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Research and Development Roadmap For Next-Generation Low-Global Warming Potential Refrigerants

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NOTICE

Research and Development Roadmap For Next-Generation Low-GWP Refrigerants

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List of Acronyms

AC or A/C	Air Conditioning
AHAM	Association of Home Appliance Manufacturers
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ARTI/AHRTI	Air-Conditioning, Heating, and Refrigeration Technology Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
CFC	Chlorofluorocarbon
CO_2	Carbon Dioxide
DOE	Department of Energy
DX	Direct Expansion
EPA	Environmental Protection Agency
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVAC&R	Heating, Ventilation, Air-Conditioning, & Refrigeration
LCCP	Life Cycle Climate Performance
MCLR	Materials Compatibility and Lubricant Research
MVAC	Mobile Vehicle Air Conditioning
ODP	Ozone Depletion Potential
ORNL	Oak Ridge National Laboratory
R&D	Research & Development
SNAP	Significant New Alternatives Program
UL	Underwriters Laboratories

Executive Summary

Refrigerants are used in a wide variety of heating, ventilation, air conditioning, and refrigeration (HVAC&R) equipment. The latest generation of refrigerants, hydrofluorocarbons (HFCs), have significant global warming potential (GWP) when released to the atmosphere.

The United States, Canada, and Mexico announced a proposal in April 2010 to phase down consumption of HFCs by 85 percent during the period 2014-2033[1] . Two recent versions of U.S. energy legislation also included this phase-down schedule. The anticipated commitment to reduce HFC consumption has stimulated interest in low-GWP alternative refrigerants.

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 ES.1** shows the business-as-usual scenario and the proposed phase-down commitment. The difference between the two demonstrates the significant challenge to implementing a phase-down of this magnitude.

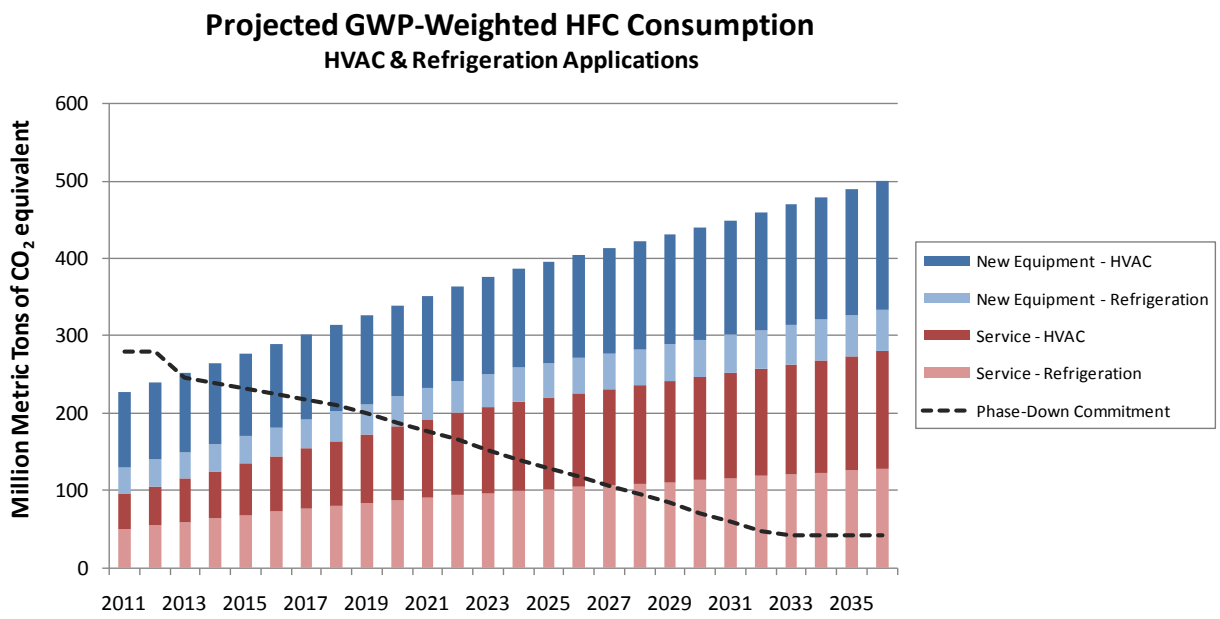

Figure ES.1: Projected GWP-weighted HFC consumption for domestic HVAC&R applications under business-as-usual scenario

Under the business-as-usual scenario, annual HFC consumption surpasses the proposed phase-down limit by 2014. After that, annual HFC consumption increases, while the phase-down target steadily decreases. As a result, achieving the proposed phase-down target becomes progressively more difficult each year. Aggressive action during the first five years of the phase-down

[1] "Proposed Amendment to the Montreal Protocol." 30 April 2010. Open-ended Working Group of the Parties to
the Montreal Protocol on Substances that Deplete the Ozone Layer: Thirtieth Meeting. Available online at http://www.epa.gov/ozone/downloads/HFCtext.pdf.

schedule would help ensure that the industry could achieve the proposed phase-down targets over the following 20 years.

Currently, five types of refrigerants have been identified as possible low-GWP alternatives to the most commonly used refrigerants today. These include:

- Low-GWP HFCs
- Hydrocarbons
- Ammonia
- Carbon dioxide
- Hydrofluoroolefins (HFOs)

Many of these alternative refrigerants suffer from one or more undesirable qualities, such as greater flammability, toxicity, or lower volumetric capacity than the HFC refrigerants they would replace.

Progress towards finding suitable low-GWP replacements varies widely by equipment type. For example, manufacturers will soon transition many new mobile vehicle air-conditioning systems to low-GWP HFO alternatives. However, no feasible low-GWP alternatives have been identified for residential and commercial air-conditioning applications, which contribute significantly to annual HFC consumption. In addition, no low-GWP alternatives have been identified as suitable drop-in replacements for the installed base of HVAC&R equipment. The servicing needs of the installed base constitute roughly half of total annual HFC consumption.

The long time periods required to develop new refrigerants and implement them in new equipment compounds the challenge to achieve a significant reduction in HFC consumption. Meeting an aggressive phase-down target such as the U.S./Canada/Mexico proposal will require an aggressive research and development program to accelerate this transition.

The U.S. Department of Energy (DOE) has a critical stake in supporting the development, evaluation, and widespread implementation of low-GWP refrigerants. During the 1990s, DOE supported the transition from ozone-depleting refrigerants to the current generation of HFCs. Similarly, DOE can play an important role in helping the HVAC&R industry transition to the next generation of low-GWP refrigerants. DOE support may involve any combination of financial, technical, or other resources.

This roadmap establishes a set of high-priority research and development (R&D) activities, supported by DOE, that will help accelerate the transition to low-GWP refrigerants across the entire HVAC&R industry. The proposed R&D activities address the major unfulfilled needs regarding the development of new refrigerants, their implementation in new equipment, and the development of drop-in replacements for the existing installed base. The schedule of R&D activities occurs within a five-year timeframe, which will accelerate the R&D activities that would likely occur at a much slower pace in the business-as-usual scenario. This aggressive schedule will enable the HVAC&R industry to achieve a significant reduction in HFC consumption over the next 20 years.

This R&D roadmap covers the following equipment types:

- Residential refrigeration
- Self-contained commercial refrigeration
- Supermarket refrigeration
- Walk-in refrigeration
- Industrial refrigeration
- Transport refrigeration
- Residential and commercial direct-expansion air conditioning
- Mobile vehicle air conditioning
- Chillers

Foam-blowing applications fall outside the scope of this roadmap. Many foam blowing applications already use low GWP fluids such as cyclopentane, so there is limited additional R&D required to commercialize them more widely.

Not-in-kind cooling technologies (i.e. non vapor compression cooling technologies such as thermoelectric, magnetic refrigeration, etc.) are another means to address the issue of reducing the direct global warming impact of air conditioning and refrigeration systems, as they use environmentally benign working fluids with very low GWP. These technologies are covered in a separate HVAC equipment R&D roadmap currently being developed by ORNL.

The R&D roadmap is organized around four primary objectives:

R&D Objective 1: Assess and mitigate safety risks
R&D Objective 2: Characterize refrigerant properties and demonstrate long-term compatibility and reliability
R&D Objective 3: Understand efficiency and environmental tradeoffs
R&D Objective 4: Support new refrigerant and equipment development

Figure ES.2 provides a high-level summary of the roadmap, followed by descriptions of each R&D Objective within the roadmap.

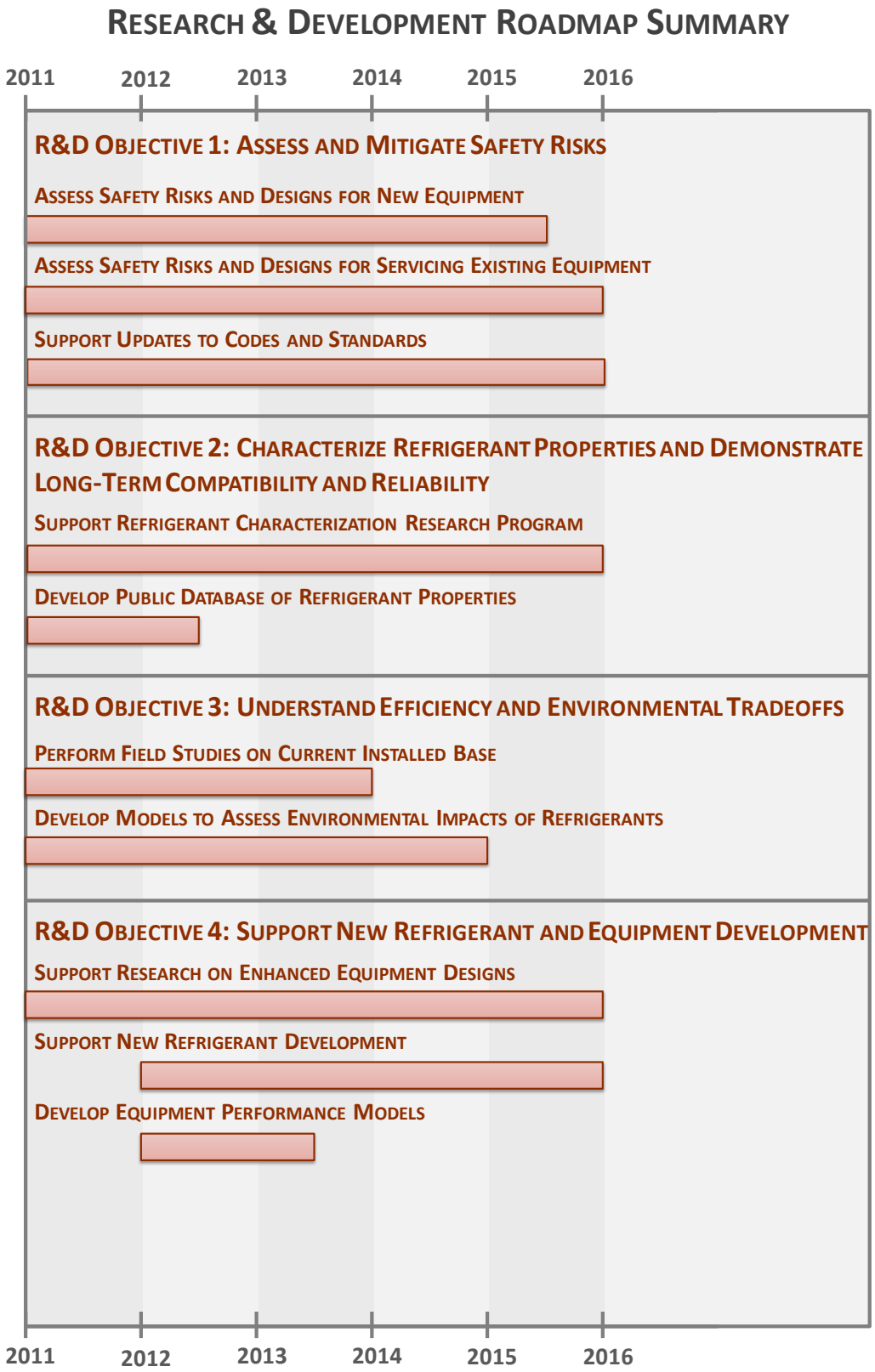

Figure ES.2: Summary of research and development roadmap

R&D Objective 1: Assess and mitigate safety risks

The activities in R&D Objective 1 seek to reduce the uncertainty regarding the safety risks associated with low-GWP refrigerants, such as flammability, toxicity, and high-pressure risks. Accurately assessing and mitigating these safety risks may enable the use of low-GWP refrigerants in higher quantities or in more applications than currently permitted. These safety assessments apply to refrigerants used in new equipment as well as drop-in replacements for the current installed base. The R&D plan recommends developing safety equipment and guidelines based on these risk assessments. DOE should use this information to support updates to applicable building codes and standards, with the goal of enabling and encouraging the more widespread use of low-GWP refrigerants in HVAC&R equipment.

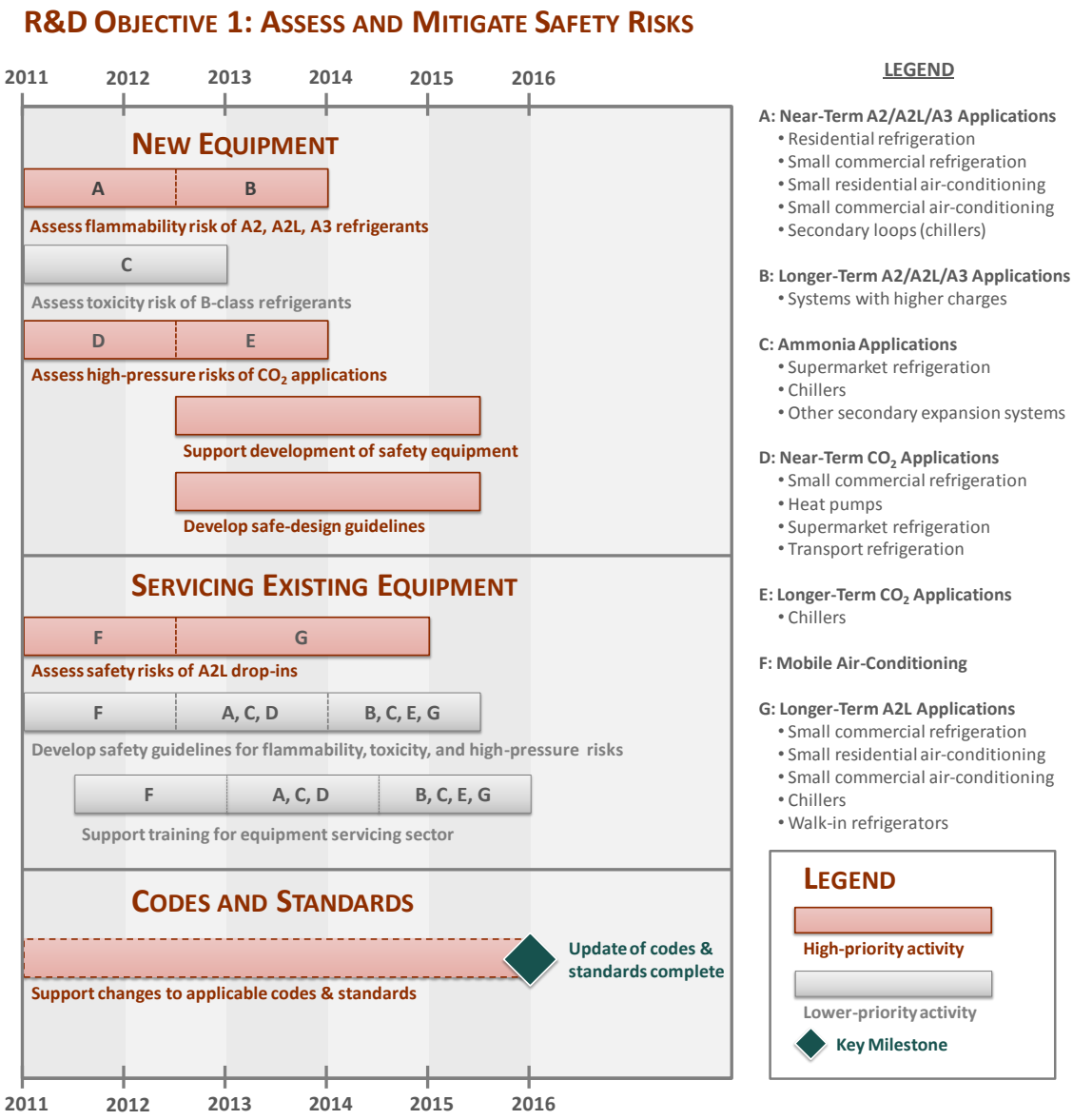

Figure ES.3: Summary of R&D Objective 1

R&D Objective 2: Characterize refrigerant properties and demonstrate long-term compatibility and reliability

The activities in R&D Objective 2 mirror those of the previous Materials Compatibility and Lubricant Research (MCLR) program during the 1990s. The new research program will characterize the thermophysical and heat transport properties of promising low-GWP refrigerants. Additional testing will reduce the uncertainty regarding the compatibility, durability, and long-term reliability of low-GWP refrigerants. These uncertainties present a significant barrier to implementing new refrigerants in HVAC&R equipment. The R&D plan also recommends supporting the development of a public database that catalogs the results from the refrigerant characterization research program. Availability of such a database would help disseminate information to the entire industry and would prevent duplication of effort.

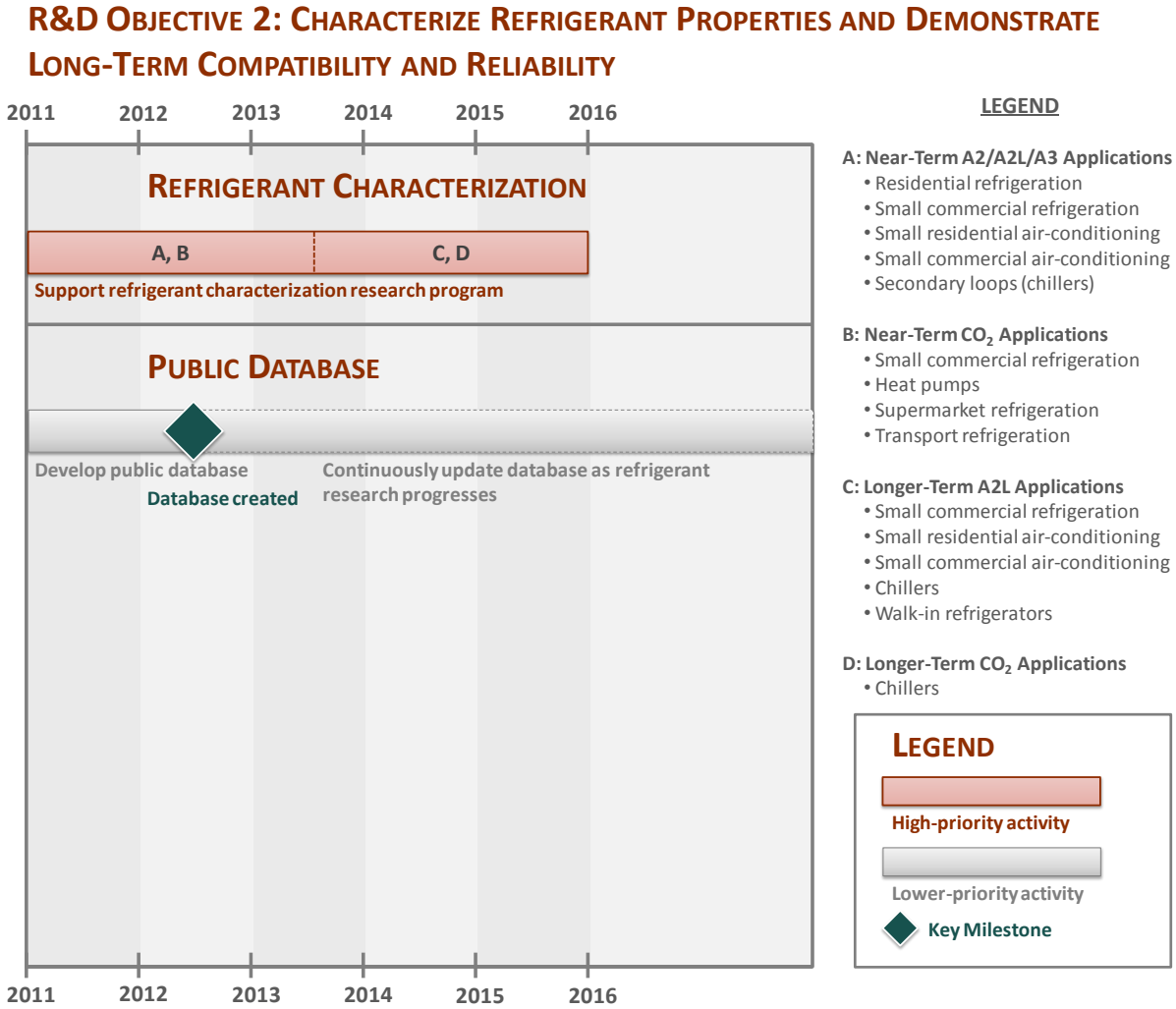

Figure ES.4: Summary of R&D Objective 2

R&D Objective 3: Understand efficiency and environmental tradeoffs

The activities in R&D Objective 3 seek to improve the understanding of higher-level tradeoffs between GWP and overall system efficiency for candidate refrigerants. While low-GWP refrigerants provide significant reduction in direct emissions, some of the most promising alternative refrigerants result in lower overall system efficiency, thus increasing indirect emissions. The R&D plan recommends supporting the development of a comprehensive life-cycle climate performance (LCCP) framework to understand and assess these environmental tradeoffs. Targeted field studies on the current installed base of equipment can provide inputs to key parameters within the LCCP models. The R&D plan also recommends developing a model to track total annual domestic HFC consumption.

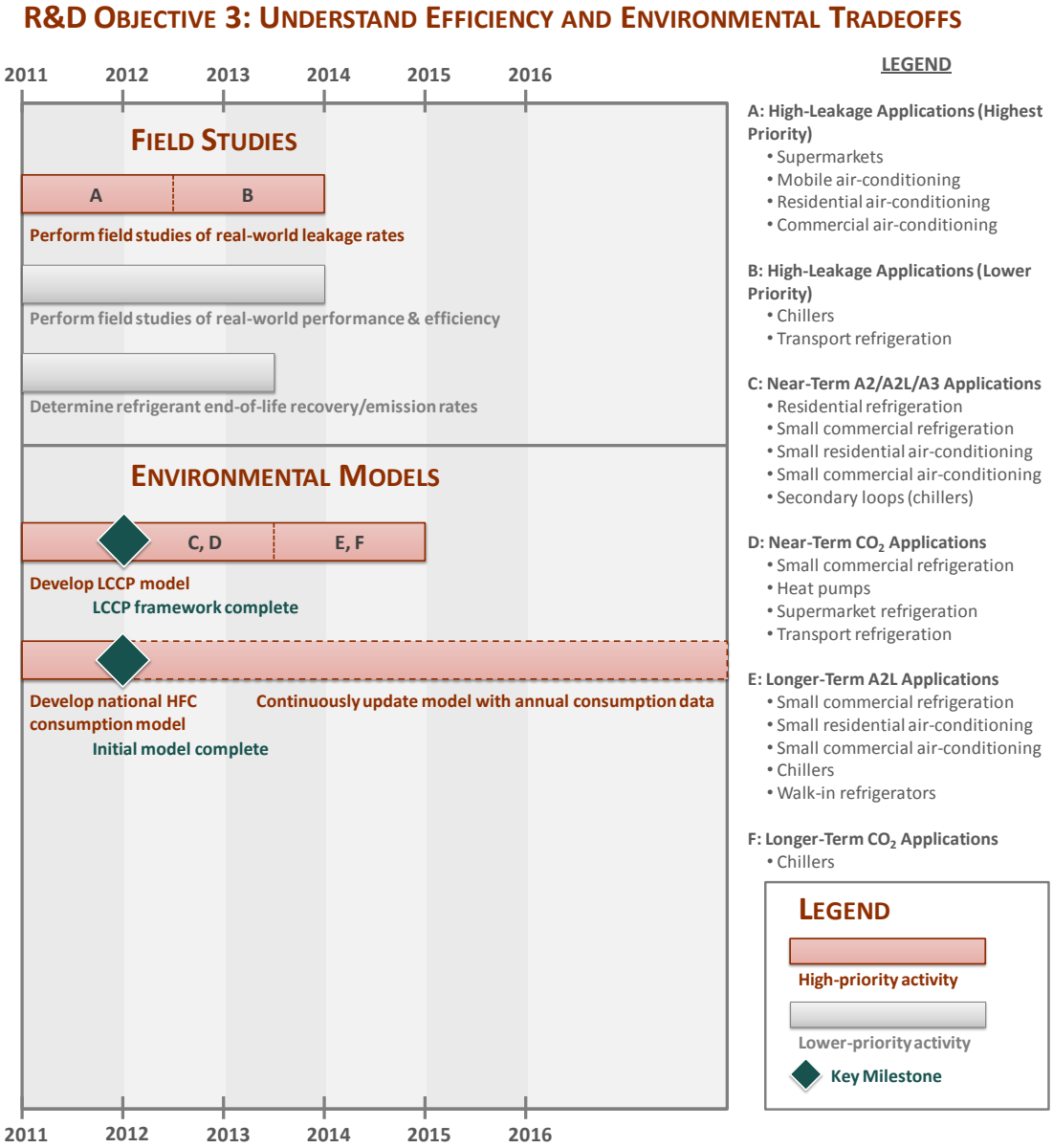

Figure ES.5: Summary of R&D Objective 3

R&D Objective 4: Support new refrigerant and equipment development

The activities in R&D Objective 4 seek to improve system-level performance of HVAC&R equipment by supporting research on equipment design and new refrigerants. Improving key aspects of equipment performance such as cycle efficiency, refrigerant leakage rates, and reduced charge quantities will increase the viability of current low-GWP alternatives and enable their use in higher-demand applications. The R&D plan recommends support for developing new low-GWP refrigerants, particularly for the stationary air conditioning service sector, where HFC-410a predominates. The plan also recommends supporting the development of publicly available equipment performance models for equipment using low-GWP refrigerants.

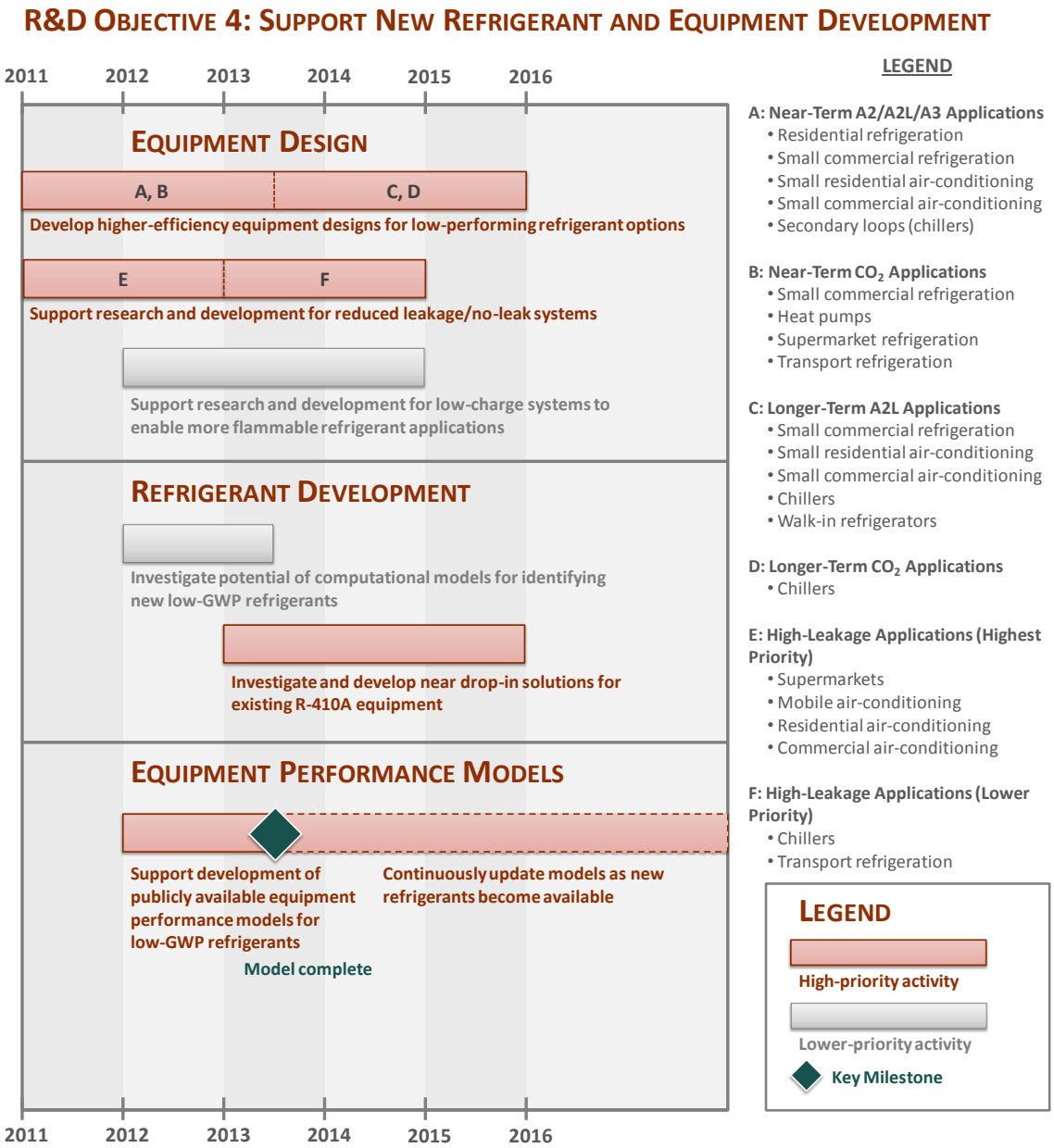

Figure ES.6: Summary of R&D Objective 4

1 Introduction

1.1 Background

Refrigerants are used in a wide variety of heating, ventilation, air conditioning, and refrigeration (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, scientists determined that CFCs and HCFCs played 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).

The United States, Canada, and Mexico announced a proposal in April 2010 to phase down consumption of HFCs by 85 percent during the period 2014-2033[2] . Two recent versions of U.S. energy legislation also included this phase-down schedule, although both bills were ultimately defeated. However, the anticipated commitment to reduce HFC consumption has stimulated interest in a fourth generation of low-GWP refrigerants.

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 1.1** shows the estimated domestic consumption of HFCs, weighted by GWP, in a business-as-usual scenario during the period 2011-2036. These estimates were derived from shipment information and equipment characteristics from the U.S. Environmental Protection Agency's (EPA) Vintaging Model[3], 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 roughly half of total annual HFC consumption, whereas servicing of installed equipment accounts for the remaining half.

[2] "Proposed Amendment to the Montreal Protocol." 30 April 2010. Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer: Thirtieth Meeting. Available online at http://www.epa.gov/ozone/downloads/HFCtext.pdf.

[3] 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.

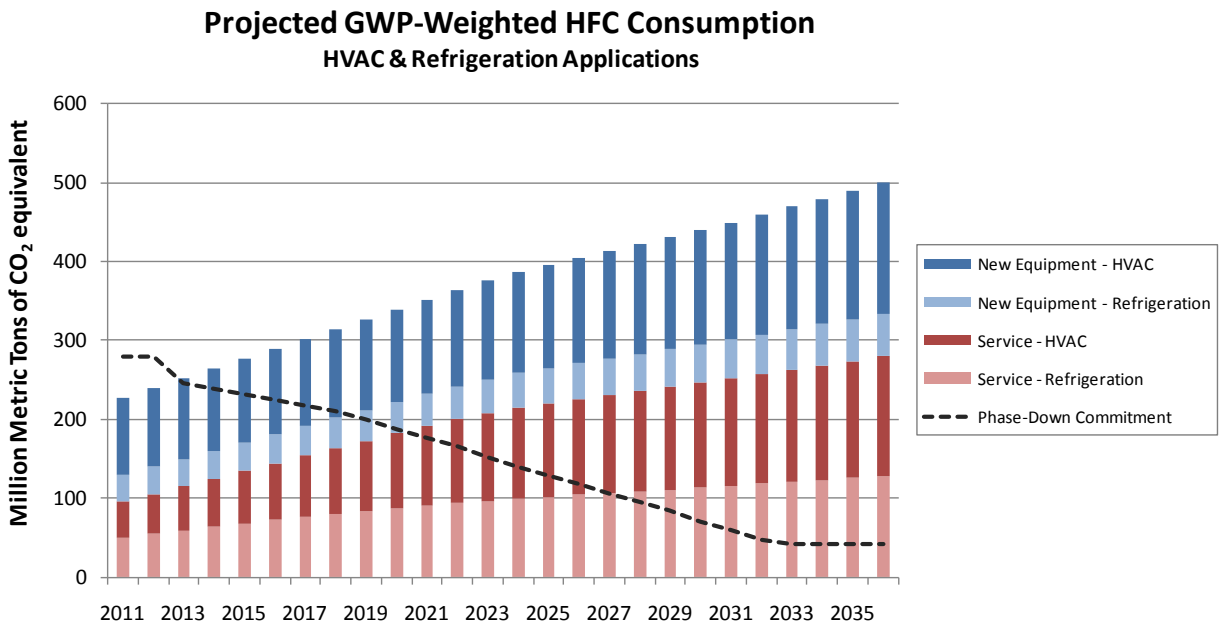

Figure 1.1: Projected GWP-weighted HFC consumption for domestic HVAC&R applications under business-as-usual scenario

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.

Under the business-as-usual scenario, annual HFC consumption surpasses the proposed phase-down limit by 2014. After that, annual HFC consumption steadily increases, while the phase-down target steadily decreases. As a result, achieving the proposed phase-down target becomes progressively more difficult each year. Aggressive action during the first five years of the phase-down schedule would help ensure that the industry could achieve the proposed phase-down targets over the following 20 years.

1.2 Previous Refrigerant Transitions

The U.S. Department of Energy (DOE) has a critical stake in supporting the development, evaluation and eventual choice of any new working fluids. Previous successful refrigerant transitions can help guide research and development activities to support the transition from HFCs to low-GWP alternatives.

During the period between 1991-2001, DOE supported the Materials Compatibility and Lubricant Research (MCLR) program, which was administered by the Air-Conditioning and Refrigeration Technology Institute (ARTI), now known as the Air-Conditioning, Heating, and Refrigeration Technology Institute (AHRTI). The MCLR program supported critical research to accelerate the introduction of CFC and HCFC refrigerant substitutes. It addressed refrigerant and lubricant properties, materials compatibility, system related issues, and test methods

development. The work was guided by the MCLR Advisory Committee, which consisted of technical experts from the refrigeration and air conditioning industry and government agencies[4].

The MCLR program conducted extensive research on the properties and materials compatibility of numerous HFC refrigerants. Properties examined included thermophysical and transport properties of refrigerants; and miscibility, viscosity, and foaming characteristics of refrigerant-lubricant mixtures. The program tested compatibility of refrigerant-lubricant mixtures with metals, motor insulating materials, elastomers, plastics, desiccants, process fluids, and lubricant additives. System-related issues studied included lubricant circulation, fractionation of blends, effects of system contaminants, products of motor burnouts, flushing and clean-out methods, the effectiveness of desiccant driers, and heat transfer enhancement technologies. Methods development research focused on the development of an accelerated method for screening the compatibility of motor insulating materials with new refrigerant-lubricant mixtures and research to improve methods for testing the flammability of refrigerants and refrigerant blends.

1.3 Objective of this Roadmap

The objective of this roadmap is to accelerate the transition to next-generation low-GWP refrigerants by targeting high-priority research and development activities. The proposed R&D activities address the major unfulfilled needs regarding the development of new refrigerants, their implementation in new equipment, and the development of drop-in replacements for the existing installed base. The schedule of R&D activities occurs within a five-year timeframe, which will accelerate the R&D activities that would likely occur at a much slower pace in the business-as-usual scenario. This aggressive schedule will enable the HVAC&R to achieve a significant reduction in HFC consumption over the next 20 years.

This R&D roadmap focuses primarily on reducing HFC *consumption*. Numerous 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 those proposed in recent U.S. energy legislation would place mandatory limits on the total annual GWP-weighted HFC *consumption*.

In addition, this R&D roadmap does not focus extensively on the energy efficiency of HVAC&R equipment. Some of the most promising alternative refrigerants result in lower overall system efficiency. In some cases, switching to low-GWP refrigerants would actually increase the total global warming impact of the system. However, as mentioned above, HFC phase-down targets as proposed would limit annual HFC consumption. Manufacturers expect to be constrained by these annual consumption limits regardless of the impact on overall efficiency. The R&D challenges associated with reducing HFC consumption are distinct from the challenges associated with improving energy efficiency. This roadmap addresses primarily the former.

[4] For more information on the MCLR program, see the AHRI website at http://www.ahrinet.org/past+programs.aspx.

This R&D roadmap covers the following equipment types:

- Residential refrigeration
- Self-contained commercial refrigeration
- Supermarket refrigeration
- Walk-in refrigeration
- Industrial refrigeration
- Transport refrigeration
- Residential and commercial direct-expansion air conditioning
- Mobile vehicle air conditioning
- Chillers

Foam-blowing applications fall outside the scope of this roadmap. Many foam blowing applications already use low GWP fluids such as cyclopentane, so there is limited additional R&D required to commercialize them more widely.

Not-in-kind cooling technologies (i.e. non vapor compression cooling technologies such as thermoelectric, magnetic refrigeration, etc.) are another means to address the issue of reducing the direct global warming impact of air conditioning and refrigeration systems, as they use environmentally benign working fluids with very low GWP. These technologies are covered in a separate HVAC equipment R&D roadmap.

1.4 Roadmap Development Process

The following provides a description of the process used to produce this roadmap:

1. Identify Application Areas and Possible Alternatives

We first determined the application areas to be addressed. We conducted a comprehensive literature survey to identify low-GWP refrigerants under consideration for each application. The scope of the literature search ranged from new refrigerants still in development to established low-GWP refrigerants in commercially available HVAC&R equipment.

2. Assess Preliminary Feasibility and Impacts

We hosted an industry forum at the International Refrigeration and Air Conditioning Conference at Purdue University to obtain preliminary feedback from industry stakeholders. We presented at an AHRTI Steering Committee meeting to enable further feedback from industry stakeholders. We conducted ten interviews with various refrigerant manufacturers, equipment and component manufacturers, and efficiency advocacy groups. Additionally, we evaluated performance and costs of low-GWP alternatives relative to today's baseline equipment using published data, presentations, and information from the interviews. Finally, we performed modeling of direct and indirect global warming impacts of identified refrigerant alternatives for each equipment type analyzed.

3. Define Research Needs

We reviewed feedback from the forum at the Purdue Conference and from the ten stakeholder interviews, and we compiled a list of R&D needs. We hosted a second public forum at the 2011

American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Winter Conference in Las Vegas to review this list and solicit further feedback. We incorporated this additional stakeholder feedback and finalized the list of R&D activities required to accelerate the commercialization of equipment using low-GWP refrigerants.

4. Create Research & Development Roadmap

We prioritized the list of R&D needs and created a roadmap with four primary objective areas. The roadmap provides a five-year schedule of R&D activities that DOE should support to accelerate the transition to low-GWP refrigerants. The roadmap serves as a guide for DOE and its partners in advancing the goal of reducing the global warming impact of HVAC&R equipment while maintaining the competitiveness of American industry.

2 Current State of the Market

The following sections describe the current state of next-generation low-GWP refrigerants and equipment. Section 2.1 describes the current state of development of low-GWP refrigerants. Section 2.2 describes the current state of development of equipment using these low-GWP refrigerants.

2.1 Current State of Low-GWP Refrigerant Development

Currently, HVAC&R equipment uses predominantly 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)
- Near-zero GWP
- High volumetric capacity

Five types of refrigerants have been identified as possible low-GWP alternatives to the most commonly used refrigerants today. These include:

- Low-GWP HFCs
- Hydrocarbons
- Ammonia
- Carbon Dioxide
- Hydrofluoroolefins (HFOs)

Many of these alternative refrigerants suffer from one or more undesirable characteristics, such as greater flammability, toxicity, or lower volumetric capacity than the HFC refrigerants they would replace.

ASHRAE Standard 34-2010[5] defines refrigerant safety group classifications based on toxicity and flammability, shown in **Figure 2.1**. 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.[6]

[5] ANSI/ASHRAE Standard 34-2007: Designation and Safety Classification of Refrigerants. Available at: http://www.ashrae.org/

[6] 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*

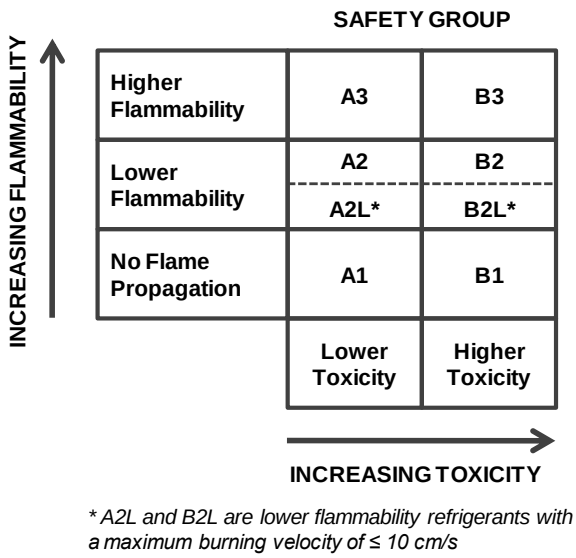

Figure 2.1: Refrigerant Safety Groupings in ASHRAE Standard 34-2010

Figure 2.2 provides an overview of the next-generation refrigerant options currently available to replace existing refrigerants.

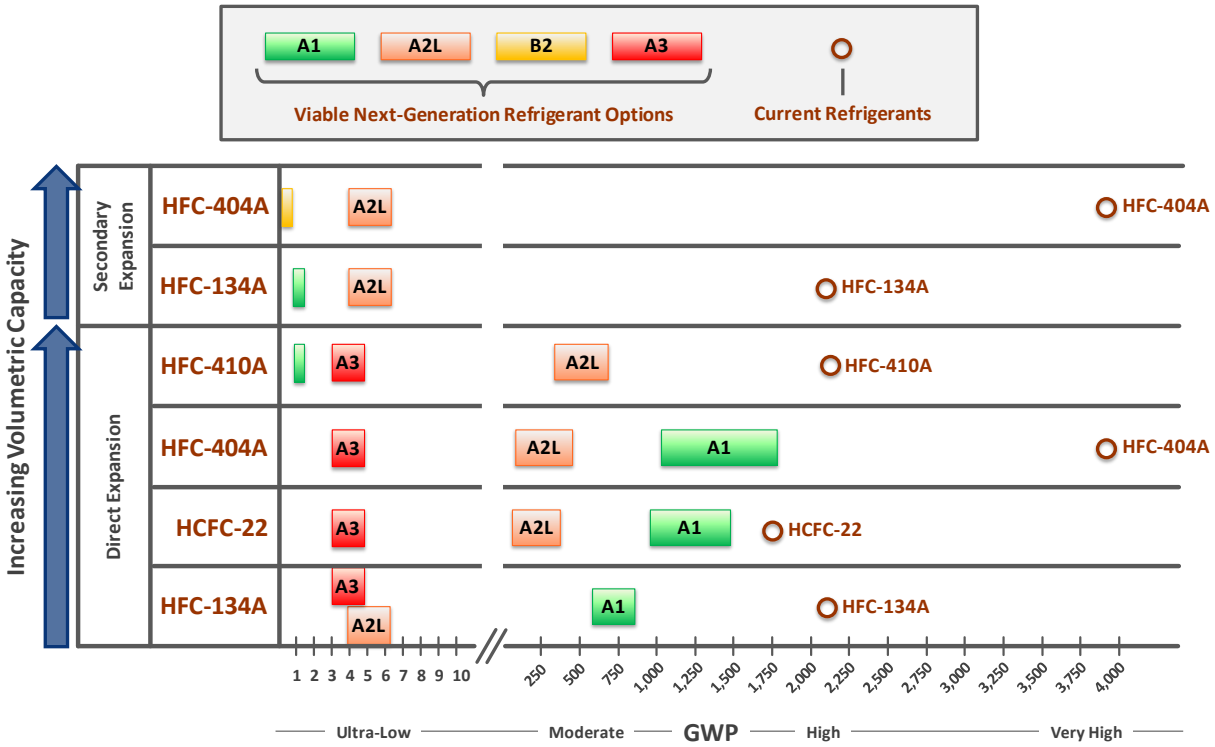

Figure 2.2: Current state of HFC/HCFC refrigerants and viable next-generation refrigerant options

The viable alternatives for each existing refrigerant have varying degrees of flammability, toxicity, and GWP. In most cases, decreasing flammability corresponds to increasing GWP. For many applications, selecting a replacement refrigerant involves a tradeoff between these two properties.

Refrigerant alternatives for lower-capacity HFC-134a applications have low or moderate GWP values, with various degrees of flammability. The A1 and A2L alternatives for these applications are most attractive. The A3 alternatives may also be acceptable in applications with small charge quantities.

The A1 and A2L alternatives for HCFC-22 and HFC-404A applications have moderate to high GWP values, making them less attractive as alternatives. The larger charge requirements for these systems may preclude the use of A3 refrigerants, despite their technical viability.

Currently, no suitable A1 alternatives exist for the highest-capacity applications such as direct-exchange air conditioning systems. Carbon dioxide refrigerant may work for smaller-capacity HFC-410A applications.

Figure 2.2 demonstrates that in general, A2L and A3 alternatives have much lower GWP values than comparable A1 alternatives. Therefore, acceptance of slightly flammable (A2L) or highly flammable (A3) fluids could have a significant impact on reducing GWP-weighted HFC consumption.

Appendix A contains a detailed list of all current and potentially viable refrigerants identified as part of the roadmap development process. The sections below describe the current state of development and implementation of each of the five types of low-GWP alternatives.

2.1.1 Lower-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 meets the criteria for classification as A2L and has a GWP of 675. HFC-152A is classified as A2 and has a GWP of 124. While these GWP values are significantly higher than other single-digit-GWP alternatives, they represent a significant improvement over current HFC refrigerants that have GWP values between 2,000 and 4,000.

HFC-32 is a versatile refrigerant that could be viable in nearly all the applications of interest. HFC-152A may be a viable replacement in commercial refrigeration applications, chillers, and industrial refrigeration; however, its A2 flammability classification poses a major barrier to adoption. HFC-32, with a safety classification of A2L, is likely to be more commercially viable.

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.

2.1.2 Hydrocarbons

The four most viable hydrocarbon refrigerants include propane, isobutane, isopentane, and propylene. These four hydrocarbons have a GWP value of 3, and they are classified as A3 refrigerants due to their high flammability. Hydrocarbons have similar volumetric capacity and performance to HFC-410A and are technically feasible replacements for many HFC-410A systems. 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 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.

Currently, the EPA is considering allowing hydrocarbons to be used in household-size refrigerators and freezers provided they comply with charge limit restrictions imposed by safety codes. At least one manufacturer plans to introduce a residential refrigerator using isobutane in 2011[7]. Propane may also be viable in small- to medium-sized stand-alone retail food refrigerators and freezers[8]. 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[9] 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 would not significantly reduce system efficiency.

2.1.3 Ammonia

Ammonia is classified as B2 and has a GWP value less than 1. 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.

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[7] http://www.appliancemagazine.com/news.php?article=1434814&zone=0&first=51

[8] "Review of Regulations and Standards for the Use of Refrigerants with GWP Values Less than 20 in HVAC&R Applications." ARTI Report No. 09001-01. William Goetzler, et al. April 2010

[9] ANSI/ASHRAE Standard 15-2007: Safety Standard for Refrigerating Systems. Available at: http://www.ashrae.org/

Ammonia has comparable efficiency to the current HFC refrigerants, so implementing ammonia as an alternative would not significantly reduce system efficiency.

2.1.4 Carbon Dioxide

Carbon dioxide (CO_2) is classified as A1 and has a GWP of 1, by definition. CO_2 has been demonstrated as a viable alternative in a number of 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. The EPA SNAP program has cited another concern about the potential lethality of carbon dioxide at high concentrations; this 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 significantly reduce system efficiency. However, transcritical CO_2 systems can raise the operating efficiency and can be used in applications such as supermarkets and vending machines. In Europe, CO_2 supermarket systems have approached the efficiency of traditional systems when used in areas with mild climates such as Denmark[10]. This approach could also prove successful in certain parts of the U.S.

2.1.5 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 is classified as A2L and has a GWP of 4. HFO-1234ze is classified as A2L and has a GWP of 6.

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 has committed to using HFO-1234yf beginning in 2013[11]. 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 refrigerant. Currently, HFO-1234ze is marketed for blowing agent and propellant applications.

[10] "Energy Consumption in Transcritical CO2 Refrigeration." Danfoss.

[11] http://media.gm.com/content/media/us/en/news/news_detail.brand_gm.html/content/Pages/news/us/en/2010/July/0723_refrigerant

Major refrigerant manufacturers are developing HFO blends suitable for applications that would traditionally use HCFC-22, HFC-404A, and HFC-410A. 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 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 HFC-123[12]. 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 will not be viable as a drop-in replacement for most HCFC-123 applications.

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 one major refrigerant manufacturer is developing HFO-based A2L refrigerant blends that can substitute for HFC-410A; these have GWP values ranging from 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[13]. Therefore, implementing HFOs as a replacement for HFCs requires a tradeoff between GWP and system efficiency.

2.2 Current State of Equipment Development

This section describes the current state of development of equipment using low-GWP refrigerants. Section 2.2.1 provides a summary of key equipment characteristics. Section 2.2.2 provides a summary of the development progress for each type of equipment.

[12] 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.

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

2.2.1 Summary of Equipment Characteristics

Nearly all HVAC&R equipment relies on vapor-compression systems to provide heat transfer. Refrigerant charge varies widely by equipment type. Total refrigerant consumption depends on the equipment's refrigerant charge size and leakage rate. Generally, applications that require larger cooling loads require larger amounts of refrigerant. These applications require large amounts of refrigerant at the time of manufacture. During operation, refrigerant may leak from the system. Many types of equipment require periodic servicing to replenish this lost refrigerant. Equipment types with significant leakage rates consume large amounts of refrigerant due to servicing. **Table 2.1** provides typical lifetimes, charge sizes, and leakage rates for the equipment categories included in this roadmap[14,15].

Table 2.1: Typical lifetimes, charge sizes, and leakage rates for HVAC&R equipment

Equipment Type	Lifetime (yrs)[a]	Charge Size (kg)[b]	Leakage Rate (%/year)[a]
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
Transport Refrigeration	12	6.4	20.6 – 27.9
Industrial Refrigeration	25	1,000 – 2,600	3.6 – 12.3
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
Mobile Vehicle Air Conditioning	5 – 12	0.9	2.3 – 18.0

a. 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
b. Source: EPA Vintaging Model

2.2.2 Summary of Low-GWP Equipment Development

Progress toward implementing low-GWP refrigerants in new equipment varies widely by equipment type.

Table **2.2** summarizes the progress made toward the transition to low-GWP refrigerants for the equipment types listed in Table 2.1. The table categorizes the development process as follows:

[14] 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
[15] EPA Vintaging Model

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 2.2: 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	◐	○	◌	◌	○
Transport Refrigeration	◐	○	◌	◌	○
Industrial Refrigeration	●	●	●	●	●
Residential A/C	○	◌	◌	◌	○
Commercial A/C	○	◌	◌	◌	○
Centrifugal Chillers	◐	○	◌	◌	◐
Scroll/Screw Chillers	○	◌	◌	◌	○
Mobile Vehicle A/C	●	●	●	○	○

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

As shown in
Table 2.2, mobile vehicle air-conditioning and industrial refrigeration applications have made the most significant progress toward the transition to low-GWP refrigerants. Residential and commercial air-conditioning applications and scroll/screw chillers lag furthest behind in the transition.

The sections below provide additional details on each equipment application's progress toward the transition to low-GWP alternative refrigerants.

Residential Refrigeration

Figure 2.3 shows the progress toward the transition to low-GWP refrigerants for residential refrigeration applications.

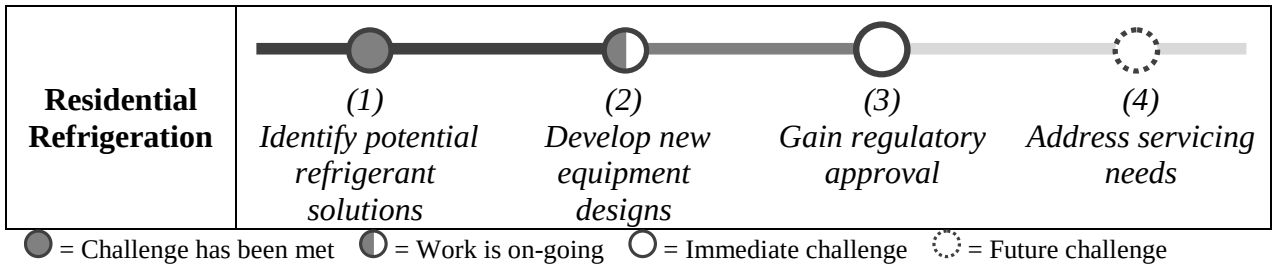


Figure 2.3: Progress toward the transition to low-GWP refrigerants for residential refrigeration applications

Current residential refrigeration equipment uses HFC-134a, for which several low-GWP alternatives exist. Residential refrigerators that use hydrocarbons have been available in Europe for several years.

Several recent developments have increased the likelihood that alternate refrigerants will be used in residential refrigeration. In the United States, the EPA SNAP program published a proposed rule for comment in May 2010 to approve use of four hydrocarbon refrigerants in household refrigerators and freezers (up to 57 g)[16]. In addition, General Electric has been developing a hydrocarbon residential refrigerator, which uses isobutane, and submitted an application for EPA SNAP approval[17]. Finally, UL has investigated changes to UL 250, its safety standard for household refrigerators and freezers, that would allow larger amounts of A3 refrigerant charge in household refrigerators (currently 50 g). The combination of these actions may help accelerate further development of hydrocarbon systems for residential refrigeration.

HFO-1234yf has been identified as a replacement for HFC-134a, and could be a less flammable refrigerant option for future refrigerator and freezer designs.

Commercial Refrigeration

Figure 2.4 shows the progress toward the transition to low-GWP refrigerants for commercial refrigeration applications.

[16] http://www.gpo.gov/fdsys/pkg/FR-2010-05-10/pdf/2010-10959.pdf

[17] "GE will introduce a green refrigerator – hydrocarbons are more environmentally friendly." January 6, 2011. CGE Consulting. http://www.cgeconsulting.com/pollutants/ge-will-introduce-a-green-refrigerator-hydrocarbons-are-more-environmentally-friendly/

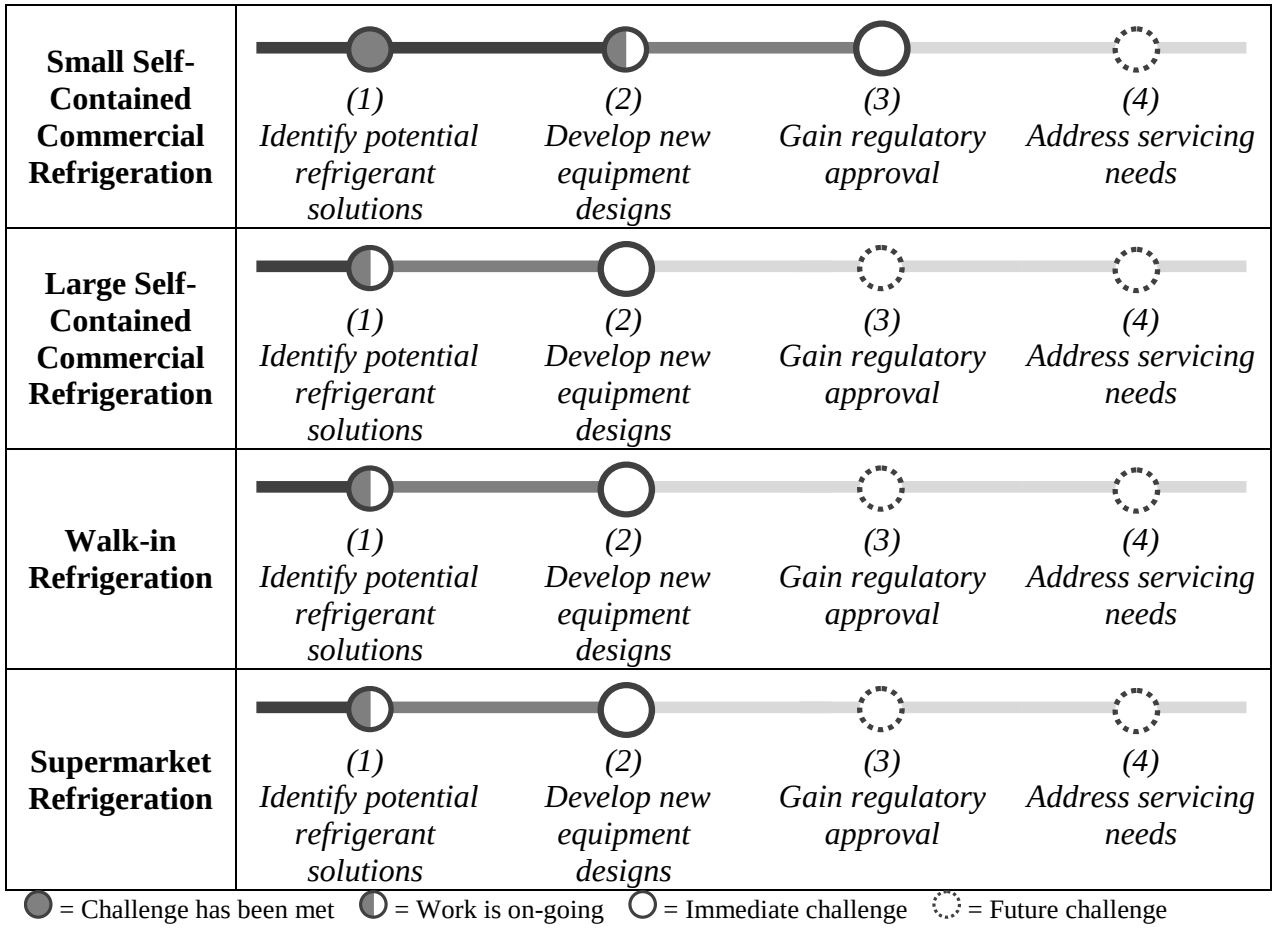


Figure 2.4: Progress toward the transition to low-GWP refrigerants for commercial refrigeration applications

Next-generation refrigerants show the most short-term promise in small and intermediate refrigeration applications. Current refrigeration equipment typically uses HFC-134a, for which several low-GWP alternatives exist. The European residential refrigeration market already uses 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.

In 2008, Ben and Jerry's ice cream company submitted a petition to the U.S. EPA to use propane refrigerant in ice-cream freezers, based on extensive safety data and commercial experience with hydrocarbon freezing technology in Europe[18]. In addition, PepsiCo has been testing a small

[18] Dominguez, A. "Ben and Jerry's, GE work on greener freezers for the US," Denver Post, 27 Sept 2009. Available at http://www.denverpost.com/greenbusiness/ci_13433294.

sample of vending machines that use CO_2 in the Washington D.C. area. These tests will provide safety and reliability data for future EPA SNAP approval[19].

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

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[20], and several next-generation A1 and A2L refrigerant alternatives are suitable for direct-expansion and cascade 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[21]. Thus, these systems consume large amounts of refrigerant and should be considered one of the high-priority sectors to address.

Transport and Industrial Refrigeration

Figure 2.5 shows the progress toward the transition to low-GWP refrigerants for transport and industrial refrigeration applications.

[19] Geller 2009. "PepsiCo Test Green Vending Machines," Reuters, accessed 7 Dec 2009, http://www.pepsico.com/Articles/Pepsi-tests-green-vending-machines.html.
[20] Heinbokel, Bernd. "CO_2 – the natural refrigerant for MT and LT in discounters, super- and hypermarkets." August 08, 2009. Carrier.
[21] Kazachki, Georgi and Hinde, David. "Secondary Coolant Systems for Supermarkets." ASHRAE Journal, September 2006.

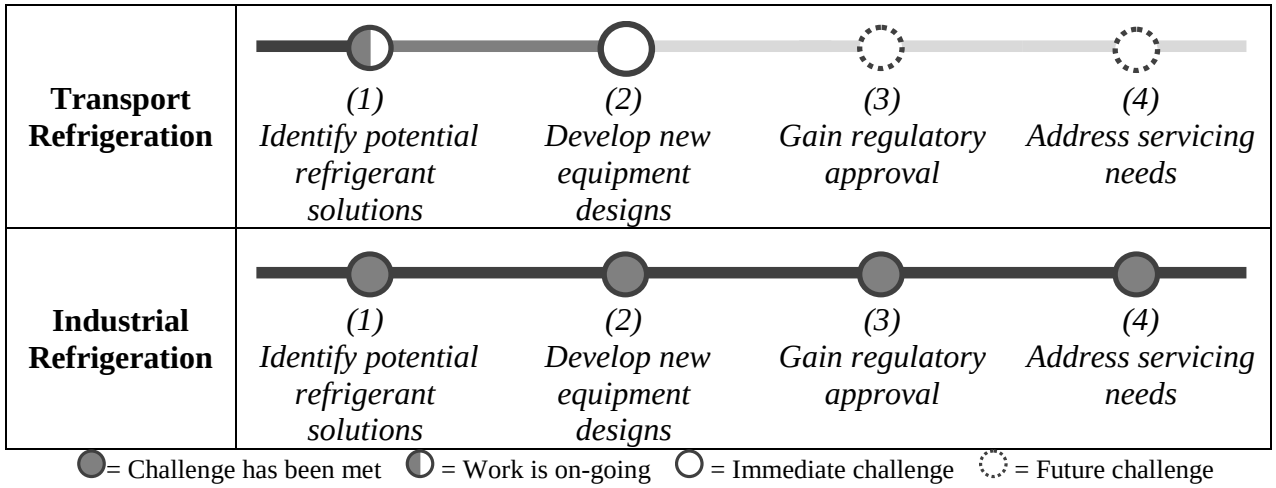


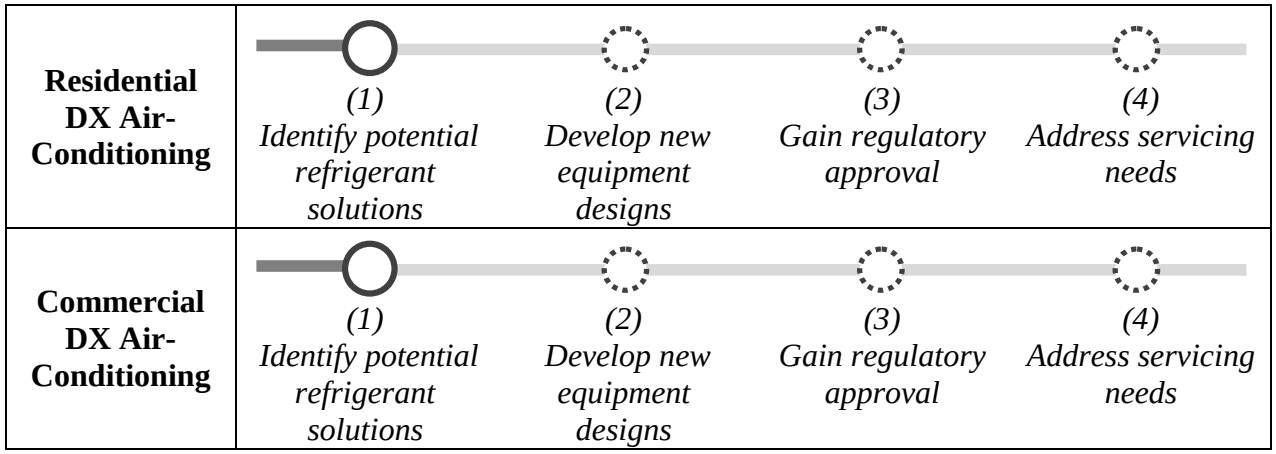
Figure 2.5: Progress toward the transition to low-GWP refrigerants for transport and industrial refrigeration applications

Numerous equipment restrictions apply to transport refrigeration applications due to widely varying outdoor conditions and limited space requirements. Some manufacturers have started investigating alternative refrigerants such as carbon dioxide for transport refrigeration equipment. While some next-generation refrigerants may be technically viable for 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.

Stationary Air-Conditioning Applications

Figure 2.6 shows the progress toward the transition to low-GWP refrigerants for stationary air-conditioning applications.



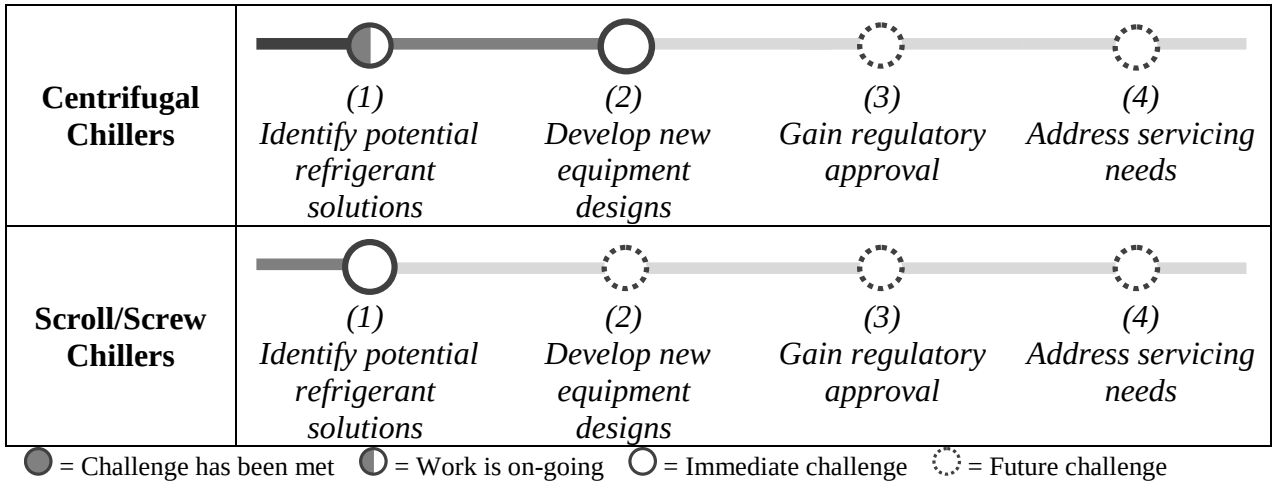


Figure 2.6: Progress towards the transition to low-GWP refrigerants for stationary air-conditioning applications

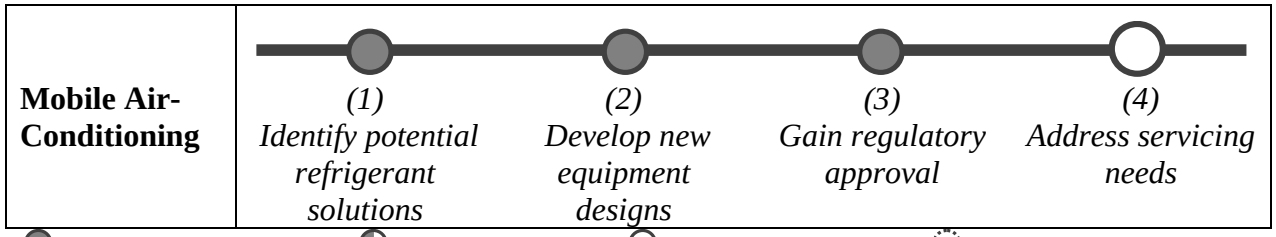
Residential and commercial direct expansion (DX) air-conditioning systems face the greatest challenges for transitioning to low-GWP refrigerants. Other than CO_2 systems with limited applications, no A1 next-generation alternatives have been identified for HFC-410A systems. Direct-expansion air-conditioning 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. Additional research and development is required to identify suitable alternative refrigerants for these applications.

Chiller applications are further along in their transition to next-generation refrigerants. Refrigerant manufacturers are currently developing A1 and A2L low-GWP alternatives for centrifugal chillers that currently use HFC-134a. Smaller chiller applications, such as those for scroll and screw chillers, face larger obstacles because they use HFC-410A; currently, only A2L alternatives exist for HFC-410A applications.

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. Further research and development is required to develop chiller equipment that can use low-GWP alternative refrigerants.

Mobile Air-Conditioning

Figure 2.7 shows the progress toward the transition to low-GWP refrigerants for mobile vehicle air-conditioning applications.



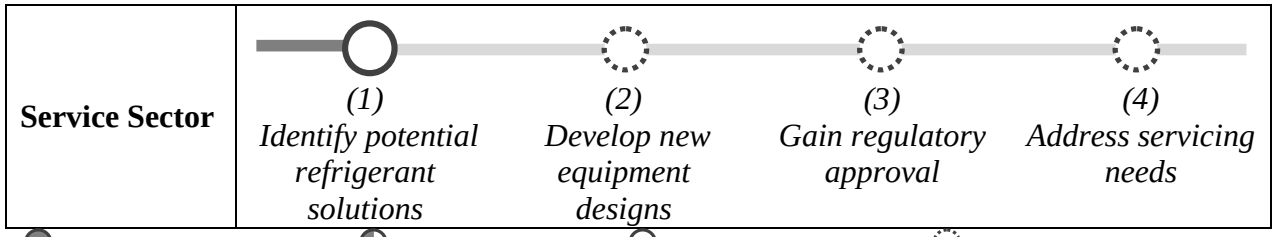
= Challenge has been met = Work is on-going = Immediate challenge = Future challenge

Figure 2.7: Progress toward the transition to low-GWP refrigerants for mobile vehicle air-conditioning applications

Mobile vehicle air-conditioning applications are quickly transitioning to using HFO-1234yf. One U.S. automobile manufacturer has already announced plans to transition to this refrigerant[22]. A recent European directive mandating a similar transition for mobile vehicle air-conditioning in Europe may compel other U.S. manufacturers to do the same[23]. Both HFO-1234yf and CO_2 have achieved EPA SNAP approval for use in vehicles in the United States[24]. To support this transition, several automobile manufacturers are collaborating to design equipment and test material compatibility for HFO-1234yf in MVAC systems.

Equipment Service sector

Figure 2.8 shows the progress toward the transition to low-GWP refrigerants for the equipment service sector.



= Challenge has been met = Work is on-going = Immediate challenge = Future challenge

Figure 2.8: 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 unclear whether moderately flammable refrigerants such as HFOs or HFO blends could be used as drop-in replacements for a system designed for a non-flammable

[22] "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

[23] Mobile Air-Conditioning (MAC) 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

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

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 2.3 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 2.3: 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 Industrial Refrigeration Centrifugal Chillers	Residential Refrigeration Self-Contained Commercial Refrigeration Walk-in Refrigeration Transport Refrigeration Residential DX A/C Commercial DX A/C Scroll/Screw Chillers Mobile Vehicle A/C

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[25]. 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[26].

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

[25] http://www2.DuPont.com/Refrigerants/en_US/news_events/article20101014.html.
[26] "Low GWP Refrigerants for Stationary AC and Refrigeration." Thomas Leck. Purdue University Conference July 12, 2010.

3 Research & Development Roadmap

This section presents research and development roadmaps for each of the four R&D Objectives. Each roadmap highlights the activities that DOE should support to enable the transition to low-GWP alternative refrigerants across the entire HVAC&R industry. DOE support may involve any combination of financial, technical, or other resources. The roadmap is designed to enable this transition on the time scale necessary to achieve a significant phase-down of HFC consumption over the next 20 years.

New refrigerants and equipment designs require years of development, testing, and approvals. **Table 3.1** shows some typical time periods required for various steps in the refrigerant and equipment development process.

Table 3.1: Typical time required for various steps in refrigerant/equipment development process

Steps in Refrigerant/Equipment Development Process	Typical Time Required*
EPA SNAP Approval	1-4 years
Building Code Changes	3-5 years
Development of Blends of Existing Refrigerants	1-3 years
Development of New Refrigerants	6-10 years
Development of New Equipment	6-13 years

*Source: Alliance for Responsible Atmospheric Policy, *Issues/Criteria for "Decision Tree" Development for Developing Country HCFC Phaseout Management Plans, Considering Potential HFC Controls, 2010.*

Because of these long timelines, many of the R&D activities presented in the following roadmaps occur within the next five years, with some occurring even sooner. Achieving an aggressive HFC phase-down schedule such as the proposal put forth by the U.S, Canada, and Mexico requires an equally aggressive R&D program beginning as soon as possible.

Figure 3.1 shows a condensed timeline of the four roadmaps. The following sections provide additional details on the R&D roadmaps for each R&D Objective.

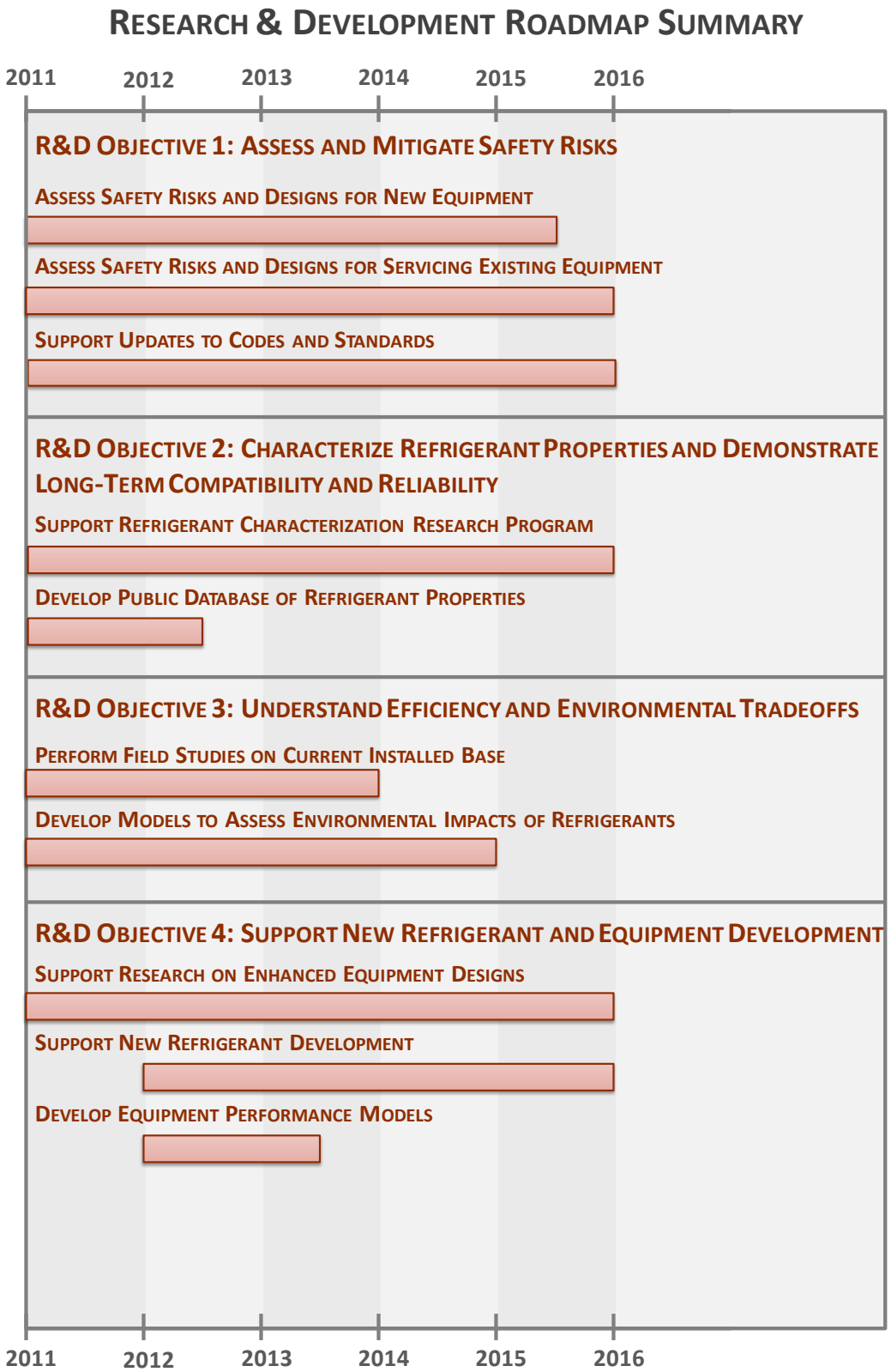


Figure 3.1: Summary of research and development roadmap

3.1 Roadmap for R&D Objective 1: Assess and Mitigate Safety Risks

The goal of R&D Objective 1 is to reduce the safety risks associated with using low-GWP refrigerants. Adequately characterizing and mitigating safety risks (e.g. flammability, toxicity, and high-pressure risks) can present a significant barrier for new refrigerants.

As depicted in **Figure 3.2**, an optimum alternative refrigerant has both a low safety risk and a high level of technical performance. The recommended programs in R&D Objective 1 seek to reduce the safety risks associated with low-GWP alternative refrigerants. As safety assessments are conducted and safer equipment designs are developed, the safety risks associated with certain refrigerants will decrease, and the refrigerants will become more acceptable for use.

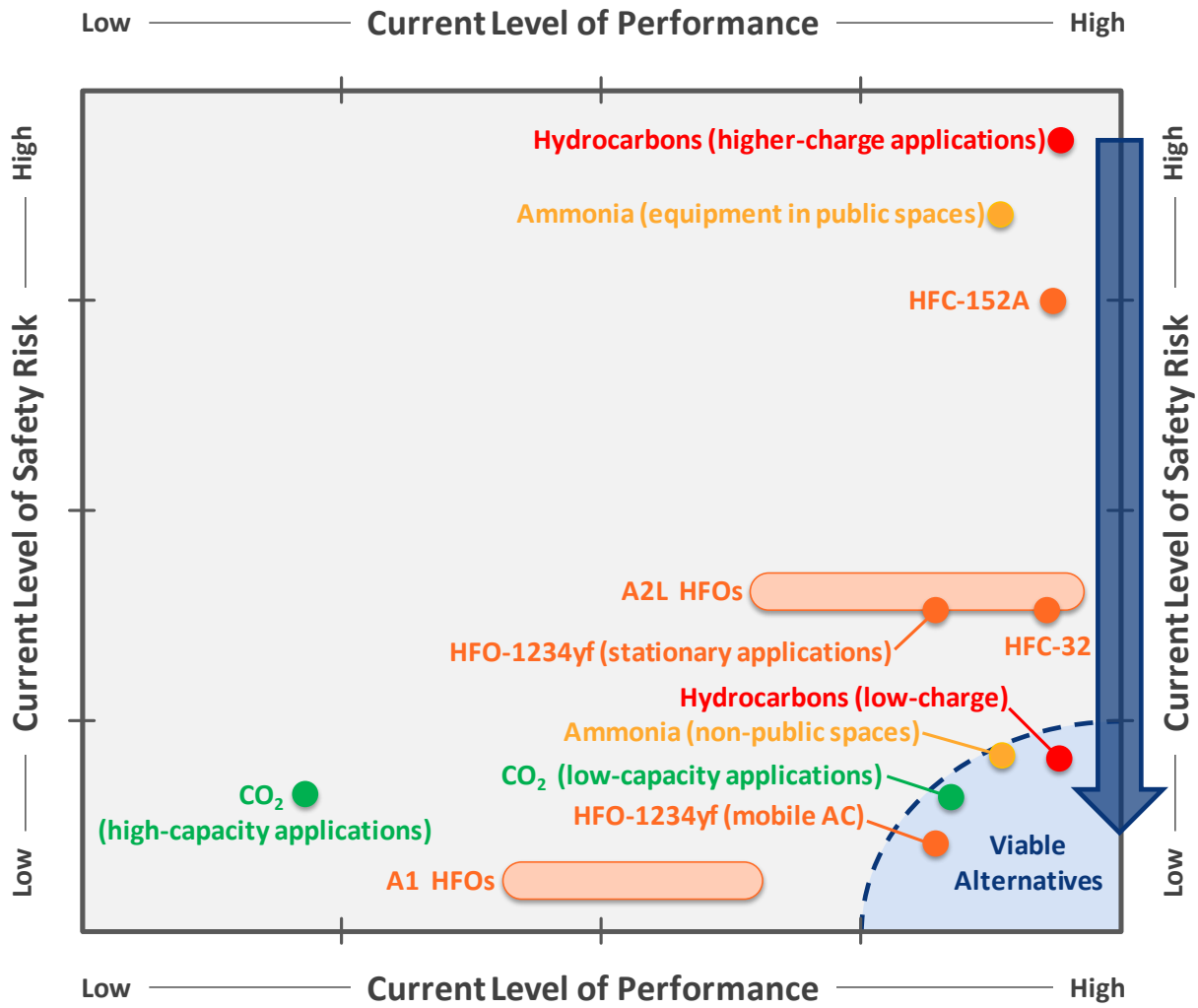


Figure 3.2: Reducing refrigerant safety risks to enable more viable refrigerant alternatives

The figure shows that several A2L, A2, and A3 refrigerants are not considered viable alternatives due to their current safety risks. However, with the proper testing, design guidelines, and safety

regulations, each of these refrigerants could be considered viable alternatives in specific applications. For example, the following applications of non-A1 refrigerants are considered viable despite safety concerns regarding these refrigerants in general:

- Hydrocarbon equipment with low charge quantities
- Ammonia equipment in non-public spaces
- HFO-1234yf in mobile vehicle air conditioning

Accurately assessing and mitigating the safety risks involved may enable the use of low-GWP refrigerants in higher quantities and in more applications than currently permitted. These assessments are particularly important for flammable refrigerants. Many low-GWP refrigerant alternatives are flammable, and without accurate assessment and mitigation of flammability risks, manufacturers may be required to use refrigerants with much higher GWPs.

Important action items that will enable use of flammable, toxic, and high-pressure refrigerants include the following:

- Performing risk assessments that accurately quantify the risks associated with these refrigerants and identifying circumstances under which their use may be acceptable
- Developing guidelines on safe use, handling, and operation of equipment using these refrigerants
- Updating codes and standards to reflect quantified risk levels and new safety measures

Figure 3.3 below shows the research and development roadmap for R&D Objective 1.

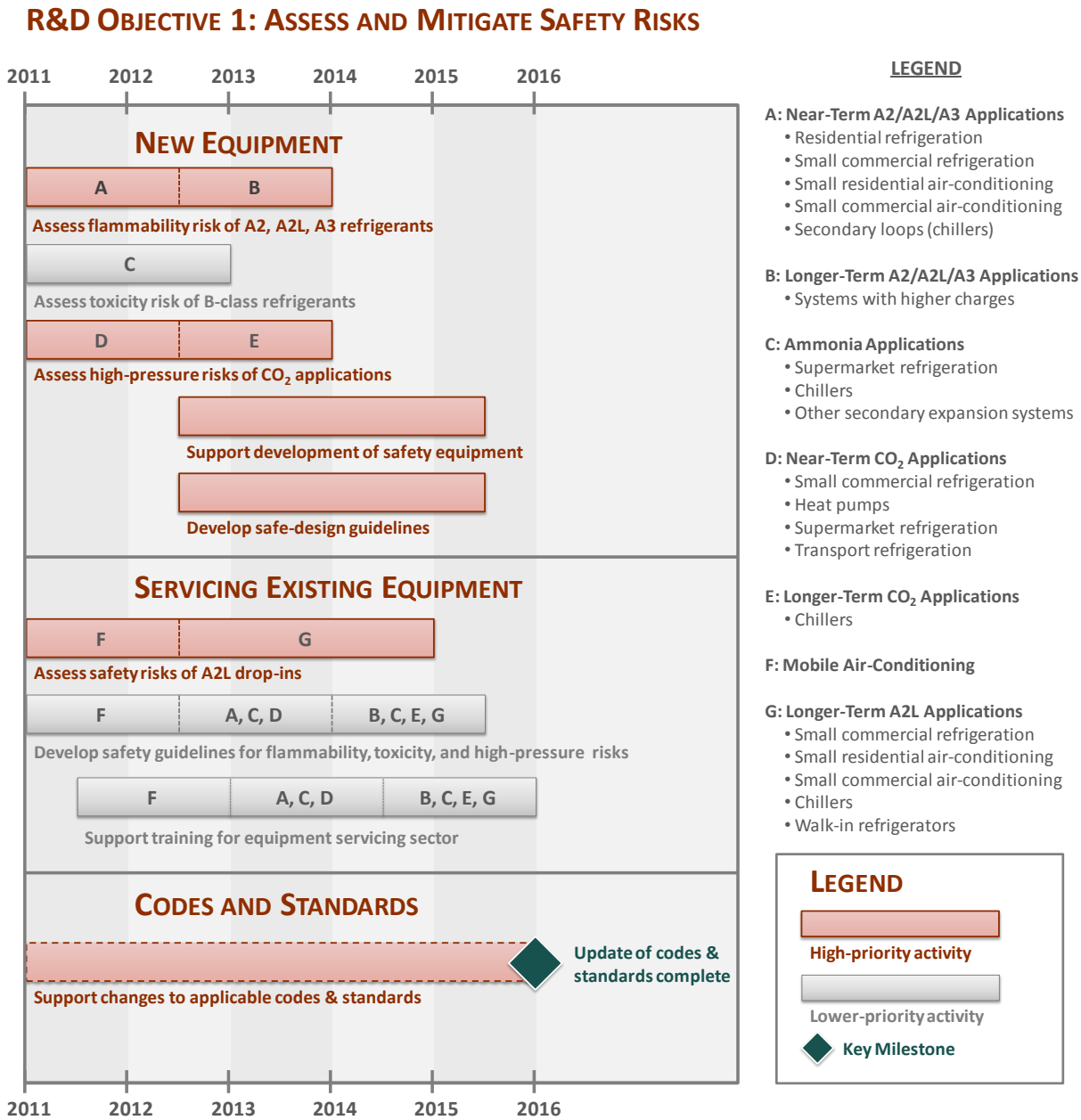


Figure 3.3: Roadmap for R&D Objective 1

The plan recommends performing risk assessments for both new and installed equipment, followed by developing guidelines and safety measures based on those assessments. Concurrently, DOE should support updates to relevant codes and standards based on the acquired body of knowledge, with the goal of enabling and encouraging more widespread use of next-generation refrigerants in HVAC&R equipment.

Priority should be given to risk assessments for A2L and A3 refrigerants in both new equipment and the equipment service sector, along with development of safety guidelines and equipment for

applications identified as viable by the risk assessments. These assessments can be performed using currently available low-GWP refrigerants and equipment, and should begin immediately to achieve a milestone of updating all relevant codes and standards by 2016. The following sections provide additional details about each program element.

3.1.1 Safety Assessments and Development of New Equipment

DOE should address three aspects of refrigerant safety that pose barriers to implementing low-GWP refrigerants: analysis of the safety risks, development of safety equipment, and development of safety guidelines. The overall objective of these programs is to enable the use of low-GWP refrigerants in new equipment applications where they are currently considered infeasible due to safety concerns. The proposed R&D programs are as follows:

- *Assess flammability risks of A2L, A2, and A3 refrigerants* – Several low-GWP refrigerant options are classified as either slightly flammable (A2L) or highly flammable (A2 and A3), including most HFOs and all hydrocarbon refrigerants. Other than flammability concerns, many of these refrigerants meet desired performance and GWP criteria. Current codes and standards, as well as manufacturing best practices, forbid the use of flammable refrigerants in most HVAC&R equipment. One way to enable the use of these refrigerants is to conduct risk assessments that determine applications and circumstances under which flammable refrigerants can be used safely.

  DOE should begin conducting these risk assessments immediately for systems with smaller charge quantities, for which using A2L and A3 refrigerants may be most feasible. These include residential refrigeration, small self-contained commercial refrigeration and small residential and commercial air conditioning. Secondary loops for chillers should also be assessed early, because flammable refrigerants may be acceptable in these systems. Assessment of these near-term applications should be completed by 2012. Assessment of other applications with higher charge quantities should follow, with all safety assessments completed by the end of 2014. These flammability risk assessments should be considered high-priority.

- *Assess toxicity risks of B-class refrigerants* – Current codes and standards, as well as manufacturing best practices, restrict the use of toxic refrigerants in many HVAC&R equipment applications. Ammonia, in particular, is a toxic refrigerant with desirable GWP and thermodynamic properties. Its primary use is in large industrial applications. One way to enable to use of ammonia in smaller, more public applications is by conducting risk assessments that determine the applications and circumstances under which toxic refrigerants could be used safely.

  DOE should begin conducting these risk assessments immediately on applications for which the use of toxic refrigerants may be most acceptable. These include supermarket systems, chillers, and secondary expansion equipment. DOE should target completion of these assessments by 2013. Because of the potentially limited number of new applications for ammonia, these toxicity risk assessments are lower priority.

- *Assess high-pressure risks of CO_2 applications* – Current codes and standards have highly restrictive safety requirements for high-pressure refrigerants. Equipment using carbon dioxide as a refrigerant requires much higher refrigerant pressures than commonly found in current equipment, in addition to the large safety factor required. DOE should conduct risk assessments of applications using CO_2 to help determine appropriate safety measures and safety factors for equipment. In the near-term, DOE should focus first on applications that show the most promise with CO_2. These include small commercial refrigeration, heat pumps, supermarket refrigeration, and transport refrigeration systems. Following that, DOE should assess other more challenging applications for which CO_2 may be viable, such as chillers. This program should begin immediately with the near-term applications completed by 2012. Assessments of longer-term applications should be completed by 2014. Because of the significant potential for the expanded use of CO_2 refrigerant in these applications, these risk assessments should be considered high priority.

- *Support development of safety equipment* – The risk assessments described above may identify the need to develop appropriate safety equipment or designs that enable the use of flammable, toxic, or high-pressure next-generation refrigerants. DOE should support research and development of safety equipment and designs that mitigate the identified risks of using these refrigerants. These studies should also include research on the performance impacts of using such safety equipment. The initial program should begin in mid-2012, after the initial risk assessments are complete, and research and development should continue until early 2015. Because developing safety equipment will be critical to accelerating the implementation of low-GWP refrigerants, this activity should be considered high priority.

- *Develop equipment design guidelines* – As best practices and appropriate safety measures are identified, DOE should develop guidance documents that summarize this information in a consistent manner. These documents should be made available to the HVAC&R industry. They will provide information about the risks associated with using alternative refrigerants and about best practices that can help ensure safety. These documents could help promote public acceptance of new refrigerants and accelerate adoption by industry. The guidelines could also be adopted by codes and standards organizations. Immediate documents should focus on current applications such as mobile vehicle air-conditioning. The program focus should then shift to near-term applications that use flammable, toxic, and high-pressure refrigerants. Because the development of these equipment design guidelines will be critical to accelerating the implementation of low-GWP refrigerants, this activity should be considered high priority.

3.1.2 Safety Assessments and Guidelines for the Equipment Service sector

DOE should support research on refrigerant safety for issues related to the use, handling, and transportation of low-GWP refrigerants for equipment already in the field. The overall objective of these programs is to enable the use of low-GWP refrigerant in equipment servicing applications where it is currently considered infeasible due to safety concerns. The proposed R&D programs are as follows:

- *Assess safety risks for A2L drop-ins* – While transitioning to next-generation refrigerants in new equipment will help mitigate the impact of high-GWP refrigerant consumption, servicing of the installed base of equipment will contribute significantly to HFC consumption over the next 20 years. Identification of potential low-GWP drop-in replacements would help mitigate this issue. Current installed HVAC&R equipment uses non-flammable A1 refrigerants. Risk assessments of A2L refrigerants as drop-in replacements may reveal applications and circumstances under which A2L refrigerants can be used as drop-in replacements for the original A1 refrigerants. Substituting A2L refrigerants in the installed base of equipment could greatly reduce the GWP-weighted HFC consumption of the equipment service sector.

  DOE should begin conducting these risk assessments immediately for mobile vehicle air-conditioning systems, particularly investigating HFO-1234yf. This should be completed by 2012. Following that, DOE should focus on other applications for which A2L drop-ins show the most potential. These include small commercial refrigeration, small residential and commercial air conditioning, chillers, and walk-in refrigerators. These assessments should begin in 2012 and continue until 2015. Because of the potential for A2L drop-ins to significantly reduce the HFC consumption of the equipment service sector, this activity should be considered high priority.

- *Develop safety guidelines for flammability, toxicity, and high-pressure risks* - The risk assessments described above may help identify certain best practices regarding the use, handling, and transportation of flammable, toxic, or high-pressure refrigerants during servicing. To enable the more widespread use of these refrigerants, DOE should support development of servicing guidelines that mitigate these risks and encourage best safety practices. The initial program should begin immediately, with the goal of producing guidance documents for each identified group of equipment every 18 months. Since MVAC has begun transitioning to HFO-1234yf, DOE should support the development of servicing safety guidelines for this application first. Following that, DOE should focus on applications that are most likely to transition to low-GWP refrigerants in the near term. DOE should conclude by focusing on applications that may transition to low-GWP refrigerants in the longer term, with the program complete by mid-2015. Because this program will not have as much of a direct impact on reducing HFC consumption, it should be considered lower priority.

- *Support training for equipment service sector* – DOE should support the training of equipment service sector personnel in using, handling, and transporting next-generation refrigerants, especially those that are flammable, toxic, or high-pressure. Adoption of low-GWP refrigerants could be delayed by a lack of trained workers for servicing this equipment. The initial program should begin in 2012, as safety guidelines are developed for each application, and conclude in 2015. Since mobile vehicle air-conditioning has begun transitioning to HFO-1234yf, DOE should support training for this application first, moving to near-term applications in 2013, and concluding with longer-term applications by 2016. Because this program will not have a direct impact on reducing HFC consumption, it should be considered lower priority.

3.1.3 Updating Codes and Standards

- *Support changes to applicable codes and standards* – The current set of building codes and standards that govern the use of HVAC&R equipment forbids the use of flammable and toxic refrigerants in most applications. Many also contain onerous requirements for assuring the safety of high-pressure refrigerants. Without changes to these codes, equipment development for many of the currently available low-GWP refrigerants would be unable to proceed. As risk assessments are conducted, guidelines are developed, and consensus on acceptable risk levels is attained, DOE should support updating all applicable building codes and standards with this new information. Applicable codes and standards include the following: UL, ASHRAE, Air-Conditioning, Heating, and Refrigeration Institute (AHRI), and Association of Home Appliance Manufacturers (AHAM) standards; building, mechanical, and fire codes; and EPA SNAP refrigerant lists. This process should begin immediately and proceed toward a milestone of updating all relevant codes and standards with the results of these programs by 2016. This activity should be considered high-priority.

3.2 Roadmap for R&D Objective 2: Characterize Refrigerant Properties and Demonstrate Long-Term Compatibility and Reliability

The activities in R&D Objective 2 will mirror those of the previous MCLR program during the 1990s. This research program will characterize the thermophysical and heat transfer properties of currently identified low-GWP refrigerants. The material property characteristics of many new low-GWP refrigerants have not been studied for many applications, and manufacturers may be reluctant to embrace their use until their characteristics are well understood. Additional testing will reduce the uncertainty regarding the durability, compatibility, and long-term reliability of low-GWP refrigerants. Assessing the materials compatibility and long-term stability of these refrigerants under real-world equipment conditions would reduce uncertainty in the viability of these refrigerants. Performing these studies may accelerate the development of equipment using low-GWP refrigerants. In particular, these studies may be helpful for enabling further use of HFO refrigerants.

Figure 3.4 below shows the research and development roadmap for R&D Objective 2.

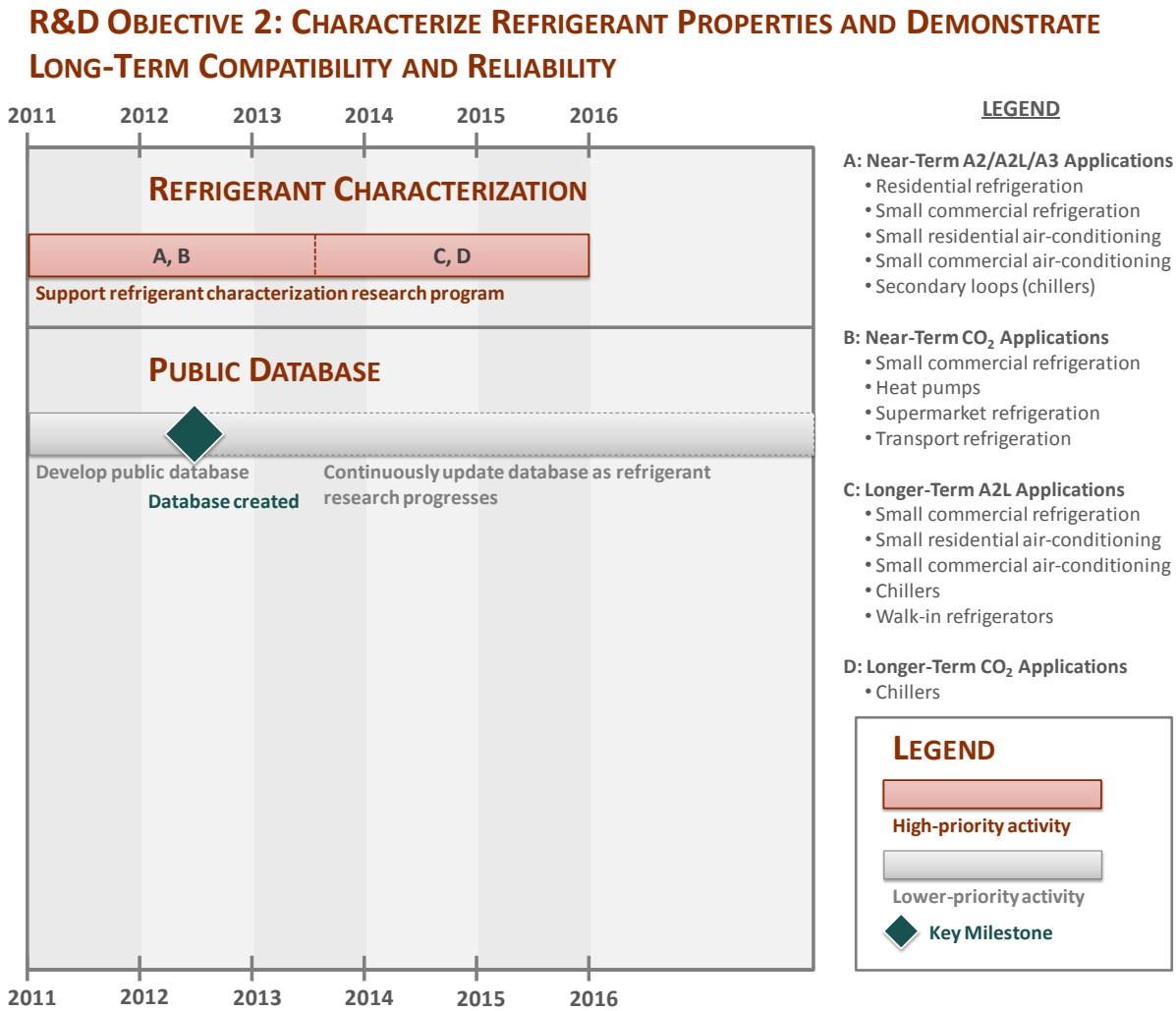


Figure 3.4: Roadmap for R&D Objective 2

The central focus of the roadmap is the refrigerant characterization research program. In parallel, DOE should support the development of a public database for accumulating and publishing the results of this research program. The following sections provide additional details about each program element.

3.2.1 Refrigerant Characterization Research Program

- *Refrigerant Characterization Research Program* – DOE should support a refrigerant characterization research program similar to the MCLR program supported by both DOE and ARTI in the 1990s. Specific activities within this research program should include the following:
    - Characterize the thermophysical and heat transfer properties of currently identified low-GWP refrigerants as well as newly developed refrigerants.

- Examine the compatibility of refrigerant-lubricant mixtures when tested with metals, motor insulating materials, elastomers, plastics, desiccants, process fluids, and lubricants.
- Examine the long-term stability of low-GWP refrigerants in equipment under real-world conditions

This research should begin immediately for all newly developed refrigerants in high-priority applications, and expand to include other applications and other refrigerants in early 2013. DOE should conclude the program by 2016 after investigating the most high-priority equipment types and available refrigerant alternatives.

Priority should be given to current refrigerant and application pairs that may be quickly developed once these studies are complete. These include many of the HFO refrigerants that are currently available, as well as hydrocarbon and CO_2 in applications in near-term applications. Because the information from this research program is critical to accelerating the adoption of low-GWP refrigerants, this activity should be considered high-priority.

3.2.2 Development of Refrigerant Characterization and Compatibility Database

- *Development of public database of refrigerant properties* – DOE should support development of a public database that accumulates and provides access to all the results from the refrigerant characterization studies. The results from these studies should be made accessible to all interested stakeholders, which will facilitate academic research and equipment development with these refrigerants. Availability of such a database would help direct resources and prevent duplication of effort within industry and academia. DOE should seek to develop the database in parallel with the refrigerant characterization research program. Database development should begin immediately, with a milestone of publishing a fully functional database in mid-2012. Once the database is complete and operational, the results of the ongoing refrigerant characterization studies should be added as research in this area progresses. Because the creation of a public database is not essential to the general success of the refrigerant characterization research program, it should be considered lower priority.

3.3 Roadmap for R&D Objective 3: Understand Efficiency and Environmental Tradeoffs

The main focus of R&D Objective 3 is to understand the higher-level tradeoffs between GWP and overall system efficiency. The primary goal of phasing down HFC consumption is to reduce the global warming impact of HVAC&R equipment. While low-GWP refrigerants provide significant reduction in direct emissions (emissions due to leakage of the refrigerant into the atmosphere), some of the most promising alternative refrigerants may result in lower overall system efficiency, thus increasing indirect emissions (emissions resulting from energy consumption during operation). In some cases, the increase in indirect emissions more than offsets the decrease in direct emissions. For these cases, switching to low-GWP refrigerants would actually increase the total global warming impact of the system.

DOE and manufacturers should understand the full life-cycle climate performance (LCCP) of HVAC&R equipment while considering the various low-GWP alternative refrigerants. To support this, DOE should develop a framework for conducting LCCP analyses on candidate low-GWP systems. The LCCP models will help DOE and manufacturers understand the tradeoffs between low-GWP refrigerants and overall global warming impacts.

In addition to the LCCP model, DOE should develop a model of national HFC consumption that will be updated annually. Finally, developing accurate LCCP and HFC consumption models will also require collecting real-world performance data with which to calibrate and validate the models.

Figure 3.5 shows the research and development roadmap for R&D Objective 3.

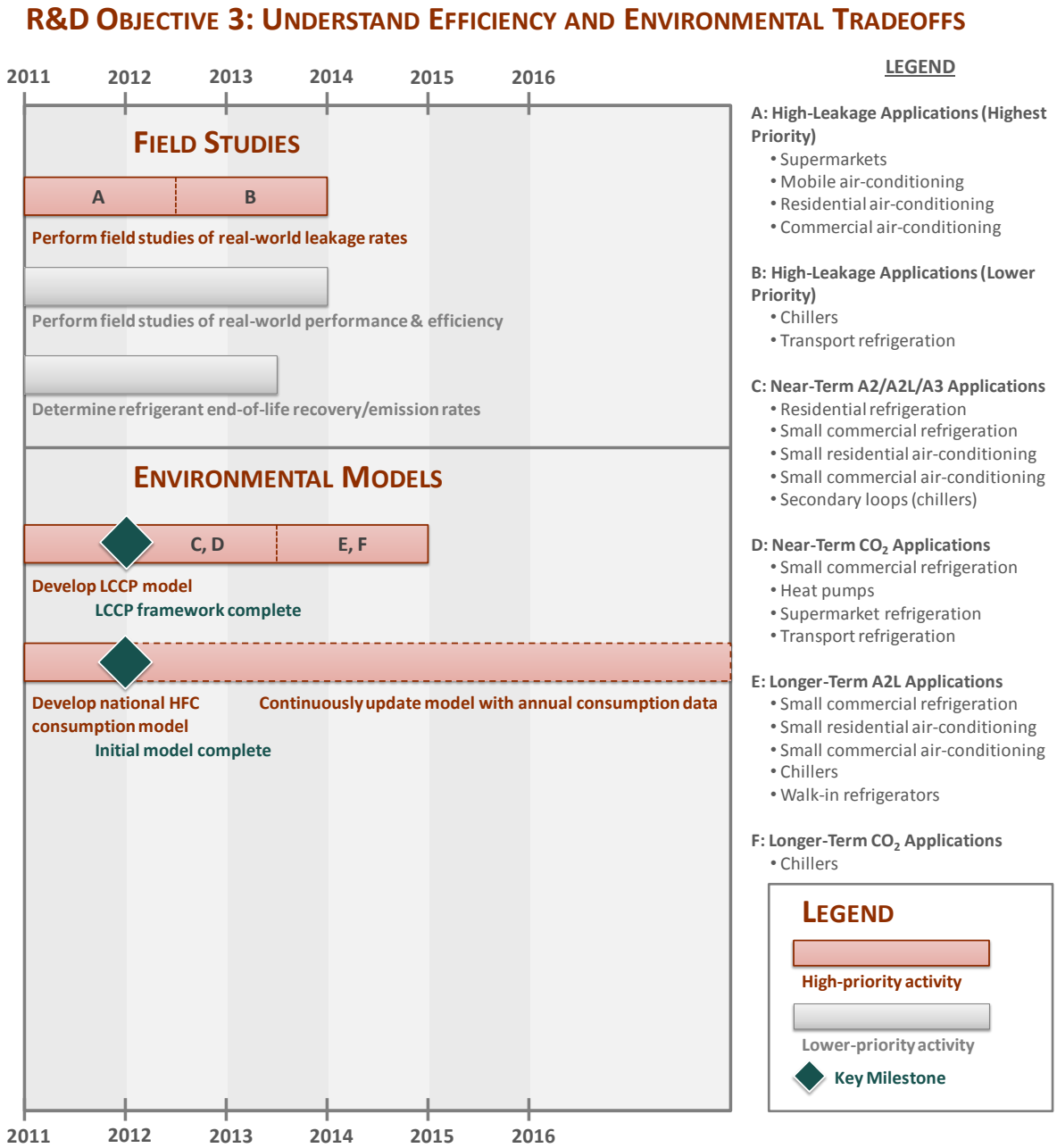


Figure 3.5: Roadmap for R&D Objective 3

The central focus of the roadmap is the development of LCCP and HFC consumption models. Targeted field studies can support these modeling efforts. The following sections provide additional details about each program element.

3.3.1 Field Studies

- *Perform field studies of "real-world" refrigerant leakage rates* – These field studies should quantify refrigerant leakage rates of installed HVAC&R equipment. As an

alternative to making physical measurements of the refrigerant, this could be accomplished by simply keeping accurate records of the amount of charge added during periodic servicing. These field studies should capture a broad range of equipment types, usage scenarios, building types, and climate zones.

The first half of this program should focus on applications with the highest refrigerant leakage rates that represent a significant portion of annual HFC consumption. These include supermarket systems, mobile air-conditioning, and residential and commercial air-conditioning. The second half of the program should focus on applications with high leakage rates but less significant annual HFC consumption, including chillers and transport refrigeration. Field studies of the highest-priority equipment should be completed by mid-2012, with lower-priority applications completed by early 2014. Because real-world equipment leakage rates are a critical component of both the LCCP and HFC modeling efforts, this activity should be considered high-priority.

- *Perform field studies of real-world performance and efficiency* – These field studies should measure the real-world performance and energy efficiency of installed HVAC&R equipment. The data from these studies will be used as inputs to the LCCP model and will also provide a benchmark for comparing the performance and efficiency of low-GWP alternatives. The scope of these studies should cover all major equipment types and refrigerants currently in use. These field studies should be completed by early 2014. Because this activity is not critical to the success of the overall goal of accelerating the implementation of low-GWP refrigerants, it should be considered lower priority.

- *Determine refrigerant end-of-life recovery and emission rates.* LCCP and refrigerant emissions models must track the status of the refrigerant at the equipment's end of life. At the end of life, refrigerant is either recovered and ultimately recycled or destroyed; or emitted into the atmosphere. Current emissions models contain assumptions about the end-of-life destination of refrigerants. This program will provide more accurate data to improve these models. The program should be completed by mid-2013. Because this activity is not critical to the success of the overall goal of accelerating the implementation of low-GWP refrigerants, it should be considered lower priority.

3.3.2 Environmental Models

- *Develop LCCP framework and model* – DOE should develop a framework for performing life cycle climate performance analyses of equipment using low-GWP refrigerants. The objective of the model is to calculate both direct and indirect emissions to help inform selection of low-GWP alternatives. Developing this framework will require defining the boundaries for the analysis. The framework must ultimately provide a standardized method that can be used to model and compare each refrigerant option. To the extent possible, DOE should use results from the field studies described above as input parameters to the LCCP model.

  This LCCP modeling program should begin immediate, with a milestone of completing the framework for analysis by 2012. Analysis results for near-term applications should be

completed by mid-2013, with longer-term applications completed by early 2015. This modeling effort should be considered high-priority.

- *Develop national HFC consumption model* – The ultimate objective of this R&D roadmap is to accelerate the phase-down of HFC refrigerants in favor of low-GWP alternatives. Future legislation or international treaties may prescribe specific phase-down targets. Measuring progress against these targets will require accurate accounting of annual HFC consumption, including breakdowns by industry sector and equipment type. A national HFC consumption model can also help inform priorities for future R&D efforts.

  Development of a comprehensive HFC consumption model should begin immediately, with a milestone of completing the initial model by early 2012. The model should be updated continuously with annual HFC consumption data. This modeling effort should be considered high-priority.

3.4 Roadmap for R&D Objective 4: Support Refrigerant and Equipment Development

The objective of R&D Objective 4 is to improve system-level performance of HVAC&R equipment by supporting research of new refrigerants as well as key technologies and design improvements. Improving key aspects of equipment performance such as cycle efficiency, refrigerant leakage rates, and charge quantities will increase the viability of current low-GWP alternatives and enable their use in higher-demand applications. DOE should also support the development of viable low-GWP refrigerants for the HFC-410A equipment service sector, since currently no viable alternatives have been identified for this important sector.

As depicted in **Figure 3.6**, a viable alternative refrigerant has both a low safety risk and high technical performance. Technical performance is indicated by the equipment's ability to meet efficiency and cooling performance targets. The recommended programs in R&D Objective 4 seek to improve the technical performance of low-GWP alternative refrigerants. Each refrigerant has distinct heat-transfer properties, and development of equipment designs that maximize the efficiency of each refrigerant will help accelerate adoption of these refrigerants.

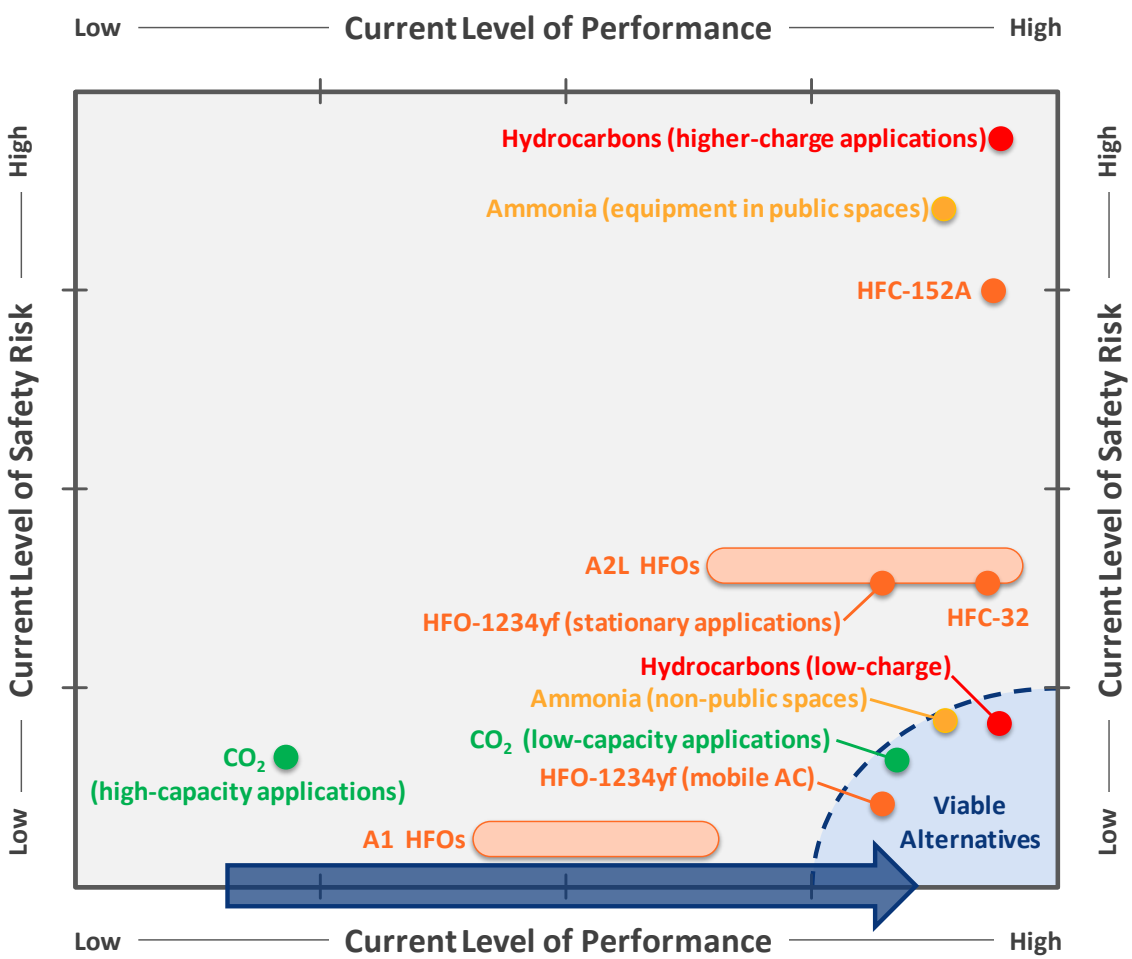


Figure 3.6: Improving refrigerant performance to enable more viable low-GWP refrigerant alternatives

Figure 3.6 indicates that many low-GWP A1 refrigerants, while acceptable from a safety standpoint, require further research and development of equipment designs to improve their performance. With further research and development, these alternative refrigerants may be suitable for meeting current equipment performance standards. Additional research may also improve the performance of low-performing A2L fluids, as well as the performance of CO_2 in high-capacity applications.

Figure 3.7 below shows the research and development roadmap for R&D Objective 4.

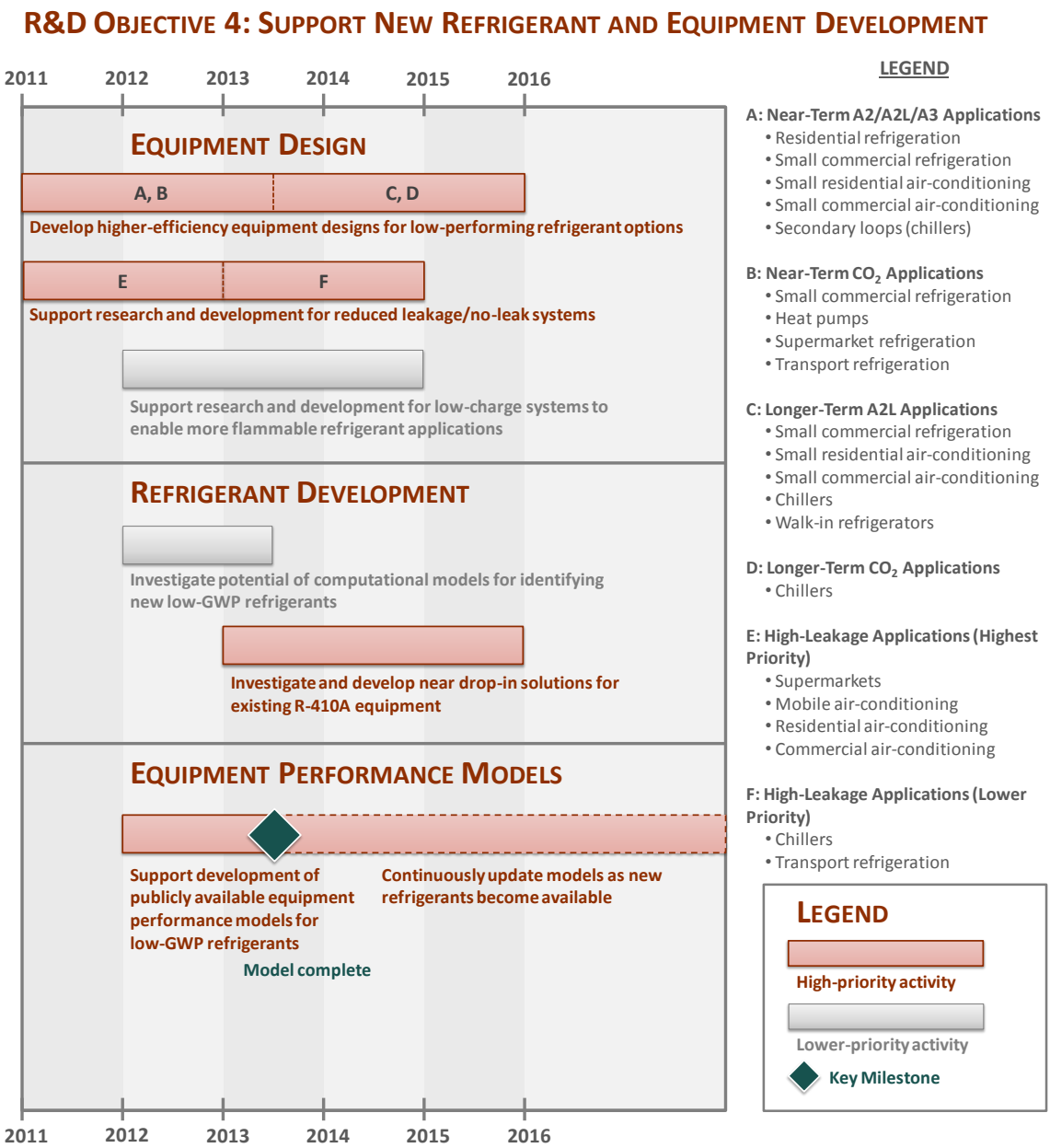


Figure 3.7: Roadmap for R&D Objective 4

The following sections provide additional details about each program element.

3.4.1 Equipment Design Research

- *Develop higher-efficiency equipment designs for low-performing refrigerant options* – Some low-GWP refrigerants have significantly lower volumetric capacities than the HFC refrigerants they would replace. Implementing these alternative refrigerants would decrease equipment efficiency, potentially offsetting the savings in direct GWP emissions with increased indirect emissions. One way to mitigate this tradeoff is to develop higher-efficiency equipment designs. Significant improvements in equipment efficiency could enable the use of low-GWP refrigerant alternatives that are currently considered infeasible or undesirable. In the near term, this program should focus on the most promising refrigerant/equipment combinations. Research on near-term applications should be completed by mid-2013, with longer-term refrigerant/equipment applications completed by early 2016. This program should be considered high-priority.

- *Support research and development of reduced leakage/no-leak systems* – The equipment service sector accounts for approximately half of annual HFC consumption, due mostly to refrigerant leakage that must be periodically replaced. Reducing refrigerant leakage would reduce the quantity of new refrigerant consumption as well as improve overall life cycle climate performance. DOE should support research into reduced leakage or no-leak systems for equipment types with the most significant leakage rates. Research on the highest-priority equipment types should be completed by early 2013, which includes supermarket systems, MVAC, and residential and commercial air conditioning systems. Research on lower-priority equipment types such as chiller and transport refrigeration should be completed by early 2015. Because of the potential to significantly reduce the HFC consumption of the equipment service sector, this program should be considered high-priority.

- *Support research and development of low-charge systems to enable more flammable refrigerant applications.* Refrigerant charge limits imposed by building code regulations significantly limit the types of applications in which flammable low-GWP refrigerants such as hydrocarbons can be used. Developing low-charge systems for applications that would typically exceed the maximum allowable charge limits could enable more widespread use of flammable low-GWP refrigerants. DOE should begin supporting this type of research in early 2012 and conclude the program by early 2015.

3.4.2 Refrigerant Development

- *Investigate potential of computational models for identifying new low-GWP refrigerants* – Other than HFOs, no radically new low-GWP refrigerant fluids have been discovered recently. DOE should investigate the potential for high-performance computer models to help discover new classes of fluids that may require fewer tradeoffs between GWP, flammability, toxicity, and efficiency. This program should begin in 2012 and continue

for approximately 18 months. If the program produces encouraging results, support for follow-on research and refrigerant development may be justified. Unfortunately, the significant time delay between the discovery of a new refrigerant and its implementation in new equipment conflicts with the need to begin significantly phasing down HFC consumption over the next five years. Therefore, this program should be considered lower priority.

- *Investigate and develop near drop-in solutions for existing HFC-410A equipment* – To date, few, if any, viable low-GWP alternatives have been identified for the installed base of HFC-410A equipment. Achieving an aggressive HFC phase-down schedule will require a dramatic reduction in HFC consumption by the equipment service sector. DOE should support research and development to find drop-in or near-drop-in alternatives for installed equipment currently using HFC-410A. Since DOE's initial focus will be supporting research and development of new equipment, this research program should begin in early 2013 and conclude by early 2016. Because of the significant HFC consumption of the HFC-410A equipment service sector, this program should be considered high-priority.

3.4.3 Equipment Performance Models

- *Support development of publicly available equipment performance models for low-GWP refrigerants* – The heat pump design model developed by DOE and ORNL provides significant value to HVAC&R manufacturers[27]. Many HVAC&R manufacturers do not have the financial resources required to develop thermodynamic performance models for equipment using low-GWP refrigerants. DOE should support the development of publicly available thermodynamic performance models that can be used to aid the design of low-GWP systems. The initial model(s) should be completed by mid-2013, with follow-on models or updates to the initial model(s) occurring over the next several years, as new refrigerants become available. Because the availability of these equipment performance models has significant potential to accelerate the implementation of low-GWP refrigerants, this program should be considered high-priority.

[27] Details on the Heat Pump Design Model available at: http://www.ornl.gov/sci/btc/apps/hpdm.html

4 Summary and Conclusion

This R&D roadmap presents an integrated strategy for accelerating the implementation of low-GWP refrigerants to achieve a significant phase-down of HFC consumption over the next 20 years. The roadmap provides recommendations for specific R&D activities that DOE should support over the next five years to enable this transition within this aggressive timeline.

The R&D roadmap is organized around four primary objectives:

R&D Objective 1:	Assess and mitigate safety risks
R&D Objective 2:	Characterize refrigerant properties and demonstrate long-term compatibility and reliability
R&D Objective 3:	Understand efficiency and environmental tradeoffs
R&D Objective 4:	Support new refrigerant and equipment development

Each of these objectives aims to reduce or eliminate existing barriers to implementing low-GWP refrigerants in HVAC&R equipment. The roadmap provides a five-year prioritized research and development plan for each of these areas. Targeted progress towards each objective will help ensure that the U.S. can significantly reduce HFC consumption and meet potential future HFC phase-down targets over the next 20 years.

Appendix A Refrigerant Characteristics

Table A.1: Most common HFC/HCFC refrigerant characteristics

ASHRAE Designation	Common Name	Safety Classification	GWP
HCFC-22	Chlorodifluoromethane	A1	1,810
HFC-134a	1,1,1,2-tetrafluoroethane	A1	1,430
HFC-404A	N/A	A1	3,900
HFC-410A	N/A	A1	2,100

Table A.2: Most viable low-GWP refrigerant characteristics

ASHRAE Designation	Common Name	Safety Classification	GWP
Hydrocarbons:			
R-290	Propane	A3	3
R-600a	Isobutane	A3	3
R-601a	Isopentane	A3	3
R-1270	Propylene	A3	3
HFCs:			
HFC-32	Difluoromethane	A2L	675
HFC-152A		A2	124
Other Natural Refrigerants			
R-717	Ammonia	B2	< 1
R-744	Carbon dioxide	A1	1
HFO-Based			
HFO-1234yf	2,3,3,3-tetrafluoropropene	A2L	4
HFO-1234ze	Trans-1,1,1,3-tetrafluoropropene	A2L	6
N/A	Honeywell L-40	A2L	200-300
N/A	Honeywell L-20	A2L	< 150
N/A	Honeywell L-41	A2L	< 500
N/A	Honeywell N-13	A1	600
N/A	Honeywell N-20	A1	1000
N/A	Honeywell N-40	A1	< 10
N/A	DuPont DR-2	A2L	<300
N/A	DuPont DR-4	A2L	< 500
N/A	DuPont DR-5	A1	< 600
N/A	DuPont XP-10	A2L	4

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