INTERNATIONAL

NOT-IN-KIND ALTERNATIVES TO HIGH GLOBAL WARMING HFCS

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October 2016

INTRODUCTION

As parties to the Montreal Protocol consider an amendment to phase down hydrofluorocarbons (HFCs), one critical concern is the availability of zero- or low-global warming potential (low-GWP) alternatives to replace high-global warming potential (GWP) HFCs. While much of the attention has focused on the next generation of fluorocarbons (hydrofluoroolefins—HFOs), not-in-kind (NIK) alternatives[1] have in the past, and are likely to continue in the future, to play an important role in phasing down substances controlled under the Montreal Protocol. While no definitive estimate exists, according to one report, NIK alternatives, recycling and emission reductions historically replaced up to 85 percent of ozone-depleting substances.[2] While the future role of NIKs may be more limited, these solutions, along with lower-GWP HFCs, are likely to continue to play an important role in expanding the range of substitute options while also providing market competition for new fluorocarbon chemical alternatives, which may be restricted in the near term by patents.

KEY FINDINGS

- In the absence of an HFC phase-down amendment, HFC growth would continue with more than 80 percent of use of HFCs in Article 5 Parties[3] in 2050.
- Alternatives to high-GWP HFCs have been developed and are being used in all major use sectors.
- National regulations in Australia, Canada, European Union, Japan and the United States have and will continue to drive the expanded use of low-GWP HFC alternatives in the near and long term.
- In most sectors a range of options exists including next-generation fluorocarbon (hydrofluoroolefins—HFOs), lower-GWP HFCs, hydrocarbons (HCs) and other non-fluorocarbon refrigerants and foam blowing agents.
- In past transitions, NIK alternatives including substitutes other than fluorocarbons (e.g., HCs, carbon dioxide), recycling and recovery, and emission reductions have reduced reliance on ozone-depleting substances (ODSs) by as much as 85 percent.

BOX 1: The Role Played by NIK Alternatives in Past ODS Transitions

By 1997, the phase out of chlorofluorocarbons (CFCs), halons, carbon tetrachloride and methyl chloroform in non-Article 5 Parties had replaced approximately 80 percent of former ODS uses with "not-in-kind" non-fluorocarbon options, about 8 percent with "in-kind" high-GWP HFCs, and about 12 percent with high-GWP "in-kind" hydrochlorofluorocarbons (HCFCs). Between 1997 and 2016, about one-third of the uses that had transitioned from ODS to HFCs made subsequent transitions to NIK. Currently, about 15 percent of uses that historically used ODS now depend on HFCs.

The early stages of the non-Article 5 phaseout of HCFCs used in-kind high-GWP HFCs in the refrigeration and air conditioning sector, NIK options in the solvents sector, and a mix of technology in the foam sector. In the on-going early stages of the Article 5 phaseout of HCFCs and in early actions to phase-down high GWP HFCs, parties are using a combination of low-GWP HFCs (sometimes in blends with HFOs), non-fluorocarbon refrigerants and foam blowing agents and other ozone-safe and climate-friendly technology, with increased emphasis on energy efficiency. Companies in Article 5 Parties are beginning to "leapfrog" high-GWP HFCs in shifting out of HCFCs and are working toward even more sustainable solutions.

- Based on the current availability of non-fluorinated alternatives and likely emission reductions, the overall opportunity for NIK alternatives to substitute for HFCs is expected to be on the order of 50 percent.
- NIK alternatives to replace high-GWP HFCs also have the potential to significantly decrease energy use in the refrigeration and air conditioning sectors.
- By providing a broader range of alternatives and emission reductions, NIKs provide market and price competition to next-generation HFO substitutes which are restricted by patents for a specified period of time.
- Efforts are underway, but will require several more years to fully address changes in codes and standards to ensure a wider range of more flammable alternatives can be used safely.

ROLE OF NIK SUBSTITUTES IN PAST TRANSITIONS FROM OZONE-DEPLETING SUBSTANCES (ODS)

The Montreal Protocol technical literature describes both chemical "substitutes" and non-chemical "alternatives" and further defines fluorocarbons or brominated compounds as "in-kind" options and non-fluorocarbon and non-brominated options as "not-in-kind." Under this definition, not-in-kind options include: hydrocarbon (HC), ammonia, and carbon dioxide refrigerants and foam-blowing agents; aqueous cleaning and no-clean soldering; containment, recovery and recycling; HC, stick and spray alternatives to CFC aerosol products; measures aimed at halting discharge testing and training with halons; and numerous other environmentally superior solutions to limiting the use and emissions of ODS.[4] Appendix A presents a list of some of the significant substitutes and alternatives used in past transitions away from ODS.

In the near future, reductions in high-GWP HFCs will likely be achieved by some combination of energy efficient HFOs, HCs with GWP less than 5, carbon dioxide (CO_2) with GWP equal to 1 (reference chemical), ammonia with GWP of approximately 0, and increased recycling and recovery. Appendix B presents a list of some of the significant substitutes and alternatives available. Over time, an HFC phasedown amendment will likely result in a broader range of NIK solutions including: 1) those that achieve lower energy demand, 2) better greenhouse gas refrigerant and foam-blowing agent containment, recovery, and reuse/destruction, and 3) innovative solutions that provide the same final user satisfaction without the use of HFCs (e.g. dry-powder inhalers without aerosol propellants replacing metered-dose inhalers (MDIs) that use HFC propellants). For air conditioning and refrigeration, these longer–term solutions could include: reduced thermal load by smaller rooms cooled only when occupied; cooling without vapor compression (magnetic, adsorption, ocean water circulation, etc.); higher efficiency appliances and lighting that reduce cooling load; and smart controls managing temperature, humidity, and air movement for low-carbon footprint.

CURRENT AND PROJECTED USES OF HFCS

HFCs are the fastest-growing greenhouse gases, increasing globally at a rate of 10 percent to 15 percent annually.[5] With GWPs up to thousands of time greater than carbon dioxide, HFCs can have a significant impact on climate change. Given their high emissions rates and relatively short atmospheric lifetimes (compared to carbon dioxide), efforts to reduce HFC emissions in the near term will significantly reduce projected temperature increases over the coming decades.

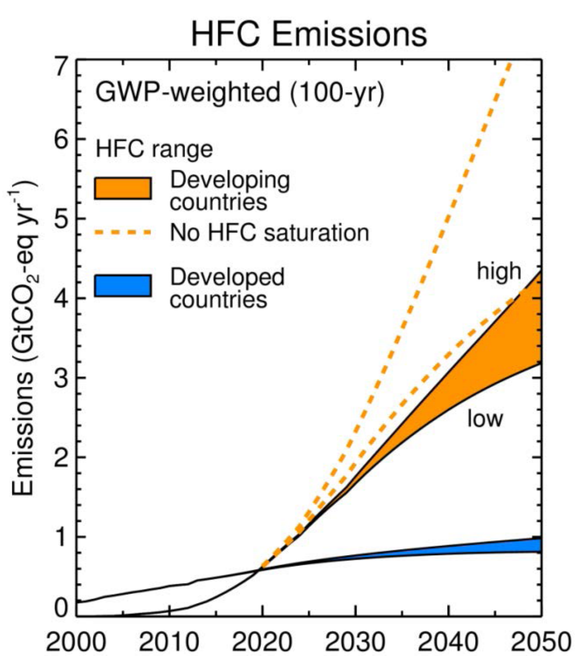
Initially, HFC consumption occurred predominately in non-Article 5 Parties as they shifted out of CFCs and HCFCs. Over time, projections show future use will be dominated by Article 5 Parties through increased consumption of HFCs particularly in refrigeration and air conditioning applications. Figure 1 shows that if HFC consumption continues as projected, developing countries could make up at least 80 percent of global HFC emissions by 2050.[6] For Article 5 Parties, the significant increase over time assumes that current uses of HFCs for developing countries follow the same transition from HCFCs to HFCs and NIK alternatives based on what has occurred in developed countries.[7] The reduction in growth in non-Article 5 Parties is driven by recent regulations—the European Union's 2006 MAC directive and 2014 revised F-Gas regulation, the United States changes to its Significant New Alternatives Policy (SNAP) regulations, and Australia's and Japan's updated fluorocarbon regulations.

As shown in Figure 2, refrigeration, and air conditioning are the dominant market sectors for HFCs, making up over 85 percent of global consumption in terms of tonnes of carbon dioxide equivalent (CO_2-eq) emissions. The foam sector is the third largest sector at 7 percent consumption. Fire protection, solvents, and technical and medical aerosol applications make up the remaining 7 percent.[8] Within the refrigeration sector, commercial systems account for nearly three-quarters of the sector's HFC consumption—about 22 percent of global HFC consumption. Within the air-conditioning sector, air-to-air stationary systems account for almost half of the sector's HFC consumption—about 25 percent of global HFC consumption.

NATIONAL EFFORTS TO PHASE DOWN HFCS

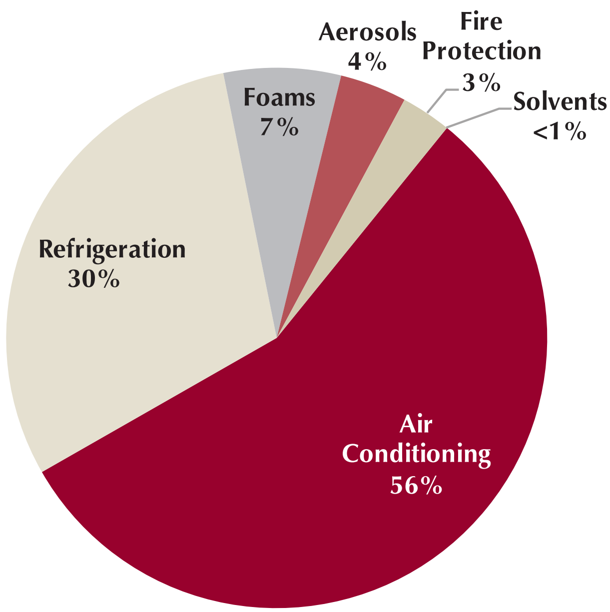
The shift away from the use of high GWP HFCs has been led by national and regional regulations instituted in a number of non-Article 5 Parties. These regulations have driven the development and commercialization of alternatives including both the next generation HFOs, lower GWP fluorocarbons and blends, and NIK alternatives.

FIGURE 1: Projected Growth in HFCs and Climate Forcing from Emissions



Source: Guus J.M. Velders, David W. Fahey, John S. Daniel, Stephen O. Andersen, and Mack McFarland, "Future Atmospheric Abundances and Climate Forcings from Scenarios of Global and Regional Hydrofluorocarbon (HFC) Emissions," Atmospheric Environment 123 (2015): 200–209, http://dx.doi.org/10.1016/j.atmosenv.2015.10.071.

FIGURE 2: Global HFC Consumption by Sector, 2012 (tonnes CO_2-eq)



Source: UNEP Ozone Secretariat, Overview of HFC Market Sectors (Nairobi, Kenya: United Nations Environment Programme, 2015), http://ozone.unep.org/sites/ozone/files/Meeting_Documents/HFCs/FS_2_Overview_of_HFC_Markets_Oct_2015.pdf.

The European Union has taken the lead in implementing a number of aggressive regulations to reduce HFCs. The 2006 Directive on Mobile Air Conditioning systems prohibits the use of fluorinated gases with a GWP of more than 150 in new types of cars and vans sold in the European Union from 2011 and all cars and vans sold in the European Union from 2017. In 2015, the European Union updated their 2006 Fluorinated Gas (F-Gas) Regulation. The original F-Gas Regulation was targeted at containment and recovery of fluorinated gases. The new regulation will phasedown GWP-weighed HFC use by 79 percent from a 2009 baseline by 2030 by prohibiting the use of HFCs with a GWP greater than 150 in new equipment across a number of sectors (e.g. refrigeration, air conditioning, and foams) starting in 2020.[9] It also prohibits the use of certain high-GWP HFCs to service and maintain certain refrigeration equipment.

The United States has taken steps to curb HFCs emissions as part of President Obama's Climate Action Plan.[10] The U.S. Environmental Protection Agency (EPA) has issued a series of regulations through its SNAP program under the Clean Air Act that limit the use of specified HFCs in certain sectors. In addition, the U.S. Corporate Average Fuel Economy (CAFE) includes an incentive where auto manufacturers could earn credits towards fuel efficiency by replacing HFC-134a in mobile air conditioning (MAC) systems with low-GWP alternatives.[11] President Obama has also instructed federal agencies, "to purchase cleaner alternatives to HFCs wherever possible."[12]

In June 2016, the Clean Energy Ministerial—which is a partnership of Australia, Brazil, Canada, China, Denmark, European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Norway, Russia, Saudi Arabia, South Africa, Spain, Sweden, United Arab Emirates, United Kingdom, and United States—launched a campaign challenging governments and industry to "develop and deploy at scale super-efficient, smart, climate-friendly, and affordable cooling technologies."[13] Also of relevance, the United States is partnering with the Air Conditioning, Heating, and Refrigeration Institute (AHRI), the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), the Alliance for Responsible Atmospheric Policy, and other governments and international organizations to conduct critical research regarding the safe use of mildly flammable and flammable refrigerants as low-GWP alternatives to HCFCs and HFCs in the air-conditioning and refrigeration sectors.[14]

In Canada, federal and provincial regulations have implemented regulations prohibiting the release of HFCs from certain equipment (e.g., refrigeration, air conditioning, etc.) and requiring the recovery of HFCs from certain equipment. In March 2016, Environment and Climate Change Canada released proposed regulations on HFCs. They are considering two approaches to regulating HFCs: prohibiting specific HFCs by specific years depending on the sector, and a gradual phase-down of HFCs from a calculated baseline.[15]

Japan has also initiated rules to phase down HFCs. In April 2013, the cabinet approved legislation revising the Fluorocarbons Recovery and Destruction Law. This revision strengthens emission reduction of HFCs at each stage of their lifecycle, and requires manufacturers and importers to phase down HFCs. One measure of the Japanese resolve to phase down high-GWP HFCs is the abandonment of HFC-410A by all Japanese manufacturers and replacement with HFC-32 that has one third the GWP and 20 percent lower refrigerant charge in air conditioners.

AVAILABILITY AND USE OF ALTERNATIVES

A number of low-GWP alternative to HFCs are already commercially available across a large number of sectors and regions. National and regional efforts in non-Article 5 Parties are helping to curtail demand for HFCs and to prove the viability and cost effectiveness of alternatives. As Article 5 Parties consider replacing high-GWP technologies, there is a desirability (and very real potential) to leapfrog from HCFCs to low-GWP alternatives—avoiding a shift first from HCFCs to high-GWP HFCs and at a later date from HFCs to a low- or zero-GWP alternative.

REFRIGERATION

The refrigeration sector makes up about 30 percent of current global HFC consumption, and is projected to grow at about 6 percent annually from 2015 to 2050.[16] During this period, refrigerant consumption of HFCs in non-Article 5 Parties is expected to decline 1.0 percent annually, while refrigerant consumption in Article 5 Parties is expected to increase 7.2 percent annually.[17] The refrigeration sector can be categorized into four subsectors:

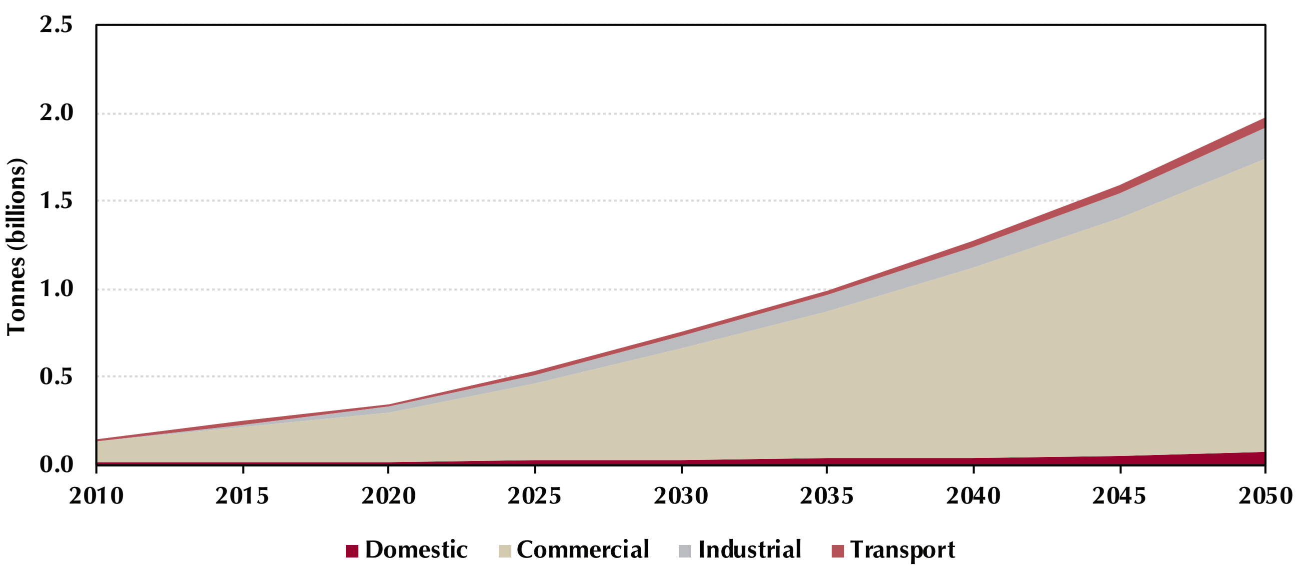
- **Domestic refrigeration and freezers** are used for the storage of food and beverages typically in households.
- **Commercial refrigeration and freezers** are used for the storage and display of food and beverage products in retail businesses.
- **Industrial refrigeration systems** are used for the processing and storage of food and beverages, and in the manufacturing of a number of chemicals.
- **Transport refrigeration and freezer systems** are used for the carriage of food and beverage products.

Figure 3 shows that growth in this market is primarily driven by commercial and industrial refrigeration systems with much of this growth occurring in Article 5 Parties.

Domestic refrigeration

HFC use in domestic refrigeration makes up about 2 percent of current consumption (in terms tonnes of CO_2-

FIGURE 3: Refrigerant Demand in the Refrigeration Sector (tonnes CO_2-eq)



Source: "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment Panel (Nairobi, Kenya: United Nations Environment Programme Ozone Secretariat, 2016), http://conf.montreal-protocol.org/meeting/oewg/oewg-38/presession/Background%20Documents%20%20TEAP%20Reports/TEAP_TFXXVII-4_Report_June2016.pdf.

TABLE 1: Indicative List of Low-GWP Alternatives for Domestic Refrigeration

FLUID FAMILY	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMA-BILITY‡	COMMENTS
HFOs	HFO-1234yf HFO-1234ze	A2L A2L	<1 <1	2L 2L	Systems not currently commercially available, but being considered for use in large refrigerant charge systems (> 0.15 kg) and in countries with HC restrictions.
HCs	HC-600a	A3		3	Already in widespread use in most regions.
	HC-290	A3		3	U.S. EPA SNAP approved in 2015 for use in smaller domestic refrigerant charge systems (≤0.057 kg).
	HC-600a	A3		3	U.S. EPA SNAP approved in 2011 for use in smaller domestic refrigerant charge systems (≤0.057 kg).
HC Blend	R-441A (Ethane, Propane, Isobutene, n-Butane)	A3	5.6	3	U.S. EPA SNAP approved in 2011 for use in smaller domestic refrigerant charge systems (≤0.057 kg).

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential from UNFCCC AR5.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment Panel (Nairobi, Kenya: United Nations Environment Programme Ozone Secretariat, 2016), http://conf.montreal-protocol.org/meeting/oewg/oewg-38/presession/Background%20Documents%20%20TEAP%20Reports/TEAP_TFXXVII-4_Report_June2016.pdf, and EPA SNAP.

equivalent) and is projected to grow about 3.8 percent annually from 2015 to 2050.[18] Growth is primarily driven by Article 5 Parties. Since 2008, domestic refrigerators and freezers have shifted their refrigerants from ozone depleting substances (e.g., CFC-12) to zero-depleting substances like HFC-134a and HC-600a (isobutane).

HFOS AND BLENDS UNDER CONSIDERATION

HFOs have energy efficiency comparable to or slightly lower than HFC-134a and lower flammability than hydrocarbons. However, hydrocarbon domestic refrigeration systems are widely available while HFO refrigerant systems are not yet commercially available. Initial assessments to replace HFC-134a with HFO-1234yf and HFO-1234ze have taken place, but these are not being pursued as a high priority because of the higher cost of HFO refrigerants, and the significant investment requirements to develop and deploy new products.[19]

USE AND AVAILABILITY OF NIKS

Since their introduction 20 years ago in China and Europe, hydrocarbons have made substantial inroads globally in replacing HFC-134a use in domestic refrigeration. More than 500 million domestic refrigerators using hydrocarbons are already operating globally.[20] More than 50 percent of new domestic refrigerator production uses HC-600a, and this is expected to increase to three-quarters of new refrigerator production by 2020.[21] Over 90 percent of new domestic refrigeration appliances in the European Union already use HC-600a. There is also fairly widespread production of HC-600a appliances in Asia and South and Central Americas. However, domestic refrigerators with HC-600a are not widely used in Canada, Japan, and the United States due to safety standards related to flammability that restrict the use of hydrocarbons in domestic refrigeration appliances with systems requiring larger charges (greater than 0.15 kg).

In the United States, efforts are underway to transition from using HFC-134a in domestic appliances to NIK alternatives. EPA's SNAP program allows the use of hydrocarbons and blends (e.g., R-600A, R-290A, and R-441A) as a refrigerant, and in April 2016, EPA proposed restricting the use of HFC-134a in new domestic appliances starting in 2021.[22] Since refrigerators in the United States are larger than their European counterparts, this would provide time for manufacturers to design R-600A refrigerators and to revise safety standards and codes to effectively address concerns about flammability.

Commercial refrigeration

Commercial refrigeration makes up about 22 percent of current HFC consumption (in terms of tonnes CO_2-equivalent), and is projected to grow about 6.3 percent annually from 2015 to 2050.[23] Future growth is primarily driven by Article 5 Parties. The commercial refrigeration sector is made up of three broad categories:

- **Stand-alone equipment** are small systems using technologies with similarities to domestic refrigerators (e.g., freezers, vending machines, and beverage coolers).
- **Condensing units** are split systems with cooling in the refrigerated space connected to a remotely located compressor and condenser (e.g., retail display).
- **Centralized systems** are large distributed systems with a number of cooling evaporators connected to a remotely located compressor pack and external condenser (e.g., used in supermarkets).[24]

The European Union's F-Gas regulation, and the U.S. SNAP program are helping to transition away from the use of HFC-134a and R-404A as refrigerants in the commercial refrigeration sector.[25] In addition, companies are taking voluntary action to phase-out HFCs. "Refrigerants, Naturally!" is a nonprofit organization made up of several global food companies (PepsiCo, Red Bull, the Coca-Cola Company, SABMiller, and Unilever) wanting to phase out the use of HFC gases from point-of-sale equipment. To meet this goal, in August 2014, Coca-Cola and PepsiCo announced that they will not use HFCs in new stand-alone equipment in the next several years.[26] Hydrocarbon replacement in stand-alone equipment can achieve higher energy efficiency than with HFC-134a. To date, carbon dioxide replacement has resulted in a reduction in energy efficiency.

HFOS AND BLENDS UNDER CONSIDERATION

HFOs and HFO/HFC blends are viable alternatives for systems requiring a larger refrigerant charge because of their energy efficiency and lower flammability. HFO-1234yf and HFO-1234ze are under development in stand-alone equipment and medium-temperature condensing units. HFC/HFO blends (e.g., R-448A, R-449A, R-449B, R-450A, and R-513A) have been approved by ASHRAE for use in new and retrofitting of existing equipment and systems, and some or all have been used in centralized systems (i.e., supermarkets), stand-alone equipment, and condensing units across Europe and in the United States.[27]

USE AND AVAILABILITY OF NIKS

In the last decade, hydrocarbons—for stand-alone small size refrigerant charge systems—and carbon dioxide—for supermarkets—have taken significant market share, especially in Europe.[28]

Hydrocarbons (e.g., HC-290, HC-1270, and HC-600a) are widely used globally in stand-alone equipment with small refrigerant charge systems (e.g., water fountains, ice machines, and small display cases). For instance, more than 3 million ice cream freezers using HC-290 are in use.[29] In addition, small plug-in HC-290 units are used in some large supermarkets with multiple stand-alone units rejecting heat into a water circuit.[30] Carbon dioxide (R-744) has also been used in stand-alone equipment (e.g., vending machines, and bottle coolers) worldwide.

Cost and energy efficiency considerations with using NIK alternatives in condensing units has limited applicability to certain regions and applications. Condensing units utilizing carbon dioxide are mainly sold in Northern Europe, but cost is currently a barrier. Small capacity condensing units using hydrocarbon refrigerants are available, but are subject to safety regulations. In general, hydrocarbon stand-alone equipment has better energy efficiency than HFC designs.

Carbon dioxide has been used successfully in new centralized systems (e.g., supermarkets) worldwide. Several thousand European supermarkets are currently using carbon dioxide systems.[31] In general, these centralized systems have better energy efficiency than HFC design systems. In cold and mild climates, transcritical carbon dioxide booster systems are used with excellent energy efficiency. Transcritical carbon dioxide allows the refrigeration system to operate at higher pressures—

TABLE 2: Indicative List of Low-GWP Alternatives for Commercial Refrigeration

FLUID FAMILY	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMA-BILITY‡	COMMENTS
HFOs	HFO-1234yf HFO-1234ze	A2L A2L	<1 <1	2L 2L	Not currently used, but being considered for stand-alone systems and medium-temperature condensing units.
HFO/HFC Blends	R-448A R-449A R-449B	A1 A1 A1	1,300 1,300 1,300	1 1 1	Limited commercial experience (both for new systems and for retrofits). Growing use in supermarkets in Europe and the United States.
	R-450A R-513A R-513B	A1 A1 A1	550 570 540	1 1 1	Being considered for medium-temperature systems; may be suitable for large systems.
	R-451A R-451B	A2L A2L	140 150	2L 2L	Being considered for medium-temperature systems; may be suitable for condensing units.
	R-454A R-455A	A2L A2L	240 470	2L 2L	Being considered for low-temperature and medium-temperature condensing units.
	R-446A R-447A R-454B	A2L A2L A2L	460 570 470	2L 2L 2L	Being considered for condensing units.
HCs	HC-290 HC-1270 HC-600a R-441A	A3 A3 A3 A3	 5.6	3 3 3 3	Already in widespread use in both Article 5 and non-Article 5 Parties in stand-alone equipment, small condensing units, and in some large supermarkets with multiple stand-alone units (in Europe).
Ammonia	R-717	B2L		2L	Used in indirect systems, but energy efficiency can be reduced if liquid secondary refrigerants are used.
Carbon Dioxide	R-744	A1	1	1	Used in stand-alone commercial refrigerant systems, limited use in condensing units (in Northern Europe and Japan), and significant use in new centralized (transcritical and cascade) systems.

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment, and from company announcements and websites.

TABLE 3: Indicative List of Low-GWP Alternatives for Industrial Refrigeration

FLUID FAMILY	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMA-BILITY‡	COMMENTS
HFOs	HFO-1233zd HFO-1336mzz	A1 A1	1 2	1 1	Being introduced for industrial refrigeration as an alternative to HCFC-123.
	HFO-1234ze	A2L	4	2L	Being introduced for industrial refrigeration as an alternative to HFC-134a.
HFO/HFC Blends	R-448A R-449A R-449B	A1 A1 A1	1,300 1,300 1,300	1 1 1	Limited commercial experience (both for new systems and for retrofits).
	R-450A R-513A R-513B R-451A R-451B R-454A R-455A R-446A R-447A R-454B	A1 A1 A1 A2L A2L A2L A2L A2L A2L A2L	550 570 540 140 150 240 150 460 570 470	1 1 1 2L 2L 2L 2L 2L 2L 2L	Being considered for small- and medium-temperature systems.
HCs	HC-290 HC-1270	A3 A3		3 3	Used in large distributed systems and chillers, especially in petrochemical plants.
Ammonia	R-717	B2L		2L	Widespread use for large systems and chillers.
Carbon Dioxide	R-744	A1	1	1	Used for cold stores and freezer dryers, and being considered for small and medium-sized industrial systems.

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment, and from company announcements and websites.

above carbon dioxide's "critical point"—resulting in a more-efficient condensing process that lowers overall energy consumption, particularly as outside temperature increases.

In hot climates, carbon dioxide cascade systems can be used with good energy efficiency.[32] Cascade systems consist of a refrigeration loop using carbon dioxide that rejects heat to an outside-facing liquefaction unit using either a more traditional HFC or HFC-HFO blend. In this arrangement, a large portion of the total system uses a NIK refrigerant while limiting the fluorinated gas to a non-distributed, tightly sealed unit. High energy efficiency is also achieved at reasonable cost by using in-kind fluorinated refrigerants with higher critical points to reject heat.

Industrial refrigeration

Industrial refrigeration makes up about 2 percent of current HFC consumption (in terms tonnes of CO_2-equivalent), and is projected to grow about 6.7 percent

TABLE 4: Indicative List of Low-GWP Alternatives for Transport Refrigeration

FLUID FAMILY	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMA-BILITY‡	COMMENTS
HFO/HFC Blends	R-452A	A1	1,900	1	Available in Europe for transport refrigeration systems; Currently awaiting EPA SNAP approval.
	R-448A R-449A R-449B R-450A R-513A R-513B	A1 A1 A1 A1 A1 A1	1,300 1,300 1,300 550 570 540	1 1 1 1 1 1	Limited commercial experience or availability.
HCs	HC-290 HC-1270	A3 A3		3 3	Limited trials in Europe and South Africa; Expected to be available in transportation refrigeration systems by 2018.
Carbon Dioxide	R-744	A1	1	1	Limited trials in the UK; Expected to be commercially available in transportation refrigeration systems by 2020. U.S. EPA SNAP approved in 2014.

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment, and from company announcements and websites.

annually from 2015 to 2050.[33] Similar to other refrigeration subsectors, growth is primarily driven by Article 5 Parties. The industrial refrigeration sector is made up three broad categories:

- **Small- and medium-sized systems** are usually dedicated to one particular refrigeration demand.
- **Large primary refrigerant distributed systems** are used to cool large loads, such as blast freezers, process heat exchangers, and cold storage facilities.
- **Large secondary refrigerant chiller systems** are used to cool a secondary heat transfer fluid which is circulated to meet a number of separate cooling demands.[34]

HFOS AND BLENDS UNDER CONSIDERATION

There is limited availability and experience with using HFOs and blends for industrial refrigeration for small- and medium-sized systems. One HFO blend (R-513A) is available and has been approved for usage in cold storage warehouses and others are under development.[35]

USE AND AVAILABILITY OF NIKS

R-717 (ammonia) is the preferred refrigerant for large systems in most markets. More than 90 percent of large industrial refrigeration installations use R-717 as a refrigerant due to its low capital cost for equipment and high energy efficiency. Conversely, for smaller installations, R-717 is not as popular—ranging from 5 percent in China and India to 25 percent in Europe and Russia.[36] In general, large R-717 industrial refrigeration systems are well suited at low-temperature and medium-temperature conditions. Since R-717 is highly toxic, various safety precautions are required, making it difficult to use this alternative cost effectively for small- and medium-sized systems. In such cases, R-744 is primarily used. Hydrocarbons (e.g., HC-290, and HC-1270) are used primarily in petrochemical plants that are already processing highly flammable products.

Transport refrigeration

Transport refrigeration makes up about 2 percent of current HFC consumption, and is projected to grow about 4.8 percent annually from 2015 to 2050 largely driven by growth in Article 5 Parties.[37] The transport refrigeration sector is made up of three broad categories:

- **Road vehicles** (e.g., vans, trucks, trailers);
- **Intermodal containers** (e.g., reefer containers); and
- **Ships** (e.g., refrigerated cargo vessels, fishing vessels, and passenger liners).[38]

HFO/HFC BLENDS UNDER CONSIDERATION

HFO/HFC blends are expected to play a key role in this sector due to the lack of available NIK alternatives. The use of more flammable refrigerants would require new system designs, special safety measures, and must address safety regulations. As such, it may be easier to deal with non-flammable refrigerants (e.g., HFO/HFC blends). A number of such blends are in the early stages of use or in development and are expected to be available in the next five years. The energy efficiency of HFO/HFC blend alternatives is expected to be higher than existing R-404A systems.[39] Regulations from non-Article 5 Parties will help drive development and deployment of low-GWP alternatives in the next several years. For instance, several manufacturers are offering R-452A systems in Europe in response to the European Union's F-Gas regulations.[40] R-452A is currently awaiting approval under the EPA SNAP program for use in the United States.[41] R-452A offers similar cooling capacity, fuel efficiency, reliability and size of refrigerant charge as R-404A.[42]

USE AND AVAILABILITY OF NIKS

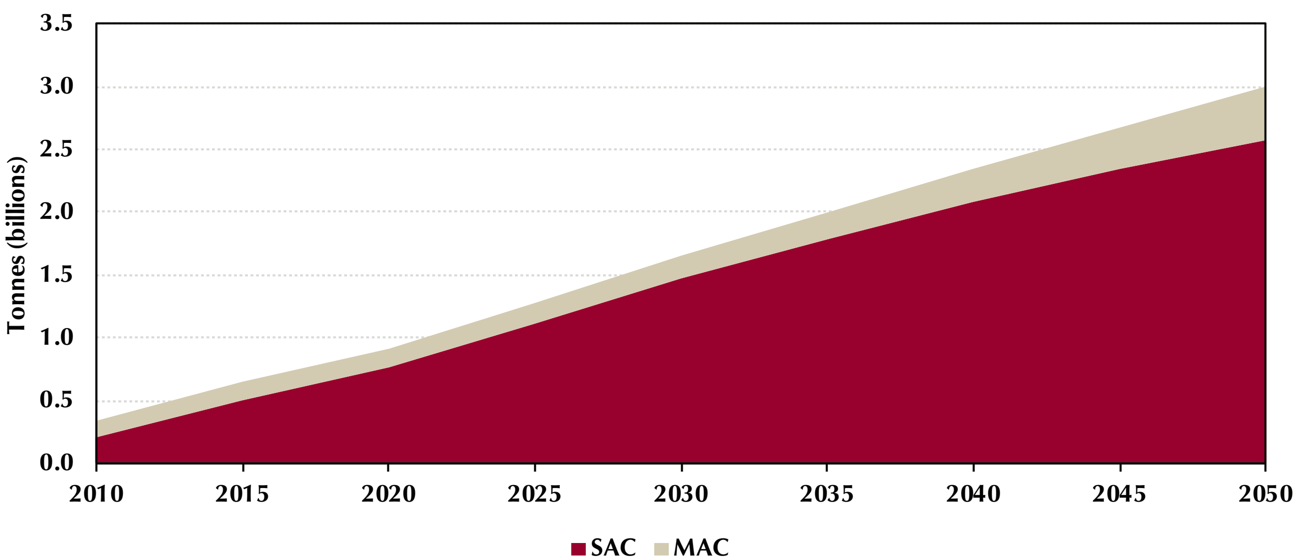
Transport refrigeration systems using R-744 have been field tested beginning in 2011, and are expected to be widely available by 2020.[43] However, reduced efficiency in high ambient temperatures and limited component supply currently limit market penetration. In October 2014, the U.S. EPA SNAP program approved R-744 for use in new equipment in refrigerated transport.[44]

The evaluation of hydrocarbons (e.g., HC-290, and HC-1270) in transport refrigeration systems is underway and, if successful, these alternatives are expected to be available by 2018.[45]

AIR CONDITIONING

The air-conditioning sector makes up over 55 percent of current HFC consumption, and is projected to grow

FIGURE 4: **Refrigerant Demand in the Air Conditioning Sector (tonnes CO_2-eq)**



Source: "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment Panel (Nairobi, Kenya: United Nations Environment Programme Ozone Secretariat, 2016), http://conf.montreal-protocol.org/meeting/oewg/oewg-38/presession/Background%20Documents%20%20TEAP%20Reports/TEAP_TFXXVII-4_Report_June2016.pdf.

TABLE 5: Indicative List of Low-GWP Alternatives for Stationary Air Conditioning

TYPE	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMA-BILITY‡	COMMENTS
HFCs	HFC-32	A2L	677	2L	Small self-contained air-conditioning systems available. Small split air-conditioning systems are also available in parts of Asia, India, and Europe.
HFOs	HFO-1234yf HFO-1234ze	A2L A2L	<1 <1	2L 2L	Considered for ducted and roof top units, subject to safety standards and codes.
	HFO-1336mzz(Z)	A1	2	1	U.S. EPA SNAP approved in 2016 for use in industrial process air conditioning (new equipment).
HFO/HFC Blends	R-446A R-447A R-454B	A2L A2L A2L	460 570 470	2L 2L 2L	Newly developed blends being developed for small split air conditioning. Also for multisplits, VRF systems and ducted systems subject to safety standards and codes.
	R-450A R-513A R-513B	A1 A1 A1	550 570 540	1 1 1	Possible alternatives for ducted and packaged roof top units.
HCs	HC-290 HC-1270	A3 A3		3 3	Used for small split air conditioning in Europe, and parts of Asia due to flammability concerns. Limited availability for chillers, available widely in Europe.
Ammonia	R-717	B2L		1	Used for chillers with small capacities due to costs.
Water	R-718	A1		1	Limited to special applications for chillers.
Carbon Dioxide	R-744	A1	1	1	Limited applicability for stationary air-conditioning systems and chillers based on reduced efficiency in high ambient temperatures. Market may not support development cost of components.

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment, and from company announcements and websites.

about 4.5 percent annually from 2015 to 2050.[46] From 2015 to 2050, HFC use in this sector in non-Article 5 Parties and Article 5 Parties is expected to grow 2.0 percent annually and 5.6 percent annually, respectively.[47] The air-conditioning sector can be categorized into three subsectors:

- **Stationary air-condition systems** are used for residential, commercial, and industrial cooling applications.
- **Chillers** are used for building air conditioning and industrial cooling applications.
- **Mobile air-conditioning systems** are used for mobile applications.

As shown in Figure 4, growth in this market is primarily driven by stationary air conditioning (e.g., air-to-air) systems in Article 5 Parties.[48]

HCFC-22 (R-22) and HFC refrigerant blends (e.g., R-410A) are primarily used in stationary air conditioning systems in most countries throughout the world today. In non-Article 5 Parties, demand for low-GWP refrigerants increases rapidly after 2020 because of the European Union F-gas regulation and U.S. SNAP regulations. There are a range of substitutes available in the air conditioning sector. Hydrocarbons are used in air conditioning systems with smaller charges while R-744 can be used in larger air conditioning systems.

Stationary air conditioning

Stationary air conditioning is the largest and the fastest growing sector.[49] The stationary air conditioning sector is made up three broad categories:

- **Self-contained air-conditioning systems** includes sealed units used for cooling small rooms in residential and commercial buildings.
- **Split air-conditioning systems** includes small split air systems that used to cool single rooms in residential and commercial buildings.
- **Large air-conditioning systems** includes large- and multi-split systems, VRF systems, and ducted and packaged rooftop systems that cool air supplied to a room or to a whole building.

LOWER GWP HFCS, HFOS, AND BLENDS UNDER CONSIDERATION

A number of lower-GWP HFCs and HFOs alone or in blends with HFCs are being used or are under development in air conditioning systems since they offer lower flammability and performance equal or better than R-410A.

For small self-contained air conditioning systems and small split air-conditioning systems, lower GWP HFC-32 (GWP equals 677 with 20 percent reduced charge) units are widely available—since they can be used under existing safety codes and standards and are produced by a number of manufacturers in Asia, Australia, Europe, the Middle East, and North America. Over the past few years, HFC-32 has been rapidly gaining market share particularly in room air conditioning with cooling capacity greater than about 1.5 tonnes where the amount of HC charge necessary to achieve energy efficient cooling capacity would be a safety concern if released into the occupied space. About 17 million HFC-32 units have been sold worldwide.[50] For manufacturers with exports to Europe, the E.U. F-Gas Regulation is seen as a strong driver for hydrocarbon use in portable self-contained units.

In addition, several HFO/HFC blends have been developed and are being considered for small split air-conditioning systems. For large air conditioning (air-to-air) systems, HFO-1234yf and HFO-1234ze are also being considered for use in ducted and roof-top units, but are not yet commercially available.

USE AND AVAILABILITY OF NIKS

The European Union F-Gas Regulation has driven the transition from high-GWP refrigerants to low-GWP refrigerants such as hydrocarbons. Hydrocarbons are widely used in air-conditioning systems with smaller charge sizes. Portable units utilizing HC-290 are widely available and window units using HC-290 are in production in Asia.[51]

Split air-conditioning systems using HC-290 are also widely available in Europe, Australia, and parts of southeast Asia. These systems are in production in India, and China has recently completed conversion of 18 production lines from HCFC-22 to HC-290 as part of their HCFC Phase-out Management Plan (HPMP).[52] Efforts are underway to better assess the risk and to establish standards and best practices of using hydrocarbons in larger charge systems.

Carbon dioxide can be used in large air conditioning systems, however the low critical temperature of carbon dioxide may not be a good option in warmer climates due to reduced efficiency and higher cost.[53] Several

TABLE 6: Indicative List of Low-GWP Alternatives for Chillers

TYPE	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMA-BILITY‡	COMMENTS
HFCs	HFC-32	A2L	677 (and 20% reduced charge)	2L	Available in small- and medium-sized chillers with positive displacement compressors.
HFOs	HFO-1233zd	A1	1	1	Available in Europe.
	HFO-1336mzz	A1	2	1	U.S. EPA SNAP approved in 2016.
	HFO-1234ze	A2L	<1	2L	Available in small- and medium-sized chillers with positive displacement compressors.
HFO/HFC Blends	R-446A R-447A R-454B	A2L A2L A2L	460 570 470	2L 2L 2L	Newly developed blends being considered for small- and medium-sized chillers.
	R-450A R-513A R-513B	A1 A1 A1	550 570 540	1 1 1	Possible alternatives for ducted and packaged roof top units.
HCs	HC-290 HC-1270	A3 A3		3 3	Suitable for medium- and large-sized chillers; available widely in Europe.
Ammonia	R-717	B2L		1	Suitable for medium- and large-sized chillers with screw compressors; Limited to chillers with small capacities due to costs.
Water	R-718	A1		1	Can be used in chillers with centrifugal compressors, but requires very large compressor swept volume.

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment, and from company announcements and websites.

companies within European are producing split ducted and rooftop systems using R-744 as a refrigerant. And two companies are producing multi-split air conditioners using R-744 for northern temperature climates.

Chillers

Chillers make up about 8.4 percent of global HFC consumption in 2012.[54] The chiller sector can be categorized into two broad categories:

- **Small- and medium-sized chillers** that use a direct expansion evaporator and air-cooled condenser.
- **Large-sized chillers** that use a flooded evaporator, a water-cooled condenser and a large screw or centrifugal compressor.[55]

Chillers have used an array of refrigerants due to the economics associated with the performance of compressors as well as the physical size of the units and manufacturing constraints over the range of capacities provided by chillers.[56] A range of low-GWP substitutes are available for use in chillers. NIK alternative refrigerants, particularly R-717, are widely used.

HFOS AND BLENDS UNDER CONSIDERATION

Chillers using a number of HFOs have become commercially available in the last few years. For medium-sized chillers with positive displacement compressors and large-sized chillers with centrifugal compressors, HFO-1234ze is now being used.[57] HFO-1233zd is considered a key alternative for low pressure centrifugal chillers and is commercially available in Europe.[58] HFO-1336mzz has been introduced for industrial chillers, and has been approved by the U.S. SNAP program for use in new chillers.[59]

In small- and medium-sized chillers using scroll compressors, HFC-HFO blends like R-452B are being introduced. These high-pressure systems are able to use the same refrigerants as direct space cooling air conditioners like room ACs.

USE AND AVAILABILITY OF NIKS

Generally, chillers are located in a machinery room or outside, making it easier to deal with safety issues related to toxicity and flammability of low-GWP refrigerants. Hydrocarbons are suitable for smaller-sized chillers, and are produced by a number of manufacturers in Europe and in other regions. HC-290 is used in chillers in industrial applications, and HC-290 and HC-1270 are used in a limited number of small air-cooled chiller installations in Europe.[60] Hydrocarbons used in centrifugal chillers are typically limited to the petrochemical industry due to safety concerns.

There are a number of NIK alternatives for medium- and large-sized chillers. R-717 (ammonia) is used fairly widely in medium- and large-sized chillers with screw compressors. R-717 chillers are being used in Europe, the Middle East, China, and the United States.[61] R-718 (water) is used in centrifugal chillers in Europe and is commercially available in Japan. R-744 is available in positive displacement chillers by many manufacturers.[62] Some Article 5 Parties (e.g., Indonesia, Malaysia, and the

TABLE 7: Low-GWP Alternatives for Mobile Air Conditioning

TYPE	CHEMICAL	SAFETY CLASS*	GWP†	FLAMMABILITY‡	COMMENTS
HFCs	HFC-152a	A2	138	2L	TATA Motors Limited (TML)/MAHLE/IGSD demonstration project using secondary loop system.
HFOs	HFO-1234yf	A2L	<1	2L	Widely used in Europe and North America.
HFO Blends	R-444A R-445A	A2L A2L	89 120	2L 2L	Blends considered for cars.
	R-446A R-447A R-454B	A2L A2L A2L	460 570 470	2L 2L 2L	Blends being considered for large vehicles.
Carbon Dioxide	R-744	A1	1	1	Mobile air-conditioning systems under development for passenger cars by Audi and Daimler and currently in use for tested by some buses in Germany.

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

Source: Compiled from "Decision XXVII/4 Task Force Report Further Information on Alternatives to Ozone-Depleting Substances," Report on the Technology and Economic Assessment, and from company announcements and websites.

Philippines) are utilizing hydrocarbon chillers for large space cooling needs.[63]

Mobile air conditioning

Mobile air-conditioning systems (MAC) make up about 17 percent of current HFC consumption (in terms of tonnes of CO_2-equivalent) and is projected to grow about 2.9 percent annually from 2015 to 2050.[64] MAC refrigerant consumption is projected to be driven by growth in developing countries. In response to the Montreal Protocol phaseout of CFC-12, all global vehicle manufacturers shifted to HFC-134a, and now in response to regulations in Japan, Europe, and North America all manufacturers are shifting to HFO-1234yf with the exception of Audi and Daimler that plan to offer CO_2 systems as an option on some vehicles in 2017. U.S. EPA SNAP has approved CO_2, HFC-152a, and HFO-1234yf and all qualify for use under European Union requirements that the refrigerant have a GWP less than 150.

MAC systems can be categorized into two sectors:

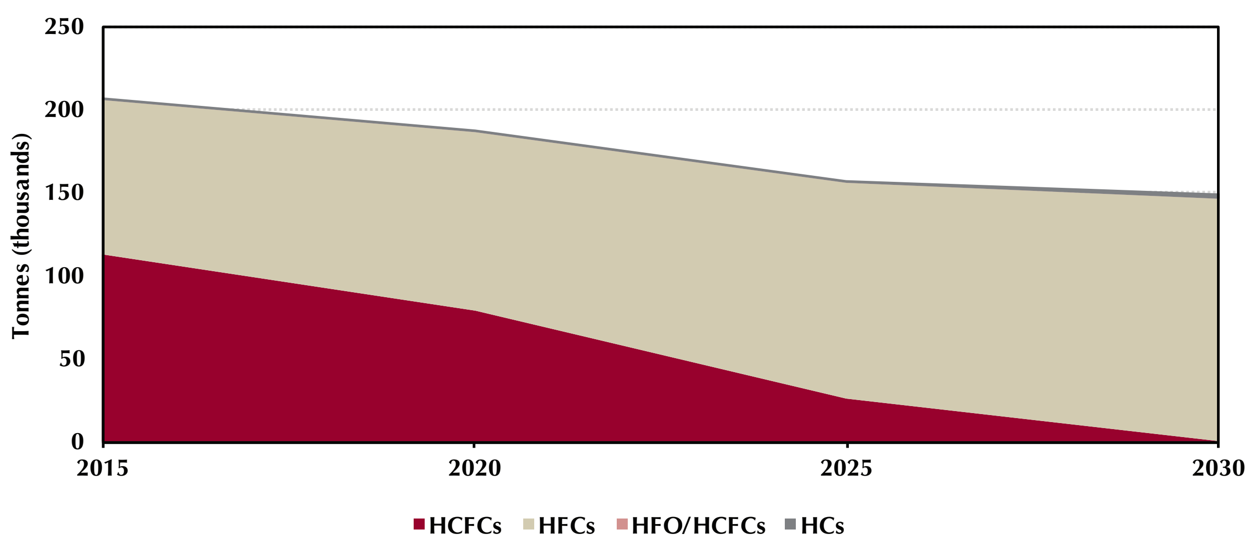
- **Mobile air-conditioning systems** used in passenger vehicles.
- **Transport air-conditioning systems** used in other vehicles (e.g., trucks, trains, airplanes and buses).

HFOS AND BLENDS UNDER CONSIDERATION

HFO-1234yf has become the dominate replacement for HFC-134a MAC systems, but other alternatives are at various stages of development. Demand for HFO-1234yf has been influenced by a number of national and regional regulations phasing out HFC-134a, such as:

- The European Union's 2006 MAC Directive banning the use of any use of any refrigerant in MAC systems with a GWP greater than 150 starting in 2017;
- The U.S. CAFE standard and greenhouse gas greenhouse gas emission standards for passenger vehicles which provides fuel efficiency credits for vehicles using refrigerants with a GWP less than HFC-134a, and a 2011 EPA SNAP rule which lists HFO-1234yf as an acceptable alternative in MAC systems and a 2015 rule require phasing out the use of HFC-134a as a refrigerant in MAC systems in new passenger vehicles starting as of model year 2021;
- Canada's proposed HFC regulations which would phase out the use of HFC-134a as a refrigerant in MAC systems in new passenger vehicles starting as of model year 2021;

FIGURE 5: Blowing Agent Demand in the PU and XPS Foam Sectors (tonnes CO_2-eq)



Source: UNEP Technology and Economic Assessment Panel, Decision XXV/5 Task Force Report: Additional Information on Alternatives to ODS (Final Report) (Nairobi, Kenya: United Nations Environment Programme Ozone Secretariat, 2014), http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports/TEAP_Task%20Force%20XXV5-October2014.pdf.

- Japan's updated fluorocarbon regulation target GWP of 150 by 2023; and
- The Republic of Korea will begin the transition to HFO-1234yf in 2017.

More than 20 automakers have equipped almost 80 vehicle models, primarily in non-Article 5 Parties, with HFO-1234yf air conditioning systems. By the end of 2016, 18 million vehicles are projected to be on the road worldwide with HFO-1234yf as their coolant.[65]

It is expected that as GWP limits are applied to vehicles larger than passenger cars and light trucks, HFO-1234yf systems will also be introduced for heavy-duty trucks.

USE AND AVAILABILITY OF NIKS

A number of NIK alternatives are being considered for MAC systems. Due to flammability concerns with HFO-1234yf, several German automobile manufacturers (e.g., Audi, and Daimler) have announced plans to deploy cars using R-744 as their coolant in 2017. In India, TML/MAHLE/IGSD have received funding for a demonstration project of a secondary loop MAC system using both HFC-152a and HFO-1234yf. A secondary loop system allows for safe use of flammable refrigerants since the system uses a smaller refrigerant charge that is separated from the passenger compartment.[66] In addition, hydrocarbons are not considered a viable refrigerant option by car manufacturers due to flammability concerns, but may be viable for electric vehicles and hybrid vehicles with hermitically sealed refrigerant systems.

For large vehicles, R-744 MAC systems are available for buses and are being experimentally used by buses in one city in Germany.[67]

FOAM SECTORS

The foam sector accounted for about 7 percent of global HFC consumption.[68] While HFC consumption (in terms of tonnes) in the foam sector is expected to grow about

TABLE 8: Low-GWP Alternatives for PU Foam

FLUID FAMILY	CHEMICAL	GWP*	FLAMMABILITY†	COMMENTS
HFOs	HFO-1336mzz	2	Non-flammable	Expected to be commercially available in 2017.
	HFO-1234ze HFO-1233zd	<1 1	Non-flammable	Commercially available.
HCs	c-pentane Iso-pentane n-pentane Blend of pentanes Propane/butane	5 5 5 5 3	Flammable	Commercially available; widely used in developed countries.
Oxygenated HCs	Methyl formate	<25	Flammable	Commercially available; increasing uptake; ingredients are flammable until blended by foam system houses, which is an advantage to small- and medium-sized enterprises (SMEs).
	Methylal	<25	Flammable	Commercially available; slow uptake.
Carbon Dioxide	CO_2	1	Non-flammable	Commercially available; widely used.
	CO_2 with co-blowing agent	1	Flammable	Commercially available; widely used.
	Supercritical CO_2	1	Non-flammable	Commercially available; Used by one company in Japan.

* Based on 100-year GWP potential.

† Flammability as classified by UNEP.

Source: UNEP Ozone Secretariat, Insulating Foam, Fact Sheets on HFCs and Low GWP Alternatives (Nairobi, Kenya: United Nations Environment Programme, 2015), http://ozone.unep.org/sites/ozone/files/Meeting_Documents/HFCs/FS_13_Insulating_Foam_Oct_2015.pdf.

1.8 percent annually from 2015 to 2030, consumption in terms of kilotonnes of CO_2-equivalent is expected to decline about 2.2 annually during this period resulting from a shift to lower GWP alternatives.[69]

The foam sector can be categorized into two broad categories:

- **Polyurethane (PU) type** foams.
- **Extruded polystyrene (XPS)** foam.

As shown in Figure 5, hydrocarbons have been widely used in the foam sector to replace CFCs and HCFCs, making up over 50 percent of consumption in 2014 and are projected to make up about 56 percent of consumption in 2020.

Polyurethane (PU) Foam

PU foam makes up about 40 percent of current blowing agent consumption (in terms of tonnes of CO_2-equivalent) and is projected to grow slightly from 2015 to 2030.[70] During this period, Article 5 Parties are projected to reduce consumption at about 5.4 percent annually while non-Article 5 Parties are projected to increase consumption at 1.9 percent annually.

The main applications of PU foam include: insulation for appliances (e.g., refrigerators, retail displays), panels and boards used for insulation, rigid panels used for insulation, block foam used for pipe and vessel insulation, spray foam used for insulation, and integral skin foams.

As shown in Table 8, a range of low-GWP alternatives are currently used as a blowing agent for PU-type foams. Hydrocarbons are primarily used for PU-type appliances, board, panels, and block foams.

HFOS UNDER CONSIDERATION

HFOs are becoming available as a low-GWP alternative blowing agent for PU-type foams. For instance, HFO-1233zd has been commercialized by a handful of companies and is available worldwide, with an economic advantage in markets demanding high appliance energy efficiency since it is less thermally conductive than other low-GWP options.[71] HFO-1366mzz has undergone pilot production and is expected to be widely available in 2017.[72] Depending on their relative costs and performance characteristics, the improved thermal efficiency of HFOs could displace some elements of hydrocarbon and carbon dioxide in certain applications, especially for some types of spray foam. However, cost and limited supply have limited adoption of HFOs.

USE AND AVAILABILITY OF NIKS

Because of their low blowing agent cost, hydrocarbons are widely applied in PU type foams, except as a blowing agent for spray foam due to flammability concerns. Hydrocarbons are extensively used for high-volume PU-type foam products (e.g., continuous board, panel manufacturing). In Article 5 Parties, transitions to low-GWP blowing agents is being driven by the enactment of Decision XIX/6 and is being funded under national HCFC Phase-out Management Plans (HPMPs). The phase-out of high GWP HCFC-141b has been targeted as part of Stage I HPMPs and has been broadly successful in larger enterprises that have invested in hydrocarbons.[73] However, because hydrocarbons require sizable capital investments to deal with flammability and safety concerns, they

TABLE 9: Low-GWP Alternatives for XPS Foam

FLUID FAMILY	CHEMICAL	GWP*	FLAMMABILITY†	COMMENTS
HFOs	HFO-1234ze	<1	Non-flammable	Commercially available; used in Europe.
HCs	Propane/butane		Flammable	Commercially available; widely used in Japan by large producers.
Oxygenated HCs	Dimethyl ether		Flammable	Commercially available; used as co-blowing agent.
Carbon Dioxide	CO_2	1	Non-flammable	Commercially available; widely used in Europe.

* Based on 100-year GWP potential.

† Flammability as classified by UNEP.

Source: UNEP Ozone Secretariat, Insulating Foam, Fact Sheets on HFCs and Low GWP Alternatives.

are primarily used by large factories and have limited use by small- and medium-sized factories.

Use of methyl formate as a co-blowing agent is increasing around the world for pour-in-place applications of spray foams and integral skin foams. The flammability risk of this alternative can be reduced for small- and medium-sized producers by using pre-blended chemicals.[74]

Excluding PU board foam, R-744 is a viable blowing agent for most foams products. R-744 application in PU integral skin foam is cost-effective for medium- and large-sized applications.[75] As such, R-744 is extensively used for microcellular elastomers (e.g., shoe soles). Spray foam with supercritical R-744 foam technology has been produced since 2003, but is only used by one company in Japan.[76]

Extruded polystyrene (XPS)

XPS makes up about 60 percent of current blowing agent consumption (in terms of tonnes of CO_2-equivalent) and is projected to decrease about 4.6 percent annually from 2015 to 2030.[77] Reductions in future growth in HFC use can be achieved primarily by Article 5 Parties shifting from HCFCs to low- and zero-GWP alternatives. XPS has been the most prevalent user of HCFCs (e.g., HCFC-142b and HCFC-22) within the foam sector due to price and availability.[78] As shown in Table 9, there are several low-GWP alternatives being used as a blowing agent for XPS foam. Use of these technologies vary by region.

HFOS UNDER CONSIDERATION

HFO-1234ze is commercially available as a blowing agent for XPS foam and has been used in Europe. The European F-Gas Regulation and the U.S. SNAP program banning the use of HFCs for XPS are expected to further drive adoption of low-GWP blowing agents for XPS.[79] In addition, the Protocol's Multilateral Fund recently funded a pilot project in Turkey to assess the use of HFO-1234ze for XPS foam in Article 5 Parties. Moreover, the second phase of HPMPs are expected to drive the transition to low-GWP blowing agents in many Article 5 Parties.[80]

USE AND AVAILABILITY OF NIKS

There is widespread use of R-744 and R-744 blends as blowing agents for XPS board foam in Europe by large producers. However, the resulting foam is not as versatile (e.g., it has reduced thermal insulating characteristics) and is unsuitable for certain XPS product types. Blends of saturated HFCs (e.g., HFC-134a/HFC-152a) have been used primarily in North America and Europe by small producers who do not have access to R-744 technology.[81]

Use of hydrocarbons as a blowing agent for XPS board foam is almost exclusively limited to Japan. Dimethyl ether (DME) is an oxygenated hydrocarbon that is often used as a co-blowing agent with R-744 or HFO-1234ze to produce XPS foam board.[82]

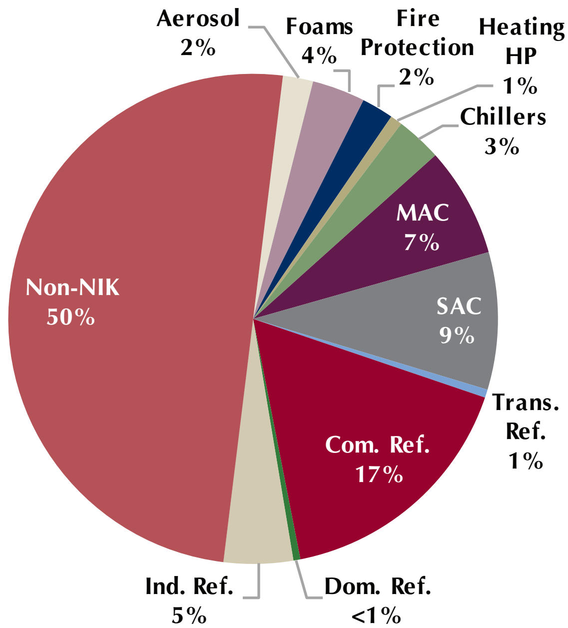
SUMMARY OF NIK SUBSTITUTION OPPORTUNITIES

Overall, the opportunity exists for a significant percentage of current HFC use to transition to NIK alternatives during the anticipated Montreal Protocol phasedown of HFCs. Based on the sector-by-sector analysis presented in this paper, the potential role of NIKs in an HFC phase down can be estimated.

While the distribution of HFC use will change over time as HFC consumption grows, particularly in developing countries, the current NIK opportunities provide a useful starting point for this analysis. As developing countries continue their growth, the distribution of HFC-consuming sectors will shift predominantly *toward* applications that can be met by NIK solutions, such as small-room air conditioners and refrigerators prevalent in emerging markets. Therefore, using the distribution of HFC-consuming sectors in 2012 may result in a conservative estimate of the total NIK opportunity during the expected HFC phasedown. The estimate also assumes that codes and standards remain as they are today; in reality, numerous efforts are underway to relax restrictions on hydrocarbon alternatives.

Based on the availability and current use of NIK alternatives described above, each of the sectors contribute the following potentials for NIK solutions. High (70 percent): domestic refrigeration, industrial refrigeration, commercial refrigeration, and fire protection; Medium (50 percent): aerosols and foams; and Low (20 percent): heating heat pumps, chillers, MAC, stationary AC, and

FIGURE 6: NIK Substitution Opportunities



Based on the 2012 distribution of HFC use, the total NIK opportunity stands at 50 percent.

transportation refrigeration. This estimate also assumes an overall decrease in HFC servicing emissions of 33 percent—reducing the overall leakage component of the refrigeration and air conditioning sectors' HFC consumption from 60 percent to 40 percent.[83] Figure 6 compiles those fractions into the overall NIK opportunity.

Worthy of note is that stationary AC—the largest sector of HFC use in 2012 at 25 percent—is listed as a low-NIK potential sector, offering just 20 percent NIK opportunity. This is largely due to the fact that in 2012, most of the air conditioners using HFCs were found in developed countries in configurations unfriendly to NIK alternatives. In addition, safety standards remain strict on the use of hydrocarbons in air-conditioning applications. The emergence of large markets for small-room air conditioners in India and other fast-growing markets, alongside current efforts to reexamine international safety standards, will drive the potential shift to NIKs upward. As such, the contribution to NIKs in air conditioning is likely to be much higher and the resulting overall 50 percent estimate of current opportunities represents a conservative assessment of the potential role of NIKs in the coming transition.

CONCLUSIONS

In the absence of an HFC phasedown amendment, future growth in HFCs would continue with over 80 percent of use in 2050 expected in Article 5 Parties. In past transitions under the Montreal Protocol, NIK alternatives including non-fluorocarbon substitutes, recycling and recovery, and emission reductions have reduced reliance on ODSs by as much 85 percent. A number of low-GWP alternative to HFCs are already commercially available across a large number of sectors and regions. Analyzing currently available non-fluorocarbon substitutes and opportunities to reduce emissions, the potential to shift to NIKs can be conservatively estimated at 50 percent. National and regional regulations in the European Union, the United States, Japan, and Canada have and will continue to drive the expanded use and drive down the costs of alternatives in the near term in these countries and likely result in additional opportunities to shift to NIK over time.

By providing a broader range of alternatives, NIKs alternatives provide market and price competition to patent-controlled next generation HFOs, and in some cases offer greater energy efficiency. In addition, NIK alternatives can help Article 5 Parties leapfrog from HCFCs to low-GWP alternatives. Efforts are underway but will require several more years to address changes in codes and standards to ensure a wider range of more flammable alternatives can be used safely.

APPENDIX A: ALTERNATIVES AND SUBSTITUTES FOR OZONE-DEPLETING SUBSTANCES: PAST TRANSITIONS

SECTOR	IN-KIND FLUORO-CARBON	NOT-IN-KIND		CONTAIN, RECOVER & RECYCLE
		NON-FLUOROCAR-BON CHEMICAL	NON-CHEMICAL SUBSTITUTE	
Refrigeration	HFCs & HFOs	Ammonia, CO_2, Hy-drocarbons	Magnetic, Thermo-Acoustic	Near-Zero Emissions; near zero emissions at end of useful life.
Air Conditioning	HFCs & HFOs	Ammonia, CO_2, Hydrocarbons, & Evaporative Cooling	Landscaping, Shad-ing, & Ventilation	Near-Zero Emissions; near zero emissions at end of useful life.
Electronics	HFCs, HFEs, & HFOs	Hydrocarbons, Aque-ous, Semi-Aqueous	No-Clean Soldering, Conductive adhe-sives,	N.A.
Aerospace	HFCs, HFEs, & HFOs	Hydrocarbons, Aque-ous, Semi-Aqueous		N.A.
Fire Protection	HFCs	Water, Water Mist, Dry Powder, Foam, Inert Atmosphere	Eliminate Fuel and Ignition	Near-Zero Emis-sions—Halt testing, training, & accidental discharge; recover and destroy when alternatives available.
Metered-Dose Inhal-ers (Asthma & COPD)	HFCs	Dry-Powder Inhalers (DPIs), oral and inject-able drugs	N.A.	
Thermal Insulating Foam	HFCs & HFOs	Hydrocarbons, Meth-yl Formate, Water	Mineral Wool, Fiberglass, Cellulose, Plastic Fiber, Wool, Cotton, Hemp, Straw, Vermiculite, and Perlite, Cementitious Foam	

APPENDIX B: CHEMICALS AND BLENDS & THEIR KEY CHARACTERISTICS

	CHEMICAL	CHEMICAL FORMATION	SAFETY CLASS*	GWP†	FLAMMABILITY‡
HCs	HC-1270	$CH_3CH=CH_2$	A3	0	3
	HC-290	$CH_3CH_2CH_3$	A3	0	3
	HC-600a	$CH(CH_3)_2\text{-}CH_3$	A3	0	3
HFCs	HFC-134a	CH_2FCF_3	A1	1,300	1
	HFC-152a	CH_3CHF_2	A2	138	2
	HFC-32	CH_2F_2	A2L	677	2L
HFOs	HFO-1233zd	$CF_3CH=CHCl$	A1	1	1
	HFO-1234yf	$CF_3CF=CH_2$	A2L	<1	2L
	HFO-1234ze	$CF_3CH=CHF$	A2L	<1	2L
	HFO-1336mzz(Z)	$CF_3CH=CHCF_3$	A1	2	1
Blends	R-290	$CH_3CH_2CH_3$	A3	0	3
	R-441A	R-170/290/600a/600 (3.1/54.8/6.0/36.1)	A3	5.6	3
	R-444A	R-32/152a/1234ze(E) (12.0/5.0/83.0)	A2L	89	2L
	R-445A	R-744/134a/1234ze(E) (6.0/9.0/85.0)	A2L	120	2L
	R-446A	R-32/1234ze(E)/600 (68.0/29.0/3.0)	A2L	460	2L
	R-447A	R-32/125/1234ze(E) (68.0/3.5/28.5)	A2L	570	2L
	R-448A	R-32/125/1234yf/134a/1234ze(E) (26.0/26.0/20.0/21.0/7.0)	A1	1,300	1
	R-449A	R-32 /125 /1234yf /134a (24.3/24.7/25.3/25.7)	A1	1,300	1
	R-449B	R-32/125/1234yf/134a (25.2/24.3/23.2/27.3)	A1	1,300	1
	R-450A	R-134a/1234ze(E) (42.0/58.0)	A1	550	1
	R-451A	R-1234yf/134a (89.8/10.2)	A2L	140	2L
	R-451B	R-1234yf/134a (88.8/11.2)	A2L	150	2L
	R-452A	R-32/125/1234yf (11.0/59.0/30.0)	A1	1,900	1
	R-454A	R-32/1234yf (35.0/65.0)	A2L	240	2L
	R-454B	R-32/1234yf (68.9/31.1)	A2L	470	2L
	R-455A	R-744/32/1234yf (3.0/21.5/75.5)	A2L	150	2L
	R-513A	R-1234yf/134a (56.0/44.0)	A1	570	1
	R-513B	R-1234yf/134a (58.5/41.5)	A1	540	1
Ammonia	R-717	NH_3	B2L	0	1
Water	R-718	H_2O	A1	0	1
Carbon Dioxide	R-744	CO_2	A1	1	1

* ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 higher toxicity/higher flammability.

† Based on 100-year GWP potential.

‡ Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.

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