

ODS Destruction in the United States and Abroad

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Controlled ODS under the Montreal Protocol

| Class I | Class II |
|---|---|
| CFC-11 (Trichlorofluoromethane) | HCFC-21 (Dichlorofluoromethane) |
| CFC-12 (Dichlorodifluoromethane) | HCFC-22 (Monochlorodifluoromethane) |
| CFC-13 (Chlorotrifluoromethane) | HCFC-31 (Monochlorofluoromethane) |
| CFC-111 (Pentachlorofluoroethane) | HCFC-121 (Tetrachlorofluoroethane) |
| CFC-112 (Tetrachlorodifluoroethane) | HCFC-122 (Trichlorodifluoroethane) |
| CFC-113 (1,1,2-Trichlorotrifluoroethane) | HCFC-123 (Dichlorotrifluoroethane) |
| CFC-114 (Dichlorotetrafluoroethane) | HCFC-124 (Monochlorotetrafluoroethane) |
| CFC-115 (Monochloropentafluoroethane) | HCFC-131 (Trichlorofluoroethane) |
| CFC-211 (Heptachlorofluoropropane) | HCFC-132b (Dichlorodifluoroethane) |
| CFC-212 (Hexachlorodifluoropropane) | HCFC-133a (Monochlorotrifluoroethane) |
| CFC-213 (Pentachlorotrifluoropropane) | HCFC-141b (Dichlorofluoroethane) |
| CFC-214 (Tetrachlorotetrafluoropropane) | HCFC-142b (Monochlorodifluoroethane) |
| CFC-215 (Trichloropentafluoropropane) | HCFC-221 (Hexachlorofluoropropane) |
| CFC-216 (Dichlorohexafluoropropane) | HCFC-222 (Pentachlorodifluoropropane) |
| CFC-217 (Chloroheptafluoropropane) | HCFC-223 (Tetrachlorotrifluoropropane) |
| Halon 1211 (Bromochlorodifluoromethane) | HCFC-224 (Trichlorotetrafluoropropane) |
| Halon 1301 (Bromotrifluoromethane) | HCFC-225ca (Dichloropentafluoropropane) |
| Halon 2402 (Dibromotetrafluoroethane) | HCFC-225cb (Dichloropentafluoropropane) |
| Halon 1011/CBM (Chlorobromomethane) | HCFC-226 (Monochlorohexafluoropropane) |
| Carbon Tetrachloride (CCl ₄) | HCFC-231 (Pentachlorofluoropropane) |
| Methyl Chloroform (1,1,1-Trichloroethane) | HCFC-232 (Tetrachlorodifluoropropane) |
| Methyl Bromide (MeBr) | HCFC-233 (Trichlorotrifluoropropane) |
| HBFCs (Hydrobromofluorocarbons) | HCFC-234 (Dichlorotetrafluoropropane) |
| | HCFC-235 (Monochloropentafluoropropane) |
| | HCFC-241 (Tetrachlorofluoropropane) |
| | HCFC-242 (Trichlorodifluoropropane) |
| | HCFC-243 (Dichlorotrifluoropropane) |
| | HCFC-244 (Monochlorotetrafluoropropane) |
| | HCFC-251 (Trichlorofluoropropane) |
| | HCFC-252 (Dichlorodifluoropropane) |
| | HCFC-253 (Monochlorotrifluoropropane) |
| | HCFC-261 (Dichlorofluoropropane) |
| | HCFC-262 (Monochlorodifluoropropane) |
| | HCFC-271 (Monochlorofluoropropane) |

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 |
| 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 |
| ERU | Emission Reduction Equivalent |
| EU ETS | European Union Emission Trading System |
| 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 | Halon Technical Options Committee |
| HWC | Hazardous Waste Combustor |
| ICRF | Inductively Coupled Radio Frequency Plasma |
| MeBr | Methyl Bromide |
| MITI | Ministry of International Trade and Industry |
| MLF | Multilateral Fund |
| MOP | Meeting of the Parties |

| | |
|---------------------|--|
| MRR | Mandatory Reporting of Greenhouse Gases Rule |
| MTCO ₂ e | Metric Tons Carbon Dioxide Equivalent |
| MTOC | Medical Technical Options Committee |
| ODP | Ozone Depleting Potential |
| ODS | Ozone-Depleting Substances |
| ODSTS | ODS Tracking System |
| PCDD | Polychlorinated Dibenzodioxin |
| PCDF | Polychlorinated Dibenzofuran |
| PFC | Perfluorocarbon |
| 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 |
| TEAP | Technology & Economic Assessment Panel |
| TFDT | Task Force on Destruction Technologies |
| TRI | Toxics Release Inventory |
| UL | Underwriters Laboratories |
| UNDP | United Nations Development Programme |
| UNEP | United Nations Environment Programme |
| UNIDO | United Nations Industrial Development Organization |
| VCS | Verified Carbon Standard |
| WTE | Waste to Energy |

1. Introduction

The *Montreal Protocol on Substances that Deplete the Ozone Layer* (Montreal Protocol), finalized 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, the Parties commit to phasing out specified ODS – chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, carbon tetrachloride (CCl₄), methyl chloroform, methyl bromide, bromochloromethane, and hydrobromofluorocarbons (HBFCs) – thereby reducing their abundance in the atmosphere and protecting the earth's fragile ozone layer. On 16th September 2009, the Montreal Protocol and its parent convention, the Vienna Convention for the Protection of the Ozone Layer, became the first treaties in the history of the United Nations to achieve universal ratification.

While the global ODS phaseout is underway, a large amount of ODS is in equipment and products such as refrigerators and air conditioners (as refrigerant and foam blowing agent), foam contained in buildings, and fire protection systems and fire extinguishers, as well as in stockpiles held by countries and industrial and commercial users. Together these sources are referred to as ODS banks. ODS from these banks could be released to the atmosphere over time through slow leakage, catastrophic leaks, and venting, unless they are recovered and properly treated. While emissions from ODS banks are not controlled by the Montreal Protocol, many countries including the United States have voluntary or regulatory requirements to reduce emissions of ODS at the end of the useful life of these equipment and products. After ODS are recovered and collected, destruction is one of several options that also include recycling or reclamation. 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 report discusses the sources of ODS for destruction in the United States and globally and the best practices for the safe, environmentally sound collection, recovery, transport, and destruction of these substances. In addition, the report identifies the technologies that are used to destroy ODS and the challenges associated with safe destruction of ODS. This report assesses the costs for the ODS waste management process and 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 hydrofluorocarbons (HFCs) are discussed.

2. Sources of ODS for Destruction

ODS that are potentially eligible 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. These 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 in 2020 will no longer be produced in the United States, will likely have a resale value because it will still be required for servicing existing equipment.

Box 1. Key Barriers to Recovery and Destruction of ODS

While there is a substantial volume of 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 tools 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 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 foams may be difficult and expensive. Similarly, although portable fire extinguishers are a good source for destruction in many

cases, 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).¹

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 extinguishing sector, which primarily uses halons. Halons are infrequently available for destruction, as they are often banked and reused in fire protection 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 domestic 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 (MLF 2008).

In the United States, ODS-containing foam is also often recovered, particularly from refrigerated appliances; however, this recovery effort is often more expensive and takes 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 higher cost than recovery of refrigerants, many countries have continued to promote foam recovery, recognizing the important benefits of recovering ODS from foams to the recovery of the ozone layer (MLF 2008). For example, the U.S. Environmental Protection Agency's (EPA) Responsible Appliance Disposal (RAD) Program, a voluntary partnership program, was developed to promote proper removal, recovery, and destruction of ODS in refrigerated appliances, including ODS-containing foam. 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).

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 extinguishing 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

¹ Some countries have established national programs to encourage halon recovery, and generally those programs requiring 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.

containers in locations where temperature and moisture are not controlled (e.g., warehouses, fields). To prevent bulked 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 AHRI Standard 700, which has a purity requirement of 99.5 percent by mole as well as other requirements for water content, particulates, turbidity, and acidity (AHRI 2016). 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., Air-Conditioning, Heating and Refrigeration Institute (AHRI), Underwriters Laboratories (UL), or Intertek).*

3.2. Consolidation and Storage

After ODS has been recovered and collected from domestic 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 is 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 is 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 has been aggregated to constitute a shipment, it is 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

Typically, ODS are transported to an approved destruction facility for final destruction, although some ODS can be destroyed on site after collection, if the facility is approved to do so. In most cases, however, certified transporters ship consolidated ODS in large containers to the destruction facility. When ODS

reaches the destruction facility,² 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.

Once the contents are confirmed, the ODS may be transferred to a holding tank and fed into the destruction unit;³ 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)⁴ of 99.99 percent for concentrated sources of ODS and 95 percent for dilute sources of ODS (i.e., foams) is recommended by the 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.*

² In some cases, (e.g., a practice in Germany) ODS recovered from domestic 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.

³ 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).

⁴ 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.

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 23rd Meeting of the Parties (MOP) in November 2011, as well as 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 that promote the exchange of information on the best technologies for the destruction of ODS. TEAP, one of the three assessment panels under the Montreal Protocol, established a Task Force on Destruction Technologies (TFDT) in response to a decision taken by the Parties. The TFDT released a report in 2002 that established destruction efficiency and air emissions recommendations for ODS destruction technologies and reviewed available technologies against these criteria (TEAP 2002). At the 15th MOP in November 2003, the Parties agreed, through Decision XV/9, to update the list of approved destruction technologies for ODS that were evaluated in the 2002 TEAP report. At the 23rd MOP in November 2011, the Parties agreed, through Decision XXIII/12, to further update the list of approved destruction technologies, specifically adding Chemical Reaction with H₂ and CO₂, Porous Thermal Reactor, Portable Plasma Arc, and Thermal Reaction with Methane.

Although the criteria used in the TEAP report to evaluate destruction technologies were not established by the Parties as required limits during ODS destruction, these criteria may be considered domestically. These recommendations include specifications for:

- Destruction and Removal Efficiency (DRE);
- Emissions of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)/dioxins and furans, hydrochloric acid (HCl), chlorine (Cl₂), HF, hydrobromic acid (HBr), bromine (Br₂), particulate matter (PM), and CO; and
- 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/m ³) | 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 |
| Particulate Matter (mg/m ³) | 50 | 50 |
| CO (mg/m ³) | 100 | 100 |

Source: TEAP (2002).

^a Emission limits are expressed as mass per dry cubic meter of exhaust gas at 0°C and 101.3 kPa corrected to 11 percent O₂.

ODS destruction technologies can be grouped into three broad categories: Incineration; Plasma; and Other Non-incineration technologies. Within these three categories, 15 technologies were approved for the destruction of concentrated sources of CFCs, HCFCs, methyl chloroform, and CCl₄. 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 I of the Report of the 23rd MOP, as well as three non-approved technologies that are cited in a 2015 report from the Chemicals Technical Options Committee (CTOC) as being newly in use and potentially approved by the Parties in the future. All of these technologies are known to be used for ODS destruction, either commercially or in demonstrations, in the United States and/or abroad. All technologies are described further in Appendix C.

Table 2. Approval Status of Available ODS Destruction Technologies

| Technology | Applicability ^a and Required Destruction and Removal Efficiency (DRE) ^f | | |
|---|---|------------------------------|-------------------------|
| | Concentrated ODS ^b | | Dilute ODS ^c |
| | CFCs, HCFCs, CCl ₄ , methyl chloroform ^d (99.99%) | Halons ^e (99.99%) | Foam (95%) |
| Incineration Technologies | | | |
| Cement Kilns | Approved | Not Approved | Not Applicable |
| Gaseous/Fume Oxidation | Approved | Not Determined | 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 | Not Approved | Not Applicable |
| Rotary Kiln Incineration | Approved | Approved | Approved |
| Plasma Technologies | | | |
| Argon Plasma Arc | Approved | Approved | Not Applicable |
| Inductively Coupled Radio Frequency Plasma | Approved | Approved | Not Applicable |
| Microwave Plasma | Approved | Not Determined | Not Applicable |
| Nitrogen Plasma Arc | Approved | Not Determined | Not Applicable |
| Portable Plasma Arc | Approved | Not Determined | Not Applicable |
| Steam Plasma Arc | Not Yet Reviewed | Not Yet Reviewed | Not Yet Reviewed |
| Other Non-Incineration Technologies | | | |
| Chemical Reaction with H ₂ and CO ₂ | Approved | Approved | Not Applicable |
| Gas Phase Catalytic Dehalogenation | Approved | Not Determined | Not Applicable |
| Superheated Steam Reactor | Approved | Not Determined | Not Applicable |
| Thermal Reaction with Methane | Approved | Approved | Not Applicable |
| Catalytic Destruction | Not Yet Reviewed | Not Yet Reviewed | Not Yet Reviewed |
| Conversion to Vinylidene Fluoride | Not Yet Reviewed | Not Yet Reviewed | Not Yet Reviewed |

Sources: UNEP (2011) and UNEP (2015).

^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 reviewed by the Parties to the Montreal Protocol.

^b Concentrated sources of ODS refer to virgin, recovered, and reclaimed ODS.

^c Dilute sources of ODS refer to ODS contained in a matrix of a solid (e.g., foam).

^d Under the Montreal Protocol, these substances are listed in Annex A, Group I; Annex B; and Annex C, Group I.

^e Under the Montreal Protocol, these substances are listed in Annex A, Group II.

^f 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.

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.⁵

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.⁶ 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 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.

⁵ 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.

⁶ 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.

Based on data submitted to TRI from 2010 to 2016, over 35 companies that destroyed ODS hazardous waste were identified. Many of these facilities are chemical manufacturing plants that destroy ODS generated on-site or used on-site in a chemical production process.⁷ The ODSTS was referenced to help identify whether companies were destroying ODS commercially. While there are a significant number of non-commercial, non-byproduct destruction facilities in the United States that have destroyed ODS-containing wastes, there are 7 companies that are thought to have destroyed ODS, either received commercially or as ODS-containing waste-derived fuel, in 11 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 2010-2016.

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

| Company | Location | Technology in Use ^a | ODS Processed in 2010-2016 |
|---|--------------------|--|---|
| A-GAS Americas | Bowling Green, OH | Plasma Arc | CFC-11, CFC-12, CFC-113, Halon 1301, Halon 1211, HCFC-22 |
| Clean Harbors Aragonite LLC | Grantsville, UT | Rotary Kiln with Liquid Injection Unit Afterburner | CFC-11, CCl ₄ |
| Clean Harbors Deer Park LLC | La Porte, TX | Gas/Fume Oxidation (2 units) | CFC-11, CFC-12, CFC-13, CFC-113, CCl ₄ , MeBr, 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, CCl ₄ , HCFC-22 |
| Clean Harbors Environmental Services Inc. | Kimball, NE | Fluidized Bed Incinerator | CFC-11, CCl ₄ |
| Eco-Services Operations | Baton Rouge, LA | Liquid Injection Incineration (2 units) | CCl ₄ |
| Heritage Thermal Services | East Liverpool, OH | Rotary Kiln Incineration | CFC-11, CFC-113, CCl ₄ , MeBr |
| Reclim | Graniteville, SC | Catalytic Destruction ^b | CFC-11, CFC-12, HCFC-22, HCFC-141b ^c |
| Ross Incineration Services Inc. | Grafton, OH | Rotary Kiln with Liquid Injection Unit | CCl ₄ |
| Veolia ES Technical Solutions LLC | Sauget, IL | Fixed Hearth Incineration | CFC-12, CFC-113, CCl ₄ |
| Veolia ES Technical Solutions LLC | Port Arthur, TX | Fixed Hearth Incineration | CFC-11, CFC-12, CFC-113, CCl ₄ , HCFC-21, HCFC-22, HCFC-123 |

Sources: EPA (2017a) and ICF (2009a).

^a Technologies that are not present in the list of Montreal Protocol approved destruction processes are described in Appendix C.

⁷ These facilities generally use fume/vapor incinerators or other types of air emissions control devices to destroy ODS.

^b Reclim is a de-manufacturing company that receives shipments of old appliances (refrigerators, freezers, dehumidifiers, and AC units) and processes them in the only U.S. plant to employ a combination of physical destruction technologies and catalytic destruction in a closed loop system. This system avoids the leakage to the environment that occurs during de-manufacturing of appliances and shipment of ODS (Sirkin 2016).

^c 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 destroyed ODS on-site from 2010 to 2016, 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)

| Company | Location | Technology in Use ^a | ODS Processed in 2010-2016 |
|--|------------------|--|--|
| Arkema Inc. | Calvert City, KY | Liquid Injection Incineration | HCFC-22, HCFC-141b |
| Axiall LLC | Plaquemine, LA | Fume/Vapor | CCl ₄ |
| 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 Chemical Co. – Cooper River Plant | Wando, SC | Other Incineration/Thermal treatment | MeBr |
| BP AMOCO Chemicals | Decatur, AL | Fume/Vapor | MeBr |
| BP Chemical Co. – Cooper River Plant | Wando, SC | NA | MeBr |
| Chemours Belle Plant | Belle, WV | Fume/Vapor | CCl ₄ |
| Chemours Washington Works | Washington, WV | NA | HCFC-22 |
| Daikin America Inc. | Decatur, AL | NA | HCFC-22 |
| DAK Americas LLC – Columbia Site | Gaston, SC | NA | MeBr |
| Dow/DuPont Chemical Co. | Pittsburg, CA | Liquid Injection Incineration | CCl ₄ |
| Dow/DuPont Chemical Co. Freeport Facility | Freeport, TX | Rotary Kiln with Liquid Injection Unit | CFC-12, CCl ₄ , MeBr, HCFC-22 |
| Dow/DuPont Louisiana Operations | Plaquemine, LA | Other Rotary Kiln | CCl ₄ , MeBr |
| | | Rotary Kiln with Liquid Injection Unit | |
| | | Other Incineration/Thermal Treatment | |
| Dow/DuPont Sabine River Works | Orange, TX | Rotary Kiln with Liquid Injection Unit | CCl ₄ |

| Company | Location | Technology in Use ^a | ODS Processed in 2010-2016 |
|--|-------------------|--|-----------------------------------|
| Dow/DuPont Washington Works | Washington, WV | Other Incineration/Thermal Treatment | HCFC-22 |
| Eagle US 2 LLC | Westlake, LA | Liquid Injection Incineration | CCl ₄ |
| | | Fume/Vapor | |
| Eastman Chemical Co. South Carolina Operations | Gaston, SC | Other Incineration/Thermal Treatment | MeBr |
| Eastman Chemical Co. Tennessee Operations | Kingsport, TN | Rotary Kiln with Liquid Injection Unit | MeBr |
| | | Other Incineration/Thermal Treatment | |
| Evoqua Water Technologies LLC | Parker, AZ | NA | CCl ₄ |
| Evoqua Water Technologies Darlington Facility | Darlington, PA | NA | CFC-11, CCl ₄ |
| Flint Hills Resources Joliet LLC | Channahon, IL | Fume/Vapor | MeBr |
| Formosa Plastics Corp. Louisiana | Baton Rouge, LA | Fume/Vapor | 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-115, HCFC-22 |
| Honeywell International Inc. Baton Rouge Plant | Baton Rouge, LA | NA | HCFC-22 |
| Indorama Ventures Xylenes and PTA LLC | Decatur, AL | NA | MeBr |
| LaFarge Midwest Inc. (Including Systech Environmental) | Fredonia, KS | NA | CCl ₄ |
| 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 | CCl ₄ |
| | | Liquid Injection Incineration | |
| 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 |
| Syngenta Crop Protection LLC | Saint Gabriel, LA | Gas/Fume Oxidation | CCl ₄ |
| Velsicol Chemical LLC | Memphis, TN | Liquid Injection Incineration | CCl ₄ |
| Westlake Vinyls Co. | Geismar, LA | Fume/Vapor | CCl ₄ |

| Company | Location | Technology in Use ^a | ODS Processed in 2010-2016 |
|----------------------|------------------|--------------------------------------|----------------------------|
| Westlake Vinyls Inc. | Calvert City, KY | Other Incineration/Thermal Treatment | CCl ₄ |

Source: EPA (2017a).

NA = Not Available.

^a 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 90 percent of the facilities in Table 4 report destruction of CCl₄ and/or methyl bromide to the TRI. These chemicals are commonly manufactured for use in pharmaceutical and agrochemical applications. They are also used as a raw material or processing agent for the manufacture of other chemicals and products. CCl₄ was the dominant ODS feedstock substance in the 1990s and early 2000s, however, HCFCs (e.g., HCFC-22) and CFCs (e.g., CFC-11, CFC-12, CFC-13, CFC-113, and CFC-115) are now the globally dominant feedstocks (Touchdown 2012). These feedstocks are commonly used to produce HFCs, fluoropolymers, and other ODS. After the feedstock is used, the waste stream (containing traces of these compounds) is sent for destruction to a third party or destroyed on-site (see Box 4).

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.

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 2015, according to EPA's National Biennial RCRA Hazardous Waste Report, 3,365,000 MT of hazardous wastes were destroyed in the United States (EPA 2017c),⁸ compared to approximately 2,100 MT of ODS destroyed in that year. 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.

⁸ 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).

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 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

About 155 destruction facilities are known to have operated in 28 countries around the world since 2008 (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. 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.⁹ 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 | 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. Colombia | 1 | Rotary Kiln | NA | NA |
| 9. Cuba | 1 | Cement Kiln | NA | NA |
| 10. Czech Republic | 1 | Rotary Kiln | 40 MT/year | NA |
| 11. Denmark | 4 | Catalytic Cracking | NA | NA |
| 12. Estonia | 1 | NA | NA | NA |
| 13. Finland | 1 | Rotary Kiln | 545 MT/year | NA |

⁹ 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.

| Country | Number of Known ODS Destruction Facilities in Operation | Known Technologies Utilized | ODS Destruction Capacity | Typical Destruction Costs (US\$) |
|--------------------|---|--|---|--|
| 14. France | 2 | NA | NA | NA |
| 15. Germany | 7 | Hazardous Waste Incinerator Reactor Cracking Porous Reactor | 1,600 MT/year ^b (Reactor Cracking) | NA |
| 16. Hungary | 5 | Rotary Kiln Liquid Injection Incineration | 75 MT/year ^a (Rotary Kiln) 13 MT/year (Liquid Injection Incineration) | NA |
| 17. Indonesia | 1 | Cement kiln | 600 MT/year | NA |
| 18. Italy | 12 | NA | NA | NA |
| 19. 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 |
| 20. Netherlands | 6 | NA | NA | NA |
| 21. Poland | 1 | NA | NA | NA |
| 22. Slovakia | 1 | NA | NA | NA |
| 23. Spain | 1 | NA | NA | NA |
| 24. Sweden | 4 | Air Plasma, among others | 100 MT/year | NA |
| 25. Switzerland | 4 or more | Rotary Kiln, among others | 910 MT/year ^b (Rotary Kiln) > 320 MT/year (others) | NA |
| 26. United Kingdom | 2 | High-Temperature Incineration | NA | NA |
| 27. 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 |
| 28. Venezuela | 2 or more | NA | NA | NA |

Sources: ICF (2010c), Alves (2015), and UNEP (2015).

NA= Not available.

^a Number represents approximate ODS destruction capacity based on known overall plant capacity and typical ODS feed rates for rotary kilns.

^b Capacity is not specific to ODS; value shown refers to capacity for all hazardous wastes and/or other types of wastes.

5. International Efforts to Destroy ODS

There is no comprehensive publicly available data on the destruction of ODS globally. 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

The U.S. EPA has two reporting programs that are relevant to the management of ODS and related chemicals. The first, the TRI Program, is covered under Title 40, Part 372 of the Code of Federal Regulations (CFR) and 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 chemicals destroyed falls under the TRI categories of “disposal,” which include disposal in landfills, surface impoundments, underground injections, and off-site transfers, and “treatment” which include methods such as biological treatment, incineration, and chemical oxidation. These methods result in varying degrees of destruction of the chemicals.

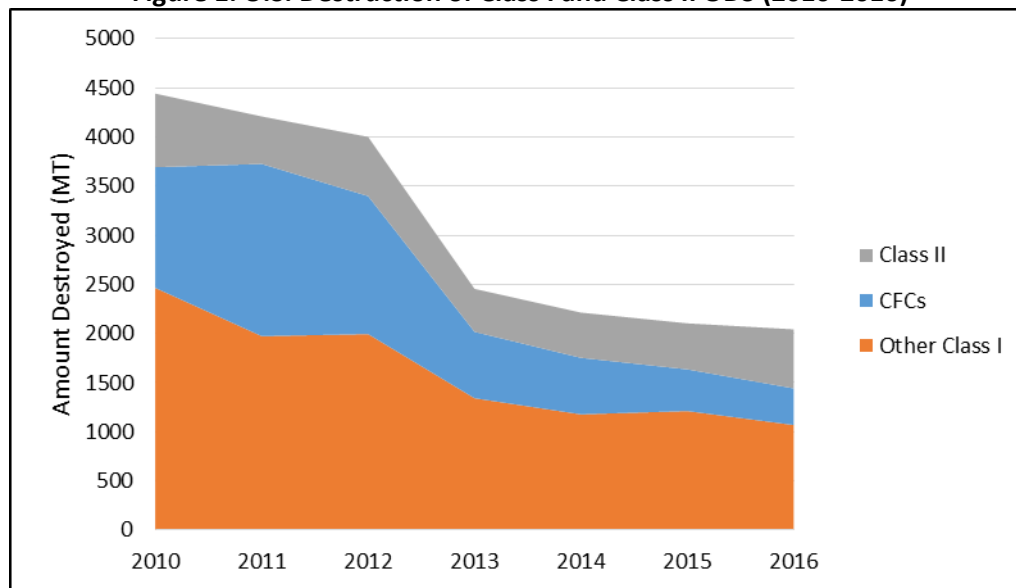
The second is covered under Title 40, Part 82 of the CFR and requires that any person who destroys a Class I or Class II ODS controlled substance reports the name and quantity of the substance destroyed for each control period to the ODSTS in quarterly and annual reports. These data are compiled and sent annually to the UNEP Ozone Secretariat consistent with Article 7 of the Montreal Protocol.

5.1.1. Reported Amount and Type of ODS Destroyed

As shown in Figure 1, destruction of ODS in the United States has decreased from 2010 to 2016 by over 50 percent, with the greatest reduction in the quantity of Class I ODS¹⁰ destroyed. Class I ODS destruction has decreased by nearly 61 percent in this period, from a total of approximately 3,690 MT in 2010 to approximately 1,440 MT in 2016. Class II ODS¹¹ 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.

¹⁰ 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 (CCl₄), and Group III (methyl chloroform); Annex C Group II (HBFCs); and Annex E Group I (MeBr).

¹¹ Per 40 CFR 82, Class II chemicals include chemical listed under Montreal Protocol Annex C Group I (HCFCs).

Figure 1. U.S. Destruction of Class I and Class II ODS (2010-2016)

Source: EPA (2017d).

5.1.2 Reported ODS Imported for Destruction

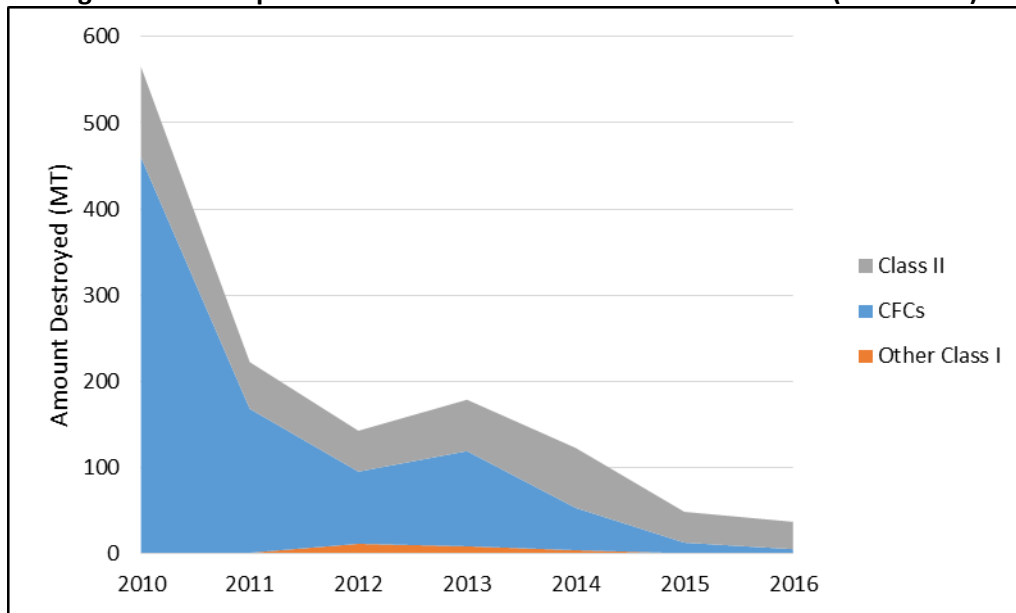
ODS may be imported for destruction as a result of equipment decommissioning, unwanted stockpiles, or mixed substances. For instance, many U.S. companies assist other countries in the decommissioning of ODS-containing equipment that is being phased out. Once the equipment has been decommissioned and 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 the Verified Carbon Standard (VCS) or the Climate Action Reserve (CAR). Similarly, countries without destruction capabilities in country may export stocks of unwanted ODS to the United States for destruction. 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 ODS, including for the sole purpose of destruction, through a shipment-by-shipment petition process (40 CFR Part 82). Additionally, the Basel Convention regulates the shipment of ODS across international boundaries (see Appendix A). ODS importers are required to submit quarterly reports on the quantity of Class I substances imported for in-house or second-party destruction.

As shown in Figure 2, the import of ODS for destruction in the United States has decreased from 2010 to 2016 by over 90 percent, with the greatest reduction in the quantity of Class I ODS imported for destruction. Class I ODS imports for destruction have decreased by 99 percent in this period, from a total of approximately 460 MT in 2010 to approximately 5 MT in 2016.

Approximately 97 percent of all Class I ODS imported for destruction throughout this period were CFCs. Class II ODS imports for destruction have decreased by 70 percent in this period, from 105 MT in 2010 to approximately 32 MT in 2016. Figure 2 below presents the total reported quantity of ODS imported for destruction from 2010 to 2016.

Figure 2. U.S. Imports for Destruction of Class I and Class II ODS (2010-2016)



Source: EPA (2017d).

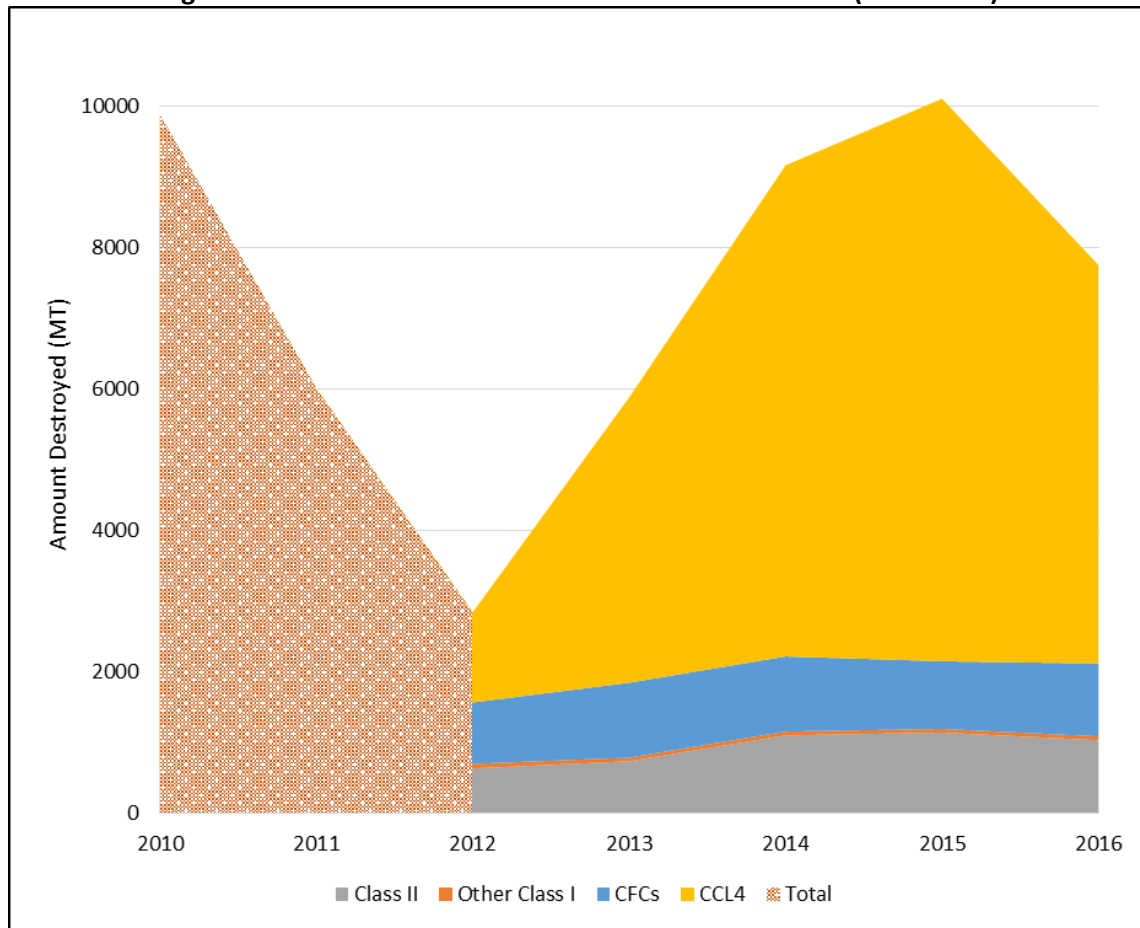
5.2. European Union

5.2.1. Reported Amount and Type of ODS Destroyed

As shown in Figure 3, 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 CCl₄ produced as an unintentional by-product from 2010 to 2012, and the subsequent destruction of the stockpiles in 2013. Since 2012, the stockpiling of CCl₄ has ceased which has increased destruction activity, but it should also be noted that the unintentional by-production of CCl₄ has decreased since 2013.

From 2013 to 2016, approximately 75 percent of all the ODS destroyed in the European Union was CCl₄ (exact data is not available from 2010 to 2011) which accounts for the increase in Europe’s destruction activity during this time. Figure 3 also illustrates that although the destruction of CFCs and Class II 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, CCl₄, halons, and Class II destroyed from 2012 to 2016.

Figure 3. Destruction of Class I and Class II ODS in the EU (2010-2016)



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

Table 6. ODS Destroyed in the EU (MT) (2010-2016)^a

| Chemical | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|----------------------------|--------------|--------------|--------------|--------------|--------------|-----------------|--------------|
| CFCs | NA | NA | 868 | 1,060 | 1,061 | 957 | 1,030 |
| CCl ₄ | NA | NA | 1,275 | 4,036 | 6,946 | 7,955 | 5,633 |
| Halons | NA | NA | 31 | 14 | 22 | C | 32 |
| Other Class I ^b | NA | NA | 35 | 36 | 35 | 52 ^c | 23 |
| Total, Class I | NA | NA | 2,210 | 5,145 | 8,063 | 8,965 | 6,719 |
| Total, Class II | NA | NA | 635 | 738 | 1,102 | 1,143 | 1,034 |
| Total, All ODS | 9,863 | 6,016 | 2,845 | 5,883 | 9,970 | 10,456 | 7,753 |

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

NA = Not available.

C = Confidential.

^a The chemical breakout data in this table for 2012 to 2016 is sourced directly from the European Environment Agency's Ozone-Depleting Substances annual reports for those years (EEA 2012-2017). The total values for 2010 to 2016 are sourced exclusively from the 2016 report as the 2010 to 2015 numbers have been updated in the 2016 report (EEA 2017).

^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. In 2016, 96 percent of the over 5,000 MT imported was intended for these uses, as well as 91 percent in 2015, 69 percent in 2014, 61 percent in 2013, and 54 percent in 2012 (data is not available from 2010 to 2011). The European Environment Agency (EEA) has not specified the intended use of the remaining material, but the quantity remaining which could be for destruction has decreased from 2012 to 2016.

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

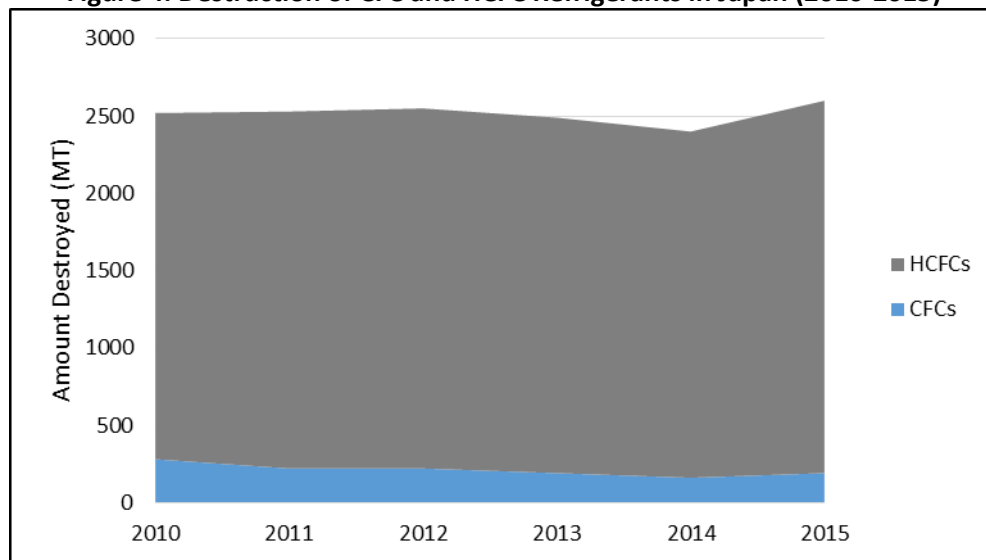
A recent Multilateral Fund project in the country of Georgia, *Pilot demonstration project for ODS waste management and disposal*, demonstrated the potential to overcome barriers to the destruction of unwanted ODS through synergies between ODS and persistent organic pollutant (POP) disposal processes. 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. 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 with future exports of ODS waste (MLF 2017).

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, 84 percent of recovered CFCs and 77 percent of recovered HCFCs were destroyed in 2015 (Japan MOE 2016). As shown in Figure 4, the total destruction of ODS refrigerants in the Japan has stayed constant at 2500 MT from 2010 to 2015.

Figure 4. Destruction of CFC and HCFC Refrigerants in Japan (2010-2015)



Source: Japan MOE (2016).

5.3.2. Reported ODS Imported for Destruction

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. For example, in 2007 the Japanese Ministry of Environment provided technical assistance to Holcim Indonesia for the retrofit of a cement kiln to process ODS. It is unknown whether Japan accepts imported ODS for destruction (ICF 2010b).

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

The following section provides estimates of the ODS destroyed based on an analysis of production data, given that the Montreal Protocol defines production as “amount of controlled substances produced, minus the amount destroyed by technologies to be approved by the Parties and minus the amount entirely used as feedstock in the manufacture of other chemicals” (UNEP 2017a).

Table 7 and Table 8 provide estimated values for CFC and halon destruction in select countries, excluding the United States and countries in the European Union. This report estimates that any production of CFCs and halons 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 7. Estimated CFC Destruction in Select Countries (MT)^a

| Country | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|--------------------|------|------|------|------|------|------|
| Australia | 22.7 | 28.6 | 14.4 | 7.1 | 13.9 | 8.5 |
| India ^b | NA | NA | 14.6 | 18.8 | NA | 32.4 |
| Mexico | - | - | - | - | - | 37.8 |

Source: UNEP (2017a).

^a Data converted from ODP Tonnes to MT using 0.95 conversion factor, representative of a mixture of CFCs.

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

Table 8. Estimated Halon Destruction in Select Countries (MT)^a

| Country | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|-----------|------|------|------|------|------|------|
| Australia | 18.7 | - | 23.3 | - | - | - |
| China | - | - | 0.3 | 0.1 | 0.2 | - |

Source: UNEP (2017a).

^a Data converted from ODP Tonnes to MT using 3.0 conversion factor, representative of halon 1211 destruction (Verdonik 2017).

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 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 if all measures are implemented to the full extent, emissions of 2 MMTCO_{2e} per year and per country will be avoided (GIZ 2014).

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).

The Japanese Ministry of Environment provided technical assistance to Holcim Indonesia for the retrofit of a cement kiln to process ODS. By 2009, the facility had destroyed over 16 MT of ODS, a rate of 8 MT of ODS per year. The vast majority of the amount was CFC-11, with the remainder being CFC-12, HCFC-22, and blends (ICF 2010b).

6. Global ODS Recovery, Transportation, and Destruction Costs

Costs are incurred throughout the entire 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 extinguishing), 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 9 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). For example, while ODS recovery from refrigeration/AC and fire protection 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 9: Range of Costs^a for Recovery, Transport, and Processing of ODS in Products and Equipment

| End-Use | Segregation/Collection Costs ^b (US\$/kg) | Transport Costs (Recovery) (US\$/kg) | Recovery Processing Costs (US\$/kg) |
|---|---|--------------------------------------|---|
| Domestic 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 Protection (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 | |

Source: TEAP (2009).

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).

According to TEAP (2009), the international average cost of transporting ODS between 200 to 1000 kilometers ranges from \$8 to \$60 per MT of ODS. According to a 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 (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 (MLF 2017).

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 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. 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.

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. 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).

7. Financing of ODS Destruction Projects

There are a variety of different mechanisms for funding ODS destruction projects, including producer responsibility programs or taxes on ODS, the generation of carbon offset credits which can be sold on the global carbon market, or support from the Multilateral Fund (MLF) and the Global Environment Fund (GEF) for both financial and project planning assistance.

7.1. Producer Responsibility Programs and Taxes

ODS destruction can be funded through voluntary or government-mandated programs that create financial and behavioral incentives for stakeholders in the process. If regulations are in place to require the collection and destruction of ODS, the collection and destruction of that ODS may not be considered “additional” (i.e., already required by law or otherwise commonly practiced) on certain carbon markets, and therefore would not be eligible for credits.

Extended producer responsibility (EPR) programs, which often rely on levies or licensing fees (usually on the production/import of ODS-containing equipment), and rebates (for the return of recovered ODS), can be used to encourage producers to safely manage the manufacture, operation, and decommissioning of ODS-containing equipment. Producer responsibility programs are thought to work best in countries with strong public support and/or government support, and in situations where few players are involved (MLF 2008). For example, Australia created Refrigerant Reclaim Australia (RRA) to develop and manage the Australian ODS recycling and destruction program. RRA operated on a voluntary basis from 1993-2004 until the *Ozone Protection and Synthetic Greenhouse Gas Management Act* took effect and required companies to exercise product stewardship over imported products (RRA 2012). The RRA is completely funded by the industry from money derived through an industry levy on import of refrigerants in bulk or in pre-charged equipment.

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 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).

An example of a 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.

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.

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.

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 operate outside the compliance market, where 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 are not eligible to generate offset credits because of additionality and double-counting of emission reductions.

7.2.1. Compliance Markets

Compliance markets exist at an international level and at national and regional levels through legally-binding policy instruments. The key aspect of compliance markets is that there is a legal requirement for those bodies covered 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 eligible¹² 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

¹² 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.

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 Western Climate Initiative (WCI). Following successful implementation of Ontario’s cap and trade system in 2016, the Ontario market will join the WCI regional carbon market in January 2018. This will allow all three governments to hold joint auctions of GHG emission allowances and to harmonize regulations and reporting. At this time, Quebec has developed a protocol for the destruction of ODS foams, while Ontario has not yet developed any protocols targeting ODS destruction. In 2017, the Ontario and Quebec governments enlisted help from the CAR to develop a protocol for ODS foam and refrigerant destruction (CAR 2017).

In addition to the North American compliance markets discussed above, several countries and cities have implemented emissions trading systems including the European Union, China, South Korea, Japan, Kazakhstan, Switzerland, Australia and New Zealand. These systems do not currently award offset credits for ODS destruction, however they may approve similar protocols in the future.

7.2.2. Voluntary Programs

Voluntary programs operate outside of compliance markets and allow organizations to offset carbon emissions on a voluntary basis. The voluntary carbon market has been used as a funding source for ODS destruction. The market demand for voluntary offsets is driven by buyers’ interest. The credits have been used by businesses and events to balance their emissions. The three most widely traded voluntary offset programs in the United States with ODS destruction protocols are the VCS, CAR, and the American Carbon Registry (ACR). Table 10 presents a breakdown of the voluntary carbon markets with ODS destruction protocols.

Table 10. Breakdown of Voluntary Markets and ODS Destruction Protocols in 2016

| Offset Program | Total Transacted Volume (millions of MTCO _{2e}) ^a | Total Value Traded (US\$ Millions) ^a | Protocol for ODS Destruction | ODS Sourced Internationally |
|--------------------------|--|---|------------------------------|-----------------------------|
| Verified Carbon Standard | 33.1 | \$76.4 | Yes | Yes |
| Climate Action Reserve | 4.4 | \$13.2 | Yes | Yes |
| American Carbon Registry | 1.8 | \$0.9 | Yes | No |

Sources: Ecosystem Marketplace (2017) and ACR (2017).

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

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 2015, approximately 300,000 MTCO_{2e} from ODS destruction projects were transacted globally in the voluntary market (Ecosystem Marketplace 2016). There are additional costs associated with the preparation, validation, and verification of ODS destruction projects, which are summarized in Table 11.

Table 11. Transaction Costs to Prepare an ODS Destruction Project

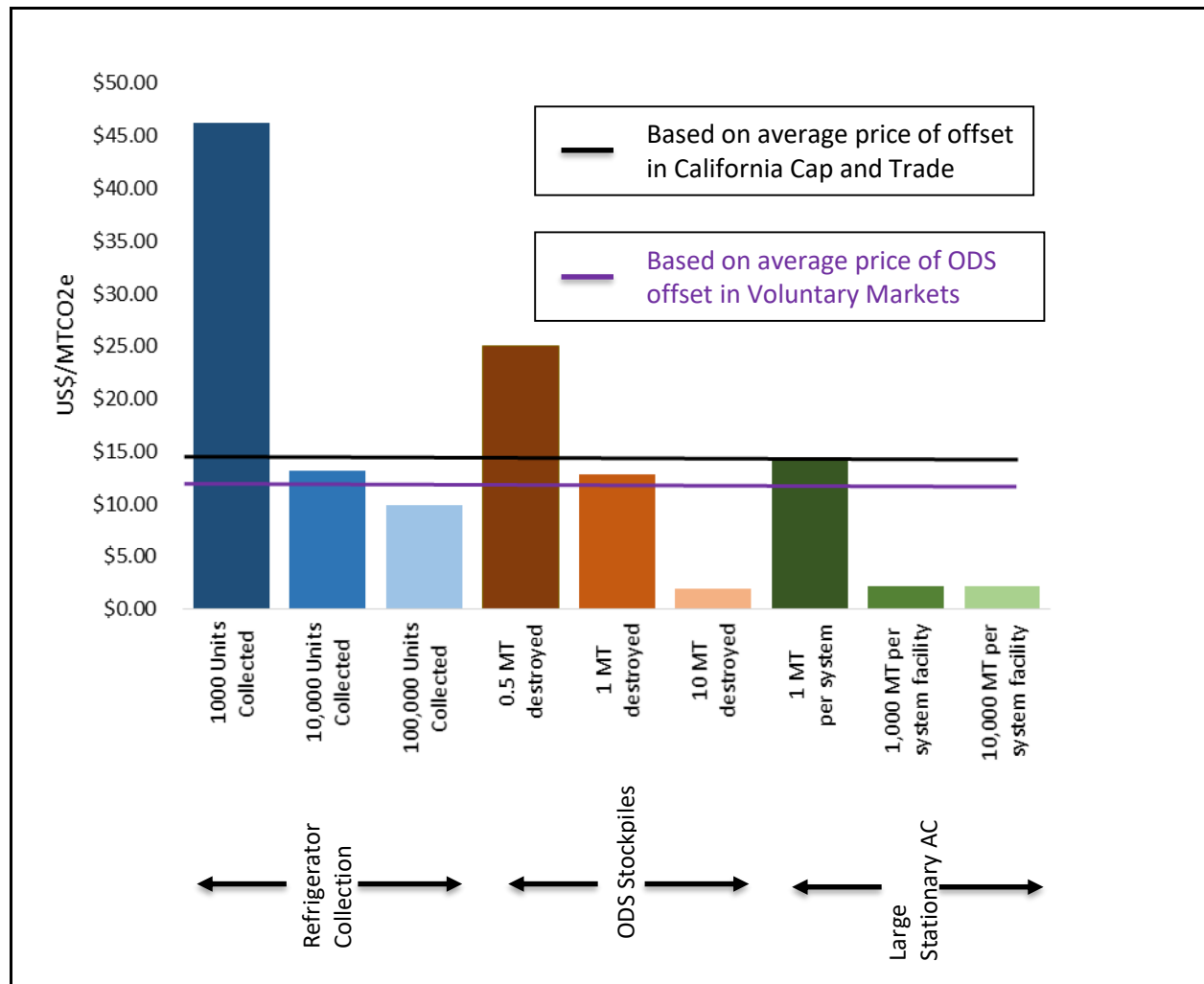
| Project Phase | Cost (US\$) |
|---------------------------|--------------------------------|
| Project Preparation | Up to \$60,000 |
| Third-Party Validation | Up to \$40,000 |
| Third-Party Verification | \$20,000 |
| Offset Marketplace Fees | Up to \$1,000 |
| Issuance/Registration Fee | \$0.05-0.20/MTCO _{2e} |

Source: ICF (2010b).

While the financial prospects of funding ODS destruction projects through the sale of carbon offset credits are promising, there are challenges throughout the process. One of the main challenges is that projects generate revenue only once the offset credits have sold. In developing 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).

Figure 5 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 5 presents three different collection programs: refrigerator collection, ODS stockpiles, and large stationary AC.

Figure 5. Break-Even Costs Compared to Average Price of Offset



Sources: ICF (2010b), Ecosystem Marketplace (2016), and Thomson (2017).

7.3. HFC-23 Destruction

HFC-23 generated as a byproduct from HCFC-22 production 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 CER credits from HFC-23 destruction, which significantly lowered the value of credits obtained from HFC-23 abatement projects. 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).

Under the Kigali Amendment, Parties commit, starting in 2020, to destroy HFC-23 emissions to the extent practicable in specified facility types using technology approved by the Parties. Facilities can also opt to install incinerators or conversion technology which converts HFC-23 to useful high-purity byproducts (e.g., CO and HF). These conversion technologies can generate positive revenue streams.

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 are funded by these organizations to show that ODS destruction is viable, develop lessons learned, and establish replicability. Due to the varying capabilities of the MLF and GEF, each organization focuses funding on different aspects within the process of ODS waste management.

The MLF focuses 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 2015). 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 situations, the international organizations collaborated with the private sector to monetize the project. For example, in 2012, the MLF, in collaboration with EOS Climate, funded the collection and transport for destruction of waste ODS from Nepal to the United States. EOS Climate acted as a project verifier and facilitated the sale of 82,400 Verified Emission Reductions (VER) in the CAR (UNEP 2017b).

The GEF focuses funding on legal and informational aspects 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).

8. Modeled Amounts of ODS Potentially Available for Destruction

The large amount of ODS currently installed in equipment and products, and existing in stockpiles, could be released to the atmosphere given emissions from ODS banks are not controlled by the Montreal Protocol. 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. In the fire protection 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). ODS recovery from appliance foams is also feasible, however, the level of effort to recover ODS from construction foams is high, and the quantity of original blowing agent that is actually recoverable is relatively lower than for the refrigeration/AC sector. 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)¹³ 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 extinguishing, 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.

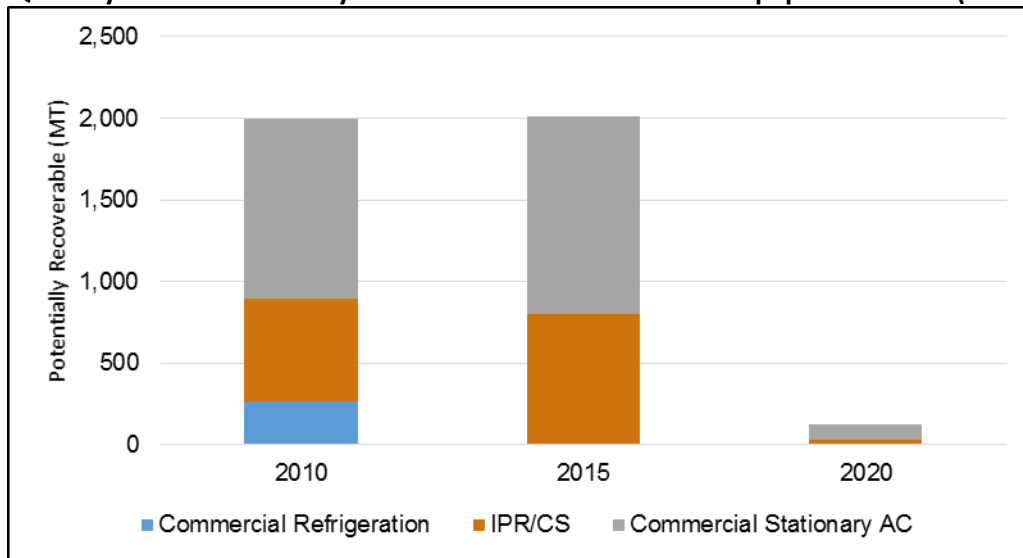
The amount of chemical potentially recoverable from equipment/products being disposed of is modeled in the VM with varying recovery rates depending on the end-use and vintage of equipment. According to assumptions in the VM, the amount of ODS recoverable from equipment at disposal varies by equipment 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 protection equipment are estimated in this analysis. Estimated quantities of HFCs potentially recoverable from retired equipment at EOL are presented in Section 10.2.

Figure 6 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.

¹³ IO version 4.4 (08.31.17).

Figure 6. Quantity of CFCs Potentially Recoverable from Retired U.S. Equipment at EOL (2010-2020)^a

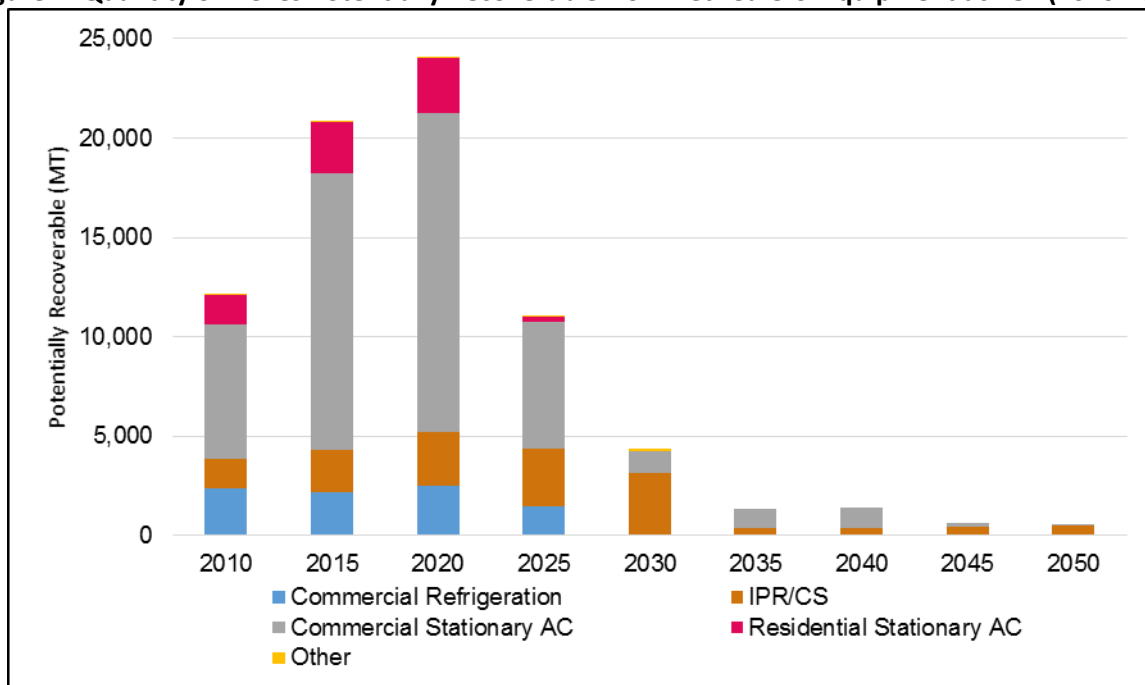


Source: EPA (2017b).

^a After 2020, CFCs are no longer expected to be available for recovery for destruction.

Figure 7 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 7. Quantity of HCFCs Potentially Recoverable from Retired U.S. Equipment at EOL (2010-2050)

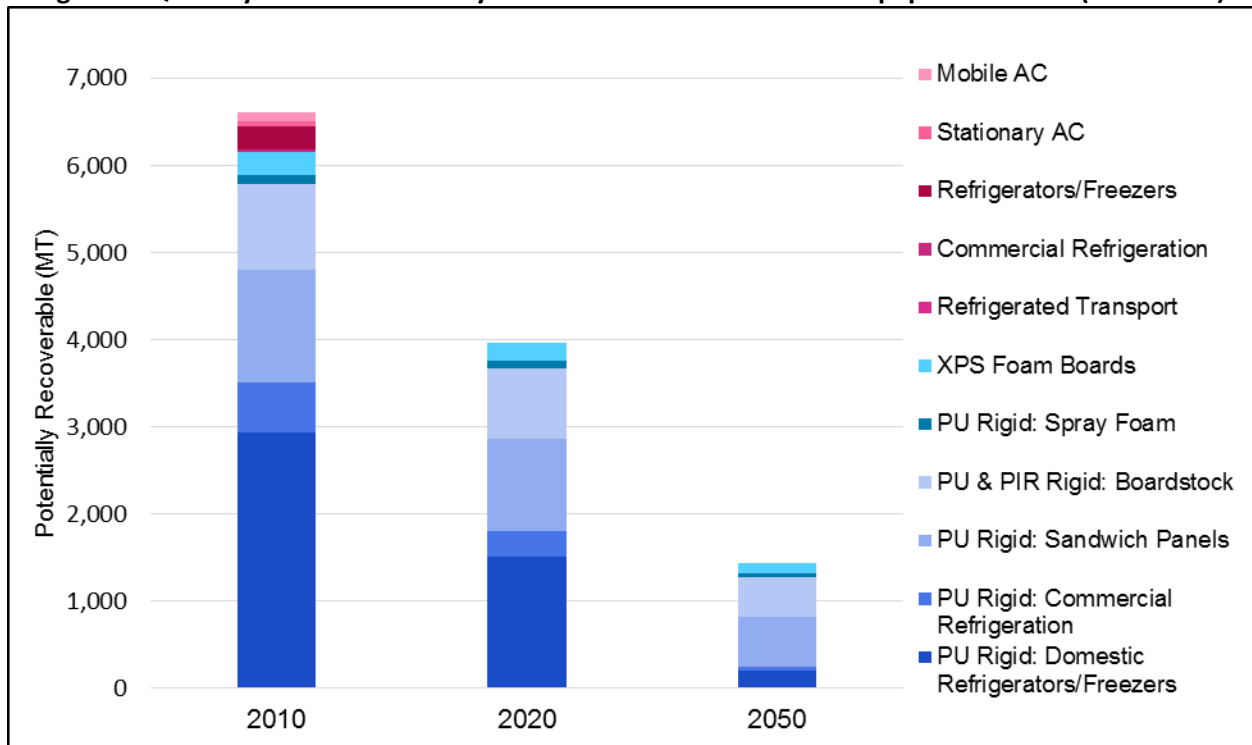


Source: EPA (2017b).

8.1.2. European Union

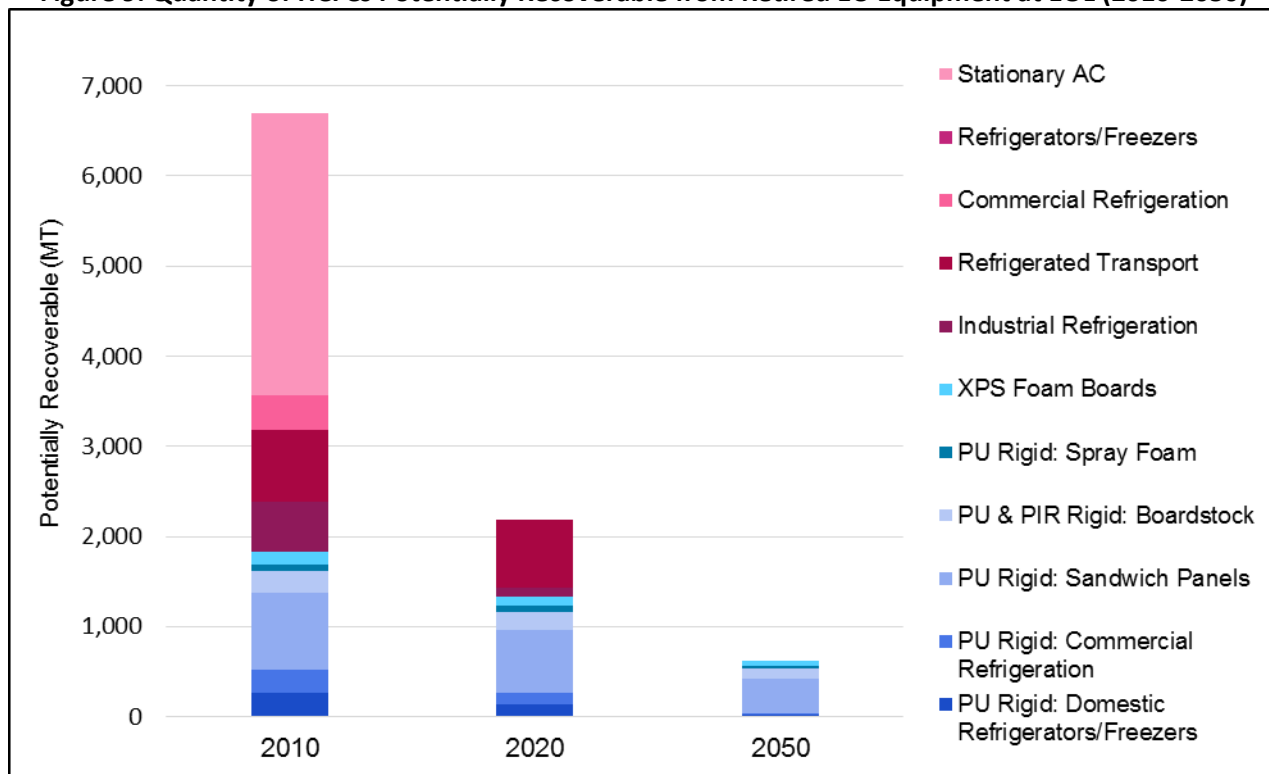
The technical and economic feasibility of recovering ODS from equipment and products at EOL in the member states of the EU was assessed in ICF (2010a). Figure 8 and Figure 9 show the quantities of CFCs and HCFCs estimated to be potentially recoverable from equipment at EOL in 2010, 2020, and 2050, based 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.

Figure 8. Quantity of CFCs Potentially Recoverable from Retired EU Equipment at EOL (2010-2050)



Source: ICF (2010a).

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

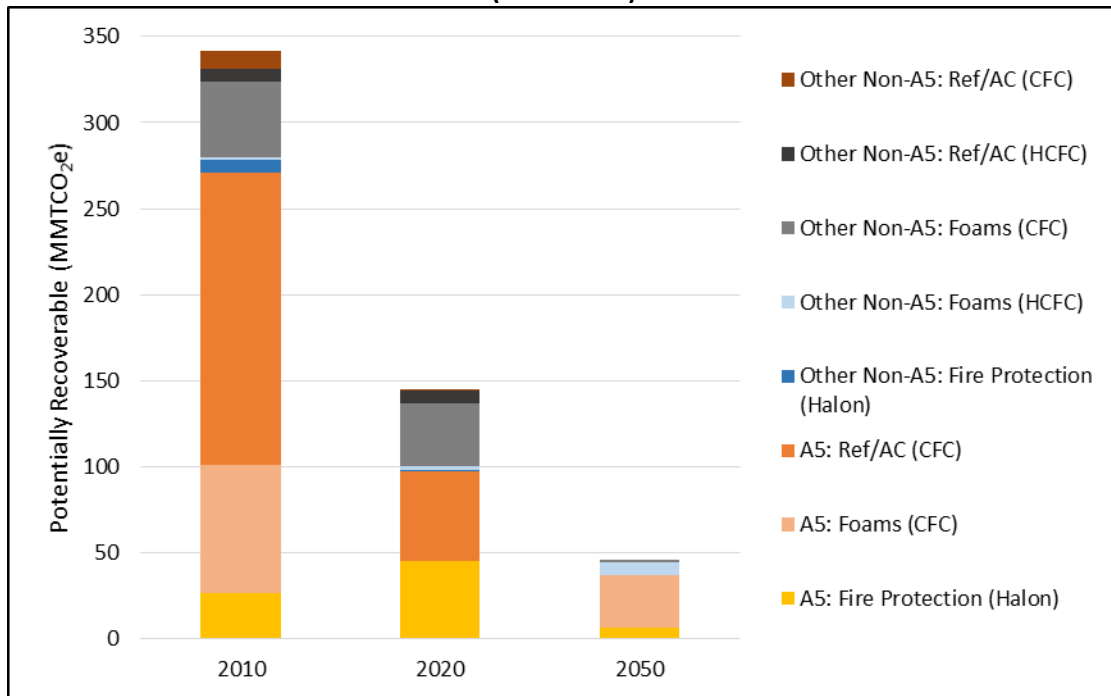


Source: ICF (2010a).

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 10, 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. All recoverable ODS will likely not be recovered due to several factors including lack of necessary recovery equipment, geographical dispersion of equipment, and cost. ODS potentially available at equipment EOL in the United States and European Union was modeled in ICF (2010b); however, the results are not included in Figure 10 because other studies are referenced. The rate of recovery is expected to vary significantly by country, with a higher proportion of material likely recovered in non-Article 5 countries and in Article 5 countries with more established recovery infrastructure or denser population centers (ICF 2010b).

Figure 10. Global Estimates of ODS Potentially Available from Retired Equipment at EOL in MMTCO₂e, (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 6, Figure 7, Figure 8, Figure 9, and Figure 10 do not account for any stockpiles since currently there is little information available on existing or future ODS stockpiles. Preliminary research indicates that the likelihood of ODS users having large stockpiles for which future planned use is not imminent is quite low because of the costs required to store surplus ODS and the current demand for most ODS. The most likely holders of surplus ODS are service companies that possess “empty” cylinders of ODS that were used to service equipment and that actually still contain a heel of up to 5 percent of the original contents (ICF 2009a). Further, there is potential to stockpile virgin ODS for future servicing needs (e.g., HCFC-22 manufactured prior to 2020 in the United States). Such stockpiling may be a risky business practice due to the uncertainty associated with market trends, although in the future, R-22 supplies will continue to be more limited and costs to service equipment with R-22 may rise (ICF 2009b).

8.2.2. Halons in Fire Extinguishing Equipment

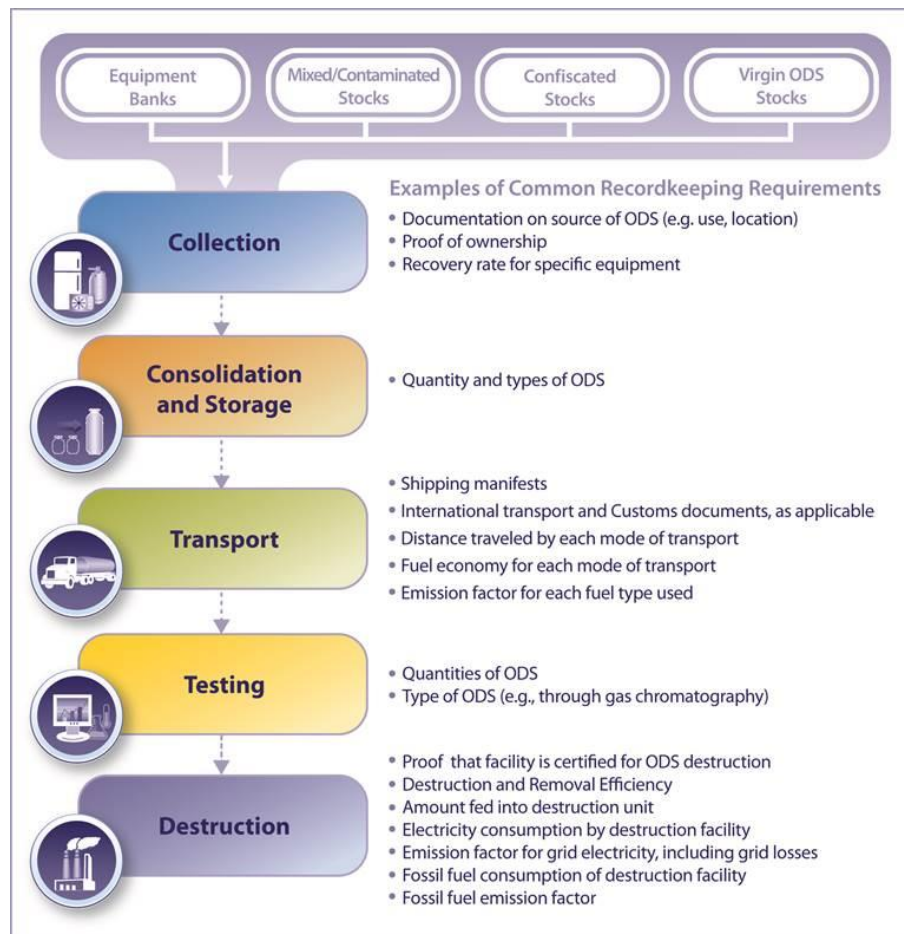
Halons can be easily collected and stored for reuse and disposal. Existing stockpiles of halon can be reclaimed for reuse, destroyed, or transformed to other useful chemical products. There is, however, continued global demand for halons so the TEAP has recommended that destruction should be avoided when possible and should only be considered if the halons are cross-contaminated and cannot be reclaimed to an acceptable purity level (UNEP 2014b).

Given destruction of halon 1301 is highly discouraged, halon stockpiles will not likely be available for destruction. Regardless, the ACR revised its ODS destruction project standard in 2017 to include halons 1211 and 1301 (ACR 2017).

9. ODS Management Needs for Developing Countries

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

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



Source: ICF (2010b).

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 developing 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 developing 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 developing 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 developed countries 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).

Coordination with Developed Countries

Developed countries may be able to facilitate ODS management in developing countries 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).

Developed and developing 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 2017b). See Appendix A for further information on transboundary movement (TBM) of ODS.

10. Implications for Addressing HFC Disposal

In October 2016, Parties agreed in the Kigali Amendment to the Montreal Protocol to phasedown HFC production and consumption. Under the Montreal Protocol, destroyed amounts are subtracted from the definition of 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 developed 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 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).¹⁴

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.

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 CCX for the destruction of the ODS components of the mixture (ICF

¹⁴ U.S. EPA is currently revisiting aspects of the 2016 rule's extension of the refrigerant management program to non-exempt substitutes. The 2016 rule remains in effect until a final rule is issued to amend the requirements.

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 may continue to be a method of financing 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 developing countries, which have only recently begun transitioning to HFCs, ODS are still commonly used in systems and equipment. In developed countries, HFCs have largely replaced ODS in equipment. Equipment containing HFCs have lifetimes up to 30 years. New 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.

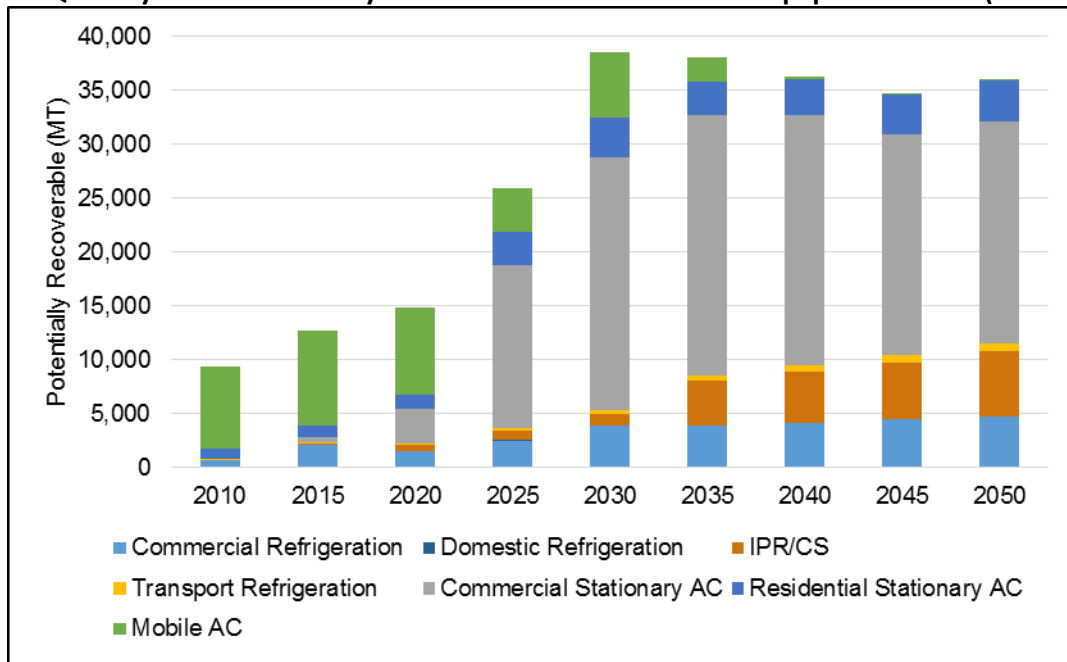
Some systems or equipment that were charged with HFCs and are nearing EOL are expected to be decommissioned with the remaining charge to be recovered. Most recovered material is expected to be reclaimed or recycled to service existing systems¹⁵ in the installed base. However, materials that are recoverable 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 11). 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 is the primary driver in potentially recoverable HFCs until 2020. In 2030, potential recovery of HFCs at EOL reaches a maximum at approximately 38,000 MT due to the commercial 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.

¹⁵ 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)..

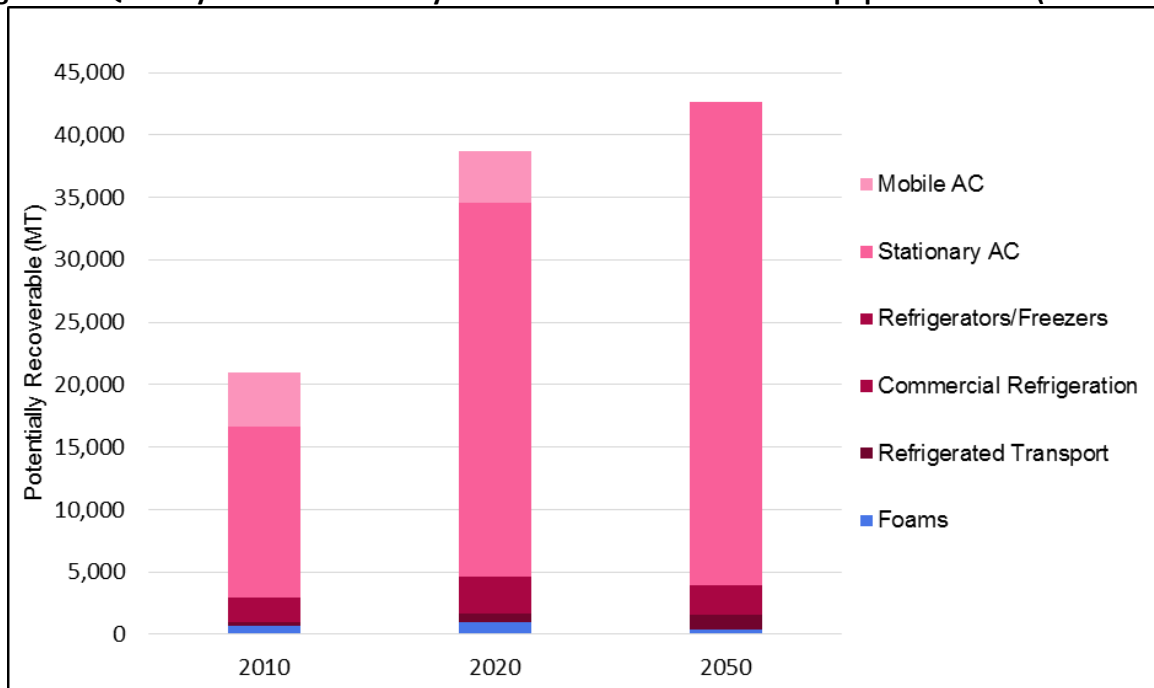
Figure 11. Quantity of HFC Potentially Recoverable from Retired U.S. Equipment at EOL (2010-2050)



Source: EPA (2017b).

As another example, Figure 12 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 12. 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.

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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 2014c). 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 2017). 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) 1013/2016, 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 2014c). 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.¹⁶

¹⁶ 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 that are classified 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 that meet the definition of hazardous waste.¹⁷ 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 (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); or
- Wastes from specific sources (Code K).

However, the majority of ODS 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."¹⁸ According to 56 FR 5913, this exemption includes CFC and HCFC refrigerants.

Table 12 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 may be considered hazardous wastes under RCRA.

¹⁷ 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.

¹⁸ 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 12. RCRA Hazardous Waste Codes for Selected ODS

| 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 | - | - | - |

^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 261.31:¹⁹

- F001**—Applies to the following spent halogenated solvents used in degreasing: tetrachloroethylene, trichloroethylene, methylene chloride, methyl chloroform, CCl₄, 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, CCl₄, 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. 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

¹⁹ 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.

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:

- 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.²⁰

Thus, while CCl₄, 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.

Code K (Wastes from Specific Sources)

ODS-contaminated wastes which may be generated from specific sources, such as the production of CCl₄, may be classified under several K waste codes (e.g., K016, K018, K021, K028, K029, K073, K095, K096, K131, K132, K150). 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. The most likely characteristic to apply to ODS waste is the toxicity characteristic (TC). CCl₄ is designated as waste code D019 if it has enough to be considered hazardous. That is, if an extract from a representative sample of a solid waste contains a concentration of CCl₄ equal to or greater than the regulatory threshold level of 0.5 mg/L, it is considered a hazardous waste.²¹ Additionally, used ODS 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.

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

²⁰ 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.

²¹ A waste extract is obtained using a specific test method called the Toxicity Characteristic Leaching Procedure (TCLP).

differently to listed wastes and 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 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). Three additional technologies that have not been evaluated by TEAP are also described, which may be suitable for ODS destruction. Fixed hearth incineration, commonly used in the United States and air plasma arc, used in an experimental facility in Sweden, are also described in this section.

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.

Reactor Cracking

CFCs and HCFCs are broken down or “cracked” into HF, H₂O, HCl, CO₂, and Cl₂ 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 CO₂, O₂, 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 Kilns²²

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 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).

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).

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 2015).

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).

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.

²² 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.”

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). Seven different types of plasma technologies are described below.

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 H₂, H₂O, CO, CO₂, 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.

Argon Plasma Arc

Argon plasma arc technology uses the patented PLASCON™ torch to create a 10,000 °C plasma arc in the presence of argon to destroy ODS. 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 PLASCON™ 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 CO₂, argon, and trace amounts of other gases, which are released into the atmosphere.

In Australia, the Department of Administrative Services Centre for Environmental Management (DASCEM), which currently manages the Australian National Halon Bank, uses argon plasma arc technology to destroy both halons and CFCs. Other plasma arc facilities are located in Mexico and the United States (TEAP 2002).

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 CO₂, which along with the HCl and HF are absorbed by a calcium hydroxide solution. There are five units known to be commercially destroying ODS in Japan. 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 5,700 °C plasma, which is created using argon and microwave energy, to break down CFCs into HCl, HF, CO, and CO₂. 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 CO₂, as the acid gases are removed by a scrubber and the CO is combusted with air in order to convert it to CO₂ (TEAP 2002).

Steam Plasma Arc

Steam plasma arc technology injects ODS and high temperature steam into a 1,300 °C reactor. H₂ and CO are formed under the plasma plume and later oxidized to CO₂ and H₂O 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 2015). This technology has not been approved by the Parties to the Montreal Protocol.

Portable Plasma Arc

The portable technology utilizes torch plasma technology to destroy ODS and eventually produce halide salts and CO₂. 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).

Other Non-Incineration Technologies

Some non-incineration technologies are considered conversion technologies, because they chemically react the ODS to make useful byproducts.

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 CO₂, 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 H₂ and CO₂

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 H₂O. 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 weak CClF₂-Br bond is cleaved, producing two radicals that react with methane to form HBr, methyl bromide, CHClF₂ and CClF₂. 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).

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. This technology has not been approved by the Parties to 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 2015). 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.

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 constituent (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 13 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 13. Thermal Stability Ranking of Selected Compounds

| Compound | | Thermal Stability Ranking | Source |
|----------------------------------|---------------------------------------|---------------------------|-------------------|
| Stability Class I | | | |
| SF ₆ | Sulfur Hexafluoride | 4 | EPA 1989 |
| C ₆ H ₅ Cl | Chlorobenzene | 20 | EPA 1989 |
| CH ₃ Cl | Methyl Chloride | 30-31 | EPA 1989 |
| CH ₃ Br | 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, GHGRP Subpart L

U.S. EPA established procedures for fluorinated gas producers to report the destruction efficiency for thermal oxidation destruction of fluorinated gases under Subpart L of the Greenhouse Gas Reporting Rule (GHGRP) 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 (CF₄) is more thermally stable and therefore more difficult to destroy than sulfur hexafluoride (SF₆) 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 destruction efficiency determination must be developed specifically for CF₄, SF₆, 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 CF₄ and SF₆, 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 13). Therefore, for these other fluorinated GHGs, the destruction efficiency 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 14, and are similar to modeled Stability Class I and Stability Class II index rankings for these compounds.

Table 14. Modeled Required Temperatures to Achieve 99.99 Percent DRE for Fluorinated Compounds

| Compound | | | Time | Required Temperature | | Index Ranking |
|--|------------------------------------|------------|------|----------------------|-----|---------------------------|
| | | | | seconds | °K | |
| Tsang et al. (1998) | | | | | | |
| CF ₃ H | Trifluoromethane | HFC-23 | 1 | 1,200 | 927 | Stability Class II |
| C ₂ HF ₅ | Pentafluoroethane | HFC-125 | 1 | 1,137 | 864 | Stability Class II |
| C ₂ H ₅ F | Fluoroethane | HFC-161 | 1 | 1,068 | 795 | Stability Class III |
| Lamb et al. (2010) | | | | | | |
| C ₂ HCl ₂ F ₃ | 2,2-Dichloro-1,1,1-trifluoroethane | HCFC-123 | 2 | 1,182 | 909 | 39 (Class II) |
| CF ₃ Br | Bromotrifluoromethane | Halon 1301 | 2 | 1,040 | 767 | 116 (Stability Class III) |
| CHF ₂ Cl | Chlorodifluoromethane | HCFC-22 | 2 | 978 | 705 | 133 (Stability Class III) |