Cutting refrigerant emissions

ODS/HFC RECLAMATION AND DESTRUCTION TECHNOLOGIES

A review for Article 5 Countries

Climate and Ozone Protection Alliance (COPA)

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CONTENTS

LIST OF ABBREVIATIONS

AFR	Alternative Fuels and Raw Material
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
APC	Air Pollution Control System
CER	Certified Emission Reduction
CFC	Chlorofluorocarbon
COPA	Climate and Ozone Protection Alliance
DRE	Destruction and Removal Efficiency
EOL	End of Life
EPR	Extended Producer Responsibility
ETS	Emission Trading System
EU	European Union
F-gas	Fluorinated gas
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GWP	Global Warming Potential
HARP	Home Appliances Replacement Program
HCFC	Hydrochlorofluorocarbon
HF	Hafinum
HFC	Hydrofluorocarbon
HPMP	HCFC Phase-out Management Plan
HTI	High-Temperature Incineration
IKI	Internationale Klimaschutzinitiative
LVC	Low-Volume Consuming
MCTOC	Medical and Chemicals Technical Options Committee
MLF	Multilateral Fund
MOF	Metal-Organic Frameworks
MSWI	Municipal Solid Waste Incineration
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substances
PCB	Polychlorinated biphenyls
PDU	Plasma Destruction Units
PCDD	Polychlorinated-p-dioxin
PCDF	Polychlorinated dibenzofuran
POP	Persistent Organic Pollutants
RAC	Refrigeration and Air Conditioning
RAC&F	Refrigeration, Air Conditioning and Foam
t	Tonnes
TEAP	Technology and Economic Assessment Panel
TFDT	Task Force on Destruction Technologies
UAE	United Arab Emirates
UNEP	United Nations Environment Programme
UNDP	United Nations Development Programme
UNIDO	United Nations Industrial Development Organization
US EPA	United States Environmental Protection Agency
VCM	Voluntary Carbon Market
WEEE	Waste Electrical and Electronic Equipment

1 INTRODUCTION

The Montreal Protocol was signed in 1987 aiming to protect the Earth's ozone layer by phasing out the production and consumption of ozone-depleting substances (ODS). Since then, it has been amended and adjusted several times to include new fluorinated substances including hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) and accelerate their phase-out. This treaty laid the ground for the mitigation of the emissions of ODS and other fluorinated greenhouse gases (mainly HFCs) from existing banks – substances that are contained in equipment or products in operation or at decommissioning. Although the efforts led by the United Nations Environmental Program (UNEP) and many countries around the world under the agreement of the Montreal Protocol have successfully slowed down and reverted the growth of the ozone hole in the Arctic (WMO et al. 2022), the bank of harmful substances and their emissions is projected to increase due to the expected surge of refrigeration and air conditioning (RAC) equipment in the future years (IEA 2018).

The work hereby presented was developed in the framework of the Climate and Ozone Protection Alliance (COPA) and feeds into the "Working Group on Technology Solutions". COPA works jointly with member countries and diverse actors across private and public sectors to accelerate the mitigation measures needed to address ODS and HFC banks. COPA has been initiated by the German Federal Ministry of Economic Affairs and Climate Action and is jointly implemented by GIZ, UNIDO, and UNDP.

The purpose of this report is to provide an overview of technical solutions for the successful management of ODS/HFCs and to identify gaps and possible topics to be addressed in-depth by the working group. This report summarizes information on the conditions, challenges, available technologies, and current state of ODS/HFC reclamation and destruction practices in Article 5[1] countries. In addition, a very brief assessment of the policy framework directly influencing reclamation and destruction practices in Article 5 countries is presented, highlighting its role in the successful management of ODS/HFCs.

The following chapters focus on ODS/HFC destruction and reclamation practices, including a description of the current technologies used to reclaim and destroy ODS/HFCs worldwide. *Chapter 2* lays the background on ODS/HFC banks in Article 5 countries, including their related emissions, challenges and international efforts to manage them sustainably. Then, *chapter 3* presents the main reclamation technologies: distillation, adsorption, and subcooling, together with the experiences, challenges and lessons learned from various ongoing reclamation projects around the world. *Chapter 4* provides a description and comparison of four selected destruction technologies that are currently relevant in Article 5 countries. These technologies are cement kiln, municipal solid waste incineration, rotary kiln incineration and argon plasma arc. It also contains the experience of the Multilateral Fund's demonstration projects and the les-

1 Article 5 countries are a group of members of the Montreal Protocol, whose annual consumption of the substances regulated by the protocol was less than 0.3 kilograms per capita at the time of entry into force of the protocol or at any time thereafter until 01.01.1999. There are currently 144 countries in this group (UNEP 2020).

sons learned and challenges faced in the course of their implementation. Finally, *chapter 5* dives deeper into the relationship between policy framework and the viability of ODS/HFC destruction and reclamation practices. It also includes some country experiences that illustrate this relationship.

The assessment of reclamation and destruction technologies suitable for use in Article 5 countries was carried out by combining two methods, a desk-based review of documents and collection of field experiences through interviews and discussions with stakeholders.

First, background information on the status of ODS/HFC banks in Article 5 countries was reviewed, including their total quantity, annual ODS/HFC waste generation and current end-of-life management practices for the safe disposal of these substances (*Chapter 2*).

Second, a literature review of available information on reclamation was conducted, and interviews and background discussions were held with refrigerant reclamation companies, RAC equipment recycling centres, and a university. Both activities focused on the technologies used for reclamation, the verification and monitoring systems in place and the main challenges faced by reclamation centres in Article 5 countries (*Chapter 3*).

Third, a literature review was conducted to assess the most relevant destruction technologies suitable for implementation in Article 5 countries. The MLF demonstration projects were the focus of this review (*Chapter 4*).

Fourth, an analysis of the relationship between ODS/HFC policies and the successful implementation of destruction and reclamation projects was undertaken (*Chapter 5*).

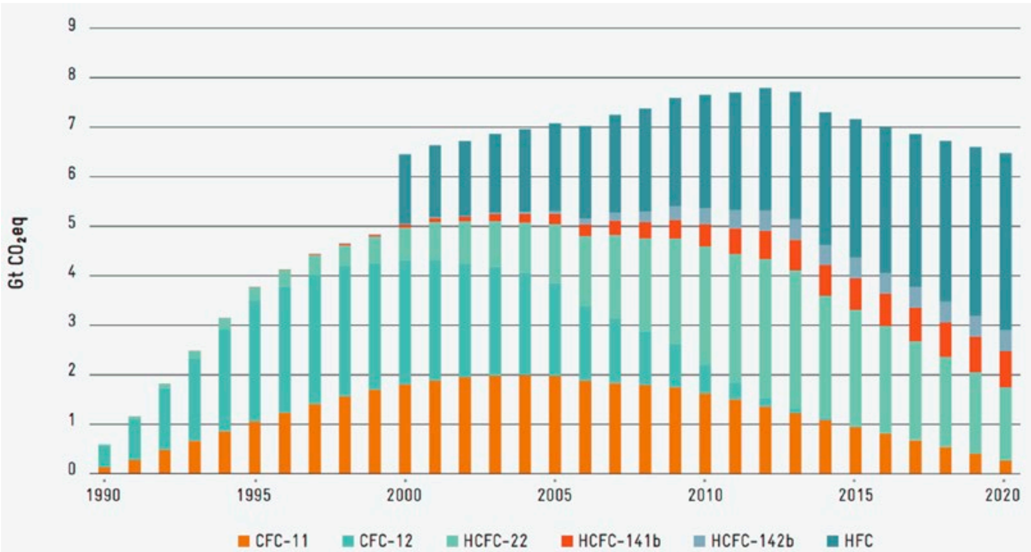
This report was set out to study destruction and reclamation technologies being practiced around the world. It became clear during the analysis that technology cannot be studied in isolation. As already laid out in GIZ 2017b, there are four core processes to sustainable ODS/HFC banks management, where technology is one of them. The others are - and this is also reflected in the current analysis - policy measures, sustainable financing structures and a collection mechanism. This is also reflected in the set-up of COPA's thematic working groups, which work together towards a global shift to the sustainable management of ODS/HFCs.

2 BACKGROUND ON ODS/HFC BANKS

The protection of the ozone layer and the efforts to keep global warming under a threshold of +1.5°C mean temperature are two crucial global goals that are directly affected by the presence of ODS and HFCs in the atmosphere. The Montreal Protocol and its Kigali Amendment aim to globally cut down the use and the emissions of these substances by setting specific phase-out goals on production and consumption. While the phase-out of chlorofluorocarbons (CFC) was completed in 2010, the phase-out goal for hydrochlorofluorocarbons (HCFC) in Article 5 countries is set for 2030. For HFCs, the phase-down plans in Article 5 countries are about to start and are scheduled to reach 20% of the baseline by 2047 (UNEP 2020).

The phase-out schedules for CFCs and HCFCs have successfully reduced the consumption and emissions across the globe of these gases, achieving a partial recovering of the ozone layer (WMO et al. 2022). Nonetheless, the historical use of ODS globally has led to large banks of these substances in existing equipment, chemical stockpiles and foams. With the global increase of RAC applications, the banks are expected to increase further from the 2020 estimate of 6.4 $GtCO_2eq$ (GIZ 2017b). The efforts to reduce the production and consumption of HFCs, agreed in the Kigali Amendment, are yet to be seen. Phase-out implementation plans are still in their first stages and joined efforts are necessary to achieve a considerable reduction on HFC consumption (Stanley et al. 2020). *Figure 1* presents the estimated ODS/HFC banks for Article 5 countries. As this report focuses on Article 5 countries, the data from industrialized countries is not shown. The global ODS/HFC bank was estimated to be around 12 $GtCO_2eq$ in 2020, with 6.5 $GtCO_2eq$ located in non-Article 5 countries. However, a recent study of foam banks (GIZ 2020a) and modelling of CFCs and HCFCs using atmospheric concentrations (Lickley et al. 2021,

***Figure 1**. ODS/HFC Bank in Article 5 countries*



Source: GIZ 2017a

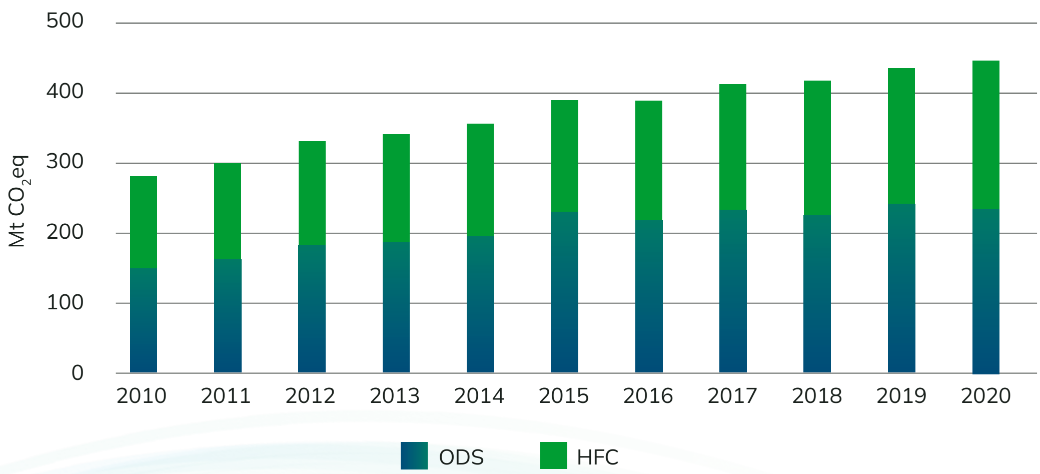
2022) has suggested that the lifetime of these gases, and therefore their banks, has previously been underestimated. More detailed information can be found in the reports “Global Banks of Ozone Depleting Substances: A country-level estimate” (GIZ 2017a) and “Banks and Emissions of CFC-11 and CFC-12. Country data and possible consequences for global modelling” (GIZ 2020a).

Although ODS banks are decreasing as they are emitted faster than new equipment is acquired, the overall bank is increasing due to the steep uptake of RAC equipment containing HFCs. These have no ozone depletion potential (ODP), but a high to very high global warming potential (GWP). Implementing the Kigali Amendment might slow down this development, but the current industry trend to medium GWP refrigerants is not enough to initiate a trend reversal. Therefore, the management of ODS/HFC banks will remain a challenge beyond 2050.

A plan for the sustainable management of the ODS/HFC banks is required before these gases are simply emitted into the atmosphere. In *Figure 2*, the total annual ODS/HFC waste from Article 5 countries is estimated. This graph shows that there has been an ongoing opportunity to recover substances contained in RAC equipment for their reclamation or destruction. However, not enough has been done to prevent these substances from being emitted into the atmosphere. The efforts must be intensified especially in Article 5 countries where the disposal of RAC equipment and foams (RAC&F) is often done manually and partially by the informal sector due to the lack of infrastructure, equipment, certification programs, and a policy framework (GIZ 2017e, 2017a).

Current and previous efforts are being undertaken as pilot projects by the Multilateral Fund (MLF), through its implementing agencies, and global projects such as the

Figure 2*. Total annual amounts of ODS/HFC waste from Article 5 countries*



Source: GIZ 2017a

International Climate Initiative (IKI) of Germany. The aim of the international projects is to support countries in the development of state-of-the-art strategies that ensure the safe disposal of ODS/HFCs. Instead, reclamation has previously played a more marginal role in the international efforts to manage ODS/HFC waste. In recent years, however, reclamation projects such as the one led by UNIDO in Chile have shown that this topic is gaining more relevance (Cerda 2019; Ministry of the Environment of Chile 2014).

The Multilateral Fund was created by the parties of the Montreal Protocol to assist with the phase-out of controlled substances in Article 5 countries. This fund is sufficiently financed to cover the incremental costs to support Article 5 countries to fulfil their obligations to reduce ODS/HFC consumption.[2] This means that the funding is primarily for manufacturing conversion, measures in the servicing sectors, and capacity building. Destruction of ODS/HFCs is not mandatory, hence only demonstration projects were financed by the MLF within specific funding windows. Between 2008 and 2014, the MLF approved 11.5 million USD only on destruction projects in Article 5 countries (MLF 2019, 2022). The MLF approves funding on a project-by-project basis and countries carry them out with the help of implementing agencies (UNEP, UNDP, UNIDO, the IBRD, and bilateral agencies).

2 For example, in the triennium 2021-2023 more than 540 million USD are available.

2.1 DEFINITIONS

The following end of life (EOL) management activities are defined in order to have a clear understanding of the terms throughout the report, and to avoid common confusions between reclamation, recovery, recycling.

All definitions refer to the context of ODS/HFC substances.

- **Destruction** is defined as the physical and chemical process to decompose the fluorinated substances by at least 99.99 percent of the molecules for concentrated sources of ODS/HFCs and 95 percent for dilute sources of ODS/HFCs (i.e., foams).

- **Reclamation** or reclaim is to reprocess ODS/HFCs to a certain purity standard. Usually, the Standard 700-2016 from the Air-conditioning Heating and Refrigeration Institute (AHRI) is used. The level of purity under this standard is set at 99.5%. Reclaimed refrigerant can be used instead of virgin refrigerant (AHRI 2016).

- **Recycling** is "to extract ODS/HFCs from an appliance and clean the ODS/HFC for reuse without meeting all of the requirements for reclamation" (EPA 2021). The substance is recommended to be reused in the same appliance where it came from to avoid the risk of transposing unwanted substances to other appliances.

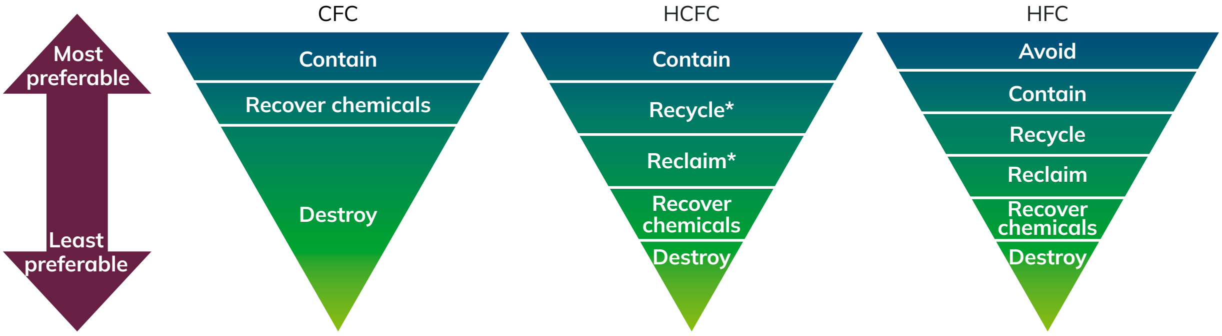
- **Recovery** and **collection** mean to transfer the residual refrigerants contained in equipment to a cylinder to be then transported to collection centres or other facilities for further treatment or storage (concentrated sources). For diluted sources, such as substances contained in foam, this process is similar but without using cylinders.

- The **recovery of chemicals** from ODS/HFCs, also known as **chemical cracking** or **chemical recycling**, involves breaking down large CFCs, HCFCs and HFCs into smaller, more useful molecules. This process is usually carried out using a catalyst, and by increasing pressure and applying high temperatures. However, this term should not be confused with **chemical repurposing**, which aims to convert refrigerants into other useful fluorinated gases (F-gases) through chemical reactions (Sheldon and Crimmin 2022). Both processes aim to obtain molecules that can be reused by the industry.

The activities outlined here are part of an integral management of ODS/HFC banks. However, the appropriate management may differ depending on the type of substance. This differentiation is based on the chemical properties of the refrigerant, mainly its ODP and GWP. By analogy with a standard waste hierarchy approach, which prioritises the circular use of resources, the management hierarchy for ODS/HFCs is illustrated in *Figure 3.* It ranks measures from most to least preferable, depending on the type of refrigerant.

Recycling (usually carried out on-site) is preferred to reclamation because it avoids the risk of leaks and emissions during the transport and processing of the gases and because reclamation facilities have higher investment costs and require large quantities of available refrigerant to maintain operating costs. Similarly, reclamation of HFCs and HCFCs is preferred to chemical recovery and destruction because it is often cheaper and the refrigerant can then be reused, achieving a circular economy and avoiding the production of virgin refrigerant. Instead, CFCs should always be contained and destroyed to prevent the depletion of the ozone layer.

__Figure 3__. ODS/HFC Bank Management Hierarchy.



**Recycling and Reclaim of HCFCs should be subject to a cutoff date that is aligned with the phase-out of HCFCs*
Source: HEAT 2023

This hierarchy is established from a circular economy perspective. However, individual cases and local conditions may change the prioritization of these measures. Further characterisation of these EOL practices can be found in the respective chapters.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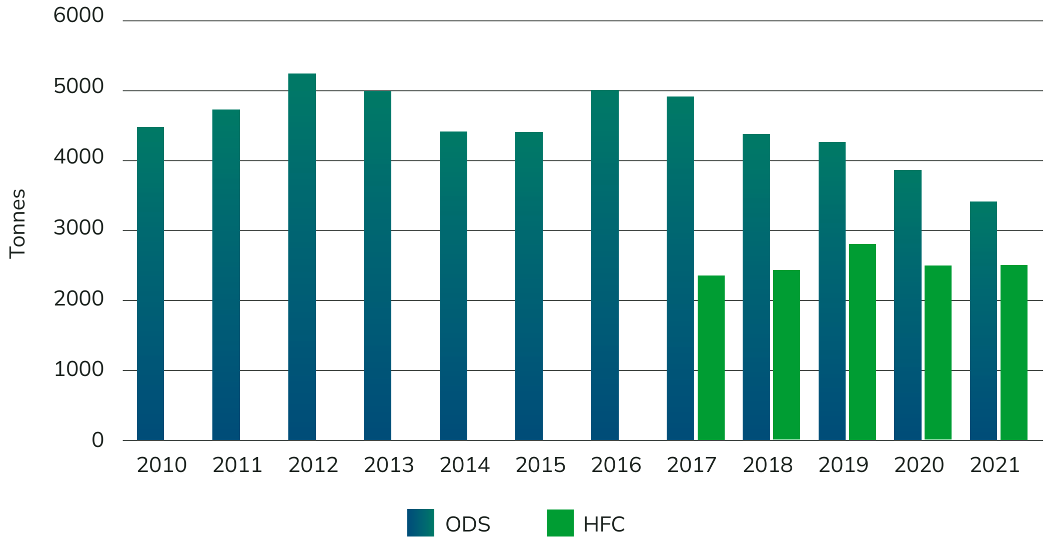
3 RECLAMATION OF ODS/HFCS

ODS/HFC reclamation is the process of thoroughly cleaning refrigerants and separating blends into their components, and then reblending them to produce an "as good as new" refrigerant. It differs from recycling, where refrigerants are cleaned of oils and particles and reused on-site in the same appliances without further testing. The Standard 700-2016 from the Air-conditioning Heating and Refrigeration Institute (AHRI) of the United States provides guidelines to the industry for the manufacturing, distribution, reclaim and any other activities concerning fluorocarbon, hydrofluorocarbon and carbon dioxide refrigerants (including blends). It establishes purity specifications and describes suitable test methods to verify the compliance of refrigerants to the standards for commercialization. Under this standard, refrigerants need to reach 99.5% purity level to be called reclaimed.

There are 63 companies certified in the United States for the reclamation of refrigerants. Annual reclamation in the US, presented in *Figure 4*, shows how ODS are being replaced by HFCs. After 2016, the reclamation of ODS has declined, while for HFCs[3] it is increasing. This is due to the phase-out of HCFCs and their replacement by HFCs. In total, annual reclamation quantities have increased over time in the US. However, in 2020 and 2021 numbers are lower, most likely due to the COVID-19 pandemic.

***Figure 4**. Annual ODS/HFC reclamation in the United States*

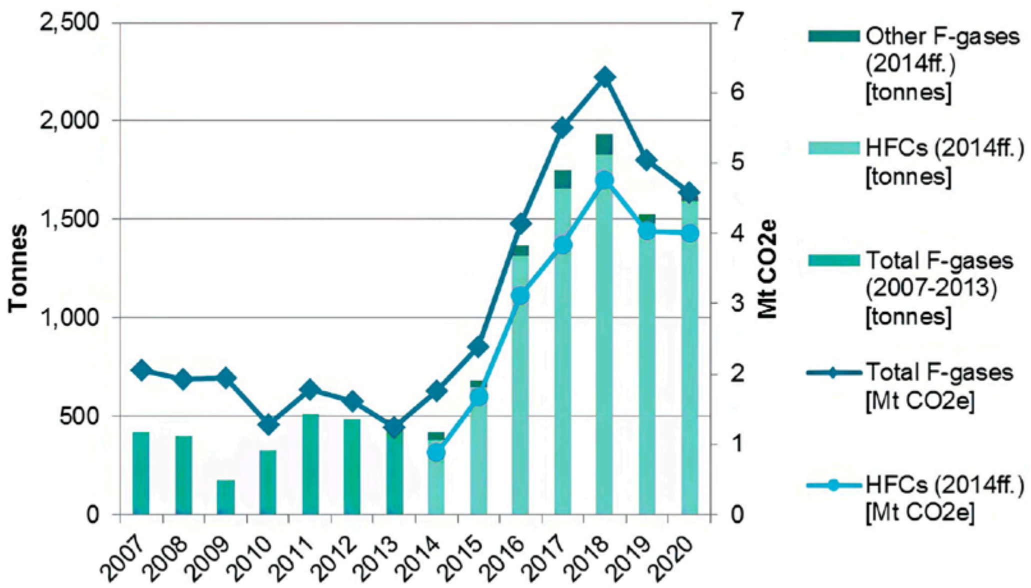


Source: US EPA. https://www.epa.gov/section608/summary-refrigerant-reclamation-trends

3 Reclamation centres in the United States were only obliged to report data for HFC reclamation after 2017.

Annual reclaimed quantities in the European Union (EU) are presented in *Figure 5*. A similar trend for HFC reclamation is observed in the EU. Reclamation of HFCs started to increase in 2014 and reached a peak in 2018 with 1829 tonnes (t) of refrigerant reclaimed. Then it declined in the years of the COVID-19 pandemic. In 2021, the European Environmental Agency (EEA) reported that reclaimed HFCs constitute 11% of all the HFCs produced in the EU and 3% of the total EU HFC supply (EEA 2021). Additionally, in Chile 31.3 t of R-22 and 0.62t of R-134a were reclaimed between 2018 and 2019 (Cerda 2019). A preliminary list of reclamation facilities worldwide is presented in Annex A.

***Figure 5**. Reclamation of fluorinated gases in the European Union*



Source: EEA 2021. https://www.eea.europa.eu/publications/fluorinated-greenhouse-gases-2021

The refrigerants are obtained in most cases through RAC technicians that collect the gas during the service and refill of the equipment. Another source of ODS/HFCs for reclamation are the manufacturers that dispose refrigerants after contamination during the production or sample gas used in trial runs (Status Consulting 2010). Additionally, refrigerants are obtained in some cases by direct contact with the industry or other end-users that have large air conditioning and refrigeration systems. In countries with regulations for a safe disposal of ODS/HFCs, it is much simpler to collect enough gas for reclamation. Whereas in countries with weak regulations and no collection infrastructure, reclaimers need to make alliances with large manufacturers or the industry to get the necessary amounts of refrigerant.

Although each type of refrigerant should strictly go into a separate cylinder, there is always a risk of cross-contamination and exposure to pollutants such as oils and other impurities. A proper collection and handling routine of the gases can prevent that different refrigerants end up in the same cylinder and reduce the number of pollutants. This is key to keep the costs of reclamation as low as possible. More pollutants mean more processing of the gas to a point where reclamation is no longer profitable, and the refrigerant will have to be destroyed.

The following subsection presents the most common reclamation technologies (distillation, adsorption and subcooling) and describes their advantages as well as disadvantages. Furthermore, it depicts a collection of experiences from reclamation projects in Chile, the United Arab Emirates, the United Kingdom and the United States, which were obtained through interviews and a literature review. This subsection concludes with a summary of the challenges and lessons learned from these experiences.

3.1 ODS/HFC RECLAMATION TECHNOLOGIES

Large gas distribution companies use state-of-the-art technology for the reclamation of refrigerants and blends. The three most common technologies found for reclamation process are distillation, adsorption and subcooling. These processes work with the difference of the physical and chemical properties of each refrigerant contained in a blend to isolate them from each other and clean them from unwanted gases, oil, particles and moisture. Specific boiling and condensation points as well as specific affinity to materials and adhesion are used for reclaiming these fluorinated gases. Desiccant driers are used to remove moisture and water or are combined with base baths to reduce acidity. Additionally, filters remove microparticles and high efficiency purge units remove non-condensables, air and moisture (Status Consulting 2010).

3.1.1 Distillation

In the distillation process, the refrigerant is heated up to boiling temperatures to separate it from oils, humidity, non-condensable gases, particles and other impurities. This is the most common reclamation method worldwide, including in the United States, according to a survey by Status Consulting 2010. It is also known to be used in Chile by a reclamation centre in Santiago. There are two main types of distillation methods that differ by the way of how the refrigerant is transported.

The first method uses a compressor to transport the gas between the evaporation and condensation stages, creating a pronounced pressure gradient that condensates the gas using the ambient heat. Although compressors often serve to separate components and remove impurities, they add oils to the transported refrigerant, requiring the operator to perform a second cleaning to meet reclamation standards. It is estimated that a compressor discharges between 0.5% and 1% of its oil during operations.

The second method omits the compressor between the evaporation and the condensation stage. Therefore, it has the advantage that no oil is added to the refrigerant and the overall energy consumption of the reclamation process is lower. However, the reclamation rate is lower too, because it takes more time to process the refrigerant (Status Consulting 2010).

Advantages: Distillation is a simple and relatively cheap process that allows the fast separation of gases. It works better for refrigerants that consist of a single gas, like HCFC-22, than with blends. It can be used to separate refrigerants from inert gases after adsorption/desorption processes. There is commercially available equipment specifically designed for reclamation using this method (Status Consulting 2010).

Disadvantages: For refrigerants composed of multiple F-gases (blends), distillation might work poorly because the boiling point temperatures of these gases are often very similar. Also, the use of a compressor might add oils to the refrigerant (Status Consulting 2010).

3.1.2 Adsorption

Adsorption technologies use different materials, including membranes and activated carbon to capture the different fluorinated gases and separate them from impurities such as humidity, oils and particles. In these methods the gas enters a chamber where only a specified refrigerant is captured by absorbent beds/materials that are exclusively designed to trap one type of gas. Then the oils and particles are cleaned from the chamber and the gas is desorbed through heat application, vacuuming or using other gases such as nitrogen or helium as removal agents (Status Consulting 2010).

The most common materials found in the literature for the adsorption of refrigerants are:

- **Activated carbon:** This material is accessible and has lower costs than the other materials for the adsorption of refrigerants. It is also available in a wide variety to be used for the retention of different refrigerants. Activated carbon can be chemically modified changing their pore size to capture different fluorinated gases (Ana Belén Pereiro Estévez, NOVA University, Interview, February 27, 2023).
- **Membranes:** This material has specific physical and chemical properties that allow them to capture refrigerants and serve as a permeable barrier for some compounds. They have the advantage of being effective without the application of temperature or pressure. Also, they can be combined with solvents and nanotechnology to improve their properties including the adsorbent potential and the type of gas that they can capture (Ana Belén Pereiro Estévez, NOVA University, Interview, February 27, 2023).
- **Metal-organic frameworks:** Commonly known as MOFs, these materials are highly complex and advanced. They are three-dimensional structures formed by an array of metal ions with very high thermal and chemical stability. They use

metals like zirconium to create highly porous structures with specific chemical properties that allow the capture of specific gases. However, these materials require advanced technology and have high costs (Wanigarathna, Gao, and Liu 2018).

- **Advanced Solvents:** There are many solvents with the ability to capture and clean refrigerants and other fluorinated gases. They can be used, for example, to remove a refrigerant from activated carbon. However, ionic liquids are the most ideal solvents for reclamation processes. They have the advantages of being non-inflammable, stable and non-volatile. Moreover, they can be immobilized[4] with a supporting structure allowing the refrigerant to pass through, while separating non-desirable molecules and pollutants (Valkenberg, deCastro, and Hölderich 2002).

Advantages: Adsorption with activated carbon is one of the most effective methods for reclamation and is often cheaper than high-tech membranes or MOFs. The cost depends on how complex the mixture is and how well the gases were collected. A proper pre-treatment of the gases (collection, transportation and storage) avoids cross-contamination and ensures that the costs of adsorption are kept to a minimum. Although adsorption is not a simple method, it requires often only one one step (adsorption process) for the gas to meet the recovery standards

Disadvantages: For this method, the membranes, the active charcoal or any other absorbent material is designed specifically for a single type of refrigerant. This requires a laboratory and advanced technology to be able to adjust or create a material with a specific value for porosity, surface area, elasticity, thermal and chemical stability among other physical and chemical properties (Status Consulting 2010). Only activated carbon is of easy access. Moreover, these materials lose their adsorption capacity overtime and need to be re-activated (carbon), cleaned or changed after 10 to 15 uses. To allow for a tailor-made process, each batch needs to be tested before treatment (Ana Belén Pereiro Estévez, NOVA University, Interview, February 27, 2023).

3.1.3 Subcooling

Refrigerant subcooling and purification is another method used to reclaim fluorinated gases. This process is carried out in three stages: First, the refrigerant is condensed and kept in a liquid state by maintaining temperatures below its boiling point. Second, the gas is filtered using coalescent filters and other types of microfilters to remove impurities and unwanted particles. Then, a micro-compressor equipped with a purge is used to capture the non-condensable impurities. This method is known to be used by A-Gas and some reclaimers in the United States (Status Consulting 2010). However, of the methods described here, it is the least used in the rec-

4 The immobilization of an ionic liquid can be achieved by adding the solvent to a supporting structure that restrains it. This is possible because the ions and cations of the solvent have the ability to create (cationic) bunds with the solid. These bunds keep the ionic liquid fixed to the supporting structure allowing the refrigerant to pass though (Valkenberg et al. 2002).

lamation process due to its high cost. Therefore, very little information is available on the subcooling method.

Advantages: This method, unlike distillation, does not require a certain amount of refrigerant to operate. It also can reclaim any type of refrigerant without main changes in the setup of the equipment. Additionally, since the refrigerants are mostly in a liquid state, the risk of a leakage is significantly lower than in other reclamation methods. Finally, it can achieve very good results in terms of the removal of particles and non-condensable gases.

Disadvantages: The major disadvantage of this method is its high cost. Setting up the equipment for this method is expensive because it is usually high-end and tailor-made technology. Moreover, the overall energy consumption of the subcooling method is up to three times higher than that of distillation. This was the case for R-22 and R-410A in tests made by the Thermal Analysis Partners (TAP) for the Status Consulting report in 2010. The high costs make this type of technology rarely used for the reclamation of refrigerants (Stratospheric Protection Division and US EPA 2020).

3.2 RECLAMATION ACTIVITIES IN PRACTICE

For this report, a series of interviews were conducted, and first-hand information gathered to understand how reclamation is taking place around the world. Prepared questions focused on the type of reclamation technologies used, the refrigerants reclaimed, the main challenges faced, the business model of the companies and the Monitoring Reporting and Verification (MRV) systems in place. Interviews were conducted with the multinational company A-Gas and Enviroserve that is based in the United Arab Emirates (UAE). In addition, a report from Regener, a reclamation company in Santiago de Chile, was studied. An interview was also conducted with SEG Umwelt Service, a Germany-based recycler of RAC equipment. Finally, the technical characteristics and technology of the reclamation process were discussed with an expert from the "Institute of Chemical and Biological Technology António Xavier" of NOVA University in Portugal.

3.2.1 Technology

In terms of technology, the interviews and correspondence with the reclaimers confirmed the information gathered from the literature. The reclaimers consulted only use distillation (except for A-Gas) to separate and reclaim refrigerants. The equipment they use is not state of the art but commercially available, including the BullDog 460 sold by RefTec International System LLC[5] and the JV90 reclaim system by Ekotez[6]. These options were chosen because of their low cost and accessibility. On the other hand, A-Gas, which is a world leader in the reclaim of ODS/HFCs, uses the three types of tech-

5 http://www.reftec.com/shop/
6 http://www.ekotez.cz/refrigerant-reclaim-unit-jv90-p-3009.html

nologies mentioned in this chapter: distillation, adsorption and subcooling. Even though adsorption is the most effective method of recovering refrigerants and in most cases affordable, the knowledge of the technology and its commercial availability is much lower than for distillation. However, the KET4F-Gas project[7] has developed two prototypes using adsorption for the reclamation of ODS/HFCs. One of the prototypes uses activated carbon and the other uses membranes to capture the refrigerants. The aim of this project is to promote the reclamation of refrigerants in the EU.

3.2.2 Business model

The reclaimers interviewed integrate other economic activities in addition to refrigerant reclamation. These help them to build a stronger business model that can cope with the fluctuations in the amount of refrigerant available for reclamation. An example of this is the recycling of waste electrical and electronic equipment (WEEE). Many reclamation centres have direct contact with end-users and industries that provide them with used refrigerants and RAC equipment. This is the case of Regener in Chile, where they collect the RAC equipment, recover the refrigerant for reclamation, and recycle the units (Cerda 2019). Other small companies also recycle precious metals from computers or other electronic waste alongside the reclamation activities. On the other hand, a large multinational company such as A-Gas focuses mainly on selling new refrigerants to various industries and sectors and in addition collects used gas for reclamation and destruction.

3.2.3 Monitoring, reporting and verification

For the monitoring, reporting and verification of the amount of refrigerant handled by each reclaimer, large companies use self-developed software to track individual shipments and cylinders and weigh the incoming and outgoing refrigerant at each facility. Smaller companies also use scales to monitor the amounts of refrigerant collected and reclaimed. All the surveyed companies report the quantities to the local authorities. Quality testing of refrigerant before and after reclamation is done in some cases by chromatography and in others by refrigerant identifiers. Chromatography is the most ideal tool for testing refrigerants as it can provide a detailed picture of the composition of the gas before and after the reclamation process. This information is needed to determine the process required to reclaim the used refrigerant. It is also the best tool for verifying that the reclaimed refrigerant is within the quality standards. However, chromatography is not a simple process. The equipment is expensive and complex to operate. As a result, in some countries chromatographers are rare, do not have all the standards (or standard samples) necessary to carry out the measurements, expensive certifications are required, or there are no qualified personnel to perform these tests.

3.2.4 Prices

Finally, some prices of reclaimed versus new refrigerant in the UAE and in Chile are presented in *Table 1*. It can be observed that the reclaimed refrigerant has in general lower prices than the new one. Reclaimers expect that, due to the restrictions on the commer-

7 “Reduction of the Environmental Impact of Fluorinated Gases in the Sudoe space (Southwestern regions of Europe) using Key Enabling Technologies” (KET4F-Gas) is a European project co-funded by the Interreg Sudoe Programme through the European Regional Development Fund (ERDF), with a funding of 1.7 million euros”. http://www.ket4f-gas.eu/.

cialization of new HCFC-22, the prices of this refrigerant will increase in the future. This trend is already seen in countries like the US (Stratospheric Protection Division and US EPA 2020). A contradicting storyline was shared during the interviews that reclaimed refrigerant can be sold with a price premium because of its green image, being the result of avoided refrigerant emission.

***Table 1**. Prices of reclaimed and new refrigerants*

Refrigerant	UAE		Chile		Units
	Reclaimed	New	Reclaimed	New	
HCFC-22	3.0-3.3	4.9	3.0	3.0-3.5*	US$/kg
HFC-134a	2.7-3.0	6.8-7.6	-	-	US$/kg
HFC-410A	4.9	8.7-9.8	-	-	US$/kg

** Expected to be 4 US$/kg in the upcoming years.*
Source: Cerda 2019; Ministry of the Environment of Chile 2014.

3.2.5 Challenges and lessons learned

Globally, reclamation is a practice far less common than destruction. However, both activities face similar challenges, such as acquiring enough ODS/HFCs to sustain operations over the long term. In the interviews conducted for this study, reclaimers were asked to rank several items according to their level of challenge. This led to the identification of three main challenges that hinder ODS/HFCs reclamation projects in Article 5 countries. These are:

1. Ensuring a steady flow of refrigerants for reclamation
2. The regulatory framework of the country
3. Commercialization of the reclaimed refrigerants.

The first two challenges are directly interlinked. Regulations assign responsibilities for the end of life (EOL) management of ODS/HFCs and prohibit the venting of these gases into the atmosphere. The enforcement of such regulations ensures that refrigerants are collected at end-of-life and safely managed (recycled, reclaimed or destroyed) by the responsible entity. It also ensures that these activities are paid for by the responsible entity. Therefore, sufficient refrigerant will be available for reclamation.

Nonetheless, there are other problems related to the absence of a proper policy framework for ODS/HFC banks. Obtaining permits to operate and handle these hazardous substances is often a challenge because in many countries ODS/HFC reclamation is not a regulated activity, or a very new task for the authority. Instead, these reclamation projects are completely new activities in some countries, causing delays in the response of environmental authorities and in the acquisition of permits and authorizations. In addition, regulations in some countries require strict tracking of refrigerants, which creates a reluctance in the industry to send the gases to reclamation centres without knowing if the environmental authorities have approved these practices.

The problem of not having enough gas for reclamation has forced some reclaimers to develop strategies and alternative methods to ensure a steady flow of refrigerant for reclamation. Some reclamation centres appeal to the environmental responsibility of large technology companies and manufacturers by asking them to do a proper disposal of RAC equipment and refrigerants, although this is not strictly required by the applying law. Others establish agreements with the industry to acquire the refrigerants directly, while providing a service to those industries by disposing of both the refrigerants and the RAC equipment. Coordinating with refrigerant servicing companies to obtain their used refrigerant is also a method commonly used by reclamation centres to obtain refrigerants. These strategies, although challenging, have made reclamation possible in countries such as Chile and the United Arab Emirates. However, reclamation centres must be proactive in their search for refrigerants and constantly look for new sources of ODS/HFCs.

The commercialization of reclaimed refrigerant is also a challenge for reclamation centres. There are two causes for this problem. One is that the price of new refrigerants has not (yet) increased as expected. With the restriction on the commercialization of HCFCs such as R-22, many countries expected an increase in the price of new refrigerant, making the reclaimed refrigerant market more competitive. Although this has happened in some countries, such as the United States, in others it has not. The other factor is the lack of knowledge and openness of the operators to the reclaimed refrigerant. Although quality standards are very high, some consumers are still reluctant to purchase reclaimed refrigerants.

The least challenging items for reclaimers were consistently the purchase of reclamation technology and recruiting, and retaining qualified staff. As mentioned above, distillation equipment is available and affordable for small to medium sized reclamation centres, and it is also comparatively easy to operate. At the same time, large reclaimers use state of the art technologies and develop their own machinery. They are also able to train and find personnel capable of operating this equipment.

The overall identified strategies that enable reclamation in Article 5 countries are:

- Develop activities that promote stakeholder engagement in EOL management of ODS/HFCs. This facilitates that servicing companies and end users of refrigerants bring the used substances to the reclaimers.
- Appeal to the environmental obligations of big tech companies and end users to enhance the collection and management of the ODS/HFC waste in their facilities.
- Diversify the activities in the reclamation centres to create a strong business model that can cope with fluctuation in the supply of gases for reclamation.
- Engage with governmental institutions and universities that can provide knowledge and technological support for the reclamation activities.
- Build a network with servicing companies and other stakeholders to promote best practices and the safe collection of refrigerants.

- Before opening a reclamation centre, ensure that there are enough companies that use large amounts of ODS/HFCs that are willing to collect their refrigerants for reclamation purposes and that they (or other companies) are willing/interested in buying reclaimed refrigerant.
- Regulations that reduce the amount of virgin refrigerant in the market contribute to the economic viability of reclaimed refrigerant.

4 DESTRUCTION OF ODS/HFCS

The destruction of ODS/HFCs is the last measure to ensure that these substances are not emitted into the atmosphere contributing to climate change and damaging the ozone layer. Where possible, recycling or reclamation of HCFCs and HFCs is preferable to their destruction due to environmental reasons and to achieve a circular economy. However, in many cases, the lack of technology and recovery equipment, the nature of the gas or gas mixture/pollution, or the absence of users that could reuse these gases leads to the venting of refrigerants or the destruction of the collected ODS/HFCs. The exception are gases whose use is prohibited due to phase-out agreements. These gases, such as CFCs, must either be broken down into their chemical components for reuse in the production of other substances, or destroyed.

The destruction of ODS/HFCs is a process that requires effort and funding. Most of the technology available require equipment with very high calibration requirements and a scarcity of spare parts for maintenance. Energy consumption is a contributing factor to the high price of ODS/HFC destruction. In addition, the by-products generated usually require additional treatment before disposal or their release to the atmosphere (GIZ 2020b). Logistical and equipment requirements for the collection and storage of ODS/HFCs prior to destruction add to the costs.

The above contributes to the fact that the management of ODS/HFCs varies dramatically from country to country. For instance, the difference of the total destroyed amounts of refrigerants between countries is very large. While in 2015 around 2550 metric tonnes of ODS were destroyed in Japan (MOE 2016), Mexico, which had the same population at that time, destroyed only 37.8 metric tonnes of refrigerant (EPA 2021). Although Japan has around 8.5 times more RAC unites in use than Mexico[8], it destroyed more than 67 times more ODS/HFC in 2015. Japan leads the destruction of ODS/HFC with more than 80 facilities for this purpose in the country, whereas other countries do not have a single one (EPA 2021)[9]. A closer comparison can be drawn with Australia that in 2016 destroyed around 40 metric tonnes of ODS and 320 metric tonnes of HFCs. Australia has around 1.6 times more RAC equipment than Mexico[8]. This difference between Article 5 and non-Article 5 countries is also observed in the technologies used to destroy ODS/HFCs. While many methods are used to destroy these substances in non-Article 5 countries, cement kilns are the dominant technology used to destroy ODS/HFCs in Article 5 countries. For example, Australia has been a leader in the use of plasma technologies for the destruction of fluorinated substances; argon plasma arc technology was developed in this country and is mainly used for the destruction of halons. In addition, Germany uses municipal solid waste incineration (MSWI) to destroy ODS/HFCs, and Japan has almost all types of technologies for this purpose. On the other hand, Algeria, Cuba, Indonesia and Mexico use cement kilns to destroy ODS/HFCs. A complete list of destruction facilities worldwide is provided in Annex B.

8 https://www.green-cooling-initiative.org/country-data#!appliances-in-use/chiller/absolute
9 A list of the destruction facilities worldwide can be found in Annex B.

For these reasons many international cooperation projects focus on countries that have a very large potential of uncontrolled ODS/HFC related emissions and weak collection and destruction policies and infrastructure. An example of these are demonstration projects financed by the MLF, with the cooperation of UNIDO, UNDP and non-Article 5 countries and the ongoing projects led by COPA and its partner countries.

The following section briefly discusses the different technologies approved by the Technology and Economic Assessment Panel (TEAP). It further describes in detail the four most relevant destruction methods for Article 5 countries and gives an overview of the main challenges for their implementation in these countries. Finally, the section summarizes the lessons learned from demonstration projects financed by the MLF.

4.1 ODS/HFC DESTRUCTION TECHNOLOGIES

Various technologies are used for the destruction of ODS/HFCs worldwide. Destruction methods have been available since the agreement of the Montreal Protocol and the technologies are well known. However, high costs, operational complexity, and the lack of financing mechanisms make them rare in Article 5 countries. Other factors that determine the technologies used in a country are:

1. the required installed capacity,
2. the environmental and local permits needed,
3. the amount and cost of airborne and wastewater emissions, including their monitoring and control,
4. the availability of equipment, supplies, and spare parts in the country,
5. its compatibility with the industry and the geographical distance between the end user and the place of destruction and
6. its synergy with ongoing projects in the area, and the cost and economic viability of the destruction method.

Although different technologies are used in each country for the destruction of hazardous substances including ODS/HFCs, only the most relevant ones are studied and approved by TEAP. Only amounts of ODS/HFC destroyed with these approved technologies can be reported under Article 7 of the Montreal Protocol in order to subtract these quantities from the consumption of the country.

The TEAP is the Montreal Protocol body responsible for formulating recommendations on ODS/HFC destruction technologies. The TEAP was established in 1990 as one of the three Scientific Assessment Panels of the Montreal Protocol. This panel approves destruction technologies for each type of substance regulated under the Montreal Protocol. However, this approval is not binding, but serves as a recommendation to the countries. The TEAP considers four parameters when approving a destruction technology (TEAP 2018b). These are:

1. The destruction and removal efficiency[10] (DRE).
2. The emissions of halogenated dioxins and furans.
3. The emissions of carbon monoxide, acid gases (HCl, HF, HBr/HBr2) and particular matter (PM).
4. The technical capability[11].

The destruction of ODS/HFC is encouraged using any type of technology that meets international standards for efficiency and emissions. The intended method should fulfil minimum national requirements and act in concordance with the current regulation of the country. Achieving the highest DRE possible is desired in order to have as low emissions as possible. No destruction method is imposed or set by the TEAP to promote solutions that are suitable according to the needs and conditions of the country. Setting too high standards might prevent countries from using technologies that are economically feasible. Nevertheless, it is important to note that Article 7 of the Montreal Protocol mandates that data should be reported only of approved methods or in cases where the method is being revised and the data is required by the Medical and Chemicals Technical Options Committee (MCTOC). This ensures comparability and the accurate analysis of the data collected (TEAP 2018b; UNEP 2018).

Destruction technologies are classified in three categories: thermal oxidation, plasma technologies, and conversion (or non-incineration) technologies (TEAP 2022a). A complete table of destruction methods and their approval status can be found in Annex C.

4.1.1 Cement kilns

This method is one of the most accessible and common for the destruction of ODS/HFC in Article 5 countries. It is estimated that around the world (excluding China) there are more than 2500 cement plants, which could potentially be used for waste management (GIZ 2020b). This method was used for the first time in Sweden in 1979 for the treatment of substances containing chlorine, since then it has become one of the most used methods for the destruction of hazardous substances (GIZ 2020b). In some Article 5 countries like Indonesia and Mexico, cement kilns have already been used for the destruction of hazardous substances (MLF 2022). However, despite its high potential, continuous destruction of ODS/HFCs in cement kilns is very limited.

The cement kilns have many intrinsic features which make them ideal for hazardous waste treatment, such as high temperatures, long residence time, good supply of oxygen during and after combustion, good turbulence and mixing conditions, thermal inertia, dry scrubbing of the exit gas, fixation of the traces of heavy metals in the clinker structure, and no generation of by-products such as slag, ashes or liquid residues. Nonetheless, before a cement plant is suitable for

10 The DRE is calculated as the number of molecules removed or destroyed. Set by the TEAP in a minimum of 99.99% removal for concentrated sources and 95% for diluted sources.

11 A destruction technology archives technical capability if it is able to destroy at least 1 kg of gas per hour.


DANGER
Hot surface
ROTARY KILN

these purposes, the infrastructure needs adjustments. The safe storage of the cylinders that contain the gases must be ensured. They should be kept at room temperature and a vacuum pump is needed for their safe extraction. A dosage area and a dosage control instrument, ideally a mass flow meter, must be implemented for the injection of the refrigerants. To ensure that no residual gas remains in the cylinders, a water bath or a recovery and vacuum system should be integrated for transferring the gases from the cylinders to the kiln. The kiln filled with the raw materials for the cement (aluminium, calcium, iron and silicon) is heated up to 1600°C. Then, the ODS/HFC are injected right into the hottest part of the kiln, ensuring destruction and that reaction products are safely bound into the clinker. The chlorine content of the final clinker is monitored to ensure high quality. This middle product is further converted into the well-known commercial cement. This method, if done correctly, ensures the complete burning of the gases and has the advantage that most of the by-products end up adhered to the cement. However, emissions still need to be monitored and controlled (GIZ 2020b; Vermeulen et al. 2009).

A successful destruction project in Mexico between 2015-2017 was conducted with this method. The previous experience that the country had with destroying hazardous substances using cement kilns and the advantage of having a large cement industry helped the country to achieve very good results. This project achieved lower destruction costs than a second project in this country using the argon plasma arc method (*Table 4*). It also proved to be more cost-efficient than exporting the substances to the United States for incineration (MLF 2022; Savigliano, Bastida, and Martínez 2017).

A more detailed description of the ODS/HFC destruction process in cement kilns can be found in page 11, Annex D. Cement kilns technical specifications.

4.1.2 Municipal solid waste incineration (MSWI)

Municipal solid waste incineration is used around the world to treat diverse types of waste collected in cities, usually non-hazardous waste. In Germany, for example, where the use of landfills is forbidden, incineration is often used as part of the variety of methods in the repertoire to deal with solid waste. On the contrary, in Article 5 countries, landfills are still being used as they are a cheaper option. The high costs of these incineration plants are associated to the high-quality technology that they require and their large size because they are usually built to process large amounts of waste. Moreover, the treatment of the residual gases is an additional expense. In general, the use of MSWI plants for ODS/HFC destruction is not recommended, as ensuring the required high temperatures for full destruction is difficult to maintain. If there are areas in the great furnace with lower temperatures than intended, parts of the substances are not destroyed completely. A series of filters are then needed to purify the exhaust gases and avoid their emission. However, an advantage of this method is that foam containing ODS/HFC can be also destroyed in MSWI plants, especially as the alternative is usually to build up piles of foams, releasing the ODS/HFC content slowly into the atmosphere (GIZ 2020b) or to crush the foam without any gas recovery. However, MSWI plants are not built for

ODS/HFC destruction. Although expensive and complex, MSWI plants are used in non-Article 5 countries to destroy ODS/HFCs.

A pilot project funded by the MLF showcases the complexity. The project was implemented in Colombia, where also persistent organic pollutants (POPs) were intended to be destroyed in parallel with ODS. However, the complicated management of these substances made this option not possible, and the destruction of POPs was then cancelled in the plant. Colombia took advantage of the infrastructure that it had to also burn ODS, which shows that this method could be explored in other industries that have already similar technology. This could reduce the cost of destruction and be an extra source of income for these industries. The only persistent problem is the treatment of the emitted gases. Experience shows that to achieve acceptable emissions of by-products, state-of-the-art technology is needed for combustion and for post-processing of the fumes (GIZ 2020b).

More information about MSWI plants can be found in Section 3.6 of the report: Thermal Destruction of (hydro)chlorofluorocarbons and hydrofluorocarbons: Management and destruction of existing ozone depleting substances banks by (GIZ 2020b).

4.1.3 Rotary kiln incineration

This technology uses oil, propane, or natural gas as fuel to burn hazardous substances. It consists of a rotary kiln furnace with a valve for the injection of fuel and air to induce incineration. The remaining gas moves to a post-combustion chamber equipped with an ash sump and a second valve for air and additional fuel. After the combustion, the material goes to a boiler for energy recovery and filtration of the gases often equipped with an air pollution control system (APC) for emission control. In the rotary kiln, the incineration is conducted at 1200°C with a residence time of 2s. (Jiang, Li, and Yan 2019; Vermeulen et al. 2009).

This method is widely used for destroying industrial waste, especially resulting from oil and gas extraction. In developed countries, rotary kilns are operated by public agencies for the management of waste or by the chemical industry for the destruction of by-products such as HFC-23. The rotary kiln has very high building and operational costs, limiting its accessibility to small industry or to Article 5 countries (Trojette and Artmann 2022).

However, the viability of this method increases as it is used in most cases to destroy not only ODS/HFCs, but also a wide range of hazardous substances, and because it can be installed close to industry and serve multiple purposes. Decomposition efficiencies of the ODS in this method shall reach 99.99%, and none of the volatile organochlorine compounds must be formed. The produced hydrochloric acid (HCl) and hafnium (Hf) with the decomposition of ODS and HFCs must be entirely removed by the existing treatment system, and concentrations of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofuranes (PCDDs/PCDFs) in flue gas shall be low enough with a concentration in the atmosphere below 1%. Impairment of fire-proof brick pieces with the decomposition of ODS and HFCs must be controlled.
This is the case for a rotary kiln administrated by the company Zeal Environmental

Technologies Limited in Ghana, that incinerates chemical sacks, cargo sludge, oily rags, surfactants, brine filters, among other waste streams (Carl and Quicker 2022; Trojette and Artmann 2022) and it is doing pilot tests to also destroy ODS/HFC. Additionally, in a demonstration project funded by the MLF, China incinerated around 195t of CFCs with this method. The costs per kilogram of destroyed substance were in the range of 8-12 US dollars, the highest of all costs illustrated in *Table 4*. The technology, although expensive, is compact and has proven to be very effective for the destruction of ODS (MLF 2022) and other hazardous waste.

More information about rotary kiln incinerators can be found in Section 3.7 of the report: Thermal Destruction of (hydro)chlorofluorocarbons and hydrofluorocarbons: Management and destruction of existing ozone depleting substances banks (GIZ 2020b).

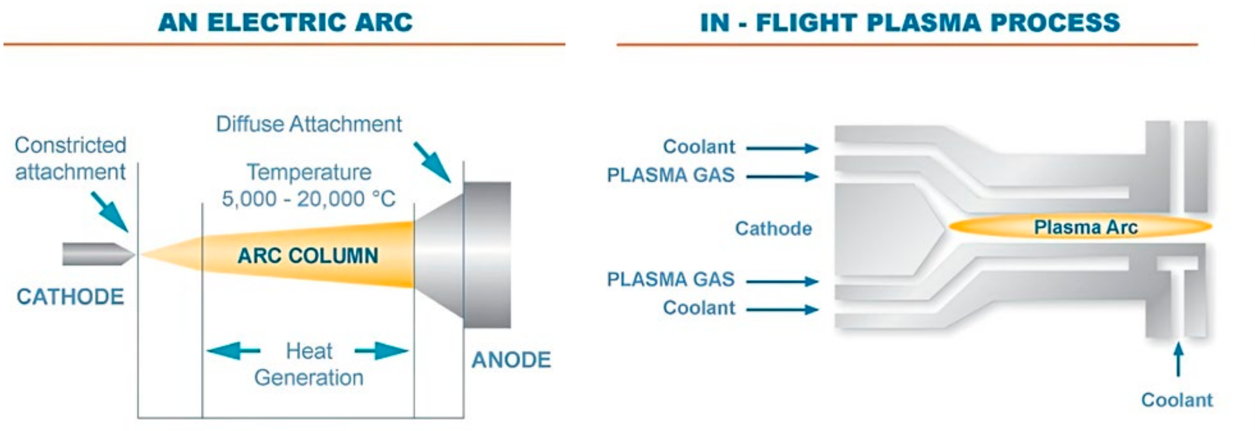
4.1.4 Argon plasma arc

Plasma methods have been used since the 1990s for the destruction of ODS. This specific method, under the patent PLASCON®, was developed in Australia by SRL Plasma Ltd. Since the invention of the method, plasma destruction units (PDUs) have been installed in Australia, Japan, Mexico, the UK and USA for the destruction of hazardous substances including halons, POPs, HFC, polychlorinated biphenyls (PCBs), and ODS.

In the PLASCON® method, electricity is applied to a medium of argon, creating a torch with temperatures between 5000 to up 20000°C in the core. This forces the gaseous state of the argon to enter a plasma state, creating a jet that destroys the substances that are directly shot into it[12]. The degradation of the molecules in contact with the plasma is a process known as pyrolysis. In contrast to the incineration, which is a thermal oxidation process that causes chemical reactions in the presence of oxygen, pyrolysis is anoxic, incurring the thermal degradation of the molecules (Tyagi et al. 2019). The hot plasma (approx. 1200°C) is then cooled down rapidly with steam that forms CO_2 in contact with the carbon produced during the pyrolysis (EPA 2021). Caustic salts are also added to convert the acids into salts, preventing the formation of dioxins and furans. In *Figure 6*, a visual description of the process described above is shown. The by-products from this destruction process are CO_2 and CO, water, and salts that are easy to dispose of (Carkner et al. 2019; TEAP 2002b). However, the regulations of each country may require compliance with discharge standards. It should also be noted that this method generally requires hydrated lime of a very fine composition to avoid equipment damage; this granule quality is sometimes challenging to obtain from local suppliers. On the other hand, liquid discharges require going through a previous process of flocculation and coagulation before discharge. Therefore, the result of flocculation and coagulation must be managed properly; in some countries, the by-product (calcium chloride) has been proven to be a raw material for other industrial processes.

12 This is why this method is known as in-flight technology.

***Figure 6**. Argon Plasma Arc technology*

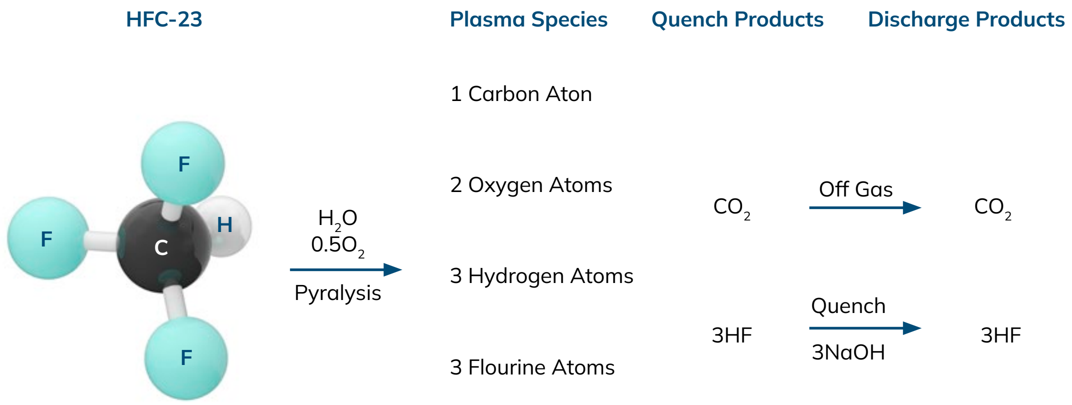


Source: The PLSACON provider at http://www.plascon.com.au/technology-overview.html

A plasma destruction unit (PDU) occupies only 24 m^2 and can be adapted and installed in chemical companies that handle and produce refrigerants. This is the case of the company Quimobásicos in Mexico. This company is starting a new project to destroy HFC-23 in-situ forming CO_2 that can be filtered and 3HF that requires further treatment (*see Figure 6*).

Plasma technologies are recognized for producing smaller quantities of by-products than incineration technologies and have the asset to generate very low emission of dioxins, due to the low volume of gas produced during the destruction (Carkner et al. 2019). Additionally, this method has the advantage that the argon is inert preventing its reaction with the elements of the torch. The disadvantage of this technology are its high costs (MLF 2022) and that the ODS must be pretreated for oil removal to ensure low emissions of acids (TEAP 2002). In addition, the PDUs are sold under a registered patent, which makes them less accessible.

Figure 7. *Destruction by pyrolysis of HFC-23*



Source: The PLSACON provider at http://www.plascon.com.au/technology-overview.htm

In the description of the ODS/HFC destruction technologies provided by TEAP 2002a, the argon plasma arc process is categorised as the most energy intensive of all the technologies approved by the panel at that time. This technology was used by the refrigerant manufacturer Quimobasicos in Mexico to destroy HFC-23 from the production of R-22. This company reported to the MLF that it had destroyed 60 kg of HFC-23 using a PDU with a total energy consumption of 250 kWh, plus the ionization of the argon to produce the plasma. This results in a total energy consumption of 4.32kWh per kilogram of gas destroyed.

Other plasma arc technologies not covered by this study are also being used for the destruction of ODS/HFCs. Among them are steam plasma arc, nitrogen plasma arc and CO_2 plasma arc. To know more about this technologies read Carkner et al. 2019; TEAP 2018a, 2018b.

4.1.5 Comparison of the technologies

To illustrate the features of the four technologies regarded as the most relevant in this study, *Table 2* shows emission data for the typical by-products of ODS/HFC destruction. The data is presented in concentration of pollutant per waste volume (mg/Nm3) and in total emissions per hour (mg/h).

The argon plasma arc is by far the technology with the lowest formation of by-products. The concentration data already shows less production of hazardous gases. However, the difference in the mass emission data is so high because pyrolysis produces much less waste in comparison with the thermal oxidation methods.

Table 2. Emissions by destruction technology

Pollutant	Cement kiln	MSWI	Rotary Kiln Incineration	Argon Plasma Arc	TEAP technical performance specification	Units
Refrigerant	CFC	CFC	***	Halon 1211	All	
DRE*	99.99%	99.99%	99.9999%	99.9998%	99.99%	
Concentration						
PCDD/ PCDF**	0.04	<1.0	0.03-0.15	0.006	0.2	ng/m^3
HCl/Cl_2	0.05	300	2.8	1.7	100	mg/m^3
HBr/Br	-	-	4	<4.0	5	mg/m^3
HF	0.4	5	0.5	0.23	5	mg/m^3
Particulates	10	30	10	<10	50	mg/m^3
CO	100	10	50	96	100	mg/m^3
Mass Emission						
PCDD/PCDF	18,000	60,000	2,300-11,800	0.2	-	ng/h
HCl/Cl_2	23,000	18,000,000	220,000	65	-	mg/h
HBr/Br	-	-	314,000	9	-	mg/h
HF	122,000	300,000	39,000	<150	-	mg/h
Particulates	4,500,000	1,800,000	785,000	<400	-	mg/h
CO	45,000,000	600,000	3,900,000	3700	-	mg/h

* *DRE: Destruction or Removal Efficiency*
** *Polychlorinated-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are the two families of polychlorinated aromatic chemicals that form the group of dioxins. These are often unwanted sub-products of chemical reactions and accumulate in living organisms. They are considered as persistent organic pollutants or POPs.*
*** *A mixture of gases was used for this test including PCB, dichlorobenzene and tetrachlorobenzene.*
Source: TEAP 2002b

The three incineration methods are quite similar in terms of the overall emissions. The carbon monoxide (CO) emissions in the cement kiln method are particularly high, this gas is the main precursor of CO_2 in the atmosphere. Additionally, the dioxins (PCDD and PCDF) and the HCl/Cl_2 are particularly high in the MSWI method. This is aggravated by the requirement of very homogeneous burning temperature to ensure low emissions [13]. Additionally, a clear difference between these two types of technologies is that, while in the thermal oxidation chemical reactions take place in an oxygenated environment (one example is the production of HCl + HF from the oxidation of CFCs and H_2O), in the plasma technologies the compounds are broken down by the high temperatures. The plasma state bends the atoms to a point where the electrons are set free allowing them to coexist with neutral molecules and negative and positive ions. This alteration of the chemical structure reduces the number of chemical reactions generating less pollutants than during the thermal oxidation.

In *Table 3* the most relevant technologies for Article 5 countries are presented and further described in this chapter.

***Table 3**. Prices of reclaimed and new refrigerants*

	Approved destruction technologies	Advantages for Article 5 countries	Disadvantages for Article 5 countries
Thermal Oxidation technologies*	Cement kilns	Already exist in many countries. Already established for hazardous waste treatment. Adjustments are easy and relatively cheap.	Low to high emissions, depending on adaptation of the technology. Measuring the emissions can be challenging
	Municipal solid waste incineration (MSWI)	Useful if there are already operating plants in the country/area.	High investment and operational cost for new plants. Not very effective as destruction method for ODS/HFCs. Risk of high emission if the incineration is not done properly.
	Rotary kiln incineration	Already exists in Article 5 countries. Only approved technology for the destruction of all ODS/HFCs**. Low emissions.	Useful only if already established (e.g., by chemical companies). High investment and operational costs.
Plasma technologies	Argon plasma arc	Compatible with the chemical industry. Effective destruction method.	Very low emissions. High costs and high requirements make their implementation difficult in Article 5 countries. Low availability for acquisition, including spare parts (only one company holds the patent)

* *Previously called "Incineration Technologies".*
** *This technology was approved for the destruction of all molecules under the Montreal Protocol except for methyl bromide.*
Source: GIZ 2020b

The technical features of thermal oxidation technologies were already described in detail in the report “Thermal destruction of (hydro) chlorofluorocarbons and hydrofluorocarbons” published by the GIZ 2020. Therefore, in this section the argon plasma arc technology is explained more thoroughly than the other three methods.

A comparison of the advantages/disadvantages of the four destruction methods referred in this chapter is presented in *Table 3*. Emissions are not included since they were just discussed. In terms of accessibility, cement kilns have a very clear advantage over the other three methods since the cement industry is present in all Article 5 countries that consume large quantities of refrigerants. For the same reason, the operational complexity of this technology is low. The only possible barrier is that the industry can be reluctant to change their practices to destroy ODS/HFC. The MSWI needs very high standards to work efficiently and has a very high energy consumption. Additionally, they are usually very large facilities that are not easy to build, and its degree of operational complexity is very high. Therefore, for Article 5 countries the construction of MSWI to destroy ODS/HFC cannot be recommended. The rotary kiln incineration has been used in China and Nigeria proving to be accessible and not too complex to be operated in Article 5 countries. However, this technology is still rare, and the treatment of the exhaust is challenging and requires the right equipment to be managed properly. For the PLASCON® method the accessibility is directly influenced by the fact that this technology has a patent. This has the advantage that the provider gives assistance in the installation and operation of the technology. It has also the disadvantage that only few companies in the world sell this type of technology, including PLASCON, the developer of this destruction method, and ASADA, that sells small portable plasma units. However, this technology has gained relevance in the past years and new plasma technology using e.g., CO_2 or nitrogen have been used for the destruction of HFC-23 (TEAP 2018a, 2018b).

The associated costs of technologies hereby described are generally high, excluding the cement kiln technology. The proper destruction of ODS/HFCs is an expensive and arduous procedure and the MSWI, rotary kiln incineration and argon plasma arc are not the exception. The costs per kg of gas destroyed are very similar across the methods, higher differences have been found between Article 5 and non-Article 5 countries (MLF 2022). Although this has not been proven, one of the reasons for these differences could be that in non-Article 5 countries, the destruction of hazardous substances has been carried out continuously for a very long time, allowing the improvement and the slow reduction of associated costs. On the contrary, in Article 5 countries destruction projects take place intermittently, adding costs such as the maintenance of old technology. Another main cost associated with the different technologies is the cost of laboratory analysis; since non-Article 5 countries often do not have local laboratory installed capacity, they must send the samples to Europe or the USA, representing higher costs.

Other non-operational costs may be related to obtaining environmental permits and the requirements that the facilities must pass in terms of firefighting and solid, liquid, and gaseous waste treatment systems (considering hazardous and non-hazardous waste). Cost estimates for the destruction of CFCs and halons were calculated by TEAP 2002a for each approved technology, these estimates were then used in GIZ 2015to make a comparison between technologies. The latter study concluded, based on 2002 data, that the three technologies with the lowest destruction costs were the superheated steam reactor, the MSWI and the argon plasma arc technology. However, these estimates may vary in Article 5 countries and do not consider the construction costs of the technology. In addition, the same report points out that the technologies recommended by TEAP for Article 5 countries are among others[14]: cement kilns, argon plasma arc and rotary kiln incineration that are discussed in this report.

Additional costs for collection, transport and destruction of ODS have been estimated by TEAP 2009 for all the RAC sectors. These are calculated for low and medium effort of refrigerant collection, depending on whether they are located in densely populated areas (low effort) or in sparsely populated areas (medium effort). Depending on the application from where the refrigerant is collected, the prices per kilogram of ODS collected, transported and destroyed range between 9-65 USD for the refrigerants in low effort areas and between 10-152 USD for the refrigerants in medium effort areas. In the report published by (GIZ 2023) on financial mechanism, the inflation rate since 2009 is used to calculate these costs in the present and the future. It is then obtained that in 2022, the average price for collection transportation and destruction of one kilogram of ODS/HFC in Article 5 countries is 38.56 USD. More information can be found in GIZ 2023 and in TEAP 2002a, 2009.

14 The total list includes retrofitted cement kilns, liquid injection incineration, gaseous/fume oxidation, rotary kiln incineration, argon plasma arc, ac plasma, inductively coupled radio frequency plasma, gas phase chemical reduction and superheated steam reactor.

Table 4. Summary of the technological and economic features of the destruction methods

Technology	Cement Kiln	MSWI	Rotary kiln Incineration	Argon Plasma Arc
Accessibility	High	Low	Low to medium	Low to medium
Degree of operational complexity	Low	High	High to medium	High
Building/adjustment costs	Low to medium (liquid feeding lines to kiln, storage facilities)	High building costs and low adjustments costs	High (Ghana – Zeal over 3 million USD)[1]	High (4.2 million USD + installation and transportation)[2,3]
Energy Consumption kWh/kg	NA	NA	NA	4.32
Destructions Costs USD/kg[5]	6.0	5.2-6.2	1.9-2.5 (non-Article 5) 8.0-29.8 (Article 5)	7.5

1 From exchange with the chief operations officer of Zeal Environmental Technologies Ghana. The costs are estimated for setting up the technology to control the emission from the kiln (1,5 million) and to set up a turbine and steam generator to convert the heat emitted by the rotary kiln into electricity.
2 Cost for a PDU bought by Quimobasicos in 2008.
3 Only the acquisition of the technology is considered.
4 From the PDU of Quimobasicos that destroyed 60 kg of HFC-23 using 259,6 kWh (TEAP 2018a).
5 Costs estimated only for destruction of ODS/HFC from Table 4 above.

4.2 MLF demonstration projects

As briefly explained above, between 2008 and 2014, the Multilateral Fund financed the design and operational phases of 12 ODS/HFC destruction projects in Article 5 countries. Some of these projects carried out domestic destruction using cement kilns, rotary kiln incineration, municipal solid waste incineration and plasma arc methods. Others, in particular low-volume consuming (LVC) countries, exported the collected ODS/HFCs for destruction abroad. This was a better option for countries that did not collect enough refrigerants to operate a national destruction facility. Nine of this initial group of projects reported results back to the MLF.

An overview of these projects is presented in Table 4. It shows the type and amount of refrigerant destroyed, the type of technology used and the costs per kg destroyed (MLF 2018, 2019, 2022).

The MLF demonstration projects have an average cost of 9.6 USD per kilogram of gas destroyed. Excluding the extremely high cost from Nigeria, which reported 29.82 USD/kg, the average is 6.3 USD/kg. These averages are made across methods and substances to provide a general overview.

__Table 5__. Overview of the MLF demo Projects

Country	Amount (t) – Destruction method	Cost of destruction	Rotary kiln Incineration
China	194.8 – Rotary kiln incineration	8-12.50[1]	CFC-11, -12
Colombia	15.1 – MSWI/high temperature incineration (HTI)	5.20 PU foam[1] 5.98 CFC-11 (l)[1] 6.20 CFC-12 (g)[1]	CFC-11, -12, CFC-foam
Georgia*	1.47 Export to France – HTI	5.99**[& 1]	CFC-12
Ghana*	1.27 Export to Poland – HTI	-	CFC-12, Methyl Bromide
	1.0 Export to USA – HTI	0.00[1]	
Mexico	74.1 – Argon plasma arc	7.50[2]	CFC-11, -12, -114, HCFC-22, -141b, HFC-134a R-407
	39.1 – Cement kiln	8.00**[& 2]	
Nepal*	9.1 Export to USA		CFC-12
Nigeria	1.5 – Rotary kiln incineration	29.82[1]	CFC-12
Turkey	9.2 Exported to Poland – Rotary kiln incineration	1.87 to 2.45[1]	CFC-12
Region ECA	41.8 Exported to Germany and Poland – Rotary kiln incineration	1.87 to 2.45[1]	CFC-12 HCFC/HFC

* *Low-volume consuming countries.*
** *Handling and transportation costs included.*
Sources:
1. *MLF 2018, 2019, 2022*
2. *Savigliano et al. 2017*

4.2.1 Challenges and lessons learned

During the review of the demonstration projects, financed by the MLF, several conclusions were drawn from their successes and failures. The foremost important one is that the technology itself was not the main challenge for the destruction projects in Article 5 countries. All countries that carried out ODS/HFC destruction already had existing facilities, which were then adapted to destroy these substances. Only in the case of Mexico, the argon plasma arc unit (PDU) was purchased. Technologies such as cement kilns, MSWI and rotary kiln incinerators were already used for other purposes in the countries (MLF 2018, 2019, 2022).

Instead, finance was one of the biggest obstacles. All the projects mentioned above ceased operations after the funding from the MLF ended. The destruction of ODS/HFCs requires very large investments, primarily for the acquisition or adaptation of destruction technologies, the high energy consumption of these methods, and the collection and transport of the used refrigerants. In addition, destruction facilities face significant challenges in creating a sustainable business model because there is no other product or service that these companies can market other than the ability to generate voluntary carbon credits. Although the corporate social responsibility, the improvement of the environmental image of high polluting industries, such as cement, and current environmental laws in place can enhance the destruction of ODS/HFCs in Article 5 countries, regulations that oblige importers or end-users to dispose of ODS/HFCs safely ensure that operators of destruction facilities generate revenue. Nonetheless, in some countries, a symbolic recognition scheme has been implemented to highlight the environmental management carried out and promote such companies as sustainable and environmentally responsible.

Therefore, policies such as Extended Producer Responsibility (EPR) and regulations prohibiting the venting of refrigerants are critical to the viability of ODS/HFC destruction. Establishing these regulations was the other major challenge identified after the implementation of the MLF demonstration projects. Policy frameworks for ODS/HFC waste management and regulation for (WEEE) disposal are present in the European Union, Japan, the United Kingdom and the US, among other countries. Having these regulations allows these non-Article 5 countries to do a proper management of ODS/HFCs and to have successful destruction facilities (see *Annex B*). However, many Article 5 countries face obstacles and challenges for setting up these regulations. EPR schemes, for example, require high institutional strength, coordination with many stakeholders and clear monitoring and enforcement mechanisms in order for it to work.

The last challenge drawn from the MLF demonstration projects was the export of refrigerants to non-Article 5 countries for destruction. The transboundary movement of hazardous waste is regulated by the Basel Convention. This agreement requires that both countries (sender and recipient) thoroughly approve the transboundary movement, which requires time and paperwork. Moreover, all countries along the export route need to be informed and involved in the movement. Furthermore, the MLF underlined the need for accessible information on ODS/HFC destruction facilities in non-Article 5 countries to facilitate the decision-making process by Article 5 countries when sending ODS/HFCs for destruction abroad. The MLF reported that it was difficult for countries to locate, select and contact destruction facilities. A list with facilities, their fees and the substances that they can destroy could facilitate the work of countries wishing to export these substances (MLF 2022).

Finally, the overall recommendations for the destruction of ODS/HFCs in Article 5 countries are:

- A detailed analysis of the costs of destruction in the country compared to exporting these gases for destruction abroad is recommended. In many cases, where there is not a steady flow of refrigerants available for destruction, it is more affordable to export the collected ODS/HFCs than to set up a destruction facility in the country.
- The adaptation of technologies that have previously been used for the destruction of other types of waste (MSWI, rotary kiln incinerator) or for other purposes (cement kiln) should be subject to testing and emission control, even if a system to reduce emissions is already in place.
- Destruction facilities should be focused not only on ODS/HFCs but also diversify on the type of waste that they can destroy. This will help the facilities to build a stronger business model.
- Appealing to the environmental and social responsibility of large companies to collect and manage their used ODS/HFCs can enhance the destruction of these substances in the country.
- The establishment of an EPR system that allocates responsibility for the proper end-of-life management of ODS/HFCs to importers or producers, as appropriate, will ensure that there is sufficient refrigerant for destruction in the country. This will also require an ODS/HFC collection system in the country. Before spending large sums of money on a destruction facility, it is important to ensure that sufficient refrigerant will be available for future operations. If the destruction of ODS/HFCs is intended to be financed with carbon credits in the voluntary market, it is crucial to ensure that there are buyers for these credits and there is both a destruction facility and enough substances available for destruction. It is also necessary to study the requirements and certifications needed to issue these carbon credits.

5 POLICY FRAMEWORK

The main ODS/HFC destruction and reclamation technologies were presented, as well as some challenges and lessons learned from experiences in the field. *Chapter 5* now provides a brief overview of the importance of a regulatory framework for the viability of ODS/HFC management, with a focus on destruction and reclamation. It also examines some of the challenges to the establishment of a regulatory framework that were briefly outlined above. It then presents three country experiences that illustrate the importance of a policy framework. A more thorough analysis of the status quo and recommendations on policy issues will be subject of another study under COPA's thematic working group on policy framework.

Proper management of ODS/HFC banks requires many more activities than just the safe disposal of these hazardous substances. For example, RAC equipment needs to be monitored to prevent leakages, an inventory of ODS/HFC banks needs to be made, management plans for the phase-out of controlled substances under the Montreal Protocol are needed, alternative technologies and substances such as natural refrigerants need to be introduced, single-use cylinders need to be replaced by refillable cylinders, etc. The implementation of all these activities is challenging and expensive. In addition, the private sector, including importers, distributors and manufacturers, does not have the economic incentives to properly manage ODS/HFC banks and make all the necessary changes to ensure that these gases are not emitted into the atmosphere. Therefore, a policy framework and government institutions are needed to make this happen (GIZ 2017b).

Regulations can ensure that the collection, destruction and reclamation of refrigerants takes place and is properly funded. They also create mechanisms for control and compliance of the RAC&F sectors and ensure best practices. In 2017, GIZ published a set of guidelines for the management and destruction of ODS banks. One of these guidelines describes how to establish a regulatory framework that enables the sustainable management of ozone-depleting substances (GIZ 2017d). It guides through the necessary steps to be taken in order to choose the policies and regulations that are needed according to the situation of each country (GIZ 2017d). Establishing a suitable set of policies is an effortful process as it provides the backbone of all following activities required to do a proper management of ODS/HFC. This means that a thorough analysis is essential to select these policies and strong government institutions are needed to implement and enforce them. Some of the activities required to develop a policy framework are the definition of the scope, a stakeholder analysis, sector prioritization study, policy selection and then policy evaluation[15] (GIZ 2017d, 2017b).

Regarding the destruction of ODS/HFCs, as briefly explained above, a policy framework is needed in order to oblige a specific group of stakeholders (importers, manufacturers, operators) to take responsibility for the

15 A detailed description of the policy measures for the management and destruction of ODS can be found in GIZ (2017d).

finance of the EOL management. The only other way to enable the destruction of these substances is to issue and sell carbon credits in voluntary carbon markets (VCMs), such as the Californian Emissions Trading System (ETS). This is a common practice, particularly in the United States. However, the problem with this solution is that from an environmental perspective, trading short-lived GHGs such as some ODS/HFCs with long-lived GHGs such as CO2 is not an effective measure to reach emissions reduction targets. In addition, the high possible profit resulting from the high GWP of ODS/HFC has attracted some questionable business practices in the past within the Clean Development Mechanism and therefore extreme caution needs to be exerted to ensure that transactions are environmentally sustainable. There is an ongoing struggle between the advantage of unregulated markets enabling the generation of carbon credits and regulated markets where potential polluters are mandated to avoid emissions from their operations. It seems more sustainable and effective in the long run to implement venting bans and to establish mechanisms such as EPRs that finance not only the destruction but also the collection and transport of ODS/HFCs.

On the other hand, reclamation of ODS/HFC has a business model through the sale of the reclaimed gas. This allows companies like Regener in Chile and Enviroserve in the UAE to exist in countries where no EPR schemes are in place. However, policies such as venting bans or restrictions in the commercialization of HCFCs contribute to the collection of ODS/HFCs and help these refrigerants reach the reclamation centres. In addition, EPR systems would provide an even better scenario to solve the main challenge of these centres, which is to find constant and enough refrigerants for reclamation.

5.1 COUNTRY EXPERIENCES

In this subchapter, positive experiences from two countries are presented with the aim of further explaining the relationship between policies and the successful management of ODS/HFC banks. Most of these experiences and lessons learned were obtained after the implementation of demonstration projects financed by the MLF in Article 5 countries and published by the Executive Committee of the MLF.

Allocating responsibilities for ODS/HFC waste management and banning the venting of these substances helps countries to achieve a proper EOL management of ODS/HFCs. Additionally, the MLF concluded that the existence of WEEE regulations and EPR schemes facilitated the collection and destruction of ODS/HFCs. This was the case in China, Colombia, Ghana and Mexico, countries where these legislations were already in place before the demonstration projects (MLF 2018). However, while these regulations have been shown to be necessary for the sustainable management of ODS/HFCs, they are sometimes rare in Article 5 countries (GIZ 2017d).

Colombia has a history of establishing EPR schemes for various products. The country started around 2009 by forcing manufacturers and distributors to fund the collection and safe disposal of tires, batteries, light bulbs, and computers. Five years later, it established a system for refrigerators and air conditioners, and in 2020 for plastic bottles and cans. In all cases, recycling and safe disposal rates increased, after the implementation of these laws. Even though there are still problems such as ensuring the recycling of RAC units and challenges to monitor and enforce these legislations, the EPR scheme for WEEE has facilitated the collection of refrigerants in the country (GIZ 2017c; OECD 2016).

Mexico has established a home appliances replacement program (HARP) with the aim to increase energy efficiency. With this program, Mexico collected around 1.9 million RAC units between 2007 and 2012. Additionally, a country-wide network of recovery and recycling centres for the collection of the replaced units was established. This was financed by the Trust Fund for Electricity Savings (FIDE from its original name in Spanish) created by the Federal Electricity Commission of Mexico. As these efforts focused on reducing electricity consumption, ODS collection was low, with only 35 tonnes of gas collected. Subsequently, two demonstration projects for ODS destruction were developed in the country, funded by the MLF and supported by UNIDO. They use the argon plasma arc operated by Quimobásicos and a cement kiln to successfully destroy all the refrigerants collected at that moment (see *Table 4*). However, the argon plasma arc unit at Quimobásicos was disconnected from the main facility after the project finished. A second project was reviewed with Quimobásicos for the destruction of HFC-23. This gas was emitted by the company during the production of HCFC-22. The renovation of the infrastructure and the reconnection of the argon plasma arc unit to the central chemical plant had to be included in the costs (Savigliano et al. 2017). In the absence of a policy to allocate responsibility for the recovery and disposal of ODS/HFCs, the facilities adapted under the MLF demonstration projects were no longer in operation after the completion of these projects, as there were no more ODS/HFCs available for destruction. There is no EPR legislation in the country, although it has been recognized by government authorities that such legislation is needed to address the current gaps in waste management in Mexico (Savigliano et al. 2017). This has made the collection of ODS/HFCs an arduous process, preventing the country from having a constant flow of gases and foams for destruction.

6 RECOMMENDATIONS AND CONCLUSIONS

After reviewing the MLF demonstration projects for ODS destruction and conducting interviews with reclaimers, the first and most important lesson to be learned from these experiences is that a policy framework to regulate and finance the proper disposal of ODS/HFCs and a venting ban is fundamental to the successful management of these substances. A policy framework that is able to assign responsibilities to importers or distributors for the collection and proper EOL management of ODS/HFCs guarantees that the destruction and reclamation of these substances operates successfully and without interruptions, creating a viable business opportunity. Some of the demonstration projects in Article 5 countries ceased to operate after the MLF project ended due to the lack of regulations to ensure funding and a steady flow of substances for destruction. This was the case, for example, in Indonesia and Mexico (MLF 2018, 2019, 2022).

Based on the interviews conducted and the exchanges with the private sector, it is possible to conclude that the acquisition of technology is often not the main barrier to the viability of destruction and reclamation initiatives in Article 5 countries. Rather, the core problem lies in the country's ability to properly manage the waste of ODS/HFCs. This includes regulations, funding, collection infrastructure, training of technicians, information campaigns to raise awareness of the problems associated with ODS/HFC emissions, etc. However, refrigerant reclamation, although challenging in the absence of regulations, is possible with additional economic activities such as the recycling of RAC equipment or precious metals from electronic waste. Moreover, reclamation is a far better outcome for used refrigerants than their destruction, as it can reduce the amount of new refrigerant entering the ODS/HFC banks. This does not apply to CFCs, which are phased out globally and due to their very high ODP, the recommendation is always to destroy them to reduce the risk of venting and affecting the ozone layer.

Countries need to conduct a thorough assessment of their ODS/HFC banks and evaluate their consumption and future waste stream in order to establish a roadmap for the sustainable management of these substances. This will enable them to make decisions on how to avoid emissions from their ODS/HFC banks. On the one hand, it may be more profitable for low volume consuming countries to collect the gases and then export them for destruction or reclamation abroad. Demonstration projects conducted by the MLF have shown that this option is often cheaper than domestic destruction. In some regions, such as Central America and the Caribbean, there are many LVC countries. For example, the MLF has proposed that a country such as Mexico develops the necessary infrastructure to destroy its own ODS/HFCs, as well as those from neighbouring countries (MLF 2018, 2019, 2022).

It can be concluded that the cement kiln is the most appropriate technology for ODS/HFC destruction in Article 5 countries. This is due to its availability in many countries for cement production and its flexibility to be adapted for refrigerant destruction. The limitations of this technology are the thresholds to the amount of substance that can be fed into the cement kiln, the need to adapt the solid alternative fuel and raw material (AFR) feed point for refrigerant injection and, to the knowledge of this study, the fact that it has not yet been used for foam destruction. In addition, more combustion protocols and injection tests are required at different points in the kiln to ensure that air emissions are below the legal limit. In the case of foams, there is also a risk of leakage of the ODS/HFCs contained in the cells during injection into the cement kiln if the foam cells break before they reach the kiln. The other technologies described in this study (rotary kiln, argon plasma arc and MSWI) could also be recommended, especially if they are already available in the country. However, they generally have much higher associated costs.

As presented in Chapter 3, these are the identified strategies for reclamation projects in Article 5 countries:

- Develop activities that promote stakeholder engagement in EOL management of ODS/HFCs. This facilitates that servicing companies and end users of refrigerants bring the used substances to the reclaimers.
- Appeal to the environmental obligations of big tech companies and end users to enhance the collection and management of the ODS/HFC waste in their facilities.
- Diversify the activities in the reclamation centres to create a strong business model that can cope with fluctuation in the supply of gases for reclamation.
- Engage with governmental institutions and universities, that can provide knowledge and technological support for the reclamation activities.
- Build a network with servicing companies and other stakeholders to promote best practices and the safe collection of refrigerants.
- Before opening a reclamation centre, ensure that there are enough companies that use large amounts of ODS/HFCs that are willing to collect their refrigerants for reclamation purposes and that they (or other companies) are willing/interested in buying reclaimed refrigerant.

Regulations that reduce the amount of virgin refrigerant in the market contribute to the economic viability of reclaimed refrigerant.

As presented in Chapter 4, these are the recommendation for the destruction of ODS/HFCs in Article 5 countries:

- A detailed analysis of the costs of destruction in the country compared to exporting these gases for destruction abroad is recommended. In many cases, where there is not a steady flow of refrigerants available for destruction, it is more affordable to export the collected ODS/HFCs than to set up a destruction facility in the country.
- The adaptation of technologies that have previously been used for the destruction of other types of waste (MSWI, rotary kiln incinerator) or for other purposes (cement kiln) should be subject to testing and emission control, even if a system to reduce emissions is already in place.
- Destruction facilities should be focused not only on ODS/HFCs but also diversify on the type of waste that they can destroy. This will help the facilities to build a stronger business model.
- Appealing to the environmental and social responsibility of large companies to collect and manage their used ODS/HFCs can enhance the destruction of these substances in the country.

- The establishment of an EPR system that allocates responsibility for the proper end-of-life management of ODS/HFCs to importers or producers, as appropriate, will ensure that there is sufficient refrigerant for destruction in the country. This will also require an ODS/HFC collection system in the country. Before spending large sums of money on a destruction facility, it is important to ensure that sufficient refrigerant will be available for future operations. If the destruction of ODS/HFCs is intended to be financed with carbon credits in the voluntary market, it is crucial to ensure that there are buyers for these credits and there is both a destruction facility and enough substances available for destruction. It is also necessary to study the requirements and certifications needed to issue these carbon credits.

Finally, distillation is currently the most suitable technology for refrigerant gas reclamation. This is due to its low cost and commercial availability. Although it can be recommended for this purpose, it has limitations, especially when recovering blends, as the gases in these mixtures often have very similar boiling points, making it difficult for this method to separate the refrigerants properly. On the other hand, adsorption, although currently less available and more expensive, is more suitable for these purposes. Adsorption technologies should be promoted for reclamation projects in non-Article 5 countries where resource availability is less of a problem. This could, in time, make these technologies more accessible for Article 5 countries. A decisive factor for the reclamation process is the diligence of the collection process. The cleaner the gases are prior to reclamation, the easier and cost-effective is the reclamation process. That shows the importance of the skills of the millions of individual service technicians who need to be properly equipped and paid to enable any of the treatment of ODS/HFCs that follows their collection.

Gaps of the study and directions for future work

This report does not address the funding requirements and operating costs of the reclamation and destruction facilities in Article 5 countries, nor the costs of the technology itself (except in a few cases), because such data is not readily available in the literature. This data gap could be closed by gathering field experiences and interviewing destruction facilities and other reclaimers and producers. These activities were beyond the scope of this study. In addition, a closer look at the technology and the views of experts and the industry will be valuable to assess the maturity of the reclamation and destruction technologies and to learn what factors help these facilities to build a strong business model. This will help to inform stakeholders and to give more concrete recommendations to Article 5 countries on technological opportunities and barriers.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8 ANNEX A. LIST OF RECLAMATION FACILITIES PER COUNTRY

No	Country	Number of Known ODS/HFC Reclamation Facilities in Operation	Known Technologies Utilized	ODS/HFC Reclamation Capacity (incl. substances)
1	Austria	3	Destruction Facility	NA
2	Australia	3	NA	NA
3	Belgium	3	NA	NA
4	Bulgaria	2	NA	NA
5	Canada	8	NA	NA
6	Chile	1	Distillation	NA
7	Croatia	1	NA	NA
8	Czech Republic	3	NA	NA
9	Estonia	1	NA	NA
10	Denmark	5	NA	NA
11	France	3	NA	NA
12	Germany	2	NA	NA
13	Hungary	1	NA	NA
14	Italy	14	NA	NA
15	Japan	6	NA	NA
16	Lithuania	1	NA	NA
17	Luxembourg	1	NA	NA
18	Netherlands	3	NA	NA
19	New Zealand	1	NA	NA
20	Norway	2	NA	NA
21	Poland	1	NA	NA
22	Slovakia	2	NA	NA
23	Slovenia	1	NA	NA
24	Singapore	2	NA	NA
25	Slovakia	5	NA	NA
26	Spain	3	NA	NA

No	Country	Number of Known ODS/HFC Reclamation Facilities in Operation	Known Technologies Utilized	ODS/HFC Reclamation Capacity (incl. substances)
27	South Africa	1	NA	NA
28	Russia	4	NA	NA
30	Thailand	1	NA	NA
31	United Arab Emirates	1	Distillation	NA
32	United Kingdom	3	NA	NA
33	United States	63	Distillation Adsorption Subcooling	NA

Source: European Commission 2008, https://ozone.unep.org/countries/additional-reported-information/reclamation-facilities

9 ANNEX B. LIST OF DESTRUCTION FACILITIES PER COUNTRY

Country	Number of Known ODS/HFC Destruction Facilities in Operation	Known Technologies Utilized	ODS/HFC Destruction Capacity (incl. substances)	Typical Destruction Costs (US$)
1. Algeria	1	Cement Kiln	NA	NA
2. Argentina	2 or more	NA	NA	NA
3. Australia	2	Argon Plasma Arc (1) Cement Kiln (1)	600 MT/year	$7/kg
4. Austria	1	NA	NA	NA
5. Belgium	2	Rotary Kiln	NA	NA
6. Brazil	4 or more	Rotary Kiln Cracking Reactor Argon Plasma Arc Chemical Reaction with H_2 and CO^2	NA	NA
7. Canada	1	Rotary Kiln	Not accepting ODS for commercial destruction	$12/kg
8. China	5	Plasma technology (1) Rotary Kiln (3) Local hazardous waste facility (1)	NA	Rotary kiln: $813/kg
9. Colombia	1	Rotary Kiln	NA	High temperature incineration: $5-6/kg
10. Cuba	1	Cement Kiln	NA	NA
11. Czech Republic	1	Rotary Kiln	40 MT/year	NA
13. Estonia	1	NA	NA	NA
14. Finland	1	Rotary Kiln	545 MT/year	NA
15. France	2	NA	NA	NA
16. Germany	7	Hazardous Waste Incinerator Reactor Cracking Porous Reactor	1,600 MT/year (Reactor Cracking)	NA
17. Ghana	1	Rotary Kiln	In construction	NA

Country	Number of Known ODS/HFC Destruction Facilities in Operation	Known Technologies Utilized	ODS/HFC Destruction Capacity (incl. substances)	Typical Destruction Costs (US$)
18. Hungary	5	Rotary Kiln Liquid Injection Incineration	75 MT/year (Rotary Kiln) 13 MT/year (Liquid Injection Incineration)	NA
19. Indonesia	1	Cement kiln	600 MT/year	NA
20. Italy	12	NA	NA	NA
21. 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 (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
22. Mexico	2	Plasma Arc Cement Kiln	NA	Plasma Arc: $8/kg Cement Kiln: $6/kg
23. Netherlands	6	NA	NA	NA
24. Nigeria	1	Rotary Kiln	NA	$30/kg
25. Poland	1	NA	NA	NA
26. Slovakia	1	NA	NA	NA
27. Spain	1	NA	NA	NA

Country	Number of Known ODS/HFC Destruction Facilities in Operation	Known Technologies Utilized	ODS/HFC Destruction Capacity (incl. substances)	Typical Destruction Costs (US$)
28. Sweden	4	Air Plasma, among others	100 MT/year	NA
29. Switzerland	4 or more	Rotary Kiln, among others	910 MT/year (Rotary Kiln) > 320 MT/year (others)	NA
30. United Kingdom	2	High-Temperature Incineration	NA	NA
31. 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
32. Venezuela	2 or more	NA	NA	NA

Source: EPA 2021, COPA TWG TS


OSV-2B

10 ANNEX C. LIST OF DESTRUCTION TECHNOLOGIES REVIEWED BY THE TEAP

Technologies	Concentrated Sources					Dilute Sources
	(H)CFCs*	Halons	Methyl Bromide	HFC	HFC-23	ODS & HFC
DRE	99.99%	99.99%	99.99%	99.99%	99.99%	95%
Thermal Oxidation Technologies						
Cement Kilns	Approved	Not Approved	Not Deter-mined	Approved	Not Deter-mined	
Gaseous/Fume Oxidation	Approved	Not Deter-mined	Not Deter-mined	Approved	Approved	
Liquid Injection Incineration	Approved	Approved	Not Deter-mined	Approved	Approved	
Municipal Solid Waste Incineration						Approved
Porous Thermal Reactor	Approved	Not Deter-mined	Not Deter-mined	Approved	Not Deter-mined	
Reactor Cracking	Approved	Not Approved	Not Deter-mined	Approved	Approved	
Rotary Kiln Incineration	Approved	Approved	Not Deter-mined	Approved	Approved	Approved
Thermal Decay of Methyl Bromide	Not Deter-mined	Not Deter-mined	Approved	Not Deter-mined	Not Deter-mined	
Plasma Technologies						
Argon Plasma Arc	Approved	Approved	Not Deter-mined	Approved	Approved	
Inductively coupled radio frequency plasma	Approved	Approved	Not Deter-mined	Not Deter-mined	Not Deter-mined	
Microwave Plasma	Approved	Not Deter-mined	Not Deter-mined	Not Deter-mined	Not Deter-mined	
Nitrogen Plasma Arc	Approved	Not Deter-mined	Not Deter-mined	Approved	Approved	
Portable Plasma Arc	Approved	Not Deter-mined	Not Deter-mined	Approved	Not Deter-mined	

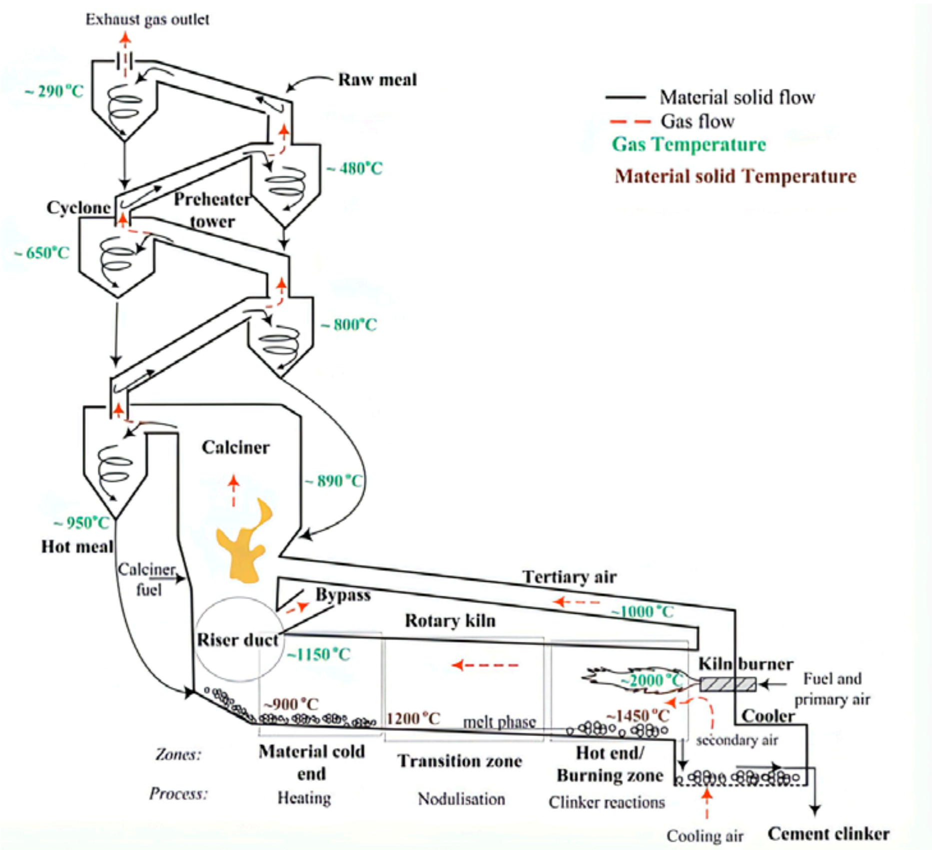
Technologies	Concentrated Sources					Dilute Sources
	(H)CFCs*	Halons	Methyl Bromide	HFC	HFC-23	ODS & HFC
Conversion (or non-incineration) Technologies						
Chemical Reaction with H_2 and CO_2	Approved	Approved	Not Deter-mined	Approved	Approved	
Gas Phase Catalytic Dehal-ogenation	Approved	Not Deter-mined	Not Deter-mined	Approved	Not Deter-mined	
Superheated steam reactor	Approved	Not Deter-mined	Not Deter-mined	Approved	Approved	
Thermal Reaction with Methane	Approved	Approved	Not Deter-mined	Not Deter-mined	Not Deter-mined	

** Including Carbon Tetrachloride and Methyl chloroform.*
*** The orange-coloured boxes refer to technologies that are to be reviewed by the UNEP TEAP*
Source: TEAP 2022band decision XXX.

11 ANNEX D. CONTROL OF EMISSIONS DURING THE DESTRUCTION OF ODS/HFC IN CEMENT KILNS

Cement production involves heating, calcination and clinkering of ground and blended raw materials. In *Figure 8* a modern cement kiln is presented. The first step to produce cement is the preparation of the raw materials followed by the pyro-processing, which covers the thermal treatment necessary to obtain the cement clinker. This process involves the preheating of the raw materials, the calcination, clinker reaction, and cooling of the clinker. The preheater region of a cement kiln has a temperature gradient ranging from approximately 250 to 850°C and gas retention time of about 25 seconds (Li et al. 2015). The clinker reactions take place in the burning zone of the kiln, where the clinker achieves temperatures of up to 1450°C and temperatures of up to 2000°C in the air surrounding the main burner (Cortada Mut et al. 2015; Karstensen et al. 2014). The high temperatures ensure destruction of ODS/HFCs only if other variables are controlled during the process. The operational control of refrigerant dosing, monitoring, sampling, oxygen supply and temperature management is important to trigger internal stabilisation reactions of chlorine in the kiln while avoiding the formation of dioxins and furans (Karstensen et al. 2014; Li et al. 2015).

Figure 8. *Schematic of a typical modern kiln system and their parts, inspired by a Cement Kiln form the Company FLSmidth.*



Source: Cortada Mut et al. 2015

The avoidance of dioxins formation, in the exhaust gas of the kiln, depends on two things: first, the chemical and physical characteristics of the refrigerant to be destroyed, and second, the rate at which the ODS/HFC is fed through the main burner to a flame of 1200°C (never during kiln start-up, shutdown, or major upset) (Karstensen 2008). Some compounds normally administrated through the main burner (as fuels, raw material or in this case ODS/HFCs) containing Sulphur (S), Chlorine (Cl), Sodium (Na) and Potassium (K). These chemicals are evaporated when exposed to high temperatures and may subsequently condense in cooler parts of the plant. In these parts, they change phases from gas to liquid, liquid to solid and solid to gas in a cyclic, almost endless, pattern depending on the concentration. In this way, condensation caused especially by recirculation of S and Cl, generates difficulties in the kiln operation because it forms material buildups, material rings and in the future shell corrosion, affecting the process stability and the operation of the kiln (Cortada Mut et al. 2015).

Inside the kiln, chlorine reacts primarily with alkali metals forming KCl or NaCl typically in the gas phase. Chlorine evaporates with a factor range of 0.900-0.996 (99.6%) in the burning zone of the kiln and condensates (in a factor range of 0.004%) in the cooler parts of the system. This residual chlorine forms chlorellestadite[16] (liquid). Conversely, the contact of residual chlorine with calcium forms $CaCl_2$ (solid/liquid), leading to the deposit of buildups and coating formation on the non-moving parts of the kiln. Therefore, build-up formation on cyclone walls, obstruction of pipes, decreased clinker output and demand of buildup removal are consequence of high internal circulation of inorganic elements, which may reduce the kiln production, cause higher heat consumption, and generate kiln/plant stops (Cortada Mut et al. 2015).

16 Chemical formula: Ca5(SiO4)1.5(SO4)1.5Cl

The presence of chlorine in the system can also lead to dioxin formation, which are carcinogenic substances. Most of the dioxins get destroyed in the cement kiln at temperatures over 1200°C, but the exposure of chlorinated substances to different temperatures during the cement production may cause the formation of dioxins and their release above the legal limit of 0.1-0.2 ng I-TEQ[17]/m^3. In other words, polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), all known as dioxins, can be unintentionally formed and released from cement kilns if the ODS/HFCs are exposed to 250-400°C and mixed with the exhaust dust without a previous oxidative breakdown of macromolecular structures at 1200°C (Li et al. 2015). Ideally, the destruction efficiency of dioxins can be over 99.0% if the ODS/HFC are heated at a minimum of 850°C. This way cement kiln dust is usually re-introduced back to the system and fed again with raw material.

A solution for chlorine and dioxins control can be the installation of a bypass system at the gas extraction point, located at the kiln side of the riser duct. The bypass system involves extracting a portion of the kiln exhaust gases, cooling them to then separating them from the gas. At this point, the kiln gases have low dust and a high gaseous concentration of Cl, which is quenched by air, to initiate condensation of the chlorides and facilitate their subsequent separation from the gas, in an electrostatic precipitator or a baghouse filter. Approximately 90% of the chlorine can be removed by extracting 5% of the kiln exhaust gas, although no more than 15% of the alkali or sulphur can be removed (Cortada Mut et al. 2015). The installation of the bypass requires extra expenses and increases heat and material losses as well as higher specific heat consumption per ton of clinker of removed kiln inlet gas. As a result, understanding the chemistry of chlorinated substances inside the kilns is a matter of critical importance. The destruction of ODS/HFCs in cement kilns requires not only information about the physical and chemical properties of the refrigerants, but a strict control of:

17 -TEQ: International Toxic Equivalent

Main stabilisation reactions (Cortada Mut et al. 2015):

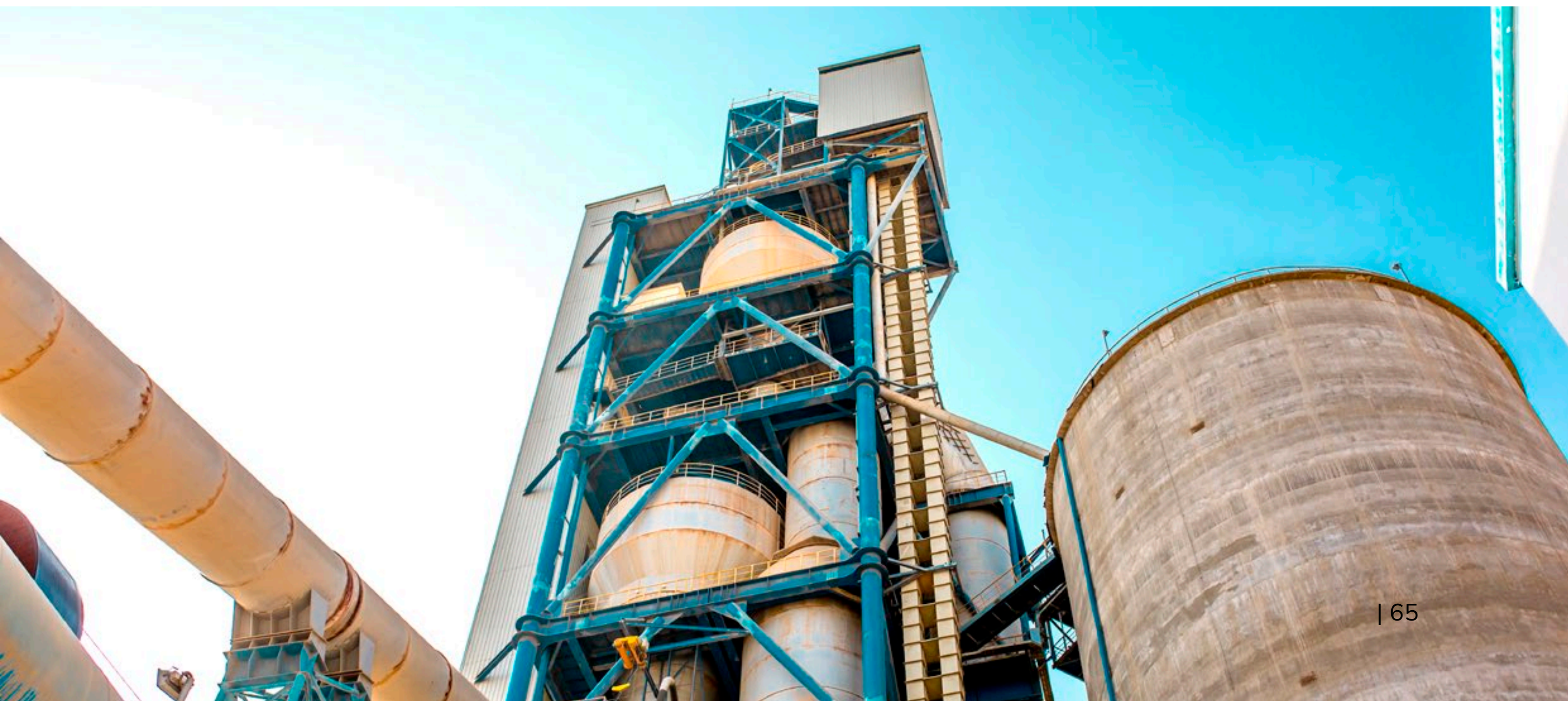
$$CF_2CL_2 + 2H_20 \rightarrow 2HCl + 2HF + CO_2$$
$$2FeS_2(s) + 5.5O_2 \rightarrow Fe_2O_3(s) + 4SO_2(g)$$
$$2FeS_2(s) \rightarrow 2FeSx(s) + 2(1\text{-}0.5x)S_2(g) \rightarrow [O_2(g)] \rightarrow Fe_2O_3(s) + 4SO_2(g)$$
$$CaO(s) + 2HCl(g) \rightarrow H_20(g) + CaCl_2(s/l)$$
$$CaCl_2(g) + 1/2\ O_2(g) + SO_2(g) + H_2O(g) \rightarrow CaSO_4(g/l) + 2HCl(g)$$
$$KCl(g) + H_2O \rightarrow KOH(g) + 2HCl(g)$$
$$2HCl(g) + \tfrac{1}{2}\ O_2(g) \rightarrow Cl_2(g) + H_2O\ (g/l)$$
$$Cl_2(g)+Fe(s) \rightarrow FeCl_2(s)$$

1. appropriate feeding through the main burner,
2. chemical reactions inside the kiln,
3. mass balance of S, Cl, KCl, NaCl, $CaCl_2$, and chlorellestadite in the system,
4. temperature monitoring and
5. exhaust gas and dust control.

At this point, the reaction affinity between volatile material must be considered:

1. chlorine reacts primarily with alkali metals, forming KCl or NaCl typically in the gas phase, residual chlorine combines with calcium, forming $CaCl_2$ (s/l), however the chlorine input is rarely greater than the alkali input,
2. excess alkali reacts with sulphur to form K_2SO4 and/or Na_2SO_4, residual alkali combines with CO_2 to form K_2CO_3 and Na_2CO_3 or with moisture to form NaOH and KOH, alkali can also be embedded in clinker minerals,
3. excess sulphur, present as SO_2 and/or SO_3 in the gas, will react with CaO(s) to form $CaSO_4$(s).

Thus, the input of chlorinated substances in cement production needs to be controlled carefully to comply with product quality, avoid operational problems and prevent cost increases in the process. The installation of a gas extraction bypass system could be a good solution to prevent exhaust gas emission containing dioxins. Controlling technical actions and chemical reactions during the destruction of existing stocks of ODS/HFCs and analysing the exhaust gases for unwanted chemicals (PCDD/PCDF, HCl, HF, HBr, HBr_2, particulate matter, and CO) in cement kilns prevents the generation of environmental liabilities.



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