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To California Air Resources Board

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Subject Senate Bill (SB) 1206 Assessment Report for Transitioning Hydrofluorocarbons (HFCs)

to Ultra-Low Global Warming Potential (GWP) and/or No-GWP Alternatives:

Request for Information (RFI)

Climate Action California and 350 Humboldt – with nearly 9,000 supporters around our state – and Environmental Action Germany (Deutsche Umwelthilfe) are grateful for the opportunity to comment on the SB 1206 RFI. We applaud your efforts to assess how California can transition away from HFCs toward ultra-low- and no-GWP alternatives no later than 2035. Our comments divide between policy recommendations and technical responses to specific questions. We did not provide comments on Sections 7 and some individual questions but have kept the numbering of the RFI for all responses.

# Our overall perspective:

1. California climate programs have a multiplier effect since they are replicated by other states in the U.S. Climate Alliance and eventually the U.S. EPA. CARB’s 2020 regulations on refrigerants (and earlier regulations) have already served as the model for New York, Washington State, and the U.S. EPA. Therefore, it is critical that the SB 1206 plan for eliminating HFCs by 2035 be as stringent as possible.
2. Fast reductions in high-GWP short-lived climate pollutants such as HFCs and methane are our best opportunity to limit warming to 1.5°C and reduce the probability of reaching near-term climate tipping points. Although we are grateful for SB 1206’s requirement to plan to eliminate all but ultra-low- and/or no-GWP alternatives no later than 2035, we encourage CARB to aim for 2030, as reductions in state, national, and global reductions in CO2 are far behind what is needed to limit warming to 1.5°C, and there’s an inevitable lag in how quickly other jurisdictions can adopt CARB requirements. A 2030 target also aligns with the Global Methane Pledge and its goal to prevent more than 8 gigatons of carbon dioxide equivalent (CO2e) emissions from reaching the atmosphere annually by 2030.
3. Europe has been several years ahead of the U.S. on decarbonization, in particular on limiting emissions from refrigerants. With their new F-gas regulations, they have taken a decisive step, elements of which California could use as a model.[[1]](#footnote-1)
4. Natural refrigerants should be required over HFOs and low-GWP HFCs, as some are PFAS (per- and polyfluoroalkyl substances) with human health and ecosystem risks. PFAS are currently being regulated by the U.S. EPA, California, and other states, and are likely to be banned here as they are proposed to be in Europe.[[2]](#footnote-2) Much environmental and human health damage can be averted by CARB giving clear early signals to the market that the future belongs to propane, CO2, ammonia, and other no-GWP alternatives. Equipment should be replaced only once rather than replacing it to accommodate HFOs and HFO-based A2Ls and then again when HFOs are banned due to PFAS concerns. A recent report conducted for the New York State Department of Environmental Conservation (NYSDEC) lays out the current state of technology, policy recommendations and considerations, and ideas for pilot projects for natural refrigerants, addressing many of the issues raised in the RFI.[[3]](#footnote-3)
5. A major problem CARB faces is slow-moving and sometimes obstructionist regulatory bodies in the U.S.[[4]](#footnote-4) For example, after years of study the International Electrotechnical Commission issued IEC 60335-2-40, which increases the amount of propane allowed in heat pumps to 988 grams under new safety standards. Yet it is likely that under current regulatory regimes it will take more years for this standard to be adopted here. This means CARB should take new steps speed up these processes. These could include filing petitions with the U.S. EPA or simply sidestepping the approvals of voluntary bodies in favor of international bodies.
6. Grants, financing, and other incentives are needed to accelerate the turnover of commercial refrigeration systems for “mom and pop” stores and those located in CalEnviroScreen disadvantaged communities. This can be accomplished by aligning funding for HFC mitigation efforts (which have historically received less than 0.001% of the state’s climate mitigation budget) with their climate impacts (5% using 100-year GWPs, nearly 10% using 20-year GWPs).
7. Increasing the ambition of the existing Refrigerant Recovery, Reclaim, and Reuse (R4) Program requirements for usage of recovered R-410 by new air conditioning and variable refrigerant flow equipment manufacturers and expanding to servicing, other high-GWP gases, and additional end-uses would de-incentivize illegal venting, incentivize end-of-live recovery, and reduce demand for virgin high-GWP refrigerants.
8. CARB should include non-HFC refrigerants, foam-blowing agents, propellants, termite fumigants, etc. in its assessment as they are part of the existing banks of high-GWP gases that will be emitted over the coming decades and continue to make a large collective contribution to the overall carbon footprint of F-gases. These include CFC, HCFC, PFC, NF3, SF6, and SO2F2, many of which are already part of CARB’s emission inventory, reporting requirements, and regulatory programs but are like HFC in that they were not addressed in the 2022 Scoping Plan Update. Including these additional F-gases would make for a more complete assessment in that they are part of many of the same economic sectors as HFC.
9. CARB collects a wealth of F-gas sales, equipment sales, and commercial refrigerant leakage data each year, and has access to atmospheric measurements of all major F-gases from the NOAA monitoring network and its own monitoring program, but this data is neither shared publicly nor analyzed on a consistent basis. More frequent (and public) tracking of overall progress toward the 2030 HFC reduction target using this data and comparison against CARB’s emission inventory estimates could help identify areas of success, remaining challenges, and mitigation opportunities for both the overall F-gas mitigation program and individual sectors and gases.
10. The non-profit Federally Funded Research and Development Center (FFRDC) Aerospace Corporation in El Segundo, CA has demonstrated rapid detection of F-gas high-emitters in airborne surveys over Los Angeles, San Francisco, and New York City using longwave-infrared hyperspectral imaging (LWIR-HSI) sensor systems. This is similar to the AVIRIS‑NG technology that CARB has funded demonstrations for identification and mitigation of methane high-emitters and is being miniaturized for deployment on satellites for global methane leak detection. As has been observed statewide and across all sectors for methane, a relatively small number of HFC-134a, HFC-152a, HCFC-22, CFC-11, and SO2F2 high-emitters dominate the overall emissions for these gases in Los Angeles. The Aerospace Corporation has offered to share data from 2010 through 2023 with CARB (gratis) so that the individual facilities can be identified. These high emission sources are likely violating existing regulations or present opportunities for additional mitigation, and efforts to eliminate or reduce these emissions (and expansion of airborne surveys to other parts of California) should result in major reductions. (See more detail in Appendix 2: Rapid Measurement Surveys of F-Gas High-Emitters.)

Section 1: Commercial and Industrial Stationary Refrigeration (Retail Food, Cold Storage, Industrial Process Refrigeration, and Ice Rinks)

* What potential technological solutions are available for existing facilities and how can their adoption be accelerated?
* Both full-store remodels using CO2 and case-by-case replacements using self-contained propane equipment are available. The problem is that existing regulations do not require ultra-low-GWP or no-GWP refrigerants for existing supermarkets. Section 39735 (f) requires: “the state board shall initiate a rulemaking requiring low or ultra-low-GWP alternatives to hydrofluorocarbons in a sector unless it is not practicable for entities in the sector to comply with the requirement.” Therefore, step one is revise the regulations and require ALL supermarkets to use only natural refrigerants by 2030. In Europe, the use of natural refrigerants in new supermarket equipment is the state-of-the-technology, which demonstrates that the transition toward natural alternatives is possible with commercially available equipment. In addition, the definition of retail stores should be expanded to include convenience stores.
* This process will be regularized and speeded up if the provision in existing regulations defining what is a “new” system is redefined so that any major repair or replacement of a condenser, compressor, or other major component of the HFC system is defined as a “new” system and thus must meet the 150-GWP requirement for new systems. Since most stores have several systems, this will not necessarily result in a complete redesign unless the choice is to use CO2. That is, if modular propane units are installed it can be system-by-system, putting less financial strain on the store and easing the disruption of construction.
* Propane has been evaluated as a refrigerant to replace HFCs for extremely low temperature storage of medicines and vaccines.[[5]](#footnote-5) Even for ultra-low temperatures, F-gas-free technologies for down to minus 110°C are available using natural refrigerants like air.[[6]](#footnote-6)
* What incentives are needed to transition existing refrigeration facilities and what GWP limit should be set for technologies supported through incentives?
* One way of doing this is to use the CPUC Refrigerant Avoided Cost Calculator to generate funds for a large-scale pilot project in CalEnviroScreen communities. Draft legislation to that effect is attached as Appendix I. (This would fit the CPUC “market transformation initiative (MTI)” model. There is a recently completed evaluation framework for MTIs.[[7]](#footnote-7))
* A more general approach is for CARB to work directly with electrical providers (utilities) to help them implement an incentives program modeled on the SMUD program. Key features would include:

a. Natural refrigerants only;

b. A process goal is to “build a network of manufacturers, engineers, technicians, and customers;"

c. End the expensive cycle of refrigeration system upgrades and retrofits due to refrigerant phase outs and replacements with a permanent long-term solution;

d. Physical system change must be made that prevents reverting to high-GWP refrigerant;

e. Require monitoring for three years, paid for by the utility in order to generate data to persuade other food retailers;

f. Use the Refrigerant Avoided Cost Calculator to set incentives; and

g. Optionally, focus on supermarkets in CalEnviroScreen communities.

* Grants, financing, and other incentives are needed to accelerate the turnover of commercial refrigeration systems for “mom and pop” stores and those located in CalEnviroScreen disadvantaged communities. This can be accomplished by aligning funding for HFC mitigation efforts (which have historically received less than 0.001% of the state’s climate mitigation budget) with their climate impacts (5% using 100-year GWPs, nearly 10% using 20-year GWPs).
* What safety testing and safety standard updates, if any, are needed for the transition to ultra-low-GWP or no-GWP alternatives in this sector?
* See the response to question no. 5 below.
* What barriers exist in bringing technologies such as ejectors, CO2 condensing units and others, to the California market, particularly for smaller refrigeration systems such as those found in convenience stores?
* The main barrier is the exclusion, heretofore, of smaller refrigeration systems from the Refrigerant Management Program and existing regulations. Smaller systems are perfect candidates for modular hermetically sealed stand-along units, which are widely available commercially in California. Including requirements for them when a new rule-making occurs will allow this to happen over a several year period.

Section 2: Stationary Air Conditioning & Space Conditioning Heat Pumps

5. There are limited ultra-low-GWP and/or no-GWP technologies for this sector. How can technological innovation be encouraged?

1. Heat pumps

* We align ourselves with the March 2023 position paper by over 45 European academic and research institution refrigerant scientists representing 24 institutions who propose the use and further development of propane rather than F-gases for heat pumps.[[8]](#footnote-8) The paper makes these key points:
* Efficiency: Propane is a highly efficient refrigerant, and this has been proven amply in practice.
* Safety: “[P]ropane and other hydrocarbons are highly flammable, and of course, this needs to be considered carefully when designing systems. The use of natural gas (e.g., LNG as fuel in cars), which is common and accepted almost all over the world, involves similar risks. Hydrocarbons used in heat pumps, however, are contained in hermetic systems. International safety standards are already in place and are constantly being improved.” Propane has been used safely in heat pumps for decades, particularly air-to-water heat pumps installed outdoors, which are the most used type of heat pumps. Even for in-house installation, propane heat pumps are possible and available with adequate safety measures (e.g., ventilation tubes) to comply with safety standards.[[9]](#footnote-9)
* Availability: “A recent survey has shown that several hundred designs of hydrocarbon heat pumps from about 48 different manufacturers are commercially available in Europe. All the basic research and development work to optimize the design of heat exchangers as well as compressors using low-GWP refrigerant has been done in the past 15 years. Air-to-water heat pumps are already well established in the market. Other product groups will follow this transition and the dynamics of its demonstrated path.”[[10]](#footnote-10)
* Future: “The change to propane for indoor heat pumps is still challenging and will probably require more than three years, due to complex safety regulations and building requirements. Therefore, we argue for the early announcement of clear and ambitious fade-out dates of synthetic refrigerants, taking different development time spans for different product classes (indoor/ outdoor/ monobloc/ split/ multi-split/VRF) and application areas (residential/commercial/industrial) into account. Any development of new products should clearly focus on natural refrigerants.”
* A U.S. firm making propane heat pumps specifically made the request of CARB (in a public comment) that CARB focus development on propane: “We are a seed-stage hardware startup in San Francisco, California that is building AC/heat pump units that are easier to install and more pleasant to use. Our technology allows us to make a 9K BTU heat pump that uses 350 grams of R-290 in a safe manner by containing the refrigerant to a hermetically sealed outdoor unit. Regulation that pushes the industry towards the safe and timely uptake of units using very-low-GWP natural refrigerants would help us introduce climate-friendly heat pumps into more homes, particularly in the United States.
* New international standards for heat pumps were adopted in 2022.

“The landmark revision of the safety standard IEC 60335-2-40, which previously limited charge sizes to 334g for an A3 refrigerant in a standard-sized split system in a standard size room, was approved after a six-and-a-half-year revision process. The revised safety standard allows for using a larger charge of flammable refrigerants (up to 988g of R-290 in a standard split AC system) in new equipment designed according to certain additional safety requirements to ensure the same high level of safety as equipment using non-flammable refrigerants.”[[11]](#footnote-11) This revision will allow for heating of approximately 1000 square feet.

* A recent German research break-through may offer many new propane heat pump applications, possibly including central heating. The Fraunhofer Institute announced:[[12]](#footnote-12)

“The project goal was to develop a nearly market-ready heat pump module which uses the climate-friendly refrigerant propane, does not exceed the 150g limit for indoor use and yet still provides sufficient heat for single-family homes,” explained Dr Lena Schnabel, head of the heating and cooling department at Fraunhofer ISE. “We have now achieved this goal in cooperation with our industry partners and have given them the tools to develop a market-ready heat pump.”

Research continues on heating for multi-family homes that are easy to implement and can be broadly applied. The project aims to develop heat pump solutions for floor heating systems, central heating systems installed indoors, and heat pumps in the higher performance classes which are installed outdoors. These advances could revolutionize propane heat pumps. Funding is from the German government but only amounts to $7 million.

It seems critical that these breakthroughs be developed further and be made available in the U.S., with California taking the lead. With the information available it is not possible to judge how best to do this, but a CARB exchange with the Fraunhofer Institute could answer many questions and provide direction for CARB actions here.

* There are still research questions regarding both safety and efficiency of natural refrigerants. This research needs support. For example, in Germany a consortium of universities has been funded recently to understand the behavior of the typical oil-refrigerant mixtures in the compressor of a heat pump, something that is not currently fully understood thermodynamically but which affects heating or cooling performance.[[13]](#footnote-13) CARB could make the transition to natural refrigerants go quicker by convening a conference of refrigerant researchers to generate priorities for on-going research that would be funded through the budget. As noted elsewhere in our responses, expenditures on reducing emissions from refrigerants lag considerably behind the benefits to be created by improving and adopting natural refrigerants.

1. Air conditioning

* The goal for air conditioning should be to transition to propane. Current regulations favor HFC-32. However, creditable projections by researchers from the International Institute for Applied Systems Analysis (IIASA), the United Nations Environment Programme, and the University of Leeds, UK indicate using propane for air conditioning alone as an energy-efficient and commercially available low-GWP alternative in split ACs could avoid 0.09 (0.06 to 0.12) °C increase in global temperature by the end of the century. This is significantly more than the 0.03 (0.02 to 0.05) °C avoided warming from a complete switch to HFC-32 in split ACs.[[14]](#footnote-14) Propane also is more efficient, less expensive, and works better in warm weather.

6. What types of ultra-low-GWP technologies for this sector are available in other markets globally, but not in the U.S.? What do you see as the primary market barriers to the adoption of these technologies in the U.S.?

* “R-290 has already been frequently used in moveable air conditioners by Asian and European equipment producers for a number of years and is widely available on the European market. From 2020 onwards, R-290 is expected to be the refrigerant of choice for this type of application due to the placing on the market prohibition set out by the EU F‑gas Regulation (Annex III (point 14)). Major Asian equipment manufacturers perceived this policy measure as the main driver for the market uptake of hydrocarbon-based products. Since 2012, R-290 has also been used in commercially available split air conditioners (with cooling capacities up to 7 kW) by some major Chinese and Indian manufacturers....The actual globally installed base is over 1 million units today [2018], mainly in India (800,000) and China (latest information is that 300,000 units have been surpassed).”[[15]](#footnote-15) By 2022, 2% of split air conditioners were propane in India.
* The major barriers are within the regulatory systems. “It appears technically possible to avoid F-gases today in new single split air conditioning with a cooling capacity below 7 kW by using the refrigerant R-290 (propane), unless national legislation or codes prohibit its use. The latter has apparently prevented a large-scale rollout of such equipment in the EU so far. R-290 units provide good energy efficiency and are available at a very modest price increase that would likely disappear if mass produced and marketed at large scale.”[[16]](#footnote-16)
* To achieve the global warming reductions possible with propane in air conditioning and heat pumps, CARB is going to have to become much more proactive. We suggest developing a joint strategy for speeding regulatory approval along with the California Attorney General. The Attorney General has been critical in many climate-related decisions ranging from the current suit against fossil fuel producers to the defense of California’s priority in emissions reductions from vehicles.
* Specifically, no SNAP alternative has ever been approved by the U.S. EPA unless supported by an American chemical manufacturer. Since chemical manufacturers have no financial incentive to promote propane we have to break this pattern, which may even be a conscious design by the chemical manufacturers to create a barrier to natural refrigerants.

7. How can centralized ducted AC systems be transitioned to ultra-low-GWP or no-GWP technologies?

* Heat pumps that use propane can power centralized ducted AC systems (and heating systems) if the processing unit is located outside. They are more developed in models that heat water to be circulated in the home (hydronic) rather than forced air.[[17]](#footnote-17) ASHRAE just proposed Addendum E to amend its 15.2-2022 Safety Standard for Refrigeration Systems in Residential Applications to allow up to 4.9 kg (10.9 lbs) of flammable (A3) refrigerants like propane (R-290) in outdoor heat pumps and air conditioners in the U.S. Assuming ASHRAE approval, UL and the U.S. EPA still need to approve. CARB can get involved by lobbying for quick approval. Christina Starr of the Environmental Investigation Agency said in June, “It is totally possible to enable hydrocarbons across the [AC and heat pump] sector before the end of this decade, but we need the industry experts to get engaged and open up the discussion on this.” CARB could use membership in the UL 2-40 committee and the ASHRAE 15 committee to facilitate quick adoption. Starr added “The UL is open for proposals on this.”
* Another option is absorption heat pumps that use ammonia as the refrigerant. They are highly efficient. They are currently more appropriate for large homes (and industrial uses). Although typically powered with gas, they can be powered from solar thermal collectors. Since new homes will be required to have rooftop solar, solar power may become a feasible type of installation.[[18]](#footnote-18)
* The CEC has a $2.5 million contract with Electric Power Research Institute, Inc. to develop, test, and demonstrate ammonia- and carbon dioxide-based heat pumps in multi-family and small commercial applications to improve heating and cooling efficiencies while advancing a low global warming potential refrigerant solution. The final report is not due until January 2024, but presumably most of what they will learn has already been learned.

8. Many other countries don’t use centralized air conditioning systems. Do you have recommendations for creating a market for small self-contained modular heat pump technology (vs. central systems) in California? Please see #9.

* Also, given California’s housing shortage this combination of a two-story moveable prefabbed house and a propane heating system is intriguing:

“SOUTH KOREA: LG Electronics will launch a household energy management platform, including its ESS energy storage system and Therma V R-290 Monobloc heat pump, at IFA 2023 next month. LG’s latest HVAC and energy solutions, as well as its newest smart home appliances and services, will be featured in its prefabricated Smart Cottage at the IFA Berlin Trade Fair (September 1-5, 2023). The Smart Cottage is a two-storey, studio-style modular home with a small footprint yet boasting all the most modern appliances and facilities. It can be easily transported and placed in the desired location. To reduce environmental impact, the home’s replaceable module components have been made with low-carbon steel materials produced by POSCO, a renowned South Korean steel company. LG’s Therma V R-290 air-to-water monobloc heat pump is integrated with the ESS energy storage system to provide a convenient way to maximise the efficiency of a home’s renewable energy use, and serves as a back-up power source in the case of blackouts.”

9. Do you have recommendations for creating a market for secondary loop/indirect cooling systems in California, particularly for residential and light commercial applications?

* Creating a market for the types of propane heat pumps that exist or will exist soon depends on CARB making it very clear to manufacturers, architects, HVAC sales, and other components of the heat pump market that there will be no market for heat pumps or air conditioners unless they are propane, CO2, or ammonia based. This means rapidly passing regulations to this effect but with a several year lead-in time. In Europe, where all F-gases are soon to be banned (unless there are safety issues) it is very clear to manufacturers what the future looks like. It should look the same way in California.

10. What are the benefits of and potential for expanding the use of integrated heat pump technology (units that provide space conditioning and water heating and/or other uses) in California?

* The big advantage at the moment is that it is about the only way to get space conditioning using natural refrigerants. For some smaller spaces it is feasible. Whether there is room for innovation and growth in this market will depend on whether IEC 60335-2-40 can be approved for California. If so, that is likely to be the path that is commercialized.

11. What mechanisms, policies, and or incentives can be used to increase recovery and reuse of high-GWP HFCs from existing AC or HP systems, particularly in the residential sector?

* Unlike solar and EVs and batteries, heat pumps have not yet been greatly incentivized by the Inflation Reduction Act, so a relevant question is how to *prevent* installation of heat pumps that are not propane-based. There is only a short window, and CARB should make every effort to clear the regulatory hurdles and grow the market for propane heat pumps during this lull.[[19]](#footnote-19)
* HVAC service companies need to be incentivized, perhaps by including all high-GWP gases in the R4 program for use in subsequent servicing activities, i.e., only allow sales of recovered refrigerant.

12. What type of safety testing and safety standard updates are needed for the transition to ultra-low-GWP (such as hydrocarbons) and/or no-GWP alternatives?

* MVAC systems using CO2 or propane need additional testing. For example, mixing flame retardants with hydrocarbons may work better than mixing with other refrigerants.[[20]](#footnote-20)

# The 2022 edition of IEC 60335-2-40[[21]](#footnote-21) addresses the safety and performance of electric heat pumps, air conditioners, and dehumidifiers. It has already been unanimously approved by the International Electrotechnical Commission (IEC) National Committees and was developed by representatives of 17 countries. It does not “need” testing but the safety standards embedded in it need adoption. If this does not happen rapidly through Underwriters Laboratory, California should take the lead.[[22]](#footnote-22)

Section 3: Non-Space Conditioning Heat Pumps (Water Heaters, Clothes Dryers, Pool and Spa Heaters)

13. There are limited ultra-low-GWP and/or no-GWP technologies for these equipment types. What can be done to spur technological innovation?

* Propane heat pump dryers exist and are rated Energy Star by the U.S. EPA. If CARB acts to get these dryers made into a standard (or de facto standard) technological innovation will follow as the market will be guaranteed.

Section 4: Motor Vehicle Air Conditioning (MVAC)

15. What emerging ultra-low-GWP and no-GWP technologies show promise in integrating passenger comfort cooling and heating systems as well as thermal management for batteries and other vehicle systems and components for electric vehicles, and what barriers exist for their commercialization?

* The SAE Thermal Management Refrigerants Cooperative Research Program is investigating refrigerants for MVAC in these vehicles, but only the HFO research is adequately funded, and not the CO2 and hydrocarbon research. CARB should step in to increase funding and attention to these two sub-teams, perhaps in partnership with Tesla and other EV manufacturers.
* European car manufacturer Daimler, Mercedes, and Volkswagen use CO2 MAC systems in some of their car lines, including in electric vehicles. Mahle, Valeo, and Sanden are some of the manufacturers of CO2 MAC systems for passenger cars with Sanden stating that their CO2 system increases driving range up to 50% in electric vehicles in winter conditions.[[23]](#footnote-23) Currently around 400,000 cars in Europe use CO2 as a MAC refrigerant, with 5.5 million anticipated to be using this technology by 2028.[[24]](#footnote-24)

16. What barriers exist for the transition of medium-duty, heavy-duty, and off-road vehicles to ultra-low-GWP and/or no-GWP alternatives?

* Currently, SNAP listings have not covered all of these categories. CARB can petition to have U.S. EPA extend current listings across all these categories.

17. What are the opportunities and barriers for transitioning MVAC systems in existing light-duty, medium-duty, heavy-duty, and off-road vehicles to ultra-low-GWP and/or no-GWP alternatives?

* While alternatives exist (HFO-1234yf can be used in existing systems and R-430A is below 150 GWP), they are not SNAP approved as drop-in replacements for HFC-134a. CARB could file a petition to get them SNAP approved. It could take 2 to 5 years, but since ICE engines using HFC-134a will still be operating at least through 2035 (or later), we believe it could be worth doing now.[[25]](#footnote-25) The continued availability of small cans of HFC-134a is only a small part of this problem.[[26]](#footnote-26)
* CARB should consider as an alternative or added measure an extended producer responsibility system that measures the externalized emissions of HFC-134a and requires them to captured and reclaimed or to compensate the state at the new U.S. EPA social cost of carbon figure of $190 per metric ton of CO2e. This is justified by the leaks in new cars coming off the assembly line but also by the fact that in general automobiles must be recharged after approximately six years. This alternative would require legislation.

18. What are the opportunities and barriers for transitioning the MVAC systems in new light-duty, medium-duty, heavy-duty, and off-road vehicles to ultra-low-GWP and no-GWP alternatives?

* The SAE Thermal Management Refrigerants Cooperative Research Program is investigating refrigerants for MVAC in these vehicles but only the HFO research (not for CO2 and hydrocarbon) is adequately funded. CARB could step in to increase funding and attention to these two SAE subteams.

19. What type of safety testing and safety standard updates are needed to transition to ultra-low-GWP and/or no-GWP alternatives?

* Our understanding is that Tesla is interested in propane as an MVAC refrigerant. CARB could team up with Tesla to fund the necessary testing and attempt to get approval for propane as an EV refrigerant in general under SNAP.
* SAE standard 639 covers HFC-134a, HFO-1234yf, HFC-152a, and R-744 (CO2). This is for highway approval, but not offroad. To get propane approved an update from the U.S. EPA is needed.

Section 5: Transport Refrigeration

21. What are the opportunities and barriers for transitioning new TRUs to ultra-low-GWP and/or no-GWP alternatives?

* CARB’s report on TRU stated:

“Cryogenic TRU systems for trailers have been commercially available in Europe since at least 2002. No new commercial deployments of cryogenic TRU systems for trailers exist in the U.S. Other manufacturers with commercially available cryogenic TRU systems offer their products only in Europe. These companies include Cryotherm, Thermo King, and Valeo-Transfrig. Cryogenic liquid fueling infrastructure is not common in the U.S. and additional infrastructure is needed to facilitate market growth.”

* Cryogenic TRU systems for trucks is another area in which the technology exists but needs market development in California. The recent CARB rules open the door to further cryogenic development on one hand but, by allowing a 2200-GWP alternative, shut it on the other. New regulations should specify a date-certain for new equipment to be cryogenic. CARB should consult with the firms making this equipment in Europe as to what else would cause them to enter our market. Likewise, CARB could consult with cryogenic liquid fueling station manufacturers and distributors as to how to increase the infrastructure.
* Another possibility is retrofitting R-404a TRUs with propane. Some research has found this to be feasible but much more would need to be done.[[27]](#footnote-27)

22. How can end-of-life refrigerant recovery from existing systems be increased?

* End-of-life refrigerant recovery could be incentivized by including all high-GWP gases in the R4 program for use in subsequent servicing activities, i.e., only allow sales of recovered refrigerant.

23. How can high-GWP refrigerant leakage be decreased in existing systems?

* Leaks in light-duty vehicle refrigerant systems were reduced over time by giving GHG reduction credits for certain system components that resulted in lower leak rates (as modeled) and use of low-GWP refrigerants. This is a potential model for TRUs.

Section 6: Recovery and Reclamation

24. Despite venting prohibitions, refrigerant recovery rates are low, especially in the residential sector. What practices and processes can be put in place to ensure proper recovery?

* Financial incentives are needed.

25. What incentives can be provided to technicians for investing their time and effort to properly recover HFCs from equipment, especially from the residential sector?

* Expand the R4 Program requirements to include recover and reuse of all high-GWP gases for servicing of equipment, so the OEMs provide financial incentivizes.

28. When is it appropriate to destroy HFCs?

* The Compliance Offset Protocol Ozone Depleting Substances (ODS) for the California Cap & Trade Program incentivizes recovery and destruction of stockpiles of refrigerants that are subject to global bans on new production, preventing future emissions and incentivizing use of lower-GWP substitutes. On March 2, 2021, the CARB Compliance Offsets Task Force recommended that HCFC‑22, HFC-134a, HFC-125, HFC-32, and HFC-143a be added as eligible for the ODS offset protocol.[[28]](#footnote-28) HCFC-22 is still one of the most used refrigerants in the state, and both causes 1800 times as much global warming per ton as CO2 and contributes to depletion of the protective stratospheric ozone layer. As of January 1, 2020, production and import of HCFC-22 refrigerant is illegal in the U.S. so it makes sense to add it the ODS protocol, which offers offsets for refrigerants being destroyed (rather than vented or reclaimed/recycled). The HFCs recommended by the Compliance Offsets Task Force are neither banned nor are they ODS, so it doesn’t make sense to include them in an ODS offset protocol. Current HFC production caps under the Kigali Amendment to the Montreal Protocol are not yet stringent enough to greatly constrain supply, so destruction would not necessarily reduce supply or increase refrigerant costs and incentivize adoption of ultra-low-GWP and/or no-GWP alternatives.

29. How can the State enable financial and/or *regulatory* mechanisms, like extended producer responsibility schemes or other fees, to improve the recovery and reclamation of HFC refrigerants?

* Create a market for recovered and reclaimed high-GWP refrigerants by requiring the OEMs and gas suppliers to only reuse recovered and reclaimed refrigerants.

Section 8: Other Non-Refrigerant HFC Sources (Fire Protection, Aerosol Propellants, Foams, Solvents, MDI)

35. Are there emerging technologies for non-refrigerant HFC end-uses (including products with application-specific allowances) that show promise in addressing the transition to ultra-low-GWP or no-GWP alternatives?

* Dry-powder inhalers are available to replace propellant-based inhalers but have been adopted at a much lower rate than in other countries, such as Sweden. Adoption of a regulation that outlaws propellant inhalers unless they are ultra-low-GWP (like HFO-1234ze) would speed up this transition.
* A recent report says that a Japanese firm has developed a -85℃ ultra-low temperature freezer operating on hydrocarbon refrigerants. They are intended for drug discovery and life science research. Again, these products will enter the commercial market if CARB signals that in a limited time (say 3 years) non-natural refrigerants will not be sold in new equipment.

Section 9: Not-In-Kind and Passive Cooling Technologies

36. Which not-in-kind technologies are nearest to commercialization? What barriers exist for commercializing them and how can those barriers be addressed?

* Rebound Technologies has a product now commercially available that uses a freeze point suppression cycle uses a natural, non-toxic, non- corrosive brine as the refrigerant. It is highly innovative, providing energy storage at the same time so as to take advantage of cheaper electricity rates. It is commercially available for cold storage.
* Another firm, MIMIC, which grew out of a solid state project at Rensselaer Tech appears to have a portable air conditioner available for $250. A thermoelectric heat pump with integrated thermal storage seems to be market ready if not yet available. It has a variety of features including 20% more efficient, no moving parts, linkable to other HVAC components, modular linking, no noise.[[29]](#footnote-29)
* Fraunhofer has an experimental electrocaloric heat pump with extraordinarily high efficiency (so much less power use).[[30]](#footnote-30) A Harvard group has a solid barocaloric refrigerant system at a promising stage.[[31]](#footnote-31) A Cambridge University group has incorporated as Barocal Ltd. This is the same group that was among the finalists of the RMI Air Conditioner competition.[[32]](#footnote-32) Blue Frontier is a start-up which uses liquid desiccants to cool, with ultra-low-GWP refrigerants mounted outdoors. These do not cool but run a heat pump that regulates the salt content of the desiccant.[[33]](#footnote-33) Another firm is Phonomics, which also uses solid state refrigerants.[[34]](#footnote-34)
* MagnoTherm Solutions GmbH is a German company that got approximately $7 million in funding to scale their magnetocaloric refrigerators, which the company claims are 40% more efficient than compressor-based systems.[[35]](#footnote-35)
* These and similar not in-kind approaches need encouragement, and when commercially available they need wide promotion. CARB could support these products financially when they are close to commercial. It could fund American researchers to work with the Fraunhofer Institute. It could proactively include new technologies in regulations so that they don’t go through the long delays associated with other refrigerant changes in the U.S. At the least, CARB needs a strategy for monitoring and assisting these developments since they might revolutionize heating and cooling, and we need that to happen before increasing the installed base of HFC/HFO air conditioning and heat pumps in the next few years. We encourage CARB to proactively track research and market developments.

Section 10: Overarching Questions

38. What factors around PFAS (per- and polyfluoroalkyl substances) should be considered as California transitions to ultra-low- and/or no-GWP alternatives?

* Given the recent proposal in Europe that are designed to ban PFAS and will affect not only HFCs but HFOs, California should proactively move away from F-gases in all their forms. Equipment should be replaced only once rather than replacing it to accommodate HFOs and HFO-based A2Ls and then again when HFOs are banned due to PFAS concerns. This will likely require legislation.

39. What types of ultra-low-GWP and/or no-GWP pilot or demonstration projects from other regions or countries could be implemented in California? Please be specific as to types of equipment/applications.

* “APARTMENT HEAT PUMP: The Qvantum wall-mounted, ultra-compact sized hydro unit is a pre-plumbed indoor unit with all necessary functions and connections. Domestic hot water is produced instantaneously with heat from the integrated buffer tank. The buffer tank can also be used to avoid energy peak prices for both heating and hot water. It also has integrated support for active cooling. Combined with the single compressor module, QG-6 (M), the hydro unit offers a complete heat pump solution that fits in any apartment. It is the ideal companion to a single Qvantum compressor module. The modular design makes it possible to install the compressor module and the hydro unit with various types of energy grids, in this way offering the perfect product to replace gas boilers.”[[36]](#footnote-36)
* These units, from Sweden, are also designed to work with district-wide geothermal bore holes as is being pioneered in Massachusetts by the non-profit HEET in conjunction with utilities.[[37]](#footnote-37)
* There are many ultra-low-GWP systems available in Europe that replace gas-fired boilers rather than, as is common in California gas burning ducted furnaces. It may be possible to encourage the use of this approach in new California multi-family residences.[[38]](#footnote-38)
* In the UK, Aldi is requiring all their new supermarkets to use natural refrigerants. They recently also decided to require new supermarkets to install propane air-source heat pumps from a German heat pump manufacturer. Perhaps CARB could encourage this “natural” synergy between refrigerants and heat pumps in California.

40. Are there additional control measures for refrigerant management, such as requirements for maintenance, servicing, and leak detection/repair, that could support California’s climate goals?

* There is starting to be available digitalized regulating equipment for heat pumps: Bessemer Venture Partners says " After successful installation, operations and maintenance are crucial to ensure continued efficiency, performance, and longevity of HVAC systems. The lack of useful software to manage residential and industrial energy can hamstring the attractiveness of getting a heat pump installed in the first place. A number of the startups building in this space are blending hardware and software while wrapping their products in improved user interfaces. For example, Pulse Industrial sells a hardware device that captures steam heating data and an accompanying software platform with AI and ML tools to analyze and extract value from this data. Other companies offer pure SaaS [software as a service] solutions that enable residential and commercial building managers to measure and optimize the efficiency of heating and cooling devices across their properties by leveraging hard-to-access data from HVAC equipment and the grid. These solutions then optimize HVAC systems to minimize emissions and energy use and ensure that they run only when necessary. In addition to a new wave of companies focusing on sustainable design and electrification, startups building tools to measure and optimize existing building systems will play a crucial role in enabling the built environment to meet emissions reduction and cost savings goals."[[39]](#footnote-39)
* The firm *Flair* “is pioneering smart and flexible climate control, selling a smart vent that can redirect air from one part of the house to another, balancing temperatures and avoiding wasted energy. Customers have told the company they’ve saved as much as 30% of their electricity bills by installing the system. The company’s devices are installed in 30,000 homes with ductless mini split systems, which make up the bulk of HVAC systems outside the U.S., Flair sells a smart thermostat that customers can use to control the temperature from anywhere via an app. That could allow these smart thermostat-connected HVAC units to be integrated into the grid and participate in load flexibility programs.”

41. Do you have any suggestions for legislative, or regulatory changes that are needed to transition away from HFCs and to ultra-low-GWP and/or no-GWP alternatives?

We have mentioned most of these suggestions before but bring them together here.

LEGISLATION

Legislation to create a CPUC pilot in CalEnviroScreen communities to help transition independent supermarkets to natural refrigerants using Avoided Refrigerant Calculator-based benefits.

Legislation, if necessary, to petition U.S. EPA to approve ultra-low-GWP drop-in alternatives to HFC-134a for MVAC systems.

Legislation to conform our F-gas regulations to those of Europe except in instances where we want measures to be more stringent such as the date F-gases will be eliminated.

Legislation would be necessary if CARB decided to use international approval as sufficient for California, as with IEC 60335-2-40.

Legislation would be needed for extended producer responsibility. Such a law might be used for HFC-134a in MVAC systems and for equipment that typically has refrigerants that are vented rather than reclaimed. CalRecycle has extensive EPR programs and a checklist for proposing new ones.[[40]](#footnote-40)

Other legislation aimed at independent and small chain supermarkets with the same goal.

New legislation or regulations to establish standards for ultra-low-GWP refrigerants (which don’t yet exist) and to give priority to refrigerants that do not use F-gases. This should include the goal of eliminating HFCs by 2030.

REGULATION

New regulation to require vending machines and convenience stores to transition to natural refrigerants.

Regulation to require all HFC-134a to be reclaimed. (Would work in tandem with the proposal above.)

Regulation to change the definition for when major repairs of an existing refrigerant system make it subject to the regulations applying to new refrigerant systems.

BUDGET ACTIONS

Budget proposal to align funding for HFC mitigation efforts (which have historically received less than 0.001% of the state’s climate mitigation budget) with their climate impacts (5% using 100-year GWPs, nearly 10% using 20-year GWPs).

Budget proposal to support CalRecyle in administering an extended producer responsibility program for all F-gases with a GWP of 150 or higher.

Budget proposal for incentives to increase sales of propane heat pumps that heat or cool water rather than air ducts. Large budget proposal for incentives directed toward adopting natural refrigerants.

New budget proposal for research on safety for natural refrigerant EV systems, perhaps with Tesla or other industry partners.

Budget proposal for widespread initiatives to increase the number and skills (related to heat pumps and natural refrigerants) of HVAC technicians.

Budget proposal for widespread initiatives to increase the salvage and reclaiming of HFCs from the existing bank.

Budget proposal for a conference of HVAC/MVAC experts on what the greatest research needs are, with funding for several follow-up RFPs.

42. Do you have any other comments that would support the SB 1206 assessment report?

* CARB should include non-HFC refrigerants, foam-blowing agents, propellants, termite fumigants, etc. in its assessment as they are part of the existing banks of high-GWP gases that will be emitted over the coming decades and continue to make a large collective contribution to the overall carbon footprint of F-gases. These include CFC, HCFC, PFC, NF3, SF6, and SO2F2, many of which are already part of CARB’s emission inventory, reporting requirements, and regulatory programs but are like HFC in that they were not addressed in the 2022 Scoping Plan Update. Including these additional F-gases would make for a more complete assessment in that they are part of many of the same economic sectors as HFC.
* CARB collects a wealth of F-gas sales, equipment sales, and commercial refrigerant leakage data each year, and has access to atmospheric measurements of all major F-gases from the NOAA monitoring network and its own monitoring program, but this data is neither shared publicly nor analyzed on a consistent basis. More frequent (and public) tracking of overall progress toward the 2030 HFC reduction target using this data and comparison against CARB’s emission inventory projections could help identify areas of success, remaining challenges, and mitigation opportunities for both the overall F-gas mitigation program and individual sectors and gases.
* The non-profit Federally Funded Research and Development Center (FFRDC) Aerospace Corporation in El Segundo, CA has demonstrated rapid detection of F-gas high-emitters in airborne surveys over Los Angeles, San Francisco, and New York City using longwave-infrared hyperspectral imaging (LWIR-HSI) sensor systems. This is similar to the AVIRIS‑NG technology that CARB has funded demonstrations for identification and mitigation of methane high-emitters and is being miniaturized for deployment on satellites for global methane leak detection. As has been observed statewide and across all sectors for methane, a relatively small number of HFC-134a, HFC-152a, HCFC-22, CFC-11, and SO2F2 high-emitters dominate the overall emissions for these gases in Los Angeles. The Aerospace Corporation has offered to share data from 2010 through 2023 (gratis) so that the individual facilities can be identified. These high emission sources are likely violating existing regulations or present opportunities for additional mitigation, and efforts to eliminate or reduce these emissions (and expansion of airborne surveys to other parts of California) should result in major reductions. (See more detail in Appendix 2: Rapid Measurement Surveys of F-Gas High-Emitters.)

APPENDIX 1: PROPOSED CPUC AVOIDED REFRIGERANT CALCULATOR BASED INCENTIVES FOR CALENVIROSCREEN COMMUNITIES TO SWITCH TO NATURAL REFRIGERANTS

SECTION 1.  (a) The Legislature finds and declares all of the following:

(1) In 2022, leaks of hydrofluorocarbon (HFC) refrigerants were responsible for 18 million metric tons of carbon dioxide equivalent (CO2e). By 2045 HFCs will be one of the major remaining sources of emissions of greenhouse gases. Reduction of HFC emissions is crucial to California’s climate goals.

(2) Natural refrigerants, such as carbon dioxide, ammonia, hydrocarbons, air, and water, are available now. They have a global warming potential (GWP) of under 10, some under one. We can skip temporary solutions using other classes of chemicals and go straight to ultra-low refrigerants with a GWP of less than 10.

(3) Despite the fact that the federal American Innovation and Manufacturing (AIM) Act of 2020 (Pub. L. 116-260), Chapter 884 of the Statutes of 2022), and Subarticle 5 (commencing with Section 95371) of Article 4 of Subchapter 10 of Chapter 1 of Division 3 of Title 17 of the California Code of Regulations are ratcheting down the availability of HFCs, there is little movement among supermarket owners and other stationary refrigeration users to adopt ultra-low-GWP refrigerants.

(4) While large chains of supermarkets can afford to switch to ultra-low-GWP refrigerants, supermarkets with only one or a few stores and supermarkets serving disadvantaged communities cannot afford the replacement of HFC refrigeration systems.

(5) In addition, refrigeration technicians to install and service refrigeration equipment using ultra-low-GWP refrigerants are in need of additional training. Lack of stores with this equipment makes it uneconomical to buy that training for themselves, and in turn the lack of technicians makes stores unwilling or unable to switch to ultra-low-GWP refrigerants.

(b) It is the intent of the Legislature to establish the Ultra-low-GWP Refrigerant Incentive Pilot Program to do all of the following:

(1) Build on the success of the Tech Clean Program for housing electrification by providing incentives to supermarkets for switching to ultra-low refrigerants and distributing these incentives through technicians who have undergone training in natural refrigerants.

(2) Aims to transform, over a four year period, the California supermarket industry in disadvantaged communities by increasing the availability of low-emissions equipment and reducing emissions of greenhouse gases to help improve the health, safety, and well-being of all Californians and advance California’s mission to achieve carbon neutrality by 2045.

(4) Through a combination of market incentives, supply chain engagement, workforce development, consumer education, regional pilots, and a quick-start grant program, install ultra-low-emissions refrigeration equipment in California supermarkets and collect and publish energy and greenhouse gas emissions impacts plus market data to inform California’s long-term decarbonization plan, including strategies to make ultra-low-GWP refrigeration technologies accessible to more Californians, with a strong focus on disadvantaged communities.

(5) Integrate funding from the program with complementary funding sources, ranging from local initiatives and national programs, to enhance the financial benefits to supermarkets and to expand the number of supermarkets that would benefit from participation in the program.

(c) It is also the intent of the Legislature that projects receive incentives under the programs only if they result in avoided emissions as documented by the Public Utilities Commission’s Refrigerant Avoided Cost Calculator.

SEC. 2.  Section 76002 of the Public Resources Code is amended to read:

76002.  *(a)* The Public Utilities Commission shall ~~consider developing~~ *develop* a strategy for including low-GWP refrigerants in equipment funded by the energy efficiency programs overseen by the Public Utilities Commission.

*(b) For purposes of the strategy developed pursuant to subdivision (a), the global warming potential (GWP) of a refrigerant shall be calculated using the 20-year GWP, as defined by the United Nations’ Intergovernmental Panel on Climate Change.*

SEC. 3.  Chapter 8.5 (commencing with Section 2845) is added to Part 2 of Division 1 of the Public Utilities Code, to read:

Chapter 8.5. Ultra-low-GWP Refrigerants Incentive Pilot Program

2845.  For purposes of this chapter, the following definitions apply:

(a) “Avoided emissions” means the difference between the emission of ultra-low global warming potential refrigerant for which an incentive is provided under the program and the anticipated emission of refrigerant being replaced under the program in the next 10 years based on at least the previous three years of emission data maintained by the State Air Resources Board and is computed using the commission’s refrigerant avoided costs calculator.

(b) “Disadvantaged community” means a community identified as disadvantaged pursuant to Section 39711 of the Health and Safety Code.

(c) Eligible applicants” means an owner of an entity that installs, repairs, or maintains refrigeration equipment for supermarkets.

(d) “Program” means the Ultra-Low Global Warming Potential Refrigerants Incentive Pilot Program required pursuant to Section 2845.5.

(e) “Ultra-low-GWP refrigerant” means a refrigerant with a global warming potential of 10 or less.

2845.5.  (a) (1) The commission, in consultation with the Energy Commission, shall, until January 1, 2028, develop and supervise the administration of the Ultra-Low Global Warming Potential Pilot Refrigerants Incentive Pilot Program and shall require two electrical corporations selected by the commission to implement the program in the electrical corporation’s service territory to provide incentives to eligible applicants for the replacement, in supermarkets, of refrigeration equipment operating with an hydrofluorocarbon refrigerant with a global warming potential of 1800 or more with ultra-low-GWP refrigerants.

(b) The commission may determine whether the selected electrical corporation or a third party, including the Energy Commission or CARB, shall administer the program.

2845.10.  The program shall do all of the following:

(a) (1) Provide a minimum amount of incentive determined by the commission’s refrigerant avoided costs calculator.

(2) The incentive shall be set to encourage the complete replacement of hydrofluorocarbon refrigerant equipment with equipment using ultra-low-GWP refrigerants.

(3) Eligibility standards for supermarkets that serve disadvantaged communities may have a different standard from those serving other communities to facilitate the participation of supermarket serving disadvantaged communities in the program.

(b) Reserve a minimum of 70 percent of the amount allocated for the program for supermarkets located in disadvantaged communities.

(c) Provide up to one hundred thousand dollars ($100,000) for a training program to eligible applicants on the installation and operation of Ultra-low-GWP refrigerant equipment.

(d) Ensure that supermarkets and eligible applicants can participate in the program by leveraging an electrical corporation’s mechanism for paying upfront costs with cost recovery from its ratepayers through monthly bills.

(e) Ensure that the program has sufficient funding to provide financial assistance to at least 500 supermarkets and at least 100 eligible applicants.

2545.15.  In supervising the administration of the program, the commission shall do all of the following:

(a) Ensure that projects funded by the program are offered technical assistance to facilitate the implementation of the project.

(b) Ensure that the use of the Ultra-low-GWP refrigerant equipment that received an incentive under the program does not result in higher food price for low-income communities.

(c) (1) Develop program guidelines that include, at a minimum, a list of eligible technologies, a process to evaluate new technologies, criteria for scoring and selecting projects, and a process and a set of program metrics by which to evaluate and track the program’s results.

(2) The program metric, at a minimum, shall include the number of ultra-low-GWP refrigerant systems installed and the cost per metric ton of avoided emissions.

(d) Implement an outreach plan to encourage the submission of applications from eligible applicants for projects for supermarkets located in disadvantaged communities.

2545.20.  An eligible applicant may submit an application under the program on behalf of one or more supermarkets and may use the incentive to upgrade skills and equipment to be fully compatible with serving ultra-low-GWP refrigerant equipment. Amounts used for this purposes shall be identified in the application and approved by the staff of the commission.

2545.25.  On or before July 1, 2028, the commission shall submit to the Legislature a report evaluating the outcome and success of the program and including a recommendation as to the continuation or expansion of the program.

2545.30.  This chapter shall become inoperative on July 1, 2032 and is repealed on January 1, 2033.

Appendix 2: Rapid Measurement Surveys of F-Gas High-Emitters

**Summary**

The Aerospace Corporation (El Segundo, CA) has demonstrated rapid detection of F-gas high-emitters in airborne surveys over Los Angeles, San Francisco, and New York City using longwave-infrared hyperspectral imaging (LWIR-HSI) sensor systems. Their primary LWIR-HSI sensor (named Mako) offers good sensitivity (0.1 to 2 kg/hr) for all individual F-gases (CFC, HCFC, HFC, SF6, NF3, PFC, SO2F2) at 2‑meter resolution, making this is a potential tool for compliance with the Montreal Protocol, Kigali Amendment, and national and state-level regulations. The sensor can detect 700 gases including CO2, N2O, methane, ammonia, and other air pollutants of regulatory interest – during both day and night – and a smaller, lighter prototype (named Akira) is being demonstrated at the end of 2023. They’re looking for partners and/or funders that can use the existing data streams and help facilitate further deployments on aircraft, drones, the Space Station, and small satellites.

**The Aerospace Corporation**

[The Aerospace Corporation](https://aerospace.org/) is a non-profit Federally Funded Research and Development Center (FFRDC) with 4000 employees. Its major clients are the Air Force, Space Force, NASA, NOAA, and USGS. The engineering and laboratory facilities are headquartered in El Segundo, CA with major regional offices in Chantilly, VA and Colorado Springs, CO, and a [comprehensive network of locations](https://aerospace.org/locations) throughout the U.S. to provide its customers with dedicated on-site support.

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**Remote Sensing for F-Gas Emission Sources**

The Aerospace Corporation’s thermal-infrared hyperspectral imaging (TIR-HSI) program has received $80 million in internal and external investments over the past 30 years to develop sensor systems for rapid airborne remote sensing of gas plumes, Earth surface composition, and other parameters over large areas at 2-meter resolution or finer. Unique capabilities of the Mako longwave-infrared HSI (LWIR-HSI) sensor system[[41]](#endnote-1), first commissioned in 2010, are day/night remote sensing of 700 gases, including all the fluorine-containing gases (CFC, HCFC, HFC, SF6, NF3, PFC, SO2F2) of regulatory interest as well as methane, N2O, ammonia, and tetrachloroethene (perc) at high sensitivity (detectable flux rates of 0.1 to 2 kg/hr for F-gases, 10 kg/hr for methane and N2O), but 5000 kg/hr for CO2.

Mako LWIR-HSI instrument for 700 gas species



(a) CAD depiction with components labeled, (b) photograph showing installation in DeHavilland DHC-6 Twin Otter aircraft. For scale, the liquid helium cryostat outer diameter is 33 cm.

The proof-of-principle of detecting high-emitters of F-gases was documented in a peer-reviewed paper[[42]](#endnote-2) that describes airborne and fixed site surveys of Los Angeles County, San Francisco East Bay, and New York City. In California the most frequently observed F-gases were HFC-134a, HCFC-22, and HFC-152, while in New York City HCFC‑22, HFC-32, and HFC-134a were prevalent.

Mako airborne survey (12,000 ft asl, 2-m resolution) across Los Angeles County over 3 hours (32 km2/min, 2500 km2 total) on April 1, 2019 (additional data available for 2010-23)

Map

Description automatically generated

The most numerous gases present are HFC-134a (yellow, 46 sources), HCFC-22 (red, 16 sources), HFC-152a (magenta, 7 sources), and methane (cyan, 31 sources).

Converting California’s 2019 annual emission rates (representing all residential and office AC, car and truck AC, supermarkets and other commercial refrigeration facilities, servicing, dismantlers, etc.)[[43]](#endnote-3) to an average hourly emission rate for Los Angeles County and comparing to the minimum detection rates is consistent with relatively few high emitters dominating the emissions, as has been observed for methane:

* HFC-134a: 133 kg/hr all sources in Los Angeles County vs. ≥32 kg/hr for 46 high-emitting sources
* HCFC-22: 89 kg/hr all sources vs. ≥9.6 kg/hr for 16 high-emitting sources
* HFC-152a: 60 kg/hr all sources vs. ≥4.2 kg/hr for 7 high-emitting sources

The spectral resolution is sufficient such that the individual constituents of multiple HFC blends (e.g., R‑407C) were discriminated.ii Emissions of the termite fumigant SO2F2 (at individual houses) and banned CFC-11 (foam blowing at a construction site, faulty air conditioning plant, vehicle dismantler, and a building undergoing demolition) were also observed in Los Angeles. SF6 has been observed only rarely despite its high detectability (0.1 kg/hr) and may be evidence of the effectiveness of California’s three SF6 regulations (electricity transmission and distribution, semiconductor operations, all other sources) adopted in 2009-11.

Mako airborne survey (12,000 ft asl) of CFC-11 plumes across Los Angeles County

A picture containing graphical user interface

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**Next Steps**

Their current effort is aimed at developing and demonstrating (by the end of 2023) a considerably more compact instrument (named Akira) that will be compatible with deployment aboard small piloted aircraft, drones, and small satellites (or the Space Station).

1. <https://data.consilium.europa.eu/doc/document/ST-14409-2023-INIT/en/pdf> and <https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4781> [↑](#footnote-ref-1)
2. The U.S. EPA does not consider trifluoroacetic acid (TFA), a breakdown product of HFO-1234yf and HFC‑134a, *or* HFO-1234yf to be in the PFAS category. The U.S. EPA view is in direct contradiction to the European Chemical Agency (European Chemical Agency. PROPOSAL FOR A RESTRICTION SUBSTANCE NAME(S): Per- and polyfluoroalkyl substances (PFAS). 2023. PrePrint (<https://cdn.ca.emap.com/wp-content/uploads/sites/11/2023/02/rest_pfas_axv_report_en.pdf>) and the Organization for Economic Co-operation and Development, an organization that includes 38 countries. See OECD (2021), Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance, OECD Series on Risk Management, No. 61, OECD, Publishing, Paris. (<https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/terminology-per-and-polyfluoroalkyl-substances.pdf>) Regardless of what the U.S. EPA may eventually decide, states can adopt their own definitions. California is among 27 states pursuing litigation against chemical companies for PFAS contamination of water. (<https://www.saferstates.com/toxic-chemicals/pfas/>) TFA yields for HFOs differ greatly, with most producing small amounts. but HFO-1234yf yields 100%. (<https://www.fluorocarbons.org/news/eeap-2022-tfa-yields-from-hfcs-and-hfos/>) [↑](#footnote-ref-2)
3. êffecterra, Inc. (September 2023) Synthesis Report: New York State Assessment of Natural Refrigerants. (<https://www.linkedin.com/posts/effecterra_new-york-state-assessment-of-natural-refrigerants-activity-7112918498481225728-1IqD/>) [↑](#footnote-ref-3)
4. We are not the only one to conclude this. “Given the technical readiness and available production capacity, the EU market entry seems to have been delayed mostly as a result of standards and codes restricting the use of A3 refrigerants unnecessarily…” European Commission. The availability of refrigerants for new split air conditioning systems that can replace fluorinated greenhouse gases or result in a lower climate impact. March 2020. (<https://climate.ec.europa.eu/system/files/2020-09/c_2020_6637_en.pdf>) But it is even worse in the U.S.: “The North American market has often lagged behind the rest of the world in modernizing standards and codes. Hundreds of millions of household fridges using hydrocarbons proliferated around the world for decades with nearly zero market uptake in the U.S. and Canada due to more restrictive standards that allowed only a tiny amount of 57 grams of hydrocarbon refrigerant to be used. When the U.S. and Canadian safety standard (UL/CSA 60335-2-24) was updated in 2018 to harmonize with international standards allowing up to 150 grams, it allowed North America to begin a transition to hydrocarbons in new household fridges to be complete by 2023.” (<https://us.eia.org/blog/20200325-room-for-improvement/>) [↑](#footnote-ref-4)
5. Bani Issa, Abd Alrhman Mohammad, Elias N. Pergantis, John K. Brehm, Eckhard A. Groll, and Davide Ziviani. "Modeling of an Ultra-Low Temperature Refrigeration System for Independent Vaccines and Medical Supplies Storage." (2022). <https://docs.lib.purdue.edu/iracc/2424/> [↑](#footnote-ref-5)
6. <https://mirai-intex.com/products/closed-cycle/c2> [↑](#footnote-ref-6)
7. “CPUC Decision 19-12-021 (the Decision) authorized funding for and creation of a statewide Market Transformation Administrator (CalMTA) and adopted a framework for identifying and managing a portfolio of California market transformation initiatives.” California Market Transformation Evaluation Framework DRAFT Version 2.0 (Revised 10/6/23). (<https://pda.energydataweb.com/api/view/3876/CalMTA-Market-Transformation-Evaluation-Framework-V2-101923.pdf>) [↑](#footnote-ref-7)
8. <https://www.energy.kth.se/polopoly_fs/1.1241311.1679563728!/PositionPaper_ReviewFGas.pdf> [↑](#footnote-ref-8)
9. Examples that it’s technologically possible: <https://hautec.eu/sole-wasser-waermepumpe-r290/> (brine) and <https://hautec.eu/wasser-wasser-waermepumpe> (water) [↑](#footnote-ref-9)
10. Around 400 models of air-to-water heat pumps are already included in the German BAFA subsidy list, showcasing the wide availability of heat pumps with natural refrigerants as well as the market reaction of heat pump manufacturers (the number of R290 heat pumps was around 175 models in April 2023, and grew by 228% over the next six months). (<https://www.bafa.de/SharedDocs/Downloads/DE/Energie/beg_waermepumpen_pruef_effizienznachweis.pdf?__blob=publicationFile&v=8>) R290 heat pumps also have the highest energy efficiency which is another important factor in reducing the overall climate and environmental impact of the products. For the air-to-water heat pumps in the BAFA list, the R290 models are about 7% more efficient (ETAS 55) than the F-gas models. [↑](#footnote-ref-10)
11. <https://www.coolingpost.com/world-news/standard-revision-a-milestone-for-propane-ac/> [↑](#footnote-ref-11)
12. <https://www.coolingpost.com/world-news/engineers-develop-optimised-propane-heat-pump/> [↑](#footnote-ref-12)
13. <https://www.coolingpost.com/world-news/e4m-funding-for-heat-pump-efficiency-research/> [↑](#footnote-ref-13)
14. Purohit, Pallav, Lena Höglund-Isaksson, Nathan Borgford-Parnell, Zbigniew Klimont, and Christopher J. Smith. "The key role of propane in a sustainable cooling sector." *Proceedings of the National Academy of Sciences* 119, no. 34 (2022). (<https://www.pnas.org/doi/10.1073/pnas.2206131119>) [↑](#footnote-ref-14)
15. European Commission. The availability of refrigerants for new split air conditioning systems that can replace fluorinated greenhouse gases or result in a lower climate impact. March 2020. (<https://climate.ec.europa.eu/system/files/2020-09/c_2020_6637_en.pdf>) [↑](#footnote-ref-15)
16. Ibid. [↑](#footnote-ref-16)
17. A European example is described at: [https://hydrocarbons21.com/panasonics-R-290-heat-pumps-to-feature-hydrosplit-monobloc-design-keeping-R-290-outside/](https://hydrocarbons21.com/panasonics-r290-heat-pumps-to-feature-hydrosplit-monobloc-design-keeping-r290-outside/) [↑](#footnote-ref-17)
18. <https://www.energy.gov/energysaver/absorption-heat-pumps#:~:text=Absorption%20heat%20pumps%20are%20essentially,as%20gas%2Dfired%20heat%20pumps>. [↑](#footnote-ref-18)
19. Technically, it appears that more warming is avoided by installation of a heat pump even if the HFC in it is leaked. This result stems from the fact that heat pumps replace air conditioners which already use HFCs, so the additive warming potential is small. (See: Pistochini, Theresa, Mitchal Dichter, Subhrajit Chakraborty, Nelson Dichter, and Aref Aboud. "Greenhouse gas emission forecasts for electrification of space heating in residential homes in the US." *Energy Policy* 163 (2022): 112813: <https://www.sciencedirect.com/science/article/pii/S0301421522000386> ) However, it is obviously better to install heat pumps that don’t use HFCs. [↑](#footnote-ref-19)
20. Prabakaran, R., Lal, D.M. & Kim, S.C. A state of art review on future low global warming potential refrigerants and performance augmentation methods for vapour compression based mobile air conditioning system. *J Therm Anal Calorim* **148**, 417–449 (2023). (<https://doi.org/10.1007/s10973-022-11485-3>) [↑](#footnote-ref-20)
21. <https://webstore.iec.ch/preview/info_iec60335-2-40%7Bed7.0.CMV%7Den.pdf> [↑](#footnote-ref-21)
22. <https://etech.iec.ch/issue/2022-03/much-awaited-new-iec-standard-on-refrigerants> [↑](#footnote-ref-22)
23. Environmental Investigation Agency (2021). Pathway to Net Zero Cooling Product List, page 23. <https://eia-international.org/wp-content/uploads/2021-Pathway-to-Net-Zero-Cooling-Product-List-SPREADS.pdf> [↑](#footnote-ref-23)
24. Information shared at European Parliament event on natural refrigerants 25 January 2023. [↑](#footnote-ref-24)
25. A cost-benefit analysis should be performed using the U.S. EPA’s new social cost of carbon figure of $190 per metric ton. [↑](#footnote-ref-25)
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27. Ramaube, M., and Zhongjie Huan. "Testing and performance evaluation of a R404A transport refrigeration system retrofitted with R-290." In *AIUE Proceedings of the 17th Industrial and Commercial Use of Energy (ICUE) Conference*. 2019. [↑](#footnote-ref-27)
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30. <https://publica-rest.fraunhofer.de/server/api/core/bitstreams/93a6da7c-3246-4b0c-bb2a-65bf0818cdf2/content> [↑](#footnote-ref-30)
31. Cooling Post, 22 August 2022. (<https://www.coolingpost.com/world-news/scientists-build-cooling-system-using-solid-refrigerants/>) [↑](#footnote-ref-31)
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33. <https://bluefrontierac.com/> [↑](#footnote-ref-33)
34. <https://cheddar.com/media/keeping-it-cool-phononic-cools-and-heats-with-solid-state-chip> [↑](#footnote-ref-34)
35. Cooling Post, 12 April 2023. (<https://www.coolingpost.com/world-news/magnetocaloric-firm-attracts-e6-3m-funding/>) [↑](#footnote-ref-35)
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37. <https://heet.org/geo/> [↑](#footnote-ref-37)
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