ODS Destruction in the United States and Abroad

April 2021

EPA 430-R-21-006

Prepared for the U.S. Environmental Protection Agency by ICF

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Acronyms

AC	Air Conditioning
ACR	American Carbon Registry
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
Br	Bromine
CAA	U.S. Clean Air Act
CAR	Climate Action Reserve
CARB	California Air Resources Board
CCl_4	Carbon Tetrachloride
CCX	Chicago Climate Exchange
CFC	Chlorofluorocarbon
CO	Carbon Monoxide
CNCo	China Navigation Company
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTOC	Chemicals Technical Options Committee
DE	Destruction Efficiency
DRE	Destruction and Removal Efficiency
EEA	European Environmental Agency
EOL	End-of-Life
EPA	U.S. Environmental Protection Agency
EPR	Extended Producer Responsibility
EU ETS	European Union Emission Trading System
FTOC	Flexible and Rigid Foams Technical Options Committee
GEF	Global Environment Fund
GHG	Greenhouse Gas
GWP	Global Warming Potential
HBFC	Hydrobromofluorocarbon
HBr	Hydrogen Bromide
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCl	Hydrochloric Acid
HF	Hydrofluoric Acid
HFC	Hydrofluorocarbon
HTOC	Halons Technical Options Committee
HWC	Hazardous Waste Combustor
ICRF	Inductively Coupled Radio Frequency
MCTOC	Medical and Chemicals Technical Options Committee
MeBr	Methyl Bromide
MLF	Multilateral Fund

MOP	Meeting of the Parties
MRR	Mandatory Reporting of Greenhouse Gases Rule
MT CO_2 Eq.	Metric Tons Carbon Dioxide Equivalent
MMT CO_2 Eq.	Million Metric Tons Carbon Dioxide Equivalent
MTOC	Medical Technical Options Committee
ODP	Ozone Depletion Potential
ODS	Ozone-Depleting Substances
ODSTS	ODS Tracking System
PCDD	Polychlorinated Dibenzodioxin
PCDF	Polychlorinated Dibenzofuran
PM	Particulate Matter
POHC	Principal Organic Hazardous Constituent
POP	Persistent Organic Pollutant
QPS	Quarantine and Pre-Shipment
RAD	Responsible Appliance Disposal
RCRA	Resource Conservation and Recovery Act
RMC	Refrigerant Management Canada
RRA	Refrigerant Reclaim Australia
RTOC	Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee
SPREP	Secretariat of the Pacific Regional Environment
TEAP	Technology & Economic Assessment Panel
TFDT	Task Force on Destruction Technologies
TRI	Toxics Release Inventory
UL	Underwriters Laboratories
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
VCS	Verified Carbon Standard (currently known as Verra)
WTE	Waste to Energy

Controlled substances under the Montreal Protocol

Annex A
CFC-11 (Trichlorofluoromethane, $CFCl_3$)
CFC-12 (Dichlorodifluoromethane, CF_2Cl_2)
CFC-113 (Trichlorotrifluoroethane, $C_2Cl_3F_3$)
CFC-114 (Dichlorotetrafluoroethane, $C_2Cl_2F_4$)
CFC-115 (Chloropentafluoroethane, C_2ClF_5)
Halon 1211 (Bromochlorodifluoromethane, $CBrClF_2$)
Halon 1301 (Bromotrifluoromethane, $CBrF_3$)
Halon 2402 (Dibromotetrafluoroethane, $C_2Br_2F_4$)
Annex B
CFC-13 (Chlorotrifluoromethane, $CClF_3$)
CFC-111 (Pentachlorofluoroethane, C_2FCl_5)
CFC-112 (Tetrachlorodifluoroethane, $C_2Cl_4F_2$)
CFC-211 (Heptachlorofluoropropane, C_3Cl_7F)
CFC-212 (Hexachlorodifluoropropane, $C_3Cl_6F_2$)
CFC-213 (Pentachlorotrifluoropropane, $C_3Cl_5F_3$)
CFC-214 (Tetrachlorotetrafluoropropane, $C_3Cl_4F_4$)
CFC-215 (Trichloropentafluoropropane, $C_3Cl_3F_5$)
CFC-216 (Dichlorohexafluoropropane, $C_3Cl_2F_6$)
CFC-217 (Chloroheptafluoropropane, C_3ClF_7)
Carbon Tetrachloride (CCl_4)
Methyl Chloroform (1,1,1-Trichloroethane, $C_2H_3Cl_3$)
Annex C
HCFC-21 (Dichlorofluoromethane, $CHCl_2F$)[a]
HCFC-22 (Chlorodifluoromethane, $CHClF_2$)[a]
HCFC-31 (Chlorofluoromethane, CH_2ClF)
HCFC-121 (Tetrachlorofluoroethane, C_2HCl_4F)
HCFC-122 (Trichlorodifluoroethane, $C_2HCl_3F_2$)
HCFC-123 (Dichlorotrifluoroethane, $C_2HCl_2F_3$)[a]
HCFC-124 (Chlorotetrafluoroethane, C_2HClF_4)[a]
HCFC-131 (Trichlorofluoroethane, $C_2H_2Cl_3F$)
HCFC-132 (Dichlorodifluoroethane, $C_2H_2Cl_2F_2$)
HCFC-133 (Chlorotrifluoroethane, $C_2H_2ClF_3$)
HCFC-141 (Dichlorofluoroethane, $C_2H_3Cl_2F$)
HCFC-141b (1,1-Dichloro-1-fluoroethane, CCl_2FCH_3)[a]
HCFC-142 (Chlorodifluoroethane, $C_2H_3F_2Cl$)
HCFC-142b (1-Chloro-1,1-difluoroethane, $CClF_2CH_3$)[a]
HCFC-151 (Chlorofluoroethane, C_2H_4ClF)
HCFC-221 (Hexachlorofluoropropane, C_3HCl_6F)
HCFC-222 (Pentachlorodifluoropropane, $C_3HCl_5F_2$)
HCFC-223 (Tetrachlorotrifluoropropane, $C_3HCl_4F_3$)
HCFC-224 (Trichlorotetrafluoropropane, $C_3HCl_3F_4$)
HCFC-225 (Dichloropentafluoropropane, $C_3HCl_2F_5$)
HCFC-225ca (3,3-Dichloro-1,1,1,2,2-pentafluoropropane, $CHCl_2CF_2CF_3$)[a]

HCFC-225cb (1,3-Dichloro-1,1,2,2,3-pentafluoropropane, $CHClFCF_2CClF_2$)[a]
HCFC-226 (Chlorohexafluoropropane, C_3HClF_6)
HCFC-231 (Pentachlorofluoropropane, $C_3H_2Cl_5F$)
HCFC-232 (Tetrachlorodifluoropropane, $C_3H_2Cl_4F_2$)
HCFC-233 (Trichlorotrifluoropropane, $C_3H_2Cl_3F_3$)
HCFC-234 (Dichlorotetrafluoropropane, $C_3H_2Cl_2F_4$)
HCFC-235 (Chloropentafluoropropane, $C_3H_2ClF_5$)
HCFC-241 (Tetrachlorofluoropropane, $C_3H_3Cl_4F$)
HCFC-242 (Trichlorodifluoropropane, $C_3H_3Cl_3F_2$)
HCFC-243 (Dichlorotrifluoropropane, $C_3H_3Cl_2F_3$)
HCFC-244 (Chlorotetrafluoropropane, $C_3H_3ClF_4$)
HCFC-251 (Trichlorofluoropropane, $C_3H_4Cl_3F$)
HCFC-252 (Dichlorodifluoropropane, $C_3H_4Cl_2F_2$)
HCFC-253 (Chlorotrifluoropropane, $C_3H_4ClF_3$)
HCFC-261 (Dichlorofluoropropane, $C_3H_5Cl_2F$)
HCFC-262 (Chlorodifluoropropane, $C_3H_5ClF_2$)
HCFC-271 (Chlorofluoropropane, C_3H_6ClF)
HBFCs (Hydrobromofluorocarbons)
BCM (Bromochloromethane, CH_2BrCl)
Annex E
Methyl Bromide (MeBr, CH_3Br)
Annex F
HFC-23 (Trifluoromethane, CHF_3)
HFC-32 (Difluoromethane, CH_2F_2)
HFC-41 (Fluoromethane, CH_3F)
HFC-125 (Pentafluoroethane, C_2HF_5)
HFC-134 (1,1,2,2-Tetrafluoroethane, CHF_2CHF_2)
HFC-134a (1,1,1,2-Tetrafluoroethane, CF_3CH_2F)
HFC-143 (1,1,2-Trifluoroethane, CHF_2CH_2F)
HFC-143a (1,1,1-Trifluoroethane, CF_3CH_3)
HFC-152 (1,2-Difluoroethane, CH_2FCH_2F)
HFC-152a (1,1-Difluoroethane, CHF_2CH_3)
HFC-227ea (1,1,1,2,3,3,3-Heptafluoropropane, C_3HF_7)
HFC-236cb (1,1,1,2,2,3-Hexafluoropropane, $CF_3CF_2CH_2F$)
HFC-236ea (1,1,1,2,3,3-Hexafluoropropane, $CF_3CHFCHF_2$)
HFC-236fa (1,1,1,3,3,3-Hexafluoropropane, $CF_3CH_2CF_3$)
HFC-245ca (1,1,2,2,3-Pentafluoropropane, $CHF_2CF_2CH_2F$)
HFC-245fa (1,1,1,3,3-Pentafluoropropane, $CF_3CH_2CHF_2$)
HFC-365mfc (1,1,1,3,3-Pentafluorobutane, $CF_3CH_2CF_2CH_3$)
HFC-43-10mee (1,1,1,2,2,3,4,5,5,5-Decafluoropentane, $CF_3CF_2CHFCHFCF_3$)

[a] Identifies the most commercially viable substance as prescribed in the Montreal Protocol.

1. Introduction

The *Montreal Protocol on Substances that Deplete the Ozone Layer* (Montreal Protocol), adopted in 1987, is a global agreement to protect the stratospheric ozone layer by phasing out the production and consumption of ozone-depleting substances (ODS). By joining, Parties commit to phasing out specified ODS – chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, carbon tetrachloride (CCl_4), methyl chloroform, methyl bromide (MeBr), bromochloromethane, and hydrobromofluorocarbons (HBFCs) – thereby reducing their abundance in the atmosphere and protecting the Earth's fragile ozone layer. One-hundred-ninety-seven United Nations (UN) Member States have ratified the Montreal Protocol and its first four amendments. On October 15, 2016, the Parties to the Montreal Protocol agreed on the Kigali Amendment to phase down high global warming potential (GWP) hydrofluorocarbons (HFCs), and, as of March 31, 2021, over 115 Parties have ratified, accepted, or approved the Amendment.

The global ODS phaseout is underway; however, there is a large amount of ODS in equipment and products such as refrigerators and air conditioners (as both refrigerant and foam blowing agent), foam contained in buildings, and fire suppression systems and fire extinguishers, as well as in stockpiles held by countries and industrial and commercial users. Collectively, these sources are referred to as ODS banks. Unless properly managed, ODS from these banks could be released to the atmosphere over time through equipment leaks and other intended or unintended releases. The global ODS phaseout of production and consumption does not control emissions at the end of the useful life of these products and equipment, but many countries including the United States have voluntary or regulatory requirements to reduce emissions of ODS. After ODS are recovered and collected, destruction is one of several options. Other options include recycling or reclamation to promote the reuse of these substances. When choosing whether to recycle, reclaim, or destroy ODS, factors to consider include costs and demand for reclaimed or recycled ODS (e.g., for servicing existing equipment).

This report provides information concerning the sources of ODS for destruction in the United States and globally and the technologies, best practices, and challenges for the safe and environmentally sound collection, recovery, transport, and destruction of these substances. In addition, this report provides information on potential costs for the ODS waste management process and discusses the primary funding sources for waste management projects. Historical and current destruction trends for the type and quantity of ODS destroyed in the United States and other countries are analyzed based on available data. Projections of potentially recoverable ODS are estimated to illustrate the volume of available ODS from banks that could be available for destruction. Finally, parallels for collection and disposal of HFCs are discussed.

2. Sources of ODS for Destruction

ODS that are potentially available for destruction originate from a variety of sources. Unwanted and/or contaminated ODS may be contained in old equipment, previously recovered from equipment, or otherwise stored in bulk. Recovered ODS are generally stored in tanks or cylinders in industrial or commercial facilities. Because CFCs and halons have been globally phased out since 2010,[1] production and consumption of some HCFCs[2] has now been phased out by non-Article 5, and ODS are required for servicing legacy equipment, recovered ODS may have market value (depending on the quality of the recovered material, whether a market exists in that location for used ODS, and whether shipment to another location makes economic sense). A significant amount of ODS are recovered and either recycled or reclaimed. While ODS without a market value are good candidates for destruction, ODS with a resale value are less likely candidates for destruction. For instance, used HCFC-22, which as of 2020 is no longer produced in the United States, will likely have a resale value because it will still be required for servicing existing equipment. As another example, production of halon 1301 was phased out globally for fire suppression applications in 2010; however, unless too contaminated for use, recycled halon 1301 continues to be used in important applications such as military legacy equipment, commercial aircraft, and oil and gas facilities.

Box 1. Key Barriers to Recovery and Destruction of ODS

While there may be unwanted ODS that needs to be recovered and properly treated, in different countries there can be informational, financial, technological, logistical, and legal barriers that could stand in the way of effective recovery and destruction. Stakeholder outreach and technician training is essential to ensure persons recovering ODS from equipment or in bulk understand the environmental hazards of ODS and have the necessary technical skills to prevent their release to the environment.

Another barrier is the significant cost associated with specific equipment, training, and infrastructure needed to properly recover, transport, store, and destroy ODS. In some countries, a wide geographic distribution of ODS banks compared to centralized destruction facilities presents a significant obstacle to efficient collection. For countries without domestic facilities, shipping ODS to another country for destruction may present logistical and legal barriers due to international conventions and decisions that regulate the international movement of ODS.

Some ODS with market value may be destroyed because they cannot be feasibly recycled or reclaimed for reuse. In some cases, the market value of the ODS may be lower than the value of carbon offset credits that would be generated from their destruction (see Section 7). There are numerous reasons why recycling or reclamation may not be possible, including contamination (e.g., ODS mixed with non-ODS gases, mixed ODS) or a lack of access to reclamation facilities. In some cases, destruction may be challenging due to barriers that stand in the way of effective collection, recovery, and transportation (see Box 1).

The remainder of this section describes the primary sources of unwanted ODS for destruction, including ODS-containing equipment and bulk ODS stockpiles.

2.1. ODS-Containing Equipment

ODS recovered from equipment during servicing or decommissioning is an important source of ODS for destruction. However, not all ODS can be easily captured and/or made available for destruction. For example, recovering ODS foam blowing agents from building and appliance insulation foams may be difficult and expensive. Similarly, although halon 1211 portable fire extinguishers are a seemingly good source for

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[1] Parties are required, under the Montreal Protocol, to reduce their consumption and production by 100 % (with possible essential use exemptions) of Annex C Group II and III substances by 1996, Group E substance by 2002, and of Annex A and Annex B substances by 2010.

[2] Non-Article 5 countries are required, under the Montreal Protocol, to decrease HCFC consumption and production to at least 99.5 % below baseline levels in 2020.

destruction in many cases given the wide use of other alternatives, there may be instances in which it may not be feasible to collect them because they are widely dispersed and expensive to collect (ICF 2010c).[3]

The feasibility of recovering ODS from equipment depends on a variety of factors including availability of recovery equipment, relative amounts of ODS to be recovered, and technical training. The majority of unwanted ODS that can be most easily recovered from equipment comes from the refrigeration and/or air-conditioning (AC) sector, which primarily includes CFCs and HCFCs, and some from the fire suppression sector, which primarily uses halons. Halons are infrequently available for destruction, as they are often banked and reused in fire suppression equipment to maintain existing systems and fill new systems (see Section 8.2.2).

Within the refrigeration/AC sector, ODS may be recovered for destruction from household appliances (such as refrigerators, freezers, room AC units and dehumidifiers) or from commercial or industrial equipment (such as supermarket refrigeration systems or large building chillers). Because commercial and industrial equipment contains greater amounts of ODS per unit, these applications may provide a larger source of ODS for destruction at a lower level of effort and cost.

ODS-containing foam may also be recovered, particularly from refrigerated appliances; however, this recovery effort may be more expensive and could require a higher level of effort than recovering refrigerant. ODS-containing foam can either be destroyed whole, or the ODS blowing agent may be separated from the foam material using special technology and then reclaimed or destroyed. Although recovery from foams is more complex and expensive than recovery of refrigerants, many countries have continued to promote foam recovery, recognizing the important benefits of avoided ODS emissions from foams to the recovery of the ozone layer. For example, the U.S. Environmental Protection Agency's (EPA) Responsible Appliance Disposal (RAD) Program is a voluntary partnership program to promote proper removal, recovery, and destruction of ODS in refrigerated appliances, including ODS-containing foam. Estimated RAD benefits from proper disposal of 1,000 old refrigerators include 1,920 metric tons carbon dioxide equivalent (MT CO_2 Eq.) avoided foam emissions (EPA 2020a). In 2019, the RAD program partners collected more than 600,000 household refrigeration and air conditioning appliances and achieved a reduction of 2.3 million MT CO_2 Eq. emissions (EPA 2020e). In the European Union, Regulation (EC) 1005/2009 requires that ODS blowing agent be recovered from appliance foam and safely destroyed. The regulation also requires that construction foam be destroyed, although recovery of blowing agent from the foam is optional (EU 2009, European Commission 2019).

2.2. Bulk ODS

Bulk stockpiles of ODS may originate from a variety of sources. For example, small quantities of ODS that have been evacuated from refrigeration/AC or fire suppression equipment during servicing or decommissioning may be consolidated into stockpiles for storage, and ODS refrigerant recovered from large commercial and industrial equipment at service and decommissioning may be collected in sufficient quantities to be considered "bulk" (see Section 8). Some suppliers have active programs to recover material from their customers. The material is analyzed for quality and either recycled or consolidated for destruction. In addition, ODS that has been produced but never used (i.e., virgin material) may also be stored in stockpiles for later use.

As these stockpiles remain in storage, they typically leak, and over time, significant quantities of ODS can be emitted into the atmosphere (ICF 2010c). This is especially the case when ODS are stored in original containers in locations where temperature and moisture are not controlled (e.g., warehouses, fields). To prevent bulked

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[3] Some countries have established national programs to encourage halon recovery, and generally programs that require halon owners to donate substances and pay for destruction have had limited success. Programs offering compensation for the recovery and destruction of halons have higher recovery rates.

ODS from being emitted into the atmosphere, it is important to properly destroy it in a timely manner. Since bulk stockpiles of ODS are already consolidated, collecting ODS from these stockpiles for destruction is generally a cost-effective option.

3. The Process of ODS Destruction: Best Management Practices

The process of ODS waste management includes the collection, storage, consolidation, transportation, and destruction of ODS. Recovery of material begins when ODS are recovered from equipment or stockpiles and ends with the actual destruction. Each of the steps that lead to ultimate destruction should be carried out using practices that aim to prevent fugitive emissions.

After ODS are recovered and collected, or even consolidated, destruction is only one of several options that owners have; ODS can also be sent for recycling or reclamation (see Box 2), or it can be stored indefinitely. When choosing whether to recycle, reclaim, or destroy ODS, factors that are considered include the cost of each option and the demand for reclaimed or recycled ODS (e.g., for servicing existing equipment).

This section provides a guide to best practices for ODS destruction to minimize fugitive emissions and maximize the amount of ODS that is destroyed.

Box 2. ODS Recycling versus Reclamation

Recycling: *To extract ODS from an appliance and clean the ODS for reuse without meeting all of the requirements for reclamation*. In general, recycled ODS are cleaned using oil separation and single or multiple passes through devices, such as replaceable core filter-driers, which reduce moisture, acidity, and particulate matter. These procedures are usually implemented in the field at the job site. In the United States, ODS recovered or recycled from stationary equipment must be returned to the same system or other systems owned by the same person. If the material changes ownership, it must be reclaimed instead.

Reclamation: *To reprocess ODS to a certain purity standard*. Reclamation is required for reuse after resale to distinguish from recycled ODS. The process requires specialized machinery typically not available at a particular job site or automobile repair shop. The technician will recover the ODS and then send it either to a general reclaimer or back to the manufacturer. In the United States, Canada, and Mexico, reclaimed refrigerant must be reprocessed to Air-Conditioning, Heating and Refrigeration Institute (AHRI) Standard 700, which has purity requirements specific to the reclaimed refrigerant (e.g., 99.5 wt% for R-11) as well as other requirements for water content, particulates, turbidity, and acidity (AHRI 2017). In the United States, Canada, and Mexico, reclaimed halon 1211 and halon 1301 must be reprocessed to ASTM D7673 Standard and ASTM D5632 Standard, respectively, which have purity requirements of 99 percent by mole (Robin 2012).

3.1. Recovery and Collection

The first step in performing ODS destruction is the collection and/or recovery of ODS from obsolete or non-repairable appliances, commercial or industrial equipment, or from stockpiles. Recovery of ODS from equipment should be performed by properly trained service technician and consists of the ODS being evacuated and recovered. Evacuation and recovery of ODS from commercial and industrial equipment can generally be performed on site using mobile recovery equipment, whereas recovery of ODS from household appliances is typically performed after transportation of the equipment to a waste facility upon decommissioning. In addition, some facilities have the capability to shred entire refrigeration units, capturing the ODS from foams and cooling systems in a sealed environment.

ODS may also be collected from stockpiles held at industrial facilities or other warehouses. Surplus industrial stocks are likely to be stored in tanks, thus, collection may entail either pick-up or transfer from tank to tank. In general, because of the costs of storage, however, industrial users may limit the length of time that they store large quantities of ODS.

Best Practices: Recovery and Collection

ODS should be recovered from equipment by a properly trained technician using appropriate equipment in order to minimize loss during the evacuation process, estimated at 0.5 percent to 3 percent of the charge for refrigeration/AC equipment (ICF 2010c). *In the United States, technicians must be certified under Title VI of the Clean Air Act (CAA), obtained by passing an EPA-approved exam. In addition, the recovery equipment used for evacuating small appliances must be certified by an EPA-approved certification agency (e.g., AHRI, Underwriters Laboratories (UL), or Intertek).*

3.2. Consolidation and Storage

After ODS has been recovered and collected from household appliances, commercial equipment, and industrial facilities, it is frequently consolidated into a storage tank, utilizing best practices to reduce emissions. This step is undertaken in order to avoid shipping many smaller containers of ODS, which leads to inventory and recordkeeping complications, damage or loss during shipment, and additional transport expenses. After sufficient ODS has been aggregated to constitute a shipment, it may be stored temporarily, awaiting transportation to a destruction facility. This process of consolidation prior to shipment may occur several times at multiple levels of the supply chain (MLF 2008). For example, ODS service companies may consolidate their recovered stocks and send them to an aggregator that further consolidates received stocks into an even larger shipment. During consolidation, the ODS may undergo various tests in order to determine what materials are present and if there are any contaminants.

The storage medium used generally depends on the source of the ODS. ODS recovered from appliances are often transferred to cylinders, each with a capacity of about 14 to 22 liters (L) (about 14 to 23 kilograms (kg)) (MLF 2008). It is likely that a recipient early on in the chain (i.e., one of the first to receive the material) will store the recovered ODS until enough are bulked together for shipment. ODS recovered from bulk and industrial stocks, which typically are recovered in larger quantities, are generally stored in large containers, such as pressure vessels, which range in size from 950 to 1,890 L (holding between 1,000 and 2,000 kg of refrigerant). When sufficient ODS have been aggregated to constitute a shipment, they are often transported in ISO tanks, which can hold approximately 24,000 L (holding about 25,000 kg of refrigerant).

During consolidation, ODS may be transferred between containers using hoses and pumping equipment. A vacuum pump is also used to evacuate the hoses after transfer, in order to prevent the emission of residual gas in the hoses. Depending on the number of times ODS stocks are consolidated, several transfers may be undertaken. During consolidation, the transfer of ODS from one container to another is a potential source for ODS loss. It is estimated that 1 percent to 3 percent of the gas is typically lost during transfer from small cylinders to bulk storage (ICF 2010c).

The containers in which ODS are bulked and stored, such as cylinders and pressure vessels, are also a potential source of leaks. Disposable, or “one-way,” cylinders are expected to fail about 0.8 percent of the time; these cylinders are not designed for long-term storage of ODS. Taking into account the risk of valve leaks, a 2 percent to 3 percent annual leak rate can be assumed for cylinders. However, this leak rate can significantly increase under improper storage conditions; cylinders can easily rust if kept outside, resulting in the entire contents being lost in only four or five years (ICF 2010c). By contrast, failure of pressure vessels is extremely uncommon; the average leak rate has been estimated at 0.025 percent per year (ICF 2010c).

Best Practices: Consolidation and Storage

To avoid losses, the residual refrigerant ("heel") of the cylinder being emptied should be pumped out and all hoses should be fully evacuated following transfer. Transfer equipment should be well maintained, and dry-break coupling should be used for hose connections. Pressure vessels and ISO tanks should be used instead of cylinders when possible. Temporary storage times should be kept to a minimum, and all cylinders should be stored in a safe indoor area with leak monitoring procedures. *In the United States, the Department of Defense (DOD) ODS Reserve Program has instituted a leak monitoring and detection program that minimizes emissions during storage using installed automated leak detection equipment and manual leak monitoring procedures.*

3.3. Transportation

ODS may be transported several times from recovery to ultimate destruction. For example, ODS may be transported from service companies to distributors for consolidation, and then shipped again to the destruction facility. It is also possible that multiple shipments may occur during the consolidation process. International transportation of ODS waste is subject to legal requirements in line with the Basel Convention for transporting hazardous waste (see Appendix A).

ODS are shipped in a variety of container types (e.g., steel cylinders, bulk storage tanks, ISO containers, tanker trucks, rail cars), which can range in size from 14 to 24,000 L (holding between 14 to 25,000 kg). These containers are typically sent either by truck or by rail (MLF 2008). In preparation for shipment, ODS may be transferred to a specific transportation container. Some storage containers, such as smaller 14 kg cylinders, may be transported as-is, without requiring ODS transfer. ISO shipping containers are used for shipping an estimated 50 to 70 percent of all refrigerants delivered to customers and transported for destruction (EIA 2014).

Best Practices: Transportation

Use of an ISO shipping container for transportation of ODS is recommended. Used ODS should be classified with the proper waste code, and shipments should be clearly labeled. Fugitive emissions from the actual transport of the ODS, if done correctly, can be considered negligible. When transferring ODS from pressurized storage into an unpressurized shipping container, however, there is a risk of loss through vent holes, which are used to equalize the pressure as the shipping container is filled. Thus, a closed loop transfer system with dry-break couplings should be used instead. By using these two technologies, a loss of between 0.0004 percent and 0.05 percent can be assumed (ICF 2010c). This leak rate is a substantial reduction from the 5 percent loss experienced without the use of a closed loop system or dry-break couplings (ICF 2010c). *In the United States, the Resource Conservation and Recovery Act (RCRA) waste codes are used to classify hazardous wastes, some of which include ODS (see Appendix B). RCRA facility permits specify what specific hazardous waste codes these facilities are permitted to receive, treat, and/or store, and in what quantities.*

3.4. Destruction

ODS should be destroyed at an approved facility which typically means the collected ODS are transported. In most cases, certified transporters ship consolidated ODS in large containers to the destruction facility. When ODS reaches the destruction facility,[4] the ODS containers are commonly stored for a week to a month before destruction. Prior to destruction, the ODS may undergo additional tests in order to determine what materials are being destroyed and if any contaminants are present in the stocks.

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[4] In some cases, (e.g., a practice in Germany) ODS recovered from household appliances is sent for reclamation prior to destruction since some destruction operators require purified ODS to ensure accurate process control and consistent flow rate (MLF 2008). Process control may be easier if the destruction facility is processing pure compounds rather than ODS mixtures.

Once the contents are confirmed, the ODS may be transferred to a holding tank and fed into the destruction unit;[5] alternatively, it may be fed into the destruction unit directly from the container (i.e., cylinder or ISO-tank) it arrives in. The allowable feed rate of ODS at any hazardous waste combustor (HWC) facility will be site-specific and will be influenced by the design of the unit and the amount of other hazardous wastes being treated at the time. Hazardous waste combustors must be compliant with numerous operating conditions and limits any time hazardous waste is being treated. These include limits on, for example, minimum combustion zone temperature, minimum residence time, maximum waste feed rates, and continuous compliance with a carbon monoxide (CO) limit, which is a measure of incomplete combustion. Commercial hazardous waste combustors can only combust controlled amounts of fluorinated and brominated compounds due to the corrosive nature of the resulting acidic gases (hydrogen fluoride (HF) and hydrogen bromide (HBr)) and the flame quenching nature of bromine- containing ODS.

Best Practices: Destruction

A destruction and removal efficiency (DRE)[6] of 99.99 percent for concentrated sources of ODS and 95 percent for dilute sources of ODS (i.e., foams) is recommended by the Montreal Protocol's Technology & Economic Assessment Panel (TEAP), along with other emissions limits and the use of a Montreal Protocol approved destruction technology. Hazardous waste incinerators generally exceed the TEAP recommendations, often achieving a DRE of up to 99.9999 percent. The DRE can be used to estimate the ODS emitted through exhaust gases. For example, an ODS destruction technology with a DRE of 99.99 percent results in 0.01 percent of ODS emissions. In addition, sampling of ODS shipments should be conducted, and detailed checks of arriving containers should be carried out. The quantity destroyed should be measured or calculated and documented (UNEP 2003). *In the United States, any entity destroying ODS must report the type and quantity of ODS destroyed annually to EPA. EPA requires that destruction be carried out using technologies approved by the Parties to the Montreal Protocol.*

4. ODS Destruction Technologies and Facilities in the United States and Worldwide

This section presents the ODS destruction technologies approved by the Parties to the Montreal Protocol at the 30th Meeting of the Parties (MOP) in November 2018, where Parties agreed, through Decision XXX/6, to further update the list of approved destruction technologies in Previous Decision (i.e., V/26/ VII/35, and XIV/6). This section also presents information on known ODS destruction facilities in the United States and abroad, including the location of facilities and their associated destruction capacities.

4.1. Montreal Protocol-Approved ODS Destruction Technologies

Parties to the Montreal Protocol have taken decisions (e.g., Decision XV/9, Decision XXIII/12, and Decision XXIX/4) that promote the exchange of information on the best technologies for the destruction of ODS. Recently, at the 30th MOP in November 2018, the Parties agreed, through Decision XXX/6, to further update

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[5] According to information from industry representatives, the average rate at which ODS can be fed into an HWC can vary from around 1,000 to 4,000 kg/hour (as compared to the maximum waste feed rate for a rotary kiln unit in Arkansas, which is 93,300 kg/hour, or the maximum rate for a fixed hearth incinerator in Illinois, which is about 12,000 kg/hour). For a 60,000 kg shipment of ODS, this would result in a total destruction time of 15 to 60 hours. For a plasma arc unit, the typical feed rate for ODS is around 20 kg/hour (EPA 2010a).

[6] DRE is a measure of the efficiency of destroying, degrading, and/or removing a chemical in a treatment device (which includes its air pollution control system), prior to being emitted to the atmosphere via the stack. DRE is calculated by feeding a measured mass of chemical into the system and dividing by the mass of that chemical that escapes in the exhaust stream; the percent that has not been emitted is the DRE.

the list of approved destruction technologies (UNEP 2018).[7] For the United States, in 2020 domestic regulations (i.e., 40 CFR 82.3, 82.104, and 82.270) were updated to expand the list of destruction technologies to be consistent with the Montreal Protocol.

While not included in the Montreal Protocol decisions, there are additional criteria discussed in the 2002 TEAP report to evaluate destruction technologies that may be considered by countries for their domestic requirements. These include specifications for:

1.1.1. Destruction and Removal Efficiency (DRE);
1.1.2. Emissions of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)/dioxins and furans, hydrochloric acid (HCl), chlorine (Cl_2), HF, hydrobromic acid (HBr), bromine (Br_2), particulate matter (PM), and CO; and
1.1.3. Technical capability when destroying ODS on a commercial scale.

Table 1 presents the DRE and emission limits recommended by the TEAP (for concentrated ODS).

Table 1: Summary of Technical Performance Qualifications for ODS Destruction[a]

Efficiency/Emission	Diluted Sources	Concentrated Sources
DRE (%)	95	99.99
PCDD + PCDFs (ng-ITEQ/m^3)[b]	0.5	0.2
HCl/Cl_2 (mg/m^3)	100	100
HF (mg/m^3)	5	5
HBr/Br_2 (mg/m^3)	5	5
Total Suspended Particles (mg/m^3)	50	50
CO (mg/m^3)	100	100

Source: TEAP (2018a).

[a] Emission limits are expressed as mass per dry cubic meter of exhaust gas at normal conditions (i.e., 0°C and 101.3 kPa) corrected to 11 percent O_2.

[b] ITEQ refers to the international toxic equivalency used for PCDDs and PCDFs.

ODS destruction technologies can be grouped into three broad categories: Thermal Oxidation (Incineration); Plasma; and Conversion (or Non-incineration) technologies. Within these three categories, 16 technologies were approved for the destruction of concentrated sources of CFCs, HCFCs, methyl chloroform, CCl_4, and methyl bromide. Only six of these technologies were approved for the destruction of concentrated sources of halons, as sufficient evidence was not available for the other technologies to demonstrate that they could effectively destroy halon while meeting the designated criteria (UNEP 2003).

Table 2 summarizes the list of approved technologies for destroying ODS presented in Annex II of the Report of the 30th MOP, as well as nine non-approved technologies that are described in the 2018 reports from the 2018 Task Force on Destruction Technologies (TFDT), a subsidiary body established by TEAP, as being evaluated and potentially approved by the Parties in the future. Most, if not all, of these technologies are known to be used for ODS destruction, either commercially or in demonstrations, in the United States and/or abroad (TEAP 2018a). All technologies are described further in Appendix C.

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[7] Decision XXX/6 can be accessed at: https://ozone.unep.org/treaties/montreal-protocol/meetings/thirtieth-meeting-parties/decisions/decision-xxx6-destruction-technologies-controlled-substances?q=treaties/montreal-protocol/meetings/thirtieth-meeting-parties/decisions/decision-xxx6-destruction#_ftnref1

Table 2. Approval Status of Available Destruction Technologies

Technology	Applicability[a] and Required Destruction and Removal Efficiency (DRE)[b]			
	Concentrated ODS[c]			Dilute ODS[d]
	CFCs, HCFCs, CCl4, methyl chloroform[e] (99.99%)	Halons[f] (99.99%)	Methyl Bromide[g] (99.99%)	Foam (95%)
Thermal Oxidation (Incineration) Technologies				
Cement Kilns	**Approved**	Not Approved	Not Determined	Not Applicable
Gaseous/Fume Oxidation	**Approved**	Not Determined	Not Determined	Not Applicable
Liquid Injection Incineration	**Approved**	**Approved**	Not Determined	Not Applicable
Municipal Solid Waste Incineration	Not Applicable	Not Applicable	Not Applicable	**Approved**
Porous Thermal Reactor	**Approved**	Not Determined	Not Determined	Not Applicable
Reactor Cracking	**Approved**	Not Approved	Not Determined	Not Applicable
Rotary Kiln Incineration	**Approved**	**Approved**	Not Determined	**Approved**
Thermal Decay of Methyl Bromide	Not Applicable	Not Applicable	**Approved**	Not Applicable
Electric Heater	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Fixed Hearth Incinerator	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Furnaces Dedicated to Manufacturing	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Plasma Technologies				
Argon Plasma Arc	**Approved**	**Approved**	Not Determined	Not Applicable
Inductively Coupled Radio Frequency Plasma	**Approved**	**Approved**	Not Determined	Not Applicable
Microwave Plasma	**Approved**	Not Determined	Not Determined	Not Applicable
Nitrogen Plasma Arc	**Approved**	Not Determined	Not Determined	Not Applicable
Portable Plasma Arc	**Approved**	Not Determined	Not Determined	Not Applicable
Steam Plasma Arc	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Air Plasma Arc	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Alternating Current Plasma	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
CO_2 Plasma	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Conversion (Non-Incineration) Technologies				
Chemical Reaction with H_2 and CO_2	**Approved**	**Approved**	Not Determined	Not Applicable
Gas Phase Catalytic De-halogenation	**Approved**	Not Determined	Not Determined	Not Applicable
Superheated Steam Reactor	**Approved**	Not Determined	Not Determined	Not Applicable
Thermal Reaction with Methane	**Approved**	**Approved**	Not Determined	Not Applicable
Catalytic Destruction	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Solid Alkali Reaction	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed

Sources: UNEP (2011), UNEP (2015b), HTOC (2018a), TEAP 2018a, and UNEP (2018).

[a] Not approved indicates the technology was reviewed and did not meet the TEAP recommendations for the process; Not applicable indicates the technology is not feasible for the process; Not determined indicates the technology was not reviewed for destruction of that compound; Not yet reviewed indicates the technology has not been fully reviewed by the Parties to the Montreal Protocol.

[b] Per the TFDT screening process, technologies must be demonstrated to achieve the required DRE while also satisfying emissions criteria. See TEAP (2002) for more information.

[c] Concentrated sources of ODS refer to virgin, recovered, and reclaimed ODS.

[d] Dilute sources of ODS refer to ODS contained in a matrix of a solid (e.g., foam).

[e] Under the Montreal Protocol, these substances are listed in Annex A, Group I; Annex B; and Annex C, Group I.

[f] Under the Montreal Protocol, these substances are listed in Annex A, Group II.

[g] Under the Montreal Protocol, this substance is listed in Annex E, Group I.

There are also facilities in operation around the world that employ technologies that have either not been approved by Parties to the Montreal Protocol or do not meet the eligibility criteria (see Box 3 for an example of one of these other technologies).

Incineration and plasma arc destruction facilities are also capable of accepting HFCs for destruction (see Section 10.1). Tsang et al. (1998) assessed the relative thermal stability of fluorinated compounds, including HFCs, as compared to the thermal stability of chlorinated compounds and concluded that fluorinated compounds can be destroyed at high efficiency by incineration. Modeled required temperatures for destruction of HFCs to 99.99 percent DRE in Tsang et al. (1998) are similar to modeled required temperatures for HCFCs and halons in Lamb et al. (2010) (see Appendix D).

Box 3. Other ODS Destruction Technologies

In addition to the ODS destruction technologies described in Table 2, there are other destruction and emission recapture technologies that are beyond the scope of this report. One example is methyl bromide recapture/destruction systems, which recapture methyl bromide from fumigation applications that can then be recovered and destroyed by chemical conversion or thermally destroyed (e.g., by incineration).

Facilities in California and Florida use an alkyl halide scrubbing system which is able to chemically destroy captured methyl bromide through a proprietary scrubbing process using an aqueous reagent mix that converts methyl bromide to non-hazardous water-soluble products.

4.2. ODS Destruction Facilities in the United States

Destruction facilities in the United States that have destroyed ODS can generally be grouped into three main categories:

1. Those that **commercially** destroy ODS for other companies,
2. Those that destroy ODS generated as a **byproduct or waste stream** of chemical manufacturing or is used on-site in a chemical production process, and
3. Those that burn waste as fuel and receive blended **waste-derived fuel** from outside sources.[8]

In order to identify U.S. facilities that destroy ODS for any of the above purposes, information was collected from the Toxics Release Inventory (TRI) and the ODS Tracking System (ODSTS). The TRI is a database established to provide communities with information about toxic chemical releases in accordance with the 1990 Pollution Prevention Act; established in accordance with the Emergency Planning and Community Right-to-Know Act of 1986; therefore, waste management activities, including the treatment and/or destruction of hazardous waste, must be reported to TRI.[9] The ODSTS is a centralized database maintained by the U.S. EPA of company reported quantities of ODS production, imports, exports, and destruction. In accordance with Article 7 of the Montreal Protocol, Parties are required to report these data to the United Nations Environment Programme (UNEP) Ozone Secretariat each year. The reporting requirements are different between the TRI and the ODSTS, but the information can be combined to generate a clear picture of destruction activities.

Based on data submitted to TRI from 2010 to 2019, over 70 facilities that destroyed ODS hazardous waste were identified.[10] Many of these facilities are chemical manufacturing plants that destroy ODS generated on-site or used on-site in a chemical production process.[11] The ODSTS was referenced to help identify whether companies were destroying ODS commercially. While there are a significant number of non-commercial, non-

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[8] Because most ODS have negligible fuel value and a high halogen content (associated with corrosion and air emissions), the ODS content of waste-derived fuel is expected to be low. Because ODS will effectively dilute the fuel value of waste feed, fuel blending facilities do not typically accept large quantities of ODS for blending with other waste-derived fuel.

[9] TRI reporting exemptions are applied to quantities below 11,340 kg/year for manufacture and processing, or 4,540 kg/year for other use, as well as laboratory activities, and alternative transformation technologies.

[10] Facilities that reported under the TRI categories "treatment" and "energy recovery" were assumed to destroy ODS.

[11] These facilities generally use fume/vapor incinerators or other types of air emissions control devices to destroy ODS.

byproduct destruction facilities in the United States that have destroyed ODS-containing wastes, there are 19 companies that are thought to have destroyed ODS, either received commercially or as ODS-containing waste-derived fuel, in 26 locations across the country. Hereinafter these facilities are referred to collectively as "commercial facilities."

Table 3 lists the technologies, operating companies, facility locations and chemicals processed by commercial destruction facilities reported to the TRI database from 2010-2019.

Table 3. Commercial Destruction Facilities and Technologies in Use in the United States

Facility[a]	Location	Technology in Use[b]	ODS Processed in 2010-2019
A-Gas US Inc.	Bowling Green, OH	Plasma Arc	CFC-11, CFC-12, CFC-113, Halon 1301, Halon 1211, HCFC-22
Ash Grove Cement	Foreman, AR	NA	Methyl Chloroform
Buzzi Unicem USA-Cape Girardeau	Cape Girardeau, MO	NA	CCl_4
Buzzi Unicem USA – Greencastle Plant	Greencastle, IN	NA	Methyl Chloroform
Chemical Waste Management Inc.	Kettleman City, CA	NA	Methyl Chloroform
Chemical Waste Management of the Northwest Inc.	Arlington, OR	NA	CFC-11, CFC-113, CCl_4, Methyl Chloroform
Chill-Tek, Inc.	Las Vegas, NV	Refrigerant Destruction System (RDS©)[c,d]	CFC-11, CFC-12[e]
Clean Harbors Aragonite LLC	Aragonite, UT	Rotary Kiln with Liquid Injection Unit Afterburner	CFC-11, CCl_4, Methyl Chloroform, HCFC-253
Clean Harbors Deer Park LLC	La Porte, TX	Gas/Fume Oxidation (2 units)	CFC-11, CFC-12, CFC-13, CFC-113, CCl_4, MeBr, Methyl Chloroform, HCFC-21, HCFC-22, HCFC-124, HCFC-141b, HCFC-225
Clean Harbors El Dorado LLC	El Dorado, AR	Rotary Kiln Incineration with Single Thermal Oxidation Unit (2 units) and Rotary Kiln Incineration with Secondary Combustion Chamber	CFC-11, CFC-12, CFC-114, CCl_4, HCFC-22, HCFC-142b, HCFC-253, Methyl Chloroform
Clean Harbors Environmental Services Inc.	Kimball, NE	Fluidized Bed Incinerator	CFC-11, CCl_4, Methyl Chloroform
Continental Cement Co LLC	Hannibal, MO	NA	CFC-11, CFC-113, CCl_4, Methyl Chloroform
Eco-Services Operations	Baton Rouge, LA	Liquid Injection Incineration (2 units)	CCl_4
Giant Cement Co.	Harleyville, SC	NA	CCl_4
Heritage Thermal Services	East Liverpool, OH	Rotary Kiln Incineration	CFC-11, CFC-12, CFC-113, CFC-114, CCl_4, MeBr, Methyl Chloroform
Holcim (US) Inc Holly Hill Plant	Holly Hill, SC	NA	Methyl Chloroform
Keystone Cement Co.	Bath, PA	NA	Methyl Chloroform

Table 3. Commercial Destruction Facilities and Technologies in Use in the United States

Facility[a]	Location	Technology in Use[b]	ODS Processed in 2010-2019
LaFarge Midwest Inc. (Including Systech Environmental)	Fredonia, KS	NA	CCl_4
Lehigh Cement Co.	Logansport, IN	NA	Methyl Chloroform
Norlite LLC	Cohoes, NY	NA	CFC-113, CCl_4, Methyl Chloroform
Recleim	Graniteville, SC	Catalytic Destruction[f]	CFC-11, CFC-12, HCFC-22, HCFC-141b[g]
Ross Incineration Services Inc.	Grafton, OH	Rotary Kiln with Liquid Injection Unit	CCl_4, Methyl Chloroform
Safety-Kleen Systems Inc	Smithfield, KY	NA	Methyl Chloroform
Veolia ES Technical Solutions LLC	Sauget, IL	Fixed Hearth Incineration	CFC-12, CFC-113, CCl_4
Veolia ES Technical Solutions LLC Port Arthur Facility	Port Arthur, TX	Fixed Hearth Incineration	CFC-11, CFC-12, CFC-113, CCl_4, HCFC-21, HCFC-22, HCFC-123, HCFC-142b, Methyl Chloroform
Wayne Disposal Inc.	Belleville, MI	NA	CFC-11

Sources: EPA (2020d), EPA (2018c), and ICF (2009a).

NA = Not available.

[a] Facility names listed are from the latest TRI report; however, they may vary throughout report years.

[b] Technologies that are not present in the list of Montreal Protocol approved destruction processes are described in Appendix C.

[c] Chill-Tek, Inc. (2020a).

[d] The RDS© system used by Chill-Tek, Inc. destroys ODS through incineration (Chill-Tek, Inc. 2020b).

[e] Chill-Tek, Inc. began destroying "ODS and other mixed HCFC and HFC refrigerant[s]" that cannot be reclaimed in 2015 (Chill-Tek, Inc. 2020b). Chill-Tek, Inc. primarily destroys CFC-11 and CFC-12 (Chill-Tek, Inc. 2020b).

[f] Recleim is a de-manufacturing company that receives shipments of old appliances (refrigerators, freezers, dehumidifiers, and AC units) and processes them in a plant that employs a combination of physical destruction technologies and catalytic destruction in a closed loop system. This system avoids the leakage to the environment that can occur during de-manufacturing of appliances and shipment of ODS (Sirkin 2016).

[g] Based on the refrigerants and foam blowing agents recovered by RAD partners.

In addition to those facilities that destroy ODS commercially, Table 4 lists destruction companies that report on-site ODS destruction from 2010 to 2019 either as a by-product of fluorochemical manufacture or when it is used as raw material in a manufacturing process. Facilities that destroy ODS-containing byproducts from chemical manufacture generally do not have the capacity, infrastructure, or permitting to accept ODS wastes generated offsite. Some of these facilities have indicated that they do accept offsite waste for destruction, but only wastes generated at other facilities operated by the same entity. ODS destruction units at these facilities may have additional capacity available to destroy ODS generated by other entities, but the facilities may not have adequate hazardous waste storage and handling infrastructure or the appropriate regulatory permits to do so.

Table 4. Facilities that Destroy Byproduct ODS or Utilize Raw Material ODS in the United States (Non- Commercial)

Facility[a]	Location	Technology in Use[b]	ODS Processed in 2010-2019
3M Cottage Grove Center	Cottage Grove, MN	NA	HCFC-142b
Arkema Inc.	Calvert City, KY	Liquid Injection Incineration	HCFC-22, HCFC-124, HCFC-132b, HCFC-133a, HCFC-141b, HCFC-142b, Methyl Chloroform
Axiall LLC	Plaquemine, LA	Fume/Vapor	CCl_4, Methyl Chloroform
BASF Corp.	Geismar, LA	NA	CCl_4
BASF Corp. – Hannibal Site	Palmyra, MO	NA	MeBr
BAYER Cropscience	Kansas City, MO	Fume/Vapor	MeBr
Blue Cube Operations LLC – Plaquemine Site	Plaquemine, LA	NA	CCl_4, MeBr
BP AMOCO Chemicals	Decatur, AL	Fume/Vapor	MeBr
BP Chemical Co. – Cooper River Plant	Wando, SC	Other Incineration/Thermal treatment	MeBr
Calgon Carbon Corp	Catlettsburg, KY	NA	CCl_4
Chemours Belle Plant	Belle, WV	Fume/Vapor	CCl_4
Chemours Co.	Gregory, TX	NA	CFC-113, CFC-114, CFC-115, HCFC-124, CCl_4
Chemours El Dorado	El Dorado, AR	NA	CCl_4
Chemours Washington Works	Washington, WV	Other Incineration/Thermal Treatment	CFC-114, HCFC-22, HCFC-124, HCFC-124a
Daikin America Inc.	Decatur, AL	NA	HCFC-22, HCFC-124, HCFC-124a
DAK Americas LLC – Columbia Site	Gaston, SC	NA	MeBr
DDP Specialty Electronic Materials US Inc. - Plaquemine Met	Plaquemine, LA	NA	CCl_4
Dover Chemical Corp	Dover, OH	NA	CCl_4
Dow Agrosciences LLC	Pittsburg, CA	Liquid Injection Incineration	CCl_4
Dow Chemical Co. Freeport Facility	Freeport, TX	Rotary Kiln with Liquid Injection Unit	CFC-12, CCl_4, MeBr, Methyl Chloroform, HCFC-22
Dow Chemical Co. Louisiana Operations	Plaquemine, LA	Other Rotary Kiln	CCl_4, MeBr
		Rotary Kiln with Liquid Injection Unit	
		Other Incineration/Thermal Treatment	
DuPont Sabine River Works	Orange, TX	Rotary Kiln with Liquid Injection Unit	CCl_4
Eagle US 2 LLC	Westlake, LA	Liquid Injection Incineration	CCl_4, Methyl Chloroform
		Fume/Vapor	
Eastman Chemical Co. South Carolina Operations	Gaston, SC	Other Incineration/Thermal Treatment	MeBr

Table 4. Facilities that Destroy Byproduct ODS or Utilize Raw Material ODS in the United States (Non- Commercial)

Facility[a]	Location	Technology in Use[b]	ODS Processed in 2010-2019
Eastman Chemical Co. Tennessee Operations	Kingsport, TN	Rotary Kiln with Liquid Injection Unit Other Incineration/Thermal Treatment	MeBr
Evoqua Water Technologies LLC	Parker, AZ	NA	CCl_4
Evoqua Water Technologies Darlington Facility	Darlington, PA	NA	CFC-11, CCl_4, Methyl Chloroform
Flint Hills Resources Joliet LLC	Channahon, IL	Fume/Vapor	MeBr
Formosa Plastics Corp. Louisiana	Baton Rouge, LA	Fume/Vapor	CCl_4, Methyl Chloroform
Formosa Plastics Corp. Texas	Point Comfort, TX	NA	CCl_4
GB Biosciences Corp.	Houston, TX	Fume/Vapor	CCl_4
Georgia Gulf Lake Charles LLC	Westlake, LA	Fume/Vapor	CCl_4
Honeywell International Inc. Geismar Plant	Carville, LA	Other Incineration/Thermal Treatment	CFC-13, CFC-113, CFC-114, CFC-115, HCFC-22, HCFC-124, HCFC-124a, HCFC-133a
Honeywell International Inc. Baton Rouge Plant	Baton Rouge, LA	NA	HCFC-22
Indorama Ventures Xylenes and PTA LLC	Decatur, AL	NA	MeBr
Ineos Joliet LLC	Channahon, IL	NA	MeBr
Mexichem Fluor Inc.	Saint Gabriel, LA	Other Incineration/Thermal Treatment	HCFC-22
Occidental Chemical Corp.	Wichita, KS	Fume/Vapor	CCl_4
Occidental Chemical Corp.	Gregory, TX	Fume/Vapor Liquid Injection Incineration	CCl_4
Occidental Chemical Holding Corp. – Geismar Plant	Geismar, LA	Liquid Injection Incineration	CCl_4
Olin Blue Cube Freeport TX	Freeport, TX	NA	CCl_4, MeBr
Oxy Vinyls LP Deer Park VCM Plant	Deer Park, TX	Fume/Vapor	CCl_4
Oxy Vinyls LP La Porte VCM Plant	La Porte, TX	Fume/Vapor	CCl_4
Rubicon LLC	Geismar, LA	Fume/Vapor	CCl_4
Shintech Plaquemine Plant	Plaquemine, LA	NA	CCl_4
Solvay Specialty Polymers USA LLC	Thorofare, NJ	Liquid Injection Incineration	HCFC-141b, HCFC-142b
Spruance Plant	Richmond, VA	NA	CFC-11
Syngenta Crop Protection LLC Saint Gabriel Facility	Saint Gabriel, LA	Gas/Fume Oxidation	CCl_4
US Magnesium LLC	Grantsville, UT	NA	CCl_4
Velsicol Chemical LLC	Memphis, TN	Liquid Injection Incineration	CCl_4

Table 4. Facilities that Destroy Byproduct ODS or Utilize Raw Material ODS in the United States (Non- Commercial)

Facility[a]	Location	Technology in Use[b]	ODS Processed in 2010-2019
Westlake Lake Charles North	Westlake, LA	NA	CCl_4
Westlake Vinyls Co.	Geismar, LA	Fume/Vapor	CCl_4
Westlake Vinyls Inc.	Calvert City, KY	Other Incineration/Thermal Treatment	CCl_4

Source: EPA (2020d).
NA = Not Available.
[a] Facility names listed are from the latest TRI report; however, they may vary throughout report years (e.g., Dow/DuPont Chemical Co. to Dow Chemical Co.).
[b] Information on destruction technologies is taken from pre-2005 TRI reports, as available; starting in 2005, TRI no longer required companies to report this information.

Approximately 83 percent of the facilities in Table 4 reported destruction of CCl_4 and/or methyl bromide to the TRI between 2010 and 2019. Additionally, CFCs and HCFCs used as feedstocks to produce HFCs, fluoropolymers, and other ODS may generate *de minimis* amounts of ODS containing waste which may be subject to reporting under TRI in that the waste stream (containing trace quantities of ODS) may be required to be sent for destruction to a third party or destroyed on-site (see Box 4).

4.3. Capacity of U.S. Destruction Facilities

The capacity for hazardous waste incineration at U.S. commercial HWC facilities varies greatly, from about 500 kg/hour to about 14,000 kg/hour. On an annual basis, total destruction capacity for a single facility can be upwards of 40,000 metric ton (MT) of material per year. However, this capacity does not directly translate to a facility's potential capacity to destroy ODS, because all facilities (with the exception of the plasma arc facility) process ODS as a small part of a much larger variety of hazardous wastes.

In 2017, according to EPA's National Biennial RCRA Hazardous Waste Report, 3,307,000 MT of hazardous wastes were destroyed in the United States (EPA 2018b),[12] compared to approximately 2,581 MT of ODS destroyed in that year. In 2017, ODS destruction volumes were less than 0.1% of hazardous waste destruction and as such, there is no expected need for additional facilities to meet ODS destruction demand. However, it is expected that in the event of a surge in need for ODS destruction, there is significant available capacity in facilities that do not have RCRA permits. These facilities, many of which are cement kilns that destroy non-hazardous waste, could be retrofitted and apply for permits to accept ODS.

The plasma arc unit in Bowling Green, OH, is the only destruction facility in the United States currently dedicated to destroying ODS, including CFCs, HCFCs, and halons, but the facility has also investigated using the unit to destroy other wastes. The facility does not have a

Box 4. Companies That Destroy ODS But Do Not Report to the TRI

In addition to the ODS destruction facilities identified in Table 3 and Table 4 based on the TRI database, several other types of companies reported destruction activities to the ODSTS. These are:

- Pharmaceutical Companies
- Laboratories
- Semiconductor Manufacturers
- Specialty Chemical Manufacturers

These companies may not report to the TRI database for several reasons (e.g., due to threshold limits, laboratory activity exemptions, or alternative transformation technologies used), but limited information is available.

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[12] This includes hazardous wastes that were destroyed by the following management methods: incineration (H040), defined as "thermal destruction other than use as a fuel"; energy recovery (H050), defined as "used as fuel (includes on-site fuel blending before energy recovery)"; and fuel blending (H061), defined as "waste generated either onsite or received from offsite" (see Appendix B).

RCRA permit, so any waste they destroy must be classified as non-hazardous. The capacity of the plasma arc unit ranges from 34 to 36 kg/hour of a 100 percent ODS feed, and they have indicated that additional units could be added to meet requirements for additional capacity.

4.4. International ODS Destruction Facilities and Technologies

In 2008, about 155 destruction facilities were known to be in operation in 28 countries around the world (MLF 2008). While there has not been a comprehensive study to update this list since 2008, there are some known cases of new facilities or facilities that stopped destroying commercially. For example, a retrofit cement kiln in Cuba, a retrofit rotary kiln in Colombia, and new destruction technologies in Brazil have all recently begun operation with assistance by the United Nations Development Programme (UNDP) (Alves 2015). Conversely, at least one facility has stopped accepting ODS on a commercial scale: the rotary kiln in Swan Hills, Alberta, Canada.

Japan operates approximately 80 ODS destruction facilities with a mixture of incineration, plasma arc, and non-incineration technologies. The Japanese Ministry of Environment has provided assistance to other countries seeking to construct or retrofit their own destruction equipment.

Table 5 lists countries with known commercial destruction facilities, as well as the type of technologies they use, their capacities to destroy ODS, destruction costs in U.S. dollars.[13] Data on the amounts of ODS destroyed at each facility are not readily available.

Table 5. Commercial Destruction Facilities and Technologies around the World

Country	Number of Known ODS Destruction Facilities in Operation	Known Technologies Utilized	ODS Destruction Capacity	Typical Destruction Costs (US$)
1. Algeria	1	Cement Kiln	NA	NA
2. Argentina	2 or more	NA	NA	NA
3. Australia	2	Argon Plasma Arc (1) Cement Kiln (1)	600 MT/year	$7/kg
4. Austria	1	NA	NA	NA
5. Belgium	2	Rotary Kiln	NA	NA
6. Brazil	4 or more	Rotary Kiln Cracking Reactor Argon Plasma Arc Chemical Reaction with H_2 and CO_2	NA	NA
7. Canada	1	Rotary Kiln	Not accepting ODS for commercial destruction	$12/kg
8. China	5	Plasma technology (1) Rotary Kiln (3) Local hazardous waste facility (1)	NA	Rotary kiln: $8-13/kg[a]
9. Colombia	1	Rotary Kiln	NA	High temperature incineration: $5-6/kg[a]
10. Cuba	1	Cement Kiln	NA	NA

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[13] Estimated costs here and throughout the report have not been adjusted to account for inflation because the costs are typical and expected to shift as the market fluctuates and operational costs change.

Table 5. Commercial Destruction Facilities and Technologies around the World

Country	Number of Known ODS Destruction Facilities in Operation	Known Technologies Utilized	ODS Destruction Capacity	Typical Destruction Costs (US$)
11. Czech Republic	1	Rotary Kiln	40 MT/year	NA
12. Denmark	4	Catalytic Cracking	NA	NA
13. Estonia	1	NA	NA	NA
14. Finland	1	Rotary Kiln	545 MT/year	NA
15. France	2	NA	NA	NA
16. Germany	7	Hazardous Waste Incinerator Reactor Cracking Porous Reactor	1,600 MT/year[b] (Reactor Cracking)	NA
17. Hungary	5	Rotary Kiln Liquid Injection Incineration	75 MT/year[c] (Rotary Kiln) 13 MT/year (Liquid Injection Incineration)	NA
18. Indonesia	1	Cement kiln	600 MT/year	NA
19. Italy	12	NA	NA	NA
20. Japan	80	Cement Kilns/Lime Rotary Kilns (7) Nitrogen Plasma Arc (8) Rotary Kiln Incineration/ Municipal Solid Waste Incinerators (24) Liquid Injection Incineration (7) Microwave Plasma (5) Inductively Coupled Radio Frequency Plasma (1) Gas-Phase Catalytic Dehalogenation (1) Superheated Steam Reactors (25) Solid-Phase Alkaline Reactor (1) Electric Furnace (1)	36 MT/year (one catalytic facility) 2,600 MT/year[b] (one incinerator)	Rotary Kilns: $4/kg Superheated Steam: $5/kg Plasma Arc: $9/kg Reactor Cracking: $4-6/kg Gas Phase Catalytic Dehalogenation: $5-7/kg
21. Mexico	2	Plasma Arc Cement Kiln	NA	Plasma Arc: $8/kg[a] Cement Kiln: $6/kg[a]
22. Netherlands	6	NA	NA	NA
23. Nigeria	1	Rotary Kiln	NA	$30/kg[a]
24. Poland	1	NA	NA	NA
25. Slovakia	1	NA	NA	NA
26. Spain	1	NA	NA	NA
27. Sweden	4	Air Plasma, among others	100 MT/year	NA
28. Switzerland	4 or more	Rotary Kiln, among others	910 MT/year[b] (Rotary Kiln) > 320 MT/year (others)	NA

Table 5. Commercial Destruction Facilities and Technologies around the World

Country	Number of Known ODS Destruction Facilities in Operation	Known Technologies Utilized	ODS Destruction Capacity	Typical Destruction Costs (US$)
29. United Kingdom	2	High-Temperature Incineration	NA	NA
30. United States	11	Rotary Kilns Plasma Arc Fixed Hearth Units Liquid Injection Units Cement Kilns Lightweight Aggregate Kilns	318 MT/year (Plasma Arc)	$2 - $13/kg
31. Venezuela	2 or more	NA	NA	NA

Sources: ICF (2010c), Alves (2014), UNEP (2015b), Government of Australia (2020), and MLF (2018b).
NA= Not available.
[a] Destruction cost calculated based on actual ODS destroyed and not destruction capacity (MLF 2018b).
[b] Capacity is not specific to ODS; value shown refers to capacity for all hazardous wastes and/or other types of wastes.
[c] Number represents approximate ODS destruction capacity based on known overall plant capacity and typical ODS feed rates for rotary kilns.

5. International Efforts to Destroy ODS

Twelve Article 5 parties and twenty-two non-Article 5 parties reported an estimated 57,800 MT of ODS destruction[14] to UNEP between 2009 and 2019 (UNEP 2020). ODS destruction in Article 5 parties (over 7,200 MT of ODS from 2009 to 2019) is significantly lower than in non-Article 5 parties (over 50,500 MT of ODS from 2009 to 2019). In 2009, Article 5 parties reported total annual destruction of approximately 5,800 MT, more than 12 times the amount reported in other years between 2009 and 2019. The larger destruction in 2009 is primarily a result of an increase in CFC destruction in Romania, which accounted for approximately 99% of all ODS destruction by A5 countries in 2009. Non-Article 5 parties reported total annual destruction volumes ranging from approximately 5,000 MT in 2009 to more than 8,000 MT in 2019. The large destruction volume in 2019, is primarily the result of the destruction of approximately 4,000 MT of CCl_4 by France, twice as much as in previous years, and made up almost half of all ODS destroyed in non-Article 5 countries in that year. Figure 1 shows global ODS destruction from 2009 to 2019.

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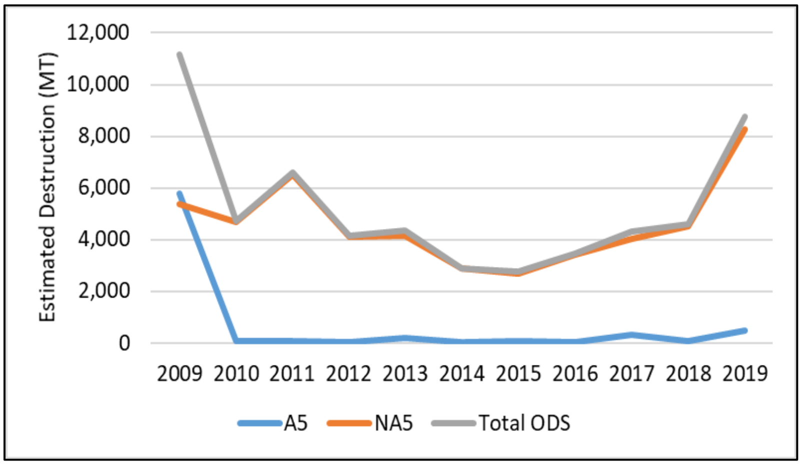
[14] ODS destruction estimates determined based on negative ODS production, a detailed description of the methodology used to calculate the quantity of ODS destroyed is explained in detail in Section 5.4 below.

Figure 1. Estimated Global ODS Destruction (MT)



Source: UNEP (2020).

The remainder of this section presents ODS destruction data from U.S., European, and Japanese government agencies in addition to estimates of CFC and halon destruction in other Article 5 and non-Article 5 countries.

5.1. United States

Under Title 40, Part 82 of the Code of Federal Regulations (CFR), the U.S. EPA requires that any person who destroys a Class I or Class II ODS controlled substance reports the name and quantity of the substance destroyed for each control period to the ODSTS in quarterly and annual reports. The ODSTS data are evaluated, aggregated, and are included as part of the United States' annual reporting consistent with Article 7 of the Montreal Protocol.

In addition, under Title 40, Part 372 of the CFR, the U.S. EPA tracks the management of toxic chemicals, including ODS from certain sources, and requires facilities in certain industry sectors to report annually on the volume of toxic chemicals managed as waste. The volume of ODS destroyed falls under the TRI categories of "energy recovery," which can include combustion of chemicals in an industrial furnace or boiler, and "treatment" which includes methods such as incineration and chemical oxidation (EPA 2018a). These methods result in varying degrees of destruction of the chemicals.

5.1.1. Reported Amount and Type of ODS Destroyed

As shown in Figure 2 destruction of ODS in the United States has decreased from 2010 to 2018 by over 40 percent, with the greatest reduction in the quantity of Class I ODS[15] destroyed. Class I ODS destruction has decreased by 45 percent in this period, from a total of approximately 3,690 MT in 2010 to approximately 2,030 MT in 2018. Class II ODS[16] destruction has varied but remained relatively stable since 2010 with a maximum of 749 MT of destruction in 2010 and a minimum of 437 MT of destruction in 2013.

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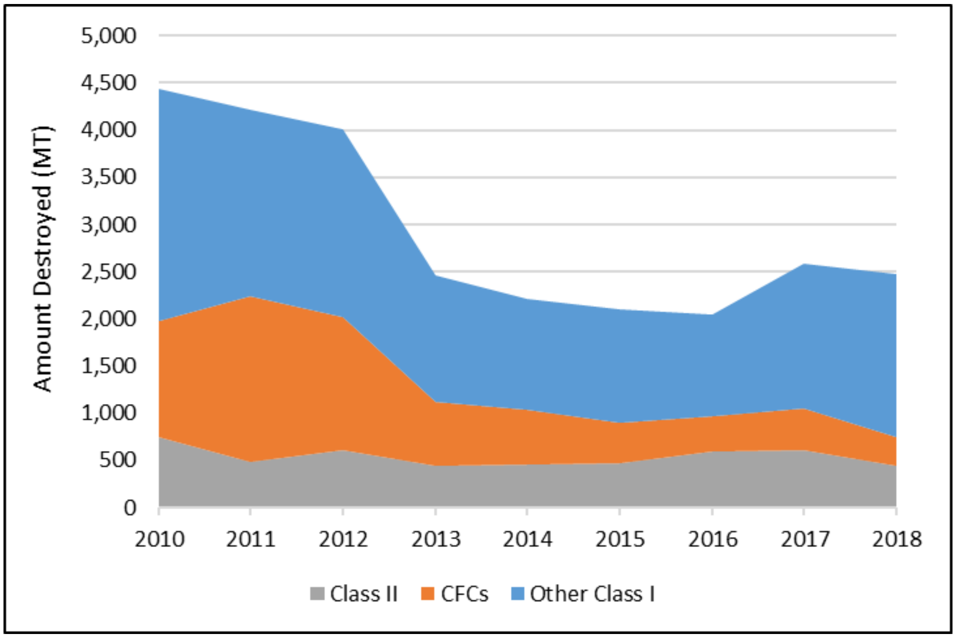
[15] Per 40 CFR 82, Class I chemicals include chemicals listed under Montreal Protocol Annex A Group 1 (CFCs) and Group 2 (halons); Annex B Group 1 (CFCs), Group II (CCl_4), and Group III (methyl chloroform); Annex C Group II (HBFCs); and Annex E Group I (MeBr).

[16] Per 40 CFR 82, Class II chemicals include chemical listed under Montreal Protocol Annex C Group I (HCFCs).

Figure 2. U.S. Destruction of Class I and Class II ODS (2010-2018)[a]



Source: EPA (2019).

[a] "Other Class I" includes CCl_4.

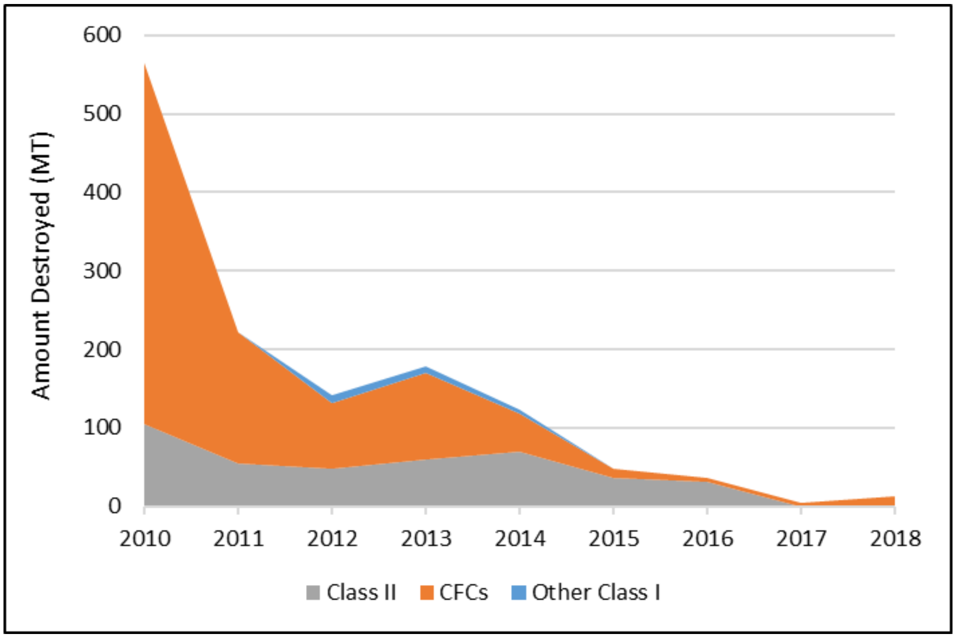
5.1.2. Reported ODS Imported for Destruction

ODS may be imported for destruction as a result of equipment decommissioning, unwanted stockpiles, or mixed substances. For instance, many U.S. companies assist other countries in the decommissioning of ODS-containing equipment that is being phased out. Once the equipment has been decommissioned and the ODS recovered, companies might export the ODS to the United States for destruction, especially if the country where the ODS originated does not have destruction capabilities or wants to earn offset credits on the voluntary carbon exchanges, such as Verra (formerly the Verified Carbon Standard or VCS) or the Climate Action Reserve (CAR). ODS may also arrive in the United States in the form of mixtures from other countries. Bulk refrigerant and halon waste are occasionally mixed for consolidation purposes and shipped to the United States for destruction.

Current EPA regulations govern the import of used and virgin ODS for the sole purpose of destruction, through a shipment-by-shipment petition process petition process called a Certification of Intent to Import ODS for Destruction (40 CFR Part 82, 85 FR 15258). Additionally, the Basel Convention regulates the shipment of ODS across international boundaries (see Appendix A). ODS importers are required to submit a copy of the destruction verification within 30 days after the destruction is complete (40 CFR Part 82, 85 FR 15258).

The reported import of all ODS for destruction in the United States has decreased from 2010 to 2018 by 98 percent. In this period, the quantity of Class I ODS imported for destruction decreased by 97 percent, from a total of approximately 460 MT in 2010 to less than 15 MT in 2018. Approximately 97 percent of all Class I ODS imported for destruction throughout this period were CFCs. Similarly, Class II ODS imports for destruction have decreased greatly in this period, from 105 MT in 2010 to zero MT in 2017 and 2018. Figure 3 below presents the reported quantity of ODS imported for destruction from 2010 to 2018.

Figure 3. Imports for Destruction of Class I and Class II ODS (2010-2018)[a]



Source: EPA (2019).

[a] "Other Class I" includes CCl_4.

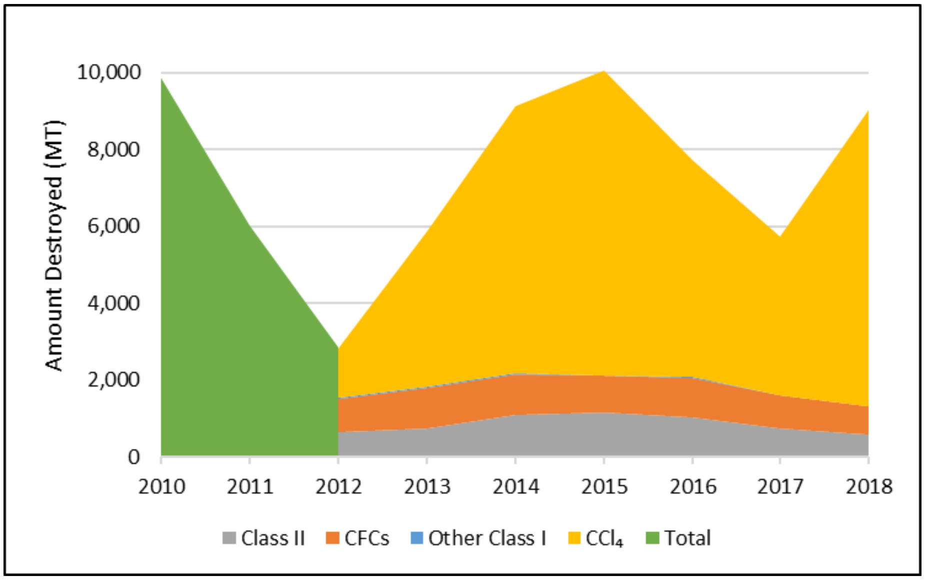
5.2. European Union

5.2.1. Reported Amount and Type of ODS Destroyed

As shown in Figure 4, the total destruction of ODS in the European Union decreased from 2010 to 2012, increased from 2012 to 2015, and decreased in 2016. The initial decrease is a result of the stockpiling of CCl_4 produced as an unintentional by-product from 2010 to 2012, and the subsequent destruction of the stockpiles in 2013. Since 2012, the stockpiling of CCl_4 has ceased which has increased destruction activity, but it should also be noted that the unintentional by-production of CCl_4 has decreased since 2013. Unintentional production of CCl_4 decreased by 5% between 2017 and 2018 (EEA 2019) driving a decrease in ODS destruction.

From 2013 to 2016, approximately 75 percent of all the ODS destroyed in the European Union was CCl_4 (exact data is not available from 2010 to 2011) which accounts for the increase in Europe's destruction activity during this time. In 2018, CCl_4 destruction accounted for 85% of total ODS destruction in that year. Figure 4 also illustrates that although the destruction of CFCs and Class II ODS are similar, the destruction of CFCs decreased in 2015 while the destruction of Class II has been increasing since 2012. Table 6 presents the total quantity of ODS destroyed in the European Union from 2010 to 2016 as well as the quantity of CFCs, CCl_4, halons, and Class II destroyed from 2012 to 2016.

Figure 4. Destruction of Class I and Class II ODS in the EU (2010-2018)[a]



Sources: EEA (2012), EEA (2013), EEA (2014), EEA (2015), EEA (2016), EEA (2017), EEA (2018), and EEA (2019).

[a] Values for 2017 are from EEA (2018) which are underestimated since the total ODS destruction value for 2017 varied significantly from EEA (2018) to EEA (2019).

Table 6. ODS Destroyed in the EU (MT) (2010-2018)[a]

Chemical	2010	2011	2012	2013	2014	2015	2016	2017	2018
CFCs	NA	NA	868	1,060	1,061	957	1,030	858	739
CCl_4	NA	NA	1,275	4,036	6,946	7,955	5,633	4,129	7,708
Halons	NA	NA	31	14	22	C	32	NA	C
Other Class I[b]	NA	NA	35	36	35	52[c]	23	NA	C
Total, Class I	NA	NA	2,210	5,145	8,063	8,965	6,719	4,987	8,447
Total, Class II	NA	NA	635	738	1,102	1,143	1,034	735	578
Total, All ODS	9,863	6,016	2,845	5,882	9,969	10,439	7,753	9,743	9,056

Sources: EEA (2012), EEA (2013), EEA (2014), EEA (2015), EEA (2016), EEA (2017), EEA (2018), and EEA (2019).

NA = Not available. C = Confidential.

[a] The chemical breakout data in this table for 2012 to 2018 are sourced directly from the European Environment Agency's Ozone-Depleting Substances annual reports for those years (EEA 2012-2019). The total values for 2010 to 2011 are sourced exclusively from the 2016 report as the 2010 to 2011 numbers have been updated in the 2016 report (EEA 2017). The total values for 2012 to 2018 are sourced exclusively from the 2019 report as the 2012 to 2018 numbers have been updated in the 2019 report (EEA 2019).

[b] "Other Class I" includes other CFCs, HBFCs, methyl bromide, and methyl chloroform.

[c] "Other Class I" includes other CFCs, HBFCs, methyl bromide, methyl chloroform, and halons.

5.2.2. Reported ODS Imported for Destruction

Per Regulation (EC) No 1005/2009 of the European Parliament and of the Council on substances that deplete the ozone layer, imports of controlled substances (ODS) are prohibited, with several exceptions including imports of controlled substances for destruction. However, all imports of controlled substances, including for destruction, require a license. In Europe, the majority of ODS imported are intended for use as feedstock or re-export for refrigeration. Table 7 shows the volume of ODS imported relevant for consumption and the percent of the total volume of imported ODS that could be destroyed. The European Environment Agency (EEA) has not specified the intended use of the remaining material, but the quantity remaining which could be for destruction decreased from 2012 to 2016 and remained constant in 2017 and 2018.

Table 7. ODS Imported in the EU (MT) (2012-2018)[a]

Chemical	2012	2013	2014	2015	2016	2017	2018
Total Imported	9410	8461	6843	6046	5127	6287	8712
Imported relevant for consumption	3844	3149	2142	550	423	502	504
Percent intended for feedstock use, process agents, quarantine and pre-shipment (QPS) service	59%	63%	69%	91%	92%	92%	94%

Source: EEA (2019).

Transfers of ODS between European countries do not require licenses, so some European countries with destruction capabilities such as France, Germany, and the United Kingdom receive ODS both in bulk and in equipment (e.g., whole refrigerators) for destruction from other European countries that lack destruction capacity (MLF 2008) (see Box 5).

Box 5. European Union Import of ODS from Georgia

A recent Multilateral Fund (MLF) project in the country of Georgia, *Pilot demonstration project for ODS waste management and disposal*, demonstrated the potential to overcome barriers to the destruction of unwanted ODS through synergies between ODS and persistent organic pollutant (POP) disposal processes. Under the Stockholm Convention, Georgia is obliged to destroy hazardous waste including POPs, so the MLF project identified a waste subcontractor to collect, aggregate, pack, and transport the ODS and POPs together to a destruction facility in France, which allowed for overall savings and increased efficiency. With MLF funding, the project disposed of 1.2 MT of unwanted ODS wastes and Georgia is in the process of establishing a National Environmental Fund to fund future exports of ODS waste (MLF 2017a).

5.3. Japan

5.3.1. Reported Amount and Type of ODS Destroyed

In Japan, CFCs and HCFCs are controlled and they must be recovered from home appliances, cars, and commercial equipment when the equipment containing these gases is decommissioned. According to the *Law Concerning the Recovery and Destruction of Fluorocarbons*, recovered refrigerants must be either recycled or destroyed.

Approximately, 85 percent of recovered CFCs and 64 percent of recovered HCFCs were destroyed in 2019 (Japan MOE 2020). As shown in Figure 5, the total destruction of ODS in Japan stayed constant at 2,500 MT from 2010 to 2015 and decreased in 2016 to 2018.[17]

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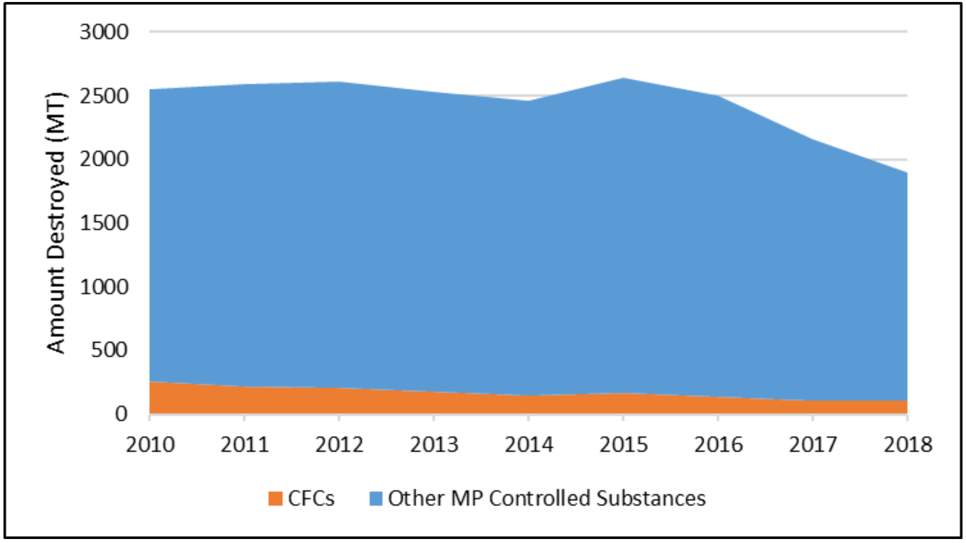
[17] It is assumed that controlled substance destruction reported to UNEP is for ODS destruction.

Figure 5. Destruction of ODS in Japan (2010-2018)



Source: UNEP (2020).

5.4. Destruction of ODS in Article 5 and Non-Article 5 Countries

The following section provides the values of ODS destruction as reported by countries to UNEP, excluding the United States, Japan, and countries in the European Union, and which is available through the Data Access Centre (Table 8). In addition, estimates for CFC, Halon, and HCFC destruction in select countries are provided in Table 9, Table 10, and Table 11, respectively.

Table 8. Reported Destruction of ODS in Select Countries (MT)[a]

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Australia	298.95	296.07	172.12	44.75	74.35	42.85	38.11	47.54	29.42	32[b]
Brazil	16.46	-	-	-	-	-	-	-	-	-
Cameroon	6.00	8.00	11.00	-	-	-	-	-	-	-
China	-	-	11.18	10.79	18.52	17.81	12.53	168.11	16.01	101.16
Colombia	-	-	-	-	3.21	0.17	0.83	-	-	-
Costa Rica	-	-	-	-	0.20	-	-	0.81	0.80	0.95
Cuba	-	-	-	-	-	0.52	0.53	-	-	0.05
Ecuador	-	-	0.04	-	-	-	-	-	0.95	1.79
Georgia	-	-	-	-	1.47	-	-	-	-	-
India	-	-	16.33	19.82	-	34.12	-	7.65	15.29	9.05
Malaysia	-	-	-	-	-	-	4.93	-	1.50	0.68
Mexico	-	-	-	-	3.03	62.85	39.07	-	-	-
Nigeria	-	-	-	-	-	-	-	-	1.50	-
Norway	0.42	1.20	-	-	-	-	-	-	-	-
Republic of Korea	2,950.20	4,075.40	4,674.20	4,622.70	4,499.40	3,799.20	3,839.70	3,698.50	4,228.80	3,563.80
Russian Federation	-	-	-	-	-	-	230.02	-	0.29	-
Viet Nam	-	-	-	-	-	-	0.12	-	-	-

Source: UNEP (2020), unless otherwise noted.

[a] As of 2019, destruction volumes reported to UNEP for controlled substances may include HFC destruction volumes as well as ODS destruction volumes. Unless otherwise noted, it is assumed that reported controlled substance destruction is ODS destruction.

[b] Reported controlled substance destruction to UNEP is 417 MT of which approximately 385 MT are HFC destruction and 32 MT are ODS destruction (Government of Australia 2020a).

Destruction estimates for CFCs, halons, and HCFCs are based on an analysis of production data reported to UNEP, given that the Montreal Protocol defines production as the "amount of controlled substances produced, minus the amount destroyed by technologies approved by the Parties and minus the amount entirely used as feedstock in the manufacture of other chemicals" (UNEP 2019). Equation 1 illustrates the Montreal Protocol's definition of production:

$$\text{Net Production} = \text{Gross Production} - \text{Destruction} - \text{Feedstock} \qquad \text{Equation 1}$$

$$\text{Net production} = \text{production reported to UNEP}$$
$$\text{Gross production} = \text{total produced by the country}$$
$$\text{Destruction} = \text{amount destroyed by the country}$$
$$\text{Feedstock} = \text{amount transformed for feedstock uses by the country}$$

This report estimates that any production of CFCs, halons, and HCFCs in these countries will be used as feedstock in the producing country; therefore, these values would cancel each other out in the above formula. As a result, a negative reported ODS production value should closely resemble the amount of ODS destroyed in that country. Since the values are reported for each calendar year, a negative production value is also possible if the feedstock value exceeds the production value for a given reporting period.

Table 9. Estimated CFC Destruction in Select Countries (MT)[a]

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Australia	22.71	28.60	15.24[b]	7.48[b]	14.58[b]	8.90[b]	7.18[b]	7.54[b]	1.37[b]	3.10[b]
Cameroon	5.70	7.60	10.45	-	-	-	-	-	-	-
China[c]	NA	NA	NA	165.87	NA	14.73	3.33	203.40	11.88	31.45
Colombia	-	-	-	-	2.66	0.19	0.38	-	-	-
Cuba	-	-	-	-	-	0.29	0.48	-	-	0.10
Ecuador	-	-	-	-	-	-	-	-	0.95	1.52
India[c]	NA	-	14.63	18.81	-	32.40	-	-	-	-
Mexico	-	-	-	-	-	37.81	11.02	-	-	-
Norway	0.29	0.10	-	-	-	-	-	-	-	-

NA = Not applicable.

Source: UNEP (2020), unless otherwise noted.

[a] Data converted from Ozone Depletion Potential (ODP) Tonnes to MT using 0.95 conversion factor, representative of a mixture of CFCs.

[b] Government of Australia (2020b).

[c] In 2010, 2011, 2012, and 2014, China and India reported positive production data, potentially due to production of CFCs under an essential use exemption for use in metered dose inhalers (UNEP 2015a). These data are not presented because it is not possible to estimate destruction quantities when the production value is positive.

Table 10. Estimated Halon Destruction in Select Countries (MT)[a]

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Australia	18.67	-	23.26[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	0.04[b]
China	-	-	0.27	0.13	0.17	-	-	0.33	-	-
India	-	-	-	-	-	-	-	92.17	50.97	425.87
Russian Federation	-	-	-	-	-	-	-	-	0.93	-

Source: UNEP (2020), unless otherwise noted.

[a] Data converted from ODP Tonnes to MT using 0.33 conversion factor, representative of halon 1211 destruction (Verdonik 2017).

[b] Government of Australia (2020b).

Table 11. Estimated HCFC Destruction in Select Countries (MT)[a]

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Australia	236.90	266.27	133.62[b]	37.27[b]	59.78[b]	33.95[b]	30.93[b]	39.99[b]	28.04[b]	29.11[b]
Colombia	-	-	-	-	0.73	-	0.91	-	-	-
Costa Rica	-	-	-	-	0.18	-	-	0.73	0.73	0.36
Malaysia	-	-	-	-	-	-	4.91	-	1.46	0.73
Norway	-	1.09	-	-	-	-	-	-	-	-

Source: UNEP (2020), unless otherwise noted.

[a] Data converted from ODP Tonnes to MT using 18.2 conversion factor, representative of HCFC-22 destruction (OzonAction n.d.).

[b] Government of Australia (2020b).

In addition to the data available through the Data Access Center, some information is available through international projects focused on ODS destruction, as highlighted in Box 6.

Box 6. International ODS Destruction Projects

The United Nations Industrial Development Organization (UNIDO) collaborated with the government of Ecuador and the private sector on ODS related projects. As a first stage in 2011, a project for the replacement of 330,000 obsolete refrigerators was implemented and 2.7 MT of CFC-12 were recovered and stored. In addition, some HFC-134a was also recovered. As a second stage in 2015, technological capacity was developed for the destruction of CFCs and the 2.5 MT recovered earlier in the project were destroyed (UNIDO 2018, UNIDO 2019) If additional ODS is collected in the future, the system is capable of reprocessing or destroying (UNIDO 2019).

The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) project *Management and Destruction of Ozone Depleting Substances* aims to establish policy framework conditions to establish national ODS banks management and technology cooperation. GIZ estimates that potential mitigation is approximately three times larger than the estimated reduction from phase-out management plans. GIZ estimates that if all measures are implemented to the full extent, approximately 1,500 million metric tons carbon dioxide equivalent (MMT CO_2 Eq.) will be avoided (GIZ 2018, GIZ 2019).

GIZ collaborated with the Colombian Ministry of Environment and Sustainable Development, the Colombian Ministry of Mines and Energy, and national implementing partners on Colombia's NAMA for the Domestic Refrigeration Sector (NAMA Facility 2020). It is estimated that an annual reduction of approximately 3.8 MT CO_2 Eq. by 2030 will be achieved through the phase-in of new fridges and proper waste management (NAMA Facility 2020).

GIZ collaborated with the Brazilian Ministry of the Environment on the *Introduction of a Comprehensive Refrigerator Recycling Programme in Brazil* to establish a pilot recovery and recycling system for old household refrigerators and freezers. A state-of-the-art refrigerator recycling facility established through the program recovers ODS refrigerant and foam-blowing agents from up to 400,000 units annually, ensuring the proper destruction of up to 120 MT of CFC-11 and CFC-12 each year (GIZ 2011).

6. Global ODS Recovery, Transportation, and Destruction Costs

Costs are incurred throughout the process of ODS destruction, including for transportation and recovering ODS from products and equipment. This section presents estimates of these costs based on information received from personal communication with destruction project developers, the 2009 TEAP Decision XX/7 Task Force report, and other sources.

6.1. ODS Recovery Costs from Products and Equipment

For ODS that are contained in products (e.g., appliance foam) and equipment (e.g., refrigeration/AC, fire suppression), there are additional costs associated with the collection of equipment, transportation of the ODS-containing products/equipment to processing facilities prior to shipment of the recovered ODS waste to a destruction facility, and the actual recovery of ODS from those products/equipment. Table 12 presents the range of estimated costs by end-use for segregation/collection, recovery transport, and recovery processing based on TEAP (2009) and confirmed by a destruction project developer EOS Climate (2016) and by the American Carbon Registry (ACR 2019). For example, while ODS recovery from refrigeration/AC and fire suppression equipment requires a low level of effort and relatively low cost, the separation and collection of ODS are more difficult and costly for foams contained in appliances, and even more so for foams contained in buildings.

Table 12. Range of Costs for Recovery, Transport, and Processing of ODS in Products and Equipment[a]

End-Use	Segregation/ Collection Costs[b] (US$/kg)	Transport Costs (Recovery) (US$/kg)	Recovery Processing Costs (US$/kg)
Household Refrigeration (refrigerant & foam blowing agent)	$6-10	$6-40	$10-20 for refrigerant; $20-30 for blowing agent
Commercial Refrigeration (refrigerant & foam blowing agent)	$8-20	$8-50	$8-15 for refrigerant; $25-35 for blowing agent
Transport Refrigeration (refrigerant)	NA	NA	$15-20
Industrial Refrigeration (refrigerant)			$4-6
Air Conditioning (refrigerant)	$1-2[c]	NA	$4-35
Fire Suppression (halon)			
Steel-faced Panels (foam blowing agent)	$75-90	$5-10	$30-40
Block – Pipe (foam blowing agent)	$10-15	$15-20	
Block – Slab (foam blowing agent)	$80-100	$5-10	

Sources: TEAP (2009), EOS Climate (2016).

NA = Not Available.

[a] Note that the range of costs for each sector reflects the estimated costs for collection, recovery, and transport of ODS from sources in densely and sparsely populated areas, requiring low or medium effort. In general, ODS recovery in sparsely populated areas involves medium effort and higher costs, while recovery from densely populated areas involves low effort and lower costs. Thus, the costs associated with low effort recovery is reflected in the lower bound of the cost range and medium effort recovery in the upper bound of the cost range.

[b] Costs are generally higher for equipment with smaller charge sizes because it requires the same amount of effort to collect smaller volumes of refrigerant or blowing agent.

[c] Awareness raising for recovery schemes.

6.2. ODS Transportation Costs

Costs associated with transporting ODS to a destruction facility can vary greatly depending on distance, quantity, and whether the transport is within or beyond national borders. In some countries, the only viable means of transporting ODS to a destruction site is by sea or by plane, which can add significant costs.

In the United States, bulk quantities of ODS in-state are generally the most economical to transport. According to one destruction company, a railcar carrying 86 MT (190,000 lb) of waste-containing ODS costs approximately $800 for in-state shipments (about $9 per MT of ODS); these costs approximately double for out-of-state shipments. The same source estimates that a tank truck carrying 19 MT (42,000 lb) of waste can cost up to $700 for in-state shipments ($35 per MT). Prices for out-of-state shipments were not provided by the source, as they are highly variable (ICF 2009a). Another destruction company reported the cost to transport waste refrigerant varies from $300 to $600 per MT, depending on the refrigerant type. Another company charges $3 per kilometer for transport in a pressurized ISO tanker, or a tanker can be leased (with a minimum 1-year lease) for $1,000 per month (ICF 2009a). The costs have been confirmed by ACR (2019).

Older estimates from TEAP (2009) indicate that the international average cost of transporting ODS between 200 to 1000 kilometers ranges from $8 to $60 per MT of ODS ($0.04 to $0.06 per MT per km). According to more recent information, an ODS destruction project in Brazil, it costs approximately $3,000 per MT to transport bulk waste ODS to the European Union by sea and an additional $1,000 per MT for transaction costs related to the Basel Convention for transporting hazardous waste into the European Union (approximately $0.4 per MT per km) (UNDP 2014). According to an ODS destruction project in the country of Georgia, it costs approximately $1,000 per MT to transport bulk waste ODS by land and $3,600 per MT by sea to the European Union (approximately $0.2 to $0.9 per MT per km) (MLF 2017a). According to an ODS destruction project in Mexico, the cost of transportation and consolidation of ODS waste within Mexico was $1,400 per MT (MLF 2018b).

6.3. ODS Destruction Costs

The price of bulk ODS destruction depends on several factors including the type of ODS, composition/purity, quantity, the type of container the ODS are stored in, technology used, and transportation needs. ODS destruction costs are difficult to estimate, because each of the cost factors also vary due to indirect factors such as geographical location, firms contracted, and demand for services. For example, if a destruction facility has a large amount of refrigerant to destroy in a given week, prices may increase or the facility may even refuse to accept additional shipments.

6.3.1. Concentrated Sources of ODS

According to MLF (2008), the average estimated cost to destroy concentrated ODS in the United States ranges from $1.50 to $12.50 per kg, this range was confirmed by ACR (2019). This range is in line with TEAP (2009), which estimates that international average costs to destroy ODS ranges from $4 to over $6 per kg for concentrated refrigerant or blowing agent, or $6 to $8 per kg for halon. In addition, the estimated cost to destroy liquid bulk ODS provided by a destruction company was within the ranges provided by MLF (2008) and TEAP (2009) with higher costs for ODS streams containing higher concentrations (Veolia 2021).

Actual destruction costs will depend on the amount of ODS sent for destruction (with bulk quantities generally costing less) and the technology used. In general, commercial facilities using incineration technologies (e.g., rotary kilns, cement kilns, reactor cracking) have lower costs than facilities using plasma arc technologies. ODS destruction costs in pilot projects (i.e., in China, Colombia, Georgia, Mexico, Turkey, and the ECA Region) ranged from $1.87 to $12.50 per kg (MLF 2018b). In addition, a pilot project in Nigeria had ODS destruction costs of $29.82 per kg; this high cost was likely due to the lower than expected quantity of ODS destroyed (MLF 2018b).

6.3.2. Dilute Sources of ODS

The average estimated cost to destroy dilute ODS was not analyzed separately from concentrated ODS in MLF (2008) or TEAP (2009). Typically, dilute ODS will cost more to destroy than concentrated ODS. Dilute sources of ODS include foam blocks removed from appliances or buildings. For example, in the United States, appliance foam is sometimes recovered manually in large chunks, placed into large plastic bags (which are sealed to capture any off-gassing ODS), and then destroyed in municipal solid waste combustors or waste-to-energy facilities. One U.S. municipal waste-to-energy (WTE) facility reported charging $0.18 per kg for destruction of bulk appliance foam; another facility reportedly charges $0.14 per kg plus an additional $120 per load (ICF 2009a). To put these costs in perspective, if the average U.S. refrigerator contains 5 kg of foam, destruction of the bagged foam in a WTE facility will cost roughly $830 to $910 for 1,000 units.

Most recently, another facility indicated that destruction costs for solids (which could include foam and foam-containing products) could typically be below $5 per kg of ODS depending on factors such as pH, reactivity, and volatility (Veolia 2021). In the United States, municipal solid waste destruction facilities may charge lower prices when compared to private facilities since their prices are resolved on a no-profit basis (ICF 2009a). A pilot program in Colombia that destroyed ODS-containing foams through rotary kiln incineration noted a destruction cost of $5.20 per kg of foam (MLF 2018b).

7. Financing of ODS Destruction Projects

Globally, there are a variety of mechanisms for funding or offsetting the cost for ODS destruction. For example, in some countries, taxes on ODS or the availability of carbon offset credits may be available resources. In some cases, there may be relevant projects funded by the MLF or the Global Environment Fund (GEF). However, the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC) states that there is currently little financial incentive for ODS destruction and, because of this, destruction is only successful when it is regulatory driven (RTOC 2018). Requirements to destroy obsolete ODS where resources are unavailable may create an unfunded mandate to collect and properly dispose ODS. Market based incentive schemes (voluntary or compliance) may provide a financing stream for ODS destruction.

7.1. Producer Responsibility Programs and Taxes

In some countries, ODS destruction can be funded through voluntary or government-mandated programs that encourage or require producers to manage ODS contained in their products over the lifetime of the product and create financial and behavioral incentives for stakeholders in the process.

Extended producer responsibility (EPR) programs, used in countries such as Australia, Germany, and France, often rely on levies or licensing fees (usually on the production/import of ODS-containing equipment), and rebates (for the return of recovered ODS). These programs can be used to encourage producers to safely manage the manufacture, operation, and decommissioning of ODS-containing equipment. For example, Australian industry created Refrigerant Reclaim Australia (RRA) in 1993 to develop a recovery program for Australian ODS and, eventually, synthetic greenhouse gas refrigerants. It worked with companies for reprocessing and destruction of recovered refrigerant (RRA n.d.). Recovery was done on a voluntary basis from 1993 to 2004 when the *Ozone Protection and Synthetic Greenhouse Gas Management Act* took effect and made recovery compulsory (RRA 2012, RRA n.d.). Subsequently, a condition on licenses was implemented which required companies to exercise product stewardship over imported products (RRA 2012). From 1993 to 2017 the RRA had recovered approximately 6,500 MT of ODS and synthetic greenhouse gas refrigerants of which 91% was destroyed (RRA n.d.). The RRA is fully funded from money derived through an industry levy on import of refrigerants in bulk or in pre-charged equipment (89% of total revenue) (Miller and Batchelor 2012b, RRA 2019, Government of Australia 2020).

The European Union mandates the recovery for reclamation, recycling, or destruction of ODS when it is technically and economically feasible to do so according to Regulation (EC) 1005/2009 (EU 2009). The European Union provides a directive for the collection of waste from electrical and electronic equipment (WEEE) (e.g., potentially ODS-containing refrigerators, freezers, and other cooling appliances). General guidelines are set at the Union level; however, Member States can develop financing programs based on national preference. Member States are encouraged to make producers take full responsibility for the WEEE collection, in particular by financing the collection of WEEE throughout the entire waste chain, including from private households, in order to avoid separately collected WEEE becoming the object of suboptimal treatment and illegal exports, to create a level playing field by harmonizing producer financing across the European Union and to shift payment for the collection of this waste from general tax payers to the consumers of EEE, in line with the ‘polluter pays’ principle (EU 2012). Some Member States (e.g., Germany and France) have made producer responsibility mandatory (European Commission 2019). It was expected that, given Regulation (EC) 1005/2009 and other parallel provisions, 14,000 ODP tonnes would be recovered annually in the European Union (European Commission 2019).

An example of an EPR voluntary partnership is Refrigerant Management Canada (RMC), an industry partnership that organizes the collection, transport, and destruction of ODS waste in Canada. It was established in 2000 as an industry-led EPR organization with the goal of managing Canada’s surplus bank of

ODS. RMC organizes the export of ODS to the United States and earns offset credits based on successful destruction.

While EPR programs are designed to incentivize ODS management, there are four key issues they may face: share of responsibilities and dialogue between stakeholders; defining costs to be covered; fair competition; and transparency and surveillance (Deloitte 2014).

Fees and taxes can also be assessed outside of a producer responsibility program to generate revenue to fund ODS collection, recycling, and disposal. For example, disposal fees can be added to the cost of new appliances containing ODS, which also encourages consumers to purchase non-ODS containing equipment. Taxes can also be imposed, for instance, on the production of new equipment containing ODS. As with EPR programs, taxes imposed on the production of ODS-containing equipment may introduce the potential for unfair competition from other producers not subject to the tax (e.g., foreign companies) (OECD 2011).

Japan requires the recovery and recycling or destruction of fluorocarbons from commercial equipment during service and disposal events. At the time of disposal, consumers pay a fee that covers collection, transport, and recycling – which costs approximately $40 for a refrigerator and $30 for an AC unit. The Japanese law mandates that the fee for fluorocarbon recovery and destruction be paid by end-users (ICF 2010a). Because there is a legal requirement to destroy the refrigerant, offset credits for the destruction of the ODS cannot be awarded. Similarly, Denmark established a fee by installers and refrigerant wholesalers to cover the cost of destruction (European Commission 2019).

Another possibility is leveraging the interest of producers of ODS substitutes as a means of funding ODS destruction. In Italy, for example, a producer of halon alternatives offered to collect and destroy halons from users who committed to using the alternative. In China, a fire extinguisher program was developed that gave a new alternative-based fire extinguisher to those needing to refill their halon extinguishers (ICF 2010b).

7.2. ODS Destruction Offset Programs

Carbon markets can be broadly divided into two key segments—the compliance market and the voluntary market. The key difference between the two types of carbon markets is the existence of a legal requirement for certain industries to reduce and/or offset their emissions. As a result, the price of carbon offset credits sold on the compliance market is approximately 2 to 10 times higher than credits sold on the voluntary market, depending on the type of project. Compliance markets are created and regulated by mandatory regional, national, or international greenhouse gas (GHG) emissions reduction programs. Voluntary markets are not mandatory and thus, operate outside the compliance market. In voluntary markets organizations can offset carbon emissions on a voluntary basis. Projects are not eligible for offset credits if they are not going above the level of compliance required by the corresponding national law. Therefore, companies operating in countries where ODS destruction is required by law are not eligible to generate offset credits because there is no additionality. Legal requirements to destroy ODS in those countries creates a disincentive to collect and destroy obsolete ODS because the economic incentive (i.e., generating ODS offset credits) is removed.

7.2.1. Compliance Markets

Compliance markets exist at an international level and at regional (e.g., Western Climate Initiative [WCI]), national (e.g., South Korea and Japan) and subnational levels (e.g., Regional Greenhouse Gas Initiative [RGGI] and California) through legally-binding policy instruments. The key aspect of compliance markets is that there is a legal requirement for covered entities[18] to keep their emissions under a set target. They can do so by either decreasing their own emissions or purchasing allowances or carbon offset credits that are considered

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[18] Covered entities are those, defined per regulations, that have a legal requirement to maintain emissions under a set target.

eligible[19] for compliance purposes from a marketplace. Several compliance markets have approved protocols for ODS destruction.

In 2012, the California Air Resources Board (CARB) enacted a cap and trade program that establishes a statewide ceiling on carbon emissions, which declines each year. Companies operating within the state have to lower their emissions or purchase offset credits. Under the CARB protocols, emissions reductions for offset credits must be based in the United States. Currently, ODS destruction projects are only available for credits if they source the materials from within the United States, and the destruction takes place within the United States (CARB 2017).

In 2012, Quebec enacted an independent cap and trade system similar to California. Due to their similar or identical GHG emission allowances law and regulation, Quebec and California linked their two programs in 2014, thus forming a joint carbon market within the framework of the WCI. This has allowed the California and Quebec governments to hold joint auctions of GHG emission allowances and to harmonize regulations and reporting. In 2017, the Ontario and Quebec governments enlisted help from CAR to develop a protocol for ODS foam and refrigerant destruction (CAR 2017). By July 2019, Quebec had issued 534,618 carbon credits from ODS destruction 70% of which were from ODS in foams or used as refrigerants (Government of Quebec 2019).

Following successful implementation of Ontario's cap and trade system in 2016, the Ontario market joined the WCI regional carbon market in January 2018. That same year, Nova Scotia joined the WCI in order to use its IT system and manage its new cap and trade program which will be administered independently from the California and Quebec programs (Matheson and Tamblyn 2018). In July 2018 Ontario eliminated its cap-and-trade carbon tax, citing a burden on families and businesses, and left the WCI (Ontario Ministry of the Environment 2018).

In addition to the North American compliance markets discussed above, Table 13 shows the progress of several countries and regions in implementing emissions trading systems. These systems do not currently award offset credits for ODS destruction; however, they may approve similar protocols in the future.

Table 13. Emission Trading Systems

Subnational Level	Country Level		Regional Level
Established Emissions Trading Systems	Established Emissions Trading Systems	Establishing Emissions Trading Systems	Established Emissions Trading Systems
California (USA)	Japan	China	European Union
Shenzen, Shanghai, Beijing, Guangdong, Tianjin, Hubei, Chongqing, Fujian (China)	Kazakhstan	Colombia	WCI
RGGI	New Zealand	Mexico	
	South Korea	Ukraine	
	Switzerland		

Source: ICAP (2019).

7.2.2. Voluntary Markets

Voluntary markets allow organizations to offset carbon emissions on a voluntary basis. Voluntary carbon markets have been used as a funding source for ODS destruction projects (see Box 7). ODS destruction projects are attractive due to the permanence of the reductions and the messaging around the rationale. The market demand for voluntary offsets is driven by buyers' interest and credits from these sources have been

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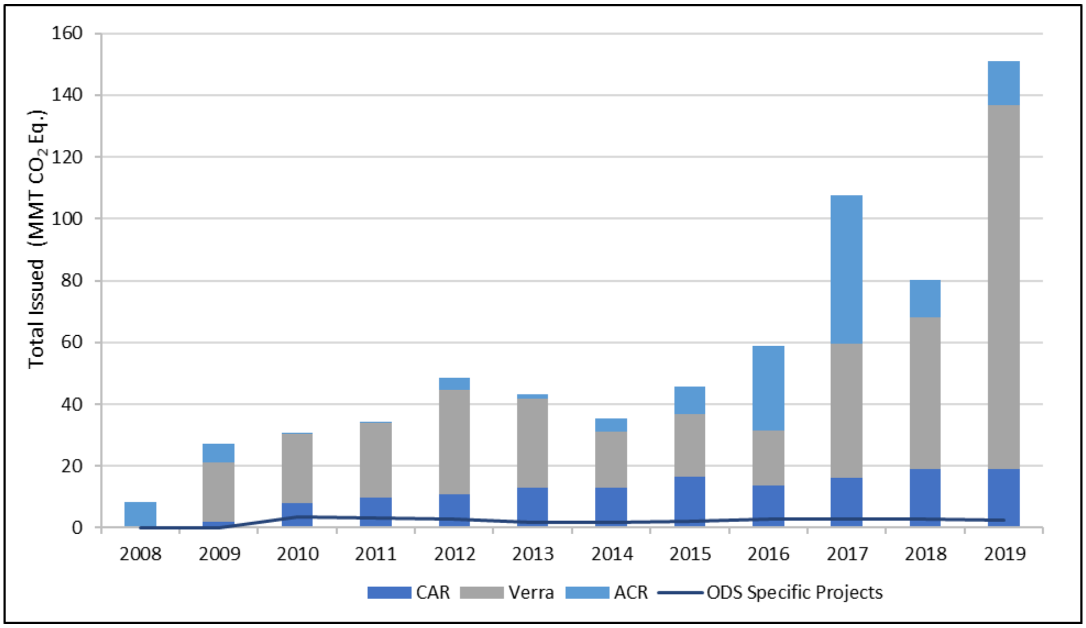
[19] Eligibility criteria for offsets in compliance markets are different from market to market. Certain vintages, types of projects, geographical origin of the credits are considered when deciding on eligibility of credits.

used by businesses and events to offset their emissions. For example, the Aviation sector has adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to complement their measures to achieve the global aspirational goal of becoming carbon-neutral from 2020 onwards (ICAO n.d.). The adoption of CORSIA is estimated to increase demand for voluntary offsets by 3,000 MMT CO_2 Eq. from 2020 to 2035 (World Bank 2019).

The three most widely traded voluntary offset programs in the United States with ODS destruction protocols are the Verra, CAR, and the ACR. Verra represents more than 60% of the total credits issued from the three voluntary markets, as of October 2019. From 2010 to 2019 CAR registered 110 projects related to ODS Destruction resulting in 1,375 MT of ODS destroyed (CAR 2020). Likewise, ACR registered 77 projects related to ODS from 2013 to 2019 (ACR 2020a). As shown in Figure 6, the volume of issued carbon credits grew from 2008 to 2012 and recovered from a 2014 dip with rapid growth from 2015 to 2017 at which point there were 97 million MT CO_2 Eq. issued in credits. In addition, carbon credits issued almost doubled from 2018 to 2019; however, this increase was not observed for credits issued for ODS specific projects which have remained constant at 2.7 million of MT CO_2 Eq. since 2016.

Figure 6. Annual Volume Issued (MMT CO_2 Eq.)[a]



Sources: CAR (2020), Verra (2020), and ACR (2020a).

[a] The totals presented in this figure for ODS Specific Projects from 2008 to 2017 are the sum of the credits issued for ODS projects in CAR and ACR. For 2018 the totals for ODS Specific Projects considers CAR, ACR, and Verra.

The estimated number of ODS destruction projects in the United States will likely remain constant in the near future and the number of international projects is estimated to increase (ACR 2020b)[20].

Offset prices in voluntary carbon markets can range as a result of project costs, buyer's preferences and type of transaction. In the first quarter of 2018 prices ranged from 0.1-70 US$ per MT CO_2 Eq. with an average of 3-6 US$ per MT CO_2 Eq. (Ecosystem Marketplace 2018). Table 14 presents a breakdown of the voluntary carbon markets with ODS destruction protocols in 2018.

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[20] Because of the timelines and processes in project development and verification, the impacts of COVID-19 on U.S. ODS destruction projects are expected to be negligible while COVID-19 impacts on international projects will be more significant (in part as a result of international and in-country travel restrictions) (ACR 2020b, Tradewater 2020).

Table 14. Breakdown of Voluntary Markets and ODS Destruction Protocols in 2018

Offset Program	Total Credits Issued (millions of MT CO_2 Eq.)[a]	Total Value Traded (US$ Millions)[a,b]	Total Credits Issued for ODS Projects (millions of MT CO_2 Eq.)	Total Value Traded for ODS Projects (US$ Millions)[a,b]	Protocol for ODS Destruction	ODS Sourced Internationally
Verra	49.6	$140	0.020	$0.1	Yes	Yes
Climate Action Reserve	18.9	$54	1.60	$4.6	Yes	Yes
American Carbon Registry	11.9	$34	1.07	$3.1	Yes	No

Sources: Ecosystem Marketplace (2019), CAR (2020), Verra (2020), and ACR (2020a).

[a] The totals presented in this column account for all offset projects eligible under the voluntary program, of which a small portion are ODS destruction projects.

[b] The traded value is calculated based on the credits issued and there may be variations with actual traded value since it does not consider credits transacted more than once or credits issued which were not sold. In addition, the traded value was calculated considering the weighted average credit price of 2.84 US$ per MT CO_2 Eq. as reported in Ecosystem Marketplace (2019) for 2018.

7.2.3. Carbon Prices and Profitability

The sale of carbon credits on the compliance and voluntary markets is one potential method for funding ODS destruction projects. In 2016, approximately 1.4 million MT CO_2 Eq. from gases (i.e., ODS and N_2O) projects were transacted globally in the voluntary market for a total value of $8 million (Ecosystem Marketplace 2017).[21] There are additional costs associated with the preparation, validation, and verification of ODS destruction projects, which are summarized in Table 15.

Table 15. Transaction Costs to Prepare an ODS Destruction Project

Project Phase	Cost (US$)
Project Preparation[a]	Approx. $60,000
Third-Party Validation and Verification	Up to $20,000
Offset Marketplace Fees	Up to $1,000
Issuance/Registration Fee	$0.12-0.20/MT CO_2 Eq.

Source: ACR (2019).

[a] Project preparation costs vary according to the financing model used and the approach of companies performing collection/aggregation, in some cases, costs could be much higher.

While the financial prospects of funding ODS destruction projects through the sale of carbon offset credits are available, there are challenges. One of the main challenges is that projects generate revenue only once the offset credits have sold. In s countries, upfront capital is rarely available to support an ODS destruction project. Some firms previously provided upfront financing to companies and reclaimed their investment once the credits were sold; however, this business model is no longer effective because of the drop in offset prices. Other firms provide funding by brokering the sale of credits to potential buyers.

In the voluntary market, offset-buying firms often assist in the development of specific projects that match their corporate responsibility profile. In 2015, an estimated 4 percent of total transactions represented early-stage financing in the voluntary market. Payment-on-delivery and spot contracts were the most common contract types in 2015 (Ecosystem Marketplace 2017).

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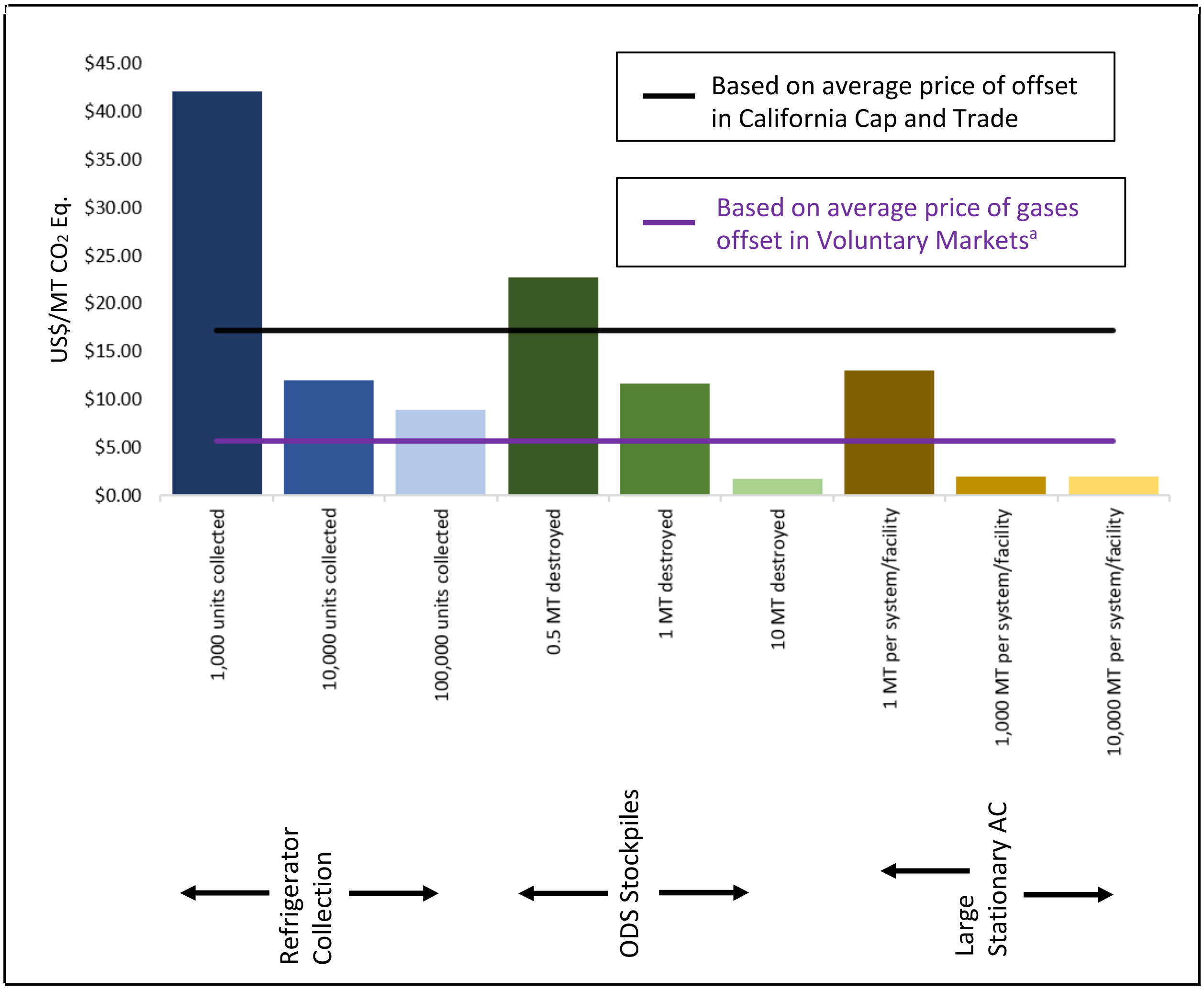
[21] Disaggregated data for ODS projects was reported by Ecosystem Marketplace 2017.

Box 7. Case Study: International ODS Destruction Project in the Voluntary Carbon Market

An ODS destruction project between private industry in Ghana and a third-party aggregator sought to destroy a CFC stockpile of more than 15 MT in Ghana by exporting the ODS for destruction to the United States. Costs were to be funded through offsets under the voluntary carbon market. In 2017, a first phase of the project resulted in the generation of 20,000 carbon offset credits and the successful destruction of over 1.8 MT of CFCs following the Verra protocol. The sale of those carbon credits enabled the funding of a second phase in which 13.6 MT of ODS were destroyed in April 2019 and will result in 130,000 additional carbon offset credits (Berwald 2019, Tradewater 2019).

Figure 7 shows the break-even costs of ODS destruction projects based on the recovery, transport, destruction, and project development costs from ICF (2010b). The break-even cost represents the price that would have to be generated in the carbon market in order to cover the full costs of the project. As shown, the break-even price decreases as the project size increases, as a result of realizing project economies of scale associated with the mostly fixed project development costs. The projects are compared on a sectoral basis because it is often the most efficient way of collecting ODS. Figure 7 presents three different collection programs: refrigerator collection, ODS stockpiles, and large stationary AC.

Figure 7. Break-Even Costs Compared to Average Price of Offset



Sources: ICF (2010b), Ecosystem Marketplace (2017), and CARB (2019).

[a] This average price includes both ODS and N_2O.

7.3. HFC-23 Destruction

HFC-23 is generated as a byproduct from HCFC-22 production. HFC-23 destruction was a source of carbon credits on a variety of international carbon markets starting in 2005. In 2013, the European Union Emissions Trading System (EU ETS), New Zealand, and Australia imposed a ban on the use of certified emission reduction (CER) credits from HFC-23 destruction, which significantly lowered the value of credits obtained from HFC-23 abatement projects. Likewise, Verra announced in 2014 that it would no longer approve new methodologies and projects relating to HFC-23 destruction (Verra 2014). This step was taken because it was determined that allowing credits from the destruction of HFC-23 could create a perverse incentive to increase production of HCFC-22, a gas which both depletes the ozone layer and is a powerful GHG (Levitan 2010). Historically, nineteen HFC-23 destruction projects were approved by the Clean Development Mechanism (CDM) Executive Board (MLF 2017b). During the CDM period (i.e., 2003-2014) a cumulative HFC abatement of approximately 53,3000 MT was achieved (Stanley et al. 2020).

It is likely that abatement measures are not being implemented as CDM finance sources are no longer available. For example, as of 2017, Argentina and Mexico, which in previous years had CDM projects, have resumed venting practices of HFC-23 byproduct (MLF 2017b, MLF 2018a). Specifically, recent studies indicate that abatement measures are not yet successfully being implemented and/or HCFC-22 production is larger than reported because of an increase in the atmospheric HFC-23 concentration growth rate from 2016 to 2018 (Stanley et al. 2020).

Under the Kigali Amendment to the Montreal Protocol, Parties agreed, starting in 2020, to destroy HFC-23 emissions to the extent practicable using destruction or conversion technologies approved by the Parties. In addition, there are also some national requirements to reduce HFC-23 emissions. For example, in 2016, India announced a requirement for the destruction of HFC-23 using an efficient and proven technology such as thermal oxidation (MLF 2017b, Ozone Cell 2016). It is expected that the atmospheric HFC-23 concentration growth rate will be reduced as abatement measures are implemented as a result of national requirements and the Kigali Amendment provisions.

7.4. MLF- and GEF-Funded Destruction Projects

In some cases, international organizations (e.g., MLF and GEF) fund projects that assist in ODS collection, management, and destruction. Demonstration projects have been funded by these organizations to show that ODS destruction is viable, develop lessons learned, and establish replicability. Due to the varying comparative advantages of the MLF and GEF, each organization has focused funding on different aspects within the process of ODS waste management. Projects by UNIDO, GIZ and others are presented in Box 6. As of 2016, UNIDO had completed over 1,340 ODS projects through the MLF, GEF, and bilateral contributions, some of which were focused on or had an element of ODS destruction (UNIDO 2018, UNIDO 2016).

The MLF demonstration projects focused funding on financial, technological, and logistical aspects by developing demonstration projects that assist countries in building/retrofitting destruction facilities or assist with the collection and transport of ODS to countries with destruction facilities (GIZ 2017a, MLF 2018b, MLF 2019). Most recently, in 2017 and 2018, ODS waste management and disposal projects (i.e., in China, Colombia, Georgia, Mexico, Nepal, Nigeria, and Turkey) funded by the MLF resulted in the destruction of more than 350 MT of ODS (MLF 2018b). In 2014, the MLF funded a cement kiln retrofit in Algeria, which has led to the destruction of approximately 31 MT of ODS per year (GIZ 2015). In 2011, the MLF funded the collection and transport for destruction of 8.8 MT of bulk ODS from Ghana to the European Union (UNDP 2011).

In some instances, international organizations collaborated with the private sector to monetize projects. For example, in 2012, UNDP, in collaboration with EOS Climate, funded the collection and transport for destruction of waste ODS from Nepal to the United States using MLF resources. EOS Climate acted as a project aggregator and facilitated the sale of 82,400 Verified Emission Reductions (VER) in the CAR (UNEP 2017).

The GEF focuses funding on legal and informational aspects of ODS offset destruction by developing policy and legislation to support the phaseout of ODS and responsible end-of-life (EOL) practices. From the late 1990s to the late 2000s, the GEF funded the development and implementation of policy and legislation in Eastern Europe and Central Asia to phase out consumption and promote responsible ODS recovery, recycling, reclamation, and destruction (Batchelor 2010). By 2012, the GEF had invested $235 million across 18 economies in transition in 29 projects to phaseout ODS (GEF 2017a). In 2017, the GEF approved for implementation a regional demonstration project for the collection and destruction of POPs and ODS, in Ukraine, Belarus, Kazakhstan and Armenia, which aimed to destroy at least 418 MT of ODS (GEF 2017b).The project, implemented by UNIDO, has evaluated legal frameworks and technologies, it will result in three new ODS destruction facilities and is expected to begin destruction activities before 2021 (GEF 2020).

8. Modeled Amounts of ODS Potentially Available for Destruction

While under the Montreal Protocol production and consumption of ODS are being phased out, large amounts of ODS currently installed in equipment and products, and existing in stockpiles, could be released to the atmosphere given emissions are not controlled. Alternatively, ODS banks can be recovered and properly treated, i.e., reused (after recycling or reclamation) or destroyed. To demonstrate the scope of available ODS banks, the sections below present modeled estimates of the amount of ODS potentially available for destruction in the United States, European Union, and globally from 2010 through 2050 via recovery from equipment and products, and from stockpiles.

8.1. ODS Recoverable from Equipment and Products

As discussed in Section 3.1, ODS refrigerant from refrigeration/AC equipment is typically relatively easy to recover, making the refrigeration/AC sector one of the largest accessible ODS banks. RTOC (2018) estimates global refrigeration banks to be ten to twenty times larger than the annual refrigerant demand and states that the largest bank is for HCFC-22, which is estimated to be larger than 1 million MT for unitary air conditioners.

In the fire suppression sector, halons may also be recovered, including halon 1211, which is most commonly found in hand-held extinguishers, and halon 1301, commonly used in total flooding systems (NFPA 2008).

Recovery from appliance foams is also feasible; however, the recovery effort may be more expensive and could require a higher level of effort than for refrigerants. Specifically, recovery from construction foam is lower than for the refrigeration/AC sector as the quantity of original blowing agent that is actually recoverable is relatively lower. The Flexible and Rigid Foams Technical Options Committee (FTOC) estimates that global banks of blowing agents in foams will exceed 5 million MT by 2020 and states that if they enter the waste streams, they will become broadly unreachable (FTOC 2019). This highlights the importance of establishing additional mechanisms for ODS containing foam collection and eventual destruction. To address this, countries promote foam recovery via different mechanisms such as the United States, which established the RAD Program, and the European Union, which established regulation to recover appliance foam. In addition, some regions treat ODS in foams as a hazardous waste to promote recovery; however, difficulties in determining the blowing agent within the foam results in an inability to monitor shipments and hinders these efforts (FTOC 2019). Furthermore, treatment as hazardous waste creates additional burdens since destruction in hazardous-waste-permitted facilities is more costly and if regulated, the destruction would not trigger the additionality requirement to qualify projects for emission reduction credits (ICF 2010a).

The following sections present modeled estimates of the amount of ODS potentially recoverable in the United States, European Union, and globally from 2010 through 2050.

8.1.1. United States

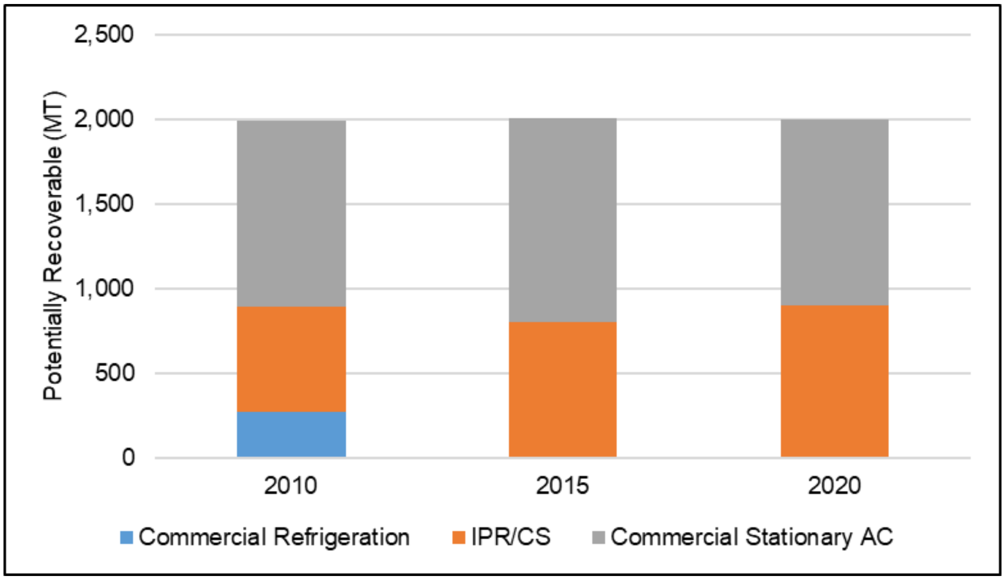
The U.S. EPA Vintaging Model (VM)[22] was used to develop estimates of available banks of ODS for recovery in the United States. The VM estimates consumption and emissions from six industrial sectors: refrigeration/AC, foams, aerosols, solvents, fire suppression, and sterilization. The model, named for its method of tracking annual "vintages" of new equipment that enter into service, models the consumption and emissions of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment.

The amount of chemical potentially recoverable from equipment/products being disposed of is modeled in the VM with varying recovery rates depending on the end-use and vintage of equipment. According to assumptions in the VM, the amount of ODS recoverable from equipment at disposal varies by equipment and gas type, ranging from about 90 percent of the original charge recovered at disposal for large equipment such as chillers or cold storage to about 65 percent recovered for small equipment like small retail food units (e.g., display coolers and freezers). Additionally, the VM assumes that ODS are not recoverable from retired U.S. equipment at EOL from foam applications.

Only ODS potentially recoverable from refrigeration, AC, and fire suppression equipment are estimated in this analysis. Estimated quantities of HFCs potentially recoverable from retired equipment at EOL are presented in Section 10.2.

Figure 8 presents the breakdown of total CFCs potentially recoverable from retired U.S. equipment at EOL by end-use from 2010 through 2020. The model's assumptions on equipment lifetimes dictate that CFCs will only be available from three end-uses: commercial refrigeration, industrial process refrigeration (IPR) and cold storage (CS), and commercial stationary AC, specifically chillers. All other end-uses that previously used CFC refrigerant (e.g., motor vehicle air conditioners) were modeled to reach their EOL before 2010. After 2020, CFCs are no longer expected to be available for recovery from any end-use in the United States.

Figure 8. Quantity of CFCs Potentially Recoverable from Retired U.S. Equipment at EOL (2010-2020)[a]



Source: EPA (2020b).

[a] Commercial Stationary AC and IPR/CS values for 2020 were extrapolated to illustrate the volume of CFCs that are still in equipment and available for destruction since equipment that is beyond their expected lifetime is still operational.

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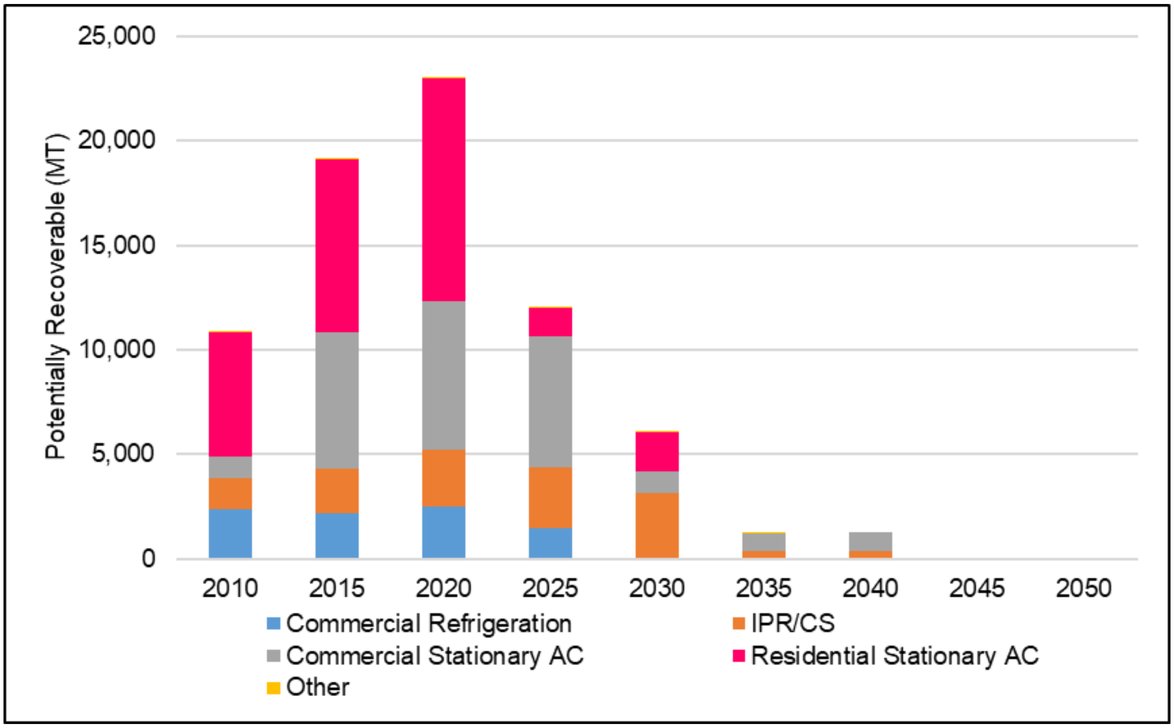
[22] IO version 5.1 (03.20.20).

Figure 9 presents the breakdown of total HCFCs potentially recoverable from retired U.S. equipment at EOL by end-use from 2010 through 2050. From 2010 to 2020, most of the HCFCs potentially recoverable will have come from the retirement of residential stationary AC equipment, as well as some from commercial stationary AC, IPR/CS, and commercial refrigeration. The model's assumptions on equipment lifetimes dictate that the majority of HCFCs will have been collected by 2030. Commercial stationary AC and IPR/CS remain as the dominant end-uses from which HCFC refrigerants may be potentially recoverable from equipment at EOL through 2050.

Figure 9. Quantity of HCFCs Potentially Recoverable from Retired U.S. Equipment at EOL (2010-2050)

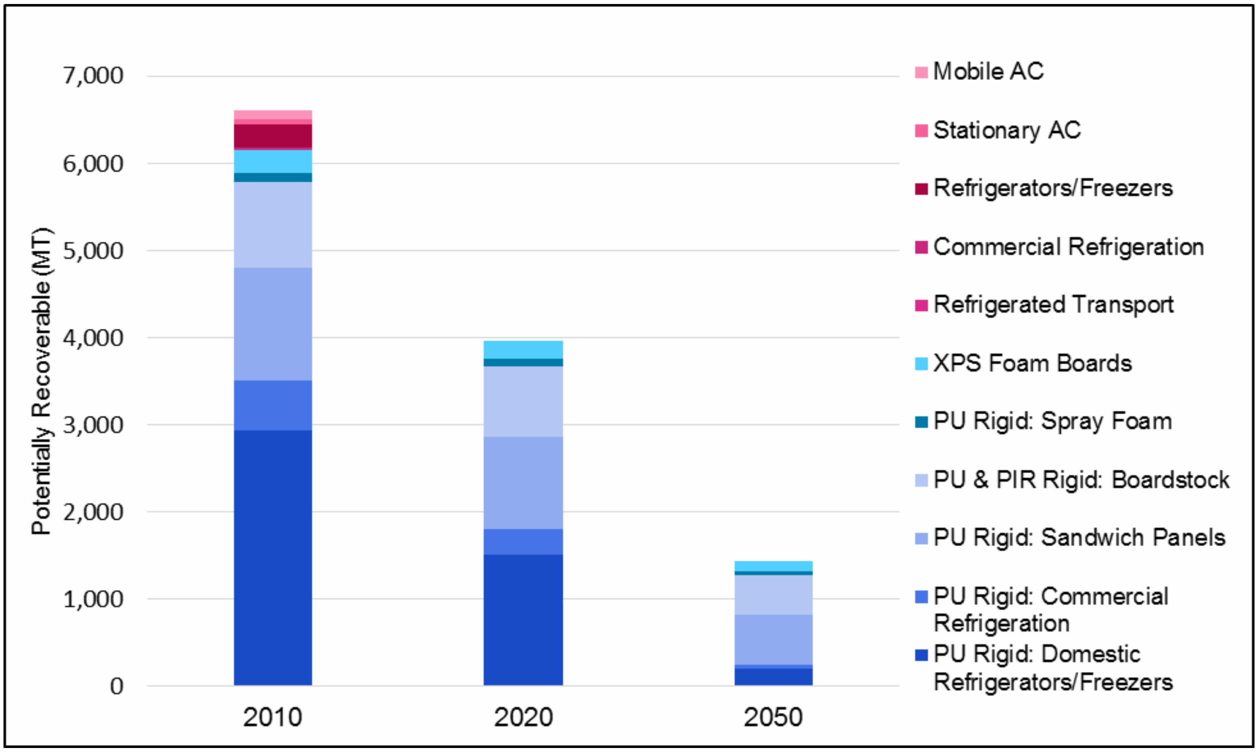


Source: EPA (2020b).

8.1.2. European Union

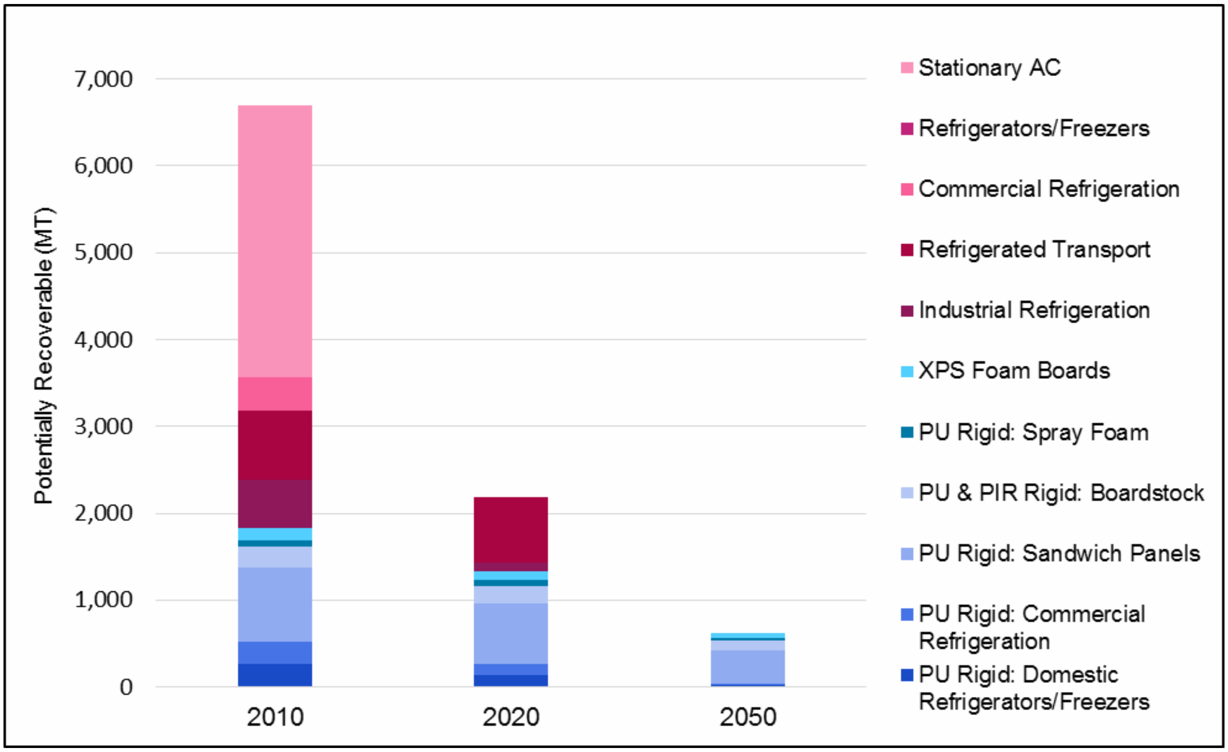
The technical and economic feasibility of recovering ODS from equipment and products at EOL in the member states of the EU was assessed in ICF (2010a). Figure 10 and Figure 11 show the quantities of CFCs and HCFCs estimated to be potentially recoverable from equipment at EOL in 2010, 2020, and 2050, based on a bottom-up modeling methodology used to estimate banks. This analysis assumes that ODS from foam applications is potentially recoverable. By 2050, CFCs and HCFCs from refrigeration/AC equipment are no longer expected to be available for recovery. Approximately 2,000 MT of CFCs and HCFCs will be potentially recoverable from foam products at EOL by 2050, although ODS recovery from foam applications typically require a medium to high effort. Since recovery from foam poses technical and cost challenges (i.e., abatement cost larger than $50 per MT CO_2 Eq. for 2012-2050) and, in practice, there is little, if any, recovery of ODS from foam applications, it is likely that ODS will not be recovered from foam by 2050 (European Commission 2019).

Figure 10. Quantity of CFCs Potentially Recoverable from Retired EU Equipment at EOL (2010-2050)



Source: ICF (2010a).

Figure 11. Quantity of HCFCs Potentially Recoverable from Retired EU Equipment at EOL (2010-2050)

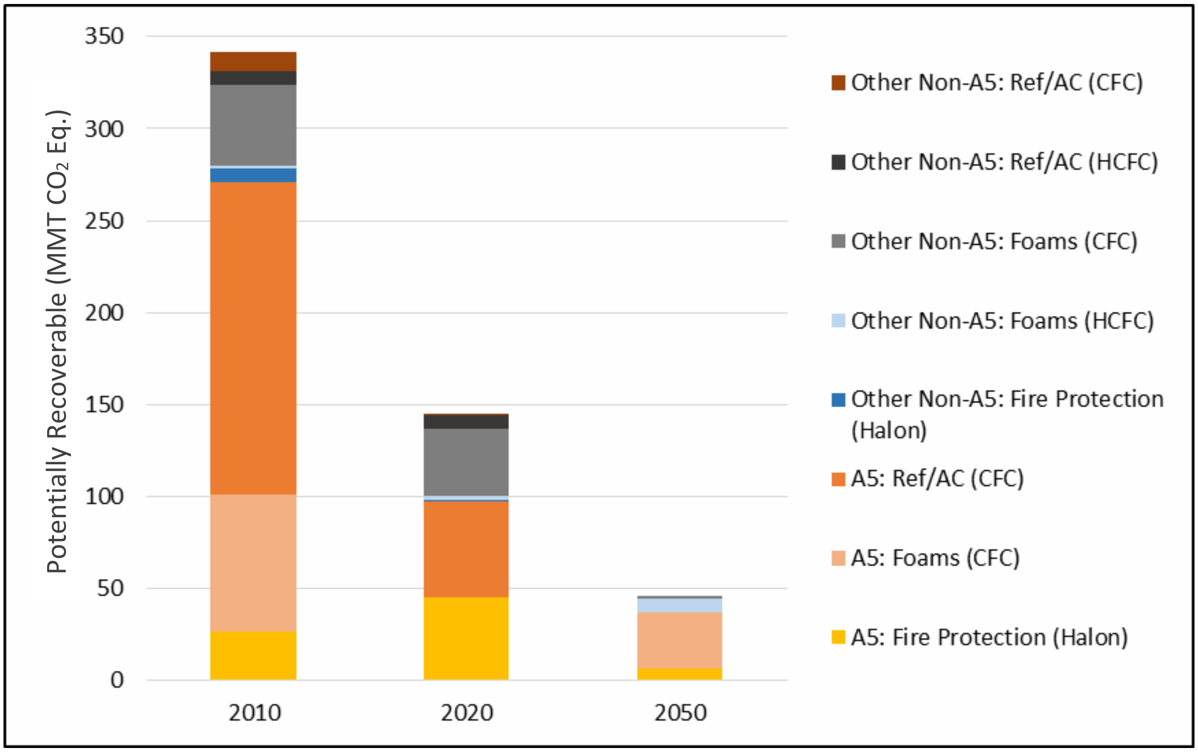


Source: ICF (2010a).

8.1.3. Global

Global estimates are based on EPA's VM and data from the European Commission of ODS potentially recoverable from retired equipment at EOL (ICF 2010b). As shown in Figure 12, the majority of ODS for destruction is expected to be CFCs from refrigeration/AC equipment, particularly from Article 5 countries. HCFCs are not modeled in Article 5 countries because it is assumed that they would be recovered for reuse. GIZ (2018) estimates that the Article 5 countries with the largest ODS banks are China (i.e., approx. 1,200,000 MT ODS), Republic of Korea (i.e., approx. 180,000 MT ODS), Saudi Arabia (i.e., approx. 100,000 MT ODS), Brazil (i.e., approx. 100,000 MT ODS), and India (i.e., approx. 100,000 MT ODS).

Figure 12. Global Estimates of ODS Potentially Available from Retired Equipment at EOL in MMT CO_2 Eq., (2010-2050)



Source: ICF (2010b).

"Other Non-A5" does not include estimates for the United States and EU.

8.2. Availability of Stockpiles

8.2.1. CFCs and HCFCs in Refrigeration/AC Equipment

The estimates of ODS potentially available for destruction in Figure 8, Figure 9, Figure 10, Figure 11, and Figure 12 do not account for any stockpiles since currently there is little information available on existing or future ODS stockpiles. Preliminary research indicates such stockpiles are likely small given the costs required to store surplus ODS and existing demand. The most likely holders of surplus ODS are service companies with cylinders of ODS that were used to service equipment and contain small residual amounts of up to 5 percent of the original contents (ICF 2009a). It is possible that stockpiled materials intended for servicing needs of equipment will not be required. Any such stockpiled material would be eligible for destruction.

8.2.2. Halons in Fire Suppression Equipment

Halons can be easily collected and stored for reuse and disposal. Existing stockpiles of halon can be reclaimed for reuse, destroyed, or transformed to other useful chemical products. In order to maximize halon supply, some countries have implemented halon banks which act as virtual or physical centralized management for

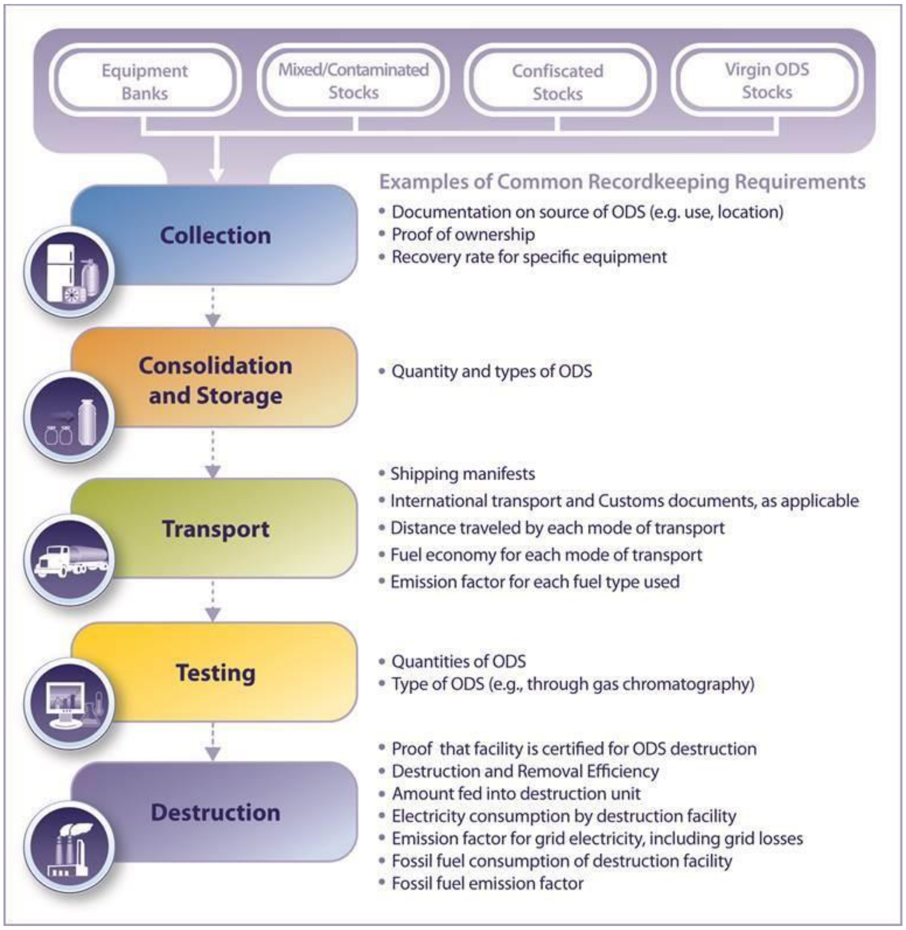
ODS and may involve recovery, reclamation, reissue, transfer and/or storage (HTOC 2018b). Argentina (2 MT stockpile of Halon 1301 in 2018), Australia[23] (94 MT stockpile of Halon 1211 and 168 MT stockpile of Halon 1301 in 2018), China (2,000 MT stockpile of Halon 1211), Japan (16,250 MT of Halon 1301 in 2018), South Africa (30 MT stockpile from 2006 to 2010), South Korea (2,500 MT stockpile of Halon 1301 in 2018) and the United States (North America has an estimated Halon 1301 stockpile of 11,502 MT in 2019) are among those with halon banks (HTOC 2018b, HTOC 2018c). According to the Halons Technical Options Committee (HTOC) estimates, the worldwide bank of Halon 1301 is 37,750 MT (HTOC 2018c).

There is continued global demand for halons particularly for high-value, niche applications such as aviation. Given this continued demand, it may only be appropriate to consider destroying halons that are cross-contaminated and cannot be reclaimed to an acceptable purity level (UNEP 2014a, HTOC 2018a).Regardless, the ACR revised its ODS destruction project standard in 2017 to include halons 1211 and 1301 with eligibility limited to halon 1211 and 1301 sourced from equipment or systems in the United States and halon 1301 not originating from stockpiles (ACR 2017).

9. ODS Management Needs

Many countries may face the challenge of maintaining sound management of ODS through equipment operation and throughout the process of collection, consolidation and storage, transportation, and

Exhibit 1. The Process of ODS Destruction and Illustrative Recordkeeping Requirements



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[23] The Australian National Halon Bank, established in 1993, was set up to maintain a stock of halon for non-defense uses until the transition to alternatives was complete and for the stock to be managed under controlled conditions to prevent accidental releases (Commonwealth of Australia 2019). It also collects and disposes of halon recovered from decommissioned systems.

destruction of waste ODS (see Exhibit 1). In every step of the process, project management, training, recordkeeping, and legal and logistical infrastructure are key to efficient ODS disposal.

Collection

Most countries lack a network of collection facilities to utilize economies of scale when developing national or regional projects for storing and transporting ODS. One territory in Brazil manages waste CFCs across several companies and reclamation centers with different storage standards. Their logistical need was addressed by placing recycling centers in 120 cities, four of which were advanced centers that are capable of consolidating, identifying, and transferring ODS waste to labelled cylinders. Brazil also purchased a fleet of refillable cylinders for collecting ODS because non-refillable cylinders previously made up the refrigerant market (MLF 2014). Streamlining the ODS waste collection process is key to the success of the subsequent technical steps of ODS disposal.

Consolidation and Storage

Data tracking on the size of remaining ODS stock and the amount of destroyed ODS are important for managing the consolidation and storage of waste ODS. Carbon credits can only be earned if proper data tracking procedures are employed throughout the entire project. Another challenge in waste consolidation is the proper and consistent classification of different types of ODS waste. This needs to be addressed in some countries such as China, where waste ODS are classified differently in each province (GIZ 2015). In a project in Indonesia, officials were not able to identify the types of ODS found in unlabeled cylinders, which complicated project management and storage activities (ICF 2013). Consistent tracking of waste from the beginning can help avoid logistical issues later in the waste management process.

Transport

Depending on the land area and available infrastructure, transportation of waste ODS can be the biggest obstacle to proper management. Some countries do not have a road or rail network that would facilitate waste ODS transportation. For instance, Brazil initially lacked proper vehicles or transport containers for ODS waste transport but invested in the required transportation equipment in order to collect and transport waste from a widespread project area (MLF 2014). Technical standards should be established for handling, labelling, and transportation of ODS waste and may include legal requirements if waste ODS are classified as a hazardous substance in the country or if the waste is shipped abroad.

Testing

Properly trained personnel are often needed at each aggregation and destruction facility to test incoming shipments of waste ODS. Mandatory training and certification for technicians can help ensure best practices are followed; however, some countries do not require such training (GIZ 2015). In the country of Georgia, for example, skilled personnel are needed to operate the gas chromatograph used for analysis of incoming waste ODS (MLF 2015). The composition of incoming waste is important because it can determine whether the shipment is eligible for carbon offset credits or if it contains an elevated level of contaminants.

Destruction

A key component in ODS destruction plans is the determination of a suitable facility for the destruction to take place. Consultation with experts is often helpful to select the appropriate means for ODS destruction, because the pros and cons for each option vary depending on the region, resources, and volume of waste ODS. Options to destroy ODS include exporting ODS to other countries, using mobile destruction units, retrofitting existing waste destruction facilities, or building new ODS destruction facilities.

Few countries have existing capacity to destroy ODS, and building or retrofitting new destruction facilities is not always feasible, cost-effective, or environmentally-sound, given the carbon footprint of new construction. In these countries, exporting waste ODS to countries with destruction capabilities is a preferred option.

Although this is usually the easiest method for destruction, some countries ban the import or export of ODS. For instance, Saudi Arabia faces a need for ODS waste management, but it is illegal to export ODS, which means that all waste disposal must happen domestically (ICF 2010b).

Another option is to use mobile destruction units, current models of which can destroy hazardous waste at rates of 5 kg/hour and can provide a cost-effective destruction option for small stockpiles of ODS (MLF 2008). Mobile destruction units are small in size and can be used on one-off projects without the need to secure stable sources of ODS.

Instead of exporting ODS waste or using small mobile units, it can be more cost effective in some cases to build or retrofit a destruction facility if a large volume of ODS is expected to be available for destruction. Retrofitting is an option if there is a cement kiln or a similar facility that can be easily converted. Algeria and Indonesia approached the need for an ODS destruction facility by modifying existing cement kilns to destroy ODS waste after analyzing the cost-benefits of each option. Existing kilns contain similar infrastructure to what is needed to destroy ODS, which simplifies the conversion process (MLF 2014).

International Cooperation

Countries collaboration may facilitate ODS management by utilizing existing infrastructure and minimizing the need for construction of new facilities. For example, the Nordic Environmental Financing Corporation planned an initiative to recover and destroy ODS from appliances at EOL in the greater Moscow region, using an existing retailer network for collection. The units were intended to be transported to Finland for recovery and destruction using existing idle capacity of Finnish trucks that deliver new refrigerators to Russia and return empty. Projects like this, which minimize the implementation of new infrastructure by utilizing existing capacity, are a way to destroy ODS at lower cost (ICF 2010b).

Countries can work to facilitate compliance with the legal requirements relevant for the transport of waste ODS, as in the case of a UNDP-subsidized project in Nepal that used a third party company to execute the collection and transport of confiscated ODS to the United States for destruction. It was reported that a primary challenge during project implementation was the lengthy process to get approval for the export of the ODS to the United States because of the need for Nepalese parliamentary clearance (UNEP 2017). See Appendix A for further information on transboundary movement (TBM) of ODS.

An additional example of ongoing international cooperation for the disposal of ODS is the “Moana Taka Partnership” signed in March 2018. This partnership between the Secretariat of the Pacific Regional Environment (SPREP) and the China Navigation Company (CNCo) will result in pro bono transportation of ODS, among other recyclable waste, from Pacific island countries (27 eligible countries) to ports in Asia Pacific to be sustainably treated and recycled (SPREP 2018).

10. Implications for Addressing HFC Disposal

In October 2016, Parties agreed on the Kigali Amendment to the Montreal Protocol to phasedown HFC production and consumption. The Amendment also includes provisions to destroy HFC-23 emissions generated in HFC and HCFC production facilities to the extent practicable using technology approved by the Parties. This section discusses the similarities in waste management between ODS and HFCs and the current and projected quantities of HFC available for destruction.

10.1. Sources, Practices, Technologies, and Costs: Parallels to ODS

Sources

The sources of recoverable HFCs are similar to those for ODS, although the time period in which they will be available for recovery varies based on the country. Projections of the potential sources of recoverable HFCs and when they will become available are addressed in the next section.

Practices

The best installation, handling, recovery, recycling, reclamation, and disposal practices are identical between ODS and HFCs (see Section 3). However, individual governments do not necessarily regulate the refrigerant management practices the same between ODS and HFCs.

Several countries have implemented HFC refrigerant management practices. The European Union introduced an updated F-gas regulation in 2015 that helps to prevent emissions in existing equipment by requiring checks, proper servicing, and recovery of the gases at the end of the equipment's life, similar to what was already required for ODS (EU 2014). In 2017, Canada issued its *Regulations Amending the Ozone-depleting Substances and Halocarbon Alternatives Regulations,* which requires the proper destruction or recovery for recycling and reclamation of HFCs that are no longer in use, as well as outlines the schedule for HFC phasedown (Government of Canada 2017). In the United States, Section 608 of the Clean Air Act prohibits the knowing release of refrigerant during the maintenance, service, repair, or decommissioning of refrigeration/AC equipment. In 2016, the U.S. EPA updated the existing requirements related to ODS refrigerants and extended them to include HFCs (EPA 2016a). In February 2020, the U.S. EPA issued the final rule *Protection of Stratospheric Ozone: Revisions to the Refrigerant Management Program's Extension to Substitutes* that rescinds the 2016 extension of the leak repair provisions to appliances using substitute refrigerants (e.g., HFCs) (EPA 2020c). The U.S. EPA 2020 rule maintains provisions on the sales restriction and technician certification requirement, safe disposal requirements, evacuation requirements, reclamation standards, and requirement to use certified recovery equipment for substitute refrigerants (e.g., HFCs) (EPA 2020c).

Technologies

Incineration and plasma arc destruction facilities that destroy ODS are also capable of accepting HFCs for destruction. Tsang et al. (1998) assessed the relative thermal stability of fluorinated compounds, including HFCs, as compared to the thermal stability of chlorinated compounds and concluded that fluorinated compounds can be destroyed at high efficiency by incineration. Modeled required temperatures for destruction of HFCs to 99.99 percent DRE in Tsang et al. (1998) are similar to modeled required temperatures for HCFCs and halons in Lamb et al. (2010) (see Appendix D).

Other non-incineration technologies are also feasible for destruction/conversion of HFCs. Some of these technologies use chemical reactions or catalysts to dissociate chemical bonds.

Parties to the Montreal Protocol approved, at the 30th MOP and through Decision XXX/6, approved destruction technologies for HFCs. These technologies were evaluated by the 2018 TFDT and include technologies approved for ODS destruction and other technologies such as Electric Heater and Furnaces Dedicated to Manufacturing. A total of 12 and eight destruction technologies were approved for group I and group II (i.e., HFC-23) concentrated sources, respectively, and two for group I diluted sources. HFC destruction technologies are included in Table 16 and all technologies are described in Appendix C.

Table 16. Approval Status of Available Destruction Technologies

Technology	Applicability[a] and Required Destruction and Removal Efficiency (DRE)[b]		
	Concentrated HFCs[c]		Dilute ODS[d]
	HFCs[e] (99.99%)	HFC-23[f] (99.99%)	HFCs[e] (95%)
Thermal Oxidation (Incineration) Technologies			
Cement Kilns	**Approved**	Not Determined	Not Applicable
Gaseous/Fume Oxidation	**Approved**	**Approved**	Not Applicable
Liquid Injection Incineration	**Approved**	**Approved**	Not Applicable
Municipal Solid Waste Incineration	Not Applicable	Not Applicable	**Approved**
Porous Thermal Reactor	**Approved**	Not Determined	Not Applicable
Reactor Cracking	**Approved**	**Approved**	Not Applicable
Rotary Kiln Incineration	**Approved**	**Approved**	**Approved**
Thermal Decay of Methyl Bromide	Not Applicable	Not Applicable	Not Applicable
Electric Heater	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Fixed Hearth Incinerator	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Furnaces Dedicated to Manufacturing	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Plasma Technologies			
Argon Plasma Arc	**Approved**	**Approved**	Not Applicable
Inductively Coupled Radio Frequency Plasma	Not Determined	Not Determined	Not Applicable
Microwave Plasma	Not Determined	Not Determined	Not Applicable
Nitrogen Plasma Arc	**Approved**	**Approved**	Not Applicable
Portable Plasma Arc	**Approved**	Not Determined	Not Applicable
Steam Plasma Arc	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Air Plasma Arc	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Alternating Current Plasma	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
CO_2 Plasma	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Conversion (Non-Incineration) Technologies			
Chemical Reaction with H_2 and CO_2	**Approved**	**Approved**	Not Applicable
Gas Phase Catalytic De- halogenation	**Approved**	Not Determined	Not Applicable
Superheated Steam Reactor	**Approved**	**Approved**	Not Applicable
Thermal Reaction with Methane	Not Determined	Not Determined	Not Applicable
Catalytic Destruction	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed
Solid Alkali Reaction	Not Yet Reviewed	Not Yet Reviewed	Not Yet Reviewed

Sources: UNEP (2011), UNEP (2015b), HTOC (2018a), TEAP (2018c), and UNEP (2018).

[a] Not approved indicates the technology was reviewed and did not meet the TEAP recommendations for the process; Not applicable indicates the technology is not feasible for the process; Not determined indicates the technology was not reviewed for destruction of that compound; Not yet reviewed indicates the technology has not been fully reviewed by the Parties to the Montreal Protocol.

[b] Per the TFDT screening process, technologies must be demonstrated to achieve the required DRE while also satisfying emissions criteria. See TEAP (2002) for more information.

[c] Concentrated sources of HFC refer to virgin, recovered, and reclaimed HFCs.

[d] Dilute sources of HFCs refer to HFC contained in a matrix of a solid (e.g., foam).

[e] Under the Montreal Protocol, these substances are listed in Annex F, Group I.

[f] Under the Montreal Protocol, these substances are listed in Annex F, Group II.

Costs

Costs associated with HFC waste management are expected to be similar to that of ODS. HFCs are collected from appliances and other sectors using the same procedures outlined for ODS. In addition, HFC destruction costs are expected to be similar because the incineration and plasma arc destruction technologies are capable of destroying the chemical at the existing operating conditions.

HFCs are currently often destroyed as part of mixed refrigerant projects, where ODS destruction is the focus. For example, a private company acquired shipments of mixed refrigerant through its buyback program consisting of CFCs, HCFCs, HFCs, and hydrocarbons (HCs). Containers received from the buyback program were consolidated into larger tanks and shipped to a destruction facility. The company received carbon credits from the Chicago Climate Exchange (CCX) for the destruction of the ODS components of the mixture (ICF 2010b). Although the destruction of HFC material was not eligible for offset credits, it was successfully destroyed as part of the refrigerant mixture.

The sale of carbon offset credits earned through compliance and voluntary markets can be a method of financing HFC destruction if they are no longer produced and when there are no country-specific regulatory requirements for HFC destruction. Currently, credits are available through the ACR which developed a protocol for the destruction of high-GWP (e.g., CFC-11, CFC-12, HCFC-22, HFC-134a, and HFC-245fa) insulation foams from appliances, buildings, or other sources (ACR 2017). The blowing agent must be destroyed according to the procedures detailed in the protocol in order to be eligible for credits.

10.2. Current and Projected Quantities Available for Destruction

In Article 5 countries, ODS are still commonly used in systems and equipment. In non-Article 5 countries, HFCs have largely replaced ODS in equipment. Equipment containing HFCs have lifetimes up to 30 years. HFC-containing equipment is entering the market so the installed base of HFC-containing equipment and amount of HFCs recovered at EOL is expected to grow for another 20 years.

Some older systems or equipment containing HFCs, or retrofitted with HFC containing blends, are nearing their EOL and are expected to be decommissioned with the remaining charge to be recovered. Most recovered material is expected to be reclaimed or recycled to service existing systems[24] in the installed base. However, materials that are recoverable from equipment and products may also be available for destruction.

Using the same methodology discussed in Section 8, the VM was used to develop estimates of recovery quantities of HFC refrigerants, foam blowing agents, and fire suppression agents potentially available for destruction from retired equipment from 2010 through 2050 for the United States (see Figure 13). As expected, the quantity of HFCs recoverable from retired equipment/products at EOL is expected to continue to increase through 2030, when ODS are completely phased out, and then become relatively stable.

The model's assumptions dictate that mobile AC (MACs or MVAC) is the primary driver in potentially recoverable HFCs until 2020. In 2030, potential recovery of HFCs at EOL reaches a value of approximately 41,000 MT due mainly to commercial and residential stationary AC equipment. From 2030 to 2050, most of the HFCs potentially recoverable will come from commercial and residential stationary AC equipment, IPR/CS, and commercial refrigeration.

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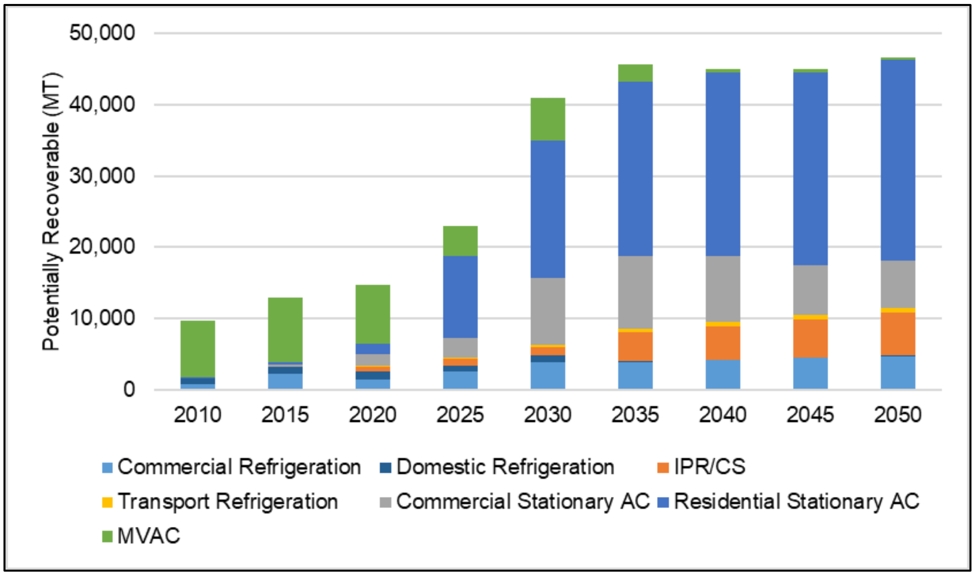
[24] Reclamation is important when handling HFC blends (e.g., R-404A, R-407C, R-410A) because previous evaporation of different components at different rates during leaks or other releases may lead to the refrigerant remaining in the equipment to be off-specification (i.e., one component may be present in higher or lower amounts than allowed).

Figure 13. Quantity of HFCs Potentially Recoverable from Retired U.S. Equipment at EOL (2010-2050)[a]



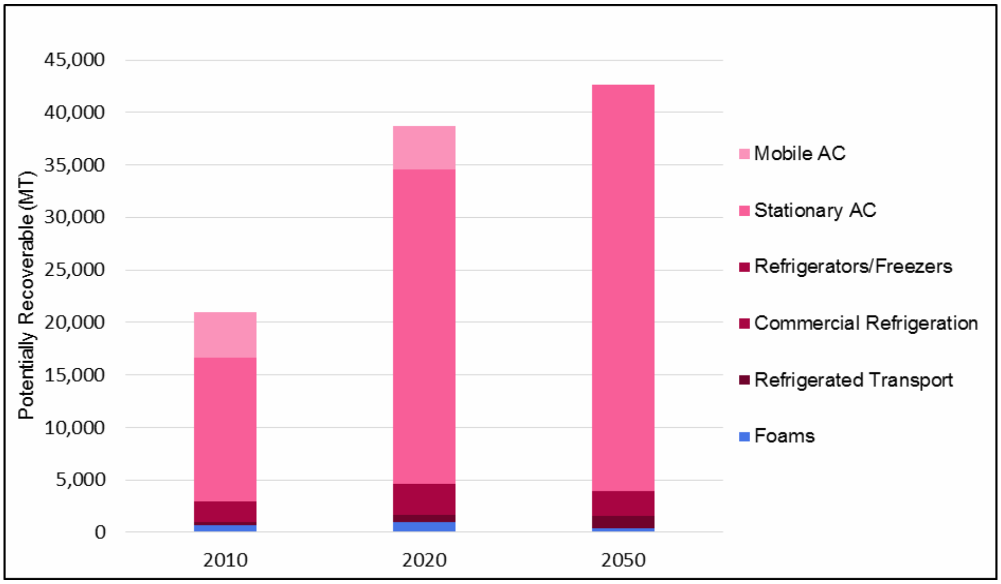
Source: EPA (2020b).

[a] As of October 2019, HFCs are not being systematically recovered for destruction in the United States.

As another example, Figure 14 shows the quantities of HFCs estimated to be potentially recoverable in the EU from equipment at EOL in 2010, 2020, and 2050, based on a bottom-up modeling methodology used to estimate banks (ICF 2010a). This analysis is based on relevant EU regulations and assumes that ODS from foam applications is potentially recoverable. These estimates demonstrate that less than 43,000 MT of HFCs will be potentially recoverable from refrigeration/AC equipment at EOL in 2050.

Approximately 360 MT of HFCs will be potentially recoverable from foam products at EOL in 2050 (and higher amounts in 2020), although recovery from foam applications typically require a medium to high effort.

Figure 14. Quantity of HFCs Potentially Recoverable from Retired EU Equipment at EOL (2010-2050)



Source: ICF (2010a).

The capacity at destruction facilities in the United States, European Union, and globally are expected to be sufficient to destroy the potentially available HFC banks.

11. References

Air-Conditioning, Heating, and Refrigeration Institute (AHRI). 2017. AHRI Standard 700-2017 with Addendum 1, Specifications for Refrigerants. September 2017. Available online at: http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_700_2017_Add_1.pdf.

Alves, Anderson. April 7-11, 2014. ODS Destruction Montreal Protocol Unit/Chemicals. UNDP. Available online at: http://www.pnuma.org/ozono/Reuniones%20Anuales%20Conjuntas%20y%20Talleres/SURINAME%202014/Presentaciones_Dia_2/Anderson_Alves_UNDP_Presentation_SRV_Destruction.pdf.

American Carbon Registry (ACR). 2017. 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. July 2017. Available online at: http://americancarbonregistry.org/carbon-accounting/standards-methodologies/destruction-of-ozone- depleting-substances-and-high-gwp-foam/acr-destruction-of-ods-and-high-gwp-foam-july-2017-v1- 0.pdf.

American Carbon Registry (ACR). 2019. Personal Communication between ACR (Eric Ripley) and ICF (Mark Wagner and Paula Garcia Holley) on October 18, 2019.

American Carbon Registry (ACR). 2020a. Project Credits Issued. Database accessed August 2020. Available online at: https://acr2.apx.com/myModule/rpt/myrpt.asp?r=112.

American Carbon Registry (ACR). 2020b. Personal Communication between ACR (Eric Ripley) and ICF (Mark Wagner and Paula Garcia Holley) on July 29, 2020.

ASADA. Undated. Technical Information. Undated. Available online at: http://www.asada.co.jp/english/e-catalog/hvac/index_f.html#106.

Batchelor, T.A. and V. Smirnov. 2010. Evaluation of GEF-Funded UNEP and UNDP Projects that Phased Out Ozone-Depleting Substances in Countries with Economies in Transition. Terminal Evaluation. Report to the UNEP Evaluation and Oversight Unit, Nairobi. March 2010. 749 pp.

Berwald, J. 2019. One overlooked way to fight climate change? Dispose of old CFCs. April 2019. Available online at: https://www.nationalgeographic.com/environment/2019/04/disposing-old-cfcs-refrigerants-reduces-climate-change-greenhouse-gases-cheaply/.

Chill-Tek, Inc. 2020a. Refrigerant Disposal. Available online at: https://www.chilltek.com/disposal/.

Chill-Tek, Inc. 2020b. Personal Communication between Chill-Tek, Inc. (Michael Gerhart) and ICF (Paula Garcia Holley and Mark Wagner) in October 2020.

California Air Resources Board (CARB). 2017. Early Action Offset Credits. March 2017. Available online at: https://www.arb.ca.gov/cc/capandtrade/offsets/earlyaction/credits.htm.

California Air Resources Board (CARB). 2019. Summary Results Report. California Cap-and-Trade Program, and Québec Cap-and-Trade System August 2019 Joint Auction #20. August 2019. Available online at: https://ww3.arb.ca.gov/cc/capandtrade/auction/aug-2019/summary_results_report.pdf.

Climate Action Reserve (CAR). 2017. ODS Destruction Protocol Stakeholder Meeting: Ontario and Quebec. Presented on March 3, 2017.

Climate Action Reserve (CAR). 2020. Voluntary Offset Project Registry. Database accessed on August 2020. Available online at: https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=112.

Commonwealth of Australia. 2019. Australian Halon Management Strategy 2019. Available online at: https://www.environment.gov.au/system/files/resources/8cb927dc-8da9-4bc5-a396-d079d2f3f133/files/australian-halon-management-strategy-2019.pdf.

Deloitte. 2014. Development of Guidance on Extended Producer Responsibility (EPR): Final Report. Prepared by BIO by Deloitte for the European Commission – Directorate-General for Environment. Available online at: https://www2.deloitte.com/content/dam/Deloitte/fr/Documents/sustainability-services/deloitte_sustainability-les-filieres-a-responsabilite-elargie-du-producteur-en-europe_dec-15.pdf.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). 2011. Capturing ozone-depleting substances and greenhouse gases form household refrigerator: Introduction of a comprehensive refrigerator recycling programme in Brazil. Available online at: http://star-www.giz.de/cgi-bin/getfile/53616c7465645f5fbc9b49f49f422c7bc331c464c52558384b6c363e96a1eca126f567f82ebd3c5a9cef7502c0518dfb9a2ca0c089739bf8c01ec1b31b8d5add6c4f7857003e648d/giz2011-0681en-proklima-brazil.pdf.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). 2015. Management and Destruction of Existing Ozone Depleting Substances Banks. August 2015. Available online at: http://star-www.giz.de/cgi-bin/getfile/53616c7465645f5f672456942ce0959439796fd86689c1465610f66a12fcaf75457153f919f17c69aeb32be07b7dc87ad18011aaf1c43344ca13ffdb1f1b24ab/giz2019-0137en-study-ods-banks-management-proklima.pdf.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). 2017a. Global Roadmap on ODS Bank Management: Management and Destruction of Existing Ozone Depleting Substances Banks. Available online at: http://star-www.giz.de/cgi-bin/getfile/53616c7465645f5fbfd558da4dd10798db1b3b3c7ade167ae247f1e9cfcc1e26dc3ce202f4801226d964221c0769e596d43ad4266cb0c7d05a9e681ec59f1285/giz2018-0362en-ods-global-roadmap.pdf.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). 2017b. Guideline for the Transboundary Movement of ODS Waste. March 2017. Available online at: http://star-www.giz.de/cgi-bin/getfile/53616c7465645f5f6a7c61500594a2c2a8a5d2d7731bee2f3a4db694b7ae5248206dd53d811670d0a5ef54e7a93bd3ad40572b7da9a4b397aef82c2e2a5a47f8/giz2018-0367en-no4-guideline-ods-transboundary-movement.pdf.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). 2018. Global banks of ozone depleting substances A country-level estimate. Available online at: http://star-www.giz.de/cgi-bin/getfile/53616c7465645f5ff2842c6527dc79859b0f14ccfe1d95e6f07ccfad5bc443377d5dc6af713787476f2c59e8d7f439f2e53b8f4c34cbf9aefb0a8657c052571a/giz2018-0361en-ods-country-level-estimate.pdf.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). 2019. Personal Communication between GIZ (Monica Silva, Miriam Frisch, and Verena Maas) and ICF (Mark Wagner and Paula Garcia Holley) in December 2019.

Ecosystem Marketplace. 2017. Unlocking Potential: State of the Voluntary Carbon Markets 2017. May 2017. Available online at: http://www.forest-trends.org/documents/files/doc_5591.pdf#.

Ecosystem Marketplace. 2018. Voluntary Carbon Market Insights: 2018 Outlook and First-Quarter Trends. July 2018. Available online at: https://www.forest-trends.org/wp-content/uploads/2018/09/VCM-Q1-Report_Full-Version-2.pdf.

Ecosystem Marketplace. 2019. Financing Emissions Reductions for the Future: State of the Voluntary Carbon Markets 2019. December 2019. Available online at: https://www.forest-trends.org/wp-content/uploads/2019/12/SOVCM2019.pdf.

Environmental Investigation Agency (EIA). 2014. New Trends in ODS Smuggling. Presented to the 26th Meeting of the Montreal Protocol. 17-21 November 2014. Available online at: https://eia- international.org/wp-content/uploads/EIA-New-Trends-in-ODS-Smuggling-lo-res.pdf.

EOS Climate. 2016. Personal Communication between Jeff Cohen, EOS Climate, and ICF. December 13, 2016.

European Commission. 2019. Evaluation of Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer. November 2019. Available online at: https://ec.europa.eu/clima/sites/clima/files/ozone/docs/swd_2019_406_en.pdf.

European Environment Agency (EEA). 2012. Ozone-depleting substances 2011: Aggregated data reported by companies on the production, import, export, destruction and use of ozone-depleting substances in the European Union – Summary. Available online at: https://www.eea.europa.eu/publications/ozone-depleting-substances-2011-summary.

European Environment Agency (EEA). 2013. Ozone-depleting substances 2012: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union. Available online at: https://www.eea.europa.eu//publications/ozone-depleting-substances.

European Environment Agency (EEA). 2014. Ozone-depleting substances 2013: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union. Available online at: https://www.eea.europa.eu//publications/ozone-depleting-substances-2013.

European Environment Agency (EEA). 2015. Ozone-depleting substances 2014: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union. Available online at: https://www.eea.europa.eu//publications/ozone-depleting-substances-2014.

European Environment Agency (EEA). 2016. Ozone-depleting substances 2015: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union. Available online at: https://www.eea.europa.eu//publications/ozone-depleting-substances-2015.

European Environment Agency (EEA). 2017. Ozone-depleting substances 2016: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union. Available online at: https://www.eea.europa.eu//publications/ozone-depleting-substances-2016.

European Environment Agency (EEA). 2018. Ozone-depleting substances 2018: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union, 2006-2017. Available online at: https://www.eea.europa.eu/publications/ozone-depleting-substances-2018.

European Environment Agency (EEA). 2019. Ozone-depleting substances 2019: Aggregated data reported by companies on the import, export, production, destruction and feedstock and process agent use of ozone-depleting substances in the European Union, 2006-2018. Available online at: https://www.eea.europa.eu//publications/ozone-depleting-substances-2019.

European Parliament and the Council of the European Union (EU). 2009. Regulation (EC) No 1005/2009 on Substances that Deplete the Ozone Layer. Official Journal of the European Union. September 2009. Available online at: http://eur-lex.europa.eu/legal- content/EN/TXT/HTML/?uri=CELEX:32009R1005&from=EN.

European Parliament and the Council of the European Union (EU). 2012. Directive (EU) 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE). Official Journal of the European Union. July 2012. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0019&from=EN.

European Parliament and the Council of the European Union (EU). 2014. Regulation (EU) No 517/2014 on Fluorinated Greenhouse Gases and Repealing Regulation (EC) No 842/2006. Official Journal of the European Union. April 2014. Available online at: http://eur-lex.europa.eu/legal-content/EN/ TXT/ PDF/?uri=CELEX:32014R0517&from=EN.

Girgis, M. 2018. PLASCON® process – Plasma arc technology. Toxfree Australia. January 2018. Available online at: http://conf.montreal-protocol.org/meeting/oewg/oewg-40/presession/SiteAssets/Australia_Decision-XXIX-4_1.pdf.

Global Environment Facility (GEF). 2017a. World Ozone Day 2017: celebrating 30 years of the Montreal Protocol. Available online at: https://www.thegef.org/news/world-ozone-day-2017-celebrating-30-years-montreal-protocol.

Global Environment Facility (GEF). 2017b. Request for CEO Endorsement. 2017. Available online at: https://www.thegef.org/sites/default/files/project_documents/1-11-17_-_Rev_CEO_Endorsement_Doc.pdf.

Global Environment Facility (GEF). 2020. Personal Communication between GEF (Evelyn Swain) and ICF (Mark Wagner and Paula Garcia Holley) on July 30, 2020.

Government of Australia. 2020a. Personal Communication between the Government of Australia (Annie Gabriel and Patrick McInerney) and the U.S. EPA (Nancy Akerman) on September 23, 2020.

Government of Australia. 2020b. Personal Communication between the Government of Australia (Annie Gabriel and Patrick McInerney) and the U.S. EPA (Nancy Akerman) on October 19, 2020.

Government of Canada. 2017. Regulations Amending the Ozone-depleting Substances and Halocarbon Alternatives Regulations. Part II: Vol. 151, No. 21. Available online at: http://www.gazette.gc.ca/rp-pr/p2/2017/2017-10-18/html/sor-dors216-eng.html.

Government of India Ministry of Environment, Forest and Climate Change (Ozone Cell). 2016. Control of Emission/Venting of Hydrofluorocarbon (HFC)-23, Produced as By-product While Manufacturing of Hydrochlorofluorocarbon (HCFC)-22, in the Atmosphere. October 13, 2016. Available online at: http://www.ozonecell.com//downloadfile_2.jsp?filename=1482401969634-ORDER-13-OCTOBER-2016.pdf.

Government of Japan. 2015. Submission of Japan's Intended Nationally Determined Contribution (INDC). July 2015. Available online at: https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/Japan/1/20150717_Japan's%20INDC.pdf.

Government of Quebec. 2019. Register of Offset Credit Projects. July 2019. Available online at: http://www.environnement.gouv.qc.ca/changements/carbone/credits-compensatoires/registre_creditscompensatoires-en.htm.

Halons Technical Options Committee (HTOC). 2018a. Technical Note #5 Destruction Technologies for Halons and Other Halogenated Gaseous Fire Extinguishing Agents. December 2018. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available online at https://ozone.unep.org/sites/default/files/2019-04/HTOC_technical_note5_2018.pdf.

Halons Technical Options Committee (HTOC). 2018b. Halons Technical Options Committee 2018 Assessment Report Volume 3. December 2018. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available online at https://ozone.unep.org/sites/default/files/2019-04/HTOC_supplement_report2_2018.pdf.

Halons Technical Options Committee (HTOC). 2018c. Halons Technical Options Committee 2018 Assessment Report Volume 1. December 2018. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available online at https://ozone.unep.org/sites/default/files/2019-04/HTOC_assessment_2018.pdf.

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. Available online at: http://unep.ch/ozone/data_reporting/USA-Decision-XX-7-ODS-Destruction.pdf.

ICF International. 2009b. The U.S. Phaseout of HCFCs: Projected Servicing Needs in the U.S. Air- Conditioning and Refrigeration Sector. Prepared by ICF International for the U.S. Environmental Protection Agency. December 2009. Available online at: https://pdfs.semanticscholar.org/81af/f1b8435fdccdb45b71f5bdcaafea897711fc.pdf.

ICF International. 2010a. Identifying and Assessing Policy Options for Promoting the Recovery and Destruction of Ozone Depleting Substances (ODS) and Certain Fluorinated Greenhouse Gases (F-Gases) Banked In Products and Equipment. Prepared by ICF International for the European Commission. May 2010. Available online at: https://ec.europa.eu/clima/sites/clima/files/ozone/docs/ods_f- gas_destruction_report_en.pdf.

ICF International. 2010b. Study on Financing the Destruction of Unwanted Ozone-Depleting Substances through the Voluntary Carbon Market. Final Report. Prepared by ICF International for the World Bank. February 2010. Available online at: http://www.multilateralfund.org/sites/61/Document%20Library2/1/61Inf2.pdf.

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.

ICF International. 2013. Prepared by ICF International for the World Bank. Establishment of a Private- Public Financing System for Disposal of ODS for the Philippines.

International Carbon Action Partnership (ICAP). 2019. Emissions Trading Worldwide Status Report 2019. Berlin: ICAP. Available online at https://icapcarbonaction.com/en/?option=com_attach&task=download&id=625.

International Civil Aviation Organization (ICAO). N.d. What is CORSIA and how does it work? Available online at: https://www.icao.int/environmental-protection/pages/a39_corsia_faq2.aspx.

Japan Ministry of the Environment (MOE). 2016. Let’s Protect the Ozone Layer 2016 Edition. 2016. Available online at: https://www.env.go.jp/en/earth/ozone/leaf2016/Full.pdf.

Japan Ministry of the Environment (MOE). 2020. Personal communication between the Japan MOE (Kohei Senoo) and the U.S. EPA (Nancy Akerman) in October 2020.

Lamb, C., Dellinger, B., Wagner, M., &, Lanza, R. (2008). Incinerability of Halons and HCFCs: Theoretical Calculations of DRE and Ozone-Depleting or Global-Warming Gases, Paper # 13. Presented at Twenty- seventh Annual International Conference on Thermal Treatment Technologies, Montreal, Canada, May 12–16, 2008.

Lamb, C., Dellinger, B., Wagner, M., &, Lanza, R. (2010). Incinerability of Halons and HCFCs: Theoretical Calculations of DRE and Ozone-Depleting or Global-Warming Gases, Environmental Engineering Science, Volume 27, Number 7, 2010.

Levitan Dave. 2010. China, India Opposed to Closing $5 Billion Loophole in Kyoto Treaty. Inside Climate News. June 2010. Available online at: https://insideclimatenews.org/news/20100616/china-india- opposed-closing-5-billion-loophole-kyoto-treaty?page=show.

Matheson, C. and Tamblyn, G. 2018. Nova Scotia Joins Western Climate Initiative Inc. Available online at: https://novascotia.ca/news/release/?id=20180514001.

Medical and Chemical Technical Options Committee (MCTOC). 2018. 2018 Assessment Report. December 2018. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available online at: https://ozone.unep.org/sites/default/files/2019-04/MCTOC-Assessment-Report-2018.pdf.

Midwest Refrigerants. 2017. Groundbreaking Fluorocarbon Conversion Technology Advances under Montreal Protocol. December 2017. Available online at: http://www.midwestrefrigerants.com/MWR-UNDP_PRESS_RELEASE_12-6-17.pdf.

Miller, M., &, Batchelor, T. 2012a. Information Paper on Feedstock Uses of Ozone-Depleting Substances. Produced for the European Commission under Service Contract. December 2012. Available online at: https://ec.europa.eu/clima/sites/clima/files/ozone/docs/feedstock_en.pdf.

Miller, M., &, Batchelor, T. 2012b. Information Paper on Funding Sources for Measures to Protect the Global Environment. Produced for the European Commission under Service Contract. December 2012. Available online at: https://ec.europa.eu/clima/sites/clima/files/ozone/docs/funding_information_en.pdf.

Multilateral Fund (MLF). 2008. Study on the Collection and Treatment of Unwanted Ozone-Depleting Substances in Article 5 and Non-Article 5 Countries. Prepared by ICF International for the Multilateral Fund of the Montreal Protocol. May 2008.

Multilateral Fund (MLF). 2014. Pilot Demonstration Project on ODS Waste Management and Disposal. April 2014. Available online at: http://www.multilateralfund.org/72/English/1/7219.pdf.

Multilateral Fund (MLF). 2015. Desk Study on the Evaluation of the Pilot Demonstration Projects On ODS Disposal and Destruction. October 2015. Available online at: http://www.multilateralfund.org/75/English/1/7510.pdf.

Multilateral Fund (MLF). 2017a. Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol: Seventy-ninth Meeting–Reports on Projects with Specific Reporting Requirements. July 3-7, 2017. Available online at: http://www.multilateralfund.org/79/English/1/7914.pdf.

Multilateral Fund (MLF). 2017b. Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol: Seventy-ninth Meeting– Key Aspects Related to HFC-23 By-Product Control Technologies (Decision N°78/5). July 3-7, 2017. http://www.multilateralfund.org/79/English/1/7948.pdf.

Multilateral Fund (MLF). 2018a. Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol: Eighty-second Meeting – Cost-Effective Options for Controlling HFC-23 By-Product Emissions (Decision 81/68(e)). November 1, 2018. Available online at: http://multilateralfund.org/82/English/1/8268.pdf.

Multilateral Fund (MLF). 2018b. Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol: Eighty-second Meeting– Synthesis Report on the Pilot ODS Disposal Projects (Decision 79/18(e)). December 3-7, 2018. Available online at: http://www.multilateralfund.org/82/English/1/8221.pdf.

Multilateral Fund (MLF). 2019. Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol: Eighty-fourth Meeting – Final Report on the Evaluation of the Pilot Demonstration Projects on OD Disposal and Destruction. December 16-20, 2019. Available online at: http://www.multilateralfund.org/84/English/1/8411.pdf.

NAMA Facility. 2020. Colombia – NAMA for the Domestic Refrigeration Sector. Available online at: https://www.nama-facility.org/projects/colombia-nama-for-the-domestic-refrigeration-sector/.

National Fire Protection Association (NFPA). 2008. Halon Frequently Asked Questions. 2008. Available online at: http://www.nfpa.it/d_faq.htm.

Ontario Ministry of the Environment, Conservation and Parks. 2018. Ontario Introduces Legislation to End Cap and Trade Carbon Tax Era in Ontario. Available online at: https://news.ontario.ca/ene/en/2018/07/ontario-introduces-legislation-to-end-cap-and-trade-carbon-tax-era-in-ontario.html.

Organization for Economic Co-Operation and Development (OECD). 2011. Environmental Taxation: A Guide for Policy Makers. Available online at: http://www.oecd.org/env/tools-evaluation/48164926.pdf.

OzonAction. n.d. GWP-OD Calculator. United Nations Environment Programme (UNEP). Available online at: https://www.unenvironment.org/ozonaction/resources/gwp-odp-calculator/gwp-odp-calculator.

Refrigerant Reclaim Australia (RRA). 2012. Destruction of Waste ozone Depleting Substances and Synthetic Greenhouse Gases Program. 2012. Available online at: https://refrigerantreclaim.com.au/wp-content/uploads/2013/02/RRA-Destruction-Consultation-Paper-Response.pdf.

Refrigerant Reclaim Australia (RRA). 2019. Annual Report 2017 – 2018. 2019. Available online at: https://refrigerantreclaim.com.au/wp-content/uploads/2019/RRA%2048814%2017-18%20Annual%20Report%20Web%20AW.pdf.

Refrigerant Reclaim Australia (RRA). n.d. Refrigerant Reclaim Australia. Available online at: https://refrigerantreclaim.com.au/.

Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC). 2019. Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee 2018 Assessment Report. February 2019. Nairobi, Kenya: United Nations Environment Programme (UNEP). Available online at: https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf.

Rigid and Flexible Foams Technical Options Committee (FTOC). 2019. Rigid and Flexible Foams Technical Options Committee 2018 Assessment Report. March 2019. United Nations Environment Programme (UNEP). Available online at: https://ozone.unep.org/sites/default/files/2019-04/FTOC-assessment-report-2018.pdf.

Robin, Mark. 2012. DuPont Chemicals and Fluoroproducts. ASTM Standards for Halon 1211. November 2012. Available online at: https://www.fire.tc.faa.gov/pdf/systems/Nov12Meeting/Robin-1112-Halon1211ASTMStds.pdf.

Secretariat of the Pacific Regional Environment Programme (SPREP). 2018. "Moana Taka Partnership" Unfolds Exciting Recycling Possibilities for the Pacific Islands. March 2018. Available online at: https://www.sprep.org/news/moana-taka-partnership-unfolds-exciting-recycling-possibilities-pacific-islands.

Sirkin, Sam. 2016. Personal communication between Sam Sirkin and ICF. November 18, 2016.

Stakeholders in Methyl Bromide Reduction (STIMBR). 2019. Response to an additional information request from the EPA. June 2019.

Stanley, K.M., Say, D., Mühle, J., et al. 2020. Increase in global emissions of HFC-23 despite near-total expected reductions. *Nature Communications*, 11:397. Available online at: https://doi.org/10.1038/s41467-019-13899-4.

Technology and Economic Assessment Panel (TEAP). 2002. Report of the UNEP Technology and Economic Assessment Panel (TEAP), Report of the Task Force on Destruction Technologies. Montreal Protocol on Substances that Deplete the Ozone Layer. April 2002. Available online at: https://ozone.unep.org/sites/default/files/2019-05/TEAP02V3b%20%281%29.pdf.

Technology and Economic Assessment Panel (TEAP). 2009. UNEP Technology and Economic Assessment Panel (TEAP) Task Force Decision XX/7 – Phase 2 Report. Environmentally Sound Management of Banks of Ozone-Depleting Substances. October 2009. Available online at http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports/teap-october-2009- decisionXX-7-task-force-phase2-report.pdf.

Technology and Economic Assessment Panel (TEAP). 2018a. Report of the Technology and Economic Assessment Panel Volume 2 Decision XXIX/4 TEAP Task Force Report on Destruction Technologies for Controlled Substances. Nairobi, Kenya: United Nations Environment Programme (UNEP). April 2018. Available online at: http://conf.montreal-protocol.org/meeting/oewg/oewg-40/presession/Background-Documents/TEAP-DecXXIX4-TF-Report-April2018.pdf.

Technology and Economic Assessment Panel (TEAP). 2018b. Report of the Technology and Economic Assessment Panel Supplement to the April 2018 Decision XXIX/4 TEAP Task Force Report on Destruction Technologies for Controlled Substances. Nairobi, Kenya: United Nations Environment Programme (UNEP). May 2018. Available online at: http://conf.montreal-protocol.org/meeting/oewg/oewg-40/presession/Background-Documents/TEAP-DecXXIX4-TF-Supplemental-Report-May2018.pdf.

Technology and Economic Assessment Panel (TEAP). 2018c. Report of the Technology and Economic Assessment Panel Volume 1 Decision XXIX/4 TEAP Task Force Report on Destruction Technologies for Controlled Substances (Addendum to the May 2018 Supplemental Report – Revision). Nairobi, Kenya: United Nations Environment Programme (UNEP). September 2018. Available online at: https://ozone.unep.org/sites/default/files/2019-04/TEAP-DecXXIX4-TF-Addendum-to-May2018-Report_September2018.pdf.

Tran, Richard; Kennedy, Eric; Dlugogorski, Bogdan. 2000. A Process for Conversion of Halon 1211. University of Newcastle. May 2000. Available online at: https://www.nist.gov/sites/default/files/documents/el/fire_research/R0002203.pdf.

Tradewater. 2019. Tradewater Ghana Offset Credits. Available online at: https://www.tradewater.us/assets/docs/tradewater-ghana-offset-credits.pdf.

Tradewater. 2020. Personal Communication between Tradewater (Gabe Plotkin and Tim Brown) and ICF (Mark Wagner and Paula Garcia Holley) on July 28, 2020.

Tsang, W., Burgess Jr., D. R., and Babushok, V. (1998) On the Incinerability of Highly Fluorinated Organic Compounds, Combustion Science and Technology, 139:1, 385-402.

United Nations Development Program (UNDP). 2011. Pilot Demonstration Project on ODS-Waste Management and Disposal. 18 February 2011. Available online at: http://www.undp.org/content/dam/ghana/docs/Doc/Susdev/UNDP_GH_SUSDEV_Pilot%20demostration%20project%20on%20ODS%20waste%20mgt.pdf.

United Nations Development Program (UNDP). 2014. Prepared by Ministry of Environment (MMA). Pilot Demonstration Project on ODS-Waste Management and Disposal. March 2014. Available online at: https://info.undp.org/docs/pdc/Documents/BRA/72ExCom_UNDP%20BRA%20ODS%20Waste%20MgtDisposal%20Project%20-%20FINAL.docx.

United Nations Environment Programme (UNEP). 2003. Report of the Fifteenth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. United Nations Environment Programme. OzL.Pro.15/9. Fifteenth meeting of the Parties to the Montreal Protocol on Substances that deplete the Ozone Layer. Nairobi. November 11, 2003.

United Nations Environment Programme (UNEP). 2011. Decision XXIII/12: Adoption of New Destruction Technologies for Ozone-Depleting Substances. 2011. Available online at: https://ozone.unep.org/new_site/fr/Treaties/decisions_text.php?m_id=152&show_all.

United Nations Environment Programme (UNEP). 2014a. Report of the Halons Technical Options Committee (HTOC). 2014. Volume 1, 2014 Assessment Report. December 2014. Available online at: http://ozone.unep.org/Assessment_Panels/TEAP/Reports/HTOC/HTOC%202014%20Assessment%20Report.pdf.

United Nations Environment Programme (UNEP). 2014b. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. August 2014. Available online at: http://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf.

United Nations Environment Programme (UNEP). 2015a. Report of the Medical Technical Options Committee (MTOC). February 2015. Available online at: https://ozone.unep.org/sites/default/files/2019-08/MTOC-Assessment-Report-2014.pdf

United Nations Environment Programme (UNEP). 2015b. Report of the Chemicals Technical Options Committee (CTOC). June 2015. Volume 1, 2014 Assessment Report. June 2015. Available online at: http://conf.montreal-protocol.org/meeting/oewg/oewg-36/presession/Background%20Documents%20are%20available%20in%20English%20only/CTOC%20Assessment%20Report%202014.pdf.

United Nations Environment Programme (UNEP). 2017. Report of the Technology and Economic Assessment Panel: Volume 4 Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 2018-2020. May 2017. Available online at: http://conf.montreal-protocol.org/meeting/oewg/oewg-39/presession/Background-Documents/TEAP-XXVIII_5-TF-Report-May%202017.pdf.

United Nations Environment Programme (UNEP). 2018. Decision XXX/6: Destruction technologies for controlled substances. November 2018. Available online at: https://ozone.unep.org/treaties/montreal-protocol/meetings/thirtieth-meeting-parties/decisions/decision-xxx6-destruction.

United Nations Environment Programme (UNEP). 2019. The Montreal Protocol on Substances that Deplete the Ozone Layer. 2019. Available online at: https://ozone.unep.org/treaties/montreal-protocol.

United Nations Environment Programme (UNEP). 2020. Data Centre. Accessed on December 14, 2020. Available online at: https://ozone.unep.org/countries/data-table?q=countries/data.

United Nations Framework Convention on Climate Change (UNFCCC). 2017. Lesotho's Nationally Determined Contribution (NDC). December 2017. Available online at: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Lesotho%20First/Lesotho%20First%20NDC.pdf.

United Nations Industrial Development Organization (UNIDO). 2016. Montreal Protocol Division. September 2016. Available online at: https://www.unido.org/our-focus/safeguarding-environment/implementation-multilateral-environmental-agreements/montreal-protocol.

United Nations Industrial Development Organization (UNIDO). 2018. Ecuador – pioneering the destruction of ozone depleting substances. May 2018. Available online at: https://www.unido.org/stories/ecuador-pioneering-destruction-ozone-depleting-substances.

United Nations Industrial Development Organization (UNIDO). 2019. Personal Communication between UNIDO (Ole Nielsen) and ICF (Mark Wagner) in October and November 2019.

United States Environmental Protection Agency (EPA). 1989. Handbook - Guidance on Setting Permit Conditions and Reporting Trial Burn Results - Volume II of the Hazardous Waste Incineration Guidance Series, U.S. Environmental Protection Agency, Office of Research and Development, Office of Solid Waste and Emergency Response, EPA/625/6-891019 January 1989. Available online at: https://www.wbdg.org/FFC/EPA/EPACRIT/epa625_6_89_019.pdf.

United States Environmental Protection Agency (EPA). 2010a. Technical Support Document for Emissions from Production of Fluorinated Gases: Final Rule for Mandatory Reporting of Greenhouse Gases, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/production/files/2015-02/documents/subpart-l_techsuppdoc.pdf.

United States Environmental Protection Agency (EPA). 2010b. Fact Sheet: Fluorinated Gas Production Information Sheet Subpart L, Mandatory Reporting of Greenhouse Gases. 40 CFR Part 98, Subpart L. U.S. Environmental Protection Agency. November 2010. Available online at: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100BBRP.PDF?Dockey=P100BBRP.PDF.

United States Environmental Protection Agency (EPA). 2016a. The EPA's Updated Refrigerant Management Requirements. September 2016. Available online at: https://www.epa.gov/sites/production/files/2016-09/documents/608_fact_sheet_technicians_0.pdf.

United States Environmental Protection Agency (EPA). 2016b. International Agreements on Transboundary Shipments of Hazardous Waste. December 2016. Available online at:

https://www.epa.gov/hwgenerators/international-agreements-transboundary-shipments-hazardous-waste#basel.

United States Environmental Protection Agency (EPA). 2017. Preliminary Information on Manufacturing, Processing, Distribution, Use, and Disposal: Carbon Tetrachloride. February 2017. Available online at: https://www.epa.gov/sites/production/files/2017-02/documents/carbon_tetrachloride.pdf.

United States Environmental Protection Agency (EPA). 2018a. Descriptions of TRI Data Terms: Text Versions. May 2018. Available online at: https://www.epa.gov/toxics-release-inventory-tri-program/descriptions-tri-data-terms-text-version.

United States Environmental Protection Agency (EPA). 2018b. Resource Conservation and Recovery Act 2017 Biennial Report Summary. Accessed: October 2019.

United States Environmental Protection Agency (EPA). 2018c. Ozone-Depleting Substances (ODS) Destruction Technologies. March 2018. Available online at: https://www.epa.gov/ods-phaseout/ozone-depleting-substances-ods-destruction-technologies.

United States Environmental Protection Agency (EPA). 2019. Ozone Depleting Substances Tracking System (ODSTS). Accessed: October 2019.

United States Environmental Protection Agency (EPA). 2020a. The Benefits of EPA's Responsible Appliance Disposal (RAD) Program. January 7, 2020. Available online at: https://www.epa.gov/sites/production/files/2020-01/documents/rad-communicating-rad-program-benefits.pdf.

United States Environmental Protection Agency (EPA). 2020b. Vintaging Model. Version VM IO file_v5.1_03.20.20.

United States Environmental Protection Agency (EPA). 2020c. Revised Section 608 Refrigerant Management Regulations. Available online at: https://www.epa.gov/section608/revised-section-608-refrigerant-management-regulations.

United States Environmental Protection Agency (EPA). 2020d. Toxics Release Inventory (TRI) Program. Database last accessed on August 18, 2020. Available online at: https://www.epa.gov/toxics-release-inventory-tri-program/tri-basic-data-files-calendar-years-1987-2018?.

United States Environmental Protection Agency (EPA). 2020e. U.S. Environmental Protection Agency's Responsible Appliance Disposal (RAD) Program 2019 Program Update. November 23, 2020. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/responsible-appliance-disposal-program-update-2019.pdf.

Veolia North America (Veolia). 2021. Personal communication between Veolia (Scott Hilton) and ICF (Mark Wagner and Paula Garcia Holley) on January 27, 2021.

Verdonik, Daniel. 2017. Personal communication between Daniel Verdonik and ICF. September 6, 2017.

Verra. 2014. Top Voluntary Carbon Market Program to Ban HFC-23 Projects. January 2014. Available online at https://verra.org/top-voluntary-carbon-market-program-ban-hfc-23-projects/.

Verra. 2020. Verified Carbon Standard Project and Credit Summary. Database accessed on August 2020. Available online at: https://registry.verra.org/app/search/VCS.

World Bank Group. 2019. State and Trends of Carbon Pricing 2019. Washington, DC: World Bank. © World Bank. Available at: https://openknowledge.worldbank.org/handle/10986/31755 License: CC BY 3.0 IGO.

12. Appendices

Appendix A: Transboundary Movement of ODS

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Basel Convention), is an international treaty that was designed to reduce the movements of hazardous waste between nations, specifically to prevent transfer of hazardous waste from developed to less developed countries. Entering into force in 1992, the Basel Convention states that Parties shall take the appropriate measures to ensure that the TBM of hazardous and other wastes is reduced to the minimum consistent with the environmentally-sound and efficient management of such wastes (UNEP 2014b). The United States is not a Party to the Basel Convention. As hazardous substances, ODS wastes fall under the Basel Convention and are subject to the regulations for TBM. Countries without the means for domestic destruction of ODS usually export ODS waste for destruction.

The national legislation of the importing and exporting countries must be reviewed on a case-by-case basis, as they may contain additional or slightly different provisions than the Basel Convention. Each Party has the right to pass stricter legislation and can, for example, prohibit the import of hazardous or other wastes, including ODS (GIZ 2017b). Several regional agreements have been devised that only allow the import of waste from other member countries of the agreement. The Bamako Convention is a treaty between 25 African nations prohibiting the import of any hazardous waste. The Waigani Convention is a treaty between 10 Pacific Islands Forum countries prohibiting the import of any hazardous waste.

The European Union, through Regulation (EC) 1013/2006, established procedures and control regimes for the shipment of waste between Member States, within the Community or via third countries; waste imported into and exported from the Community to third countries; and waste in transit through the Community, on the way from and to third countries. All CFCs, HCFCs, and HFCs are considered and treated as hazardous waste according to Title II, Article 3.1.b.iii, because they are not explicitly listed as a “green waste” in Annex III (UNEP 2014b). Consequently, shipment of ODS requires prior written notification and consent. In addition, this regulation includes labelling requirements. Because many Member States have few, if any, ODS and F-gas destruction facilities, these gases are often shipped across Member State borders, which triggers the administrative requirements of this regulation (ICF 2010a).

Generally, TBM is only allowed between Parties of the Basel Convention. It is, however, possible to enter into bilateral, multilateral, or regional agreements with non-Parties, e.g. to cooperate on ODS waste management and destruction. Such agreements must comply with the principle of environmentally- sound management. Examples include agreements several Parties to the Basel Convention have with the United States.[25]

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[25] The United States is party to the OECD Council Decision c(2001)107/FINAL as amended, the US-Mexico bilateral agreement, the US-Canada bilateral agreement, and import-only agreements with the Philippines, Malaysia, and Costa Rica (EPA 2016b).

Appendix B: Resource Conservation and Recovery Act

In addition to the stratospheric ozone protection regulations for ODS under the CAA, several ODS and HFCs are identified as hazardous wastes and are thus also regulated under RCRA in the United States. Therefore, the regulations that apply to facilities that handle these hazardous wastes apply to U.S. facilities that destroy ODS and/or HFCs that meet the definition of hazardous waste.[26] Subtitle C of RCRA (42 USC, Section 6921-6930) requires that facilities that store, treat, or dispose of hazardous waste are subject to permitting requirements implementing regulatory standards that apply to all aspects of a hazardous waste's management. Combustion of hazardous waste, including combustion of ODS that are identified or listed as hazardous wastes under the subtitle C regulations, is subject to regulation as a form of hazardous waste treatment.

Wastes are identified as hazardous either because they are a listed hazardous waste or because they exhibit a hazardous waste characteristic. There are four characteristics defined by regulation: ignitability, corrosivity, reactivity, and toxicity. The characteristic hazardous wastes are labeled with a D code. There are four lists of hazardous wastes as well. The following RCRA listed hazardous waste codes may apply to some ODS and HFCs (see 40 CFR Part 261, sections 261.31-33):

- Wastes from non-specific sources (Code F);
- Commercial chemical products (Code U);
- Characteristic wastes (Code D);[27] or
- Wastes from specific sources (Code K).

However, the majority of ODS and HFCs likely to be destroyed are not classified as RCRA hazardous waste. According to 40 CFR 261.4(b)(12), refrigerants that meet the following definition are exempt from classification as hazardous wastes: "used chlorofluorocarbon refrigerants from totally enclosed heat transfer equipment, including mobile air conditioning systems, mobile refrigeration, and commercial and industrial air conditioning and refrigeration systems that use chlorofluorocarbons as the heat transfer fluid in a refrigeration cycle, provided the refrigerant is reclaimed for further use."[28] According to 56 FR 5913, this exemption includes CFC and HCFC refrigerants.

Table 17 summarizes the RCRA hazardous waste codes that may apply to controlled substances (i.e., not including ODS byproducts or ODS-containing wastes from chemical manufacture). The remainder of this appendix discusses the circumstances in which ODS and HFCs may be considered hazardous wastes under RCRA.

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[26] While the stratospheric ozone protection regulations (40 CFR Part 82, Subpart A) apply to ODS controlled substances, RCRA regulations and the CAA NSPS and MACT standards are universally applicable to the destruction of ODS, regardless of whether the ODS are deemed a controlled substance under 40 CFR 82.3.

[27] Any ODS-containing and HFC-containing waste must be characterized with respect to RCRA waste codes.

[28] Reclamation is defined in 40 CFR 82.152 as "to reprocess refrigerant to all of the specifications in Appendix A to 40 CFR Part 82, Subpart F…that are applicable to that refrigerant and to verify that the refrigerant meets these specifications using the analytical methodology prescribed in Section 5 of Appendix A of 40 CFR Part 82, Subpart F."

Table 17. RCRA Hazardous Waste Codes for Selected ODS and HFCs

Chemical Name	Hazardous Waste Codes			
	U[a]	F	D	K
CFC-11 (Trichlorofluoromethane)	U121	F001 F002	-	-
CFC-12 (Dichlorodifluoromethane)	U075	F001	-	-
Other CFCs and HCFCs	-	F001	-	-
CCl_4	U211	F001	D019	-
Methyl Chloroform (1,1,1-Trichloroethane)	U226	F001 F002	-	-
Methyl Bromide	U029	-	-	-
HFC-152a	-	-	D001	-

[a] Code U only applies to the controlled substances listed above if they were manufactured and subsequently disposed of without ever being used.

Code F (Wastes from Non-Specific Sources)

ODS may be classified under hazardous waste codes F001 or F002 if they meet one of the following listing descriptions under 40 CFR 261.31:[29]

- **F001**—Applies to the following spent halogenated solvents used in degreasing: tetrachloroethylene, trichloroethylene, methylene chloride, methyl chloroform, CCl_4, and chlorinated fluorocarbons; all spent solvent mixtures/blends used in degreasing containing, before use, a total of ten percent or more (by volume) of one or more of the above halogenated solvents or those solvents listed in F002, F004, and F005; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.
- **F002**—Applies to the following spent halogenated solvents: tetrachloroethylene, methylene chloride, trichloroethylene, methyl chloroform, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, ortho-dichlorobenzene, CFC-11, and 1,1,2-trichloroethane; all spent solvent mixtures/blends containing, before use, a total of ten percent or more (by volume) of one or more of the above halogenated solvents or those listed in F001, F004, or F005; and still bottoms from the recovery of these spent solvents and spent solvent mixtures.

In short, CCl_4, methyl chloroform, and all CFCs and HCFCs may be classified as Code F hazardous wastes if they have been used as solvents prior to disposal. Unlike ODS substances, HFCs are not specified under waste codes F001 and F002 as they are not "chlorinated fluorocarbons" and do not meet the classification criteria.

The generator of the waste is responsible for determining whether the waste is to be classified as hazardous versus non-hazardous and if hazardous, assigning the waste code. Additionally, any destruction facility receiving waste is responsible for verifying that the waste is correctly identified (ICF 2010c).

Code U (Commercial Chemical Products)

ODS may be classified as Code U hazardous wastes (as defined in 40 CFR 261.33) if they are commercial chemical products or manufacturing chemical intermediates that are discarded or intended to be discarded (i.e., abandoned by being disposed of; burned/incinerated; or accumulated, stored, or treated but not recycled before or in lieu of being abandoned by being disposed of, burned, or incinerated, see 40 CFR 261.2(a) and (b)). A commercial chemical product/manufacturing chemical intermediate is defined in 40 CFR 261.33(c) and (d) as:

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[29] Waste codes F024 and F025 also apply to hazardous wastes that could contain ODS; however, these would not be considered controlled substances as they are byproducts of manufacturing processes.

- a chemical substance that is manufactured or formulated for commercial or manufacturing use which consists of the commercially pure grade of the chemical;
- any technical grades of the chemical that are produced or marketed;
- all formulations in which the chemical is the sole active ingredient; and
- any residue remaining in a container or in an inner liner removed from a container that has held any commercial chemical product or manufacturing chemical intermediate named in this section of the regulations.[30]

Thus, while CCl_4, methyl chloroform, methyl bromide, CFC-11, and CFC-12 have designated U waste codes—U211, U226, U029, U121, and U075 respectively—this code is limited to container residues and products that were manufactured but never used. Therefore, refrigerants removed from equipment (which are not classified as hazardous wastes) and used solvents (some of which do fall under waste Code F) would not fall under hazardous waste Code U; a controlled substance that was manufactured and never used would be considered a Code U waste if it was discarded or intended to be discarded. No HFC substances are identified under 40 CFR 261.33(e) and (f), and, therefore, HFCs are not classified as Code U hazardous wastes.

Code K (Wastes from Specific Sources)

ODS-contaminated wastes which may be generated from specific sources, such as the production of CCl_4 or pesticides, may be classified under several K waste codes (e.g., K016, K018, K021, K028, K029, K073, K095, K096, K131, K132, K150). It is possible, but unlikely, that HFCs be classified under K waste codes as the specific sources (e.g., organic chemical, metallurgical, and pesticide production processes) do not normally use or produce HFCs, and any HFCs would likely be introduced as a contaminant to the process. These waste codes apply mainly to wastes/residues from the production of various chemicals, and therefore these wastes will not fall under the definition of controlled substances. However, RCRA regulations would still apply to any such wastes being sent for destruction.

Code D (Characteristic Wastes)

Code D includes wastes that exhibit any of the four characteristics—ignitability (D001), corrosivity (D002), reactivity (D003), and toxicity (D004 through D043)—as described in 40 CFR 261.21 to 261.24. ODS and HFC waste may classified under several D waste codes according to the waste-specific characteristics. The most likely characteristics to apply to ODS or HFC waste are the toxicity characteristic (TC) and ignitability. HFC-152a is designated a waste code D001 as it meets the characteristics of ignitability described in 40 CFR 261.21(a). CCl_4 is designated as waste code D019 if it has enough concentration under the Toxicity Characteristic Leaching Procedure (TCLP) to be considered hazardous. That is, if an extract from a representative sample of a solid waste contains a concentration of CCl_4 equal to or greater than the regulatory threshold level of 0.5 mg/L, it is considered a hazardous waste. Additionally, used ODS or HFC contaminated with any of the other Code D chemicals are considered hazardous wastes if an extract contains any of the contaminants listed in 40 CFR 261.24 at a concentration equal to or greater than the specified values, for example, ODS or HFC solvent waste contaminated with metals from electronics or metal cleaning.

The Mixture and Derived-From Rules

According to 40 CFR 261.3(a)(2)(iv), any combination of a listed hazardous waste with non-hazardous waste is defined as a listed hazardous waste. Even if a small amount of listed hazardous waste is mixed with a large quantity of non-hazardous waste, the resulting mixture bears the same RCRA waste code and regulatory status as the original listed component of the mixture. The mixture rule applies differently to listed wastes and

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[30] Unless the container is empty, as defined in 40 CFR 261.7(b). According to this section, “a container that has held a hazardous waste that is a compressed gas is empty when the pressure in the container approaches atmospheric.” Therefore, any heels in containers that held ODS would most likely not be considered hazardous waste.

characteristic wastes. A mixture involving characteristic wastes is hazardous only if the resulting mixture itself exhibits a characteristic (i.e., ignitability, corrosivity, reactivity, or toxicity). Once a characteristic waste no longer exhibits one of the four regulated properties, it is no longer regulated as hazardous provided it is also not a listed hazardous waste. However, EPA places certain restrictions on the manner in which a waste can be treated, including a dilution prohibition (see the Land Disposal Restrictions regulations in 40 CFR Part 268).

Furthermore, hazardous waste treatment, storage, and disposal processes often generate waste residues (i.e., "derived-from" wastes). Residues produced from the treatment of listed hazardous wastes are generally still themselves considered hazardous wastes under the RCRA derived-from rule (see 40 CFR 261.3(c)(2)), which states that any material derived from a listed hazardous waste is also a listed hazardous waste. For example, ash created by incinerating a listed hazardous waste is considered derived-from that hazardous waste. Thus, such ash bears the same waste code and regulatory status as the original listed waste that was treated in the incinerator, regardless of the ash's actual properties.

Appendix C: Description of ODS and/or HFC Destruction Technologies

This section provides brief descriptions of each of the ODS destruction technologies that have been approved by the Parties to the Montreal Protocol, as reported in UNEP (2011) and UNEP (2018). Nine additional technologies which may be suitable for ODS and/or HFC destruction but that have not been fully evaluated by TEAP are also described. Of these, fixed hearth incineration is commonly used in the United States and air plasma arc is used in an experimental facility in Sweden. In addition, conversion to vinylidene fluoride is also described; however, it was determined this is not a destruction technology by TEAP (TEAP 2018a).

Thermal Oxidation (Incineration) Technologies

Incineration technologies utilize “a controlled flame to destroy ODS in an engineered device” (TEAP 2002). Temperatures in these reactors reach over 1,000 °C in order to break down the ODS.

Approved by the Parties of the Montreal Protocol

Reactor Cracking

CFCs and HCFCs are broken down or “cracked” into HF, H_2O, HCl, CO_2, and Cl_2 in a 2,000 °C reaction chamber. After the products are broken down, they are moved to the absorber for cooling. The entire process results in waste gases consisting mainly of CO_2, O_2, water vapor, and technical grade quality HF and HCl. The reactor cracking process results in few emissions since hydrogen and oxygen are used as the fuel and oxidant, resulting in a reduced volume of flue gas. The reactor cracking process is only designed to destroy fluorocarbons and cannot destroy foams or halons (TEAP 2002).

Gas/Fume Oxidation

The gas/fume oxidation process destroys CFCs, HCFCs, halons, and other wastes in a heat-resistant combustion chamber using fume steam at temperatures around 1,000 °C. An external fuel such as natural gas or fuel oil is used to heat the steam. In general, most gas/fume incinerators are associated with fluorochemical production plants which do not offer destruction services to outside entities (UNEP 2006).

Rotary Kiln Incineration

Rotary kilns utilize a rotating cylinder to destroy hazardous wastes such as CFCs, halons, other ODS, and ODS-containing foams. The cylinder is set at an incline to allow the ash/molten slag to fall out. The afterburner uses temperatures around 1,000 °C to ensure the breakdown of all the exhaust gases. Rotary kiln incinerators are not specifically designed to destroy ODS, so the feed must be regulated to prevent an excess of fluorine from harming the equipment (TEAP 2002).

Liquid Injection Incineration

Liquid injection incinerators inject either liquid or vapor wastes into a chamber together with sufficient combustion air to maintain proper combustion efficiency. Liquid wastes are typically fed to the incinerator through atomizers that convert liquid feeds into fine liquid droplets which enhances combustion efficiency (TEAP 2002). These types of incinerators are most typically used to destroy wastes such as ODS, oils, solvents, and wastewater at manufacturing sites.

Cement Kilns[31]

Cement kilns are primarily used to produce clinker from the conversion of calcium, silica, alumina, and iron to tricalcium silicates, dicalcium silicates, tricalcium aluminate, and tetracalcium aluminoferrite. Gypsum is then

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[31] The listing of cement kilns under incineration technologies in this section is not intended to imply that cement kilns are defined under U.S. regulations as “incinerators.”

typically added to the clinker during the grinding process to make cement. Due to the intense heat of a cement kiln (up to 1,500 °C), some cement kilns are also used to destroy organic compounds, such as ODS. However, the fluorine and chlorine content of the raw material fed into the kiln must be monitored and controlled in order not to affect the quality of the clinker. Cement kilns generally consist of tilted, rotating cylinders that are heated on one end. The raw material is fed into the higher, cooler end of the kiln and falls down towards the heated end. The heated gases used to convert the raw materials into clinker travel from the hot end of the cylinder and out of the higher (cold) end of the kiln. The gases then pass through a pollution control device that removes the particulate matter and other pollutants from the gases (TEAP 2002).

Porous Thermal Reactor

Porous reactors are high-temperature systems with a porous layer that facilitates the decomposition of ODS and other industrial waste gases. Destruction takes place in an oxidizing atmosphere with a continuous supply of an auxiliary gas. Appropriate heat transfer is critical to the proper function of the reactor. The solid structure and porous layer ensure that the heat is spread evenly and reduces the volume of the unit. A commercial plant is operating in Germany (UNEP 2015b).

Municipal Solid Waste Incineration

This process employs moving grates for the destruction of solid materials including foams containing ODS. Waste is dumped into a refuse pit and then transferred mechanically to a bin that feeds the waste in a controlled manner onto the moving grate which moves through the combustion zone. Combustion air is drawn through the refuse pit and introduced into the combustion zone. ODS waste is fed into the incinerator with other solid waste (TEAP 2002).

Thermal Decay of Methyl Bromide

This technology, submitted to TEAP by one company in Australia, involves the capture and destruction of methyl bromide, used as a fumigant, in a portable system (TEAP 2018). In this process, air containing methyl bromide is fed into a diesel engine at a controlled rate where combustion occurs as a single pass destruction step. During combustion, pressures and temperatures of about 60 atm and 2,600 °C, respectively, are reached. After destruction of methyl bromide, the exhaust gases (e.g., HBr) are converted through a multi-stage water-based scrubbing system into bromine salts (TEAP 2018b, STIMBR 2019). Once residual water and particulate matter are removed, the airstream is vented to the atmosphere (STIMBR 2019).

Not Yet Approved by the Parties of the Montreal Protocol

Fixed Hearth Incinerator

Fixed hearth incinerators function similarly to rotary kiln incinerators but utilize fixed combustion chambers to destroy liquid wastes at temperatures ranging from 760 – 980 °C. Solid wastes are placed in the primary combustion chamber where they are burned; the residue ash is removed from the primary chamber, and the by-product gases move into the secondary combustion chamber for further destruction. While fixed hearth incinerators are typically utilized to incinerate sewage sludge, medical wastes, and pathological waste, they can also be used to destroy ODS (ICF 2009a).

Electric Heater

Electric heater technology, from Japan, is intended for use in the destruction of HFCs. It is a flameless combustion process in which HFCs are fed to a reactor with operating temperatures ranging from 900 °C to 1,200 °C. Exhaust gases from the reactor are then passed through a wet scrubber prior to release (TEAP 2018a). The 2018 TFDT indicates that Electric Heater has a high potential for HFC destruction (TEAP 2018a).

Furnaces Dedicated to Manufacturing

Furnaces dedicated to manufacturing were proposed as a destruction technology for HFCs when the temperatures in the oxidation chamber were 1,200 °C or higher and when the HFC retention time was greater than two seconds (in addition to other TEAP criteria); however, there is no concrete data on HF levels and furnace susceptibility to this byproduct. The 2018 TFDT indicates that there are insufficient data available on this technology and as such, it is unable to be assessed (TEAP 2018a).

Non-Incineration Technologies

Non-incineration technologies do not necessarily utilize very high temperatures to destroy ODS, although elevated temperatures are used to assist the breakdown of the ODS. Although they reach higher temperatures than incineration technologies, plasma technologies are considered to be non- incineration technologies because they involve the thermo-chemical decomposition of organic material in a limited oxygen environment.

Plasma Technologies

Plasma technologies utilize plasma, which produces intense heat, to destroy ODS. A plasma arc is created from the discharge of a large electric current between a separate cathode and anode or in a magnetic field while an inert gas is present. ODS destruction occurs when the ODS is heated to a gaseous state and passed through the plasma arc (4,700 - 19,700 °C) and subsequently ionized (or decomposed into its basic molecular structure). Plasma destruction units are generally designed to be relatively small, compact, and transportable. They consume a large amount of energy in order to generate the plasma but tend to have very high destruction efficiencies and low gas emissions (TEAP 2002). Nine different types of plasma technologies are described below.

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Argon Plasma Arc

Argon plasma arc technology uses an electric plasma torch such as the patented PLASCON™ torch to create a 3,000 °C plasma arc in the presence of argon to destroy ODS (TEAP 2018a). The ODS are almost instantaneously broken down through a heat- degradation process called pyrolysis, during which the molecules are broken down into their constituent atoms and ions. This causes the ODS to be converted into an ionized gas, which is then moved into a reaction chamber or flight tube, located below the torch, in order to be cooled to below 100°C with water. The process is followed by rapid alkaline quenching that prevents the formation of dioxins and furans. An alkaline scrubber located downstream of the quench is used to neutralize waste acid formation. The final solid and liquid by-products of the process are halide salts and water, which can be released into the municipal sewage system. The final gaseous by-products include CO_2, argon, and trace amounts of other gases, which are released into the atmosphere.

In Australia, argon plasma arc technology to destroy ODS (i.e., CFCs, HCFCs, and halons) as well as other greenhouse gases (i.e., HFCs) was developed by SRL Plasma Ltd. and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The argon plasma arc plant run by Cleanaway was commissioned by the Australian National Halon Bank in 1996 for ODS destruction (Girgis 2018, Government of Australia 2020). Other plasma arc facilities (supplied by SRL Plasma Ltd.) are located in Mexico, Japan, and the United States (Girgis 2018, TEAP 2018a).

Nitrogen Plasma Arc

Similar to argon plasma arc technology, nitrogen plasma arc technology utilizes nitrogen plasma created by a plasma torch to break down liquefied fluorocarbon gases into CO, HF, and HCl. The CO is then combined with air to form CO_2, which along with the HCl and HF are absorbed by a calcium hydroxide solution. There is one unit known to be commercially destroying ODS in China (TEAP 2018a). Because of their compact size (9 m x 4.25 m), these units can be used as mobile destruction facilities (TEAP 2002).

Inductively Coupled Radio Frequency (ICRF) Plasma

ICRF plasma technology uses 10,000 °C plasma created using an inductively coupled radio frequency torch to destroy ODS. Gaseous ODS and steam are placed into the destruction unit through the plasma torch, heated, and then moved into a reactor chamber where the gases are broken down. Inductively coupled plasma devices use radio frequency to produce plasma therefore eliminating the need for electrodes or the need for cooling. The gases are then cleaned with a caustic solution to remove the acid gases (TEAP 2002).

An ICRF plant in Ichikawa City, Japan has operated commercially since 1995 (TEAP 2002). This is the only ICRF plasma destruction facility known to be in operation in the world.

Microwave Plasma

Microwave plasma technology uses upwards of 6,000°C plasma, which is created using argon and microwave energy, to break down CFCs into HCl, HF, CO, and CO_2 (TEAP 2018a). There are two types of microwave plasma gasifiers; the plasmatron based system, and the direct injection system. The plasmatron is a microwave driven torch and the direct injection system is a process where microwaves are injected into a small area within a reaction chamber. The final byproducts of the destruction process that are released into the atmosphere consist only of halide salts and CO_2, as the acid gases are removed by a scrubber and the CO is combusted with air in order to convert it to CO_2 (TEAP 2002).

Portable Plasma Arc

The portable technology utilizes torch plasma technology to destroy ODS and eventually produce halide salts and CO_2. The unit has been used to destroy ODS in Ghana and several countries in Latin America. The unit takes the flue gases and bubbles them through a neutralization process, before dehydrating the resulting solution. It has a capacity of 1-2 kg/hour of ODS (ASADA Undated).

Not Yet Approved by the Parties of the Montreal Protocol

Air Plasma Arc

Air plasma arc technology destroys CFCs and HCFCs by injecting them into a reaction chamber filled with air, liquefied petroleum gas, and water. The air is heated to about 1,300°C in a plasma generator, and the CFCs and HCFCs are broken down into H_2, H_2O, CO, CO_2, HCl, and HF. These resulting gases are cooled by water injection once they leave the reaction chamber and are scrubbed in a spray tower. The acids are washed out of the gases as calcium chloride and fluorspar by adding calcium hydroxide to the mixture. The gas is washed a second time in a packed bed to ensure that all acids are removed. The gas is released through a stack after passing through a wet electrostatic precipitator, the fluorspar is removed as sludge in a settling tank, and the calcium chloride solution is either used for dust reduction on gravel roads or is disposed (ICF 2009a).

An experimental air plasma destruction facility is in Sweden destroying CFC-11, CFC-12, and HCFC-22 at a rate of about 300 kg/hour (ICF 2009a). This is the only known air plasma facility.

Steam Plasma Arc

Steam plasma arc technology injects ODS and high temperature steam into a 1,300 °C reactor. H_2 and CO are formed under the plasma plume and later oxidized to CO_2 and H_2O through addition of small amounts of air in a separate zone. The gas stream is then rapidly quenched to prevent any reformation of dioxins and furans. The DRE was over 99.9999 percent when CFC-12 was applied (UNEP 2015b).

Alternating Current Plasma Arc

Alternating current (AC) plasma technology is a process similar to that of ICRF Plasma technology; however, AC plasma is produced directly with 60 Hz high-voltage power (TEAP 2018a). AC Plasma technology was designed for hazardous waste destruction; however, a demonstration showed that CFCs were destroyed to non-detectable limits (TEAP 2002). The 2018 TFDT indicates that there are insufficient data available on this technology and as such, it is unable to be assessed (TEAP 2018a).

CO_2 Plasma Arc

CO_2 plasma arc technology destroys ODS by injecting the substance directly to the plasma generation point at over 5,000 °C and (TEAP 2018a). After ODS decomposition, in the reactor, the atoms are reacted with O_2 and the products (e.g., CO_2) are cooled to 70 °C (TEAP 2002). In this process, CO_2 produced is later used as the gas which sustains the plasma and other exit gas is cleaned by conventional chemical scrubbing (TEAP 2018a). The 2018 TFDT indicates that there are insufficient data available on this technology and as such, it is unable to be assessed (TEAP 2018a).

Conversion (Non-Incineration) Technologies

Non-incineration technologies are those that destroy substances via chemical transformation (TEAP 2018a).

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Superheated Steam Reactor

The superheated steam reactor destroys CFC, HCFCs, and HFCs in a reactor with walls that are electrically heated to 850 – 1,000 °C. The fluorocarbons are first mixed with steam and air and preheated to about 500°C before being placed in the reactor. The byproducts of the process, HF, HCl, and CO_2, are quenched with a calcium hydroxide solution to neutralize the acid gases and minimize dioxin and furan emissions. Because of their compact size, superheated steam reactors can be used as mobile destruction facilities (TEAP 2002).

There are 11 known units in operation in Japan (TEAP 2002). It is not clear whether these units destroy ODS commercially.

Gas Phase Catalytic Dehalogenation

The gas phase catalytic dehalogenation process destroys CFCs at 400 °C, which requires less energy consumption than incineration technologies. The process emits no dioxins or furans and very small amounts of other pollutants (TEAP 2002). It is unknown whether this technology is currently in use for commercial ODS destruction.

Chemical Reaction with H_2 and CO_2

This process operates at a temperature range of 300 – 1,000 °C and a pressure range of 1 – 30 atmospheres and converts ODS and HFCs to HF, HCl, CO, and H_2O. A catalyst is used to assist the conversion of the organic halide to anhydrous hydrogen halide and carbon monoxide. The technology is used by a company in the United States and is being supported by the Multilateral Fund for a China demonstration project for HFC-23 conversion. The reaction technology separates and collects the byproducts at a high purity and sells them to recoup operating costs (Midwest Refrigerants 2017).

Thermal Reaction with Methane

The reaction of methane and ODS occurs in a plug flow reactor at atmospheric pressure and high temperature (up to 800 °C). In the case of halon destruction, the reaction occurs when the relatively week $CClF_2$-Br bond is cleaved, producing two radicals that react with methane to form HBr, methyl bromide, $CHClF_2$ and $CClF_2$. The reaction kinetics for this process have been studied; however, it is unknown whether the technology is currently in use for commercial ODS destruction (Tran 2000).

Not Yet Approved by the Parties of the Montreal Protocol

Catalytic Destruction

In this process fluorocarbons and hydrocarbons are destroyed at modest temperatures using a catalyst to assist the conversion. Several commercial plants are operating in Sweden, Denmark, and the UK (UNEP

2015b). An appliance recycling plant with ODS destruction capabilities is operating the technology in the United States (Sirkin 2016). This technology has not been approved by the Parties to the Montreal Protocol; however, it has been demonstrated to operate in accordance with the guidelines outlined by TEAP for destruction technologies.

Solid Alkali Destruction

In this process destruction of ODSs and HFCs occur via a vapor phase reaction using alkali metal vapor and/or alkaline earth metal vapor in a heated reactor (TEAP 2018a). The 2018 TFDT indicates that there are insufficient data available on this technology and as such, it is unable to be assessed (TEAP 2018a).

Not Approved by the Parties of the Montreal Protocol

Conversion to Vinylidene Fluoride

Conversion of HFC-152a to vinylidene fluoride (or vinyl fluoride) is a commercial chemical production process that is being used at chemical production plants in the United States. HFC-152a is either a feedstock or a chemical intermediate in these production processes. A Chemours facility in Louisville, Kentucky uses HFC-152a as a feedstock for vinyl fluoride production (Louisville 2016). Other commercial processes have been developed to produce vinylidene fluoride from HFC-152a. The HFC-152a undergoes a chlorination and dechlorination process to produce the vinylidene fluoride. The technology is being used in the United States as a commercial process that uses HFC-152a as a feedstock to make either vinyl fluoride or vinylidene fluoride. The 2018 TFDT concluded that the technology is not a destruction process but rather part of a chemical manufacturing process (TEAP 2018b).

Appendix D: Incinerability of HFCs

Thermal Stability Ranking System

U.S. EPA established a system for ranking the thermal stability of hazardous wastes for the purposes of developing methods for testing the DRE of hazardous waste incinerators. Hazardous waste incinerators in the U.S. are required to demonstrate the ability to destroy hazardous wastes (including chlorinated and fluorinated compounds that are regulated as hazardous wastes) to a DRE of > 99.99 percent (40 CFR 266.104 *Standards to Control Organic Emissions*). In general, hazardous waste incinerator operators test the incinerator using one or more principle organic hazardous constituents (POHCs) as surrogates for all other hazardous waste compounds; once the incinerator demonstrates the ability to destroy the POHCs that are tested to a DRE of > 99.99 percent, it is assumed that the incinerator also has the ability to destroy any other compounds that are ranked lower on the U.S. EPA's thermal stability index. For example, chlorobenzene is a Stability Class I compound ranked 20th on the incinerability scale, methyl bromide is a Stability Class I compound ranked 31st – 33rd, and HCFC-123 is a Stability Class I compound ranked 39th. If the incinerator is demonstrated to achieve a DRE of > 99.99 percent when tested using chlorobenzene, it is assumed that the incinerator would also destroy tetrachloroethylene and methyl bromide (lower ranked compounds) to at least a 99.99 percent DRE. Table 18 provides a summary of thermal stability rankings from the U.S. EPA Incinerability Index (EPA 1989), from *Theoretical Estimation of Incinerability of Halons and HCFCs* (Lamb et. al, 2008.), and from *Incinerability of Halons and HCFCs: Theoretical Calculations of DRE and Ozone-Depleting or Global-Warming Gases* (Lamb et. al. 2010).

Table 18. Thermal Stability Ranking of Selected Compounds

Compound		Thermal Stability Ranking	Source
Stability Class I			
SF_6	Sulfur Hexafluoride	4	EPA 1989
C_6H_5Cl	Chlorobenzene	20	EPA 1989
CH_3Cl	Methyl Chloride	30-31	EPA 1989
CH_3Br	Methyl Bromide	31-33	Lamb et. al, 2010
Stability Class II			
HCFC-123	2,2-Dichloro-1,1,1- trifluoroethane	39	Lamb et. al, 2008
Stability Class III			
CFC-113	1,1,2-Trichloro-1,2,2- trifluoroethane	85-88	EPA 1989
CFC-12	Dichlorodifluoromethane	85-88	Lamb et. al, 2010
CFC-11	Trichlorofluoromethane	89-91	Lamb et. al, 2010
Halon 1301	Bromotrifluoromethane	116	Lamb et. al, 2008
Halon 2402	1,2-Dibromotetrafluoroethane	131	Lamb et. al, 2008
HCFC-22	Chlorodifluoromethane	133	Lamb et. al, 2008
Halon 1211	Bromochlorodifluoromethane	143	Lamb et. al, 2008

Destruction Efficiency Determination, Greenhouse Gas Reporting Rule Subpart L

U.S. EPA established procedures for fluorinated gas producers to report the destruction efficiency (DE) for thermal oxidation destruction of fluorinated gases under Subpart L of the Greenhouse Gas Reporting Rule or the Mandatory Reporting of Greenhouse Gases Rule (MRR) based on the results of the thermal destruction system performance tests that are based on EPA's thermal stability index (EPA 2010b). EPA has determined that carbon tetrafluoride (CF_4) is more thermally stable and therefore more difficult to destroy than sulfur hexafluoride (SF_6) which has a thermal stability ranking of 4 (only benzene, cyanogen, and hydrogen cyanide are ranked higher). U.S. EPA therefore required under Subpart L that a DE determination must be developed specifically for CF_4, SF_6, and all other fully saturated perfluorinated compounds (i.e., any fluorinated compound having no hydrogen atoms, e.g., tetrafluoroethylene and hexafluoropropene) for the purposes of Subpart L reporting.

U.S. EPA also concluded that fluorinated compounds having hydrogen atoms (e.g., 1,2-difluoroethane (HFC-152)) are not likely to be as thermally stable as CF_4 and SF_6, and therefore would not be as difficult to destroy by thermal oxidation. This is because these compounds can be dissociated at the C-H and C-C bonds that are not as strong as C-F and C-S bonds. U.S. EPA concluded that these other fluorinated compounds are less difficult to destroy than the Stability Class I compounds (e.g., chlorobenzene and methyl bromide) that are listed in the U.S. EPA's thermal stability index (see Table 18). Therefore, for these other fluorinated GHGs, the DE may be developed for the purposes of Subpart L reporting using incinerator performance test data for any Stability Class I compound on the U.S. EPA's Thermal Stability Rankings List (75 FR 74793; EPA 1989). Incinerators that have been tested using one or more Stability Class I compounds as POHCs and that demonstrate a DRE of > 99.99 percent for the Stability Class I POHCs tested are deemed capable of destroying fluorinated GHGs to at least a 99.99 percent DRE based on the results of the tests conducted for the Stability Class I POHCs.

Incinerability of Fluorinated Compounds

Tsang et al. (1998) assessed the thermal stability of fluorinated compounds (i.e., HFCs) under combustion conditions based on chemical kinetic properties and computer simulations and provided comparisons to chlorinated hydrocarbons (i.e., HCFC and halons). Tsang et al. (1998) concluded that fluorinated compounds are generally more thermally stable than chlorinated compounds, but that conditions achievable in incinerators are capable of destroying fluorinated compounds at high levels of efficiency. Tsang et al. (1998) provided chemical kinetics calculations of the temperature required to achieve 99.99 percent destruction in one second for fluorinated compounds including HFC-23, HFC-125, and HFC-161. The modeled required temperatures for 99.99 percent destruction for these fluorinated compounds are similar to modeled temperatures for 99.99 percent destruction for HCFCs and halons modeled in Lamb et al. (2010), as shown in Table 19, and are similar to modeled Stability Class I and Stability Class II index rankings for these compounds.

Table 19. Modeled Required Temperatures to Achieve 99.99 Percent DRE for Fluorinated Compounds

Compound			Time	Required Temperature		Index Ranking
			seconds	K	°C	
Tsang et al. (1998)						
CF_3H	Trifluoromethane	HFC-23	1	1,200	927	Stability Class II
C_2HF_5	Pentafluoroethane	HFC-125	1	1,137	864	Stability Class II
C_2H_5F	Fluoroethane	HFC-161	1	1,068	795	Stability Class III
Lamb et al. (2010)						
$C_2HCl_2F_3$	2,2-Dichloro-1,1,1-trifluoroethane	HCFC-123	2	1,182	909	39 (Class II)
CF_3Br	Bromotrifluoromethane	Halon 1301	2	1,040	767	116 (Stability Class III)
CHF_2Cl	Chlorodifluoromethane	HCFC-22	2	978	705	133 (Stability Class III)