Reducing the Climatic Impact of Harvard's Halocarbon Use

Implementation Plan

This Report and Implementation Plan are student work product completed to fulfill requirements of the Climate Solutions Living Lab, a 12-week course offered at Harvard Law School. This report and plan were researched and written under tight time constraints to answer specific questions posed to the students in their course assignment. Any opinions expressed in the report are those of the students and not of Harvard University or Harvard Law School. If you would like to learn more about Harvard Law School's Climate Solutions Living Lab, please contact Professor Wendy Jacobs at wjacobs@law.harvard.edu.

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With sincere gratitude,

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Project Summary

The Implementation Plan describes the process for applying HFC Management Protocol in actual practice in Harvard University, as well as steps to scale up and replicate the initiative through "*HFC Drawdown: We're Still in Kigali*" campaign in higher education institutions. The Implementation Plan has three components: (1) readily applicable pilot project for a refrigeration unit in Harvard University (2) detail campaign plan for *HFC Drawdown: We're Still in Kigali,* and (3) an HFC-Alternative Management Manual that provides guidance for refrigerant selection, operation management, and disposal of HFC refrigerants.

Pilot Project

- Pilot Project 1 applies to a set of refrigeration systems in a cafeteria on campus, currently operating with HFC based refrigerant R-404a. Pilot Project proposes replacing R-404a with R-442A, a "drop-in replacement" with lower global warming potential and higher efficiency. The replacement will avoid emission of 20 $MTCO_2$ annually. The replacement requires capital cost of $42,063, and has compelling positive net present value of $263,388 due to the operation cost reduction. This project could be implemented immediately.
- Pilot Project 2 proposes an alternative scenario for the same refrigeration system by replacing it with a new CO_2 based system, with lower global warming potential and higher efficiency, in 11 years – at the end of the existing system's equipment life. The replacement will avoid emission of 53 $MTCO_2$ annually. The replacement requires capital cost of $551,967 and positive net present value of $52,908.
- Pilot Project 3 applies to a large water chiller unit on campus, currently operating with HCFC-123, which is an ozone depleting substance and a greenhouse gas. Pilot Project proposes replacing the unit with a new system that uses HFO-1234yf or a retrofit with R-514a. This project is an initial case study to begin the planning process for larger pieces of equipment with substantial construction limitations.

HFC Drawdown: We're Still in Kigali

- This plan provides recommendations, potential frameworks, and considerations for the process by which Harvard and/or other institutions may pursue a voluntary pledge committing to reduce HFCs and the scope of commitments that a potential pledge may include.
    - The process includes an assessment of the key internal stakeholders at Harvard and the team's recommendations for leveraging external partnerships.
- Included are draft supplemental documents consisting of executive-level briefing material and a draft pledge. Both are intended as guidance documents to assist the development and approach of an Institutional pledge.

- The project team recognizes that the collective agency among the initial HFC Drawdown pledge participants may be an important element towards creating a sense of shared ownership, momentum, and accountability.

HFC-Alternative Selection Manual

- The manual is a comprehensive guideline for best practices in HFC emissions throughout equipment's lifecycle.
- Equipment Selection
  - There are many alternatives to HFCs. Selecting the appropriate alternative requires consideration of safety, cost, ease of service, and state of technology. The Manual provides Selection Matrix to determine the best refrigerant for given application.
  - When and how to make such transition requires consideration of cost and logistics. The Manual provides Prioritization Matrix to determine which equipment could be prioritized for HFC reduction.
  - Harvard will be able to reduce more than 70% of Harvard's HFC use by 2036 using the Manual for its equipment selection.
- Operation
  - Minimizing direct emission of HFCs from leaks is key. The Manual provides best practice guideline to maintain and repair HVACR system in order to minimize leaks and improve efficiency
  - Using certified reclaimed refrigerants for recharging needs is a newly developed offset methodology that can reduce new production of HFCs and achieve additional emission reduction.
- End of Life
  - Any halon, CFC, or HCFC refrigerants recovered from retired equipment shall be destroyed. Destruction of these refrigerants will eliminate the potential risk of atmospheric release and provides offset credit for Harvard's emissions.
  - Any HFC refrigerants recovered from retired equipment shall be reclaimed for reuse in other equipment. Because there is no limit in HFC production in U.S., displacing the need for new production by reclaiming used refrigerants is will provide the most benefit in terms of climate change mitigation.

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Feasibility Study Acronyms

ACR	American Carbon Registry
AHRI	Air-conditioning, Heating & Refrigeration Institute
CAA	Clean Air Act
CFC	Chlorofluorocarbon
CSLL	Climate Solutions Living Laboratory Course
EH&S	Harvard Environmental Health and Safety
EPA	United States Environmental Protection Agency
FY	Fiscal Year
GHG	Greenhouse Gas
GRF	Green Revolving Fund
GWP	Global Warming Potential
HBS	Harvard Business School
HLS	Harvard Law School
HMS	Harvard Medical School
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVAC/R	Heating, Cooling, Air Conditioning, and Refrigeration
$MTCO_2e$	Metric Tons of Carbon Dioxide Equivalent
NPV	Net Present Value
ODS	Ozone Depleting Substance
ODP	Ozone Depleting Potential
OFS	Harvard Office for Sustainability
OSHA	Occupational Safety and Health Act
ROI	Return on Investment
SCAR	Social Cost of Atmospheric Release
SCC	Social Cost of Carbon
SLCP	Short-Lived Climate Pollutant
SNAP	Significant New Alternative Policy
WMB	We Mean Business Coalition

Pilot Projects

We apply here an equipment life cycle analysis to the University equipment using halocarbons. Using this life cycle analysis, we identify two pilot projects the University could enact. Each pilot project would yield considerable environmental benefits by reducing the use of refrigerants with high global warming potentials. Below, we discuss the technical and financial considerations of these pilot projects, which vary in cost, risk and ease of implementation, and calculate their climatic benefit.

Generally, HFC projects are avoided at first glance because of perceived high capital costs and the significant construction disturbances. Many buildings were built around their biggest refrigeration and HVAC systems, so these projects loom large in many people's minds.

Luckily, while some HFC projects fall into that description, there are also many HFC replacement projects that institutions can undertake that are not only simple to implement but actually reduce operational costs. In addition, with creative construction and financing solutions, careful planning and a proactive approach, the challenges described above can be overcome.

For our pilot project, we selected two projects which illustrate the variation in complexity, costs and ease of implementation typical of HFC projects. We show that while there are challenges with some units, many of these challenges are addressable, and that proactive planning can set up the conditions to implement Kigali-compliant decisions for HFC use when the timing is right. For illustration, we also include a third case study which depicts a large R-123 unit that faces substantial construction challenges as an example of how advanced planning can help reduce hurdles for such projects.

Pilot Project 1: R-404A to R-442A Drop-In Retrofit: Improving Efficiency and GHG Emissions in 24 Hours

The first pilot project relates to a set of refrigeration systems cooling food storage and preparation rooms in Harvard Law School's Wasserstein Hall cafeteria. Figure 1 illustrates the operation of these systems. Compressed refrigerant gas passes through a condenser, which rejects excess heat resulting from the compression. The refrigerant then expands, cools, and evaporates. The chilled lines remove heat from the food storage rooms. Warmed refrigerant comes back to the condensers, where its accumulated heat is removed using a campus chilled water supply. The refrigerant is then compressed and the cycle repeats.

The current setup, installed in 2011, consists of 13 individual systems each servicing a separate room. All 13 units were installed at the same time in 2011. Each system uses the gas blend R-404A[1] as a refrigerant. Individually, none of these systems uses over 50 pounds of refrigerant, and so these units are not recorded in the University's inventory. Collectively, these units use 300 pounds of R-404A. Although R-404A is a commonly used refrigerant, it is disadvantageous in two ways. First, its global warming potential is larger than other substitute HFCs. Second, the energy efficiency of R-404A is lower than other substitute HFCs, meaning more power is consumed to achieve the same cooling capacity. Despite these drawbacks, R-404A continues to be used as a refrigerant due to technological momentum and technicians' unfamiliarity with available substitutes.

One option is to replace the current R-404A with another HFC exhibiting a lower global warming potential and a better energy efficiency. The best replacement is R-442A. This gas is also an HFC blend[2], but is better formulated to maximize cooling capacity and minimize atmospheric warming. Its 20-year global warming potential (GWP)[3] is 3926, which is 40% lower than the value for R-404A (6437)[4]. Further, a R-442A system would consume 7 – 12% less energy[5] than the current system since this gas has a greater energy efficiency than R-404A.

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[1] R-404A is a mixture with the following approximate composition: HFC-125 (44%), HFC-143a (52%), and HFC-134a (4%). National Refrigerants, n.d. *R-404A Safety Data Sheet.* [Online] Available at: http://www.refrigerants.com/pdf/SDS%20R404A.pdf [Accessed April 2019].

[2] R-442A is a mixture with the following approximate composition: HFC-32 (31%), HFC-125 (31%), HFC-134a (30%), HFC-152 (5%), and HFC-227 (3%). Refrigerant Solutions, n.d. *R-442 MSDS.* [Online] Available at: http://rscool.com/wp-content/uploads/2018/07/R-442A-RS-50-Safety-Data-Sheet-Jul-2-2018.pdf [Accessed April 2019].

[3] GWP potential – the measure of how much heat energy a greenhouse gas absorbs relative to CO_2 – is usually defined over 100-year time intervals. However, many of the halocarbon gases in use at Harvard have much shorter atmospheric lifetimes. We discuss 20 year GWP values to better account for the warming potential of these short-lived greenhouse gases on timescales relevant to the University decision making process. This shorter timeframe is also relevant from a broader policy perspective, given that halocarbon regulations are likely to strengthen within decades.

[4] Where possible in this report, we have used the 20 year GWP defined by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013). These values are not given for halocarbon mixtures. We have therefore calculated the GWPs of halocarbon mixtures by taking the mass-averaged 20 year GWP of the mixture.

[5] GasServei, n.d. *R442A MSDS.* [Online] Available at: https://www.gas-servei.com/images/Technical-data-sheet-RS50-R442A-ENGLISH.pdf [Accessed April 2019].

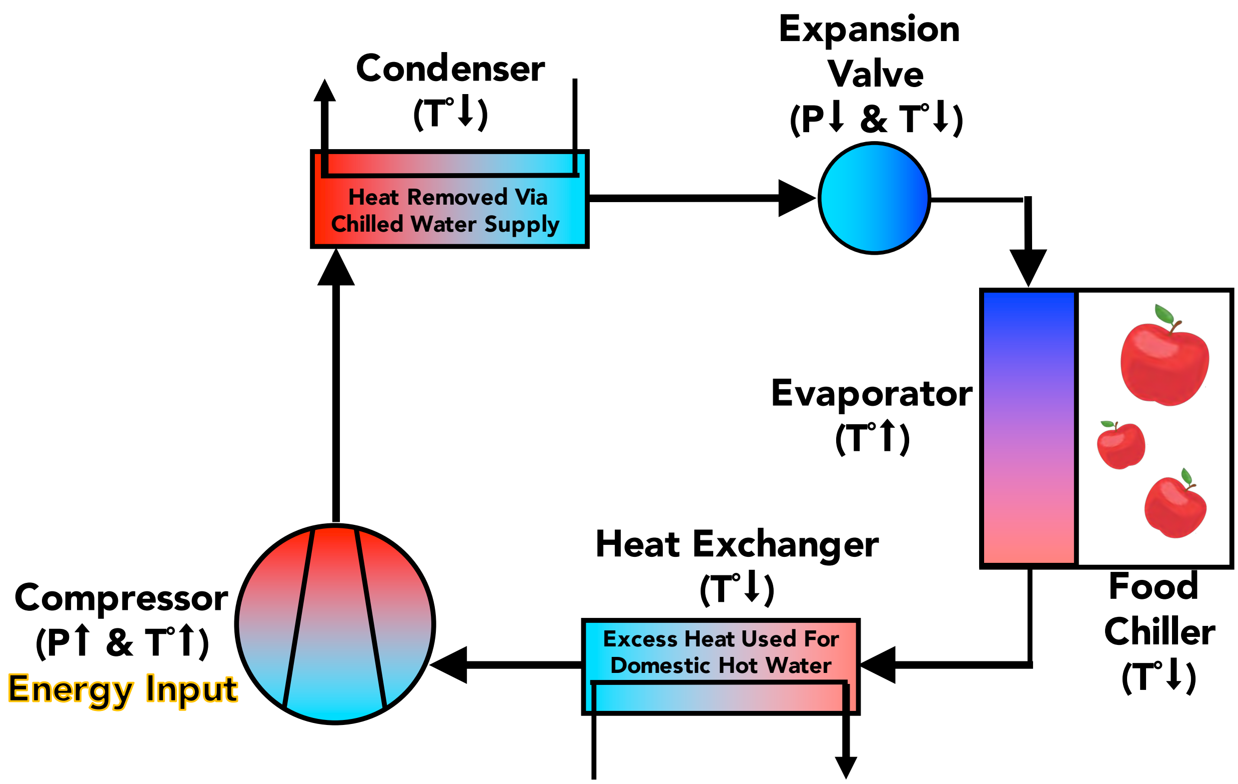

Figure 1: Refrigeration Cycle. Refrigerant gas is compressed, which raises its temperature. A condenser cooled by Harvard's centralized chilled water supply removes heat from the gas, causing it to change to a liquid. As the liquid expands and evaporates, it cools and removes heat from the cold storage rooms. The heat energy from the warm refrigerant is used to heat domestic hot water, and the cycle repeats.

R-442A is a drop-in replacement for R-404A. It would not be necessary to replace most components, including compressor oil, seals, and tubing of the current systems[6]. Due to the higher cooling capacity of R-442A, the flow rate through the system will be approximately 40% smaller, which may necessitate replacing the expansion valves[7] (Figure 1). In addition, the discharge temperature for R-442A is hotter than for R-404A, which may degrade the O-rings of the access ports. Consultation with Joe Warren & Sons – a commercial food and refrigeration service – indicates these rubber gaskets should be replaced to avoid leakage.

Other considerations involve disruptions to food service during the refrigerant replacement. It would take 24 to 48 hours of adjusting expansion valves and flow rates to fully ensure the newly charged refrigeration systems are operating properly. During this time, it is likely that the cold storage or food preparation rooms would be unusable. Fortunately, it might be possible to stagger the upgrade process, so that only

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[6] GasServei, n.d. *The new high efficiency refrigerant with low GWP: R442.* [Online] Available at: https://www.gas-servei.com/images/RS50_Replaces_R-404A_SK_FOODS_EN.pdf [Accessed April 2019]. It is important to verify that the system oil is polyol ester, or "POE:"

[7] Refrigeration Solutions Limited, n.d. *Retrofit Procedure to Replace R-404A or R507.* [Online] Available at: http://www.refsols.com/files/RS-50/RS-50_Retrofit_procedure_for_R-404A_and_R507.pdf [Accessed April 2019]. Up to 40% smaller valves may be required:

a few systems are down at any one time. Further, it is likely that the chilled water supply used to cool the refrigerant (Figure 1) will need to be adjusted. The hotter discharge temperature of R-442A will increase the heat burden on the chilled water supply, which could compensate by increasing the flow rate or decreasing the temperature of the water.

In summary, the option to replace R-404A with R-442A is fairly feasible from a technical perspective. This replacement is in fact encouraged by leaders in the refrigeration industry[8]. The project would require only minimal retrofits to the existing unit, and environmental benefits would stem from the increased energy efficiency and lower global warming potential of the replacement. These climate benefits are quantified and discussed later in the report.

During our research, we discussed the potential switch over with Harvard's long-standing refrigeration maintenance vendor, Joe Warren & Sons[9]. The project costs described in Table 1 below reflect his input from that conversation. The major costs are the vendor labor and materials to perform the change out, the cost of the R-442A refrigerant and the preparation costs required internally. As described above, while the change-out is simple, there will be 24-48 hours in which the refrigeration systems will be unusable. Therefore, the food stored in the systems will need to be moved for that time-period and then moved back into the systems following the project. These costs have been estimated below.

For the following project descriptions, several different terms and assumptions are used and may sometimes appear contradictory. For clarity, below are the rationale behind the various units.

- In our feasibility report, we calculate the potential CO_2e benefits of the projects using the 20-year GWP. We also use the 20-year GWP when calculating CO_2e in this report EXCEPT when referring to qualified carbon offsets. The standard requires offset calculations use the 100-year GWO figure.
- Likewise, our project life time is listed as 11 or 20 years, depending on the pilot project. "Project life time" reflects the period of economic analysis per the forecasted and depreciated equipment life[10]. This is not the construction period or the period required for carbon offset calculations. For example, The ACR uses a 10-year project life for calculating viable offsets. The GRF requires an 11-year NPV analysis, even if the true equipment life is far beyond 11 years.

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[8] Milnes, J., 2011. *RACPlus.* [Online] Available at: https://www.racplus.com/features/-is-it-time-to-stop-using-R-404A/8610668.article
[Accessed April 2019].

[9] Warren, J., 2019. *Owner, Joe Warren & Sons* [Interview] (19 April 2019).

[10] US Department of Energy, n.d. *Technical Support Document - Proposed Rulemaking on Commercial Refrigeration Equipment.* [Online]
Available at: https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/cre2_nopr_tsd_2013_08_28.pdf [Accessed April 2019].

Table 1: Projected Capital Costs for the R-442A Change Out

CAPITAL COSTS				
Costs Per Compressor System				
	Vendor Labor + Materials ($)			2,400[11]
	Harvard Labor ($)			230[12]
	R-442A ($)			119[13]
	Total Per System			2,749
COSTS FOR ENTIRE SYSTEM				
		Units	**Per Unit**	
	Compressor Systems	13	$ 2,749	35,740
				35,740
Other Costs				
	Contingencies ($)	10%		3,574
				3,574
Total Cost ($)				**42,063**

As described above, R-442A is an attractive retrofit option because in addition to substantial reductions in GWP, it also increases system energy efficiency with estimates ranging from a 7 – 12% efficiency gain. For our base case, we have assumed a 10% energy efficiency improvement. Tables 2 and 3 describe the annual operating cost changes following R-442A change-out and the assumptions behind those changes.

[11] Warren, J., 2019. *Owner, Joe Warren & Sons* [Interview] (19 April 2019) – Total hourly rate including materials is $150/hr. Assumes 16 hours of work per system.

[12] Harvard University, 2015. *Labor Agreement between Harvard University and IUOE Local 877, IBEW Local 103, Plumbers and Gasfitters Local Union No. 12, and New England Regional Council of Carpenters Local 51.* [Online] Available at: https://hr.harvard.edu/files/humanresources/files/union_atc.pdf
[Accessed April 2019]. This uses Harvard's agreed upon union wage rate for refrigeration maintenance. Assumes 8 hours of work at $42.45/hour.

[13] Carvalho, S., 2014. *Alternatives to High-GWP Hydrofluorocarbons,* Washington, DC: Institute for Governance and Sustainable Development. We assume that the costs for R-442A are $5.16/lb, in line with other new replacement HFCs like R1234yf. We also assume here that total refrigeration gas required will not change when R-404A is replaced with R-442.

Table 2: Initial assumptions used in operating cost calculations for R-404A to R-442A change-out

ASSUMPTIONS	
Electric Cost ($/kwh)	0.13[14]
Energy Efficiency Improvement (%)	10%
Refrigerant Cost ($/lb)	5.16[15]
Refrigerant Annual Leakage (%)	6%
Maintenance Costs/Hour ($/hr)	42.45[16]
Increase in Maintenance Costs	0%[17]

An annual leakage rate of 6% (in other words, 6% of the refrigerant will leak per year) was used to represent the actual calculated average leakage rate of Harvard equipment[18]. Electric costs and maintenance costs were escalated annually at an estimated 3% inflation. The costs for R-442A were decreased over time reflecting the technology's maturity and marketplace adoption. It was decreased using industry estimates for the cost curve of new refrigerants based on historic cost reductions with similar product introductions[19].

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14 Electricity Local, 2019. *Electricity Local.* [Online] Available at: https://www.electricitylocal.com/states/massachusetts/boston/ [Accessed March 2019]. Assume that Harvard is charged the commercial electric costs. This is likely slightly high because Harvard generates much of its own electricity and is therefore a conservative estimate.

15 Carvalho, S., 2014. *Alternatives to High-GWP Hydrofluorocarbons,* Washington, DC: Institute for Governance and Sustainable Development. We assume that the costs for R-442A are $5.16/lb, in line with other new replacement for HFCs like R-1234yf. We also assume here that total refrigeration gas required will not change when R-404A is replaced with R-442A.

16 Harvard University, 2015. *Labor Agreement between Harvard University and IUOE Local 877, IBEW Local 103, Plumbers and Gasfitters Local Union No. 12, and New England Regional Council of Carpenters Local 51.* [Online] Available at: https://hr.harvard.edu/files/humanresources/files/union_atc.pdf [Accessed April 2019]. This uses Harvard's agreed upon union wage rate for refrigeration maintenance. Assumes 8 hours of work at $42.45/hour.

17 Author assumption that no extra time will be required on the system as it will run substantively the same after refrigerant change-out.

18 More information on the leak rates derived from the University's emissions inventory can be found in the Feasibility Study. At a high level, this number was calculated comparing the University's stock of HFCs, reported emissions releases and repurchase quantities across reported equipment.

19 Steed, J., 2018. *Consumer Cost Impacts of the US Ratification of the Kigali Amendment,* Arlington, VA: Inforum. Availble at: http://www.ahrinet.org/App_Content/ahri/files/RESOURCES/Consumer_Costs_Inforum.pdf

Table 3: Estimated change in operating costs for R-404A to R-442A change-out

ANNUAL OPERATING COSTS (Year 1)				
Operating Costs		**R-404A**	**R-442A**	**Difference**
	Electric Usage[20] ($)	411,710	374,282	(37,428)
	Refrigerant Costs ($)	147	88	(59)
	Maintenance Costs ($)	849	849	--
Total Cost	**($)**			**(37,487)**

In total, the project presents a compelling financial case. Table 4 shows the financial projects and details a positive net positive value for the project. The analysis uses an 8% discount rate which is Harvard's internal discount rate for operating projects. Because this project reflects relatively few risks and is in line with many of Harvard's typical operating projects, using the standard 8% discount rate is appropriate.

Note that this analysis assumes an 11-year equipment life[21] because it's assumed that after 11 years, the system will be replaced with the CO_2 system described below. 11 years is also the analysis duration used in the Green Revolving Fund (GRF) application. While we do not anticipate using GRF funds for this project, keeping the analysis consistent allows for easy translation if the school would prefer to use the GRF.

Table 4: Summary financials for R-404A to R-442A change-out

SUMMARY FINANCIALS	
Project Time Length (years)	11
Discount Rate	8%
Net Present Value	$263,065
IRR	92%

We felt that it was important to show this analysis without including the impact of the social costs of atmospheric release or other co-benefits. While many schools have made progress in including these costs in decision making, other schools are still deciding if it's appropriate to include them in decision making. Importantly, this project makes a compelling case because even without including other costs, the project makes financial sense. We believe this is important because it becomes a very scalable project that can be implemented in many institutions, regardless of how progressive the institution is in internally pricing carbon.

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[20] Electric usage calculated from the electric rating of the existing equipment and adjusted for R442 to reflect the predicted energy efficiency gains.

[21] US Department of Energy, n.d. *Technical Support Document - Proposed Rulemaking on Commercial Refrigeration Equipment.* [Online]
Available at: https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/cre2_nopr_tsd_2013_08_28.pdf [Accessed April 2019].

For those institutions who have decided to internalize the externalities of their emissions, this project presents an even more compelling case. Tables 5-7 summarize what the project financials look like when the social cost of atmospheric release is accounted for.

Table 5: Social Cost of Atmospheric Release Assumptions for R-404A to R-442A Change-Out

ASSUMPTIONS	
Social Cost of R-404A ($/MT)	558,131
Social Cost of R-442A ($/MT)	268,677
Annual Chance of Catastrophic Release	0.05%

Table 6: Annual Operating Cost Changes when Incorporating the Social Cost of Atmospheric Release Assumptions for R-404A to R-442A Change-Out

ANNUAL OPERATING COSTS (Year 1)			
Operating Costs	**R-404A**	**R-442A**	**Difference**
Social Cost of Atmospheric Release ($)	4,596	2,2123	(2,384)
			(2,384)
Total Cost Difference ($)			**(2,384)**

Table 7: Summary Financials when Incorporating the Social Cost of Atmospheric Release Assumptions for R-404A to R-442A Change-Out

SUMMARY FINANCIALS	
Project Time Length (years)	11
Discount Rate	8%
Net Present Value	$286,083
IRR	98%

With a total capital cost of $42,063, this project would fall into the operating budget process at HLS. Because there is an energy savings, this project could also be funded by the Green Revolving Fund. Because HLS has used the GRF frequently in previous years and has other projects lined up to use the GRF including solar installations and lighting changes, we have assumed that this project would not use the GRF but rather would be funded internally to not crowd out the other projects. With that assumption, the funding timeline is described in Figure 2 below.

From conversations with the school, it is assumed that this project would be installed the summer following funding release. It is rare that projects are installed the same year funding is approved. In addition, because of the potential disruption to operations, it would be preferred to install it during the summer when class is not in session.

Figure 2: Baseline Assumed Funding Pathway for R-404A to R-442A Change-Out

Pilot Project 2: R-404A to CO_2 Replacement: Significant Investment for Significant Improvements

An alternative pilot project to reduce the climatic impact of these 13 individual systems is to replace them with units using natural refrigerants. Options include standalone CO_2 or hydrocarbon units, which could service individual cold rooms, or a centralized unit using CO_2 as a refrigerant servicing all 13 rooms[22].

The primary benefit of natural refrigerants is that their global warming potentials are much lower than those of HFCs. The 20-year global warming potential of propane and butane are approximately 29 and 20, respectively, whereas the value for CO_2 is by definition 1. These refrigerants are also thermodynamically more efficient refrigerants than HFCs. This can improve the energy efficiency of these units from 10 – 43%[23], and reduce the mass of refrigerant needed to achieve the same cooling capacity. The lower operating temperature of these refrigerants yield several benefits over HFCs. First, the lower discharge temperature will reduce the burden on the chilled water supply used to cool the compressed gas (Figure 1). Second, the lower temperature helps extend the lifetime of the compressors and valves[7].

Upgrading the existing units to ones using natural refrigerants present some logistical challenges. Since CO_2 units operate under higher pressures, they require stronger piping than the current HFC systems. Existing piping from the refrigeration skid to the cold rooms is extensive, often buried within concrete or penetrating fire protective walls. Fortunately, the piping required by a CO_2 unit is smaller in diameter than for HFCs. This might allow for new piping to be threaded through existing pipes, greatly reducing the construction costs of upgrading the units. An alternative could be to install standalone units that each service an individual cold room. Both hydrocarbon and CO_2 units could be adopted. The proximity of these units to the rooms they are serving would limit the quantity of piping that would need to be replaced.

In summary, replacing existing HFC-based units with ones using natural refrigerants would require greater foresight and commitment from Harvard Law School. Construction to upgrade piping or relocate units would likely disrupt food service for several weeks. Other factors to consider are worker safety and space. As discussed in the feasibility report, hydrocarbon and CO_2 systems carry flammability and pressure hazards. Locating standalone units nearer to the cold rooms may also reduce the usable space available to the cafeteria workers. However, the overall environmental benefits of this pilot project option may outweigh these challenges. We quantify the potential climatic benefits of using natural refrigerants below.

Because of the challenges described above, for this project, we assume that this is installed at the end of life of the existing R-404A system. The predicted lifetime of these units is 20 years[24]. Therefore, the comparison at end of life is between installing a new R-404A replacement system and installing a new CO_2 based systems. We recognize that in delaying the installation of a replacement system, there will be a continued climatic impact of the existing HFCs. To test the impact of the delay, we calculated the

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[22] It is not possible to have a centralized hydrocarbon based unit, since the hydrocarbon charge required to service all 13 rooms would be too great a fire hazard. https://www.giz.de/expertise/downloads/giz2010-en-guidelines-safe-use-of-hydrocarbon.pdf

[23] Department of Energy (2015): *Understand How the New Standards Impact You and Why Natural Refrigerants is the Solution,* http://naturalrefrigerants.info/post-doe-epa-understand-new-standards-impact-natural-refrigerants-solution/

[24] US Department of Energy, n.d. *Technical Support Document - Proposed Rulemaking on Commercial Refrigeration Equipment.* [Online]
Available at: https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/cre2_nopr_tsd_2013_08_28.pdf
[Accessed April 2019].

present value of the social cost of the R-442A emissions that would occur from this system between now and the CO_2 system installation. For this calculation, a discount rate of 3% was used to reflect a more equal value of life now and in the future. In comparison, we calculated the cost of the project if installed today, before the end of life of the R-404A system. As seen below, this calculation shows that while there is noticeable impact from continuing to operate the refrigeration system with HFCs, it is dwarfed by the capital cost that would be incurred by an early change-out. While this is not a perfect comparison, it helps Harvard decide how to prioritize amongst projects such that Harvard's capital can be used to reduce overall climatic impacts in the most cost-effective way possible.

All the financials that follow are based on a comparative model between those two projects.

Table 8 describes the capital cost difference between the two projects. Note that these capital costs are based off a similarly sized and complex installation in a supermarket. That system also had a centralized refrigeration system with decentralized refrigeration systems and also required substantial piping between the compressors and the freezers. The demolition costs are estimated as a percentage of the installation costs. It's assumed that for the CO_2 systems, substantial demolition of the piping would be required whereas only slight modifications would be required for the new R-404A system.

Table 8: Projected Capital Costs for the CO_2 Change Out

CAPITAL COSTS				
Costs Per Compressor System[25]		**R-404A**	**CO_2**	**Difference**
	Engineering and Design ($)	20,000	30,000	10,000
	Demolition ($)	55,737	311,199	255,462
	New Equipment ($)	1,125,353	1,246,939	121,586
	Electrical Installation ($)	75,030	101,450	26,420
	Equipment Installation (Incl. Piping) ($)	278,687	414,933	136,245
	Initial CO_2 Load ($)	31,724	1,980	(29,744)
		1,586,532	2,106,502	**499,970**
Other Costs				
	Contingencies @10% ($)	158,653	210,650	51,997
				51,997
Total Cost	**($)**	**1,745,185**	**2,317,152**	**551,967**

As described above, CO_2 is an attractive replacement option because in addition to substantial reductions in GWP, it also increases system energy efficiency with estimates ranging from a 10 – 43% efficiency gain. For our base case to be conservative with new technology, we have assumed a 10% energy efficiency improvement. Tables 9 and 10 describe the annual operating cost changes following CO_2 change-out and the assumptions behind those changes.

[25] Hill Phoenix, 2014. *DeCo2ded: Understanding ROI on CO_2 Refrigeration Systems,* s.l.: Hill Phoenix. Accessible at: http://www.r744.com/files/Hillphoenix_CO2_ROI_WhitePaper_v10_Oct24_2014.pdf. All costs per Hill Phoenix report unless otherwise noted.

Table 9: Assumptions used in operating cost calculations for CO_2 change-out

ASSUMPTIONS *(Notes same as above unless noted)*	
Electric Cost ($/kwh)	0.13
Energy Efficiency Improvement (%)	10%
Refrigerant Cost ($/lb)[26]	0.50
Refrigerant Annual Leakage (%)	6%
Maintenance Costs/Hour ($/hr)	42.45
Increase in Maintenance Costs[27]	10%

Table 10: Estimated change in operating costs for CO_2 change-out

ANNUAL OPERATING COSTS (Year 1)				
Operating Costs		**R-404A**	**CO_2**	**Difference**
	Electric Usage ($)	411,710	374,282	(37,428)
	Refrigerant Costs ($)	147	43	(144)
	Maintenance Costs ($)	849	933	85
Total Cost ($)				**(37,487)**

In total, the project presents a compelling financial case. Table 11 shows the financial projects. The analysis uses an 8% discount rate which is Harvard's internal discount rate for operating projects. Because this project reflects relatively few risks and is in line with many of Harvard's typical operating projects, using the standard 8% discount rate is appropriate. This project analysis reflects a standard 20-year equipment lifetime. Capital costs are an important driver of the NPV for this pilot project. A sensitivity analysis below showcases the impact of capital costs.

Table 11: Summary financials for CO_2 change-out

SUMMARY FINANCIALS	
Project Time Length (years)	20
Discount Rate	8%
Net Present Value	$ 52,315
IRR	10%

Again, we felt that it was important to show this analysis without including the impact of the social costs of atmospheric release or other co-benefits. While many schools have made progress in including these

[26] Hill Phoenix, 2014. *DeCo2ded: Understanding ROI on CO2 Refrigeration Systems,* s.l.: Hill Phoenix. Accessible at: http://www.r744.com/files/Hillphoenix_CO2_ROI_WhitePaper_v10_Oct24_2014.pdf.

[27] Author assumptions – assumes some time will be required to train maintenance staff on the operation of the new system and that there will be a learning curve over time that may require more hours, particularly as the system will operate at a higher pressure than the previous system.

costs in decision making, other schools are still deciding if it's appropriate to include them in decision making. Importantly, this project makes a compelling case because even without including other costs, the project makes financial sense. We believe this is important because it becomes a very scalable project that can be implemented in many institutions, regardless of how progressive the institution is in internally pricing carbon.

For those institutions who have decided to internalize the externalities of their emissions, this project presents an even more compelling case. Tables 12-14 summarize what the project financials look like when the social cost of atmospheric release is accounted for.

Table 12: Social Cost of Atmospheric Release Assumptions for CO_2 Change-Out

ASSUMPTIONS	
Social Cost of R-404A ($/MT)	558,130.77
Social Cost of CO_2 ($/MT)	100.00
Annual Chance of Catastrophic Release	0.05%

Table 13: Annual Operating Cost Changes when Incorporating the Social Cost of Atmospheric Release Assumptions for CO_2 Change-Out

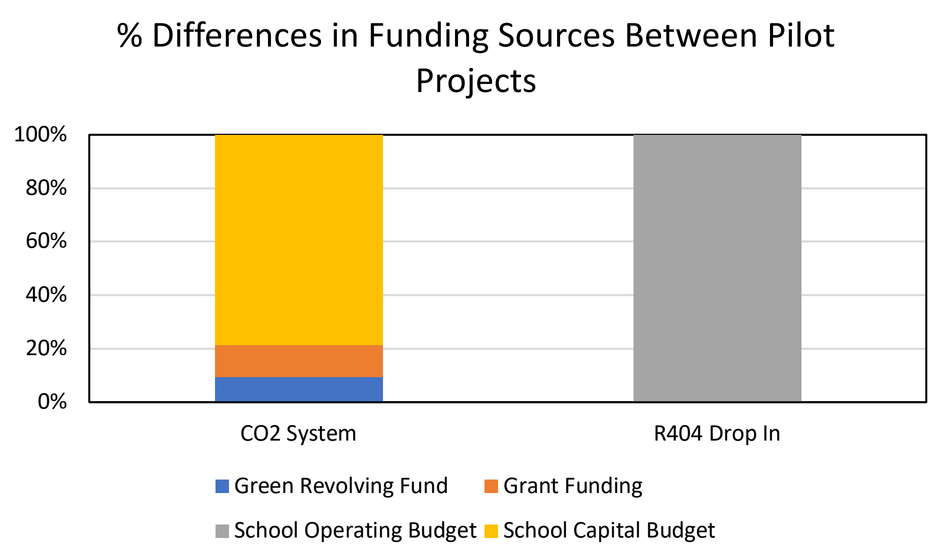
ANNUAL OPERATING COSTS (Year 1)			
Operating Costs	**R-404A**	**CO_2**	**Difference**
Electric Usage ($)	411,710	374,282	(37,428)
Refrigerant Costs ($)	196	4	(192)
Maintenance Costs ($)	849	934	85
Social Cost of Atmospheric Release ($)	4,596	1	(4,596)
			(42,083)
Total Cost			**(42,083)**

Table 14: Summary Financials when Incorporating the Social Cost of Atmospheric Release Assumptions for CO_2 Change-Out

SUMMARY FINANCIALS	
Project Time Length (years)	20
Discount Rate	8%
Net Present Value	$97,434
IRR	11%

Because the scale of our projects is very different, our two pilot projects will require different funding sources and pathways. Figure 3 below describes the differences between the two projects.

Figure 3: Difference in % of the funding sources between Pilot Project 1 and 2



The CO_2 system will rely upon the school's internal capital cost process, the GRF and external grants. Because the money will be sourced internally, we are assuming that the project will not require a debt load. While Harvard University does sometime take out loans on behalf of the school, HLS' balance sheet can fund this internally. Table 15 summarizes the funding sources assumed for the CO_2 project. This funding stack is reflected in the financials described above, including the effect of grants and repayment of the GRF.

Table 15: Funding sources for the CO_2 Change Out

FUNDING		
FUNDING SOURCES		
	Green Revolving Fund	220,000
	Mass Save Custom Project Incentive	275,983
	Internal School Funding	1,821,169
Total Capital Stack		2,317,152

Like the R-442A change out, the CO_2 project will need to go through the extensive internal planning process. Unlike the R-442A change out which was able to use the operating budget, the CO_2 system will need use the capital budget. In talking with school administrators[28], it is very rare that a capital project is installed in the fiscal year after proposal. Typically, it will need to be worked into the 5-year master capital plan. This point is why it's crucial that end-of-life and replacement scenarios be developed for all

[28] Stanton, B., 2019. *Energy Manager* [Interview] (7 March 2019).

major equipment users of HFCs well ahead of their actual end-of-life. Many of these projects are capital intensive and will require at least 5 years of planning to be worked into the master capital plan. However, with forward thinking, this can be accomplished in the least intrusive way possible and at the lowest cost possible.

The GRF is only available to a maximum of $1MM and is paid back by the operational savings that the project generates. Figure 4 depicts how the GRF is distributed and paid back over the course of the loan term. In order to maintain an attractive, positive NPV for the project (a requirement to receive GRF funding), the project is limited to about $220,000 of funding from the GRF.

Figure 4: Depiction of how the GRF funds are dispersed and paid back over the course of a project.

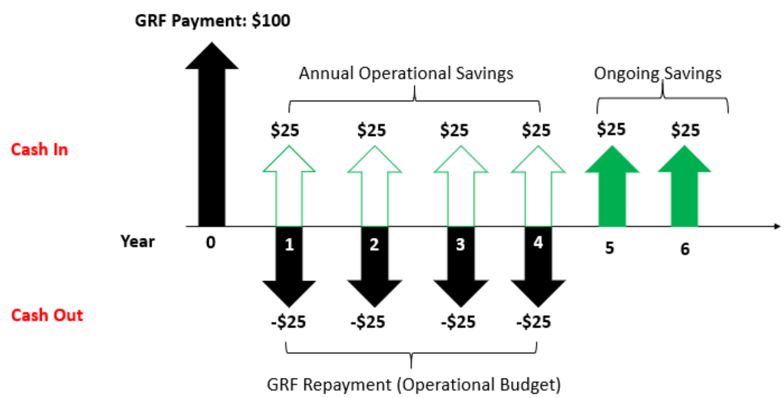


Exhibit 9. Cash flow diagram for the Green Revolving Fund.

Finally, the remainder of the project will be covered with grants. Because the CO_2 project will save energy costs, this opens the project up to various energy efficiency grants. Importantly, this will depend heavily on the grant programming that is around in 11 years when the project is installed. However, the grants that are available today are good indicators of the magnitude of grant funding that could be available in the future.

Currently, Mass Save has a very valuable program for institutions who wish to change out HVAC equipment to more energy efficient equipment. Many specific grants are available, but the one that is most appropriate for this project would be the "Custom Project – Existing Equipment Upgrade" grant. Mass Save describes the grant as, "Custom incentives are available for more complex or one-of-a-kind projects that do not fit the category descriptions of prescriptive measures."[29] The grant is sponsored by Eversource and National Grid and is available to their customers. While Harvard does produce most of its own electricity, it is also a customer of National Grid and therefore qualifies. The grant covers up to 50% of the incremental higher cost of newer, higher efficiency equipment and also covers 50% of the cost of technical assistance in scoping the project.

[29]Mass Save, 2019. *Custom - Existing Buildings and Existing Equipment Upgrade.* [Online] Available at: https://www.masssaveapplicationportal.com/MeasureReqs_Custom_R [Accessed April 2019].

The grant covers the upgrade of the following pieces of equipment[30]:

Project Types

Building Shell	Heating	Other
Combined Heat and Power	Heat Recovery	Process
Compressed Air	Hot Water	Refrigeration
Control	HVAC	Steam Trap
Food Service	Lighting	Ventilation

The following actions are required before the project can be approved[31]:

1. All applications for incentives under the Custom Application Process require documentation of the proposed cost, projected electricity and/or natural gas savings and the related non-energy savings.
2. Before starting the application process, check with your Program Administrator to determine eligibility of the proposed project, confirm the project type (New Construction vs. Retrofit) and agree on documentation and deliverables for detailed savings projections and cost estimates.
3. This information will be submitted to the Program Administrator for review and evaluation of potential incentives.
4. The PA may also require completing a Minimum Requirements Document which describes the minimum equipment specifications and operational requirements of the proposed system. The customer will be required to sign this document.
5. After successful review and project approval, the Program Administrator will notify the customer in writing of the project approval, the incentive amount and the terms and conditions required to receive final incentive payment.
6. A final Custom Project information package must be submitted in electronic format. Contact a Program Administrator for details of this submittal.

The grant approval process occurs on a rolling basis, so it can be begun at any point. Steps 1-5 take at least 45 days to complete[32] and substantially more if there are program backlogs or if there are questions around an institution's application. However, compared to federal grants that have a set time frame and can take months for approval, the Mass Save program is relatively straightforward. Because the CO_2 system will be implemented in several years, the length of this process can easily be built into the capital planning process.

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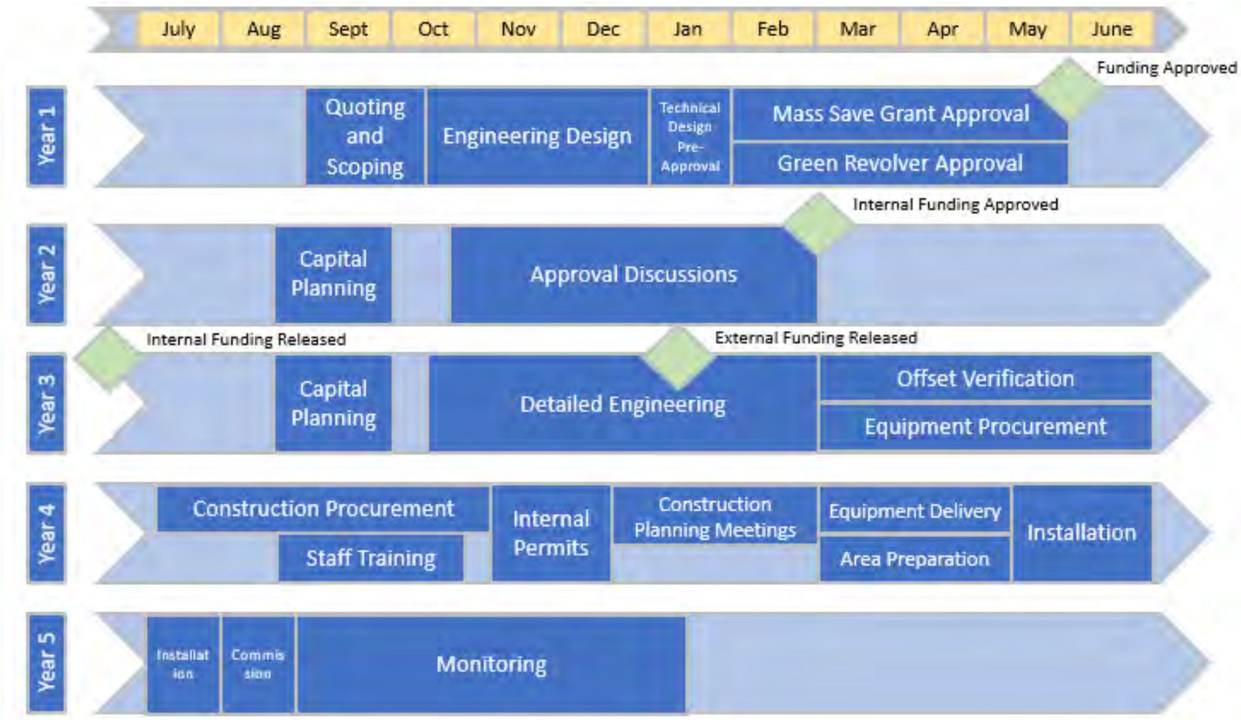
[30] Mass Save, 2019. *Custom - Existing Buildings and Existing Equipment Upgrade.* [Online] Available at: https://www.masssaveapplicationportal.com/MeasureReqs_Custom_R [Accessed April 2019].

[31] Mass Save, 2019. *Custom - Existing Buildings and Existing Equipment Upgrade.* [Online] Available at: https://www.masssaveapplicationportal.com/MeasureReqs_Custom_R [Accessed April 2019].

[32] Mass CEC, 2019. *Mass Solar Loan Lender FAQ.* [Online] Available at: https://files.masscec.com/solar-loan/MassSolarLoanLenderFAQ.pdf [Accessed April 2019].

Figure 5 below describes what the financial and installation approval process would look like.

Figure 5: Baseline Assumed Funding Pathway for CO_2 Change-Out



Water Chiller Case Study

While the above pilot projects proposed changes to refrigeration systems, the majority of the University's HFCs are used in air conditioning units. This pilot project focuses on upgrading a water chiller servicing Harvard Business School. Chilled water is produced centrally and distributed to various buildings that use it to cool air (Figure #6). Of the four units servicing the business school, one is primarily used as a backup in case another of the three should fail. This unit is a Trane (Model CVHF1060) chiller charged with 2,000 pounds of HCFC-123.

This unit is ideally suited to be a focus of a pilot project. First, it uses an HCFC refrigerant that has a small but demonstrable potential to deplete stratospheric ozone[33]. Second, the unit is sparingly used. This gives users more flexibility in choosing how to upgrade the unit since they are more tolerant of the inherent risks of adopting newer technology. In this pilot project, we recommend replacing the existing unit with one using a hydrofluoroolefin (HFO) as a refrigerant. HCFC-123, which is currently used, already has a fairly low 20-year global warming potential (292). This is lower than any possible HFC replacements, making an HFO based system a logical choice. HFO-1234yf, for example, has zero ozone depletion potential and a 20-year global warming potential of 4.

An HFO system could achieve a large enough cooling capacity to suit the needs of the users. HFO-1234yf was developed as a replacement for HFC-134a, and has similar thermodynamic and efficiency properties as HCFC-123. Since HFOs are slightly flammable, however, they are not suitable as a drop in replacement using the current unit. Fortunately, only changes at the chilled water plant would be necessary. This includes a new HFO unit, as well as some minor upgrades in fire response equipment to counter the flammability of HFOs. The distribution of chilled water from the plant to the buildings would not require modification.

The Harvard Business School is ideally situated – technologically speaking – to be a first mover in upgrading outdated halocarbon equipment. The redundancy and centralized nature of the unit make would minimize the disruption and costs of upgrading to an HFO unit. Given the large HFC charge of this unit, the environmental benefits of this pilot project could be worthwhile despite the low global warming potential of HCFC-123.

[33] Wuebbles, D.J. and Patten, K.O., 2009. Three-dimensional modeling of HCFC-123 in the atmosphere: Assessing its potential environmental impacts and rationale for continued use. *Environmental science & technology*, *43*(9), pp.3208-3213.

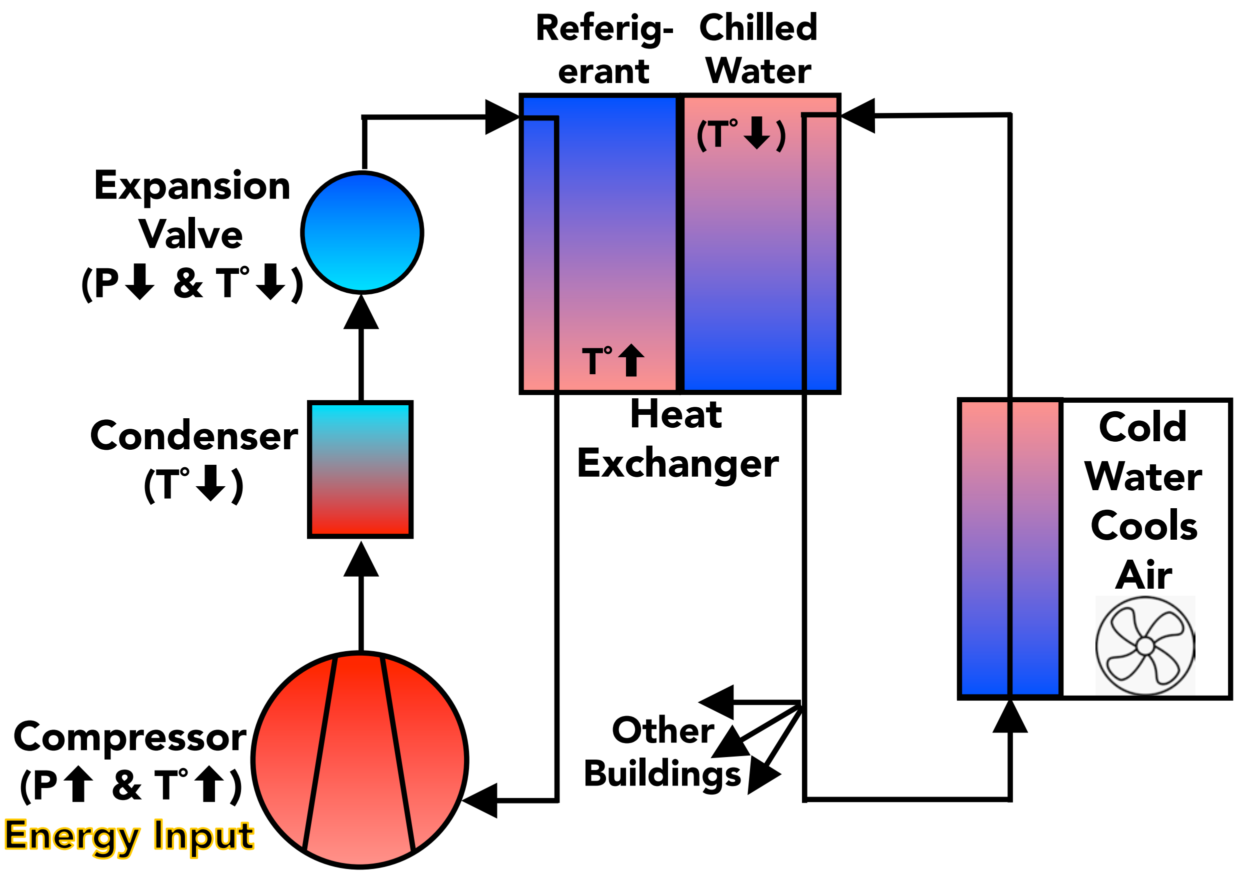


Figure 6: Chilled Water Cycle. Compressed refrigerant cools upon expansion. The cold refrigerant then chills a closed water loop via a heat exchanger. The chilled water is produced centrally and distributed to various buildings, which use it to remove heat from air. The cycle repeats as warmed water returns to the central water chiller plant.

Despite these benefits, the HBS system suffers from some of the logistical limitations that are typical of HFC change-outs. The system sits below ground in an area not readily accessed from the ground level. Therefore, to replace the systems, substantial construction and disruption to the area would be required including potentially tearing up the ground. A crane would be required to hoist and navigate the existing system from its location and the new system into place. These challenges are not insurmountable, but would need to be worked into the capital plan far ahead of the equipment failing. Speaking with Trane, the cost of the hoisting and positioning alone could run $500,000 before considering the cost of the equipment, local construction, any piping changes, installation and disposal of the existing system. Therefore, the Trane representative recommended prioritizing energy efficiency projects on the equipment before complete system changes. For example, a thorough cleaning of the heat exchange tubes can yield substantial gains in energy efficiency.

However, in the interest of reducing the climatic benefit of HFCs, Trane has solutions to help retrofit older units with R514a and these retrofits could be done relatively cost effectively. We recommend that HBS work with Trane to determine what short-term quick win projects can be completed to increase energy efficiency while working towards retrofit options.

Risks and Sensitivities

The largest uncertainty in the analysis for Pilot Project 1 (the R-404A to R-442A switch out) above is the energy efficiency gain of the system running with R-442A compared with R-404A. Figure 7 below describes a sensitivity analysis of project NPV compared with energy efficiency. Because all of the cost savings result from energy efficiency gains, the project is almost completely reliant upon energy efficiency to maintain a positive NPV. While research suggests a substantial gain is possible, more analysis should be completed to confirm the potential energy gain on this particular system before proceeding.

Figure 7: Sensitivity analysis for the R-404A to R-442A switch out, with respect to energy efficiency

		% Energy Efficiency (100% is baseline)								
Capital Cost		98%	99.00%	100.00%	101.00%	102.00%	103.00%	104.00%	105.00%	106.00%
	$ (42,063)	$ (109,376.29)	$ (74,890.92)	$ (41,095.25)	$ (7,968.80)	$ 24,508.10	$ 56,354.39	$ 87,588.25	$ 118,227.18	$ 148,288.02

The largest uncertainty in the analysis above for Pilot Project 2 (the R-442A to CO_2 system) is the capital cost of the project and the energy efficiency of a CO_2 system compared to the existing HFC system. Indeed, the CO_2 system requires grant funding for it to be NPV positive based on current equipment and installation costs. Figure 8 below shows a sensitivity analysis of the NPV of the CO_2 project based on both incremental capital cost (The difference between the CO_2 system and the HFC system) and energy efficiency. The analysis shows that the project is very sensitive to energy efficiency. In fact, if the energy efficiency drops below a 2% gain, the project is NPV negative at all realistic incremental capital costs. Again, while research suggests a substantial gain is possible, more analysis should be completed to confirm the potential energy gain on this particular system before proceeding.

Figure 8: Sensitivity analysis for the R-442A to CO_2, with respect to energy efficiency and capital costs

		% Energy Efficiency (100% is baseline)								
Incremental Capital Cost		85.00%	90.00%	95.00%	100.00%	105.00%	110.00%	115.00%	120.00%	125.00%
	0	$ (1,032,064.74)	$ (702,426.24)	$ (407,486.53)	$ (142,040.79)	$ 98,124.40	$ 316,456.39	$ 515,802.99	$ 698,537.38	$ 866,653.01
	$ (100,000.00)	$ (1,127,773.77)	$ (798,135.28)	$ (503,195.57)	$ (237,749.83)	$ 2,415.36	$ 220,747.35	$ 420,093.96	$ 602,828.34	$ 770,943.97
	$ (200,000.00)	$ (1,223,482.81)	$ (893,844.31)	$ (598,904.60)	$ (333,458.87)	$ (93,293.67)	$ 125,038.32	$ 324,384.92	$ 507,119.30	$ 675,234.94
	$ (300,000.00)	$ (1,319,191.85)	$ (989,553.35)	$ (694,613.64)	$ (429,167.90)	$ (189,002.71)	$ 29,329.28	$ 228,675.88	$ 411,410.27	$ 579,525.90
	$ (400,000.00)	$ (1,414,900.88)	$ (1,085,262.38)	$ (790,322.68)	$ (524,876.94)	$ (284,711.75)	$ (66,379.75)	$ 132,966.85	$ 315,701.23	$ 483,816.87
	$ (500,000.00)	$ (1,510,609.92)	$ (1,180,971.42)	$ (886,031.71)	$ (620,585.97)	$ (380,420.78)	$ (162,088.79)	$ 37,257.81	$ 219,992.20	$ 388,107.83
	$ (600,000.00)	$ (1,606,318.95)	$ (1,276,680.46)	$ (981,740.75)	$ (716,295.01)	$ (476,129.82)	$ (257,797.82)	$ (58,451.22)	$ 124,283.16	$ 292,398.80
	$ (700,000.00)	$ (1,702,027.99)	$ (1,372,389.49)	$ (1,077,449.78)	$ (812,004.04)	$ (571,838.85)	$ (353,506.86)	$ (154,160.26)	$ 28,574.13	$ 196,689.76
	$ (800,000.00)	$ (1,797,737.03)	$ (1,468,098.53)	$ (1,173,158.82)	$ (907,713.08)	$ (667,547.89)	$ (449,215.90)	$ (249,869.30)	$ (67,134.91)	$ 100,980.72
	$ (900,000.00)	$ (1,893,446.06)	$ (1,563,807.56)	$ (1,268,867.85)	$ (1,003,422.12)	$ (763,256.92)	$ (544,924.93)	$ (345,578.33)	$ (162,843.95)	$ 5,271.69
	$ (1,000,000.00)	$ (1,989,155.10)	$ (1,659,516.60)	$ (1,364,576.89)	$ (1,099,131.15)	$ (858,965.96)	$ (640,633.97)	$ (441,287.37)	$ (258,552.98)	$ (90,437.35)
	$ (1,100,000.00)	$ (2,084,864.13)	$ (1,755,225.63)	$ (1,460,285.93)	$ (1,194,840.19)	$ (954,675.00)	$ (736,343.00)	$ (536,996.40)	$ (354,262.02)	$ (186,146.38)
	$ (1,200,000.00)	$ (2,180,573.17)	$ (1,850,934.67)	$ (1,555,994.96)	$ (1,290,549.22)	$ (1,050,384.03)	$ (832,052.04)	$ (632,705.44)	$ (449,971.05)	$ (281,855.42)
	$ (1,300,000.00)	$ (2,276,282.20)	$ (1,946,643.71)	$ (1,651,704.00)	$ (1,386,258.26)	$ (1,146,093.07)	$ (927,761.08)	$ (728,414.47)	$ (545,680.09)	$ (377,564.46)

2. Climatic Benefits

Each of the three proposed pilot projects would uniquely yield environmental benefits. Here, we discuss the climatic relevance of these projects, quantify their greenhouse gas emissions reductions, and discuss the assumptions behind these calculations.

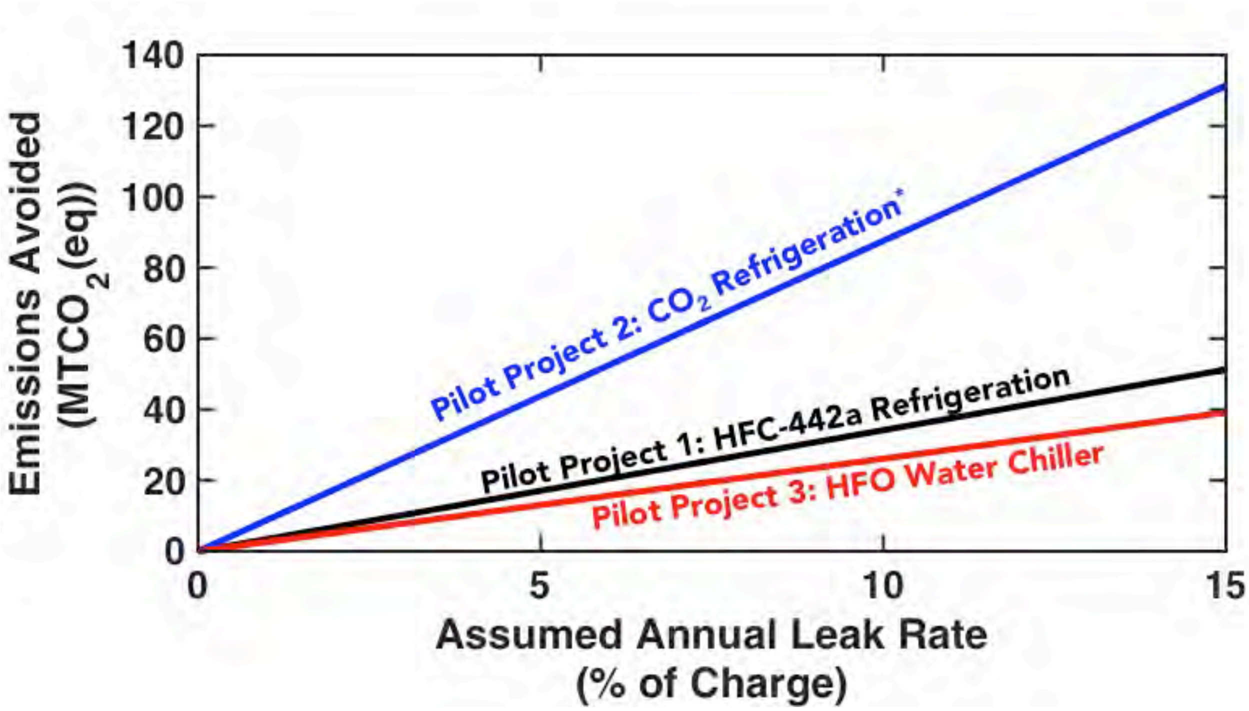
The goal of each pilot project is to reduce climatic impact of greenhouse gas emissions associated with the use of Harvard's HVACR equipment. In Pilot Project 1, we propose to achieve this by using a less potent HFC. In Pilot Projects 2 and 3, we instead propose using different refrigerants by installing newer technology. We acknowledge in all cases that refrigerant leaks are inherent in the normal use of equipment, and propose to minimize the warming associated with these leaks by using refrigerants with lower global warming potentials.

The climatic impact of these pilot projects ultimately depends on the refrigerant leak rate of the equipment. Actual leak rates for specific pieces equipment are not tracked. To explore the likely possible range of climatic benefits associated with each pilot project, we perform a sensitivity analysis and calculate total annual emissions over a range of likely leak rates. The average annual leak rate for Harvard's halocarbon-containing equipment ranges from 2 to 10% of the total charge capacity, with an average 6%[34]. In the absence of record keeping, the EPA recommends an assumed annual leak rate as high as 15%. EPA regulation requires corrective actions for leaks exceeding 10% for comfort cooling, and 20% for commercial refrigeration, only for equipment charged with than 50 pounds of refrigerants.

The greenhouse gas emissions reductions of each pilot project are quantified by subtracting the emissions impact – measured in equivalent metric tons of CO_2) – of the proposed equipment from the current equipment. Calculations take into account any change in energy efficiency and charge capacity discussed above. Figure 9 illustrates each pilot project's estimated annual greenhouse gas emissions reductions as a function of assumed leak rate. At the University average annual leak rate of 6%, the emissions avoided for Pilot Projects 1, 2, and 3 are the equivalent of 20, 53, and 16 metric tons of CO_2 respectively.

[34] More information on the leak rates derived from the University's emissions inventory can be found in the Feasibility Study.

Figure 9 – Emissions Reduction Sensitivity Analysis.



"The total greenhouse gas emissions reductions associated with the three proposed pilot projects depends on the assumed leak rate of the refrigerant."

Both pilot projects generate offsets from their implementation.

Pilot Project 1 generates offsets from the reclamation of R-404A, per ACR standard "Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from Certified Reclaimed HFC Refrigerants".

The standard calculates carbon offsets using the following formula:

$$BE_{HFC_{rp}} = \sum_{n}^{y} [VR_{HFC,j_{rp}} \times ER10_{HFC,j} \times GWP_{HFC,j})] \times (1 - RR_{BL}) \div 1000$$

Where:

$$BE_{HFC_{rp}} = \text{Baseline emissions during the reporting period (MT CO2e)}$$

$VR_{HFC,j_{rp}}$ = Total quantity of virgin HFC j reclaimed from the equipment*(kg)*

$$ER10_{HFC,j} = \text{The 10 year loss accumulated rate of HFC equipment j from equipment}$$

$$\text{(\% as given in table 3)}$$

$$GWP_{HFC,j} = \text{the 100 year GWP of HFC refrigerant j, given}$$

$$RR_{BL} = \text{Baseline Refrigerant Reclamation Rate (\% per year, given)}$$

Note that for many of our calculations, we have used the 20-year GWP number for HFCs to reflect the urgency in timing for HFCs. However, the standard for offsets uses the 100-year GWP number. Therefore, for calculating the number of qualifying offsets, we use the 100-year number.

For Pilot Project 1, the variables are as follows:

$$\mathrm{VR}_{\mathrm{HFC,j_{rp}}} = 136.4 \text{ kg}$$

$$\mathrm{ER10}_{\mathrm{HFC,j}} = 89\%$$

$$\mathrm{GWP}_{\mathrm{HFC,j}} = 3922$$

$$\mathrm{RR}_{\mathrm{BL}} = 8.90\%$$

Therefore, the baseline offset credits produced from the reclamation of R-404A during the pilot project are:

$$\mathrm{BE}_{\mathrm{HFC_{rp}}} = 434 \text{ MT CO2e}$$

An EPA report quantified the cost of reclamation for refrigeration units as follows:

$$\text{Cost Range} = 24 - 85 \text{ \$/kg}$$

Much of the cost on the high range is due to transportation costs in report ranges. The $24/kg number is more reflective of costs in a city with a thriving refrigeration service industry. Thus, taking the low cost estimate figure, the cost per offset is as follows:

$$\frac{\$}{\text{Offset}} = \$\,7.55$$

Pilot Project 2 generates offsets according to the standard, “Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from Advanced Refrigeration Systems.”

The standard calculates offsets using the following formula:

$$\mathrm{BE_y} = \sum_{i}^{n} [\mathrm{Q_{BR,j,i}} \times \mathrm{ERA_{REF,j}} \times 10)]/1000 \times \mathrm{GWP_{REF,j}}$$

Where:

$$\mathrm{BE_y} = \text{baseline emissions in year y (MT CO2e)}$$

$$\mathrm{Q_{BR,j,i}} = \text{Quantity of refrigerant in equipment i used in baseline system (kgs)}$$

$$\mathrm{ERA_{REF,j}} = \text{Annual amortized emission rate of refrigerant leaks (\%, given in Table 4)}$$

$$\mathrm{GWP_{HFC,j}} = \text{the 100 year GWP of HFC refrigerant j, given}$$

Note again that for many of our calculations, we have used the 20-year GWP number for HFCs to reflect the urgency in timing for HFCs. However, the ACR standard for offsets uses the 100-year GWP number. Therefore, for calculating the number of qualifying offsets, we use the 100-year number.

For Pilot Project 2, the variables are as follows:

$$Q_{BR,j,i} = 136.4 \text{ kg}$$

$$ERA_{REF,j} = 25.75\%$$

$$GWP_{HFC,R442} = 1888$$

Therefore, the baseline offset credits produced from the change from R-442A to CO_2 during the pilot project are:

$$BE_{HFC_{rp}} = 662.9 \text{ MT CO2e}$$

The NPV of our project is positive. This does not preclude an offset per the ACR (because it meets the practice component of additionality wherein the market is generally not accepting of the technology yet), but does create an offset that has no cost.

$$\text{NPV of Project} = \$190{,}000$$

Thus, the cost/MT of CO_2 achieved from this offset is as follows:

$$\frac{\$}{\text{Offset}} = -\$286$$

Legal Implementation

In order to implement the pilot project, Harvard University will need to make contractual arrangements with relevant service providers. We identified three key services for the pilot project: (i) engineering and installation service, (ii) gas supply and processing service, and (iii) offset verification service. In this section, key elements of the contracts are discussed for each of these services.

Engineering and Installation Service Agreement

Pilot project requires modification of existing equipment as well as installation of new equipment depending on the type of required changes. Harvard University typically retains third-party service providers to perform these services, including Joe Warren & Sons. If the project requires modification of the building or installation or modification of the existing pipelines and related construction work, a separate engineering consultant may be required to review the technical feasibility, compliance with relevant technical codes and building codes, and technical designing of the construction and mechanical works depending on the capacity of the service provider. For the Pilot Project, no specific permits or authorization appears to be required for Harvard University. Engineering and Installation Service Agreement entered into between such service provider and Harvard University should cover the physical implementation of the pilot project which includes the following:

Scope

- Procurement of equipment and necessary material for installation, removal, modification of equipment
- Procurement of labor necessary to complete the task in the period specified by Harvard University
- Technical review of the project concept including expected performance of the drop-in refrigerant or alternative refrigeration system, compliance with applicable standards and regulations including building codes, fire codes, health and safety standards
- Installation of new refrigerant and equipment

Representations & Warranty

- Service provider represents that it has all permits, certification, and qualification required by laws and regulations for performing its scope of work, including Clean Air Act Section 608 certification for handling refrigerant gas.
- Service provider warrants that the work will be conducted in compliance with applicable EHS (Environment, Health and Safety) laws and regulations, as well as EHS standards required Harvard University.
- Service provider warrants that the equipment will perform as its designed specifications upon completion of the work. In case the procured equipment is found to be defective during installation, Service provider will be responsible for arranging repair or procuring a replacement equipment from the manufacturer.

Covenant

- Service provider shall provide maintenance and services for leaks, malfunctions, or other problems related to workmanship of the installation work for specified period of time.
- Service provider shall provide all relevant information related to the replaced refrigerants necessary for management of refrigerants and equipment to relevant employees of Harvard University.
- Service provider shall provide all relevant information and support necessary for warranty claims against the manufacturer of the equipment in relation to the defects, malfunctions, break-down or any other problems related to the equipment.

Remedy

- Service provider shall rectify all problems related to the work at its own cost if such problem has arisen from breach of its obligations under the contract.

Gas Service Agreement

Refrigerant gas and service company is involved in the offset credit aspect of the project. All of the Pilot Project scenarios involve removal of R-404 refrigerant gas. Gas service companies can recover and reclaim this gas to be used for other equipment, and such an activity will qualify as offset under ACR's Certified Reclaimed HFC Refrigerant Methodology because it will displace new production of HFCs. Offset credit will be used for reducing Harvard University's GHG emission.

Scope

- Recovery of HFC refrigerant
- Reclamation of HFC refrigerant
- Preparation of documentary requirements, record keeping, and information provision required for the verification and certification of offset credit

Representations & Warranties

- Gas service company represents that it holds all permits, certifications, authorizations and qualifications under the relevant laws and regulations required for carrying out its scope of work under the contract
- Gas service company represents that all of its employees relevant to refrigerant management hold Clean Air Act Section 608 certification and the tools and equipment have been duly certified as required under the relevant laws and regulations.
- Gas service company warrants that it will comply with all laws and regulations in relation to recovery, processing, handling of refrigerant gas.
- Gas service company warrants that it will take all reasonable care to minimize emission of refrigerant gas into the atmosphere during its work.

Covenant

- Gas service company acknowledges that Harvard University shall maintain all rights to any environmental incentives, including offset credits, created by the reclamation of HFC refrigerants under the contract.
- Gas service company shall not seek to claim, use, transfer, assign, or sell any environmental incentives related to the reclamation of HFC refrigerants under the contract.
- Gas service company shall fully cooperate with the verification service provider for verification of the offset credit.

Remedy

- If the reclamation of HFC refrigerant gas fail to produce offset credit as a result of Gas service company's breach of its obligation, it shall procure offset credit at equal amount that the contract would have produced, at its own cost, and provide it to Harvard University.

Offset Verification Service Agreement

Harvard University uses General Reporting Protocol developed by The Climate Registry for its greenhouse gas inventory ("Inventory Protocol"). The Inventory Protocol requires all offsets to be used by Harvard University to satisfy six requirements: real, additional, permanent, transparent, verified, and owned unambiguously. Accordingly, Harvard University needs an independent third party to validate and verify the performance of the offset project. Since American Carbon Registry ("ACR") is currently the only organization the provides methodology for offset credits from reclamation of HFC refrigerants, ACR should be the verifier of offsets for the pilot project.

Scope

- Validation and verification of the offset activity in accordance with ACR Certified Reclaimed HFC Refrigerant Methodology
- Issuance of offset credit

Representation and Warranty

- ACR represents that it holds all it holds all permits, certifications, authorizations and qualifications under the relevant laws and regulations required for carrying out its scope of work under the contract
- ACR warrants that the offset credit issued under Certified Reclaimed Refrigerant Methodology is real, additional, and permanent, and therefore recognizable in the offset credit market.

Covenant

- ACR shall notify Harvard University prior to making any changes to its Certified Reclaimed HFC Refrigerant Methodology.
- ACR shall notify Harvard University when new offset methodology becomes available in relation to refrigerant gases.

Remedy

- If any of the offset credit issued by ACR is later revoked, cancelled, or invalidated as a result of ACR's breach of its obligation under the contract, it shall procure offset credit at equal amount that the contract would have produced, at its own cost, and provide it to Harvard University.

Kigali Proposal

Adoption and scaling of a pledge to comply with the Kigali Amendment, *HFC Drawdown: We're Still In Kigali*

The HFC-team believes that this project's potential benefits can be most uniquely and effectively scaled by leveraging the broad social capital of Harvard University as an influential thought leader amongst its community, peers, partners, and external audience. It can do so by establishing a pledge, adoptable by others, that establishes a commitment to a science-based drawdown of HFC stocks.[35] Importantly, this recommendation draws on successful subnational pledge efforts amongst U.S. states, cities, towns, businesses, institutions, and other organizations reaffirming their commitment to the Paris Agreement following the U.S. withdrawal at the federal level. The response to Paris needed more than just state action to be successful. It was the accumulation of key influencers across a broad range of sectors that make the response to Paris meaningful.

With respect to HFCs, some states have begun taking regulatory action. There is some expectation that in Massachusetts a SLCP phase-down may accompany the state's 2018 Comprehensive Energy Plan. This may include a state-wide regulatory framework on HFCs similar to the California Cooling Act.[36] Rather than solely relying on state-level action, Harvard has the opportunity to act in concert with or independent from the state to build buy-in from sub-state actors, particularly in the higher education and healthcare sectors.

Consideration of this pledge, which we are calling *HFC Drawdown: We're Still In Kigali* (HFC Drawdown), is consistent with the 2016-2017 Climate Task Force's recommendation that "Harvard should broaden its response to concerns over climate change to address more comprehensively the damages associated with its energy choices."[37] Refrigerant leakage represents approximately 2% of Harvard's emissions thanks to effective management of leakage risks. Therefore Scope 1 and Scope 2 emissions may not see a substantial decrease from action on HFCs, but life cycle assessments indicate that 90% of atmospheric leakage occurs at equipment end-of-life.[38]

This plan provides recommendations, potential frameworks, and considerations for the process by which Harvard and/or other institutions may pursue a voluntary pledge committing to reduce HFCs and the scope of commitments that a potential pledge may include. This resource is not intended to be a

[35] At least one commitment related to reducing SLCPs exists that Harvard is aware of. The We Mean Business (WMB) Coalition's commitment is discussed in further detail later in this plan. While Harvard should evaluate joining this commitment, we believe there is substantial added impact to Harvard leading an effort with other partner institutions in advancing a pledge, whether the WMB or otherwise.

[36] Dynatemp Refrigerants Company. An Update on the State By State HFC Phase-down. 2019. http://dynatempintl.com/an-update-on-the-state-by-state-hfc-phase-down/

[37] Harvard University. *2016-2017 Harvard Climate Change Task Force Report*. Section 3.1: Problem Framing – A comprehensive approach to managing the damages of energy use. https://green.harvard.edu/sites/green.harvard.edu/files/2016-2017HarvardClimateChangeTaskForceReport.pdf

[38] See HFC Feasibility Analysis, *Reducing the Climatic Impact of Harvard's Refrigerant Use*, for additional detail on refrigerant lifecycle assessment.

final product of a pledge or its pathway, but a guidance document to assist the development and approach of an Institutional pledge. Moreover, the project team recognizes that the collective agency among the initial HFC Drawdown pledge participants may be an important element towards creating a sense of shared ownership, momentum, and accountability.

The implementation plan for the HFC Drawdown pledge has been significantly informed by feedback and guidance received during the course of our stakeholder engagement, particularly since the team's final presentation on April 23, 2019.

Following the proposed implementation plan are two intentionally draft versions of documents to the plan.

The first is a "2-page overview" of the proposal for an intended audience of University Leadership with an appended draft of the pledge, HFC Drawdown. The document is currently longer than two-pages in anticipation of future editing by Harvard's OFS. As advised by OFS, this executive-level document is structured to communicate the proposal to Harvard University's leadership. The post-semester project team will continue to develop and edit the document in partnership with Jaclyn Olsen, Associate Director of OFS, and other Harvard stakeholders following the submission of the final Implementation Plan for CSLL. The project team hopes that the Emmett Environmental Law Clinic will continue to help lead the implementation of this project as well.

The second supplemental document is draft text of the proposed pledge, HFC Drawdown, including associated elements and principles for consideration. This text is informed by pledges that Harvard has signed onto, external benchmarked pledges, and HFC-specific elements. The draft is aspirational but not meant as either a ceiling or a floor. Rather, it is intended to be further evaluated and developed by stakeholders who are party to the formation and release of a pledge, whether that is Harvard on its own or Harvard in partnership with other institutions, such as those on the Boston GRC Higher Ed. working group.

Is Harvard *still in Kigali*?

Not yet, but here's how we might get there:

As partners throughout the semester, but particularly since the HFC team's presentation, Harvard's Office for Sustainability (OFS) and Harvard's Environmental Health and Safety (EH&S) have indicated interest in advancing the project, including the proposed pledge to comply with the HFC drawdown timeframe set forth in the Kigali Amendment. Both offices have provided specific descriptions of the roles they will play in further evaluating and facilitating the adoption of the pledge by Harvard. Following the submission of the team's report, follow up meetings will be scheduled between EH&S, CSLL and the HFC-team, and school-specific stakeholders to collect and begin addressing questions, gaps, and concerns regarding the implementation process. The HFC-team is in the process of scheduling a presentation to OFS with additional groups including EH&S, Harvard Green Building Services, and Harvard Strategic Procurement.

EH&S manages Harvard's environmental regulatory compliance requirements, including its greenhouse gas inventory and refrigerant management program. While OFS is positioned to facilitate the adoption of the pledge by the University's leadership, EH&S is best positioned to confirm the feasibility of the Kigali drawdown timeline for Harvard's facilities. EH&S's expertise will help determine whether the proposal is within an acceptable level of risk from a technological perspective and regulatory perspective.

Working collaboratively with EH&S, OFS is positioned to convene the appropriate stakeholders from across Harvard to develop the language for, vet the feasibility of, and build institutional buy-in for the HFC Drawdown pledge. A broad range of institutional stakeholders will be important to engage.

Campus Services (CS): This CSLL project has made such progress to date due to the collaborative nature and support of Harvard's Campus Services division, which includes EH&S and OFS as well as Engineering and Utilities (E&U), and Green Building Services (GBS). E&U manages large portions of Harvard's HFC-containing equipment and will need to support the feasibility of any pledge prior to its advancement. GBS supports sustainable design, construction, and operations of buildings across the university. GBS assists in the development and implementation of Harvard's Green Building Standards. Elements of the HFC project recommendations may be deemed suitable for inclusion in future updates to the Green Building Standards and any adoption of a drawdown timeframe will have implications for GBS's work. Their inclusion and support is also essential. The Vice President of CS, Meredith Weenick, joined the team presentation and is familiar with this project's continuance. OFS and other CS departments would continue to ensure she is updated as needed and any questions or concerns are addressed.

Capital Project Services (CAPS): CAPS supports schools and units responsible for capital spending on Harvard's buildings and infrastructure by coordinating the 5-year capital plan, maintaining building information, and providing tools and reporting frameworks to capital project managers. Given the implications of the HFC Drawdown pledge to capital projects over the next several decades, this group should be engaged in evaluating the proposal.

Sustainability Management Council (SMC): The SMC is comprised of key Senior University staff including facilities and operational leaders from across campus. SMC expertise shapes the proposed GHG reduction policies and principles prior to Executive Committee review. The support of this stakeholder group will be crucial to building institutional support for the HFC Drawdown pledge. Garnering support from school-specific SMC members prior to sharing the proposal with the entire Council will help develop diverse support and early adopters.

Strategic Procurement Office (SPO): SPO facilitates relationships with Harvard's approved vendors as well as assists in the development of contracts. Depending on the breadth of refrigerant-containing equipment and devices that are incorporated into the pledge, SPO can assist in developing project and product requirements for vendors to comply with. For example, if vending machines or window AC units with low/no GWP refrigerants are incorporated in the drawdown timeframe, SPO's vendor relationships can assist in ensuring compliance at scale.

Office of the President and Provost (OPP) and Executive Vice President (EVP): Given the public nature of the pledge, OPP and EVP will need to be engaged following the vetting of the proposal throughout the SMC and other stakeholders. OPP will determine whether the deans from across Harvard's Schools and Institutes will need to approve the pledge. Ensuring SMC and broad institutional support beforehand is critical for OPP to decide to take this leadership opportunity. Ultimately, the decision to advance or halt this effort lies with the University's leadership.

This effort will also benefit from the support of a number of Harvard academic departments, clinics, and departments. Most notably this includes, Harvard Law School's Emmett Environmental Law Clinic and Harvard T.H. Chan School of Public Health's Center for Health and the Global Environment (C-CHANGE), and Harvard Kennedy School's Sustainability Science Program. Each has been engaged throughout this project and their respective expertise

Beyond Harvard, who else is *still in Kigali*?

Socializing the pledge and encouraging other institutions to sign on can occur through several existing partnerships pertaining specifically to climate change and sustainability. OFS manages the of the Boston Green Ribbon Commission's (GRC) Higher Education Working Group, which is co-chaired by Harvard's Executive Vice President, Katy Lapp.[39] OFS also represents Harvard on the Ivy Plus Sustainability Working Group through the Council of Ivy Presidents. These two partner groups represent key constituents who can help advance a broad spread of the pledge. Other active partnerships that OFS may consider advancing the pledge through are the Cambridge Community Compact for a Sustainable Future, the EcoAmerica MomentUS Initiative, the International Sustainable Campus Network, and the Northeast Campus Sustainability Consortium.[40]

Given the local importance of addressing contributing factors to sea level rise, the HFC-team believes that the Boston GRC Higher Ed working group would be the best avenue to advance the scaling of this pledge. Harvard is actively involved with this partnership and the HFC Drawdown pledge alignment with both the State of Massachusetts potential forthcoming HFC regulations and the climate efforts of the Cities of Boston and Cambridge make this group an effective catalyst of scaling these impacts.

EH&S maintains active engagement with their counterparts across the GRC institutions and can facilitate the sharing of the project components throughout that group of stakeholders while OFS advances the spread of the project through the institutional leadership of partner institutions.

While there are many stakeholders within Harvard and many more outside, the team believes that this proposal is pragmatic in its structure and intriguing in its potential and that implementing it will result in immediate and long-term benefits to the campus community and beyond.

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[39] Boston Green Ribbon Commission Higher Education Working Group. https://www.greenribboncommission.org/work/higher-education-working-group/

[40] Harvard University Office for Sustainability. Commitments: Our Partners. https://green.harvard.edu/commitment/our-partners

(Draft Executive Briefing Document)

HFC Drawdown: We're Still In Kigali

A Proposal to adopt a pledge of compliance with the 2016 Kigali Amendment to the Montreal Protocol

"US Institutions helped demonstrate our country's commitment to climate leadership, forging the way to reach the Paris Agreement. Today more than ever we need to show leadership in the US where we can. Voluntary commitments by Harvard and the Boston GRC Higher Ed group to reduce HFC's could catalyze the momentum needed to show the world we're still in on Kigali."

Gina McCarthy, Harvard T.H. Chan School of Public Health, Former EPA Administrator, Lead for U.S. Delegation, Kigali Amendment

Background:

Additional summary information on the context of this proposal is supplied in the Climate Solutions Living Lab's HFC-team's reports, Reducing the Climatic Impact of Harvard's Refrigerant Use: A Feasibility Analysis and the accompanying Implementation Plan.

The Kigali Amendment to phase down HFCs under the Montreal Protocol entered into force in 2019 for developed nations. Under the agreement, countries commit to cutting the production and consumption of HFCs by more than 80% over the next 30 years to avoid more than 70 billion metric tons of carbon dioxide equivalent emissions by 2050. Evidence suggests that replacing high-GWP HFCs with low-GWP alternatives could avoid 0.1°C of warming by 2050, whereas more comprehensive action under the Kigali Amendment could limit the growth of HFCs and avoid up to 0.5° C warming by the end of the century.[41] The U.S. under the current administration withdrew from the Amendment.

Some have argued for formal inclusion of subnational actors into international agreements like Paris and Kigali, however it is currently limited to nation states.[42] In the response to the U.S. federal government's withdrawal from the Paris Agreement, subnational actors reaffirmed their commitment to the Agreement, often via public pledges.

Appendix 24 of the 2016-2017 Harvard Climate Change Task Force report recommends that Harvard commits to phasing out SLCPs and should work to influence the same commitments in its supply chain. This briefing document suggested that "Harvard may choose to raise the profile of this issue by signing on to the We Mean Business (WMB) Coalition commitment" on SLCPs. There is institutional familiarity with the potential of joining a public commitment.[43]

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[41] Xu et al. The Role of HFCs in Mitigating 21st century climate change. Atmospheric Chemistry and Physics. 2013
[42] Yale Environment 360. To Move Paris Accord Forward, Bring Cities and Companies On Board. 2018. https://e360.yale.edu/features/to-move-paris-accord-forward-bring-cities-and-companies-on-board
[43] Harvard University. *2016-2017 Harvard Climate Change Task Force Report* – Appendix 24: Short-Lived Pollutants

The case for Harvard's leadership:

As an influential institution in higher education, Harvard has an outsized potential to affect change beyond its operational control. In the context of reducing the global climate impacts from hydrofluorocarbons (HFCs), in addition to effective management of the institution's HFC stock and a strategic stepwise reduction, Harvard has the opportunity to lead a consortium of other institutions in pledging to reduce their HFC stock along a science-based and pragmatic timeframe. The recommended drawdown timeframe is based on the schedule set forth under the Kigali Amendment to the Montreal Protocol.

Harvard can draw attention and bring others along when it takes a public stance on issues. There can be a social cost to not influencing others through actions that can benefit the broader public as well as the institution.

The WMB Coalition commitment to "Reduce Short-Lived Climate Pollutant (SLCP) Emissions" has been signed by 22 companies. However, the number and makeup of companies has flatlined since Harvard's 2016-2017 Climate Change Task Force completed its report. Given the lack of momentum the WMB commitment currently has, Harvard may consider multiple approaches. It could leverage the existing commitment and help bring momentum to it by requesting that Universities can join and facilitating the spread of the commitment amongst its peers. Alternatively, Harvard could lead a consortium of its peers in higher education and/or health care, via the Boston Green Ribbon Commission (GRC) working groups that it sits on, in developing and sharing a new pledge. This proposal recommends that Harvard develop a separate pledge effort through its partners in the GRC.

Benefits to a phased drawdown of HFCs:

Most HFCs are contained within equipment, so emissions are the result of wear, faulty maintenance, or leakage at the end of a product's lifetime. At Harvard, short-lived pollutants, which are primarily from HFCs released from cooling equipment, represent approximately 2% of the University's Scope 1 and Scope 2 greenhouse gas (GHG) emissions inventory annually.

In evaluating potential recommendations to contain and eliminate the mechanisms by which halocarbons are released into the atmosphere, our team evaluated opportunities at all phases of refrigerant lifecycles. The CSLL team's research centered on equipment with more than 50 pounds of refrigerant. Accordingly, that is where the most detailed analysis was conducted for management and reduction potential. However, the steps integrated into the HFC Drawdown Pledge may pertain to all halocarbon-containing equipment, including small air-conditioning units, vending machines, and more in addition to equipment with more than 50lbs of refrigerant.

Existing capital and operational project constraints limited the aggressiveness that could be realistically pursued in any proposed solutions. Under these constraints, a phase-down approach was deemed most feasible and aligned with external frameworks. Detailed analysis of pilot projects at HLS and a HFC-alternative selection manual, included in the CSLL HFC-team's reports provide guidance for the University's approach to a HFC drawdown. The Implementation Plan for the HFC Drawdown includes a proposed pathway for Harvard's internal vetting of this pledge.

Timeliness of action:

While the institutional determination of the feasibility is important, quick and decisive action is important for this pledge. As discussed in our team's feasibility study, short-lived climate pollutants effectively upweight the impact of other GHGs and lock in sea-level rise for centuries. Boston has been identified as one of the cities in the U.S. and the world that is most vulnerable to flooding associated with climate change.[44]

In addition to the climate imperative for action, delay may result in a missed opportunity for Harvard to lead in a relatively low-risk, high-impact way. If Massachusetts announces HFC regulations prior to Harvard and its partners announcing a pledge, the University will need to comply with the regulatory restrictions but will no longer be positioned as an influencer on this specific issue.

It is the HFC-team's stance that the adoption of the pledge will position Harvard as an early leader of future regulations that have a moderate-to-high degree of being introduced the state level. By initiating this sub-national and sub-state action on HFC reduction, Harvard benefits from the ability to draw from existing frameworks at the international, national, and state levels, while setting an ambitious but achievable structure that works within Harvard's and other participating institution's capacities.

A history of market transformation:

Harvard has previously successfully engaged in signing and implementing Pledges of this nature.

In 2015 Harvard was among 318 institutions of higher education that signed the American Campuses Act on Climate Pledge, affirming a commitment to accelerate the global transition to low-carbon energy.[45] As with many other non-state actors within the U.S., following the current White House Administration's 2017 announcement to remove the U.S. from the 2015 Paris Agreement, Harvard was among a group of institutions of higher education who reaffirmed their commitment to the American Campuses Act on Climate Pledge.[46]

In another example of institutional leadership, in November 2015 Harvard became the first university to sign a national pledge stating a preference for purchasing flame retardant-free furniture. Other signatories to the pledge include Kaiser Permanente, Facebook, Blue Cross Blue Shield Massachusetts, and Autodesk.[47] Since signing onto this pledge, Harvard has successfully pursued an expansion of the actions set forth in the pledge via the Harvard Healthier Building Materials Academy. This effort has effectively catalyzed a shift in building materials manufacturers towards healthier materials, a testament to the impact that Harvard's proactive engagement can have at transforming markets.

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[44] Tran Viet Duc, "Which Coastal Cities Are at Highest Risk of Damaging Floods? New Study Crunches the Numbers," The World Bank, August 19, 2013, accessed October 2016, http://www.worldbank.org/en/news/feature/2013/08/19/coastal-cities-at-highest-risk-floods.

[45] The White House Office of the Press Secretary. Fact Sheet: American Campus Act on Climate Pledge. https://obamawhitehouse.archives.gov/the-press-office/2015/11/19/fact-sheet-ahead-conference-climate-change-more-200-colleges-and

[46] Harvard University. Affirmation of Leading Research Universities' Commitment on Progress on Climate Change. https://www.harvard.edu/commitment-to-progress-on-climate-change

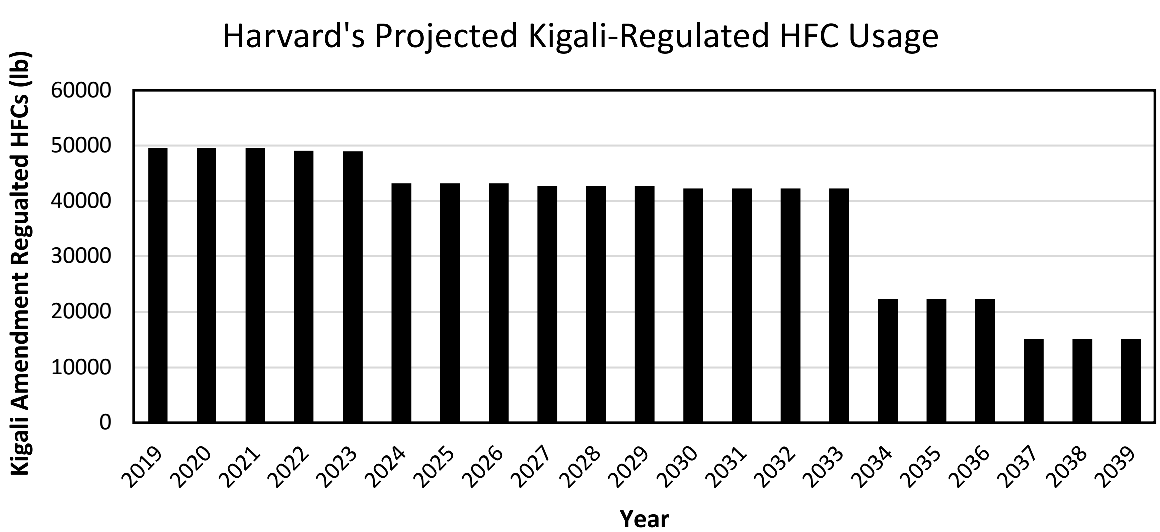
[47] Harvard Office for Sustainability. Avoiding *Chemical Flame Retardants On Campus.* https://green.harvard.edu/sites/green.harvard.edu/files/Chemical%20Flame%20Retardant-Free%20Toolkit%20and%20Buyer%E2%80%99s%20Guide.pdf

Challenges and Potential Risks:

Ultimately, there are risks to both action and inaction. By adopting the HFC Drawdown pledge, Harvard commits itself to engaging in an effort that cannot be guaranteed to occur. It is a risk that technological advancements in climate-friendly HFC-alternatives may proceed at a slower pace than the drawdown timeline and therefore implementation of alternatives may be prohibitively expensive. It is a risk that the University's decision making criteria may not result in decisions that phase out refrigerants in compliance with the timeframe set forth in the pledge. Additionally, current HFC-alternatives or lower GWP HFCs can operate at lower refrigeration capacities and may require larger mechanical systems to achieve the same cooling loads. The energy consumption of such equipment has the potential to increase, which with Harvard's current fossil fuel mix in electricity consumption would result in increased GHG emissions. This would mitigate some of the climactic benefits of avoiding the release of HFCs and be in opposition to Harvard's climate goals in the short term.

There are several considerations to make that can assist in minimizing this risk and facilitating its avoidance. First, Harvard should consider the non-linearity of developing solutions. A near-term increase in CO2 emissions may be overshadowed by the benefits associated with avoiding the climactic impacts from SCLPs. The trajectory of technological development in this field is such that alternatives do exist for many applications already. Additionally, many U.S. companies support the U.S. adoption of the Kigali Amendment due to the clarity it would send to the HVACR sector.

Lastly, Harvard's own Fossil Fuel Free goal provides an important benchmark for taking action that is ambitious and science-based, yet risks not being achieved. Harvard chose to adopt this goal because it recognized the importance of taking action from a moral perspective but critically from a science-based perspective. The science is clear that phasing out HFC and other SLCPs will achieve immediate and lasting climate benefits for communities around the world, including our own.



(Draft Pledge)

HFC Drawdown: We're Still In Kigali

A Pledge of Compliance with the 2016 Kigali Amendment to the Montreal Protocol

"As institutions of higher education, [include other sectors as applicable], we applaud the progress already made to address short-lived climate pollutants in the ambitious agreement to phase out HFCs made at the 2016 United Nations Negotiations in Kigali. We recognize the urgent need to act now to avoid irreversible costs to our global community's economic prosperity and public health that come with inaction on short-lived climate pollutants. Today our [institute/organization/company] pledges to phase-down our HFC stock in compliance with the timeframe set forth for Non-A5 parties (developed countries) in the Kigali Amendment to the Montreal Protocol, while enhancing sustainable and resilient practices across our [institute/organization/company]."[48]

"By Signing the *HFC Drawdown: We're Still In Kigali Pledge* [*institution/organization/company*] Agrees to the Following Measures:[49]

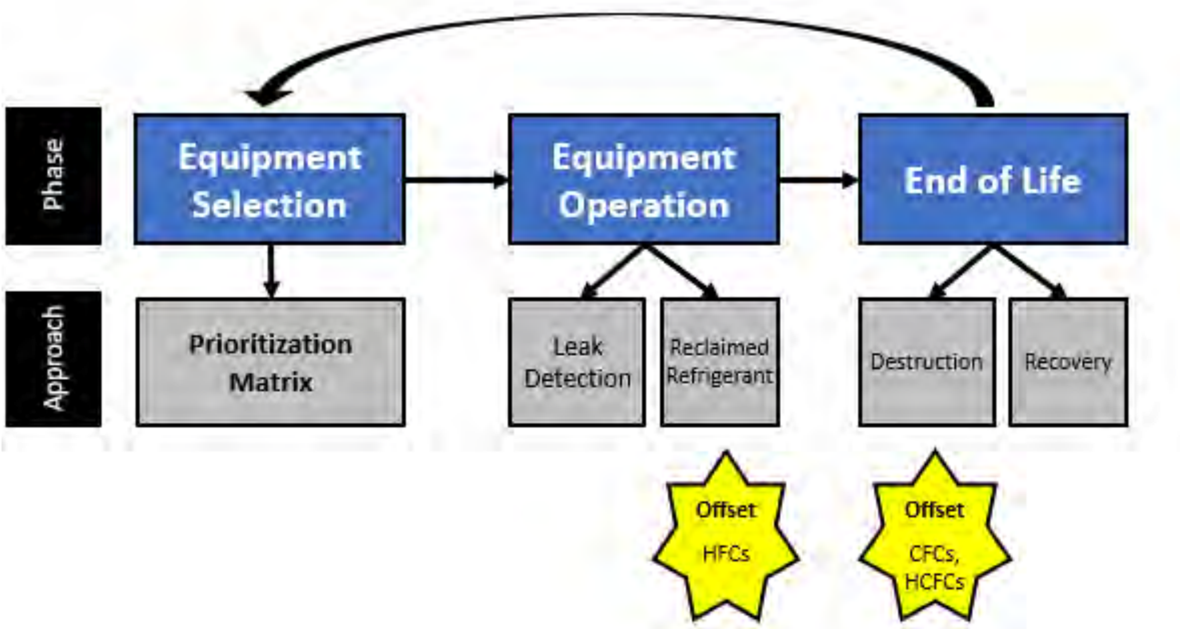
- Include measurement and reporting of HFCs into their GHG accounting
- End-of-life and replacement scenarios shall be developed for all major users of HFCs well ahead of their actual end-of-life.
    - Many of these projects are capital intensive and will require at least 5 years of planning to be worked into the master capital plan. However, with forward thinking, this can be accomplished in the least intrusive way possible and at the lowest cost possible.
- In alignment with the drawdown timeframe of the Kigali Amendment and where alternative technologies are available and codes allow, non-HFC refrigerants shall be installed *in new equipment*.
    - Where they are not available, lowest GWP and non-ODS refrigerants will be prioritized in a cost-benefit evaluation.
- In alignment with the drawdown timeframe of the Kigali Amendment and where alternative technologies are available and codes allow, non-HFC refrigerants shall be *retrofitted in existing equipment*.
    - Where they are not available, lowest GWP and non-ODS refrigerants will be prioritized in a cost-benefit evaluation.
- Ensure, through verification mechanisms approved by the Pledge Consortium, that refrigerant is reclaimed and recycled at the end of its useful life, whether during the retrofitting process or decommissioning of equipment.
- Use of reclaimed refrigerant in new equipment and recharging of existing equipment.
- Consider incentives for *Living Laboratory* projects that advance the state of technology associated with HFC alternatives, reclamation, recycling, destruction, process verifications, leak reduction/detection, and other stages of HFC lifecycles.

[48] United Nations Environment Programme. Frequently asked questions relating to the Kigali Amendment to the Montreal Protocol. https://ec.europa.eu/clima/sites/clima/files/faq_kigali_amendment_en.pdf
[49] More resources on HFC-reduction decision-making considerations can be found in the Feasibility Study and the HFC-Alternative Selection Manual that accompany this pledge.

- This pledge (may) include refrigerant-containing equipment in:
  - Buildings: Heating, ventilation, air-conditioning, and refrigeration (HVACR), vending machines, auxiliary equipment containing refrigerants
  - Transportation: Air conditioning systems
  - Fire suppressant materials

HFC-Alternative Selection Manual

To facilitate the adoption of the Kigali amendment by other institutions, we have captured our learnings and recommendations in the following manual. The manual's goal is to be a guideline for best practices in reducing HFC emissions throughout equipment's lifecycle.



Equipment Selection

An institution must consider several factors when selecting new refrigeration or air conditioning equipment. These include safety, cost, ease of service, and the state of technology. An important consideration is the current state of technology. While CO_2 based systems are quickly emerging as a standard option for refrigeration applications, this refrigerant has not yet been successfully applied to air conditioning or water chilling applications. Further, users should consider whether the hazards of certain refrigerants pose too great a risk to purchase equipment using them. For instance, users with sensitive populations, such as hospitals or nursing homes, should avoid particularly toxic refrigerants like ammonia. Spaces with poor ventilation coupled to outdated fire suppression systems may wish to avoid flammable refrigerants like HFOs. Finally, regulations limit the hydrocarbon charge in some commercial refrigeration equipment[50]. This in turn places an upper limit on the cooling capacity a hydrocarbon system can achieve.

While some equipment may provide greater environmental benefits and returns of investments in the long term, this equipment may also be prohibitively expensive for some institutions or in applications where large construction costs would be needed to replace existing HFC units. An example of this scenario is discussed in Pilot Project 2 above, where replacing an existing series of HFC-based systems with a CO_2 system could involve considerable piping modifications. Institutions should also consider whether it is a priority to invest in state-of-the-art technology, such as advancements in CO_2 air conditioning units[51]. It is our recommendation that the University should embrace its role as an innovator and be the first adopters of new technology that shows promise to greatly reduce its environmental impact.

Users should also consider whether ease of equipment service is a top priority. Although newer technology can yield greater reductions in greenhouse gas emissions, it is sometimes difficult to find technicians trained to service these state-of-the-art units. Users critically relying on their HVACR systems – for example, hospitals – must ensure their equipment can be speedily brought back online in the case of failure.

Figure 10 below summarizes these concerns to help users select the best refrigerant for their needs.

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[50] The EPA SNAP protocol currently limits the charge of hydrocarbons in commercial self-contained refrigeration systems to 150 grams. Industry groups are advocating to increase this to 500 grams.
[51] Europe is currently subsidizing research on carbon dioxide based air conditioning systems. https://www.ntnu.edu/multipack/about

Figure 10: Selection matrix for the best refrigerant for given applications:

	HFCs	HFOs	Natural Refrigerants
Application	Can be used in all applications	Newer: More common in HVAC and Auto	Currently limited to refrigeration only
Energy Efficiency	Baseline	Generally lower	Can be higher depending on application and vintage
Flammability	Class 1	Generally Class 2L	Varies: Can be Class 3 (Propane) or Class 1 (CO2)
GWP	High	Medium	Very Low

6

In prioritizing equipment change-out, the same considerations from above apply but costs and practical logistics become a more guiding constraint. Based on our analysis of Harvard's equipment, we developed the following prioritization matrix to determine how Harvard should prioritize HFC reductions.

Figure 11: Prioritization Matrix

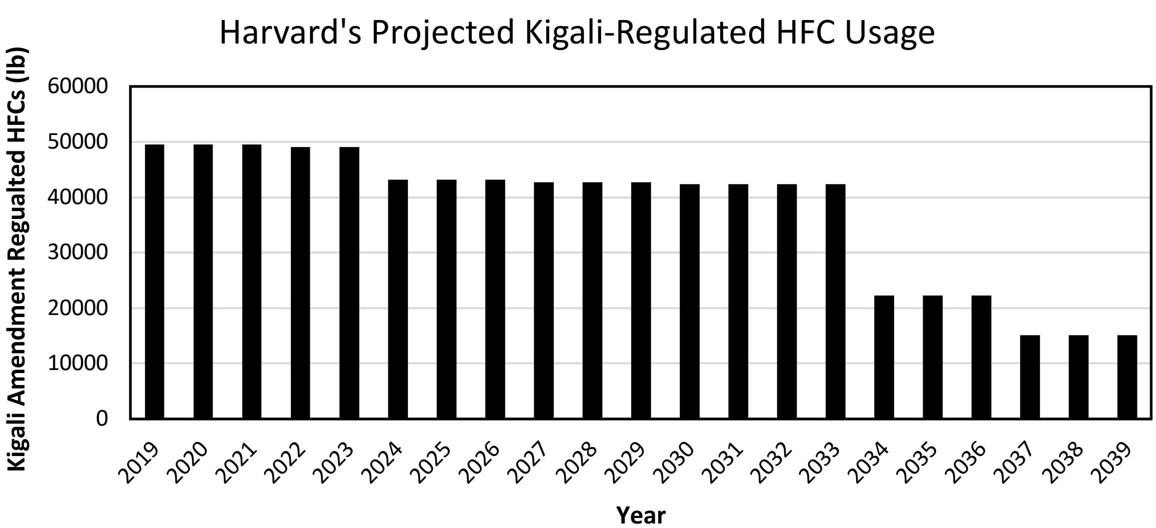
	Green	Yellow	Red
End of Life	<5 Years	5-10 years	>10 Years
Refrigerant	Halons, CFCs, HCFCs	Medium and High Pressure Systems	Low Pressure Systems
Ease of Construction	Drop-In Replacement	Equipment Change-Out, No Building Changes	Equipment Change-Out, Building Changes (Including Fire Code) Required
Capital Cost	<$50,000	$50,000 - $500,000	>$500,000+
System Criticality	Serves as Back-Up Only	Runs in parallel with other units	Single unit / critical capacity on system

This matrix serves as a general guideline to think about project prioritization. Many projects will have meet criteria from several different buckets. The user should use judgement to determine which bucket feels most appropriate to place the overall project.

This matrix is intended to be dynamic. Over time, the projects that are red will become yellow as their end-of-life approaches or as technology or building code changes evolve. Continuously evaluating projects against this matrix will allow organizations to stay on top of their commitments to the Kigali amendment and make decisions to accelerate project timelines if required.

To illustrate the power of this protocol, we assessed Harvard's HFC usage if the protocol was followed. The graph below illustrates Harvard's overall HFC usage over time if projects were prioritized using the matrix in Figure 12. The deciding criteria for most of these projects tended to be the equipment life and the capital costs required. Conservatively, this produces a 70% reduction of Harvard's HFC use, limited by one particular piece of equipment. The biggest limitation is one large chillers in crucial service operations that would require a B2L flammability classification. Our projection below shows a 70% reduction to reflect this challenge. However, while this piece of equipment will require careful coordination between stakeholders, these limitations are surmountable and the project itself could be financially attractive. Because this project is expected to occur in 10-15 years (allowing sufficient time for fire code adjustments, stakeholder coordination and technology development that could make installation more straightforward), we are confident that there is a path towards replacing this equipment which would yield a close to 100% reduction in Harvard's use of Kigali amendment regulated HFCs.

Figure 12: Harvard's projected use of HFCs regulated by the Kigali Amendment



Operation

There are two main ways that institutions can reduce emissions from HFCs during equipment operation and increase energy efficiency. Recall from the feasibility study that much of an HVACR system's greenhouse gas emissions occur from its energy usage, so making the system as energy efficient as possible is a crucial element to reduce overall system greenhouse gas emissions. The first and main way is to reduce leaks and improve efficiency is through best practice maintenance. The second is to use reclaimed refrigerant during operation.

In our study, we've been fortunate to work with an institution that has reduced leaks to a very low rate from best practices and we hope to capture some of those practices here for other institutions to follow.

1. Detect Leaks Quicker

There are various levels of leak detection that institutions can implement. It's important to note that HFOs and HFCs are odorless and colorless and cannot be detected without instruments. Therefore, proper leak detection best practices are important because leaks are very difficult to detect otherwise. In contrast, ammonia is detectable by odor even at low concentrations.

- Leak Inspections
  - If an institution suffers from high leak rates, monthly inspections may be warranted. Once the leaks are under control, quarterly inspections may be more appropriate. While these inspections have costs associated, the overall environmental and efficiency benefits pay off overall and this is the lowest cost method to detect leaks.[52]
- Walk-Throughs post repairs
  - Following any repair, best in class institutions request a walk-through with a hand-held leak detector to ensure the leak has been repaired and to catch any other leaks early. This can be completed while the technician is waiting for the system to complete its initial cycling, so it's a fairly low cost and high reward way to detect leaks.[53]
- Embedded leak detection systems
  - Direct Systems
    - These systems are directly monitor the concentration of refrigerants in the air and can be either fixed or portable systems. Best in class systems can be automatic systems that automatically link with central control systems. If there's a link, automatic systems send an alarm which can be immediately rectified.
    - Active Systems: The control company Emerson describes active systems as the following, "centralized system with sniffing technology that utilizes tubing

[52] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[53] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].

connected to multiple zones. The central unit takes air samples from zones to determine if there is refrigerant present in the air." [54]

    - Passive System: Again, Emerson describes these systems as, "zone-specific hardware with infrared technology placed in the specific areas where sensing is desired. There are no moving parts and generally require less maintenance than an active (tubing) system. If you need to sample a lot of different areas in a single location, this may become cost prohibitive." [55]

- Indirect Systems
    - Because refrigeration loss often causes refrigeration system operating changes, these changes can be used to infer refrigeration loss. A benefit of this approach is that it can often use existing sensors and analyze data that is already being collected such as temperatures, pressures and liquid levels. However, it is often harder to pinpoint a leak with this method and it can take longer to identify a leak. [56]

2. Tackle leaks when they're identified

Many institutions will wait to repair a leak because of either the importance of running the system or because the leak is small and can be dealt with later. Best practice is to immediately isolate the leak and call a technician upon finding a leak, even if that requires temporarily isolating a unit.[57]

3. Use secondary systems where possible

Secondary refrigeration systems use less refrigeration and confine refrigeration to a single room, similar to the unit we describe in our pilot project. These systems tend to have lower leak rates and make it easier to detect and fix leaks.[58]

4. Frequent replacement of O-Rings in systems requiring high temperatures[59]
5. Use loop piping, reduce the number of piping joints and use valve caps [60]
6. Set goals and track refrigeration use and other refrigeration related key performance indicators (KPIs)[61]

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[54] Wallace, J., n.d. Industry Sets Sights on Reducing Refrigerant Leaks. *E360 Outlook*. Available at: https://climate.emerson.com/documents/v2-n2-reducing-refrigerant-leaks-en-us-103232.pdf [Accessed April 2019].
[55] Wallace, J., n.d. Industry Sets Sights on Reducing Refrigerant Leaks. *E360 Outlook*. Available at: https://climate.emerson.com/documents/v2-n2-reducing-refrigerant-leaks-en-us-103232.pdf [Accessed April 2019].
[56] Wallace, J., n.d. Industry Sets Sights on Reducing Refrigerant Leaks. *E360 Outlook*. Available at: https://climate.emerson.com/documents/v2-n2-reducing-refrigerant-leaks-en-us-103232.pdf [Accessed April 2019].
[57] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[58]Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[59] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[60] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[61] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].

The EPA GreenChill program has tracking as a key part of its program. Research shows that simply setting a goal for refrigerant leaks and then tracking those leaks can significantly improve overall performance.

There are a few ways to measure refrigeration leakage and KPIs around refrigerant management:

- **Leak Rate**[62]
    - The most important metric for an institution to know, leak rate can be measured at the system level or at the equipment level. Best in class institutions will track this at the equipment level, but institutions should at least know this for the institution level.
    - $Leak\ Rate = \frac{Refrigerant\ Leaked\ (lb)}{Refrigerant\ in\ Equipment\ (lb)}\ x\ 100\%$
- **Pounds of Refrigerant Leaked**
    - Leak rates can be deceiving when an institution has equipment of various sizes[63]. If a unit of 3000 lbs is leaking 20% (600 lbs/year) but a unit of 300 lbs is leaking 30% (100 lbs/year), looking only at leak rates would have you prioritize the wrong pieces of equipment. Leak rates must be looked at in parallel with amounts leaked per unit.
- **Leak Repair Response Time**[64]
    - This will vary depending on what leak detection system an institution has. It could be minutes from alarm to technician arrival or simply time from someone noticing a leak to the leak being repaired. Regardless, tracking this number will impose a discipline around leak repairs which can be one of the most significant ways to reduce leakage.

Preventative Maintenance Suggested for Refrigeration Systems

The following section summarizes best practices in preventative maintenance as suggested by Air Conditioning, Heating and Refrigeration News.

- Evaporators[65]
    - Every six months, check the following:
        - Electrical connections – Make sure they're tight and there's no fraying on the insulation
        - Fan motors and blades – clean the surfaces, replace any worn blades and ensure free turning and tight screws. Motor lubricant should be applied and any motors with worn bearings should be replaced.
        - Defrost heaters – check the amp draw and voltage at each heater terminal. Check the condition of the heater terminals.
        - Drain Pans – Check condition and make sure they drain freely. The visible slope should be away from the evaporator

[62] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[63] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[64] Witman, K., 2018. *Five Simple Steps To Reduce Your Refrigerant Leak Rate.* [Online] Available at: https://blog.mybacharach.com/articles/definitive-guide-to-leak-rate-reduction/ [Accessed April 2019].
[65] Maxson, S., 1999. *ACHR News.* [Online] Available at: https://www.achrnews.com/articles/98243-preventive-maintenance-keeping-refrigeration-equipment-in-shape [Accessed April 2019].

        - Evaporator Coil Surface – Wash periodically to increase heat transfer on the fins and coils.
        - Temperature Glide – The evaporator temperature will need to be monitored and adjusted such that the mean temperature equals the desired evaporator set point.
- Compressors[66]
    - Every six months, check the following:
        - Electrical connections – Make sure they're tight and there's no fraying on the insulation
        - Electrical components – Check for any discoloration in the conductors and remove any contaminants from the contactor. Check the defrost timer motor and make sure the clock mechanism rotates freely. Replace any worn relays if necessary.
        - Control System – Ensure pressure controls are working correctly, ensure oil safety and high pressure controls are functioning correctly, check the room thermostat and make sure the liquid line solenoid closes completely and the compressor pumps down and cycles off.
        - Oil Levels – check that oil is between 1/3 and 2/3 of sight glass
        - Defrost controls – check that the defrost termination temperature control stops the defrost cycle and allows the evaporator fan 2 minutes of delay before restart
        - Refrigeration Line Insulation – Replace any worn insulation
        - Refrigerant Level – Check that the liquid line in the sight glass is free and full of liquid refrigeration.
        - System Superheat – Check the suction superheat
        - Capillary and Super Hose Lines – Check that the lines secure and are not rubbing into any objects that could cause refrigerant leaks
        - Replace all missing valve caps and unit covers

Use of Reclaimed Refrigerant

In the absence of a cap on refrigerant production in the United States, the American Carbon Registry has certified the use of reclaimed refrigerant as a carbon offset in the United States. They assert, "Re-using previously used HFC refrigerant that has been recovered from equipment, and reclaimed to virgin-grade purity, either to "recharge" existing systems that require servicing, or in newly manufactured equipment, displaces new production of virgin refrigerant that would otherwise be manufactured to meet that demand."[67]

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[66] Maxson, S., 1999. *ACHR News.* [Online] Available at: https://www.achrnews.com/articles/98243-preventive-maintenance-keeping-refrigeration-equipment-in-shape [Accessed April 2019].

[67] American Carbon Registry, n.d. *Certified Reclaimed HFC Refrigerants.* [Online] Available at: https://americancarbonregistry.org/carbon-accounting/standards-methodologies/certified-reclaimed-hfc-refrigerants [Accessed April 2019].

Details for the carbon offset can be found in ACR Standard "*Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from Certified Reclaimed HFC Refrigerants".*

To receive an offset, institutions need to do the following:

1. Develop relationships with service providers who are dedicated to using reclaimed refrigerant. Because this is a new market, this may be difficult to do. Vendors like A-Gas can refer institutions to service providers to whom A-Gas sells the reclaimed gases.
2. Collect data from the service provider on the following information about the reclaimed gases:
    a. Facility name and address where HFC was recovered
    b. Equipment/Product from which the HFC was extracted
    c. Date of recovery
    d. Cylinder number, gross refrigerant weight and net refrigerant weight of each container received by the EPA-certified reclaimer
    e. Dates received by the EPA-certified reclaimer
    f. Attestation from the EPA-certified reclaimer regarding the source of the HFC
    g. Chain of custody and ownership of the recovered HFCs including: name/address of each person buying the HFC, quantity of HFC purchased/sold at each transaction.
    h. Documentation from the reclaimer is an EPA-certified reclaimer including: the most recent equipment list provided to the EPA and the physical address where the reclamation was processed.
    i. Documentation showing that used HFC refrigerant processed by the EPA-Certified reclaimer is tested by an AHRI certified refrigerant testing laboratory to meet the AHRI 700-2015 Standard for Specification for Fluorocarbon Refrigerants.

Complete details on the offset protocol can be found in the standard including assumed equipment leakage rates per type of equipment.

In our calculations for our pilot project, we assumed the following parameters:

- Price of reclaimed HFC: 200% of virgin HFC. Reclaimed HFC is not widely available on the market yet, so this price is an estimate from talking with A-Gas and looking at the cost to reclaim HFCs. This will need to be continually monitored to evaluate the effectiveness of a given offset. However, as the market accepts the practice more frequently, this price will drop.

End of Life

Destruction: Halon, CFC, HCFC

Any halon, CFC, or HCFC gas recovered from retired equipment shall be destroyed. Destruction of these gases may qualify for offset credit.

Recovered refrigerant gas can be reprocessed to meet the specifications of new product, and then deployed to equipment using the same type of gas. Reclamation has been a popular choice for Ozone Depleting Substance ("ODS") refrigerant gases such as halon, CFC, and HCFC, because most of these gases are no longer available in the market. Production of these gases have been completely (or almost) phased out under the Montreal Protocol. While reclamation of halon, CFC, and HCFC gases can be profitable, it will lead to eventual release of these gases into the atmosphere, causing ozone depletion and climate change.

Destruction of these gases have multiple environmental benefits. If the recovered gases are destroyed, possibility of potential release and its environmental impact is eliminated because they will no longer be used. Further, it will accelerate retirement of older equipment that uses these gases because destruction will decrease the availability of these gases in the market making it more expensive to maintain and operate such equipment.

Reclamation and destruction of ODS refrigerants should be conducted in accordance with the technical standards under Clean Air Act Title VI and EPA regulations. EPA provides a list of certified refrigerant reclaimer companies at https://www.epa.gov/section608/epa-certified-refrigerant-reclaimers. EPA also provides a list of commercially available destruction facilities for ODS refrigerants at https://www.epa.gov/ods-phaseout/ozone-depleting-substances-ods-destruction-technologies.

Destruction of ODS refrigerant is recognized as an offset activity by a number of standards. ACR Methodology for Destruction of Ozone Depleting Substances and High-GWP Foam (ACR Destruction Methodology) recognizes the widest range of ODS refrigerants, including the HCFC-22.[68]

Institutions should retain certified reclaimers and destruction facilities for recovery and destruction of ODS refrigerants, and retain independent third-party verifier to validate the activity and issue offset credits.

Reclamation : HFC refrigerants

HFC refrigerants from retired equipment should be recovered and reclaimed for use in other equipment. Reclamation of HFC refrigerant may qualify for offset credit.

Contrary to ODS refrigerants, currently there are no limitation to production or importation of HFC refrigerants in United States. Destruction of recovered HFC refrigerants may instantly reduce the total

[68] American Carbon Registry, n.d. Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from the Destruction of Ozone Depleting Substances and High-GWP Foam Ver. 1.1 [Online] available at: https://americancarbonregistry.org/carbon-accounting/standards-methodologies/destruction-of-ozone-depleting-substances-and-high-gwp-foam [Accessed April 2019]

amount of HFC gas in existence, but it may not be permanent because the same amount can be replaced with new production. Meanwhile, if HFC refrigerant is recovered from retired equipment, reprocess to virgin specifications and deployed back in use, it can displace new production. Also, it should be noted that the reclamation rate for HFC refrigerant in retired equipment is estimated at less than 10%.[69] This means more than 90% of the HFC refrigerants had been abandoned, eventually being released into the atmosphere at some point of at the end of their lifecycle.

Considering these factors, reclamation provides more environmental benefit because reclamation can reduce new production and also reduce potential emission from the unrecovered refrigerants. Without limitation on production, benefit from destruction is undermined by new production as well as additional energy input for the destruction process.

The requirements and procedure for reclamation of HFC refrigerants are previously discussed in the Operations section. Institutions can either produce certified reclaimed HFC refrigerants to be sold in the market, or use them for maintenance of their own HFC-using equipment. In either case, as long as the institution has born the cost of reclamation and certification process, the institution can use the offset credit to reduce its greenhouse gas emission.

Going Forward

This manual proposes two-track approach to end-of-life refrigerants: destruction for phased-out ODS refrigerants, and reclamation for HFC refrigerants. However, it is necessary to revisit this approach when regulation on production of HFC is introduced in United States, for example, by ratification of Kigali Amendment to the Montreal Protocol which requires 85% reduction of HFC use by 2036.

If new production of HFC is limited, destruction of HFC may provide more environmental benefits as destruction may achieve permanent reduction of HFC in existence without replacement by new production. On the other hand, it will undermine the value of reclamation because when production is already under phase-out, reclamation of HFC refrigerants from retired equipment may have limited or no effect on the production volume, but instead only slow down the phase-out. In this case, destruction of HFC refrigerants may be more beneficial for the environment than reclamation.

However, determining when such change would be triggered is difficult at this point. Even if United States introduces HFC regulation and implements limitation on production of HFCs, it would require additional analysis on the impact of destruction and reclamation to determine which approach would produce more environmental benefits because the allowance for production will decrease in increments. (Kigali Amendment, for example, sets the limit at 90% of baseline in the first five years.) Therefore, monitor regulatory developments should be monitored as an ongoing effort to develop best practice for end-of-life approaches.

[69] American Carbon Registry, n.d. Certified Reclaimed HFC Refrigerants. p.22 [Online] Available at: https://americancarbonregistry.org/carbon-accounting/standards-methodologies/certified-reclaimed-hfc-refrigerants [Accessed April 2019]

Reducing the Climatic Impact of Harvard's Refrigerant Use

A Feasibility Analysis

Adam Meier
Bridget Nyland
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Sejong Youn

Table of Contents

Feasibility Study Acronyms

ACR	American Carbon Registry
AHRI	Air-conditioning, Heating & Refrigeration Institute
CAA	Clean Air Act
CFC	Chlorofluorocarbon
CSLL	Climate Solutions Living Laboratory Course
EH&S	Harvard Environmental Health and Safety
EPA	United States Environmental Protection Agency
FY	Fiscal Year
GHG	Greenhouse Gas
GRF	Green Revolving Fund
GWP	Global Warming Potential
HBS	Harvard Business School
HLS	Harvard Law School
HMS	Harvard Medical School
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVAC/R	Heating, Cooling, Air Conditioning, and Refrigeration
$MTCO_2e$	Metric Tons of Carbon Dioxide Equivalent
NPV	Net Present Value
ODS	Ozone Depleting Substance
ODP	Ozone Depleting Potential
OFS	Harvard Office for Sustainability
OSHA	Occupational Safety and Health Act
ROI	Return on Investment
SCAR	Social Cost of Atmospheric Release
SCC	Social Cost of Carbon
SLCP	Short-Lived Climate Pollutant
SNAP	Significant New Alternative Policy
WMB	We Mean Business Coalition

I. Executive Summary

Halocarbons are among the most potent greenhouse gases emitted with global warming potentials hundreds to tens of thousands of times higher than carbon dioxide (CO_2). Efforts to reduce their atmospheric release are particularly valuable in the near term because of their short atmospheric lifespan. As much as 90% of predicted warming by short-lived climate pollutants (SLCPs) can be prevented within a decade and currently, SLCPs account for approximately 40-45% of present climate forcing. Scalable reductions to these greenhouse gas (GHG) sources would result in disproportionate climate benefits.

In this report, we have discussed the regulatory and health implications of Harvard's halocarbon emissions and outlined the technical, legal, financial, and institutional barriers the University faces in reducing its halocarbon use. We propose practical directions for the University and similar institutions to consider in order to meaningfully advance efforts to reduce halocarbon inventories and associated emissions.

In the absence of hydrofluorocarbon (HFC) regulation, the University enjoys broad discretion to decide how best to reduce its HFC use and emissions. Acknowledging this freedom, this report proposes two pathways designed to reduce Harvard's HFC emissions. The first option would be to dedicate resources toward reducing leaks in existing equipment. While reducing leaks is a laudable goal, we maintain that the University's leaks have already been largely minimized to the extent feasible. Total halocarbon emissions amount to approximately 3,000 $MTCO_2e$ per year, or only 1 to 2% of the University's total greenhouse gas emissions. Harvard's annual emission rates (2 to 10% of the stock) are below the industry average of 15%.

Our analysis therefore suggests that reducing HFC use in the University's equipment is the more impactful and forward-thinking alternative. Policies include replacing aging systems with natural refrigeration equipment and retrofitting viable equipment with refrigerants of lower global warming potentials (GWP). There are considerable technical, legal, financial, and public health considerations associated with these policies. If strategies are pursued in isolation or poorly managed, retrofitting equipment may reduce the cooling capacity of units and could increase energy consumption. The regulatory framework surround HFC reclamation and destruction is still evolving, and it is unclear which disposal option would yield the greatest climatic benefits – and by extension – the carbon reduction and possibly, by extension, carbon offset credits. Meaningful upgrades will require substantial financial commitment and planning. And finally, several replacement refrigerants are toxic and flammable.

These are formidable challenges. Yet the factors behind these very challenges are also the key to this project's success. There are technical obstacles – but also opportunities for innovative ideas. There are regulatory ambiguities – but also the chance to shape impending regulation. Projects may be cost ineffective in the short term – but Harvard can define a new standard of environmentalism driven by stewardship rather than finances.

In this spirit, we believe the charisma of these opportunities may drive the University to implement policies that reduce their HFC use and emissions. We propose two innovative paths forward. The first is to serve as a pilot institution that uses HFC destruction as an offset mechanism for the American Carbon Registry. The early development of this offset program will incentivize widespread HFC destruction once production limitations are promulgated. The second pathway is to characterize and implement a novel HFC destruction methodology. The innovative potential of this option may be a valuable educational and public relations resource to the University.

II. Screening

II.a Background

Halocarbons – carbon and halogen based molecules – are the fastest growing source of greenhouse gases in much of the world[1]. These gases – chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs), and halons – are among the most potent greenhouse gases emitted, with global warming potentials hundreds to thousands of times more than carbon dioxide (CO_2). They are factory-made chemicals used primarily in cooling and foam blowing applications. Although regulations for halon, CFC, and HCFC production have greatly reduced their use and emissions, the continued use of HFCs poses great danger to the environment.

Aggressive reductions in halocarbon emissions are urgently needed to mitigate rapid climate change over the coming decades. Halocarbon emissions are responsible for nearly 14% of the global warming that has already occurred; yet half of this effect is due to cumulative emissions since 2005. Without regulation, HFC-induced warming could equal 0.1 ˚C by 2050 and 0.5 ˚C by 2100. This warming could equal 12 to 71% of the warming induced by CO_2 by 2050[2]. Moreover, the sea level rise resulting from continued halocarbon emissions will persist for thousands of years after these emissions cease[3]. Comprehensive halocarbon policy is therefore requisite to mitigate the considerable impacts of unregulated halocarbon emissions.

A growing global movement is currently underway to phase out HFC production and use. The Kigali Amendment to the Montreal Protocol has been ratified by 65 nations around the world, and has taken effect on January 1, 2019, moving towards 85% reduction by 2036. Accordingly, the Parties to Kigali Amendment are implementing regulations and policy measures to achieve this target. This movement generally enjoys broad support from businesses seeking to grow the market for HFC replacements, improve their public image, or shape the extent and timing of the impending legislation. However, United States is not part of this initiative because Kigali Amendment has not been ratified by the U.S. Senate, and has no effect on the national level. Further, EPA has been repealing existing HFC regulations that were implemented as part of the Climate Action Plan during Obama administration.

The current absence of regulation, however, gives institutions like Harvard University broad discretion over when and how to reduce their halocarbon use and emissions. Harvard uses eight different types of halocarbons in reportable quantities (> 50 lbs.)[4], including regulated CFCs and HCFCs[5]. Although halocarbon emissions currently account for only one to two percent of the University's total annual greenhouse gas emissions, the climatic impact of these emissions will be more heavily manifest in the near term than emissions of longer-lived greenhouse gases, like carbon dioxide.

In this report, we investigate the details of Harvard's halocarbon use. We then discuss the technical, legal, financial, and public health obstacles towards reducing this use. We conceive two pathways to reduce halocarbon emissions and overcome the described obstacles. The first is to reduce refrigerant leaks in existing equipment, while the second is to phase out halocarbon use in existing and new equipment. Our

[1] Velders G. J. M, et al. (2012) Preserving Montreal Protocol Climate Benefits by Limiting HFCs, Science, 335(6071), 922–923.
[2] Velders G. J. M., et al. (2014) Growth of climate change commitments from HFC banks and emissions, Atmospheric Chemistry and Physics, 14, 4563–4572.
[3] Zickfeld K., et al.(2017) Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases, Proceedings of the National Academy of Sciences, 114(4), 657–662.
[4] Under federal regulation, facilities are required to maintain an inventory of equipment containing greater than 50 pounds of halocarbon refrigerant. 40 CFR Part 82 – Section 608.
[5] Although CFC and HCFC production has been restricted under the Montreal Protocol, use of these refrigerants is still permitted for equipment manufactured before the implementation of the treaty.

analysis quantifies the climatic benefit of these options and considers the viability of these options in the context of Harvard's regulatory responsibilities and decision-making framework.

II.b Project Screening Flowchart

For our project screening, we followed two major pathways to understand the best way to reduce GHG emissions from Harvard's use of HFCs. Exhibit 1 below shows those pathways based on our current assessment.

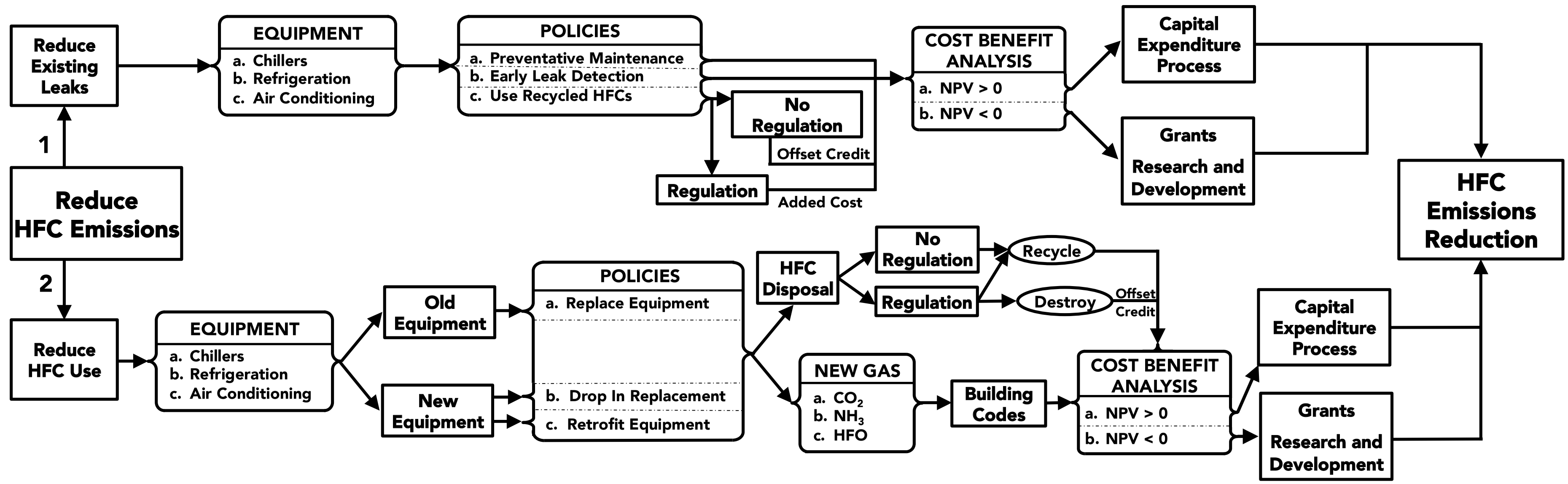

Exhibit 1. Project pathway overview. To reduce halocarbon use and emissions, the University could (1) minimize leaks in existing equipment, or (2) reduce the number and/or capacity of units that use halocarbon refrigerants.

III. Carbon Impact

The Project is expected to have three significant carbon impacts – (i) direct reduction of GHG emission during operation of equipment using refrigerants and (ii) impact on indirect emissions resulting from energy efficiency and (iii) secondary emissions impact related to the disposal or use of replaced refrigerants.

III.a Direct Emissions Reductions

Although refrigerants are designed to circulate within a “closed-loop” system in Heating, Cooling, Air Conditioning, and Refrigeration (HVAC/R) equipment units, refrigerants may leak from valves, joints or other components during normal operations, as well as during maintenance service such as refrigerant injection, refill, and reclamation.

The amount of direct emissions can be estimated by the amounts of refrigerants supplied to existing Harvard facilities for maintenance purposes, as they would represent the amount lost during operation and service. Harvard estimated its annual leak rate to be between 2 and 10% of total stock based on fugitive emissions estimates, which amounts to nearly 3,000 metric tons CO_2 equivalents ($MTCO_2e$) per year.

The Project aims to replace GHG refrigerants currently being used in Harvard facilities to non-GHG or lower-GWP refrigerants. Such replacement will eliminate or decrease the amount of GHG refrigerants Harvard facilities are emitting during operation under the same operating conditions.

Emission reduction can also be achieved by improving maintenance and service practice and reducing the annual leak rate. For example, installation of detection devices may allow quicker response and increased preventive maintenance may reduce the occurrence of failures that result in complete loss of charge. Many newer models of HVAC/R equipment incorporate leak detection devices. However, GHG emission reduction through improved practice can only be accounted when Harvard equipment uses refrigerants with some GWP.

III.b Indirect Emissions

Replacing existing refrigerants with no or lower GWP refrigerants may affect the efficiency of the equipment. If the substitute refrigerant (and/or applicable modification to the equipment) is more energy-efficient, additional emissions reductions may be achieved by consuming less electricity. The amount of emission reduction should be measured based on the carbon intensity of the electricity grid from which the equipment draws its power.

On the other hand, if the substitute refrigerant (and/or applicable modification to the equipment) is less energy-efficient, it may consume more electricity to achieve same level of output or additional equipment may be required to meet the HVAC/R demand. In such case, increased emissions from increased electricity consumption will be subtracted from the direct emissions reduction achieved by replacement of refrigerants. Likewise, the amount of emissions addition will be measured based on the carbon intensity of the electricity grid.

III.c Secondary Reduction from Disposal / Use of Replaced Refrigerants

Since 2016 revision of EPA Regulations (40 CFR Part 82, Subpart F) under Clean Air Act Section 608[6], substitute refrigerants such as HFCs and HFOs are also subject to extended refrigerant management requirements. According to these requirements, refrigerant gas cannot be 'vented' into the atmosphere at the end of its use, but it needs to be properly recovered using certified equipment. Final disposal of refrigerant gas may follow one of the four options: (i) storage, (ii) recycle, (iii) reclamation or (iv) destruction. The carbon impact of each option is discussed below.

If refrigerants from Harvard's facilities are recovered and stored, no GHG emission will occur from operation. However, if the container vessels develop leaks, such emission may be accounted as emissions of Harvard facilities depending on the state of their custody. However, there is no particular value in recovering and storing the recovered HFC gas, and this option is not considered for the project.

Recycling under the EPA rules means to extract refrigerant from an appliance (except motor vehicle air conditioning) and clean it for reuse in equipment of the same owner without meeting all of the requirements for reclamation. In this case, GHG emission will occur from operation. However, if refrigerants in Harvard facilities are replaced by this Project, Harvard will no longer use the recovered refrigerants. Therefore, recycling is not considered for the project.

Reclamation under the EPA rules means to reprocess recovered refrigerant in accordance with the requirements based on Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 700-2016 to be used for any equipment. If refrigerants within Harvard's operational control are recovered and reclaimed for use in equipment outside Harvard facilities, direct emissions may occur during operation, maintenance or disposal in such equipment. However, at the same time, reclamation and reuse of existing HFC gas may displace new production of HFCs which would have occurred without reclamation efforts. American Carbon Registry has developed an offset methodology for reclamation of HFC recognizing the environmental benefit of reclaiming HFC products and displacing new production.[7] According to this approach, reclaiming HFCs for reuse could reduce overall GHG emission from the refrigerants. In case Harvard facilities continue to operate HFC using equipment, it may use reclaimed HFC products instead of newly produced products could also have the same effect.

If refrigerants from Harvard facilities are recovered and destroyed, such refrigerants will no longer cause any GHG emission, except the GHG emissions occurring in relation to the process of destruction. In the case of ODS refrigerants under phase-out, destruction is recognized by a number of standards as an additional emission reduction qualifying as an "offset" because it eliminates the emissions that would occur when it is reclaimed and reused, and such substance cannot be replaced due to production ban.[8] In case of HFC refrigerants, Harvard may seek to claim destruction as an additional "offset" activity because it also eliminates the emissions that would occur when it is reclaimed and reused. However, because HFC production (or importation) is not currently in United States, argument can be made that such destruction will trigger additional production of new HFCs resulting in no net reduction, or "leakage." This issue will be further discussed in the legal analysis below.

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[6] 81-FR-82272, However, EPA has proposed rescission of the 2016 rule on leak control and reporting requirements in October 2018. (83-FR-49332). EPA has also noted that it is considering exclusion of HFCs for all regulations under Section 608. This proposed rule is not in effect as of the date of this report.

[7] Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from Certified Reclaimed HFC Refrigerants Version 1.1, September 2018, American Carbon Registry

[8] Pursuant to the Clean Air Act, all production and import of Class I (CFCs) refrigerants have been phased out by 1996, and most of Class II (HCFCs) refrigerants will be phased out by 2020.

IV. Legal Landscape Analysis

IV.a General background on Regulatory Regime for HFC refrigerants

Prior to discussing the current status of the HFC regulation, it is necessary to understand the general background of refrigerant regulation.

International Regulatory Regime

Refrigerant regulation began with CFCs and HCFCs, also known as Freon Gas, in order to mitigate ozone layer depletion in the stratosphere. In 1985, Vienna Convention for the Protection of the Ozone layer was signed, and subsequently the parties of the treaty agreed to the Montreal Protocol on Substances that Deplete Ozone Layer in 1987.[9] ("Montreal Protocol") The Montreal Protocol prescribed gradual decrease in production of refrigerants based on ozone depleting substances (ODS), and the parties of the Montreal Protocol implemented regulatory measures on national level to achieve the "phase-out" schedule thereunder. United States introduced "phase-out" of ODSs in Title VI of Clean Air Act, and prohibited all production and importation of CFCs in 1996.[10] For HCFCs, 99.5% of the production and importation will be phased out by 2020, and complete phase out will be achieved in 2030.[11]

Just as HCFCs were invented as alternative refrigerants with *lower* ozone depleting potential for CFCs, HFCs were invented as alternative refrigerants for HCFCs with *no* ozone depleting potential. However, all of CFCs, HCFCs, and HFCs are extremely powerful greenhouse gases, as previously discussed. In recognition of the urgent need to reduce greenhouse gas emission from HFCs, in October 2010, the parties of the Montreal Protocol agreed to amend the protocol and regulate HFCs under the same regulatory regime for ODS refrigerants in Kigali, Rwanda.[12] The Kigali Amendment to Montreal Protocol ("Kigali Amendment") prescribed an incremental reduction schedule, which will achieve 85% reduction by 2036 for developed countries (Non-Article 5 Countries), and 80-85% reduction by 2045-2047 for developing countries (Article 5 Countries, Group 1 and 2).

Kigali Amendment entered into effect on January 1, 2019 with ratification from 65 nations. However, because United States Senate has not ratified Kigali Amendment, it does not have legal effect for United States on national level.

U.S. Regulatory Regime

The U.S. introduced HFC regulation as a part of the Climate Action Plan implemented under Obama administration, through EPA SNAP (Significant New Alternative Policy) program. SNAP program implements section 612 of the amended Clean Air Act of 1990, and generates lists of acceptable and unacceptable substitutes for ODSs for each of the major industrial use sectors to promote a smooth transition to safer alternatives.[13]

In particular, SNAP Rule 20 prohibited use of 38 high-GWP HFCs including HFC-125, HFC-134a, HFC-404A for various uses such as foam blowing, motor vehicle air conditioning, and new and retrofitted retail

[9] Montreal Protocol on Substances that Deplete Ozone Layer, https://treaties.un.org/doc/publication/unts/volume%201522/volume-1522-i-26369-english.pdf
[10] https://www.epa.gov/ods-phaseout
[11] https://www.epa.gov/ods-phaseout
[12] Kigali Amendment to Montreal Protocol, https://multimedia.3m.com/mws/media/1365924O/unep-fact-sheet-kigali-amendment-to-mp.pdf
[13] https://www.epa.gov/snap/snap-regulations

food refrigeration.[14] This would allow the use of existing HFC equipment but will trigger gradual phase out of HFCs as new equipment would need to use alternative refrigerants with no or low global warming potential.

In November 2016, EPA promulgated another rule extending the refrigerant management requirements under Section 608 of the Clean Air Act to substitute refrigerants such as HFC and HFOs.[15] Under the new rule, HFCs and HFOs are also subject to 'no-venting' rule, as well as leak rate management and reporting requirements.

However, these regulations went through significant retreat since the administration change in 2017. EPA's new SNAP rule was challenged by HFC manufacturer/importer companies who argued that EPA has no authority to regulate non-ODS refrigerants under Section 612 of the Clean Air Act. The matter was decided in favor of the plaintiffs by the D.C. Circuit Court in 2017 which vacated EPA SNAP Rule 20[16]. D.C. Circuit decision was appealed by Honeywell International Inc. and National Resource Defense Council (NRDC) but the Supreme Court denied further review of the case in 2018.

Following this decision, in September 2018, EPA proposed revised rule under Section 608, rescinding the leak repair and maintenance requirements. EPA also invited comments for rescinding the application of all refrigerant management requirement to HFCs.[17] As of April 2019, the proposed rule has not been finalized.

As a result, there is currently no federal limitation in production or use of HFC refrigerants in United States. HFC refrigerants are subject to management requirements under Clean Air Act and EPA Regulations, but they could be rescinded.

In response to federal roll-back of HFC regulation, some states have taken initiative. California enacted California Cooling Act (Senate Bill 1013) in September 2018 which stated that SNAP Rules on HFC ban will continue to have effect in California.[18] The New York State Department of Environmental Conservation developed a proposal to phase-out HFCs beginning with foam blowing agent sector.[19] Maryland and Connecticut also announced their plans to begin HFC regulation.[20]

IV.b Alternative Refrigerants

Pursuant to Section 612 of Clean Air Act, EPA maintains a list of substitutes for ODS that are acceptable or unacceptable for each of the major industrial use sectors through SNAP program. If the Project considers replacing CFC, HCFC, and HFC refrigerants currently in use in Harvard facilities to a low-GWP or non-GHG refrigerants, it should choose its alternative among the substitute refrigerants listed as "acceptable" for the specific use under SNAP. Substitute refrigerants with low or no GWP such as HFOs, hydrocarbon, carbon dioxide, or ammonia are currently listed as acceptable under SNAP rules, and are valid options for Harvard facilities in reducing GHG emission.

The choice of specific refrigerant among the substitutes may be determined through consideration of cost, safety and health standards, building code and technical applicability. Toxicity and flammability of these

[14] 40 CFR Part 82, EPA–HQ–OAR–2014–0198; FRL–9926–55–OAR
[15] 40 CFR 82 EPA-HQ-OAR-2015-0453
[16] Mexichem Fluor, Inc v. EPA, 866 F.3d 451, 456 (D.C. Cir. 2017)
[17] 83-FR-49332
[18] California Senate Bill No. 1013 CHAPTER 375 An act to add Section 39734 to the Health and Safety Code, and to add Division 45 (commencing with Section 76000) to the Public Resources Code, relating to greenhouse gases.
[19] 6 NYCRR Part 494, Hydrofluorocarbon Standards and Reporting Pre-Proposal Stakeholder Draft (September 2018)
[20] https://insideclimatenews.org/news/10092018/new-york-ban-hfcs-potent-greenhouse-gas-climate-pollutant-cooling-refrigeration

substitute refrigerants, in particular, may require additional regulatory considerations. Toxicity may limit applicability to certain public facilities, require a Risk Management Plan under EPA regulations, or subject to exposure limits under Occupational Safety and Health Act standards, and flammability may be subject to additional regulatory requirements for safety, leakage, and fire suppression[21], as well as building codes prescribed by municipal authority. Analysis on additional regulatory requirements should be conducted case-by-case basis considering the specific conditions of the equipment.

IV.c Offset Qualification

Qualification Standard

If the Project intends to achieve emission reductions through an "offset" mechanism in addition to the direct emission reduction achieved from refrigerant use, it should satisfy the requirements under the General Reporting Protocol for the Voluntary Reporting Program from The Climate Registry, which is used for Harvard's carbon inventory ("Reporting Protocol").

Section 17.3 of the Reporting Protocol defines offsets as "reduction, removal, or avoidance of GHG emissions from a specific project that is used to compensate for GHG emissions occurring elsewhere, for example to meet a voluntary GHG target," and sets out six key accounting criteria as below[22]:

> **Real**: GHG reductions must represent actual emission reductions quantified using comprehensive accounting methods.
>
> **Additional**: GHG reductions or removals must be surplus to regulation and beyond what would have happened in the absence of the incentive provided by the offset credit. Offsets quantified using a project vs. performance standard methodology may establish slightly different requirements for demonstrating additionally.
>
> **Permanent**: The GHG reductions must be permanent or have guarantees to ensure that any losses are replaced in the future.
>
> **Transparent**: Offsets must be publicly and transparently registered to clearly document offset generation, transfers and ownership.
>
> **Verified**: The GHG reductions must result from projects whose performance has been appropriately validated and verified to a standard that ensures reproducible results by an independent third-party that is subject to a viable and trustworthy accreditation system.
>
> **Owned Unambiguously**: No parties other than the project developer, must be able to reasonably claim ownership of the GHG reductions.

Reporting Protocol recognizes offset credits that have been issued or recognized by major existing offset programs including American Carbon Registry, Clean Development Mechanism, Verified Carbon Standard, and The Gold Standard.

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[21] ARTI Report No. 09001-01, Review of Regulations and Standards for the Use of Refrigerants with GWP Values Less Than 20 in HVAC&R Applications.
[22] General Reporting Protocol for the Voluntary Reporting Program, Version 2.1, January 2016, The Climate Registry.

If the Project includes emission reduction activities to be claimed as offsets, the Reporting Protocol requires that such offset credit is either (i) obtained through existing offset programs or (ii) in compliance with the six criteria. The Project will prioritize using tested-and-proven existing programs to reduce the risk associated with qualification of offsets.

Case Analysis

Three potential offset activities are considered for the Project: (i) reclamation of existing HFC for reuse (ii) use of reclaimed HFC for use in existing equipment and (iii) destruction of reclaimed HFC.

Reclamation for reuse and use of reclaimed HFC may be both qualified as offsets under "Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from Certified Reclaimed HFC Refrigerants" from American Carbon Registry ("Certified Reclaimed HFC Methodology")[23]. Certified Reclaimed HFC Methodology explains that "re-using previously used HFC that has been recovered and reclaimed to virgin-grade refrigerant purity, either to recharge existing systems that require servicing, or in newly manufactured equipment, displaces new production of virgin refrigerant that would otherwise be manufactured to meet that demand. The "additionality" of this activity is derived from the fact that "there is currently little incentive for recovery, reclamation, and re-sale of HFC refrigerants", unlike other CFC or HCFC refrigerants under phase-out[24]. Certified Reclaimed HFC Methodology conservatively sets the baseline reclamation rate for HFCs in the United States at 8.9% which is the R-22 reclaim rate from 2013.

If Harvard facilities choose to replace HFCs with alternative refrigerants, it may reclaim and process the refrigerant for reuse through certified gas service providers. In return for this additional activity, offset will be created under the Certified Reclaimed HFC Methodology and the offset should be recognized as additional reduction by offset under the Reporting Protocol.

If Harvard facilities continue to use HFCs in its existing equipment, it may be able to claim offset by using reclaimed HFC refrigerants certified under the Certified Reclaimed HFC Methodology for recharge and refill, on the assumption that the cost of reclamation and processing is included in the certified reclaimed HFC and Harvard is entitled to claim the offset.

Regarding the destruction of HFCs, currently there is no offset methodology that recognizes destruction of HFC refrigerant as offset activity. On the other hand, destruction of CFC and HCFCs are accepted as offset activities by a number of standards including American Carbon Registry and California Air Resources Board. Considering that there is no limit in production of HFC products in United States, destruction of HFCs is unlikely to be accepted as valid "offset" activity. While destroying HFC product could eliminate potential emission, it could also trigger the same amount of new production. This "leakage" problem would undermine the "permanence" requirement of the offset activity because the benefit from destruction is likely to be annulled by the environmental harm created by additional production.

However, the choice between reclamation and destruction is predicated upon the regulation. If new production of HFC product is limited, as CFCs and HCFCs are, destroyed gas cannot be replaced by new production. In this case, destruction would yield more environmental benefit than reclamation. This is the case for most of ODS gases that are phased out, such as CFCs, HCFCs and Halons. Similarly, HFC destruction can potentially become an offset if sufficient limitation is put on its new production.

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[23] Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reductions and Removals from Certified Reclaimed HFC Refrigerants Version 1.1, September 2018, American Carbon Registry

[24] Id.

However, it would be premature to predict when and how such a transition will take place at this point. Theoretically, destruction of refrigerant could qualify as an offset when such destruction has no impact on the production level of the gas. This is the case for completely phased-out gas because no production is allowed. Also for almost phased-out gas, such as HCFC-22,[25] it can be reasonably assumed that the limited amount allowed for new production will be 100% filled by the remaining demand, and destruction will not affect the volume of new production. In both cases, destruction would qualify as an offset activity because it is an activity that reduces greenhouse gas emission, which is not required by regulation (additionality), and the benefit is permanent. For this reason, American Carbon Registry added destruction of HCFC-22 as an offset in its recent version of ODS Destruction Offset Methodology.[26]

Even if Kigali Amendment is ratified by United States and EPA imposes a "freeze" on the volume of production for HFCs, it would not necessarily mean destruction, instead of reclamation, becomes an offset because it would require further examination on the impact of destruction on the production. Until there is an assurance that destruction would not be replaced by new production, reclamation may continue to be the preferred option.

IV.d Regulations on Destruction

If the Project includes destruction of reclaimed refrigerants, Harvard may (i) destroy the refrigerants through commercially available destruction facilities, or (ii) destroy the refrigerants itself.

For ODS refrigerants such as CFCs and HCFCs, Montreal Protocol's Technology and Economic Assessment Panel ("TEAP") provides standards for destruction technologies including DRE (destruction and removal efficiency) of 99.99% along with other emissions limits, and list of approved destruction technologies, which is required to be used by EPA[27]. While destruction standards are not specifically set for HFCs under current US regulations, destruction technologies for ODS refrigerants are generally applicable to HFCs.[28]

If Harvard is to destroy the refrigerants itself, permit requirements may apply depending on the refrigerant gas, emissions from the destruction process, and any waste produced from such process. Air pollutant emissions may trigger permit requirements under Clean Air Act, Resource Conservation and Recovery Act ("RCRA") regulations may apply in case the refrigerants are classified as hazardous waste. NPDES permit scheme under Clean Water Act may be required in case such process results in discharge of water pollutants. More detailed analysis of the regulatory requirement may be conducted case-by-case basis with specific refrigerants.

V. Harvard Data Analysis

In this section, we explore the technical aspects of Harvard's halocarbon use and emissions. The extent of halocarbon use is affected by competing factors of technological momentum, economic costs, and environmental stewardship. While policies to reduce halocarbon use may benefit the climate and preempt regulation, it can be costly to implement the required changes. Even if cost analysis reveals long-term savings through increased energy efficiency, unfamiliarity with new refrigeration systems and

[25] HCFC-22 will be completely phased out in 2020. See https://www.epa.gov/ods-phaseout/phaseout-class-ii-ozone-depleting-substances
[26] Methodology for the Quantification, Monitoring, Reporting and Verification of Greenhouse Gas Emissions Reduction and Removals from the Destruction of Ozone Depleting Substances and High-GWP Foam, Ver 1.1, September 2017
[27] ODS Destruction in the United States and Abroad, February 2018, EPA 430-R-18-001
[28] Id.

unwillingness to prioritize replacing otherwise functional infrastructure can impede progress towards reducing halocarbon use.

Through these examples, a common theme emerges: the technical aspects of halocarbon use complement the legal, economic, and environmental aspects of Harvard's environmental interactions. We therefore consider the details of Harvard's use, emissions, and destruction of halocarbons to better inform the legal, financial, and public health branches of policymaking.

V.a Regulations on Destruction

Harvard uses eight different types of halocarbons in equipment containing over 50 pounds of refrigerant, according to the University greenhouse gas inventory. These include four classes of compounds or mixtures:

1. **Chlorofluorocarbons (CFCs)**: CFC-11
2. **Hydrochlorofluorocarbons (HCFCs)**: HCFC-123, HCFC-22
3. **Hydrofluorocarbons (HFCs)**: Single Component: HFC-134a; Mixtures: HFC-404a, HFC-407c, HFC-410a
4. **Halons**: unspecified

HFCs are used in the most abundance (34.8 t.), followed by HCFCs (10.6), CFCs (0.78 t.), then Halons (0.45 t.). Exhibit 2a illustrates campus wide halocarbon use by gas. The use of gases whose production is now banned (CFC-11) or being phased out (HCFC-123 and 22) is an example of the technological lag – yet also an opportunity for innovation – the University must confront to alter its halocarbon use.

The climatic impact of these gases varies widely. The chemical structure of gases determines how effectively they absorb infrared energy and warm the atmosphere. In addition, gases that persist in the atmosphere are more potent than gases that readily react and are removed quickly. We quantify these impacts here using global warming potential (GWP) metrics. Since halocarbons are reactive in the atmosphere, the GWP will depend on the timeframe considered. For instance, many HFCs are thousands

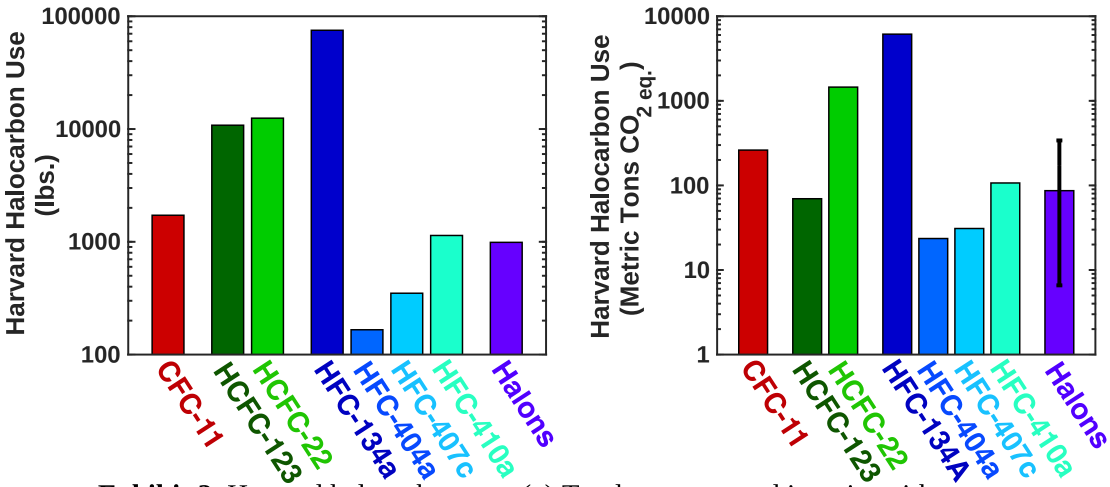

Exhibit 2. Harvard halocarbon use. (a) Total amount used in units with greater than 50 pounds of refrigerant. (b) The equivalent CO_2 mass of the halocarbon stock. 20 year GWPs were used in calculating (b).

of times more effective at warming the climate in the short term. As these gases oxidized to CO_2 or removed from the atmosphere, and their potency therefore decreases over time.

GWP potential is traditionally defined over 100-year time intervals. However, many of the halocarbon gases in use at Harvard have much shorter atmospheric lifetimes[29]. In the following discussion, we better account for the warming potential of these short-lived greenhouse gases by using a 20 year GWP. This shorter timeframe is also relevant from a policy perspective, given that halocarbon regulations are likely to strengthen within decades.

The ultimate potential impact of Harvard's emissions is influenced both by the GWPs of the gases combined with their quantity. We quantify this in terms of equivalent metric tons of CO_2 ($MTCO_2e$) by multiplying the mass in use by the GWP:

$$MTCO_2e = \text{Abundance} \times \text{GWP}$$

Exhibit 2b illustrates the $MTCO_2e$ of Harvard's halocarbon stock integrated over a 20-year timeframe[30]. The two most potent gases are HFC-134a and HCFC-22. This data becomes relevant when deciding whether to destroy or recycle halocarbons once they are retired from the University's equipment. The University may be able to sell their retired halocarbons, but they are likely to be emitted by other users and contribute to climate change. An interesting result of this analysis is that a gas' abundance alone is an insufficient metric of its potential climatic impact. By taking into account both abundance and GWP, a clearer understanding of the potential climatic impact emerges.

V.b Harvard Halocarbon Use

As of 2018, Harvard has 97 devices with charge capacities of greater than 50 pounds of refrigerant. These broadly fall into three categories: 1) chillers, 2) air conditioners, and 3) refrigerators. Chillers cool water used for centralized HVAC and scientific applications. For instance, some laboratory equipment requires chilled water as a heat sink for lasers or sensitive electronics. In cases where buildings are not serviced by the University's centralized chilled water plants, separate air conditioning units provide the desired cooling. Finally, large-scale refrigeration is employed in cafeterias and cold storage rooms across the University – including the library's 200,000 square foot book storage facility. In the case of cafeterias, we note that designers may elect more, but smaller, refrigeration units rather than fewer larger units to avoid subjection to reporting requirements.

[29] Wallington, Timothy J., et al. "The environmental impact of CFC replacements HFCs and HCFCs." Environmental science & technology 28.7 (1994): 320A-326A.
[30] Where possible, we have used the 20 year GWP defined by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013). The GWPs of halocarbon mixtures have been calculated by taking the mass-averaged GWP of the mixture.

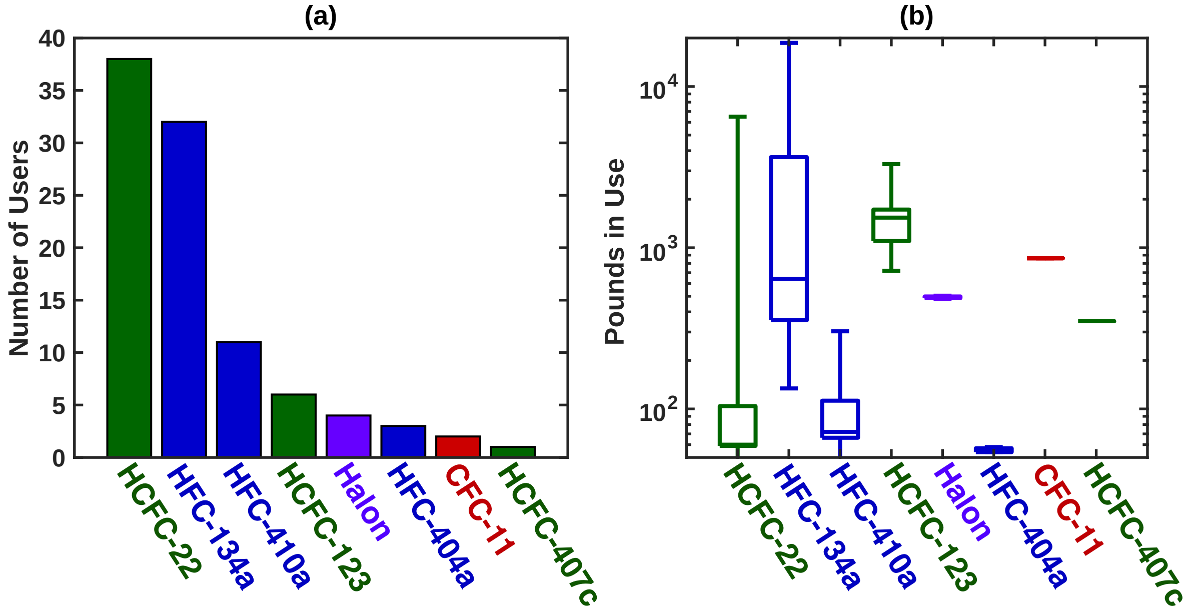

Exhibit 3. Harvard halocarbon equipment. (a) Distribution of users, according to the 2018 inventory. (b) Box plots of halocarbon use. On each box, the central line indicates the median charge capacity. The top and bottom box edges represent the 75th and 25th percentile, respectively. The whiskers extend to the highest and lowest values in each dataset.

The University's largest users of halocarbons are the centralized chilled water plants. These include a base load Carrier unit using 18,6500 pounds of HFC-134a and two smaller but more energy efficient York units using 6,500 pounds each. Smaller users are typically single zoned air conditioning units, such as several Mitsubishi split-system HVAC units each using about 65 pounds of HFC-410a.

The majority of units use HCFC-22, followed by HFC-134a and HFC-410a (Exhibit 3a). The range in charge capacity increases with increasing number of users (Exhibit 3b). This information can be used to target halocarbon reduction policies. For example, equipment using HFC-134a are both abundant and have relatively large charge capacities. Efforts to replace these units could therefore achieve substantial reductions in the University's halocarbon use. Conversely, it may be more feasible from financial and administrative perspectives to replace several smaller units, such as those using HFC-410a or 404a.

V.c Harvard Halocarbon Emissions

While the analysis above quantifies the potential climatic effect of Harvard's halocarbon stocks, actual emissions are a more direct indicator of the climatic impact of halocarbon use. Refrigerants are emitted from leakage during normal equipment use, but also from the servicing of equipment, manufacture of the gases, and equipment disposal.

Strict regulations are in place to reduce the emissions of halocarbon during their production and in the process of equipment disposal. Fugitive emissions from halocarbon production are predicted to be small relative to leakage over the lifetime products that use them[31]. Further, evacuation requirements when disposing of refrigerants now ensure that leakage during disposal accounts for only 0.5 to 3% of the initial

[31] Palandre, L., Zoughaib, A., Clodic, D. and Kuijpers, L., 2003, April. Estimation of the world-wide fleets of refrigerating and air-conditioning equipment in order to determine forecasts of refrigerant emissions. In Proceedings of the 14th Annual Earth Technologies Forum.

Table 1. Default Emissions Factors for HVAC Equipment. (IPCC 2006)

Equipment Type	Capacity (lbs.)	EF_I	EF_O	F_D	R
Air Conditioning	50 – 100	0.01	0.1	0.8	0.8
Refrigeration	50 – 2,000	0.03	0.35	1	0.7
Chillers	50 – 20,000	1	0.15	1	0.95

charge[32]. Fugitive leakage during use is therefore the primary source of halocarbon emissions over the lifespan of the refrigeration equipment.

Emissions can be estimated via two methods. The first relies on emissions factors (EFs) that are often expressed in leak rates or percentages. Under this approach, emissions are estimated by multiplying the amount of refrigerant in Harvard's equipment by an EF specifically tabulated for operation or an event, like servicing, installation, or decommissioning.

After performing an equipment inventory, the total emissions resulting from any new installations (E_I) within the past reporting period can be estimated by summing the leakage from each individual installation:

$$E_I = \sum_{i}^{n} C_i \times EF_{I,i}$$

where C is the amount of refrigerant charged into a new piece of equipment, EF_I is the emissions factor of installation, *i* is a specific unit, and n is the total number of pieces of equipment. The total emissions from regular operation (E_O) can similarly be calculated:

$$E_O = \sum_{i}^{n} C_i \times EF_{O,i} \times t$$

where EF_O is the emissions factor of operation (typically expressed in an annual leak rate), and *t* is time (typically expressed in years). This calculation estimates both unintentional leaks and leaks associated with equipment service.

Finally, fugitive emissions may result at the time of equipment disposal. This is especially the case when equipment is not vacuumed to EPA specifications, as a refrigerant "heel" of up to 5% of the charge can remain when the lines are only evacuated to atmospheric pressure[33]. The total emissions resulting from equipment disposal (E_D) can be estimated as follows:

[32] ICF International, 2010c. Destruction of Ozone-Depleting Substances in the United States. Prepared by ICF International for the U.S. Environmental Protection Agency. April 2010.

[33] ICF International, 2009a. ODS Destruction in the United States of America and Abroad. Prepared by ICF International for the U.S. Environmental Protection Agency. May 2009.

$$E_D = \sum_{i}^{n} C_i \times F_{D,i} \times (1 - R_i)$$

where F_D is the fraction of the initial charge remaining at disposal, and R is the recovery fraction.

Emissions factors for EF_I, EF_O, F_D, and R are summarized in Table 1. Assuming no loss from equipment installation or disposal within the 2018 reporting period, we can calculate emissions resulting from operation of equipment (E_O) by applying the emissions factors of operation for each category of equipment listed in Table 1. Exhibit 4 illustrates the resulting halocarbon emissions estimate. Estimated annual emissions total to 15,416 pounds of halocarbon, or about 9,251 $MTCO_2e$.

The emissions factor method is convenient in that only an inventory of equipment is needed to estimate annual halocarbon emissions. However, the estimation is prone to error because the values of emissions factors are highly uncertain and likely widely variable across individual pieces of equipment. For this reason, we recommend Harvard and other entities to adopt and improve upon their inventories of halocarbon leak rates, as discussed below.

An alternative method of estimating halocarbon emissions is a mass balance inventory. This method allows a more accurate estimate of halocarbon emissions to be quantified than the emissions factor method discussed above. The mass balance method tracks refrigerant emissions by attempting to account for all purchases, disposal, and changes in the size of the inventory. This method is superior to the emissions factor estimate because it is more accurate and can help pinpoint specific pieces of equipment that are prone to leakage.

Emissions (E) are estimated for each type of refrigerant:

$$E = (I_B - I_E) + P - S + (C_B - C_E)$$

where I_B and I_E are the refrigerant in inventory at the beginning and end of the reporting period, P is the

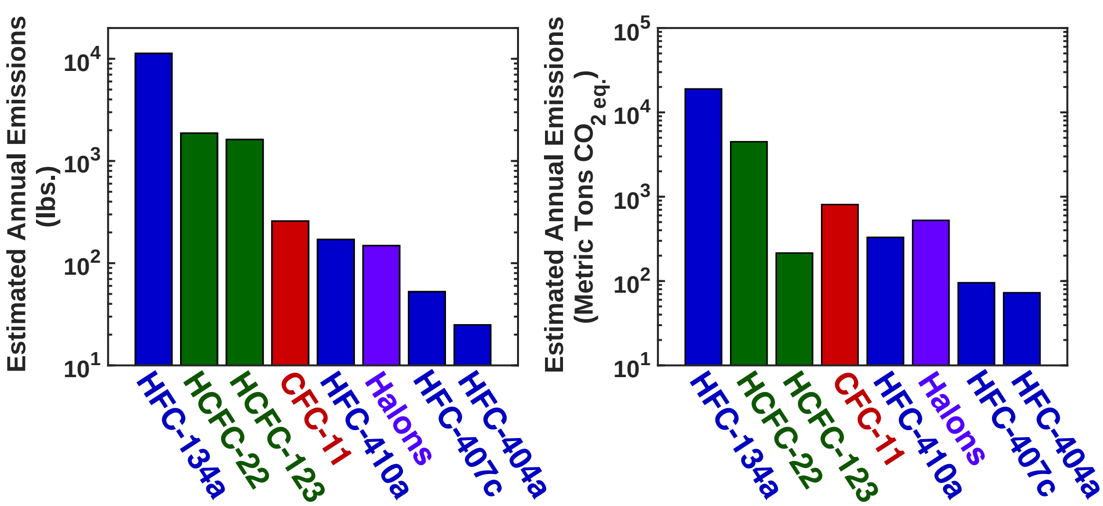

Exhibit 4. Estimated annual halocarbon emissions. Emissions are estimated using the emissions factor method, assuming leakage from equipment operation only. (a) Emissions in pounds of halocarbon type. (b) The equivalent CO_2 mass of the halocarbon stock, calculated using 20 year GWPs.

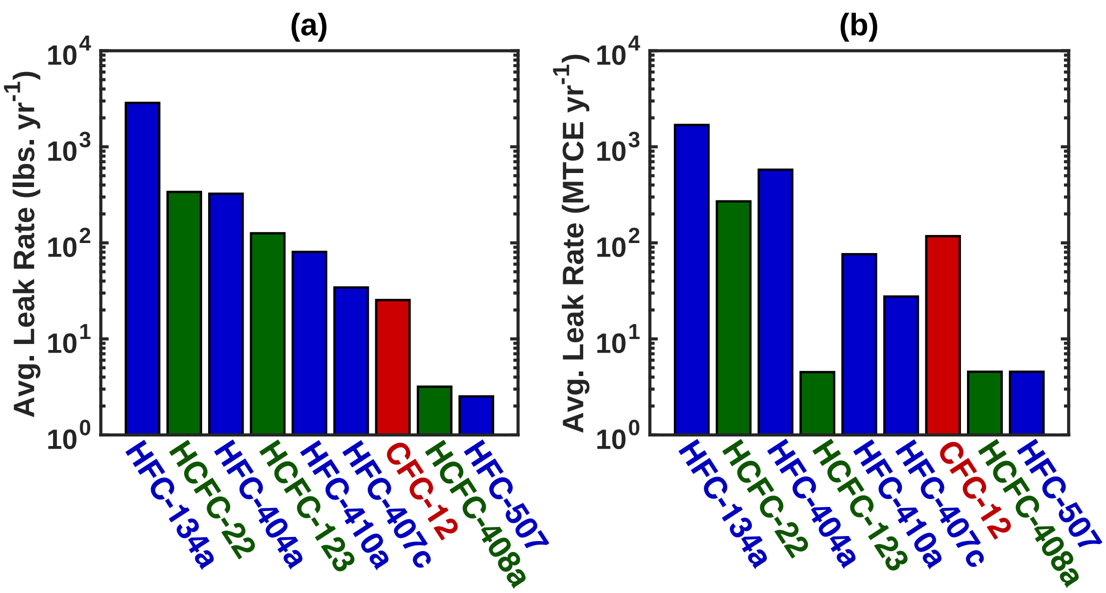

Exhibit 5. Quantified annual halocarbon leak rates. Leak rates are the average of four years of emissions data between FY2013 and 2016. (a) Leak rates in pounds of refrigerant. (b) Leak rates in metric tons of carbon dioxide equivalents, calculated using 20 year GWPs.

purchased refrigerant, S is the sold refrigerant, and C_B and C_E are the total refrigerant capacity at the beginning and end of the reporting period. While $(I_B - I_E)$ reflects the change in the inventory, $(C_B - C_E)$ reflects the change in total capacity, which may be greater than the inventory if equipment is not fully charged.

Fugitive emissions from unintended leaks – typically the largest source of halocarbon emissions – must be replaced by servicing the equipment. On short timescales, the equipment inventory remains constant, and $(I_B - I_E)$ and $(C_B - C_E)$ are zero. Similarly, if the university has not replaced its equipment, it presumably has not emptied and sold the refrigerant from its units, and S can also be ignored. An accurate estimation of annual emissions can therefore be derived by tracking the purchase (P) of new gas. Alternatively, the University could also keep track of purchases and sales towards replacing leaks versus charging and decommissioning new equipment. In both instances, the mass balance equation above reduces to a balance between halocarbon emissions from leaks and purchases to match these leaks:

$$E = P$$

Records of the University's service contracts indicate that equipment using greater than 50 pounds of refrigerant leaked nine different types halocarbon between FY 2013 and 2016. These emissions sum to nearly 2,770 $MTCO_2e$ per year, or about 1-2% of annual greenhouse gas emissions. Exhibit 5a indicates the estimated annual leakage rate of halocarbons from the Universities equipment, based leakage data from 2013 to 2016. HFC-134a was emitted in the largest quantity, followed by HCFC-22 and HFC-404a. By multiplying the leakage rate by a gas' 100 year GWP, we also estimated the average leakage rate in $MTCO_2e$ (Exhibit 5b). While the top three gases are still HFC-134a, HCFC-22, and HFC-404a, the order of impact is slightly modified.

Notably, several of the reported emissions occurred for gases that were or are no longer part of the University's halocarbon inventory. Specifically, HFC-507a, HCFC-123 and 408a, and CFC-12 use are not reported in the 2018 inventory. There are two possibilities to account for this discrepancy. First, these halocarbons may have been phased out between when the leaks were reported (FY 2013-2016) and when the inventory was compiled (2018). For instance, we believe one unit charged with CFC-12, used for

Table 2. Harvard's Estimated Halocarbon Emissions (Mass Balance Method)

Halocarbon	Yearly Emissions (lbs.)	2018 Inventory Stock (lbs.)	Annual Stock Leakage (%)
HFC-134a	2863	75118	3.8
HFC-404a	325	166	196
HFC-410a	80	1138	7.1
HFC-407c	34	350	9.8
HCFC-22	338	12483	2.7

Harvard's chilled water supply, was retired in this timeframe. Second, it is possible that these emissions occurred exclusively from equipment using fewer than 50 pounds of refrigerant. These stocks would not be reported in the inventory, which tracks use of over 50 pounds.

Several reported emissions occurred for gases whose use is recorded in the inventory. Assuming the average annual leak rate derived from data between FY 2013 and 2016 is representative of the current leak rate, we can calculate what fraction of the inventory is leaked on a yearly basis. This analysis is included in Table 2. The percentage of emissions is generally between 3 and 10% of a gas' total stock, with the exception of

HFC-404a. We are uncertain why the reported annual emissions rate of this HFC is so large (325 lbs.) relative to its current stock (166 lbs.). It is possible that a catastrophic leak between FY 2013 and 2016 sufficiently damaged a piece of equipment such that it was replaced with a unit using another refrigerant.

We note that the average annual leak rate of 3 to 10% of total charge is lower than the assumed leak rate used in the emissions factor calculations (15%). The annual emissions estimate from the emissions factor method (9251 $MTCO_2e$) is about 230% greater than the emissions estimate resulting from the mass balance method (2770 $MTCO_2e$)). One priority of future halocarbon inventories should therefore be to apply the mass balance method to calculate a more accurate emissions rate for all eight halocarbon gases included in the inventory.

VI. Technical Feasibility

While reducing halocarbon use will require a combination of legal, financial, and safety considerations, the first feasibility questions are inherently technical ones. Here, we discuss the details of refrigerant replacement, recycling, and destruction. We conclude that there are several technological solutions to reduce halocarbon use, and several options for halocarbon disposal upon its retirement.

VI.a Halocarbon Substitution

Substantial advancement in the design and production of refrigerants has followed increasingly stringent regulation on CFC and HCFC use in recent decades. These regulations, in conjunction with an increasing sense of corporate and consumer responsibility, are pushing companies and institutions to reduce the carbon footprint of their refrigeration systems by using gases with lower GWPs.

It is sometimes possible to retrofit existing HVAC equipment so that they operate using a different refrigerant without having to incur the full expense of installing a new unit. There are several potential benefits to retrofitting, including: 1) the scarcity of the original gas due to environmental regulation, 2) performance benefits of new gases, such as lower power consumption, and 3) an increased sense of environmental responsibility, which has marketable potential.

The feasibility of retrofitting equipment depends on the age of the unit and the gases being exchanged. In some instances, the existing gases can simply be evacuated and replaced with a new refrigerant. These are known as “drop in” replacements. Often, minor changes to expansion valves, updated compressors, or new oil are required. Unfortunately, many replacement gases are flammable or more toxic than the halocarbons they replace. In these instances, these gases are not suitable as replacements without considerable updates to the refrigeration and fire-response equipment.

Below, we discuss two scopes of halocarbon substitution. The first scope considers environmental benefits achievable with drop in replacements or relatively minor equipment modification. These options include substituting (1) CFCs, (2) HCFCs, and (3) high GWP HFCs for HFCs with lower GWPs. We note there are certain tradeoffs to this replacement framework. For instance, HCFC-123 has a relatively low GWP (292) but is an ozone depleting substance. The second scope offers suggestions for replacements that achieve greater climatic benefits, but require more extensive retrofitting or entirely new equipment. These include replacing currently used halocarbons with HFOs or natural refrigerants.

In our discussion below, we focus on a stepwise refrigerant substitution framework in the order from most potent to most environmental. This sequence generally proceeds as: CFCs, HCFCs, HFCs, HFOs, natural refrigerants. We note there are certain tradeoffs to this replacement framework. For instance, HCFC-123 has a relatively low GWP (292) but is an ozone depleting substance. The University must consider its valuation on these environmental effects when implementing a substitution framework.

Exhibits 6(a) and (b) illustrate possible drop in HFC replacements for the CFCs and HCFCs currently in use at Harvard. We include CFC-12 in our analysis even though its use is not recorded in the 2018 inventory because CFC-12 leaks have been reported as recently as FY2016. This suggests CFC-12 could be used in quantities smaller than those tracked in the inventory, or that the substitutions suggested in Exhibit 8 have already been carried out. In many cases, the minimum retrofit required to make a substitution is simply to exchange the compressor oil. Additional upgrades can also increase the efficiency of the retrofitted unit and minimize the loss in cooling capacity associated with the refrigerant exchange. These are discussed in this project’s associated implementation plan.

Often there are several candidate HFC substitutes. Table 3 lists the drop-in substitutions resulting in the highest difference in GWP for CFCs and HCFCs currently in use. For most applications, HFC-134a is the best alternative. The GWPs of the HFC replacements are about 60% and 30% lower than the GWP of the CFC or HCFC they are replacing, respectively.

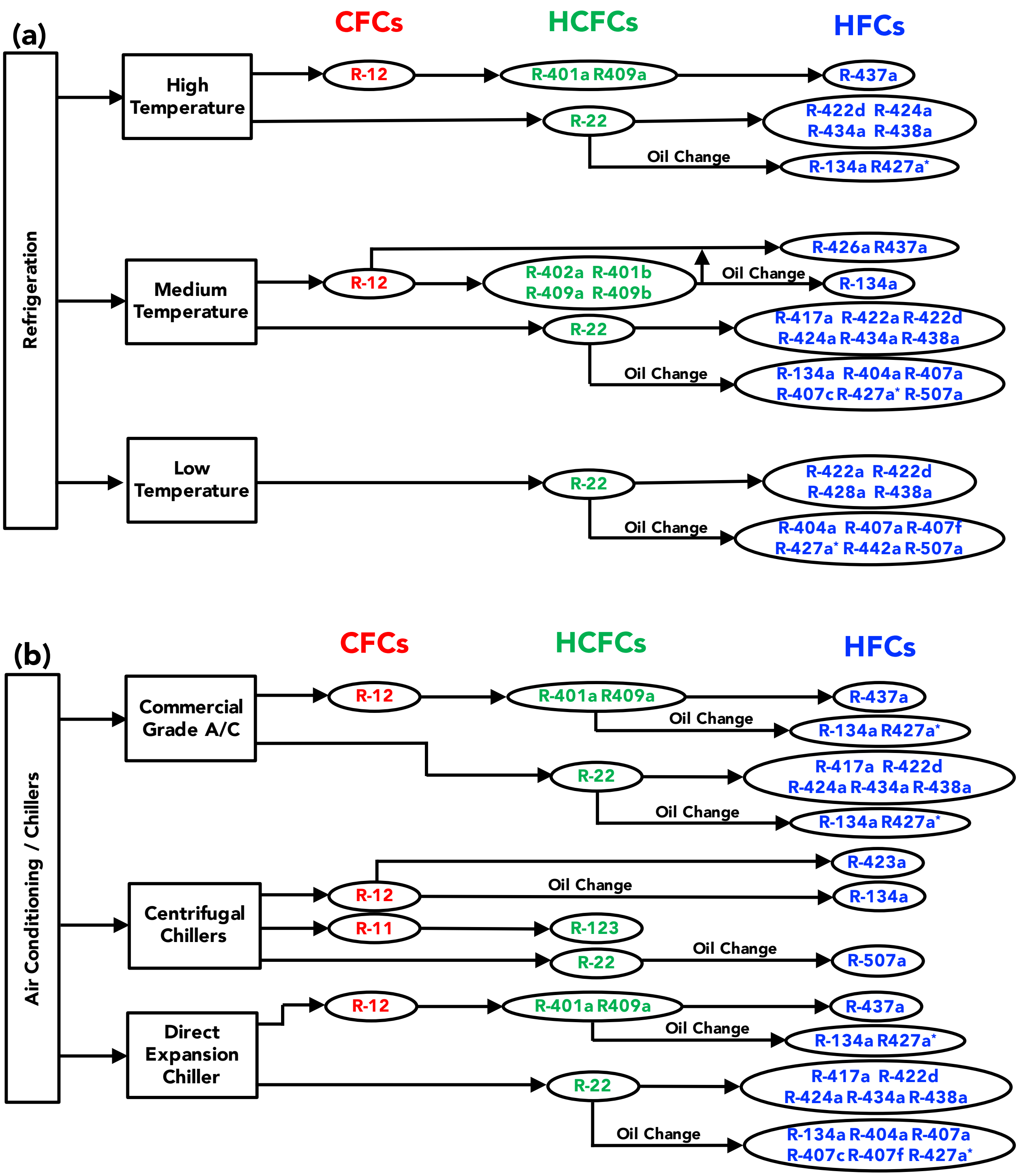

Exhibit 6. Drop-in substitution pathway. Possible HFC substitutes for CFCs and HCFCs currently in use in Harvard (a) refrigeration systems, and (b) air conditioning and chiller systems. The substitutions listed here generally require no or only minor equipment modifications. N.B. the R prefix denotes a halocarbon gas.

*These gases have high tolerance to compressor oils. When substituting in these gases, an oil change is required but flushing the system is not.

Table 3. Best Drop-In Alternatives for Harvard's CFCs and HCFCs.

Equipment	Application	Best Replacement For CFC-12	20 Year GWP	Best Replacement For HCFC-22	20 Year GWP
Refrigeration	High Temp.	HFC-437a	4676	HFC-134a	3710
	Mid Temp.	HFC-134a	3710	HFC-134a	3710
	Low Temp.	N/A	N/A	HFC-407f	3967
Air Conditioning	Commercial	HFC-134a	3710	HFC-134a	3710
Chillers	Centrifugal	HFC-134a	3710	HFC-134a	3710
	Direct Expansion	HFC-134a	3710	HFC-134a	3710

The substitution framework in Exhibit 8 considers only replacements for CFCs and HCFCs. There are, however, additional substitutes for the HFCs Harvard currently uses or might use in the future. In some cases, it is possible to substitute in another HFC with a lower GWP. These substitutions are often close to drop in replacements, although oil changes or minor equipment modifications, like new expansion valves, are sometimes needed. It is also possible to replace HFCs with other compounds, like HFOs. These newer gases have low or even negligible GWPs, yet are often flammable or toxic. Extensive equipment and fire suppression system modifications are required, precluding HFOs from being drop in replacements for HFCs.

We list the possible substitutes for HFCs currently in use at Harvard in Table 4. Of these, only HFC-404a and HFC-410a have possible drop in replacements with a lower GWP. The optimal alternatives are HFC-442a and HFC-32, which have 39% and 43% lower GWPs, respectively. HCF-134a has two relevant HFO replacements with over 99% smaller GWPs. These HFOs are mildly flammable, however, and require either more extensive retrofitting or greater safety precautions due to their flammability. In the case of HFC-404a, there are no alternative replacements with lower GWPs.

Table 4. Potential Replacements for Harvard's HFCs[34].

Original HFC	20 Year GWP	Drop In HFC Replacement	20 year GWP	HFO Replacement	20 year GWP
HFC-134a	3710	N/A	N/A	HFO-1234yf HFO-1234ze	1 <1
HFC-404a	6437	HFC-407a HFC-407f HFC-442a	4066 3967 3926	N/A	N/A
HFC-407c	4011	N/A	N/A	N/A	N/A
HFC-410a	4260	HFC-32	2430	N/A	N/A

[34] Myhre, G., et al: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

VI.b Natural Refrigerants

There are several candidate refrigerants that fall outside the halocarbon classification. These refrigerants, often called “natural refrigerants,” have zero ozone depletion potential and very low GWPs. These refrigerants were used extensively before the penetration of halocarbons during the 1950s, and are again becoming attractive alternatives due to their low environmental impact. The high efficiency of natural refrigerants also means newer equipment using them generally requires less electricity. This reduces the indirect climatic impact of refrigeration.

Although it is not possible to retrofit existing units to accommodate natural refrigerants, there are several benefits to use natural refrigerants in newly purchased or constructed systems. Halocarbons are becoming increasingly regulated on the international stage, and many environmental policy experts anticipate similar restrictions on HFC use in the United States. Natural refrigerants are not subject to the Montreal Protocol, and some are not included in the Kyoto Protocol or the UNFCCC Paris Agreement. Users of natural refrigeration systems are therefore less prone to technological obsolescence resulting from halocarbon regulation. The low environmental impact of natural refrigerants also means they are less likely to be targeted by future regulation. Since these refrigerants were among the earliest used, the technology associated with natural refrigeration is matured and has become increasingly energy efficient in recent decades. This efficiency – coupled to the low cost of the gases – makes natural refrigeration systems cost competitive when considering the decade-long lifetimes of the equipment.

There are three primary categories of natural refrigerants: (1) ammonia, (2) carbon dioxide, and (3) hydrocarbons. We discuss the applicability of each of these in turn below.

Ammonia, NH_3, was among the first commercial refrigerants. It has excellent thermodynamic properties and can be applied from high to low temperature ranges. The heat transfer coefficient of ammonia is larger than for most synthetic refrigerants, allowing smaller quantities of gas to be used and smaller unit footprints to be achieved. These properties allow ammonia units to consume 15-20% less electricity than an equivalent HFC-charged unit[35]. Ammonia is very reactive with water vapor in the atmosphere, giving it a short residence time and a GWP of nearly 0. This reactivity, however, makes ammonia toxic and under certain conditions flammable. Unlike many other refrigerants, ammonia is detectable by its scent at concentrations as low as 0.04 ppm. This characteristic provides an early warning system for even small leaks. Ammonia is among the cheapest of refrigerants, making it appealing for large scale uses. Relevant equipment includes large air conditioning units, chillers, and commercial-scale refrigeration systems.

Carbon dioxide, CO_2, is another environmentally conscious alternative to halocarbon refrigerants. By definition, it has a GWP of 1, which is hundreds to thousands of time lower than most HFC refrigerants. It has similar thermodynamic properties as ammonia, and units us low energy inputs per unit energy of cooling. Carbon dioxide is nonflammable, and only poses a mild asphyxiation hazard should substantial leaks occur. The CO_2 gas is highly pressurized (>90 bar) in the refrigeration system, however, which raises the potential for small leaks to escalate quickly[14]. Ammonia and carbon dioxide are often used together in multiple stage cooling. This can offset the amount of ammonia used, alleviating some toxicity or flammability concerns. Like ammonia, carbon dioxide is cheap and widely available. Carbon dioxide cooled systems are broadly applicable to large air conditioning units, chillers, and commercial-scale refrigeration systems.

Refrigerant-grade hydrocarbons are volatile organic compounds like propane (R-290), isobutane (R-600a), ethylene (R-1150), and propylene (R-1270). Blends of these and other compounds are also used.

[35] Benefits of Ammonia Use in Refrigeration, Danfoss Engineering Group, Primer on Industrial Refrigeration.

Hydrocarbon refrigerants have GWPs of approximately 20, meaning their emissions warm the climate less than HFCs but more than NH_3 or CO_2. They are extremely flammable and denser than air, which means they can accumulate in confined spaces during a leak. This precludes their use in unventilated areas and limits their use to smaller applications. Hydrocarbons are typically employed in personal-use appliances like refrigerators, window air conditioners, as well as vending machines and dehumidifiers.

VI.c Total Potential Emissions Reductions

We quantify the cumulative potential climatic benefit halocarbon substitution by calculating emissions avoided from applying the drop-in replacement framework for Harvard's equipment. The best alternative – defined by the drop-in replacement with the lowest GWP – for each CFC, HCFC, and HFC used in University equipment is recorded in Table X. Note that we have elected not to replace HCFC-123 with an HFC in this calculation. This choice stems from the relatively low GWP of HFC-123 and the small ozone depletion potential relative to CFCs and other HCFCs[36]. In total, applying the drop-in substitution framework to Harvard's equipment would yield 366 $MTCO_2e$ of emissions reductions annually. Even greater emissions reductions could be achieved with more extensive equipment retrofitting and replacement, yet quantifying these benefits is difficult given the large range in the extent to which these substitutions would occur.

Table 5. Estimated Potential Annual GHG Emissions Reductions from Drop-In Replacements*.

Halocarbon	20 Year GWP	Harvard Use (lbs.)	Best Drop-In Replacement	20 year GWP	Estimated Annual GHG Emissions Reduction ($MTCO_2e\ yr^{-1}$)
CFC-11	6900	1720	HFC-134a	3710	169
HFCF-123	292	10812	N/A	–	N/A
HCFC-22	5280	2483	HFC-134a	3710	120
HFC-134a	3710	75118	N/A	–	N/A
HFC-404a	6437	166	HFC-442a	3926	12.9
HFC-407c	4011	350	N/A	–	
HFC-410a	4260	1138	HFC-32	2430	64.2
Total Potential Emissions Reductions:					**366 $MTCO_2e\ yr^{-1}$**

*Calculated assuming Harvard's average equipment leak rate of 6.8%.

[36] This policy choice follows from recommendations made by the atmospheric science community: Wuebbles, D.J. and Calm, J.M., An environmental rationale for retention of endangered chemicals, Science, 1997.

VII. Organization Stakeholders and Decision Making Process

Our project occurs at Harvard University and so a key focus area when we were evaluating pilot projects was to understand how Harvard's financial planning and decision-making process works. The following section summarizes our conversations with various stakeholders within the University.

VII.a Harvard University

Harvard University manages financials through a decentralized capital planning process. Every year, each school develops a capital plan which it submits to the University. These plans are then shaped into master plans which schools develop in 5-year increments and update yearly.

For all schools, the capital budget process begins in September/October and is submitted in March. The funding is released at the start of the next fiscal year in July.

The capital plans are funded through a combination of debt and equity. Many schools can self fund projects with their internal balance sheets. For capital projects which require debt, the University takes on centralized debt and then redistributes loans to the schools in a series of intercompany loans. These loans are dispersed at a constant rate of 4% regardless of actual interest rate of the loan received by the University.

Harvard also centrally manages the Green Revolving Fund (GRF). This fund provides loans to schools for projects that reduce operating costs through sustainability initiatives. As a result, these tend to be energy, water or waste reduction projects. To qualify for GRF funds, projects must have an 11-year positive NPV and submit an application using the fund's template model. These loans are in reality cash transfers and do not officially sit on the school's books as a liability. The loans are effectively 0% interest loans and are paid back with the operational savings achieved by the project. The repayment term is determined during initial loan agreement and approval processes, depending on the time required to pay back the loan. These repayments often come out of operating budgets. The usage and payback mechanism of the loans varies among the schools[37].

Exhibit 7 illustrates the typical cash payment mechanisms for the GRF. In this example, a fictional project costs $100 to build, but saves $25 in operating costs annually. The school would receive a $100 cash loan and then repay the loan with the operating cost savings. Once the loan is paid off, the school continues to take the full benefit of the operating cost reduction. In contrast, Exhibit 8 describes the cash payments if the school did not use the GRF and instead used typical debt financing.

It's important to note that while the interest rate saving is important, the GRF's real benefit is as an extra source of liquidity outside of the capital planning process. In the capital process, sustainability projects must compete with other priorities and among themselves for funding. The GRF provides another funding mechanism that does not have to compete for capital funding. However, because the GRF repayment comes out of the Operational project budget, if there are multiple projects using the GRF, the burden on the Operational budget can be significant depending on how the school allocates payments. This is illustrated at the HLS section below.

[37] Olsen, J., 2019. *Associate Director, Harvard Office for Sustainability* [Interview] (13 March 2019).

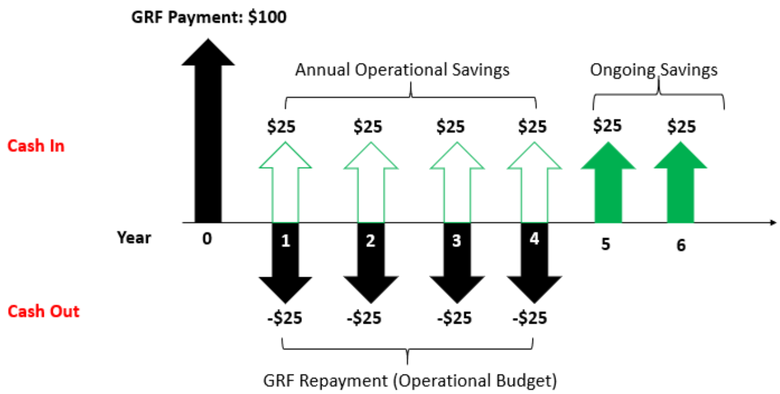

Exhibit 7. Cash flow diagram for the Green Revolving Fund.

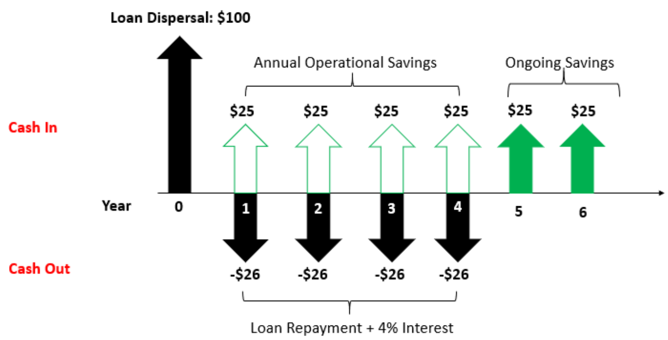

Exhibit 8. Cash flow diagram for typical debt financing.

VII.b Harvard Business School[38]

HBS's capital planning process follows the same schedule as the overall University. The process begins in the fall and is approved in March for a July funding release.

HBS has rarely used the GRF. The only notable usage was when they completed the CoGen project. They are not opposed to using the GRF, but they have not needed to use it so far.

To date, HBS Sustainability has not submitted NPV negative projects to the HBS capital planning process. Most of the projects completed so far have some energy or waste reduction element that produced a positive payback. Generally, HBS Sustainability will prioritize their projects internally and then recommend the most promising projects to the capital process. They can flag the projects they think are most impactful and can push for projects that might have greater impact but a lower return.

For sustainability based projects, beyond returns, tying the projects to the 2026 Sustainability goals is key for project approvals. Additionally, tying the project to a particular sustainability initiative also helps with

[38] Ricci, L. & Musso, J., 2019. *Associate Director for Energy Management and Sustainability* [Interview] (4 March 2019).

approvals. For example, HBS was able to fund the Green Roof projects because of a school focus on storm water.

Outside of the capital process, there are other sources of money that the project could tap into:

- Incentive programs from suppliers like EverSource for energy reduction projects
- Academic research funding is available for innovative projects
- Sustainability has some funding to play with smaller projects
- In May, the school finds out how much operational budget is left over in the year and there's room to quickly execute projects to close out the remainder of the budget.

VII.c Harvard Business School[39]

HMS's total annual capital budget is $30MM, of which $25MM are operational projects.

While the capital budget milestones are the same as the other schools, HMS's capital budgeting process occurs on an on-going basis throughout the year. There are two working groups that meet monthly to discuss the ongoing capital needs of running the facility. Peter Stroup's group leads this team and oversees the prioritization of various projects that they then recommend to the capital group. The capital

group is made of a wide cross section of stakeholders across HMS. They vote on projects proposed from the two working

groups using a variety of metrics like alignment with strategic goals, ROI and urgency.

HMS has a large deferred maintenance account of $333MM. This is maintenance that needs to be done but has been put off due to budgetary reasons. Currently, the team prioritizes projects based upon:

- Safety
- Regulatory Requirements
- ROI

Because of the deferred maintenance account, HMS has not pursued many projects with longer than 3-year ROIs. They installed solar panels which have a 7-year ROI because of HMS's Sustainability goals. They wanted to do a project that could visibly show HMS's commitment and were willing to take a longer payback period for that project.

Within the operating budget, there is a budget of $4M for emergent projects under $100,000 during the year. These are typically urgent projects that do not require major changes to the buildings.

Finally, the disturbance to the building is especially important for institutions like the medical school. The school struggles with a very low vacancy rate and tight space requirements. During our conversations, the team told us about one experiment that had been going on for 400 days, nearing completion. If the refrigeration change-out disturbed the experiment, the experiment would have had to begin again from scratch. The costs of moving lab work from one lab to another is usually absorbed by the individual departments rather than in the project budget, but this cost could be a substantial stakeholder barrier. While difficult and complex, these barriers are surmountable if the planning process is begun far enough in advance.

[39] Stroup, P., 2019. *Director of Facilities, Harvard Medical School* [Interview] (11 March 2019).

VII.d Harvard Medical School[40]

Like HBS and HMS, HLS operates on a capital process that begins in the fall, is approved in March and is released in July.

Bill Stanton walked us through the nuances of how HLS budgets for equipment replacements and maintenance. Each piece of equipment has its own budget for equipment replacement. The money set aside for this is for a direct replacement of the existing equipment. Therefore, it can be difficult to replace equipment with different systems. For example, the school just replaced a chiller in North Hall with a 1:1 replacement. Additionally, that project also ran into physical constraints like piping locations, wall enclosures, floor loads, etc. Because the budget is for direct replacement, there is no built-in money for such extensive physical changes. These changes would need to be submitted through the capital process and compete with other school priorities for funding.

HLS has made extensive use of the GRF. Most recently, HLS has used the GRF for solar panel installations and light changes. HLS pays for GRF projects through its operational project budget. As might be expected, this budget does not change significantly year on year besides adjustments for inflation and school growth. Therefore, while the organization is saving money through the GRF projects via reduced energy costs (which is an avoided cost rather than a budget allocation), the loan repayments add up in the operational project budget if multiple GRF projects are ongoing. While not insurmountable, internal accounting processes may have to be changed to encourage even further use of the GRF at HLS and other schools in the future.

In addition to the typical operating and capital budgets, there is a period at the end of the year where Operations may realize they have some flexibility in their budgets. Like at HBS, these projects must be quick to implement before the end of the fiscal year so they should be either simple or pre-scoped.

VII.e Harvard Utilities and Engineering

U&E operates uniquely in Harvard's landscape as the only entity that operates like a revenue center rather than a cost center. U&E charges the schools for their energy and utility use and uses that "revenue" to fund operations. As a result, they can fund fairly large projects internally and are able to originate debt. For projects less than $1MM, the group can self-fund. For projects larger than $1MM, the group can carry reasonable debt level for projects.

VIII. Financial Analysis

VIII.a Reduction of Leaks

For existing pieces of equipment, installing leak detection systems can be a relatively easy and cost effective way of (1) more accurately understanding actual equipment leakage rates and (2) more quickly identifying and fixing those leaks. Further, integrating leak detection into a more regular preventative maintenance program provides more opportunities to regularly tune-up equipment and continuously improve energy efficiency.

Industrial scale equipment for leak detection is well commercialized, typically runs from $1,000 - $5,000 and is relatively straightforward to install. Connections with a centralized control room would be more

[40] Stanton, B., 2019. *Energy Manager* [Interview] (7 March 2019).

complex depending on the age and status of schools' infrastructure. Even if the equipment does not directly pay back in refrigerant savings (for example because of good chiller design that has low leakage rates already), because of the relative low cost and ease of execution, we would recommend this approach for old equipment without existing embedded leak detection.[41]

However, in the case of Harvard, Harvard's leakage rate is already very low and leak detection and prevention is already a priority. Therefore, we focused most of our efforts on analyzing the potential gains that could be achieved by changing out refrigerant throughout Harvard's campus.

VIII.b Change out of HFCs

Most of the equipment that contain >50lb of refrigerant on Harvard's campus are chillers. While sharing many of the same basic functionality, the equipment varies substantially by equipment size, cooling mechanism (air cooled vs. water cooled), vendor, age, existing refrigerant, current surroundings and usage. Estimating change-out costs therefore requires analysis of each equipment's situation, but there are some generalities among systems.

VIII.c Capital Costs

Many HFC projects are avoided because of perceived high capital costs and difficult implementation. However, this is a misconception and many HFC replacement projects can be completed in a day with reasonable capital costs as low as $5,000.

The project capital costs depend mainly on two questions:

- Is a drop-in alternative available?
- Can you retrofit new equipment into the existing system easily?

In the case of drop-in alternatives, capital costs can be quite reasonable, on the magnitude of $5,000[42] per compressor and evaporator system for systems that do not require substantial oil changes. For projects that do require oil changes, project costs can be on the order of $20,000[43] per compressor and evaporator systems. The costs scale more with the number of systems, rather than the size of the component. Because much of the labor required for drop-in alternatives is incurred in changing out elastomeric fittings and recovering the gases, this process benefits from economies of scale.

If no drop-in alternative is available, but a retrofit is easily possible, these projects can also have quite reasonable capital costs, less than $100,000 depending on the piece of equipment[44].

For projects that there is no drop-in alternative and the system cannot be retrofit easily (for example, the piping must be redone or significant space must be made for the unit), the complete capital costs can be significant, on the order of $2-10MM per system[45]. Unfortunately, many buildings were built around the existing chiller units. For example, during our conversation with one school, it was revealed that changing out a chiller would require digging through a main portion of the school's campus and difficult hoisting

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[41] Emerson. "Refrigerant Leak Detection." Accessed March 2019.https://climate.emerson.com/en-us/products/controls-monitoring-systems/facility-controls-electronics/refrigerant-leak-detectors
[42] Warren, J., 2019. *Owner, Joe Warren & Sons* [Interview] (19 April 2019).
[43] Kebby, Robert. "F-Gas Regulation and R404A Alternatives." 26 June 2014. https://www.racplus.com/download?ac=1380760
[44] Foster, W., 2019. *Sales Representative, Trane* [Interview] (April 2019).
[45] Hillphoenix. "Understanding ROI on CO2 Systems." 24 October 2014. http://www.r744.com/files/Hillphoenix_CO2_ROI_WhitePaper_v10_Oct24_2014.pdf

techniques. However, while difficult, these are not insurmountable challenges which can be addressed with proactive planning and diligent incorporation into the capital plan. In our feasibility analysis below, we describe how even with challenging construction barriers, the projects can still be attractive climatically and financially.

VIII.d Operating Costs

Exhibit 9 shows the total lifetime cost of a typical chiller. Of note, almost 90% of the chiller's total cost is a result of its electric usage. In comparison, the refrigerant cost is a relatively small component of the cost stack.

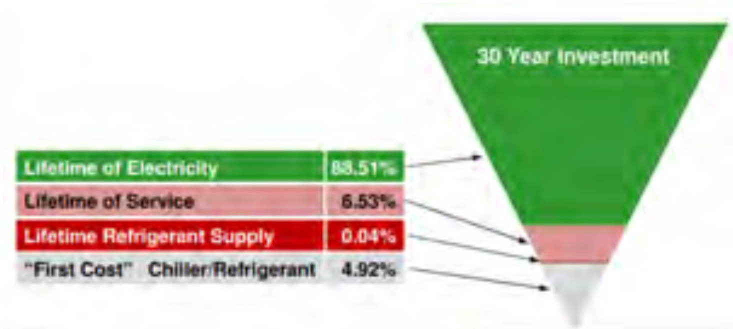

Exhibit 9. Lifetime Refrigerant Unit Costs.

As a result, our initial screening analysis focused on understanding how significantly energy and other factors influence the project NPV. Because of the complexity of our project, we focused this portion of the analysis in understanding the broad sensitivities, recognizing that the reality will be different for each individual piece of equipment.

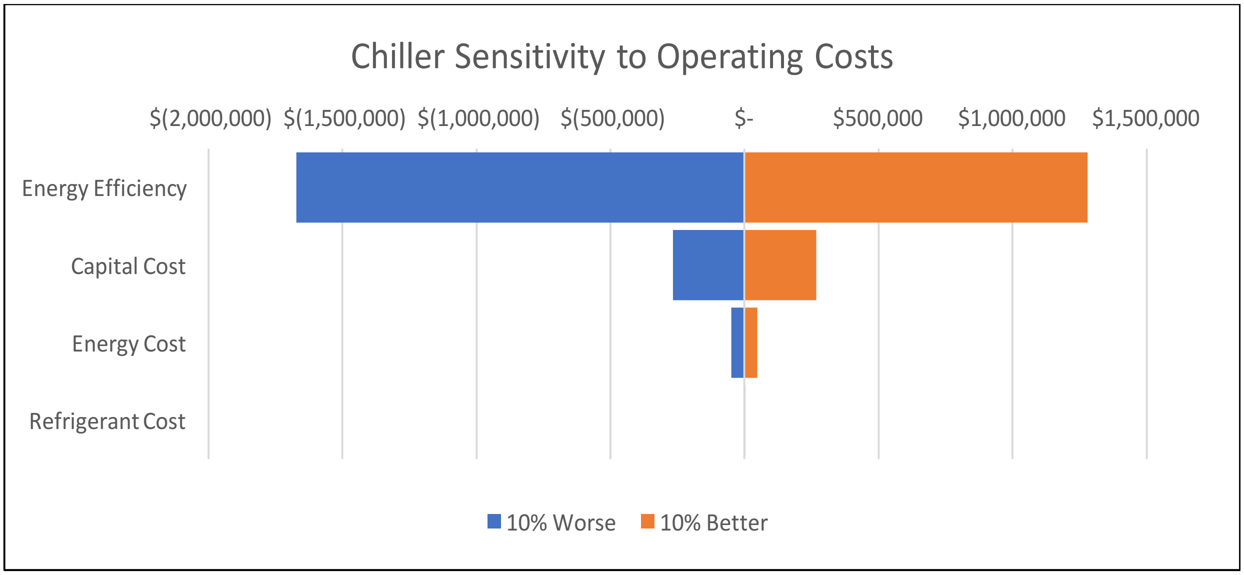

Exhibit 10. Chiller Cost Sensitivity Analysis for a project that changes out a 1000T R134a chiller for an equivalent 1000T R1233ze chiller

Exhibit 10[46] below analyzes how important refrigerant cost, capital cost, energy efficiency and energy cost are to the relative project return. For this analysis, we assessed a complete change out of a 1000T HFC-134a chiller to an equivalent HFC-1233ze chiller.

This sensitivity analysis revealed that the largest factors in project economics are energy efficiency and capital costs.

Therefore, to prioritize among Harvard's equipment to find financially attractive and climatically beneficial projects, we focused on understanding whether changing the HFC in each piece of equipment will increase energy usage and the magnitude of the capital costs. While there is an abundance of research on theoretical energy efficiency comparisons, the actual energy efficiency observed depends on the age of each piece of equipment and the specific operating conditions of the unit

To illustrate the complexity of this, we have two diverging examples from our conversations within Harvard:

i. Utilities replaced one of their HCFC-22 chillers with HFC-134a and was required to de-rate the chillers by about 20%.[47]

ii. HMS replaced their HCFC-22 chillers with HFC-134a and has seen no change in electric consumption.[48]

Further, when evaluating energy usage, it's important to compare apples to apples. Table 6 illustrates what energy efficiency comparisons could look like for a given chiller (examples for illustrative purposes only).

[46] Geister, Ryan. *"Refrigerant Update."* 2016. [Online] Available at: https://www.trane.com/content/dam/Trane/Commercial/global/CSOs/new-york-new-jersey/Trane%20Refrigerant%20Presentation%20HD%20-%20March%202016%20Con%20Ed%20Trane%20Event.pdf. [April 2019].
[47] Manning, R., 2019. *Director of Engineering and Utilities* [Interview] (8 March 2019).
[48] Stroup, P., 2019. *Director of Facilities, Harvard Medical School* [Interview] (11 March 2019)

Table 6. Example Energy Efficiency Tradeoffs for Unit Retrofit.

	New Chiller with HFC-134a	New Chiller with HFC-518
Old Chiller with R-134a	+10%	+8%
Old Chiller with R-518	+12%	+10%

In both cases, the chiller utilizing HFC-518 is less energy efficient, but the comparison point is crucial. Both new chillers would reduce energy usage compared with the existing equipment. Often, the energy efficiencies listed in research compare new pieces of equipment or pieces of equipment from the same vintage. While useful for clarity in analysis, in practice many HFC replacement projects evaluate new pieces of equipment compared with 20+ year old pieces of equipment. Therefore, for replacement projects, while the new non-HFC alternative piece of equipment may be less efficient than a new HFC unit, the non-HFC alternative will still produce substantial energy savings.

To simplify our analysis, we used the average of data points found in research to estimate out the potential energy gains or losses for changing refrigerants and compared energy efficiencies between new installations. In reality, this is a conservative estimate as it does not take into account the energy efficiency gains over time, but this allows a conservative analysis and more consistent comparisons for our initial screen.

IX. Screening Analysis Results

Based on the research described above, to determine an appropriate pilot project, we collected the estimated, order of magnitude capital and operating costs to change out all of Harvard's equipment to the lowest GWP alternative and built a financial model to compare potential projects.

As described above, true capital and operating costs are highly dependent on each piece of equipment's age, operation and location. For this initial analysis, we used average of best available data for energy efficiency and capital costs, adjusting for pieces of equipment which our conversations with stakeholders suggested would be particularly challenging. The assumptions behind the model are summarized in Appendix B. Thus, the NPVs described below were used as helpful first screens to see overall trends and prioritize between equipment classes, but not intended to capture precise project economics. Once projects were selected following this initial screen, a more detailed analysis considering equipment specifics was completed.

The financial model used assumes:

- An 8% discount rate which is Harvard's internal discount rate. Implicitly, this implies that this project is not riskier than any other operational project that Harvard undertakes.
- A 0% debt/value ratio on the debt. This was a placeholder for the initial analysis and will depend heavily upon the funding scenario of the particular school in which the project occurs.
- An 8% HFC leakage rate as calculated as closer to the actual observed leakage rate at Harvard. Industry averages are higher at approximately 15%. For our final analysis, we used a leakage rate of 6% after further review of Harvard's data. This small difference did not impact the conclusions of our feasibility screen as the results are most reliant upon the energy efficiency and capital costs.

- An 11-year project lifetime to align with the evaluation procedures for the Green Revolving Fund. The equipment life is more likely to be 20 years[49].

Our first screen looked at if all equipment was changed out today to its most climatically friendly, technically feasible alternative. For some pieces of equipment, this could be a drop-in replacement. For others, it would require equipment replacement. For those pieces that required replacement, it would require abandoning pieces of equipment even if it has remaining life. While this would have the best immediate impact on the climate, it would also require significant capital. Table 7 summarizes this analysis. Note that blacked out rows indicate that the approach is not feasible for that particular refrigerant.

Our second screen then analyzed the NPV of a more pragmatic approach that looked at replacing equipment at the end of its life as well as completing drop-ins were appropriate as soon as possible. Table 8 summarizes this analysis. Note that for this analysis, we compare the installation of new HFC-alternative equipment with a replacement in kind. Therefore, for the NPV analysis, we only consider the incremental costs between the two projects.

Table 7. Initial Analysis of Immediate Change Out or Retrofit of All Harvard Equipment Containing HFCs

			Drop-In or Retrofit Today			**Replace Today**		
	Units	**Total Refrigerant (lbs.)**	**Capital Cost ($)**	**NPV ($)**	**Annual MT CO_2e Reduced**	**Capital Cost ($)**	**NPV ($)**	**Annual MTCO_2e Reduced**
HFC-134a	6	75118	231,970	(16,677,530)	2917	29,605,641	(8,966,115)	14,757
HCFC-123	1	10812	100,000	(86,901)	9			
HCFC-22	5	2483	21,569	945,296	120			
HFC-410A	6	1138				2,181,251	(1,917,520)	75
HFC-404A	2	166	44,413	426,281	12.9	3,181,599	(2,673,079)	324
CFC - 11	2	1720				2,963,089	(2,824,790)	296

[49] US Department of Energy, n.d. *Technical Support Document - Proposed Rulemaking on Commercial Refrigeration Equipment.* [Online] Available at: https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/cre2_nopr_tsd_2013_08_28.pdf [Accessed April 2019].

Table 8. Initial Analysis of Immediate Change Out at End-of-Life for All Harvard Equipment Containing HFCs.

	Replace at End of Life		
	Incremental Capital Cost Compared with Direct Replacement In Kind	**NPV**	**Annual MTCO$_2$e Reduced**
HFC-134a	9,227,219	6,613,341	14757
HCFC-123	[redacted]		
HCFC-22			
HFC-410A	679,833	(133,062)	75
HFC-404A	757,886	(249,366)	324
CFC-11	923,509	(205,946)	296

As seen from Table 8, replacing the equipment at the end of life yields much more attractive financials, particularly for large projects that would require substantial capital approvals.

Finally, for our third screen, we recognized that by delaying some projects, because of the short-lived impact of HFCs, we could be causing significant environmental harm. Therefore, we tested the impact of NPV if the social cost of atmospheric release for the refrigerant leaked in the meantime was considered. This analysis estimates the end-of-life for each piece of equipment and uses the social costs of atmospheric release for refrigerants as described above. Table 9 shows this analysis and that, while not the social costs of delay the project are not insignificant, they do not overcome the financial advantages incurred by delaying the project.

For institutions like Harvard, this cost/benefit analysis is crucial because of the opportunity cost incurred in each capital project. Unlike typical businesses, Harvard's charter is not to maximize profits, but rather to educate future leaders and provide crucial fundamental research. Harvard also has ambitious climate goals and while Harvard is well capitalized, capital is still a scarce resource. To meet its climate goals and achieve its chartered goals, Harvard must therefore aim to meet its climate goals in the most economical way possible that still generates the most social and environmental benefits. Therefore, Harvard should prioritize projects with a positive NPV after the SCAR is included.

Table 9. Analysis of the impact of the social cost of atmospheric release for refrigerant released in the period before equipment end of life for all of Harvard's HFC containing equipment.

	NPV	**SCAR Incurred by Delaying Replacement**	**SCAR Adjusted NPV**
HFC-134a	6,613,341	(805,942)	5,807,399
HCFC-123	[redacted]		
HCFC-22			
HFC-410A	(133,062)	(9,991)	(143,053)
HFC-404A	(249,366)	(7,083)	(256,449)
CFC-11	(205,946)	(34,028)	(239,974)

Through the analyses above, we determined that there are potentially some NPV positive projects in some of the smaller (<200 T) pieces of equipment that could be executed immediately. The equipment that is running HFC-404A or HCFC-22 may have relatively easily substituted drop-in replacements. Many of these replacements have approximately equal or better energy efficiency. Further, the drop-in process can be used to tune up the piece of equipment, thereby further increasing its energy efficiency.

We also determined that when replacing equipment or installing new equipment, HFC alternatives can be very financial attractive projects compared with HFC based equipment. Some equipment, like CO2 based systems, have higher energy efficiency than HFC equipment and, even with slightly higher capital costs, are still NPV positive projects even before incorporating the social cost of atmospheric release. Others may be slightly NPV negative, but become positive when the social cost of carbon is included.

Once those projects are completed, Harvard should prioritize the remaining NPV negative projects, even when SCAR are considered. In our analyses above, those projects represent a small portion of Harvard's HFC equipment and are generally small pieces of equipment operating HFC410A. By deprioritizing these projects, equipment and refrigerant technology may decrease over time, allowing these projects to eventually have a positive NPV.

To summarize, we came away with some directional guidelines for prioritizing equipment changes:

For all options:

- Without including social costs of carbon, all pieces of equipment require equal or greater energy efficiency to produce positive payback. The degree of energy efficiency required to produce a positive NPV depends upon the capital costs of the project.

For drop-in options:

- HFC-404a can be replaced by HFC-442 or HFC-407 very easily and the replacement gas increases the energy efficiency of the system.
- Because of the low capital costs of these projects, the NPV is rarely significantly negative. If the social cost of atmospheric release is included into the analysis, these projects can become NPV positive.

For equipment replacements:

- For viable refrigeration systems, CO_2 based alternatives are financially attractive alternatives to existing HFC-404a systems.
- Larger pieces of equipment require lower amounts of increased energy efficiency to justify projects because the capital investments do not scale linearly. Further, they also benefit more from energy reduction because they use more energy.

Generally, large scale HFC replacement projects (>1000T units) make more sense when compared against brand new installations rather than retro-fits. In the case of existing equipment, replacing the system before the end of the equipment's life would void substantial depreciation benefits of the existing system. In addition, though the energy efficiency of any new system will be more than the old system, for large pieces of equipment that require substantial construction to change, the capital cost to change the equipment more than outweighs the operating cost. In contrast, for new installations or for equipment replacements, the financial comparison is between projects and therefore the financials of both systems can be compared side-by-side. Without the sunk costs of the previous project and the demolition and installation costs of the new project, the new pieces of equipment look very financially attractive.

As a result of our screening and research, we came to the following conclusions:

i. Replacement of HFC is technically feasible in many scenarios, but the organizational and institutional barriers for replacement may remain high. The biggest of such constraints will be:
   - Fire Code, Building Code, & Health and Safety Restrictions
   - Physical Limitations (Walls, piping locations, floor loads)
   - On-Going University Activity (Lab research)

ii. Stakeholder Buy-In
   - Because of budgetary constraints and risk tolerance, some schools are more likely to pilot a project with us than others. Those schools include:
     - HBS
     - HLS

iii. Identification of a pilot that is relatively *low risk* will likely exclude large HFC-containing equipment due to the high sunken costs and tendency towards risk aversion. Given that, we are aiming to identify smaller HFC-containing equipment that may allow us to pursue a proof of concept pilot.

iv. There is an opportunity for Harvard to lead through the adoption of the Kigali amendment internally and to multiply that effort through other local institutions also adopting the amendment.

v. There is an additional opportunity for Harvard to lead through multiplying its best practices in leak detection.

With those guide-lines in mind, following our initial analysis and stakeholder conversations, we returned to HLS and HBS to discuss potential pilot projects. Based on our analysis, we suggested prioritizing the following options:

- Units near the end of their equipment life
- Refrigeration units running on HFC-404a
- Equipment in open areas with relatively easy construction access

With those criteria in mind, each school proposed several pieces of equipment that could be used. Table 10 summarizes those opportunities.

Table 10. Summary of Projects Evaluated for Implementation

	HCFC-22 Stand-alone Chiller	HFC-404a Refrigeration Unit	HFC-404a Small Freezers	HCFC-123 Underground Chiller
School	HLS	HLS	HLS	HBS
End of Life	10+ years	11+ years	1-3 years	Within 5 years
Construction Access?	Roof top unit	Medium – significant open space, but it is located underground and piping would need to be adjusted for complete system installation	High – Easily accessed in dining areas	Low – Would require substantial construction to access
System Criticality	Critical – no back up	No back up, but it's a system made up of 13 individual systems	Low	Medium – Runs in parallel with other units as supplement
Potential Annual Greenhouse Gas Emissions Reductions (MT CO_2e)	59	Drop-in: 20 Replacement: 53	Low	9
Additionality	Low – HCFC-22 is already regulated under the Montreal Protocol and therefore must be replaced	High – Proof of concept for a CO_2 based system	High – Proof of concept for a CO_2 based system	Low – HCFC-123 is already regulated under the Montreal Protocol and therefore must be replaced
Feasibility	Low	Medium	High	Medium
Scalability	Medium	High	Low	Medium

To help select the best pilot projects, we plotted the projects on the following chart, depicting end of life and potential greenhouse gas emissions savings. The scale of the bubble represents the relative capital cost of the project. For our project, we wanted to both provide the most benefit to Harvard while also proving out the more scalable models for other institutions.

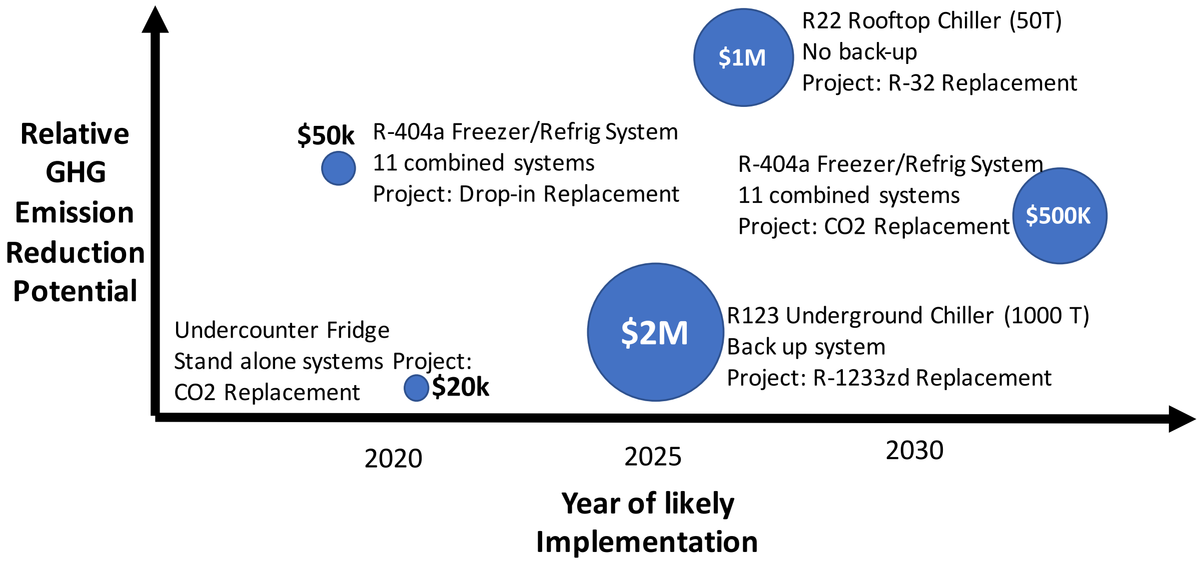

Exhibit 11: Pilot projects evaluated for implementation.

The HCFC-22 stand-alone chiller is located on the roof and is reasonably accessible. However, its criticality as the only unit for that building makes it an unlikely choice for an implemented pilot project. Further, HCFC-22 is already regulated under the Montreal Protocol and thus was less attractive from an additionality perspective.

The HFC-123 unit is attractive because, as a large unit with substantial construction constraints, it would be a good proof of concept project to showcase detailed planning of a seemingly complex and high barrier project. However, HCFC-123 is already regulated under the Montreal Protocol and thus was less attractive from an additionality perspective.

The HFC-404a under-sink options were attractive because the units are replaced fairly often, but they have a fairly low greenhouse gas impact. Further, the technology for a propane-based or CO_2-based replacement is fairly mature in this segment of the market and so additionality of our pilot would be low.

Therefore, for our implemented project, we selected the HFC-404 Refrigeration unit because it was a feasible project that produced meaningful carbon emissions in a scalable way. It also provides the opportunity to do two pilot projects with one unit. Because the unit is relatively new (installed in 2012), it is too new to do a full replacement to a CO2 based system. However, the HFC-404a can be easily changed to HFC-442, producing meaningful climatic and economic benefits immediately. The HFC-404a can also be recovered in this process, producing offsets for the University. At the end of the equipment's life in 11 years, the equipment can then be replaced with a CO2 based system. This will produce even more meaningful carbon and economic benefits. It will also be eligible to produce offsets as a leader in CO_2 refrigeration per the ACR standard of CO_2-based refrigeration systems.

X. Public Health Analysis/Social Benefits and Risks

X.a Climate Impacts of Halocarbons

HFCs pose a low risk of acute impacts to human health at levels found in the environment (they are entirely man-made – there are no natural sources). Unlike emissions from fossil fuels, HFCs do not directly degrade air quality.[50] At concentrations that might result from an accidental release or in occupational settings, they are thought to be mildly toxic and possibly carcinogenic.[51] However, due to their physiochemical properties, there is only a low potential for human toxicity and no significant health risks expected. Further, there are no observable evidences to support the assumption of carcinogenic, genetic, reproductive, and developmental effects of HFCs in humans.[52] Due to the low acute inhalation toxicity, the 1000 ppm exposure levels/standards of some HFCs have been established by the American Industrial Hygiene Association's Workplace Environmental Exposure Level (WEEL) as an 8h Time-Weighted Average (TWA).[53] Existing protocols for occupational safety and environmental management of HFCs are well established and actively practiced at institutions such as Harvard.[54, 55, 56]

We therefore center our assessment of the public health impacts from HFCs on their climactic impacts.

HFCs have GWPs ranging from hundreds to greater than 10,000 times more powerful than carbon dioxide (CO_2), making them among the most potent GHGs. HFCs degrade in the atmosphere after between 10-25 years. Because these pollutants have significantly shorter atmospheric lifetimes than CO_2, they are referred to as short-lived climate pollutants (SLCPs). Although they only stick around for a few decades in the skies, their environmental impacts persist for much longer. For example, when they warm the environment, they cause the ocean water to warm and expand. Since the oceans mix and exchange their heat on much longer timescales than the atmospheric lifetime of HFCs, this sea level rise persists even after the gases that warmed the climate initially have been removed.[57]

HFC's currently account for less than 1% of total greenhouse gases emitted by Harvard, but according to the Climate and Clean Air Coalition they will account for 9-19% of emissions by 2050 if left unchecked, due to the projected increase in air conditioning and refrigeration world-wide.[58]

The United Nations Environmental Programme's Emissions Gap Report 2017 provides a collection of strategies that could virtually eliminate HFC emissions by 2035 and reduce emissions of methane by about one-third and black carbon by 70 percent below current levels by 2030. Additional strategies targeting "super emitters" and to reduce methane from agriculture and waste could create additional

[50] DT Shindell. The social cost of atmospheric release. Climatic Change 130 (2), 313-326
[51] An Overview of Environmental Hazards and Exposure Risk of Hydrofluorocarbons (HFCs). Chemosphere, 2005. https://doi.org/10.1016/j.chemosphere.2005.03.084
[52] A.E. Mitchell, et al. Evaluating chemical and other agent exposures for reproductive and developmental toxicity. J. Toxicol. Environ. Health (A), 67 (2004), pp. 1159-1314
[53] G.M. Rush. Organic chlorofluoro hydrocarbons. E. Bingham, B. Cohreesn, C.H. Powell (Eds.), Patty's Toxicology, John Wiley and Sons, New York (2001)
[54] U.S. Environmental Protection Agency. Section 608 Technician Certification. https://www.epa.gov/section608/section-608-technician-certification-0
[55] Harvard Campus Services. Environmental Health and Safety. Refrigerant Management Plan. https://www.ehs.harvard.edu/sites/ehs.harvard.edu/files/refrigerant_management_program.pdf
[56] Harvard Environmental Health and Safety. Facility and Building Managers: Environmental Health and Safety Reference Guide. https://www.ehs.harvard.edu/sites/ehs.harvard.edu/files/Facility_Guidebook_2017.pdf
[57] Kirsten Zickfeld, Susan Solomon, Daniel M. Gilford. Thermal sea-level rise due to short-lived gases. Proceedings of the National Academy of Sciences Jan 2017
[58] Climate and Clean Air Coalition. Hydroflourocarbons (HFC). http://www.ccacoalition.org/en/slcps/hydrofluorocarbons-hfc

decreases in methane emissions.[59] While the impact from HFCs is not separated, putting these collective measures in place could avoid over 2 million premature deaths and 50 million tons of crop losses each year, cut the rate of global warming in half through 2050, and significantly slow sea level rise.[60]

As institutions evaluate operational and capital projects, cost-benefit analyses are often used as an imperfect, but valuable tool to assess the impacts of decisions. There are often many factors excluded from these analyses – often upstream and downstream impacts, which we refer to as *externalities*. Efforts to quantify and incorporate, *or internalize,* these external costs into decision-making processes are an important mechanism available to institutions to more fully account for the systemic impacts of decisions. Harvard has utilized social costing mechanisms in prior decision making and is actively "investigating potential approaches to internal energy pricing for Harvard that will more fully account for the social cost of our energy choices including, but extending beyond GHG emissions."[61]

Harvard's recent Climate Change Task Force estimates that Harvard's reliance on Fossil Fuels results in *at least* $25Million in costs to society annually. Moreover, for Harvard's climate goal the term "Fossil Fuel Free" was explicitly chosen instead of "Carbon Free" because of the importance of incorporating the social damages from upstream and downstream impacts from our energy sources including the pollutants and waste products that are produced when fossil fuels are mined and burned. The university specifies that the numerical estimate of damages reflects "only the damages that are currently well understood and monetizable. Total damages are surely much higher."[62] Indeed, NYU School of Law's Institute for Policy Integrity's guidance document for state policy documents the substantial gaps in externalities that continue to be excluded from social costing models.[63]

The social cost to carbon (SCC) estimates the dollar value of reducing climate change damages associated with a one-metric-ton reduction in CO_2 emissions. The conceptual basis, challenges, and merits of the SCC are well established. However, it is relatively newly applied to cost-benefit analysis. While the fundamental characteristics are well established, the SCC methodology is evolving as evidence strengthens on the estimated costs of climate change. There are a variety of dollar values associated with the SCC given the variability in assumptions that are included in calculations. There is currently a cross-institutional, cross-disciplinary effort to provide a comprehensive update to the social cost of carbon based on recommendations made by the National Academy of Sciences (2017).[64]

Based on consultation with researchers at Harvard's T.H. Chan School of Public Health, this team used the social costing methodology *Social Cost of Atmospheric Release* (SCAR), which extends the SCC to a broader range of pollutants and impacts, including a specific social cost estimate for HFC-134a.

[59] The Emissions Gap Report 2017. United Nations Environmental Programme, 2017. https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf
[60] Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) http://www.ccacoalition.org/en
[61] Harvard University. 2016-2017 Harvard Climate Change Task Force Report. Section 2.1: The Problem https://green.harvard.edu/sites/green.harvard.edu/files/2016-2017HarvardClimateChangeTaskForceReport.pdf
[62] Id.
[63] NYU School of Law Institute for Policy Integrity. The Social Cost of Greenhouse Gases and State Policy: A Frequently Asked Questions Guide. 2017.
[64] Resource for the Future. http://www.rff.org/research/collection/rffs-social-cost-carbon-initiative.

Table 11. Social Cost of Atmospheric Release (SCAR) for CO_2 & HFC-134a.

Valuation; discount rate	CO_2 (damages per ton in $2007 US)	HFC-134a (damages per ton in 2007 US)
Climate[a], 5%	10	19,000
Climate[a], 3%	32	36,000
Climate[a], 1.4%	67	56,000
Additional climate-health[b], 5%	16	62,000
Additional climate-health[b], 3%	45	110,000
Additional climate-health[b], 1.4%	87	160,000
Median total; 5%	27	85,000
Median total; 3%	84	160,000
Median total; 1.4%	150	210,000
Median total; declining rate	110	160,000

[a] This climate valuation includes Integrated Assessment Model-based climate-health impacts
[b] This valuation of additional climate-health impacts is based on WHO analyses[65]

Traditionally, to get the social cost of a non-carbon GHG, the GWP would be used as a multiplier in reference to the specific SCC value being used. Therefore, HFC-134a, with a GWP_{100} of 1,300 would have a social cost of $59,800/ton using the U.S. EPA's 2016 SCC value of $46/MTCO$_2$e. Using a 20-year horizon, HFC-134a's GWP would be 3,710 and the social cost would be estimated at $170,660. Given the short-term climate impacts of HFCs, our team advocates using a GWP_{20} value where possible. However, in the SCAR modeling, Shindell uses a 350-year time horizon to assess impacts to global warming.

The SCAR establishes a specific social cost for HFC-134a that varies substantially based on the discount rate chosen. Using a 3% discount rate, HFC-134a is estimated to have a social cost from its climate impacts of $36,000/ton, plus an additional $110,000 in social costs from additional climate-health impacts included in the SCAR model. The total SCAR for HFC-134a is therefore $160,000 at a 3% discount rate and at a declining discount rate. Table 11 replicates the figures depicted in Shindell's work, provided here for reference.[66]

Using this methodology, the social costs of Harvard's halocarbon stock are estimated to be approximately $9MM. This represents a low-end estimate of the costs borne by society if all of the stock released into the atmosphere. At the individual HVAC and refrigeration unit-level, these costs are not intended to be viewed in a vacuum. This is another metric, albeit an important one - to incorporate into a broader capital planning processes.

[65] Campbell-Lendrum D, Woodruff R. Climate change: quantifying the health impact at national and local levels. Prüss-Üstün A, Corvalán C (eds) Environmental burden of disease series, no. 14. World Health Organization. 2007
[66] DT Shindell. The social cost of atmospheric release. Climatic Change 130 (2), 313-326

Table 12. Harvard's Halocarbon Social Cost of Atmospheric Release.

Gas	20 Yr. GWP	S.C.A.R. ($/ton)	Harvard Stock (tons)	Total Social Cost of Stock ($)	ODP
HFC-134A	3710	160000 – 210000	37.559	6,948,415	Zero ODP
HFC-404A	6437	277600 – 364300	0.083	26,639	
HFC-407c	4011	173000 – 227000	0.175	35,000	
HFC-410A	4260	183700 – 241100	0.569	120,856	
CFC-11	6900	298000 – 391000	0.86	296,270	SCAR, Not Accounting ODP
HCFC-123	292	12600 – 16500	5.406	78,657	
HCFC-22	5280	228000 – 299000	6.2415	1,644,635	

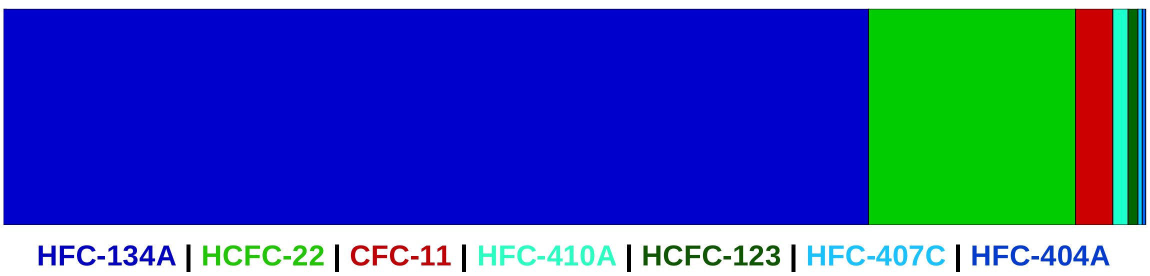

Exhibit 12. Social Cost of Harvard's Halocarbon Stock. Total: $9.1 million

X.b Refrigerant Alternatives

Substitute refrigerants may require additional regulatory considerations due to potential toxicity and flammability. The toxicity of alternatives may limit their applicability to certain public facilities, require Risk Management Plan under EPA regulations, or subject to exposure limits under Occupational Safety and Health Act (OSHA) standards. Alternatives with the known risk of flammability may be subject to additional regulatory requirements for safety, leakage reduction measures, and fire suppression, as well as building codes prescribed by municipal authority. Analysis on additional regulatory requirements should be conducted case-by-case basis considering the specific conditions of the equipment.

Based on discussions with Harvard stakeholders, the existing locations of HVAC/R equipment may post substantial challenges to retrofitting with natural refrigerants that are known to be flammable. Our team conferred with Harvard's internal risk financing and insurance group to better understand the potential cost implications of any actions that implement flammable refrigerants. As with other occupational safety hazards, the risk profiles of specific substances must be evaluated. In evaluating whether refrigerants that pose potential hazards are deemed an acceptable level of risk, institutions should engage their local code officials as well as environmental health and safety professionals in order to ensure the effective implementation of risk mitigation strategies and safety protocols. If risk mitigation strategies are prohibitively expensive or unavailable, retrofit or upgrade opportunities to lower GWP refrigerants or non-HFC alternative refrigerants may not be possible in the near term. In these situations, institutions should ensure safe equipment operational conditions for workers and community members while instituting enhanced leak detection and avoidance mechanisms in HFC-containing equipment.

There are three primary categories of alternative refrigerants being considered: (1) ammonia, (2) carbon dioxide, and (3) hydrocarbons. The environmental health and safety considerations for each are discussed below. [67]

Ammonia, NH_3, is very reactive with water vapor in the atmosphere, giving it a short residence time and a GWP of nearly 0. This reactivity makes ammonia toxic and under certain conditions flammable.[68] Unlike many other refrigerants, however, ammonia is detectable by its scent at concentrations as low as 0.04 ppm. This characteristic provides an early warning system for even small leaks.

Carbon dioxide, CO_2, is another environmentally conscious alternative to halocarbon refrigerants. By definition, CO_2 has a GWP of 1, which is hundreds to thousands of time lower than most HFC refrigerants. Carbon dioxide is nonflammable, and only poses a mild asphyxiation hazard should substantial leaks occur.[69] The CO_2 gas is highly pressurized (>90 bar) in the refrigeration system, however, which raises the potential for small leaks to escalate quickly[14]. Ammonia and carbon dioxide are often used together in multiple stage cooling. This can offset the amount of ammonia used, alleviating some toxicity or flammability concerns.

Refrigerant-grade hydrocarbons are volatile organic compounds like propane (R-290), isobutane (R-600a), ethylene (R-1150), and propylene (R-1270). Hydrocarbon refrigerants have GWPs of approximately 20, making them more environmental than HFCs but less so than NH_3 or CO_2. They are extremely flammable and denser than air, which means they can accumulate in confined spaces during a leak.[70] This precludes their use in unventilated areas and limits their use to smaller applications. Hydrocarbons are typically employed in personal-use appliances like refrigerators, window air conditioners, as well as vending machines and dehumidifiers.

Table 13. Exposure Limits for Alternative Refrigerants

Substance	CAS No.	Regulatory Limits			Recommended Limits	
		OSHA PEL		Cal/OSHA PEL	NIOSH REL	ACGIH 2018 TLV
		ppm	mg/m^3	8-hour TWA (ST) STEL (C) Ceiling	Up to 10-hour TWA (ST) STEL (C) Ceiling	8-hour TWA (ST) STEL (C) Ceiling
Ammonia	7664-41-7	50	35	25 ppm (ST) 35 ppm	25 ppm (ST) 35 ppm	25 ppm (ST) 35 ppm
Carbon dioxide	124-38-9	5000	9000	5000 ppm (ST) 30,000 ppm	5000 ppm (ST) 30,000 ppm	5000 ppm (ST) 30,000 ppm
Propane	74-98-6	1000	1800	1000 ppm	1000 ppm	See TLV® book Appendix F (D, EX)

[67] ARTI Report No. 09001-01, Review of Regulations and Standards for the Use of Refrigerants with GWP Values Less than 20 in HVAC&R Applications. http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Technical%20Results/ARTI-Rpt-09001-01.pdf
[68] Airgas. Safety Data Sheet. Ammonia https://www.airgas.com/msds/001003.pdf
[69] Airgas. Safety Data Sheet. Carbon Dioxide. https://www.airgas.com/msds/001013.pdf
[70] Airgas. Safety Data Sheet. Propane. https://www.airgas.com/msds/001045.pdf

XI. Projects Selected

XI.a Generalizable Opportunities

Two strategies with potentially low barriers to entry/implementation have emerged through our assessment that we will include as recommendations to unregulated entities. These opportunities are generalizable to Harvard and other organizations with operational control over HFC-containing equipment and therefore potentially scalable.

1. The implementation of preventative maintenance best-practices and implementing leakage detection mechanisms have the effect of reducing the likelihood of leaks and early identification of leaks while maintaining or enhancing the performance of equipment.

2. Harvard should formally consider voluntary compliance with the Kigali Amendment's planned. This step would lock Harvard in to a phased reduction of its HFC inventory. Under the Kigali Amendment, developed nations would take steps to achieve an 85% cut in HFCs, compared to the 2011-2013 baseline, by 2036. Preventative maintenance strategies have been shown to increase the usable lifespan of equipment and avoid disturbances to general business mission, thereby avoiding the embodied emissions associated with the manufacturing, transportation, and construction of new equipment. It should be noted that embodied emissions can represent a relatively low proportion of total lifetime emissions for equipment and this strategy should be coupled with lifecycle assessments of new equipment. Energy efficiency gains and reduced GWP of refrigerants may result in a net reduction of emissions through upgrading equipment, in which case replacement of equipment should be evaluated.

As a nearly 400-year-old institution, Harvard approaches equipment maintenance with the mindset that the institution, and by extension its existing assets, will be around in the coming decades and it makes sense to invest in effective maintenance of those assets. It takes fiscal responsibility seriously and approaches operational decision-making from a sound, relatively long-term lens. Preventative maintenance practices are nearly ubiquitous across Harvard's schools and units. This may not be the case in other institutions or organizations where HFC-containing equipment is operated. To the extent that there are opportunities to improve the preventative maintenance practices, organizations should strongly consider investing in these practices.

In the absence of federal ratification of the Kigali Amendment, there is an opportunity to voluntarily commit to adhere to the reduction timeframe outlined in Kigali. A public acknowledgement of this intention to commit to adherence makes sense for Harvard to consider. The existing preventative maintenance practices result in a minimized risk of emissions from leaked refrigerants.

Without institutional support for a near-term comprehensive overhaul of the refrigerant, the step of voluntarily complying with the Kigali Amendment can be pursued in parallel with a continued implementation of best practices and the pursuit of a pilot project. Similar to the voluntary and public statements made by states, cities, businesses, and other organizations to voluntarily comply with the Paris Climate Agreement, voluntary compliance with the Kigali Amendment would have the effect of publicly signaling support for Kigali within a nation that has not ratified it.[71][72] This action is replicable at other

[71] As of March 14, 2019, 23 states have signed on to the US Climate Alliance, a bipartisan group of governors that have committed their states to implement policies that advance the goals of the Paris Agreement. U.S. Climate Alliance. This represents more than 40 percent of the U.S. population and a $9 trillion economy https://www.usclimatealliance.org/

institutions and a signal from Harvard could catalyze similar actions elsewhere. While this would not result in immediate reductions in the potential impacts of HFCs to the climate, it would effectively guarantee their reclamation and/or destruction, which may have the effect of reducing the production of virgin HFCs and would decrease the potential release of HFCs into the atmosphere, thereby eliminating their GHG impact. The nuances of this action demand further investigation, which our team intends to outline throughout the remainder of the semester.

For our projects going forward, we will continue to evaluate a pilot project, but recognize that it has to have some element of “charisma” to be implemented.

XI.b Pilot Project Selection

Throughout our feasibility study, we’ve been analyzing the legal, technical and financial feasibility of the various equipment change outs. Each project’s analysis will be specific to the particular type of equipment, equipment vendor, refrigerant, building code and location among other analyses.

Our implemented project will be an HFC-404 Refrigeration unit located at HLS because it was a feasible project that produced meaningful carbon emissions in a scalable way. It also provides the opportunity to do two pilot projects with one unit. Because the unit is relatively new (installed in 2012), it is too new to do a full replacement to a CO2 based system. However, the HFC-404a can be easily changed to HFC-442, producing meaningful climatic and economic benefits immediately. The HFC-404a can also be recovered in this process, producing offsets for the University. At the end of the equipment’s life in 11 years, the equipment can then be replaced with a CO2 based system. This will produce even more meaningful carbon and economic benefits. It will also be eligible to produce offsets as a leader in CO2 refrigeration per the ACR standard of CO2-based refrigeration systems.

XI.c Evaluating a New HFC Destruction Technology

Refrigeration recovery protocols minimize the release of used refrigerants to the atmosphere during equipment evacuation. Once the replaced gases have been recovered, the University has several options. Ideally, the environmental impact of the used gases is minimized. Gases can be stored for later use, reused in other equipment, reclaimed and sold on the market, or destroyed. Through electing to reuse, reclaim, or destroy refrigerants, the University may be able to offset carbon emissions associated with subsequent production or emissions.

Although legislation is driving the innovation of more efficient and robust equipment, a substantial quantity of refrigerants is lost to the atmosphere through leaks. This requires systems to be recharged with new gas. Often, cleaned recovered gas is a viable alternative to newly produced, or virgin, product. Reclaimed gases that are checked for purity to avoid hydrolysis, corrosion, and unanticipated thermodynamic behavior are typically granted Air-Conditioning, Heating and Refrigeration Institute (AHRI) approval. Reclaimed gases are a cheaper and more environmental product than virgin products. The recovery and reclamation of used refrigerants can therefore avoid unnecessary disposal and production of new gases.

In the case where refrigerant demand surpasses supply, greater environmental benefit may be achieved by electing to destroy recovered refrigerants. This option decreases the availability, and increases the price, of the gas, stimulating consumers to consider alternatives with perhaps lower GWPs. The technologies

[72] The U.S. Climate Alliance and Related Actions. Environmental and Energy Study Institute, August 2017 https://www.eesi.org/files/FactSheet_US_Climate_Alliance_2017.08.pdf

and efficiencies of techniques to destroy ozone-depleting substances are regulated under the Clean Air Act. While similar regulation is not in place for HFC destruction, the technologies currently employed in the HFC destruction market are also those employed for CFC and HCFC destruction.

Current techniques fall into three categories: (1) incineration, (2) plasma cracking, and (3) chemical reaction[73]. Incineration processes heat halocarbons to over 1,000 ˚C until the bonds between atoms are broken. Products include HF, H_2O, HCl, CO_2, and Cl_2, which are then isolated and can be sold as inputs to industrial processes[74]. Over eight distinct incineration techniques are recognized by the Parties to the Montreal Protocol, including kilns, reactor cracking, porous thermal reactors, and fume oxidation at high temperatures. Non-incineration technologies use heat to thermally decompose halocarbon molecules in the absence of oxygen. The most widely utilized of these technologies is plasma arc destruction, which ionizes particles by exposing them to intense heat (4,700 - 19,700 °C) and electromagnetic fields. Seven different classifications of plasma arc destruction methodologies are approved. These include plasma arcs generated from ionizing different gases (e.g. air, nitrogen, argon), microwave plasma, and inductively coupled radio frequency plasma. These technologies achieve very high destruction efficiencies, but require substantial heat and energy inputs and as a result are themselves associated with considerable GHG emissions.

Other technologies chemically react the halocarbons using the change in chemical potential resulting from molecular rearrangement. These processes require lower heat and energy inputs to destroy the halocarbons. Some techniques use solid metal catalysts, while others react halocarbon molecules with methane, hydrogen, and carbon dioxide at elevated temperatures. The resulting products, including sodium fluoride and vinyl fluoride, are often marketable.

Here, we investigate a new chemical method of halocarbon destruction. Unlike many previous destruction methods, this technique is carried out at ambient temperatures and pressures. To increase the incentive for institutions like Harvard to reduce their HFC use, we propose a cheap, effective, and innovative way to destroy HFCs using photo-oxidation. By reducing the price and carbon footprint associated with HFC destruction, we aim to incentivize reducing institutional HFC use.

The details of the chemical destruction mechanism and a theoretical model of the reaction kinetics can be found in Appendix A. Briefly, we aim to enhance the natural destruction pathways of HFC gas in the atmosphere via oxidation initiated by the hydroxyl (OH) radical. The experimental design consists of four stages (Exhibit 13). First, nitrous acid vapor (HONO) is generated by bubbling nitrogen gas through an acidified solution of sodium nitrite. The HONO vapor is then photolyzed, producing OH and NO radicals. These gaseous products are then mixed with the HFC gas and allowed to react. Finally, we measure the concentration of HFC after the reaction has taken place using an infrared (IR) spectrometer. The more HFC has been destroyed, the weaker the (IR) absorption signal will be in the instrument.

We can quantify what percentage of HFC has been destroyed by comparing the final absorption signal to the signals at known concentrations. This calibration curve is constructed by sampling well-defined mixing ratios of HFC-134a blended with air. As expected, absorbance increases with increasing HFC concentration (Exhibit 14).

When HFC-134a molecules are exposed to OH radicals, a fraction of these molecules react before the absorbance is measured. This destruction efficiency depends on numerous factors, including gas phase concentrations, reaction time, experimental design, and temperature (Appendix A). The destruction

[73] ODS Destruction in the United States and Abroad, EPA 430-R-18-001, 2018.
[74] For instance, hydrohalic acids are commonly used in pharmaceuticals production. Chemicals Economics Handbook. SRI International. 2001; and R.S. Hug, Experiences with a CFC Decomposition Plant of Solvay Fluor und Derivative GmbH at Frankfurt Germany, 2000.

efficiencies at three HFC flow rates are also illustrated in Exhibit 14. The destruction efficiency decreases with increasing flow rates: as HFC spends less time in the reaction vessel, fewer molecules react. For the three flow rates considered in our preliminary experiments, destruction efficiency ranged from 94% to 78%.

We emphasize these results are only preliminary, and that they need to be further verified and explored. It is likely that the destruction efficiency can be enhanced by better controlling the production of OH radicals and by increasing the residence time within the reactor by modifying the experimental setup.

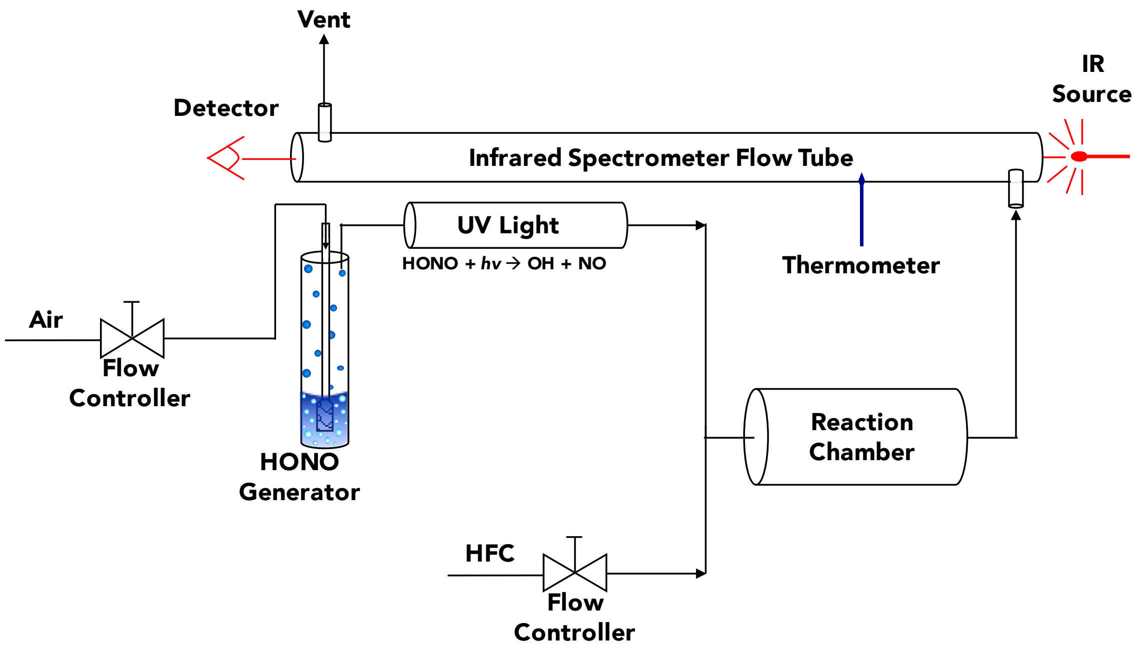

Exhibit 13. An Apparatus to destroy HFCs. By mimicking HFC destruction in the atmosphere, we hope to create a cheap, safe, and effective protocol to destroy HFC emissions from campus sources. The experimental setup above causes HFC to react with gas molecules, transforming it into products with much lower climatic impacts.

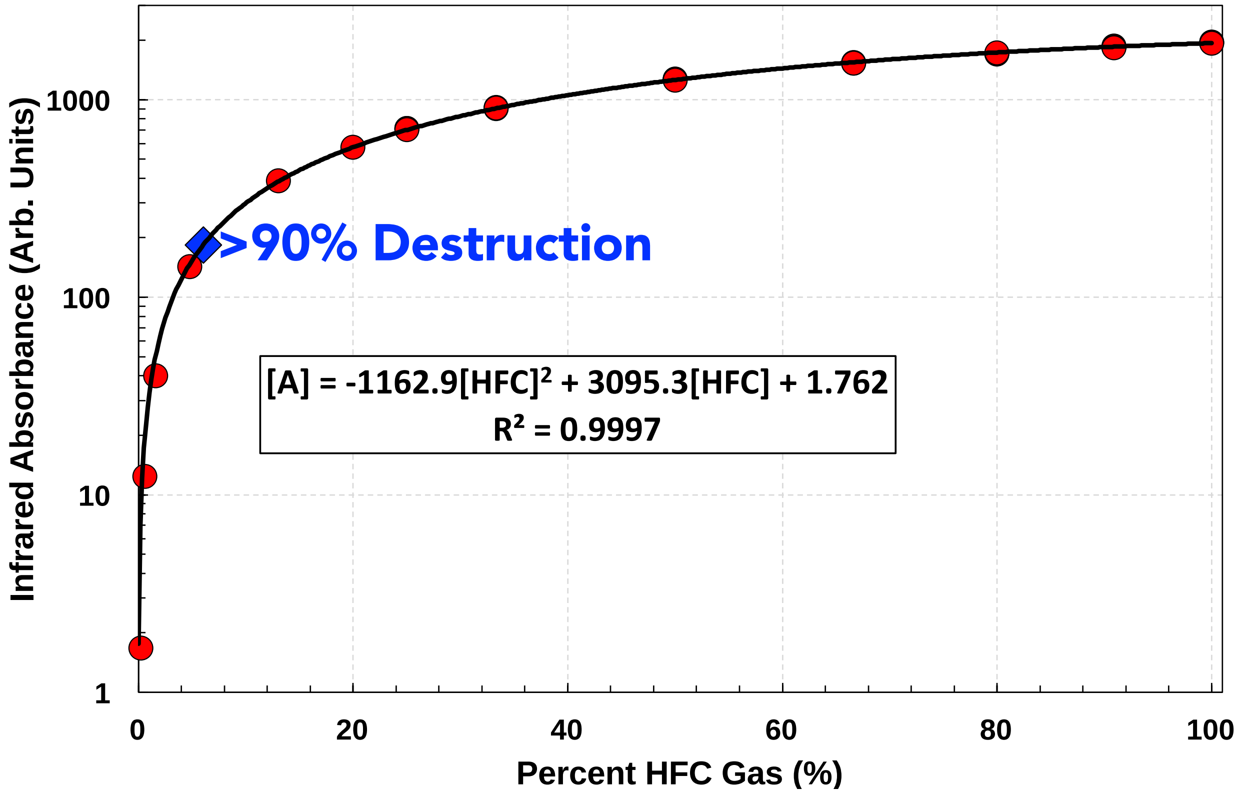

Exhibit 14. HFC-134a infrared absorbance. Shown on the plot above are (1) the cumulative absorbance at known HFC-134a concentrations (calibration curve), (2) a quadratic regression of these data points, and (3) the destruction efficiency of a plug flow reactor evaluated at a flow rate of 1 lb. day^{-1}. Details can be found in Appendix A.

XI.d Acceptance of HFC Destruction as an Offset Mechanism for ACR

As discussed previously, there is no existing offset methodology for destruction of HFCs. However, the Project suggests there is reasonable grounds to argue that destruction of HFCs can be an effective means of GHG emission reduction, and such activity deserves to be recognized as offset, especially considering the rapid increase of GHG emissions from HFC refrigerants.

Preliminary research demonstrated that very few projects have considered HFC destruction as emission reduction activity and the Project may be the first HFC destruction project from universities in United States. The Project aims to contribute to development of appropriate methodology for HFC destruction in connection with existing carbon standard organizations. American Carbon Registry, among others, have been most active in exploring emission reduction potential in HFC refrigerants, and is currently considered as the most appropriate partner for this effort.

As discussed previously, Reporting Protocol requires six elements for a valid offset activity, which serves as a useful starting point. Initial review of each element for HFC destruction case is as below:

> **Real**: destruction of HFCs will eliminate potential release of such substance into the atmosphere and reduce actual GHG in existence. However, refrigerants are not supposed to be released during operation, maintenance or disposal under the applicable regulation.

Additional: Currently, there is no regulatory requirement for HFC destruction, as long as it is not intentionally released ("vented") into the atmosphere, and there is little incentive for destruction of HFCs. HFC destruction activity will be a "surplus" to existing regulation and beyond what would have happened in the absence of the incentive provided by the offset credit.

Permanent: Destruction of HFCs are final and permanent. However, there is potential counterargument that destruction of HFCs will trigger additional production of new HFCs, replacing the destroyed amount.

Transparent: Offsets from destruction of HFCs can be publicly and transparently registered to clearly document offset generation, transfers and ownership.

Verified: Independent third-party should be able to verify and validate destruction of HFCs. Destruction facilities should be able to produce technical details to allow such process.

Owned Unambiguously: Unambiguous ownership of the offset credits can be reasonably established.

Meanwhile, ACR's methodology on Destruction of Ozone Depleting Substances and High-GWP Foam provides a meaningful comparison. This methodology recognizes destruction CFCs and HCFC-22 refrigerants as offsets, as well as destruction of HFC-134a and HFC-245fa foam blowing agents recovered from foams. This methodology appears to be the only existing offset that currently recognizes destruction of HFCs as offset. This methodology particularly discusses the basis of adding the HFC foam blowing agents in addition to the CFCs and HCFCs as below:

> "These HFCs are in production in the U.S. for use in the manufacture of foam products, particularly appliance foam. Destruction of foam recovered from end-of-life appliances does not trigger additional production of the HFC blowing agents beyond what would be produced anyway. […] At a macro-level, when an appliance reaches end-of-life, demand is created for the manufacture of a new replacement appliance. For example, the decision to purchase a new refrigerator-freezer, in general, is made when the old fridge is discarded. That decision at the consumer level translates to a decision at the manufacturing level to produce a new fridge. Today, the new fridge may be manufactured with insulation foam containing HFC-134a, HFC-245fa, or in some cases, a hydrocarbon-based blowing agent. Regardless of how the foam in the end-of-life appliance is discarded - shredded and landfilled (the baseline scenario), or incinerated in conformance with this Methodology - the same quantity of new blowing agent will be produced for use in a newly manufactured appliance. As is the case for ODS refrigerants and the other eligible ODS categories in this Methodology, destruction of CFC, HCFC, and HFC blowing agents therefore prevents greenhouse gas emissions that would otherwise occur under the baseline scenario (shredding and landfilling of the foam)."[12]

This methodology focuses on the fact that HFCs in the discarded foam will not affect new production of HFC-filled foam and it will eventually be released to air in the baseline scenario (when nothing is done) either through shredding or landfilling. Therefore, recovery and destruction of HFCs in the foam is separate and irrelevant to new production, and destruction of HFCs in the foam is permanent.

Two questions are identified for the HFC refrigerant destruction case: (i) whether destruction of HFC actually reduces emission of GHGs compared to baseline scenario, and (ii) whether destruction of HFC refrigerants will trigger additional production and will be simply replaced.

In regard to the first question, the most important difference between HFC foam blowing agents and HFC refrigerants is that HFC refrigerants are not supposed to be released into atmosphere under the applicable regulations. This changes the “baseline scenario” for HFC refrigerants because even when the appliance is discarded, HFC refrigerants are required to be recovered, not vented or abandoned to be slowly released. According to this view, there is no difference in emissions between the baseline scenario and the offset scenario where recovered HFCs are destroyed and there would be no “real” emission reduction achieved by destruction.

However, this view may be inconsistent with the reality. Although the regulations require recovery of all refrigerants prior to disposal of appliances, the actual recovery rate for refrigerants are very low, particularly for HFC refrigerants, because HFC production is currently unregulated and there is no economic incentive recover HFCs when it can simply be produced to ACR’s Certified Reclaimed HFC Refrigerant methodology uses recovery rate of HCFC-22 in 2013 of 8.2% as reference rate for HFC recovery, which it notes to be a conservative one. In reality, it is more likely that substantial amount of HFC refrigerants are not properly recovered from disposed appliances and recovery and destruction of HFC refrigerants are likely to eliminate potential release to atmosphere.

The second point raises question on whether destruction is leaked by additional production. Established methodologies for destruction of ODS refrigerants were free from these issues because new production of most ODS refrigerants were phased out under Montreal Protocol. When phased-out CFCs and HCFCs are recovered from discarded appliances and destroyed, total amount of such substance is reduced as no new production is available to replace the destruction. Also, destruction will eliminate any potential release during reuse of such substance. However, because United States has not ratified Kigali Amendment to Montreal Protocol and there is currently no phase-out scheme for production of HFCs, there is an argument that destruction of HFCs will be simply replaced by new production. According this argument, only reclamation and reuse of HFC refrigerants would be meaningful because reclaimed amount will displace the demand for new production and will be able to reduce the new production. However, if increasing number of HFC refrigerant users switch to non-GHG or low-GWP refrigerants, demand for HFC refrigerant will decrease and the volume of new production will not necessarily displace the destroyed amount of HFCs.

The theoretical challenges against HFC destruction case raise valid points, but there can also be reasonable arguments supporting the value of HFC destruction for offset credit. When and how destruction of HFCs can be qualified as valid offset activity depends on various factors including regulatory changes, market trend and industry practice. Development of innovative destruction technology could go hand-in-hand with development of offset methodology for HFC destruction as an on-going effort. In recognition of its innovative nature, one could consider applying it to voluntary offset credit market first and then potentially extending it to more stringent compliance market.

XII. Conclusion

With global warming potentials hundreds to tens of thousands of times greater than CO_2, halocarbons are among the most potent greenhouse gases emitted. Even small efforts to reduce their atmospheric release are valuable. In this report, we have discussed the regulatory and health implications of Harvard's halocarbon emissions and outlined the technical, legal, financial, and institutional barriers the University faces in reducing its halocarbon use.

In the absence of federal or state regulation, we encourage the University to lead by example and enact policies to reduce its halocarbon refrigerant use and emissions. This report proposes several pathways designed to achieve these goals. First, we recommend the University continue to expand the scope of its halocarbon inventory to include equipment using less than 50 pounds of refrigerant. This will better enable quantification of halocarbon use and emissions from University equipment.

Further, we recommend that the University prioritize substituting existing halocarbon refrigerants for more environmental choices. Policies include replacing aging systems with natural refrigeration equipment and retrofitting viable equipment with HFCs and HFOs exhibiting lower GWP values. The University could realize annual emissions reductions equivalent to over 350 metric tons of CO_2 by simply swapping out existing gases with alternatives. There are several technical, legal, financial, and public health considerations associated with these policies. However, we believe the charisma and innovative nature of these opportunities should drive the University to implement policies that reduce their HFC use and emissions.

Appendix A:

Model and Description and Experimental Design

A.1 – Gas Phase Chemistry of HFC Degradation

Hydrofluorocarbons (HFCs) are designed to be more chemically reactive than precursor refrigerant gases. All HFC molecules contain at least one hydrogen atom and are therefore susceptible to photo-oxidation in the atmosphere. These reactions ensure a shorter atmospheric residence time than chlorofluorocarbons (CFC)s, which persist long enough to be transported into the stratosphere.

In this proposed destruction protocol, we attempt to enhance the following degradation pathways that occur naturally in the atmosphere to destroy HFCs. The reactions outlined below specify the degradation pathway for HFC-134a. However, the gas-phase chemistry for all HFCs and HCFCs follow similar pathways. We refer the reader to the many studies in the literature for the atmospheric chemistry of specific compounds[75].

The gas phase chemistry of HFCs can be divided into two parts: reactions that initiate the oxidation of halocarbons into carbonyl species, and reactions that neutralize and remove these carbonyl species from the atmosphere.

A.1.a – Initiation and Carbonyl Production

Atmospheric degradation of HFCs begins with hydrogen atom extraction by an OH radical[76]:

$$\dot{O}H + CF_3CFH_2 \xrightarrow{k_1} CF_3\dot{C}FH + H_2O$$

where CF_3CFH_2 is HFC-134a, and $CF_3\dot{C}FH$ is the haloalkyl radical. The rate of this reaction, k_1, and subsequent reactions are a well-defined function of temperature (NASA JPL).

The haloalkyl radical rapidly reacts with oxygen gas to form a haloperoxy radical:

$$CF_3\dot{C}FH + O_2 \xrightarrow{k_2} CF_3CFHO\dot{O}$$

The peroxy radical can react with three species: NO, NO_2, and HO_2 radicals. Since the background tropospheric concentrations of these species are similar, the relative importance of these reactions is dictated by the reaction rates. The rate constant for the reaction of the haloperoxy radical with NO is about 3 times greater than for the reaction with NO_2 or HO_2, so the dominant loss process for the haloperoxy radical is by reaction with NO to give a haloalkoxy radical:

$$CF_3CFHO\dot{O} + N\dot{O} \xrightarrow{k_{3a}} CF_3CFH\dot{O} + \dot{N}O_2$$

Pathways of secondary importance include a reversible reaction with NO_2, creating a short-term halogen reservoir in the form of the alkyl peroxynitrates:

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[75] See e.g. Wallington, Timothy J., et al. "The environmental impact of CFC replacements HFCs and HCFCs." Environmental science & technology 28.7 (1994): 320A-326A.

[76] Radicals are molecules with unpaired electrons, making them unstable and extremely susceptible to reaction. Radicals therefore exist only for short periods of time in the atmosphere. We denote radical molecules with a dot (˙) over the atom with the unpaired electron.

$$CF_3CFHO\dot{O} + \dot{N}O_2 \xleftrightarrow{k_{3b}} CF_3CFHO_2NO_2$$

and also reaction with HO_2, which is reversible but can also produce carbonyl products:

$$CF_3CFHO\dot{O} + HO_2 \xleftrightarrow{k_{3c}} CF_3CFHO_2HO_2 \xrightarrow{k_{3d}} CF_3C(O)F + H_2O + O_2$$

The fate of the carbonyl product is discussed below.

Haloalkoxy radicals produced via Reaction 3a either undergo decomposition or react with oxygen. Decomposition occurs via a carbon-carbon bond fissure, producing trifluoromethyl radicals and formyl fluoride:

$$CF_3CFH\dot{O} \xrightarrow{k_4} \dot{C}F_3 + HC(O)F$$

The fates of both products are similar. Trifluoromethyl radicals react with oxygen, producing a dioxidanyl radical:

$$\dot{C}F_3 + O_2 \xrightarrow{k_5} CF_3O\dot{O}$$

This radical then converts to carbonyl fluoride, which hydrolyzes to produce carbon dioxide and hydrogen fluoride:

$$COF_2 + H_2O \xrightarrow{k_6} CO_2 + 2HF$$

Formyl fluoride, a product of the decomposition of the alkoxy radicals via Reaction 4 above, in turn decomposes to produce carbon monoxide and hydrogen fluoride:

$$HC(O)F \xrightarrow{k_7} CO + HF$$

For safety purposes, we note that hydrogen fluoride is a toxic gas that can be neutralized by dissolution and reaction with any base:

$$NaOH_{(aq)} + HF_{(aq)} \xrightarrow{k_8} NaF_{(aq)} + H_2O$$

In addition to decomposition, the haloalkoxy radicals produced via Reaction 3a can also react with oxygen to produce carbonyl compounds:

$$CF_3CFH\dot{O} + O_2 \xrightarrow{k_9} CF_3C(O)F + HO_2$$

A.1.b – Reactions and Removal of Halogenated Carbonyl Products

Above, we have discussed the oxidation pathway of HFC molecules into carbonyl products. These gas phase reactions are rapid (Table 1), precluding the role of heterogeneous (occurring on the surface of particulate matter) or aqueous (within water droplets). However, carbonyl byproducts of HFC oxidation are relatively stable, and their atmospheric lifetime is on the order of weeks.

This allows for two removal mechanisms of the carbonyl products of Reactions 3d and 9. Of relatively minor importance is photolysis, which cleaves the carbon-carbon bond of the halocarbonyl:

$$CF_3C(O)F + hv \xrightarrow{k_{10}} \dot{C}F_3 + H\dot{C}O$$

The trifluoromethyl radical ($\dot{C}F_3$) reacts as described in Reactions 5 – 6. The formyl radical ($H\dot{C}O$) then reacts with oxygen to produce carbon monoxide and HO_2.

The majority of carbonyl molecules react instead undergo dissolution and subsequent aqueous phase chemistry. Halocarbonyl gases are sufficiently soluble in cloud droplets such that their atmospheric lifetime is approximately 10 days:

$$CF_3C(O)F_{(g)} \xrightarrow{k_{11}} CF_3C(O)F_{(aq)}$$

Once dissolved, carbonyls hydrolyze to produce haloacetic and hydrofluoric acids:

$$CF_3C(O)F_{(aq)} + H_2O_{(l)} \xrightarrow{k_{12}} CF_3C(O)OH_{(aq)} + HF_{(aq)}$$

Since these acids are very soluble in water, this process irreversibly removes the carbonyl compounds from the gas phase.

$$CF_3C(O)OH_{(aq)} + HF_{(aq)} \xrightarrow{13} \text{Precipitation}$$

As cloud droplets precipitate, the atmospheric degradation products of HFCs are permanently removed from the atmosphere. Sufficiently diluted, these degradation products present little or no threat to human or environmental health.

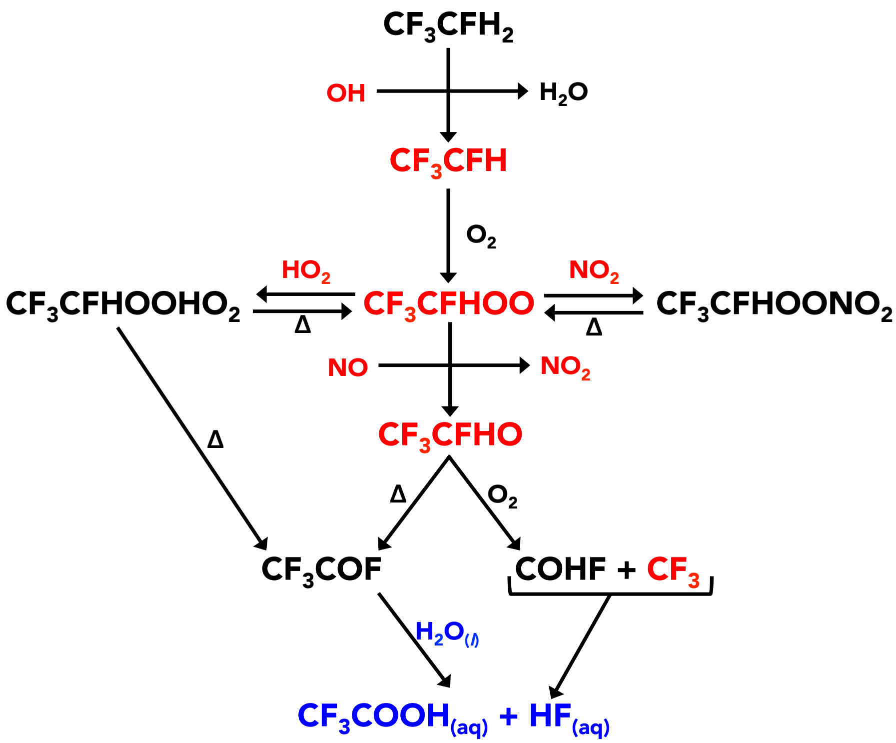

Exhibit A1. HFC-134a degradation pathway. Long lived species are shown in black, short lived radicals in red, and aqueous species in blue.

Table A1. HFC Degradation Products and Atmospheric Lifetimes

Name	Formula	Reaction Number	Approx. Lifetime
HFC-134a	CF_3CFH_2	1	10 yr
Haloalkyl Radical	$CF_3\dot{C}FH$	2	1 μs
		3a	1 min
Haloperoxy Radical	$CF_3CFHO\dot{O}$	3b	1 hr
		3c	1 day
Haloalkoxy Radicals	$CF_3CFH\dot{O}$	4, 9	1 μs
Trifluoromethyl Radicals	$\dot{C}F_3$	5	1 μs
Carbonyl Fluoride	COF_2	6	1 day
Formyl Fluoride	HCOF	7	1 min
Haloarbonyl	$CF_3C(O)F$	10 – 12	1 wk
Haloacetic Acid	$CF_3C(O)OH_{(aq)}$	13	1 wk
Hydrofluoric Acid	HF	8, 13	1 wk

A.2 – HFC Destruction Experimental Design

The reactions above demonstrate the degradation pathway from HFC gas to soluble products. Here, we discuss the design of an apparatus to enhance these reactions in order to quickly, cheaply, safely, and effectively destroy HFC gas stocks.

As indicated in Reaction 1, HFC degradation initiates via an OH radical attack:

$$\dot{O}H + CF_3CFH_2 \xrightarrow{k_1} CF_3\dot{C}FH + H_2O$$

According to Reaction 1, the rate of HFC degradation is a function of HFC and OH radical concentration, as well as the reaction rate constant:

$$\frac{d[CH_2FCF_3]}{dt} = -k_1\left[\dot{O}H\right][CH_2FCF_3]$$

We discuss each of these factors in turn below.

A.2.a – The Reaction Rate Constant

The rate limiting step in the HFC degradation process is the initial reaction with the OH radical, as implied by the atmospheric lifetimes recorded in Table A1. All other reactions involve unstable or highly reactive compounds, meaning the process proceeds rapidly after the haloalkyl radical ($CF_3\dot{C}FH$) is formed via Reaction 1.

The rate constant for this reaction, k_1, is a well-defined function of temperature (NASA JPL):

$$k_1 = A \times \exp\left(-\frac{E}{RT}\right)$$

where A is the Arrhenius factor, E is the activation energy (J mol^{-1}), R, is the ideal gas constant (J mol^{-1} K^{-1}), and T is temperature (K). The following constants are tabulated for Reaction 1:

$$A = 1.05\times10^{-12} \qquad E/R = 1630\ K$$

This allows us to calculate the rate constant k_1 as a function of temperature. Some values for relevant temperatures are given in Table 2.

Table 2. Reaction Rate Coefficients for R1

k_1 (cm^3 $molec.^{-1}$ s^{-1})	T (K)
2.680×10^{-15}	273
4.423×10^{-15}	298
6.754×10^{-15}	323
1.037×10^{-14}	353

A.2.b – OH Radical Concentration

Since the rate-limiting step of the HFC degradation process is the initial reaction with OH radicals, it follows that the rate of HFC degradation is affected by OH radical concentration. In the atmosphere, OH radical concentration is typically one million radicals per cm^3 of air. In order to speed up the HFC destruction process, we increased the OH radical concentration in our experiments.

OH radicals can be generated via a variety of processes. We generate them by photolyzing nitrous acid (HONO), which also creates NO radicals as a byproduct. These radicals are also important reactants in the HFC degradation process (see e.g. Reaction 3a). Nitrous acid is first created by reacting any nitrite salt with an acid:

$$NO^{-}_{2(aq)} + H^{+}_{(aq)} \xleftrightarrow{k_{14}} HONO_{(aq)}$$

In our experiments, we used sodium nitrite and sulfuric acid. The extent of nitrous acid production depends on the acidity of the solution, the nitrite ion concentration, and the equilibrium rate constant:

$$\left[HONO_{(aq)}\right] = \frac{\left[H^{+}_{(aq)}\right]\left[NO^{-}_{2(aq)}\right]}{k_{14}}$$

At 298 K, or approximately room temperature, $k_{14} = 4 \times 10^{-4}$ mol L^{-1}. Nitrous acid is unstable in solution and readily partitions into the gas phase:

$$HONO_{(aq)} \xleftrightarrow{H_{14}} HONO_{(g)}$$

We denote the extent of this partitioning with an H, which is a dimensionless Henry's law constant:

$$H_{14} = H_{cp} \times RT = 4.1\times10^{-1}\,\frac{mol}{m^3\ Pa} \times 8.314\,\frac{m^3\ Pa}{mol\ K} \times 298\ K = 1015.8$$

In words, this calculation shows that about one thousand times more nitrous acid partitions into the gas phase than remains in solution. Summing together the extent of aqueous nitrous acid formation and gas phase partitioning, we have:

$$HONO_{(g)} = \frac{\left[H^{+}_{(aq)}\right]\left[NO^{-}_{2(aq)}\right]}{k_{14}H_{14}}$$

The exact concentration of $HONO_{(g)}$ can be regulated by tuning the pH and nitrite ion concentration of the solution. For example, at a pH of 2.0 and for 10 g of sodium nitrite dissolved in 100 mL of solution, the following equilibrium gas phase nitrous acid concentration is achieved:

$$HONO_{(g)} = \frac{\left[0.010\ mol\ L^{-1}\right]\left[14.49\ mol\ L^{-1}\right]}{\left(4.0 \times 10^{-4}\ mol\ L^{-1}\right)(1015.8)} = 0.36\,\frac{mol}{L}$$

When this concentration is diluted over the course of 20 liters of HFC gas (the volume of the reaction vessel used in our experiments), this equates to about 1.1×10^{19} molecules per cm^3 of air. Nitrous acid is quantitatively photolyzed in the presence of 354 nm (UV) light:

$$HONO_{(g)} + h\nu \xrightarrow{k_{15}} \dot{O}H + N\dot{O}$$

Since one molecule of nitrous acid produces one OH radical, the approximate concentration in our experiments is approximately 10^{13} times greater than the ambient OH radical concentration.

A.2.c – Material Balance for HFC Reactors

There are several reactor designs we considered for our HFC destruction apparatus. These include: 1) the batch reactor, 2) the continuous stirred tank reactor, and 3) the plug flow reactor. Before considering the specifics of these designs, we introduce here a generic framework for computing the efficiency of a reactor in destroying HFC gases.

Exhibit A2 illustrates the basic design of a chemical reactor. The reaction vessel has fixed volume (V), inlet and outlet streams with flow rates (Q) and concentrations of specific chemicals (c). These concentrations change due to reactions within the vessel (R).

Summarizing the destruction of HFC within this reactor, we can state that mass is conserved:

$$\left\{\begin{matrix}\text{rate of HFC}\\ \text{accumulation within}\\ \text{the reactor}\end{matrix}\right\} = \left\{\begin{matrix}\text{rate of inflow}\\ \text{of HFC}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of outflow}\\ \text{of HFC}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of HFC}\\ \text{destruction}\end{matrix}\right\}$$

We can write this statement in terms of the variables defined above:

$$\frac{d}{dt}\int_V c_{HFC}\, dV = Q_{in} c_{HFC_{in}} - Q_{out} c_{HFC_{out}} + \int_V R\, dV$$

The equation above is the general mass balance equation that can be specialized to any reactor design. Below, we model three different reactor types, adapting the mass balance equation to calculate certain design requirements to effectively destroy HFCs.

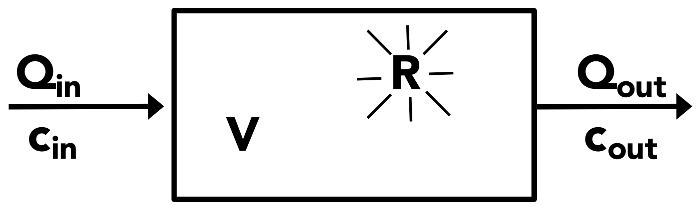

Exhibit A2 – Generic Reactor Design and Variables.

A.2.d – Dynamics for Batch Reactors

In a batch reactor, the vessel is charged with HFCs, allowing the reactions to proceed before the contents are removed. The cycle is then replicated until the stock of HFCs is consumed. Exhibit A3 illustrates the operation of a batch reactor. Note the lack of input and outputs during operation. The contents of the reactor are assumed to be homogeneous – i.e. the reactor is well stirred.

The lack of inputs and outputs while the reactions take place simplify the mass balance equation above to:

$$\frac{d}{dt}(c_{HFC}V) = RV$$

Our design also uses a rigid vessel. The reactor volume V is also constant, and can be taken out of the derivative to cancel out on both sides:

$$\frac{d}{dt}(c_{HFC}) = R$$

As per our discussion above, Reaction 1 is the rate limiting step in the HFC degradation pathway. R is therefore defined as the rate of HFC removal via reaction with the OH radical:

$$\frac{d}{dt}(c_{HFC}) = -k_1[c_{\dot{O}H}][c_{HFC}]$$

Note the negative sign, which signifies the HFC concentration is decreasing within the reactor. The above equation contains three variables: t (time), $[c_{\dot{O}H}]$, and $[c_{HFC}$. The reaction rate constant, k_1, is a function of temperature only and can assumed to be invariant with respect to other variables.
Since the stoichiometry of Reaction 1 dictates that one mole of OH radical are consumed for every mole of HFC, we conclude that the rate of change of OH and HFC concentration is identical:

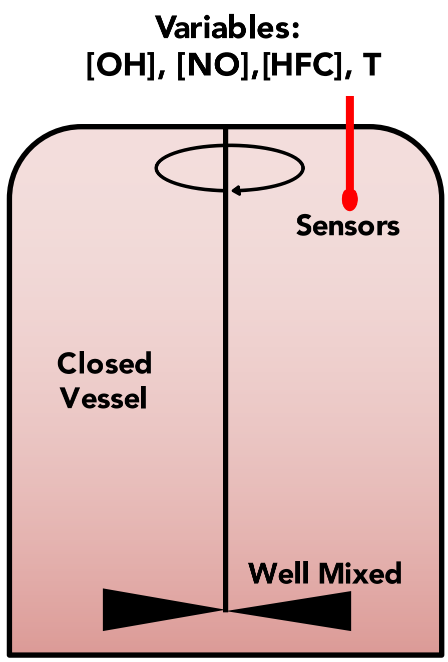

Exhibit A3 – The Batch Reactor.

$$\frac{d}{dt}\left(c_{HFC} - c_{\dot{O}H}\right) = 0$$

This implies that $c_{HFC} - c_{\dot{O}H}$ is independent of time. This value is known initially (denoted by the "o" subscript):

$$c_{HFC} - c_{\dot{O}H} = c_{HFC_o} - c_{\dot{O}H_o}$$

which allows us to solve for the concentration of OH radical at any time in terms of the concentration of HFC:

$$c_{\dot{O}H} = c_{HFC} - c_{HFC_o} + c_{\dot{O}H_o}$$

We then plug this into our original rate expression:

$$\frac{d}{dt}(c_{HFC}) = -k_1 c_{\dot{O}H} c_{HFC} = -k_1(c_{HFC} - c_{HFC_o} + c_{\dot{O}H_o}) c_{HFC}$$

This is a separable differential equation. Bring like terms to separate sides and defining the integral, we have:

$$\int_{c_{HFC_o}}^{c_{HFC}} \frac{d(c_{HFC})}{(c_{HFC} - c_{HFC_o} + c_{\dot{O}H_o}) c_{HFC}} = \int_0^t -k_1 \, dt$$

Performing the integral and evaluating the boundary conditions yields the following model mass balance equation for the batch reactor.

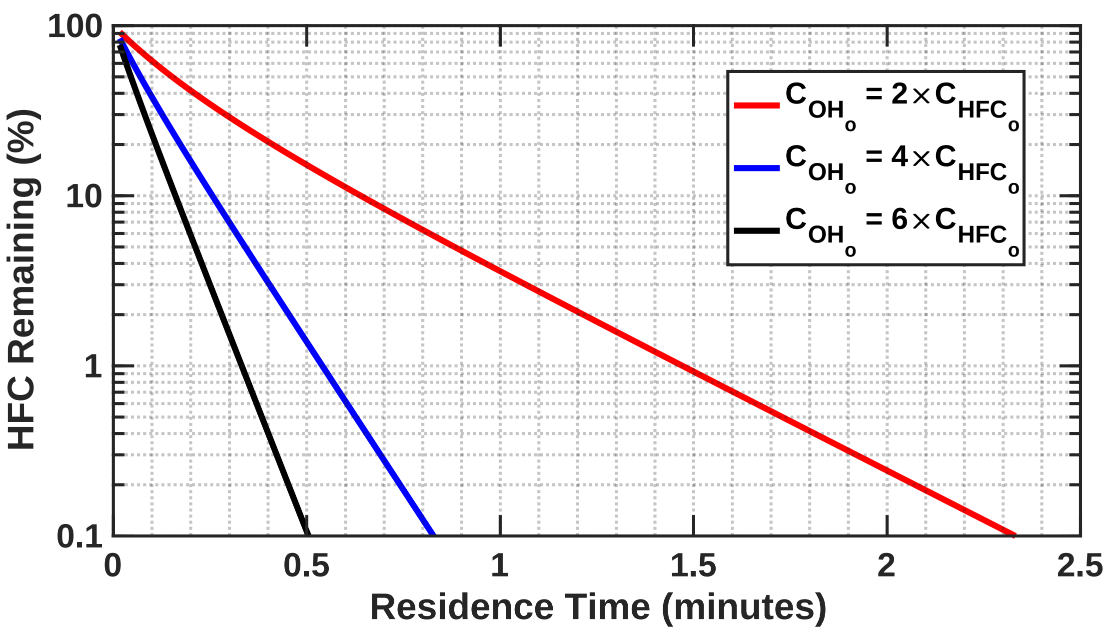

Exhibit A4 – Ideal Batch Reactor Dynamics. Modeled HFC degradation at 298 K for three different OH radical starting concentrations. The initial HFC concentration was arbitrarily modeled to be 1×10^{13} molecules cm^{-3}.

$$c_{HFC,\,Batch} = \left(c_{HFC_0} - c_{\dot{O}H_0}\right)\left[1 - \frac{c_{\dot{O}H_0}}{c_{HFC_0}} e^{\left(c_{\dot{O}H_0} - c_{HFC_0}\right)k_1 t}\right]^{-1}$$

The model equation above demonstrates that the final concentration of HFC depends on initial concentrations, temperature of the reactor (which determines the value of k_1), and time. This dynamic is illustrated in Exhibit A4 for a typical parameter values. As expected, HFC is destroyed more rapidly at higher OH radical concentrations.

The batch reactor design has notable positive and negative attributes. One beneficial feature is that the percent of HFC degradation can be extended to very high values if the residence time is lengthened (see Exhibit A4). Similarly, the same percent of HFC degradation can be achieved with lower concentrations of OH radicals, reducing the costs associated with HONO production.

In practice, however, the batch reactor is cumbersome to use. The reaction vessel must be evacuated before each batch in order to avoid any leakage of HFCs during charging. The batch reactor also takes longer to destroy a given amount of HFCs than alternative designs. For these reasons, continuous flow reactors may be preferable for destroying large stocks of HFCs.

A.2.e – Dynamics for Continuous Stirred Tank Reactors

One alternative design is the continuous stirred tank reactor (CSTR). As its name implies, gases continuously flow into and out of the reactor, which is also assumed to be well mixed (Exhibit A5). The composition of the effluent is therefore identical to the average composition within the reaction vessel.
Returning to our mass balance equation, we have:

$$\frac{d}{dt}\left(c_{HFC}V\right) = Q_{in}c_{HFC_{in}} - Q_{out}c_{HFC} + RV$$

Our reactor volume is constant, and the volumetric flowrates of the inflow and outflow are approximately constant. This simplifies the above equation to:

$$\frac{d}{dt}c_{HFC} = \frac{1}{\tau}\left(c_{HFC_{in}} - c_{HFC}\right) + R$$

where τ, the mean residence time of gases within the reactor, is defined as:

$$\tau = \frac{V}{Q}$$

We are primarily interested in the steady-state operation of the CSTR – that is, the extent of HFC degradation under normal operation of the reactor. One feature of steady-state is that the concentration of HFC in the effluent is not changing over time. This sets the time derivative of the above mass balance to zero:

$$0 = \frac{1}{\tau}\left(c_{HFC_{in}} - c_{HFC}\right) + R$$

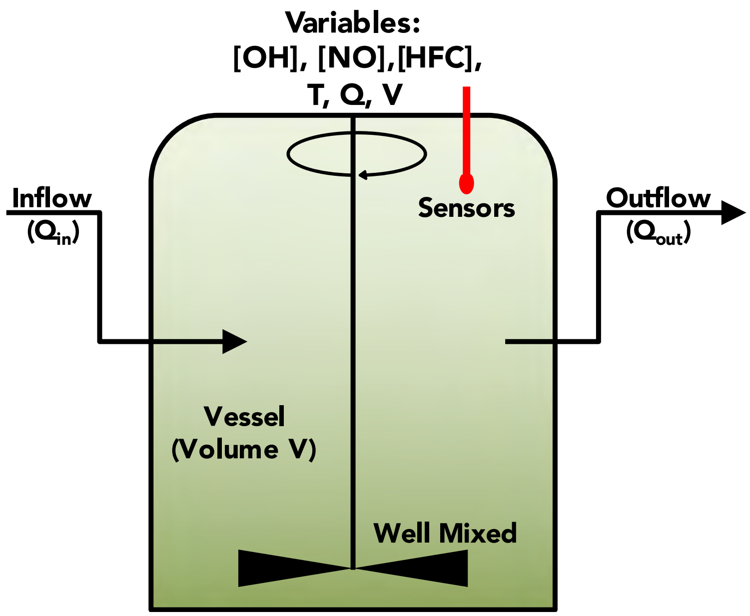

Exhibit A5 – The Continuous Stirred Tank Reactor.

Rearranging this equation, we arrive at an expression of final HFC concentration as a function of other known variables:

$$c_{HFC} = c_{HFC_{in}} + R\tau$$

Recall that the reaction rate R is given by:

$$R_{HFC} = -k_1 c_{HFC} c_{\dot{O}H}$$

As above in the case of the batch reactor, we note that the concentration of OH radicals, $c_{\dot{O}H}$, can be expressed in terms of feed concentrations and the concentration of HFC within the CSTR:

$$c_{\dot{O}H} = c_{HFC} - c_{\dot{O}H} + c_{\dot{O}H}$$

Substituting this into the rate equation, and subsequently substituting the rate into the mass balance equation above yields the following:

$$(k_1\tau)c_{HFC}^2 + \left(1 - k_1\tau(c_{HFC_{in}} - c_{OH_{in}})\right) c_{HFC} - c_{HFC_{in}} = 0$$

This is a standard quadratic equation of the form:

$$ax^2 + bx + c = 0$$

which has the generic solution:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Applying our quadratic equation, we find that the concentration of HFC in the CSTR effluent under steady state is given by:

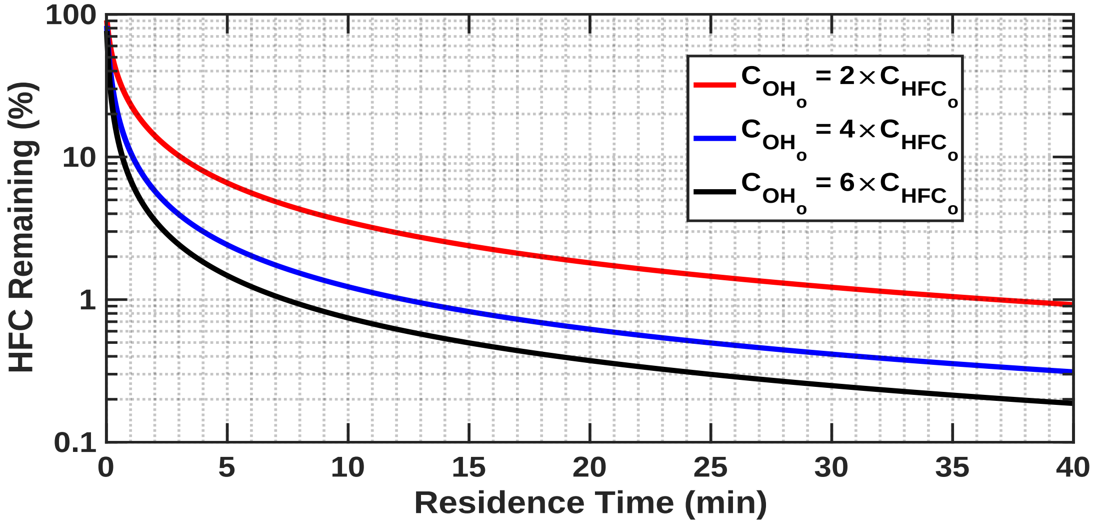

Exhibit A6 – Ideal CSTR Dynamics. Modeled HFC degradation at 298 K for three different OH radical starting concentrations. The initial HFC concentration was arbitrarily modeled to be 1×10^{13} molecules cm^{-3}. Residence time was varied by increasing feed flow rate from Q = 0.5 to 100 liters per minute at a constant reactor volume of 20 liters.

$$c_{HFC,\,CSTR} = \frac{-\left(1 - k_1\tau(c_{HFC_{in}} + c_{OH_{in}})\right) + \sqrt{\left(1 - k_1\tau(c_{HFC_{in}} + c_{OH_{in}})\right)^2 - 4(k_1\tau)c_{HFC_{in}}}}{2(k_1\tau)}$$

Like the batch reactor model, the highlighted equation above demonstrates that the final concentration of HFC from the CSTR depends on initial concentrations and temperature of the reactor (which determines the value of k_1). A time element also factors into the equation, albeit indirectly via the residence time, τ. This residence time can be adjusted by changing the flow rate (Q) or the volume of the reactor (V).

An example of how these parameters come together to determine final HFC concentration is illustrated in Exhibit A6. Residence time is varied by changing the flow rate, Q. The volume of the reaction vessel is held at a constant 20 liters. As expected, the HFC destruction efficiency increases as (1) the average time HFC spends in the reactor increases, and (2) the OH radical concentration increases.

The model demonstrates that the CSTR requires longer residence times to achieve the same degree of destruction efficiency as the batch reactor. Note the difference in the shape of the % HFC destruction curves in Exhibits A4 and A6. However, the CSTR is easier to design and use, experimentally speaking, since gases are flowing in and out at constant rates. Further, the rate and percent of HFC destruction can be increased by increasing the concentration of reactants.

A.2.f – Dynamics for Plug Flow Reactors

The final reactor design considered here is that of the plug flow reactor (PFR). The PFR is a tubular vessel with turbulent flows that thoroughly mix the gases as they proceed through the reactor. The flow velocity, temperature, and concentration of gases within the reactor only vary laterally along the length of the tube (Exhibit A7).

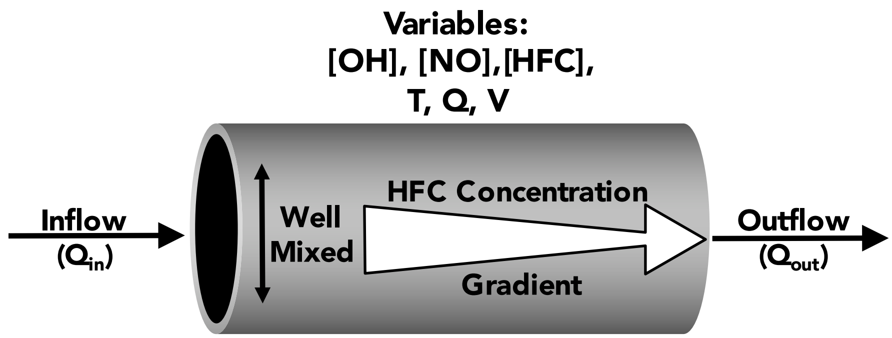

Exhibit A7 – The Plug Flow Reactor.

The steady state mass balance for the PFR can be expressed as a balance between convection (air flow) and consumption via reaction:

$$\frac{d(c_{HFC}Q)}{dV} = R$$

We recall that R for reaction one is a function of the reactant concentrations and the reaction rate constant:

$$\frac{d(c_{HFC}Q)}{dV} = -k_1 c_{HFC} c_{\dot{O}H}$$

We again substitute the concentration of OH radicals for other known quantities, transforming the differential equation into two variables (volume and HFC concentration):

$$\frac{d(c_{HFC}Q)}{dV} = -k_1 c_{HFC}\left(c_{HFC} - c_{HFC_{in}} - c_{\dot{O}H_{in}}\right)$$

This is a first order non-linear Bernoulli differential equation. To solve, we first isolate variables:

$$\frac{d(c_{HFC}Q)}{c_{HFC}\left(c_{HFC} - c_{HFC_{in}} - c_{\dot{O}H_{in}}\right)} = -k_1 dV$$

Note that flow rate, the initial reactant concentrations, and the reaction rate constant are constants. Defining the definite integral, we have:

$$Q\int_{c_{HFC_{in}}}^{c_{HFC}} \frac{d(c_{HFC})}{c_{HFC}\left(c_{HFC} - c_{HFC_{in}} - c_{\dot{O}H_{in}}\right)} = -k_1\int_0^V dV$$

Performing the definite integral yields:

$$\left.\frac{Q\left(\ln\left(-c_{HFC_{in}} + c_{\dot{O}H_{in}} + c_{HFC}\right) - \ln(c_{HFC})\right)}{c_{HFC_{in}} - c_{\dot{O}H_{in}}}\right|_{c_{HFC_{in}}}^{c_{HFC}} = -k_1 V\Big|_0^V$$

Evaluating the expression results in the following:

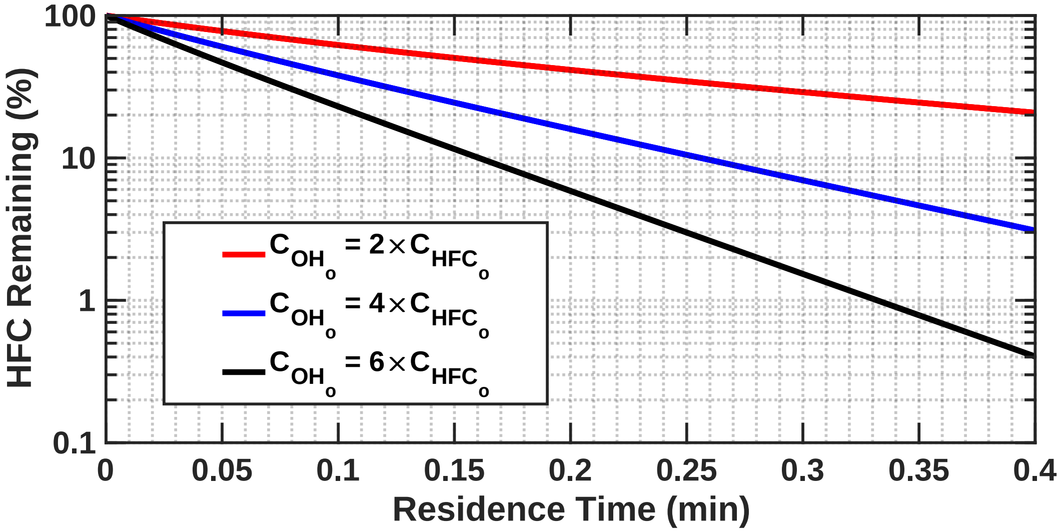

Exhibit A8 – Ideal PFR Dynamics. Modeled HFC degradation at 298 K for three different OH radical starting concentrations. The initial HFC concentration was arbitrarily modeled to be 1×10^{13} molecules cm^{-3}. Residence time was varied by increasing feed flow rate from Q = 0.5 to 100 liters per minute at a constant reactor volume of 0.2 liters.

$$\frac{Q\left(\ln\left(-c_{HFC_{in}} + c_{\dot{O}H_{in}} + c_{HFC}\right) - \ln\left(c_{HFC}\right)\right)}{c_{HFC_{in}} - c_{\dot{O}H_{in}}} - K = -k_1 V$$

where K is a constant of integration determined using the boundary conditions:

$$K = \frac{Q\left(\ln\left(c_{\dot{O}H_{in}}\right) - \ln\left(c_{HFC_{in}}\right)\right)}{c_{HFC_{in}} - c_{\dot{O}H_{in}}}$$

Solving the above equation for HFC concentration as a function of other variables and constants, we find:

$$\boxed{c_{HFC,\,PFR} = \frac{\left(c_{HFC_{in}} - c_{\dot{O}H_{in}}\right) \times e^{\left(k_1 c_{HFC_{in}} V + c_{\dot{O}H_{in}} K\right)/Q}}{e^{\left(k_1 c_{HFC_{in}} V + c_{\dot{O}H_{in}} K\right)/Q} - e^{\left(k_1 c_{\dot{O}H_{in}} V + c_{HFC_{in}} K\right)/Q}}}$$

The model equation demonstrates that the effluent concentration of HFC is determined by initial concentrations, flow rate, PFR volume, and temperature (indirectly through k_1). The dynamics of the PFR are illustrated in Exhibit A8 for three initial OH radical concentrations and a range of flow rates. The PFR is more efficient than the CSTR, even though the volume of the tubular reactor is significantly smaller (0.2 liters versus 20 liters). The increased efficiency of HFC destruction stems from the design of the reactor: due to the gradient in HFC concentration along the flow, HFC molecules in parcels with comparatively lower concentrations of HFC will still react with OH radicals. In the CSTR, the continuous addition of HFC into the well-mixed reactor impedes achieving such a high destruction efficiency.

One interesting note is that the trajectory of HFC concentration in the PFR (Exhibit A8) are identical to the trajectories modeled in the Batch reactor (Exhibit A4). This is an expected result. The gases in plug flow essentially act as if they were in a batch reactor: each parcel experiencing a declining concentration in reactants as the flow progresses through the vessel. In this way, the PFR can be considered as a sort of "continuous batch reactor.

Appendix B:
Financial Model

Exhibit B1: Summary of preliminary costs that were used for the model.

R134 Replacements	Drop-In	Installed Capital Cost	LB Refrig Basis for Capital Cost	Energy Efficiency	Cost ($/lb)	20 Year GWP (Unless noted with * = 100 year GWP due to lack of data)
R134		$ 2,596,576.00	2000	100%	$ 3.18	3830
HFO-1233ze	No	$ 2,596,576.00	2191	100%	$ 27.27	1
R-513a	Potential	$ 20,345.00	2191	96%	$ 13.64	631*
R410A Replacements	Drop-In	Capital Cost	LB Refrig Basis	Energy Efficiency	Cost ($/lb)	GHG Potential
R-410A		$ 2,596,576.00	2000	100%	$ 9.09	4340
R-32	No	$ 2,596,576.00	2000	103%	$ 0.45	2330
R22 Replacements	Drop-In	Capital Cost	LB Refrig Basis	Energy Efficiency	Cost ($/lb)	GHG Potential
R-22		$ 2,596,576.00	2000	100%	$ 4.55	5160
R-424A	Yes	$ 20,345.00	2191	110%	$ 5.16	2440*
R-404A Replacement	Drop-In	Capital Cost	LB Refrig Basis	Energy Efficiency	Cost ($/lb)	GHG Potential
R-404A		$ 2,596,576.00	2000	100%	$ 7.92	6010
R-442A	Yes	$ 20,345.00	2191	140%	$ 5.16	3926
CO2	No	$ 2,660,973.00	2000	95%	$ 0.50	1
R-11 Replacements	Drop-In	Capital Cost	LB Refrig Basis	Energy Efficiency	Cost ($/lb)	GHG Potential
R-11		$ 2,596,576.00	2000	100%	$ 25.75	4750
R-514A	No	$ 2,596,576.00	2000	100%	$ 5.16	2
R-123 Replacements	Drop-In	Capital Cost	LB Refrig Basis	Energy Efficiency	Cost ($/lb)	GHG Potential
R-123		$ 2,596,576.00	2000	100%	$ 27.28	77*
R-514A	Yes	$ 100,000.00	3000	100%	$ 5.16	2

[77][78][79][80][81][82][83][84][85][86][87][88][89]

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Notes: LB Refrigerant Basis is the amount of refrigerant in the system upon which the capital cost in the table was based. Energy efficiency is expressed in % above or below the baseline. 95% indicates that the replacement is 95% as efficient as the existing refrigerant. In other words, it uses 105% more energy than the baseline refrigerant.

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