begun developing equipment that uses low-GWP alternative refrigerants.

The ideal refrigerant has the following characteristics:

- Non-toxic
- Non-flammable
- Zero Ozone Depletion Potential (ODP)
- Zero GWP
- Acceptable operating pressures
- Volumetric capacity appropriate to the application

In most cases, earlier generations of refrigerants had favorable flammability and toxicity characteristics, but unfavorable ODP and GWP characteristics. However, most of the newer zero-ODP, low-GWP alternatives suffer from one or more undesirable characteristics, such as greater flammability, toxicity, or lower volumetric capacity than the HFC refrigerants they would replace.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 34-2013[13] defines refrigerant safety group classifications based on toxicity and flammability, as shown in Figure 3.1. Refrigerants with higher flammability or toxicity levels are more hazardous than those with lower flammability or toxicity levels. Building codes and other safety standards often restrict or discourage the use of non-A1 refrigerants.[14]

[13] ANSI/ASHRAE Standard 34-2013: Designation and Safety Classification of Refrigerants. Available at: http://www.ashrae.org

[14] Air Conditioning and Refrigeration Technology Institute. 2010. ARTI Report No. 09001-01, *Review of Regulations and Standards for the Use of Refrigerants with GWP Values Less than 20 in HVAC&R Applications.*

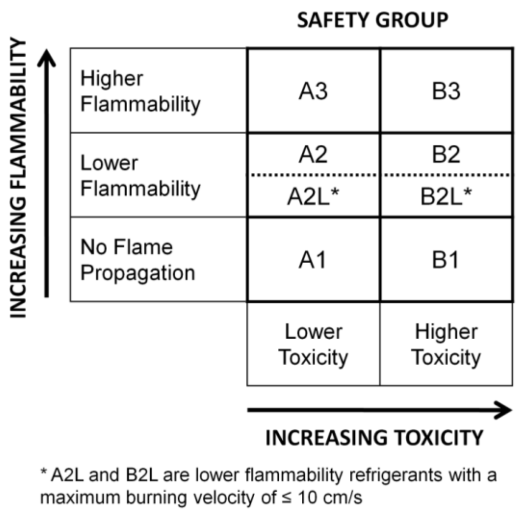


Figure 3.1: Refrigerant safety groupings in ASHRAE Standard 34-2013

Appendix C contains a detailed list of all current and potentially viable refrigerants identified as part of this report development process. Currently, five general types of refrigerants have been identified as low-GWP alternatives to the most commonly used refrigerants today. The following sections describe the current state of development and implementation of each of the five types of low-GWP alternatives.

3.1.1 Low-GWP HFCs

Although the goal of an eventual HFC phase-down is to replace current HFC refrigerants with low-GWP alternatives, two HFCs in particular warrant consideration as viable replacement options: HFC-32 and HFC-152a. HFC-32 is classified as A2L and has a GWP of 677.[15] HFC-152a is classified as A2 and has a GWP of 138.[16] While these GWP values are higher than other single-digit-GWP alternatives, they represent a significant improvement over most current HFC refrigerants that have GWP values between 2,000 and 4,000.

HFC-32 is a versatile refrigerant that is particularly suitable for air conditioning and heat pump applications. The use of HFC-32 has accelerated in the past two years, with at least one manufacturer having announced a switch to using HFC-32 in all successive models of residential air conditioners launched in Japan beginning in late 2012.[17]

HFC-152a has been investigated as an option for replacing HFC-134a in mobile vehicle air conditioning applications, but its A2 flammability classification poses a major barrier to widespread adoption. HFC-152a may also be a viable replacement in commercial refrigeration applications, chillers, and industrial refrigeration.

[15] Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, Table 8.A.1. Available at http://www.ipcc.ch/report/ar5.
[16] Ibid.
[17] Daikin press release available at http://www.daikin.com/press/2012/120927/index.html.

Both HFC-32 and HFC-152a have comparable efficiencies to the other more widely used HFC refrigerants, so implementing these alternatives would not significantly reduce system efficiency.

3.1.2 Hydrocarbons

The three most viable hydrocarbon refrigerants include propane, isobutane, and propylene. These hydrocarbons have GWP values of 3 or less,[18,19] and they are classified as A3 refrigerants due to their high flammability. Hydrocarbons are technically feasible replacements for many HFC-410A systems, despite having slightly lower volumetric capacity and performance. Hydrocarbon refrigerants have significantly lower cost compared to other synthetic alternatives.

Hydrocarbons are technically viable for small and medium-sized refrigeration and air conditioning applications, as well as chillers. However, due to their high flammability, they would be considered unsafe in most direct-expansion (DX) HVAC&R applications, except for applications with very low charges. Charge limits imposed by Underwriters Laboratories (UL) Standards and the EPA Significant New Alternatives Program (SNAP) limit the ability to use hydrocarbons in applications requiring larger volumes of refrigerant.

In 2011, the EPA issued a final rule allowing the use of isobutane and propane in household-size refrigerators and freezers and small self-contained refrigeration units, provided they comply with charge limit restrictions imposed by safety codes. Multiple manufacturers are now selling residential refrigerators using isobutane in the United States and globally. Viability in larger refrigeration applications would require extensive risk assessments to support modifications to current charge limits.

Hydrocarbons are technically viable for residential and commercial air conditioning applications, but ASHRAE Standard 15[20] charge limits and restrictions currently prevent implementation of hydrocarbons in these applications. Propane, however, shows significant promise for secondary expansion systems in supermarkets. Propane could also be viable in some chiller applications.

Hydrocarbons have comparable efficiencies to the current HFC refrigerants, so implementing them does not significantly reduce system efficiency.

3.1.3 Ammonia

Ammonia is classified as B2 and has a GWP value of 0.[21] Industrial refrigeration systems often use ammonia as a refrigerant. Due to its Class B toxicity rating, ammonia is not a likely candidate for comfort conditioning applications or indoor commercial refrigeration applications. However, ammonia could be viable for chillers and secondary expansion systems, particularly for supermarkets. Like other naturally occurring refrigerants, ammonia has a much lower cost than other synthetic alternatives. Ammonia has comparable efficiency to the current HFC refrigerants, so implementing ammonia as an alternative would not significantly reduce system efficiency.

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[18] IPCC Fourth Assessment Report, Table 2.15. Available at http://www.ipcc.ch/report/ar4.
[19] EPA SNAP Program, http://www.epa.gov/ozone/snap/subsgwps.html
[20] ANSI/ASHRAE Standard 15-2007: Safety Standard for Refrigerating Systems. Available at: http://www.ashrae.org
[21] EPA SNAP Program, http://www.epa.gov/ozone/snap/subsgwps.html

3.1.4 Carbon Dioxide

Carbon dioxide (CO_2) is classified as A1 (non-flammable, non-toxic) and has a GWP of 1, by definition. CO_2 has been demonstrated as a viable alternative for several applications including heat pump water heaters, commercial refrigerated vending machines, supermarket refrigeration, secondary expansion systems, and industrial and transport refrigeration systems. Carbon dioxide is also a technically viable option in mobile vehicle air-conditioning (MVAC) systems.

The higher design pressure required for CO_2 systems presents some safety concerns. The higher pressures also add to the overall component costs of the system. EPA SNAP has cited concern about the potential lethality of carbon dioxide at high concentrations, which is especially relevant to passenger car volumes or small room volumes. Implementing CO_2 as an alternative to HFCs often requires a complete system redesign due to the high pressure and supercritical behavior. This poses a major barrier to widespread adoption.

The theoretical cycle efficiency of CO_2 is significantly lower than that of HFCs, which can result in a reduction of overall system efficiency. Advances in transcritical CO_2 systems have enabled the use of CO_2 in some refrigeration applications such as supermarkets and vending machines. However, CO_2 is unlikely to be viable for air conditioning applications due to the inherent thermodynamic disadvantages compared to other candidate fluids. In Europe, CO_2 supermarket systems have approached the efficiency of traditional systems when used in areas with mild climates such as Denmark.[22] This approach has also been proved successful in certain parts of the U.S.; however, this approach is not viable for hotter climates.

3.1.5 Hydrofluoroolefins (HFOs)

HFOs are some of the most viable emerging alternative refrigerants. Refrigerant manufacturers have developed numerous HFO blends tailored to specific applications. HFO-1234yf and HFO-1234ze are furthest along in development. HFO-1234yf and HFO-1234ze are both classified as A2L and have GWP values less than 1.[23]

The performance of HFO-1234yf closely matches that of HFC-134a. HFO-1234yf has been widely adopted outside the U.S. for future MVAC systems, and one U.S. automobile manufacturer committed to using HFO-1234yf beginning in 2013.[24] HFO-1234yf also shows promise in chillers and commercial refrigeration applications that currently use HFC-134a.

HFO-1234ze has a lower volumetric capacity than HFO-1234yf. It could potentially be used for centrifugal compressors. HFO-1234ze is easier to manufacture than HFO-1234yf, and less costly, so it could be particularly attractive for large chillers, which require high quantities of

[22] "Energy Consumption in Transcritical CO2 Refrigeration." Danfoss. Available at http://www.ra.danfoss.com/TechnicalInfo/Approvals/Files/RAPIDFiles/01/Article/EnergyConsn/EnergyConsnHeader.pdf.
[23] IPCC Fifth Assessment Report, Table 8.A.1.
[24] Press release available at: http://media.gm.com/content/media/us/en/news/news_detail.brand_gm.html/content/Pages/news/us/en/2010/July/0723_refrigerant

refrigerant. HFO-1234ze has been approved for use with centrifugal, reciprocating, and screw chillers. It is also marketed for blowing agent and propellant applications.

Major refrigerant manufacturers are developing HFO blends suitable for applications that would traditionally use HCFC-22, HFC-404A, and HFC-410A. However, HFO-1234yf is not considered to be a viable alternative for these refrigerants because of its significantly lower volumetric capacity. The HFO blends under development are designed to offer higher capacities, with tradeoffs in either GWP or flammability. The GWP values of these blends range from less than 150 to around 600, which are still significantly lower than the GWP values of the HFCs they would replace. Therefore, these HFO blends may offer the best overall life cycle climate performance.

Refrigerant manufacturers are also currently developing HFO-based A1 replacements for HFC-134a. These blends typically have GWP values ranging from 600 to 1000. These refrigerants could be used as replacements for HFC-134a in cascade systems paired with carbon dioxide.

One refrigerant manufacturer has also identified an HFO-based A1 refrigerant with a GWP value less than 10 for chillers currently using HCFC-123.[25] However, compressors using this new refrigerant would require larger impeller diameters for the same cooling capacity because of the substantially lower volumetric cooling capacity and the higher required compression ratio. Therefore, this refrigerant may not be viable as a drop-in replacement for most HCFC-123 applications. One manufacturer has also announced the launch of a centrifugal chiller in Europe that uses HFO-1233zd, which is an A1 refrigerant with a GWP value of less than 7, as a replacement for HCFC-123.[26]

Refrigerant manufacturers are also currently developing several HFO-based A2L refrigerants options to substitute for HFC-134a, HCFC-22, and HFC-404A. These developmental refrigerants have GWP values ranging from 150 to 500. At least five major refrigerant manufacturers are developing HFO-based A2L refrigerant blends that can substitute for HFC-410A; these have GWP values ranging from around 300 to 500.

Cost represents a major concern with HFOs and HFO blends. While actual costs under full scale production conditions are unknown, current HFO-based refrigerants will almost certainly have a much higher cost than the refrigerants they would replace.

Additionally, with HFO systems, the efficiency tends to decrease as the GWP of the refrigerant decreases.[27] Therefore, implementing HFOs as a replacement for HFCs requires a tradeoff between GWP and system efficiency.

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[25] Kontomaris, Konstantinos. "A Low GWP Replacement for HCFC-123 in Centrifugal Chillers: DR-2." DuPont Refrigerants. Available online at http://www2.DuPont.com/Refrigerants/en_US/assets/downloads/20101001_UNEP_Kontomaris_paper.pdf.

[26] https://www.ejarn.com/news.asp?ID=30295

[27] Leck, Thomas J. et al. "Low GWP Refrigerants for Stationary AC and Refrigeration." 15 June 2010. DuPont Refrigerants.

3.2 State of the Industry (Since 2011 Report)

This section highlights some of the key industry developments regarding next-generation low-GWP refrigerants since the previous 2011 report. Some of the updates involve equipment types outside the scope of this report; however, such developments are listed to provide an overview of developments within the broader HVAC&R industry.

3.2.1 New Regulatory Rulings and Updates

» A final EPA SNAP rule, published in December 2011 and effective February 2012, allows the use of isobutane and propane with charge limit restrictions (up to 57 g for household refrigerators and up to 150 g for commercial refrigerators).[28]

» UL has approved the use of propane in window air-conditioning applications, with charge limits.[29]

» An EPA SNAP final rule, published in March 2012 and effective May 2012, allows the use of HFO-1234yf in motor vehicle air conditioning systems.[30]

» An EPA SNAP final rule, published and effective in August 2012, allows the use of HFO-1234ze in centrifugal, reciprocating, and screw chillers.[31]

» An EPA SNAP final rule, published and effective in August 2012, allows the use of HFO-1233zd in centrifugal chillers.[32]

» An EPA SNAP notice of proposed rulemaking, published in July 2014, proposed the following[33]:

- For aerosol propellants, listing HFC-125 as unacceptable, and HFC-134a and HFC-227ea as acceptable, both subject to use conditions, by January 2016.
- For motor vehicle air conditioning, listing numerous HCFC blends as unacceptable by 2017, and HFC-134a as unacceptable by 2021.
- For new and retrofit retail food refrigeration applications, listing R-507A and R-404A as unacceptable, along with a number of other HFC blends, by January 2016.
- For new and retrofit vending machines, listing HFC-134a and other HFC blends as unacceptable by January 2016.
- For all foam-blowing end-uses except spray foam, listing HFC-134a and other HFC blends as unacceptable by January 2017.

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[28] http://www.gpo.gov/fdsys/pkg/FR-2011-12-20/pdf/2011-32175.pdf
[29] UL 471 can be purchased at http://www.techstreet.com/products/1756548
[30] http://www.gpo.gov/fdsys/pkg/FR-2012-03-26/pdf/2012-6916.pdf
[31] http://www.gpo.gov/fdsys/pkg/FR-2012-08-10/html/2012-19688.htm
[32] Ibid.
[33] http://www.epa.gov/ozone/downloads/SAN_5750_SNAP_Status_Change_Rule_NPRM_signature_version-signed_7-9-2014.pdf

» An EPA SNAP notice of proposed rulemaking, published in July 2014, proposed the following[34]:
  - The acceptable use of R-600a (isobutene) and R-441A in retail food refrigeration, subject to use conditions.
  - The acceptable use of R-170 (ethane) in very low temperature refrigeration and non-mechanical heat transfer, subject to use conditions.
  - The acceptable use of R-290 (propane) in household refrigerators, subject to charge size constraints;
  - The acceptable use of R-290, R-600a, and R-441A in vending machines, subject to charge size constraints.
  - The acceptable use of HFC-32, R-290 and R-441A, subject to use constraints, in self-contained room air conditioners, packaged terminal air conditioners, packaged terminal heat pumps, windows AC units, and portable AC units designed for use in a single room.

» F-gas regulations in Europe include specific bans on production and imports of new equipment using certain kinds of F-gases, including the following[35]:
  - Bans on domestic refrigerators and freezers using refrigerants with GWP over 150, beginning January 1, 2015.
  - Bans on hermetically sealed refrigerators and freezers for commercial use using refrigerants with GWP over 2500, beginning January 1, 2020; and GWP over 150 beginning January 1, 2022.
  - Bans on stationary refrigeration equipment using refrigerants with GWP over 2500, beginning January 1, 2020.
  - Bans on portable air conditioners using refrigerants with GWP over 150, beginning January 1, 2020.
  - Bans on single split air conditioning systems containing less than 3 kg of charge using refrigerants with GWP over 750, beginning January 1, 2015.

3.2.2 Research and Development Activities

Researchers and industry leaders have worked to solve many of the challenges and barriers identified in the previous roadmap. Some examples of recent publications and ongoing research programs include the following:

» **National Institute of Standards and Technology (NIST)**

In the last few years, NIST has performed research to identify potential new refrigerants beyond those molecules that have already been considered. Two papers highlighted below summarize the results of this research.

In one paper,[36] NIST evaluated the effect of a refrigerant's fundamental thermodynamic parameters on its performance in the vapor compression cycle. This defines the limits of what is

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[34] http://www.gpo.gov/fdsys/pkg/FR-2014-07-09/pdf/2014-15889.pdf

[35] http://ec.europa.eu/clima/policies/f-gas/legislation/index_en.htm

[36] Domanski, Piotr et al., 2014, "A thermodynamic analysis of refrigerants: Performance limits of the vapor compression cycle." International Journal of Refrigeration, Vol. 38, pp. 71-79.

thermodynamically possible for a refrigerant and the optimal thermodynamic parameters needed to approach those limits.

In a second paper,[37] NIST examined more than 56,000 chemical compounds from a public-domain database. A subset of around 1,200 candidate fluids was identified by applying screening criteria to estimates for GWP, flammability, stability, toxicity, and critical temperature. The subset of candidate fluids was further reduced to 62 by filtering for fluids with critical temperatures between 300K and 400K. The final candidate fluids include halogenated olefins; compounds containing oxygen, nitrogen, or sulfur; as well as carbon dioxide. A key conclusion from this study is that no single fluid is ideal in all regards; all have one or more negative attributes: poor thermodynamic properties, acute or chronic toxicity, chemical instability, low to moderate flammability, or very high operating pressures.

» **University of Maryland College Park (UMCP)**

UMCP, under a contract from the Air Conditioning, Heating, and Refrigeration Technology Institute (AHRTI), created a life-cycle climate performance (LCCP) design tool for evaluating the performance of supermarket refrigeration systems and air source heat pump systems.[38] The design tool models the direct impacts of refrigeration emissions and indirect impacts of energy consumption.

ORNL used the LCCP design tool to evaluate the performance of a typical commercial refrigeration system with alternative refrigerants and minor system modifications to provide lower-GWP refrigerant solutions with improved LCCP compared to baseline systems. A key conclusion from the study shows that conventional commercial refrigeration system life cycle emissions are largely due to direct emissions associated with refrigerant leaks and that system efficiency plays a smaller role in the LCCP. However, with a transition to low-GWP refrigerants, the indirect emissions become more relevant.[39]

Other universities such as San Francisco State University are also developing LCCP tools for use with current equipment systems.[40]

» **Air-Conditioning, Heating, & Refrigeration Institute (AHRI)**

AHRI launched a low-GWP alternative refrigeration evaluation program (AREP) in March 2011.[41] The purpose of this program is to conduct cooperative research to identify suitable refrigerant alternatives. Several alternate refrigerant candidates have been identified for testing in various applications. The first phase of the program was completed in December 2013 and consisted of testing 38 low-GWP refrigerants in air conditioners and heat pumps, chillers, commercial refrigeration equipment, bus air conditioning systems, and transport refrigeration

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[37] McLinden, Mark O., et al., 2014, "A thermodynamic analysis of refrigerants: Possibilities and tradeoffs for Low-GWP refrigerants." International Journal of Refrigeration, Vol. 38, pp. 80-92.

[38] Project website: http://lccp.umd.edu/ornllccp. Final report available at: http://www.ari.org/App_Content/ahri/files/RESEARCH/Technical%20Results/AHRTI-Rpt-09003-01.pdf.

[39] Abdelaziz, Omar, Fricke, Brian and Vineyard, Edward, "Development of Low Global Warming Potential Refrigerant Solutions for Commercial Refrigeration Systems using a Life Cycle Climate Performance Design Tool", International Refrigeration and Air Conditioning Conference at Purdue, July 16-19, 2012.

[40] http://www.atmo.org/presentations/files/448_3_CHENG_SFSU_FOR_WEB.pdf

[41] http://www.ari.org/site/514/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation

systems. The second phase of the program was launched early 2014. One of the key drivers for Phase II is to evaluate substitute formulations that have been developed after some of the initial proposed alternative refrigerants were withdrawn.

» **Flammability Risk Assessments**

One of the high-priority activities identified in the 2011 roadmap was to conduct risk assessments on the flammability risks of A2, A2L and A3 refrigerants. Current codes and standards forbid the use of flammable refrigerants in most HVAC&R equipment. Flammability risk assessments quantify the risks associated with flammable refrigerants and identify circumstances under which their use may be acceptable. Various studies have been conducted by organizations such as ASHRAE and AHRI to analyze the effects of 2L flammable refrigerants in air-conditioning and refrigeration applications, and work is ongoing to complete further studies.[42]

In 2011, UL formed a joint task group to ensure the safe and consistent use of flammable refrigerants in air conditioning and refrigeration equipment.[43] One main objective was to harmonize flammable requirements with the International Electrotechnical Commission (IEC) requirements. The joint task group consists of 3 working groups with the following scope of work:

- Working group 1: Develop requirements for flammable refrigerants applicable to air conditioning equipment.
- Working group 2: Develop similar requirements for refrigeration equipment.
- Working group 3: Address requirements for the testing and evaluation of flammable refrigerants (including the new A2L types) and take into consideration the recommended requirements of the other equipment working groups.

These requirements continue to be discussed at an international level to develop consensus between all stakeholders. The latest EPA SNAP notice of proposed rulemaking contained several proposals for charge limitations of flammable refrigerants such as HFC-32 and hydrocarbons, but it also noted that these requirements will be superseded by future versions of the respective UL standard for each equipment type.

3.2.3 Summary of Equipment Characteristics

Nearly all HVAC&R equipment types use vapor-compression systems to achieve heat transfer. Many types of equipment require periodic servicing to replenish refrigerant lost during normal operation of the system. Total annual refrigerant consumption is driven by the initial refrigerant charges included in new equipment, plus the refrigerant required to service installed equipment. Table 3.1 provides typical lifetimes, charge sizes, and leakage rates for the equipment categories included in this report.[44,45]

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[42] http://www.ahrinet.org/site/511/Resources/Research/Public-Sector-Research/Technical-Results

[43] http://tc31.ashraetcs.org/pdf/UL's%20Effort%20to%20Harmonize%20Product%20Safety%20Requirements%20for%20A2L%20A2%20and%20A3%20Refrigerants.pdf

[44] Annex 3 - Methodological Descriptions for Additional Source or Sink Categories; from Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008; U.S. Environmental Protection Agency. Available at http://www.epa.gov/climatechange/emissions/usgginv_archive.html

[45] EPA Vintaging Model.

Table 3.1: Typical Lifetimes, Charge Sizes, and Leakage Rates for HVAC&R Equipment

Equipment Type	Lifetime (yrs)[1]	Charge Size (kg)[2]	Leakage Rate (%/year)[1]
Residential Refrigeration	20	0.15	0.5
Small Self-Contained Refrigeration	14	0.25	0.6
Large Self-Contained Refrigeration	14	2	0.6
Walk-in Refrigeration	20	20	20.0
Supermarket Refrigeration	15 – 20	1,500	7.8 – 29.9
Residential Air Conditioning	15	3.5	7.2 – 9.3
Commercial Air Conditioning	15	8.0	7.9 – 8.6
Centrifugal Chillers	20 – 27	720	2.0 – 10.9
Scroll/Screw Chillers	20	280	0.5 – 1.5

1. Source: Annex 3 – Methodological Descriptions for Additional Source or Sink Categories; Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008; U.S. Environmental Protection Agency. Available at http://www.epa.gov/climatechange/emissions/usgginv_archive.html
2. Source: EPA Vintaging Model

3.2.4 Equipment Development and Status

This section describes the current state of development of equipment using low-GWP refrigerants, including a summary of key equipment characteristics and the development progress for each type of equipment. Appendix D provides additional details on each equipment application's progress toward the transition to low-GWP alternative refrigerants.

Table 3.2 summarizes the progress made toward the transition to low-GWP refrigerants for the equipment types listed in this report. The table categorizes the development process as follows:

1. Viable alternative refrigerants have been identified
2. Equipment using alternative refrigerants has been developed
3. Regulatory approval for equipment using alternative refrigerants has been granted
4. Servicing needs for the installed base have been addressed
5. A1 drop-in solutions for legacy equipment have been identified

Table 3.2: Summary of Equipment Development Progress Toward the Transition to Low-GWP Refrigerants

Equipment Type	New Equipment				Service
	(1) Identify Refrigerants	(2) Develop Equipment	(3) Gain Regulatory Approval	(4) Address Servicing Needs	(5) Drop-in Solution Available?
Residential Refrigeration	●	●	●	○	○
Small Self-Contained Refrigeration	●	●	●	○	○
Large Self-Contained Refrigeration	●	◐	◐	◌	○
Walk-in Refrigeration	●	◐	◐	◌	○
Supermarket Refrigeration	●	◐	◐	◌	○
Residential and Light Commercial A/C	◐	◐	◐	◌	○
Large Commercial A/C	○	◌	◌	◌	○
Centrifugal Chillers	●	○	◌	◌	◐
Scroll/Screw Chillers	●	●	●	◌	○

Legend:
● = Challenge has been met ◐ = Work is on-going ○ = Immediate challenge ◌ = Future challenge

As shown in Table 3.2, low-GWP alternative refrigerants have now been identified for several applications. Much progress has been made in residential refrigeration and small self-contained refrigeration applications. The biggest challenges remain with high-capacity equipment types such as residential and commercial air-conditioning applications and chillers.

Some of the key industry developments regarding next-generation low-GWP refrigerants, since the previous 2011 report, include the following:

- Natural refrigerants, such as carbon dioxide and ammonia, have been used in supermarket refrigeration applications.[46]
- A manufacturer introduced the first transport refrigeration system using carbon dioxide.[47]
- HFC-32 has been investigated as a low-GWP alternative. An air-conditioner with HFC-32 was launched in Japan on November 1, 2012.[48]

[46] http://www.achrnews.com/articles/120833-carbon-dioxide-and-ammonia-use-in-supermarkets
[47] http://www.carrier.com/container-refrigeration/en/worldwide/products/Container-Units/NaturaLINE/
[48] http://www.daikin.com/csr/environment/production/06.html

- Beverage companies continue to expand their non-HFC product lines, including further deployment of CO_2 beverage vending machines.[49]

- A commercial cooler for refrigerated energy drinks has been developed using R-600a and deployed in multiple countries, including the U.S.[50]

- One manufacturer has announced the launch of a centrifugal chiller in Europe that uses HFO-1233zd as a replacement for R-123.[51]

[49] http://www.coca-colacompany.com/press-center/press-releases/coca-cola-installs-1-millionth-hfc-free-cooler-globally-preventing-525mm-metrics-tons-of-co2
[50] http://www.atmo.org/presentations/files/308_2_BRENNEIS_RED_BULL.pdf
[51] https://www.ejarn.com/news.asp?ID=30295

4 Technical and Market Barriers

Despite recent progress on next-generation low-GWP refrigerants, significant technical and market challenges still remain, creating barriers to more widespread implementation. Section 4.1 provides a discussion of the tradeoffs that must be considered when evaluating and selecting alternative refrigerants. Section 4.2 provides a discussion of all the technical and market barriers discussed during the May 2014 stakeholder workshop.

4.1 Tradeoffs Among Refrigerant Characteristics

The most viable low-GWP refrigerants have varying degrees of flammability, toxicity, GWP, and volumetric capacity. For many applications, selecting a replacement refrigerant involves tradeoffs among these four characteristics. Figure 4.1 graphically illustrates the GWP, flammability, and toxicity tradeoffs for the most viable alternatives to existing refrigerants. Generally, the lowest-GWP options have the highest flammability and toxicity ratings; conversely, refrigerant blends with the lowest flammability have relatively higher GWP values (although still lower than the HFCs they would replace). Note that the figure does not provide an indication of the tradeoffs with respect to capacity or efficiency. The discussion below the table describes some of these tradeoffs in more detail. Appendix D provides additional details on the specific low-GWP refrigerants under consideration for each equipment application covered in this report.

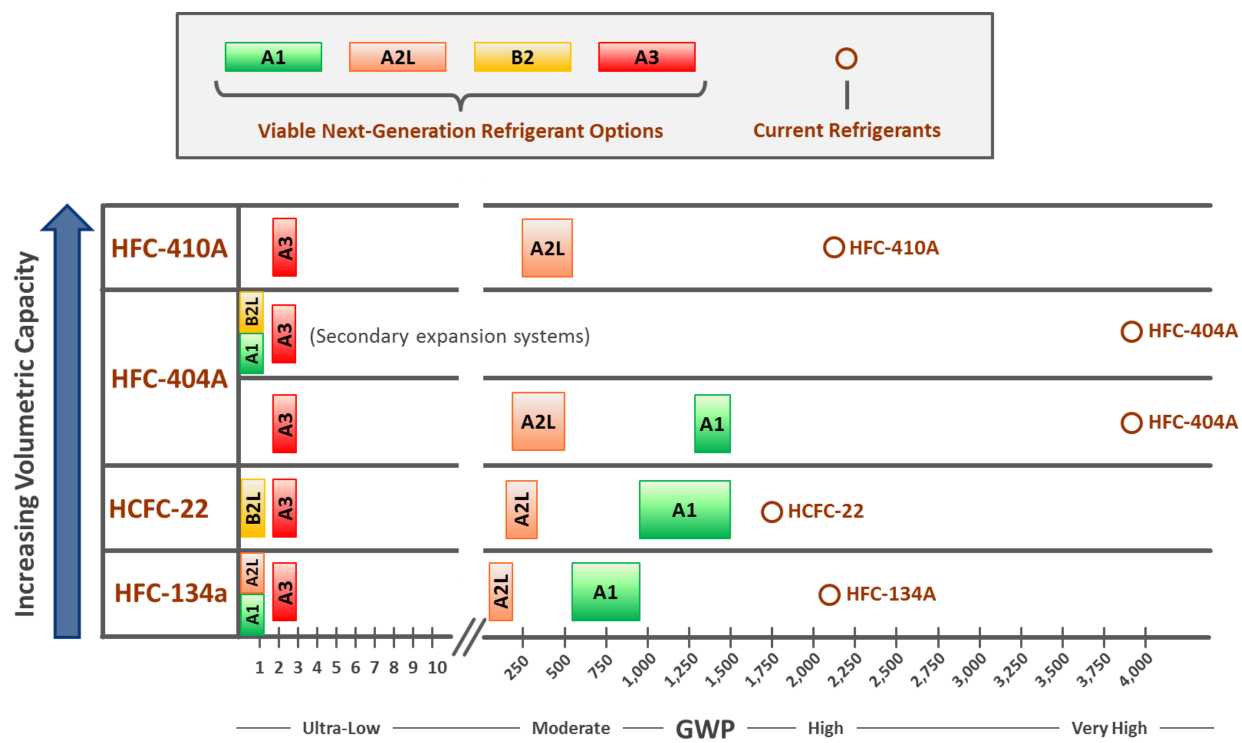


Figure 4.1: Tradeoffs among GWP, flammability, and toxicity for next-generation refrigerants

Replacements for HFC-134a Systems

Refrigerant alternatives for lower-capacity HFC-134a applications generally have low or moderate GWP values, with various degrees of flammability. The A1 and A2L alternatives for these applications generally have GWP values less than 1,000. The A3 alternatives may also be acceptable in applications with small charge quantities. CO_2 (with a rating of A1) can be used for some smaller-capacity applications.

Replacements for HCFC-22 and HFC-404A Systems

The A1 and A2L alternatives for HCFC-22 and HFC-404A applications generally have moderate to high GWP values, making reductions in GWP more challenging for these applications. The larger charge requirements for these systems may preclude the use of A3 refrigerants, despite their technical viability. For some applications—such as supermarket systems—ammonia, CO_2, and hydrocarbons show promise for secondary expansion systems. These are not likely to be viable, however, in direct exchange systems.

Replacements for HFC-410A Systems

A2L and A3 refrigerants are technically viable alternatives to HFC-410A, although the large volume of refrigerant required in air conditioning applications will likely limit the applicability of A3 fluids for only the smallest applications. Although CO_2 (with a rating of A1) could be used in some smaller-capacity applications, its lower thermodynamic performance will preclude its use for many applications currently using HFC-410A. Currently, no suitable A1 alternatives exist for the highest-capacity applications such as residential or commercial air conditioning systems.

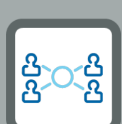
Figure 4.1 demonstrates that lower-GWP alternatives generally have higher flammability ratings, aside from a few viable applications for CO_2, ammonia, and HFO-1234yf. Therefore, the acceptance of slightly flammable (A2L) or highly flammable (A3) fluids would have a significant impact on reducing total GWP-weighted HFC consumption.

4.2 Barriers Discussed at Stakeholder Workshop

During the May 2014 workshop, industry stakeholders articulated many of the technical and market challenges facing the industry. We combined all of these inputs into five main categories of barriers, summarized in Table 4.1. For each category, the table provides specific examples of technical and market barriers discussed during the stakeholder workshop.

These technical and market barriers can be traced to the specific initiatives recommended by stakeholders at the workshop. Appendix A provides a comprehensive summary report from the workshop.

Table 4.1: Summary of Technical and Market Barriers Facing Low-GWP Refrigerants

Category	Specific Technical and Market Barriers
 New Refrigerant Development	• Lack of suitable non-flammable low-GWP options for the most challenging applications such as residential and commercial air conditioning, as well as for servicing existing equipment. • Low-GWP HFC alternatives (e.g. HFC-32) may not have low enough GWP to achieve 85% phase-down goals. • Some low-GWP alternatives (e.g. CO_2) have significantly lower efficiency performance. • Heat transfer properties and other physical characteristics not well understood for many new refrigerants and blends.
 Equipment Development	• Equipment and components need to be redesigned or reconfigured to accept new alternative fluids. • Although identifying the source of leaks is difficult, leakage rates need to be addressed, particularly in supermarket systems. • Maintaining precise temperature control in large supermarket systems is difficult, and lack of temperature control reduces performance. • Alternative system architectures need to be developed and tested as a potential solution for dealing with flammable refrigerants. • The increasing system complexity required for low-GWP refrigerants is a deterrent to market adoption.
 Modeling and Evaluation Tools	• LCCP modeling tools should incorporate more reliable estimates of equipment leakage rates. • Annualized modeling often does not address peak/extreme conditions, which drive system design requirements.
 Safety Risks	• Flammability concerns are difficult to overcome due to numerous regulations involved. • More knowledge is needed on how flammability is characterized, which is particularly important for A2L refrigerants. • Flammable refrigerant detecting equipment is expensive. • The industry lacks clear guidelines for handling flammable refrigerants throughout the entire refrigerant life-cycle.
 Industry Collaboration	• Lack of industry collaboration and coordination complicates efforts to achieve regulatory approvals. • Broad industry collaboration will be required to implement training programs for new refrigerants. • Industry lacks data on equipment performance and characteristics in the field. • The industry needs a place where it can compile field study data, risk assessment data, etc. all in one place.

5 Research & Development Initiatives

5.1 Summary

During the May 2014 workshop, industry stakeholders suggested 54 possible initiatives that DOE could support to help accelerate the transition to next-generation refrigerants. Following the workshop, Navigant refined the list of identified initiatives by combining overlapping ideas into a set of 31 unique initiatives. We then screened the list of initiatives to remove from further consideration those initiatives that did not receive any stakeholder voting support and those that were outside the scope of consideration for BTO. This resulted in a set of 21 initiatives for further evaluation.

Next, we divided the list into two categories: direct versus indirect impacts on energy efficiency. We then evaluated each initiative using the numeric scoring criteria described previously. The final scores revealed the highest-priority initiatives in each category. Appendix B provides the finalized scores for each of the initiatives.

Figure 5.1 shows the minimum, maximum, and average weighted scores for all the initiatives within each category. We defined the highest priority initiatives as having a final score of 3.0 or greater. The highest priority initiatives are described further in the next sections of this report.

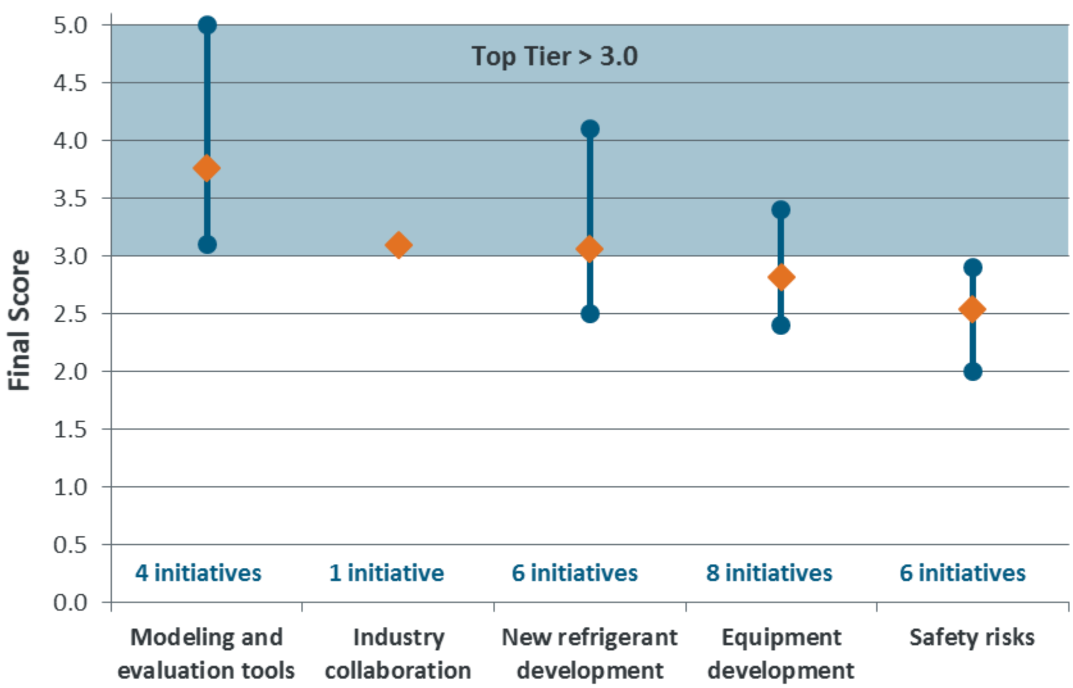


Figure 5.1: Average final scores for each initiative category

5.2 Highest Priority Initiatives

This section describes the top ten highest priority initiatives, which represent the initiatives with the highest final scores. The initiatives are grouped into two separate categories: those that could have a direct impact on maintaining or improving current energy efficiency performance, and those that could have an indirect or enabling impact on energy efficiency.

In other DOE roadmaps and R&D reports, DOE uses a prioritization tool ("P-Tool") to estimate each initiative's potential for reducing national energy consumption. The P-Tool compares investment opportunities across all of BTO activities to help inform decision-making and the development of program goals and targets. The National Renewable Energy Laboratory (NREL) originally developed the tool and describes it in more detail in their project report.[52]

Unlike most of DOE's other technology roadmaps, however, the initiatives described in this report are not intended to improve equipment energy efficiency, *per se*. Rather, one of the primary challenges in transitioning to low-GWP refrigerants is to maintain current efficiency levels after switching to the new refrigerant. A successful transition to next-generation low-GWP refrigerants may significantly reduce GWP-weighted refrigerant consumption while having a neutral effect on energy efficiency and overall national energy consumption. Therefore, the P-Tool was not applicable to informing the prioritization of the proposed initiatives.

5.2.1 Initiatives with Direct Impacts on Energy Efficiency

Table 5.1 lists the top initiatives with direct impacts on maintaining or improving energy efficiency performance and shows the category of barriers from Table 4.1 that each initiative addresses. The initiative identification numbers correspond to those listed in Appendix B. Additional details regarding each initiative are provided below the table.

Table 5.1: High-Priority Initiatives with Direct Impacts on Energy Efficiency

ID No.	Initiative/Activity	Category
1	Expand NIST modeling research to identify and explore theoretical properties of new low-GWP blends, particularly azeotropes.	Modeling and Evaluation Tools
2	Characterize the heat transfer and thermodynamic properties and efficiency performance of new refrigerants and blends.	New Refrigerant Development
10	Develop techniques for detecting and dramatically reducing refrigerant leakage in currently installed systems.	Equipment Development
12	Use modeling tools to perform system-level evaluations of newly identified fluids for specific applications.	Modeling and Evaluation Tools
11	Investigate techniques for improving temperature control and operational efficiency of secondary loops in installed supermarket refrigeration systems.	Equipment Development
13	Improve LCCP models by conducting studies to better understand differences in average annual versus peak season performance in large systems.	Modeling and Evaluation Tools

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[52] Philip Farese, et. al., "A Tool to Prioritize Energy Efficiency Investments," National Renewable Energy Laboratory, August 2012, available: www.nrel.gov/docs/fy12osti/54799.pdf.

» **#1: Expand NIST modeling research to identify and explore theoretical properties of new low-GWP blends, particularly azeotropes.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
5	5	5	**5.0**

Description: This initiative would involve conducting additional modeling research as a follow-on activity to the research results presented at the stakeholder forum, which focused exclusively on pure refrigerant compounds. The expanded research would identify and explore the theoretical performance of new refrigerant blends, particularly azeotropic blends that would be most desirable for HVAC&R equipment. Refrigerant blends could potentially provide low-GWP alternatives with more favorable flammability characteristics.

» **#2: Characterize the heat transfer and thermodynamic properties and efficiency performance of new refrigerants and blends.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
5	2	5	**4.1**

Description: The material property characteristics of many new low-GWP refrigerants have not been studied comprehensively, and manufacturers may be reluctant to use them until their characteristics are well understood. This initiative would focus on characterizing the thermophysical and heat transfer properties of currently identified low-GWP refrigerants and refrigerant blends, which help encourage their use in new equipment. This characterization will be achieved primarily through testing and modeling of these new refrigerants, similar to the testing performed in the 1990s on refrigerant options. Some of this testing may be appropriate through industry efforts such as the Alternative Refrigerants Evaluation Program (AREP)[53] by AHRI.

» **#10: Develop techniques for detecting and dramatically reducing refrigerant leakage in currently installed systems.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	4	2	**3.4**

Description: The equipment service sector accounts for approximately half of the annual HFC consumption, which is primarily a result of refrigerant leakage during normal operation and servicing events. This initiative would involve developing new techniques for detecting, and ultimately reducing or eliminating, the main sources or causes of

[53] http://www.ari.org/site/514/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation

leakage in currently installed systems. Significant reductions in equipment leakage would lead to significant reductions in annual HFC consumption.

» **#12: Use modeling tools to perform system-level evaluations of newly identified fluids for specific applications.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
5	3	1	**3.2**

Description: Many current modeling tools predict maximum theoretical thermodynamic performance of specific refrigerants. This initiative would seek to model the expected performance of refrigerants under real-world (i.e., non-ideal) conditions. Such results would help equipment manufacturers understand the viability of alternative refrigerants in their specific equipment types.

» **#11: Investigate techniques for improving temperature control and operational efficiency of secondary loops in installed supermarket refrigeration systems.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	3	2	**3.1**

Description: Maintaining precise temperature control in supermarket refrigeration systems can be challenging due to the length and configuration of the refrigerant lines throughout the supermarket. This lack of temperature control leads to a reduction in operational efficiency. This initiative would investigate techniques for improving temperature control of secondary loops in supermarket refrigeration systems, which would help maintain or possibly increase overall system efficiency.

» **#13: Improve LCCP models by conducting studies to better understand differences in average annual versus peak season performance in large systems.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	4	1	**3.1**

Description: Current LCCP models incorporate estimates of average annual average energy usage for a particular equipment type. In practice, end-users experience seasonal peak loads that result in a significant increase in energy use during those peak periods. These peak conditions may preclude the use of certain alternative refrigerants in certain climates if system performance cannot be maintained during those periods. This initiative would seek to improve current LCCP models by incorporating more detailed estimates of peak conditions during system operation. Field studies may be required to acquire this type of information.

5.2.2 Initiatives with Indirect Impacts on Energy Efficiency

Table 5.2 lists the top initiatives with indirect impacts on energy efficiency and shows the category of barriers from Table 4.1 that each initiative addresses. The initiative identification numbers correspond to those listed in Appendix B. Additional details regarding each initiative are provided below the table.

Table 5.2: High-Priority Initiatives with Indirect Impacts on Energy Efficiency

ID No.	Initiative/Activity	Category
4	Create a public repository for risk assessments, performance characteristics, material compatibility data, and fire incidents for alternative refrigerants.	Industry Collaboration
6	Develop prototype systems that demonstrate leak detection with high-reliability, inexpensive sensors.	Equipment Development
7	Characterize materials compatibility and stability of new refrigerants and blends.	New Refrigerant Development
14	Explore additional A1 refrigerants or blends as drop-in options for servicing existing equipment.	New Refrigerant Development

» **4: Create a public repository for risk assessments, performance characteristics, material compatibility data, and fire incidents for alternative refrigerants.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	2	3	**3.1**

Description: Information relevant to the development, testing, and approval of new refrigerants is often scattered among various industry entities that each conduct their own investigations. No single repository exists for consolidating the entire body of knowledge for individual refrigerants. This initiative would create a public repository for consolidating information such as risk assessments, performance characteristics, material compatibility data, fire or other safety incidents for the most promising set of low-GWP refrigerants. Such a repository could help with obtaining new UL safety approvals, for example, since all the information would be located in one place and could be used to formulate a comprehensive understanding of the new refrigerant.

» **6: Develop prototype systems that demonstrate leak detection with high-reliability, inexpensive sensors.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	2	3	**3.1**

Description: Refrigerant leakage from installed equipment represents a significant portion of annual HFC refrigerant consumption, as such equipment must be serviced each year with replacement refrigerant. One of the major challenges in reducing refrigerant leakage is detecting when and where leaks are occurring. This initiative would seek to develop new prototype systems that demonstrate advanced leak detection using high-reliability, inexpensive sensors. By developing smarter leak detection capabilities, leaks can be detected and addressed promptly when they occur, thus significantly reducing the amount of replacement refrigerant required during servicing.

» **7: Characterize materials compatibility and stability of new refrigerants and blends.**

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Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	3	2	**3.1**

Description: The implementation of a new refrigerant requires an understanding of the long-term stability and materials compatibility with all the other components of the system. Such information is required to develop confidence in the long-term reliability of the new refrigerant. This initiative would seek to characterize the long-term stability and materials compatibility of new low-GWP refrigerants, with the goal of reducing uncertainty in the viability of these fluids.

» **14: Explore additional A1 refrigerants or blends as drop-in options for servicing existing equipment.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
4	4	1	**3.1**

Description: Much of the current focus of low-GWP refrigerant development is targeted towards new equipment. However, service replacement represents approximately half of annual HFC consumption. Even if significant progress is made towards transitioning new equipment to low-GWP alternatives, the servicing needs of existing equipment will continue to represent a substantial level of HFC consumption. Many of the new alternative refrigerants under consideration are mildly or highly flammable (i.e. A2L or A3). Such refrigerants would not be suitable for use as drop-in replacements in existing equipment designed for non-flammable (A1) refrigerants. This initiative would expand the search for suitable A1 refrigerants, including refrigerant blends, that could be used as lower-GWP drop-in replacements in existing equipment. This may include modeling activities as well as refrigerant development activities.

5.3 Low-Scoring Initiatives with High Stakeholder Support

Notably, after scoring each initiative using the defined criteria, none of the safety risk initiatives were included in the top ten list. This is because many of the safety- and flammability-related issues scored poorly under the metrics "Fit with BTO Mission" or "Criticality of DOE Involvement." We judged most of the safety- and flammability-related initiatives as having a medium or low fit with the BTO mission because such activities do not directly relate to BTO's stated goals and objectives. We also scored most of these initiatives relatively low in terms of criticality of DOE involvement, because many of these activities would be performed by other entities.

Despite their low final scores, however, several safety-related initiatives received high levels of stakeholder support at the May 2014 workshop. As described previously in this report, numerous technical and market barriers are associated with the use of mildly flammable or highly flammable refrigerants. We present these initiatives in Table 5.3 to highlight these concerns even though they may not fit within the scope of activities for BTO.

Table 5.3: Low-Scoring Initiatives with High Stakeholder Support

ID No.	Initiative/Activity	Category
3	Improve flammability test methods and prediction tools for blended compounds.	Safety Risks
5	Conduct flammability risk assessments on additional A2L, A3, and B2L fluids for a wider range of applications.	Safety Risks
8	Investigate alternative system architectures that would inherently mitigate flammability risks with A2L and A3 fluids.	Safety Risks

» **3: Improve flammability test methods and prediction tools for blended compounds.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
2	3	4	**2.9**

Description: Much of the industry's flammability modeling and testing has been targeted towards pure refrigerants rather than blends. However, refrigerant blends may offer more suitable GWP, flammability, or other characteristics compared to pure fluids. This initiative would improve flammability prediction tools and test methods by expanding them to include blended compounds. This may help broaden the range of available refrigerants that can be considered for further development.

» **5: Conduct flammability risk assessments on additional A2L, A3, and B2L fluids for a wider range of applications.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
3	2	3	**2.7**

Description: As discussed broadly throughout this report, many of the most promising low-GWP alternative refrigerants are mildly or highly flammable. Flammability assessments must be performed in order to understand circumstances under which flammable refrigerants can be used safely in specific applications. The process of performing flammability risk assessments can be lengthy and burdensome. This initiative would provide support for conducting flammability risk assessments on additional A2L, A3, and B2L refrigerants, including refrigerant blends, for a wide range of applications.

» **8: Investigate alternative system architectures that would inherently mitigate flammability risks with A2L and A3 fluids.**

Fit with BTO Mission	Criticality of DOE Involvement	Stakeholder Support	Final Score
3	3	2	**2.7**

Description: Traditional methods of mitigating flammability risks involve adopting charge limits and/or requiring certain design elements within the system, both of which limit the potential applications of flammable fluids. This initiative would involve investigating alternative system architectures that may inherently mitigate flammability risks better than existing system architectures. This effort could help expand the potential range of applications for which flammable refrigerants would be acceptable.

6 Appendix A - Workshop Summary Report

This Appendix provides a copy of the summary report that DOE sent to participants after the conclusion of the May 2014 workshop.

United States Department of Energy (DOE) Next-Generation Low-GWP Refrigerants Research and Development Roadmap
May 29, 2014

Stakeholder Workshop Summary – Navigant's Washington D.C. Office

Summary
On May 29, 2014, Navigant Consulting, Inc. (Navigant), on behalf of the U.S. Department of Energy's (DOE) Building Technologies Office, hosted a stakeholder forum at Navigant's Washington, D.C. office to identify research and development (R&D) needs and critical knowledge gaps in the field of next-generation low-global warming potential (GWP) refrigerants. Interest in low-GWP refrigerants has been stimulated by the North American proposal to the Montreal Protocol to reduce hydrofluorocarbon (HFC) consumption by 85 percent by 2035. The objective of DOE's Building Technologies Office is to ensure that next-generation low-GWP refrigerants maintain or improve upon current energy efficiency performance. To help achieve this goal, DOE may support or facilitate R&D and deployment initiatives that will help accelerate the transition to low-GWP refrigerants in air conditioning and refrigeration equipment. The equipment types covered in this workshop included residential direct expansion air-conditioning, commercial direct expansion air-conditioning, chillers, residential refrigeration, self-contained commercial refrigeration and supermarket refrigeration. The meeting attendees included 28 outside participants, including academics, researchers from national laboratories, industry manufacturers and engineers, and representatives from policy organizations. A list of attendees and their affiliations is included below.

Workshop Objective
The objective of this workshop was to engage participants in a discussion on the key R&D needs that have the potential to reduce barriers to greater market penetration of next-generation low-GWP refrigerants. The output was a list of potential R&D activities that may be appropriate for DOE to support, and that industry stakeholders believe will aid the industry in accelerating the adoption of these alternative refrigerants.

Results
Discussions at the forum included large group brainstorming sessions, as well as smaller breakout group sessions. These breakout groups were organized into two topic categories:

Breakout Session 1: Refrigerant identification and basic R&D for next-generation low-GWP refrigerants

- Room 1: Air-Conditioning
- Room 2: Refrigeration

Breakout Session 2: Application and implementation challenges for next-generation low-GWP refrigerants

- Room 1: Air-Conditioning
- Room 2: Refrigeration

These discussions generated a total of 54 potential initiatives or activities for consideration. At the conclusion of the forum, Navigant posted all of the topics on the wall and asked the participants to prioritize the topics by voting on those that they felt were most important for DOE to undertake. Each participant received four priority votes to disperse among the different initiatives. Table 6.1 provides the complete list of initiatives as presented during the workshop and the number of votes allocated to each initiative.

Table 6.1: R&D Initiatives

Discussion Group	Votes	Initiative/Activity
Air-Conditioning	7	From the "NIST 25", identify and explore performance of new blends, especially azeotropes (modeling, testing)
Refrigeration	6	Heat transfer and COP properties of new fluids and mixtures
Refrigeration	6	Building codes by application and equipment design
Air-Conditioning	5	Characterize heat transfer, thermodynamic, and transport properties of new refrigerants
Refrigeration	5	Close the loop on A2L, A3 and B2L risk assessments
Refrigeration	5	Engage with NATE or other industry orgs to help out roll new refrigerants (+RSES)
Air-Conditioning	4	Determine interaction parameters for blends
Air-Conditioning	4	Improve flammability test methods and connect to real world
Air-Conditioning	4	Assess building code timelines and determine what R&D is needed and timing to facilitate code acceptance
Air-Conditioning	4	High reliability, inexpensive sensors for leak detection
Refrigeration	4	DOE and EPA collaboration
Air-Conditioning	3	Characterize materials compatibility and stability of new refrigerants
Air-Conditioning	3	Alternative system architectures to mitigate A2L risks
Refrigeration	3	Reduce and simplify end-user burden on new systems to encourage adoption (reliability/life cycle costs)
Air-Conditioning	2	Flammability prediction tools for compounds or blends
Air-Conditioning	2	Guidelines for handling A2L refrigerants throughout life cycle, especially residential
Refrigeration	2	How to identify and dramatically reduce leaks in current installed systems (30-0%)
Refrigeration	2	Temperature control and operational efficiency of secondary loop systems
Air-Conditioning	1	Explore options for drop-in refrigerants for service (better than replacing equipment?)
Air-Conditioning	1	Improve understanding of refrigerant glide

Discussion Group	Votes	Initiative/Activity
Air-Conditioning	1	Research on flame arrestors or fire mitigation strategies
Refrigeration	1	Refrigerant options at less than 150 GWP ("magic number in Europe")
Refrigeration	1	Evaluate safety risks of non-A1 fluids as potential drop ins for current equipment (limited applications may be feasible)
Refrigeration	1	Add system-level evaluations of newly identified fluids (tailored to specific implementations/applications)
Refrigeration	1	Incentivize removal of old equipment and replacement (incentives tailored to each market)
Refrigeration	1	Research into more secondary fluids (translate past research into real world)
Refrigeration	1	Further understanding of annual versus peak season performance in LCCP
Air-Conditioning	0	Assess risk of refrigerant combustion byproducts
Air-Conditioning	0	Scenario planning to achieve phaseout goals
Air-Conditioning	0	Leak rate and frequency study
Air-Conditioning	0	Tradeoff studies between direct and indirect emissions using LCCP tool
Air-Conditioning	0	Consider performance at non-design point conditions
Air-Conditioning	0	Help facilitate adoption of new building codes
Air-Conditioning	0	Guidelines for leak detectors
Air-Conditioning	0	Complete/compile risk assessments including assessing impact mitigation measures
Air-Conditioning	0	Compile field experience on flammable refrigerants incidents
Refrigeration	0	More A1 options for drop-in for servicing
Refrigeration	0	What GWP targets are acceptable (by application/by new vs. replacement)?
Refrigeration	0	How will phase downs be structured
Refrigeration	0	Prevent/reduce leakage in new systems
Refrigeration	0	Identifying major sources of leaks
Refrigeration	0	System architectures
Refrigeration	0	Lack of enforcement of maximum leakage regulations
Refrigeration	0	Reducing charge levels in new systems
Refrigeration	0	Leakage: where/when/rate/etc.
Refrigeration	0	Consider wide range of operating conditions
Refrigeration	0	CO_2 systems - maps of transcritical operation across climate zones
Refrigeration	0	Training for installation/maintenance/handling
Refrigeration	0	Engage with FMI, NAFEM, NAC to disseminate info (unbiased, 3rd party validation)
Refrigeration	0	Availability of reclaim equipment/tools for flammable fluids (leak detectors, non-sparking tools)
Refrigeration	0	DOT regulations for flammables

Discussion Group	Votes	Initiative/Activity
Refrigeration	0	Component and equipment redesign for non-A1 fluids
Refrigeration	0	Cost - how to reduce costs of new equipment
Refrigeration	0	Extend LCCP methodologies to individual locations (total cost of ownership)

Next Steps after Workshop
This forum was an important first step in developing the DOE R&D roadmap. Moving forward, Navigant, in consultation with DOE's Building Technologies Office, will undertake a process to further develop the ideas generated during the workshop. Navigant will aggregate any duplicate or related initiatives to ensure that all of the ideas being explored are unique. This process will also include consideration of additional topics through follow-up discussion with individual stakeholders and industry experts. Navigant will then prioritize the initiatives based on internal analysis, DOE input, and industry feedback.

The voting results from the forum are one element that DOE will consider in making decisions regarding which topics to support, but they are not the sole criteria. Other criteria may include fit with DOE mission, likely impact, and consideration of other R&D priorities across the Building Technologies Office.

Finally, Navigant and DOE wish to thank all of the forum participants. The suggestions, insights, and feedback provided during the forum are critically important to developing a useful next-generation low-GWP refrigerants roadmap.

Forum Attendees

The R&D roadmap forum brought together 28 individuals representing a range of organizations across the industry. Table 6.2 lists all the attendees and their affiliations.

Table 6.2: Stakeholder Forum Attendee List

Attendee Name	Organization
Karim Amrane	Air-Conditioning, Heating and Refrigeration Institute
Xudong Wang	Air-Conditioning, Heating and Refrigeration Institute
Laurent Abbas	Arkema
Richard Lord	Carrier Corporation
Steven Brown	Catholic University
Ari Reeves	CLASP
Joe Karnaz	CPI Fluid Engineering
Tony Bouza	DOE Buildings Technologies Office
Patrick Phelan	DOE Buildings Technologies Office
Bahman Habibzadeh	DOE Buildings Technologies Office
Robert Wilkins	Danfoss
Barbara Minor	Dupont
Hung Pham	Emerson Climate Technologies
Rajan Rajendran	Emerson Climate Technologies
Mark Spatz	Honeywell
Tim Anderson	Hussmann Corporation
Steve Kujak	Ingersoll Rand
Dutch Uselton	Lennox Industries
Matthew Frank	NSWC
Ed Vineyard	ORNL
Omar Abdelaziz	ORNL
Mark McLinden	NIST
Piotr Domanski	NIST
Joe Sanders	Traulsen
Charles Hon	True Manufacturing
Reinhard Radermacher	University of Maryland
Parmesh Verma	UTRC
Nathan Hultman	White House Council on Environmental Quality

7 Appendix B – Final Initiative Scores

Table 7.1 summarizes the scoring criteria for each metric.

Table 7.1: Initiative Scoring Criteria

Metric	1	2	3	4	5	Weight
Fit with BTO Mission	Weak fit with BTO mission and goals defined in Multi-Year Work Plan	(Weak to moderate fit)	Moderate fit with BTO mission and goals defined in Multi-Year Work Plan	(Moderate to strong fit)	Strong fit with BTO mission and goals defined in Multi-Year Work Plan	**40%**
Criticality of DOE Involvement	No DOE involvement required. Low risk activity.	Initiative would benefit from DOE involvement, but may not be required.	Initiative requires DOE involvement to start, but may not require DOE's continued interaction.	Initiative requires DOE involvement, and requires DOE's continued interaction.	Initiative may have originated with DOE. Initiative will not start or be carried on without strong DOE involvement. High risk activity.	**30%**
Level of Stakeholder Support	1 vote	2-3 votes	4-5 votes	6-7 votes	8 or more votes	**30%**

Table 7.2 provides the final scores for the 21 consolidated initiatives that were determined to be in-scope for BTO and that received at least one vote of stakeholder support during the workshop.

Table 7.2: Final Scores for In-Scope Initiatives

ID #	Initiative/Activity	Direct / Indirect	Metric #1	Metric #2	Metric #3	Final Score
1	Expand NIST research by modeling testing to identify and explore performance and characteristics of new blends, specifically azeotropes	Direct	5	5	5	5.0
2	Characterize heat transfer thermodynamic and COP properties of new refrigerants and mixtures	Direct	5	2	5	4.1
3	Improve flammability test method and prediction tool for compounds of blends	Indirect	2	3	4	2.9
4	Create a public repository for risk assessment, performance, compatibility data, fire incidents	Indirect	4	2	3	3.1
5	Conduct A2L, A3 and B2L risk assessments	Indirect	3	2	3	2.7
6	Develop prototype equipment that demonstrates leak detection with high reliability, inexpensive sensors	Indirect	4	2	3	3.1
7	Characterize materials compatibility and stability of new refrigerants	Indirect	4	3	2	3.1

ID #	Initiative/Activity	Direct / Indirect	Metric #1	Metric #2	Metric #3	Final Score
8	Investigate alternative system architectures to mitigate A2L risks	Indirect	3	3	2	2.7
9	Investigate alternative simpler system architectures to encourage the use and adoption of low-GWP refrigerant systems.	Indirect	4	1	2	2.5
10	Develop techniques for identifying and dramatically reducing leaks in current installed systems (30 --> 0%)	Direct	4	4	2	3.4
11	Investigate techniques for improving temperature control and operational efficiency of secondary loops in installed supermarket systems	Direct	4	3	2	3.1
12	Use modeling tools to perform system-level evaluations of newly identified fluids for specific applications.	Direct	5	3	1	3.2
13	Improve LCCP models by conduct studies to better understand differences in average annual versus peak season performance in large systems.	Direct	4	4	1	3.1
14	Explore additional A1 drop-in options for service	Indirect	4	4	1	3.1
15	Perform more research identifying new secondary fluid options	Indirect	4	3	1	2.8
16	Identify and develop additional refrigerants with less than 150 GWP	Indirect	4	3	1	2.8
17	Improve understanding of refrigerant glide in mixtures	Direct	4	2	1	2.5
18	Investigate and develop new systems using <150 GWP refrigerants that also achieve the necessary efficiency and safety requirements	Indirect	3	3	1	2.4
19	Develop prototype secondary systems using recent research results	Direct	3	3	1	2.4
20	Research on flame arrestors or fire mitigation strategies for systems using flammable refrigerants	Indirect	3	3	1	2.4
21	Evaluate safety risks for non-A1 drop-in for current A1 systems	Indirect	2	3	1	2.0

Table 7.3 lists the initiatives that were screened out from further consideration because they were determined to be out-of-scope for BTO or they received no stakeholder votes during the workshop.

Table 7.3: Initiatives not included for further consideration

Initiative/Activity	Reason for Excluding
Create specific roadmaps outlining the timelines and activities required to change building codes to enable the use of alternative refrigerants	Out of scope for BTO
Create incentives for removal and replacement of old equipment	Out of scope for BTO
Convene forum on the topic of GWP phase-down implementation to ensure collaboration/cooperation between government agencies and industry.	Out of scope for BTO
Develop guidelines for handling flammable refrigerants throughout lifecycle, including servicing	Out of scope for BTO
Implement DOT regulations for flammable refrigerants	Out of scope for BTO; No votes
Engage with industry organizations to provide appropriate training to roll out new refrigerants	Out of scope for BTO
Consider performance at wide range of operating conditions	No votes
Investigate component and equipment redesign for non-A1 fluids	No votes
For CO2 systems, develop geographic maps of transcritical operation across climate zones	No votes
Assess risk of combustion by equipment type	No votes

8 Appendix C – List of Current Refrigerants and Alternatives

This Appendix contains a detailed list of all current and potentially viable refrigerants identified as part of this report development process. Within each table, the refrigerants are ranked according to safety classification and GWP value.

Table 8.1: Characteristics of Most Common HFC/HCFC Refrigerants

ASHRAE Designation	Common Name	Composition (% by component)	Safety Classification	GWP (100-year)[1]
HFC-134a	-	-	A1	1,300
HCFC-22	-	-	A1	1,760
HFC-410A	-	R-32/R-125 (50/50)	A1	1,924
HFC-404A	-	R-125/R-143a/R-134a (44/52/4)	A1	3,943
HCFC-123	-	-	B1	79

1. IPCC Fifth Assessment Report, Table 8.A.1. Available at http://www.ipcc.ch/report/ar5. Blends calculated using weighted average of components.

Table 8.2: Characteristics of Most Viable Low-GWP, non-HFO Refrigerants

ASHRAE Designation	Common Name	Composition (% by component)	Safety Classification	GWP (100-year)[1,2]
Hydrocarbons:				
R-290	Propane	-	A3	3
R-600	Butane	-	A3	4
R-600a	Isobutane	-	A3	3
R-1270	Propylene	-	A3	2
HFCs:				
HFC-32	-	-	A2L	677
HFC-152a	-	-	A2	138
Other Natural Refrigerants:				
R-744	Carbon dioxide	-	A1	1
R-717	Ammonia	-	B2	0

1. Hydrocarbons: IPCC Fourth Assessment Report, Table 2.15. Available at http://www.ipcc.ch/report/ar4.
2. All others: IPCC Fifth Assessment Report, Table 8.A.1. Blends calculated using weighted average of components.

Table 8.3: Characteristics of HFO-Based Refrigerants in Development for R-134a Replacement

ASHRAE Designation	Common Name	Composition (% by component)	Safety Classification	GWP (100-year)[1]
N/A	Daikin D4Y	R-134a/R-1234yf (40/60)	A1	521
R-450A	Honeywell N-13	R-134a/R-1234ze(E) (42/58)	A1	547
N/A	DuPont XP-10	R-134a/R-1234yf (44/56)	A1	573
N/A	Arkema ARM-41a	R-32/R-134a/R-1234yf (6/63/31)	A1	860
HFO-1234yf	-	-	A2L	<1
HFO-1234ze	-	-	A2L	<1
N/A	Mexichem AC5	R-32/R-152a/R-1234ze(E) (12/5/83)	A2L	89
N/A	Arkema ARM-42a	R-134a/R-152a/R-1234yf (7/11/82)	A2L	107
N/A	Mexichem AC5X	R-32/R-134a/R-1234ze(E) (7/40/53)	A2L	568

1. IPCC Fifth Assessment Report, Table 8.A.1. Blends calculated using weighted average of components.

Table 8.4: Characteristics of HFO-Based Refrigerants in Development for R-404a Replacement

ASHRAE Designation	Common Name	Composition	Safety Classification	GWP[1] (100-year)
R-448A	-	R-32/R-125/R-1234yf/R-134a/R-1234ze(E) (26/26/20/21/7)	A1	1,273
N/A	DuPont DR-33	R-32/R-125/R-134a/R-1234yf (24/25/26/25)	A1	1,293
N/A	Arkema ARM-32a	R-32/R-125/R-134a/R-1234yf (25/30/25/20)	A1	1,445
N/A	Arkema ARM-30a	R-32/R-1234yf (29/71)	A2L	197
N/A	Daikin D2Y-65	R-32/R-1234yf (35/65)	A2L	238
N/A	DuPont DR-7	R-32/R-1234yf (36/64)	A2L	244
N/A	Honeywell L-40	R-32/R-152a/R-1234yf/R-1234ze(E) (40/10/20/30)	A2L	285
N/A	Arkema ARM-31a	R-32/R-134a/R-1234yf (28/21/51)	A2L	463

1. IPCC Fifth Assessment Report, Table 8.A.1. Blends calculated using weighted average of components.

Table 8.5: Characteristics of HFO-Based Refrigerants in Development for R-410A Replacement

ASHRAE Designation	Common Name	Composition	Safety Classification	GWP[1] (100-year)
N/A	Daikin D2Y-60	R-32/R-1234yf (40/60)	A2L	271
N/A	Mexichem HPR1D	R-32/R-744/R-1234ze(E) (60/6/34)	A2L	407
R-446A	-	R-32/R-1234ze(E)/R-600 (68/29/3)	A2L	461
N/A	Arkema ARM-70a	R-32/R-134a/R-1234yf (50/10/40)	A2L	469
N/A	DuPont DR-5	R-32/R-1234yf (72.5/27.5)	A2L	491
R-447A	-	R-32/R-125/R-1234ze(E) (68/3.5/28.5)	A2L	572

1. IPCC Fifth Assessment Report, Table 8.A.1. Blends calculated using weighted average of components.

9 Appendix D – Current State of Development of Equipment Types

This Appendix provides additional details on each equipment application's progress toward the transition to low-GWP alternative refrigerants.

9.1 Residential Refrigeration

Figure 9.1 shows the progress toward the transition to low-GWP refrigerants for residential refrigeration applications.

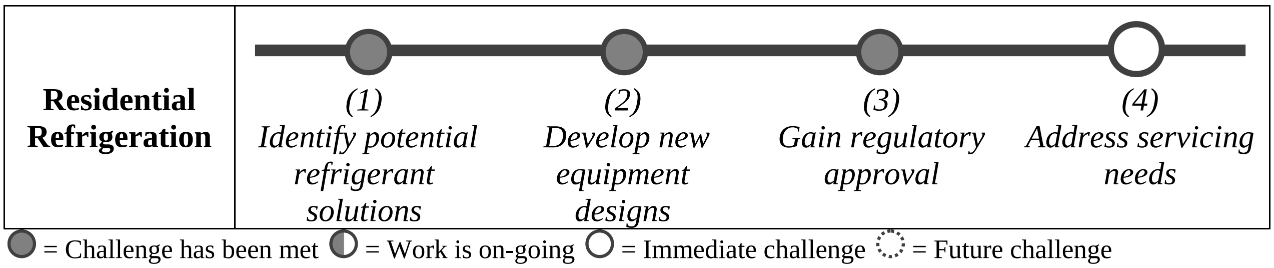

Figure 9.1: Progress toward the transition to low-GWP refrigerants for residential refrigeration applications

Residential refrigeration equipment mainly uses HFC-134a, for which several low-GWP alternatives exist. Residential refrigerators that use hydrocarbons have been available in Europe for several years. The F-gas regulation that will become effective in 2015 will have a further impact on the use of alternative refrigerants for residential refrigeration applications.

Recent developments in alternate refrigerants for residential refrigeration in the United States include the following:

- In December 2011, the EPA SNAP program issued a final rule, effective February 2012, approving the use of certain hydrocarbon refrigerants with charge limit restrictions as acceptable refrigerants in household and self-contained refrigeration applications. The rule specifically allows the use of isobutane and propane up to 57 g for household refrigerators and up to150 g for commercial refrigerators.
- Changes have been made to both UL 250 and UL 471, safety standards for household and commercial refrigerators, to allow a larger amount of A3 refrigerant charge.

In addition, HFO-1234yf has also been identified as a replacement for HFC-134a, as another flammable refrigerant option for refrigerator and freezer applications.

9.2 Commercial Refrigeration

Figure 9.2 shows the progress toward the transition to low-GWP refrigerants for commercial refrigeration applications.

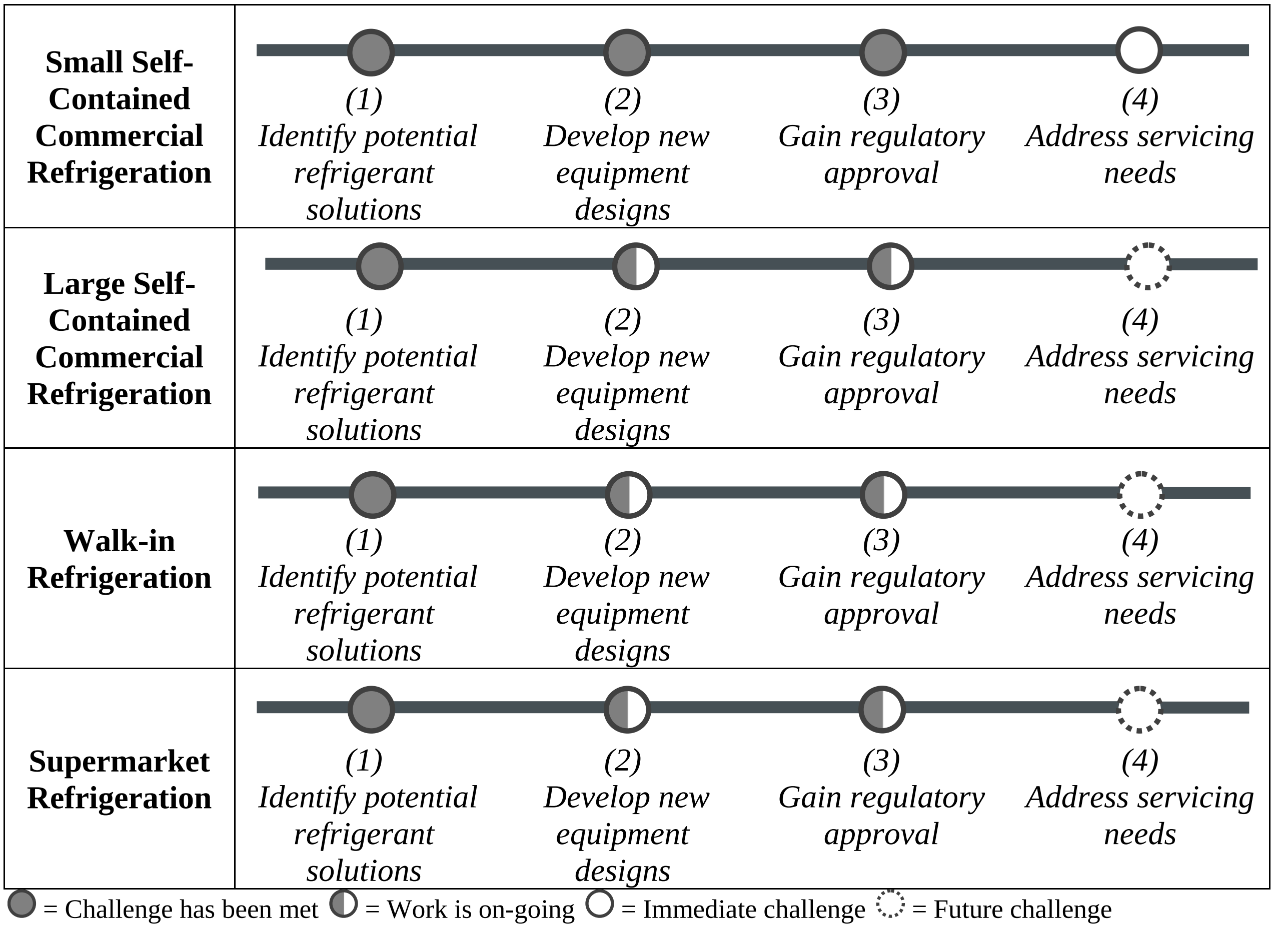

Figure 9.2: Progress toward the transition to low-GWP refrigerants for commercial refrigeration applications

Commercial refrigeration equipment typically uses HFC-134a, for which several low-GWP alternatives exist, albeit for smaller-capacity systems. Small and intermediate refrigeration applications have demonstrated major progress towards the transition to alternative refrigerants in the United States.

The European residential refrigeration market has progressed using hydrocarbon refrigerants. For larger supermarket systems, European countries with mild climates have had success using transcritical CO_2 systems. U.S. manufacturers have started to evaluate similar approaches. The F-gas regulation that will become effective in 2020 and 2022 will have a further impact on the use of alternative refrigerants for commercial refrigeration applications.

Recent developments in alternate refrigerants for commercial refrigeration in the United States and Europe include the following:

- In August 2012, EPA SNAP approved the use of carbon dioxide in new equipment for vending machines.[54]
- In July 2014, EPA SNAP issued a proposal to allow the use of R-290 (propane), R-600a (isobutane), and R-441A (hydrocarbon blend) in beverage vending machines.[55]
- PepsiCo has been testing vending machines that use CO_2.[56]
- EPA SNAP has approved the use of hydrocarbons in small refrigeration applications with charge limitations (up to 150g) and the use of CO_2 in vending machines without limitations.

For many of the smallest refrigeration applications (including small commercial refrigerators and vending machines), flammable refrigerants may be considered acceptable by safety standards due to the small charges required.

Intermediate refrigeration applications such as walk-in refrigerators and larger self-contained refrigeration equipment require additional research and development to transition to low-GWP refrigerants. The use of flammable refrigerants in these applications may require additional risk assessments, while use of available non-flammable alternatives requires additional research and development of equipment designs. Several A1 and A2L developmental refrigerants identified by refrigerant manufacturers may be appropriate for this equipment; these are generally blends of HFO refrigerants with either HFC-134a or HFC-32.[57]

Manufacturers sell direct expansion versions and cascade versions of supermarket refrigeration equipment. Cascade equipment has become popular in new installations. Cascade systems require the use of two refrigerants: one for the public area and a second for the central plant area. CO_2 and ammonia cascade systems have been in use in Europe,[58] and several next-generation A1 and A2L refrigerant alternatives are suitable for direct-expansion and cascade applications. The list of available alternatives is similar to those described above for intermediate applications.

Finally, while most refrigeration applications exhibit small amounts of refrigerant leakage, supermarket systems typically have the highest leakage rates among all HVAC&R equipment.[59] Thus, these systems consume large amounts of refrigerant and should be considered one of the high-priority sectors to address.

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[54] http://www.r744.com/web/assets/link/3441_2012-19688.pdf
[55] http://www.gpo.gov/fdsys/pkg/FR-2014-07-09/pdf/2014-15889.pdf
[56] http://phx.corporate-ir.net/phoenix.zhtml?c=78265&p=irol-newsArticle&ID=1270984&highlight=%20
[57] http://web.ornl.gov/sci/ees/etsd/btric/usnt/2013HeatPumpSummit/23HoneywellDeBernadiEHPS2013f.pdf
[58] Heinbokel, Bernd. "CO_2 – the natural refrigerant for MT and LT in discounters, super- and hypermarkets." August 08, 2009. Carrier.
[59] Kazachki, Georgi and Hinde, David. "Secondary Coolant Systems for Supermarkets." ASHRAE Journal, September 2006.

9.3 Stationary Air-Conditioning Applications

Figure 9.3 shows the progress toward the transition to low-GWP refrigerants for stationary air-conditioning applications.

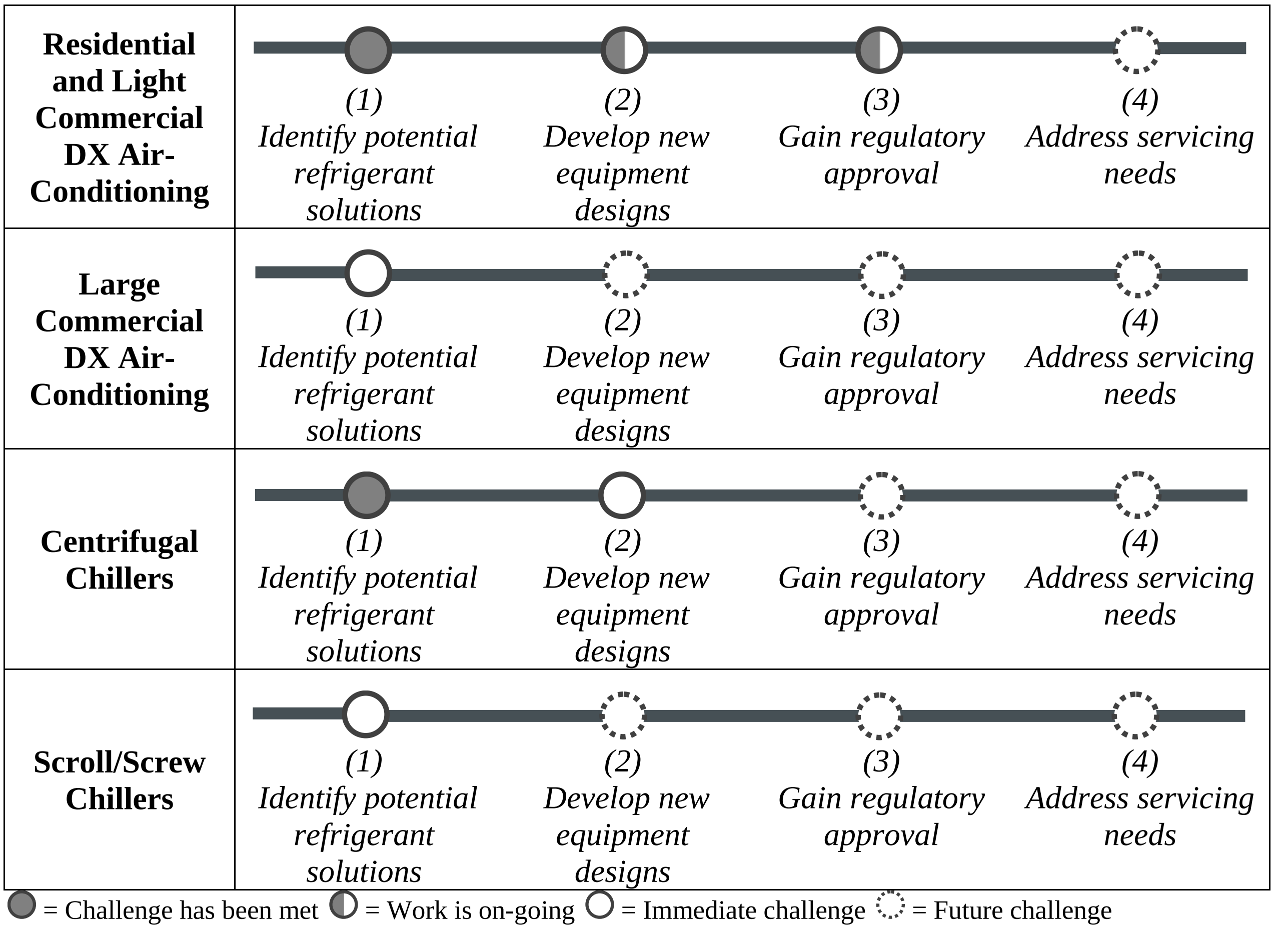

Figure 9.3: Progress towards the transition to low-GWP refrigerants for stationary air-conditioning applications

Direct Expansion Air-Conditioning

Residential and commercial direct expansion air-conditioning systems face the greatest challenges for transitioning to low-GWP refrigerants. No viable A1 next-generation alternatives have been identified for most HFC-410A systems. Direct-expansion air-conditioning equipment is often located in public areas and requires substantial amounts of refrigerant charge; these characteristics present barriers to using highly flammable or even moderately flammable refrigerants.

Japanese manufacturers such as Daikin have created lines of mini-split air conditioners using HFC-32.[60] This equipment is sold in Japan and Australia. EPA has published a proposal to allow the use of HFC-32 in a number of stationary air-conditioning applications.

[60] https://www.ejarn.com/news.asp?ID=29905

An EPA SNAP notice of proposed rulemaking, published in July 2014, proposed the following[61]:

- The use of HFC-32, R-290 and R-441A in room air conditioners, packaged terminal air conditioners, portable air conditioners, and wall-mounted and ceiling-mounted air-conditioner units, subject to charge size constraints;
- The use of R-600a and R-441A in retail food refrigeration, subject to use conditions;
- The use of R-290 in household refrigerators; and
- The use of R-290, R-600a, and R-441A in vending machines.

Additional research and development is required to identify suitable alternative refrigerants for these applications.

Chiller Applications

Chiller applications are further along in their transition to next-generation refrigerants. Refrigerant manufacturers are developing A1, A2L low-GWP alternatives for centrifugal chillers that currently use HFC-134a. A final EPA SNAP rule, published and effective in August 2012, allows the use of HFO-1234ze in centrifugal, reciprocating, and screw chillers.[62] In addition, in July 2014, Trane announced the first centrifugal chiller line using HFO-1233zd(E).[63]

Larger chiller applications do not face the same challenges as direct-expansion applications, because the refrigerant charge can be separated from public areas. This may enable the use of more hazardous non-A1 refrigerants. However, chiller applications require large amounts of refrigerant, which could pose a barrier to using highly flammable or moderately flammable refrigerants.

Smaller chiller applications, such as those for scroll and screw chillers, face larger obstacles because they use HFC-410A; currently, only A2L and hydrocarbon alternatives exist for HFC-410A applications. In July 2014, one manufacturer announced the first packaged chillers using R-1270, a hydrocarbon refrigerant.[64]

Manufacturers are currently developing chiller equipment that can use low-GWP alternative refrigerants, and further development should continue given the emergence of new HFO alternatives.

[61] http://www.gpo.gov/fdsys/pkg/FR-2014-07-09/pdf/2014-15889.pdf
[62] http://www.gpo.gov/fdsys/pkg/FR-2012-08-10/html/2012-19688.htm
[63] https://www.ejarn.com/news.asp?ID=30295
[64] http://www.hydrocarbons21.com/articles/a_first_in_north_america_r1270_chillers_successfully_installed

9.4 Equipment Service Sector

Figure 9.4 shows the progress toward the transition to low-GWP refrigerants for the equipment service sector.

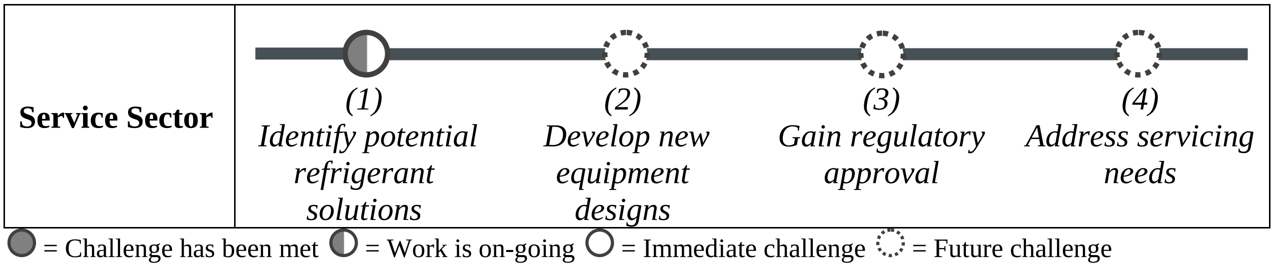

Figure 9.4 Progress toward the transition to low-GWP refrigerants for the equipment service sector

While viable alternative refrigerants have been identified for many HVAC&R equipment types, one major concern is the availability of drop-in replacements for the current installed base of equipment. Most systems currently in operation have been designed for non-flammable refrigerants and have undergone extensive material compatibility testing with their current refrigerants. It is unlikely that moderately flammable refrigerants such as HFOs or HFO blends could be used as drop-in replacements for a system designed for a non-flammable refrigerant. CO_2 is not a feasible drop-in replacement because it would necessitate a complete system redesign to accommodate its much higher operating pressure and different thermodynamic properties. Table 9.1 below shows the applications that currently have viable drop-in alternatives for service applications, and those for which no viable drop-in alternatives have been established.

Table 9.1: Summary of Availability of Drop-in Alternative Refrigerants for Each Equipment Category

Equipment Types with Viable Drop-in Alternatives Identified	Equipment Types with No Viable Drop-in Alternatives Identified
Supermarket Refrigeration Centrifugal Chillers Residential Refrigeration Self-Contained Commercial Refrigeration	Walk-in Refrigeration Residential DX A/C Commercial DX A/C Scroll/Screw Chillers

Refrigerant manufacturers are currently developing several refrigerants that could partially meet the needs of the equipment service sector. For example, one supplier has developed an A1 drop-in replacement for HFC-134a systems with a GWP value of around 600.[65] Other developmental refrigerants show promise as drop-in replacements for HFC-410A systems, although the current best available options have A2L flammability ratings and GWP values ranging from 300 to 500.[66]

[65] http://www2.DuPont.com/Refrigerants/en_US/news_events/article20101014.html

[66] "Low GWP Refrigerants for Stationary AC and Refrigeration." Thomas Leck. Purdue University Conference July 12, 2010.

Some non-flammable HFO blends could be used as drop-in replacements for HFC-404A systems. These have GWP values of approximately 1300.

To date, no A1 refrigerants have been identified as suitable drop-ins for HFC-410A equipment, which includes most air conditioning equipment. Safety concerns would likely prevent a moderately flammable refrigerant from being used in a system that was designed for a non-flammable refrigerant.

9.5 Mobile Air-Conditioning

Although not included as a covered topic in this report, developments in mobile vehicle air-conditioning have accelerated the transition to low-GWP refrigerants.

MVAC applications have begun transitioning to using HFO-1234yf.[67] A recent European directive mandating a transition for mobile vehicle air-conditioning in Europe may compel other U.S. manufacturers to do the same.[68] Both HFO-1234yf and CO_2 have achieved EPA SNAP approval for use in vehicles in the United States.[69] To support this transition, several automobile manufacturers have collaborated to design equipment and test material compatibility for HFO-1234yf in MVAC systems.

In addition, U.S. manufacturers have an incentive to adopt HFO-1234yf to comply with separate vehicle greenhouse gas standards aimed at reducing overall greenhouse gas emissions from cars.

9.6 Transport and Industrial Refrigeration

Although not included as a covered topic in this report, developments in transport and industrial refrigeration are described here.

Numerous equipment restrictions apply to transport refrigeration applications due to widely varying outdoor conditions and limited space requirements. One manufacturer has introduced CO_2 as an alternative refrigerant for container transport refrigeration equipment.[70] While other next-generation refrigerants may be technically viable for other transport refrigeration applications, much additional research and development is required to produce equipment that can withstand the unique and challenging operating conditions.

The industrial refrigeration industry typically uses ammonia as a refrigerant for large refrigeration applications. These locations implement strict safety controls to mitigate the toxicity and flammability risks. Ammonia is a low-GWP refrigerant, and therefore no alternative refrigerants are required for these applications.

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[67] "GM First to market Greenhouse Gas-Friendly Air Conditioning Refrigerant in U.S." http://media.gm.com/content/media/us/en/news/news_detail.brand_gm.html/content/Pages/news/us/en/2010/July/0723_refrigerant

[68] Mobile Air-Conditioning Directive. 2006/40/EC. May 17, 2006. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:161:0012:0018:EN:PDF

[69] http://www.epa.gov/ozone/snap/refrigerants/lists/mvacs.html

[70] http://www.carrier.com/container-refrigeration/en/worldwide/products/Container-Units/NaturaLINE/

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