

**MONTREAL PROTOCOL
ON SUBSTANCES THAT DEplete
THE OZONE LAYER**



UNEP

**REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL**

APRIL 2018

VOLUME 2

**DECISION XXIX/4 TEAP TASK FORCE REPORT ON
DESTRUCTION TECHNOLOGIES FOR CONTROLLED
SUBSTANCES**

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Foreword

The 2018 TEAP Report

The 2018 TEAP Report consists of five volumes:

Volume 1: *Decision XXIX/9 Working Group Report on hydrochlorofluorocarbons and decision XXVII/5*

Volume 2: *Decision XXIX/4 TEAP Task Force Report on destruction technologies for controlled substances*

Volume 3: *TEAP 2018 Progress report*

Volume 4: *MBTOC interim CUN assessment report*

Volume 5: *Decision XXIX/10 Task Force Report on issues related to energy efficiency while phasing down hydrofluorocarbons*

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**DECISION XXIX/4 TEAP TASK FORCE REPORT ON
DESTRUCTION TECHNOLOGIES FOR CONTROLLED SUBSTANCES**

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Executive Summary

Under the Montreal Protocol, the definition and data reporting requirements for production of controlled substances require parties to determine the quantity of ozone-depleting substances (ODS) destroyed in destruction facilities, in order to meet their reporting and compliance obligations.

Parties to the Montreal Protocol have periodically requested the Technology and Economic Assessment Panel (TEAP) to assess destruction technologies. Based on these assessments, parties have taken a number of decisions to approve destruction technologies for the purposes of Montreal Protocol requirements. The list of destruction technologies approved by parties has been updated in a sequence of decisions, with the most recent list contained in the Annex to decision XXIII/12.

At their 29th Meeting, parties requested the TEAP to report by 31st March, and if needed in a supplementary report to the 40th Open-ended Working Group (OEWG), on an assessment of destruction technologies, as instructed in decision XXIX/4. Decision XXIX/4 requests an assessment of the applicability of approved destruction technologies to hydrofluorocarbons (HFCs), and a review of any other technology for possible inclusion in the list of approved destruction technologies for all controlled substances. The decision also invited parties to submit information relevant to these tasks to the TEAP, and submissions were received from Armenia, Australia, Canada, China, the European Union, Japan, Luxembourg, Mexico, the United States, and Venezuela.

In response to Decision XXIX/4, TEAP formed a temporary subsidiary body, in the form of a Task Force on Destruction Technologies (the 2018 TFDT), which combines both TEAP and outside expertise to address the requirements of this decision. In addition to considering the relevant information provided by parties in their submissions, the 2018 TFDT also conducted literature research, reviewed other publicly available information, and requested detailed clarifications and additional information from several parties and/or technology suppliers or owners.

In 2002, a major assessment on destruction was undertaken by the TEAP Task Force on Destruction Technologies, in which screening criteria were developed for the assessment of destruction technologies in 2002 and subsequent reports. These benchmark criteria include the minimum destruction and removal efficiencies¹ (DRE), and maximum emission of pollutants to the atmosphere, to enable comparison between technologies. On this basis, recommendations were made to the parties to the Montreal Protocol, to enable their approval as destruction technologies. Chapter 2 outlines the performance and technical capability criteria against which approved technologies have been assessed.

The 2018 TFDT has used the following requirements to assess a technology that has been previously approved for ODS for its applicability to HFCs destruction:

- The DRE must be a minimum of 99.99% for concentrated sources or 95% for dilute sources.

¹ Destruction and Removal Efficiency (DRE) has traditionally been determined by subtracting from the mass of a chemical fed into a destruction system during a specific period of time the mass of that chemical alone that is released in stack gases and expressing that difference as a percentage of the mass of that chemical fed into the system.

- The Hydrogen Fluoride emissions must be demonstrated to be less than 5 mg/Nm³ and CO emissions less than 100 mg/Nm³.

Thermal oxidation and plasma arc technologies that have already met the performance criterion for chlorinated dioxins and furans for ODS destruction are considered capable of meeting the same performance criterion when used for HFCs destruction. The available data for thermal oxidation and plasma arc technologies suggests that fluorinated dioxins and furans are much more difficult to form, and not formed under conditions where chlorinated dioxins are formed. However, since HFCs may contain ODS impurities or be part of a mixed waste, it would be appropriate due diligence to undertake a dioxins/furans analysis, and may be mandatory under local requirements.

For particulates, approved ODS thermal oxidation and plasma arc destruction technologies are considered capable of meeting the same performance criterion when used for HFC destruction. However, it is suggested that particulate analysis is carried out, and may be mandatory under local requirements, as particulates may be introduced by other waste streams that are co-destroyed with ODS or HFCs.

Due to the unique and varied methods involved in conversion (or non-incineration) technologies², the 2018 TFDT considers it necessary that these technologies demonstrate they can meet all of the emissions performance criteria.

In a number of cases, the 2018 TFDT was unable to make a recommendation without additional information. The assessments are presented in Chapters 3 and 4, and a summary of recommendations provided in Chapter 5 and Appendix 3.

Subsequent to publication of the advance copy of this report, additional information has been provided to the 2018 TFDT. As a result, it will be necessary to submit a supplemental report to the 40th Open-ended Working Group that incorporates the new information.

² Conversion or non-incineration technologies irreversibly transform halocarbons (including to other saleable products, e.g. acids, vinyl monomers etc.). They primarily rely on chemical transformation to destroy substances.

1 Introduction

1.1 Decision XXIX/4

At their 29th Meeting, parties to the Montreal Protocol requested the Technology and Economic Assessment Panel (TEAP) to report by 31st March, and if needed in a supplementary report to the 40th Open-ended Working Group (OEWG), on an assessment of destruction technologies, as instructed in decision XXIX/4.

Decision XXIX/4: Destruction technologies for controlled substances

Considering the chemical similarity of hydrofluorocarbons and hydrochlorofluorocarbons, and chlorofluorocarbons and halons, and taking note of the practice to often destroy them together,

Noting the need to approve destruction technologies for hydrofluorocarbons and to keep the list of approved destruction technologies annexed to decision XXIII/12 up-to-date,

1. To request the Technology and Economic Assessment Panel to report by 31 March 2018, and if necessary to submit a supplemental report to the Open-ended Working Group at its fortieth meeting, on:

(a) An assessment of the destruction technologies as specified in the annex to decision XXIII/12 with a view to confirming their applicability to hydrofluorocarbons;

(b) A review of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances;

2. To invite parties to submit to the Secretariat by 1 February 2018 information relevant to the tasks set out in paragraph 1 above;

1.2 The Task Force (composition)

In response to decision XXIX/4, TEAP formed a temporary subsidiary body, in the form of a Task Force, which combines both TEAP and outside expertise to address the requirements of this decision.

Member	Affiliation	Party
Helen Tope (co-chair)	MCTOC	Australia
Helen Walter-Terrinoni (co-chair)	FTOC	USA
Rick Cooke	MCTOC	Canada
Lambert Kuijpers	RTOC	Netherlands
Andy Lindley	MCTOC	UK
Bella Maranion	TEAP	USA
Jeff Morsch	US DoD	USA
Elvira Nigido	HTOC	Australia
Makoto Ohno	ASADA	Japan
Marta Pizano	MBTOC	Colombia
Ian Porter	MBTOC	Australia
Sidi Menad Si-Ahmed	TEAP	Algeria
Jianjun Zhang	MCTOC	PRC

The Task Force on Destruction Technologies (2018 TFDT) worked entirely by email and other electronic means.

1.3 Background and previous assessments of destruction technologies

Article 1, paragraph 5, of the Montreal Protocol states,

“Production” means the amount of controlled substances produced, minus the amount destroyed by technologies to be approved by the Parties and minus the amount entirely used as feedstock in the manufacture of other chemicals. The amount recycled and reused is not to be considered as “production”.

In accordance with Article 7 of the Montreal Protocol, Parties are required to report data on the production of controlled ozone-depleting substances (ODS).

These definitions require parties to determine the quantity of ODS destroyed in destruction facilities, in order to meet their reporting and compliance obligations.

The Montreal Protocol also allows remanufacture of ODS to replace a portion of ODS destroyed under specific conditions (within the same year as destruction, within the same group of substances, etc.). In practice, parties have not typically remanufactured ODS to offset quantities otherwise destroyed.

In addition to these obligations, ODS destruction has been developed to meet regulatory requirements and voluntary objectives to help protect stratospheric ozone and climate.

More recently, the Kigali Amendment to the Montreal Protocol in 2016 includes hydrofluorocarbons (HFCs) as controlled substances and, in relation to their destruction, states in Article 2J, paragraphs 6 and 7, that³:

6. Each Party manufacturing Annex C, Group I, or Annex F substances shall ensure that for the twelve-month period commencing on 1 January 2020, and in each twelve-month period thereafter, its emissions of Annex F, Group II, substances generated in each production facility that manufactures Annex C, Group I, or Annex F substances are destroyed to the extent practicable using technology approved by the Parties in the same twelve-month period.

7. Each Party shall ensure that any destruction of Annex F, Group II, substances generated by facilities that produce Annex C, Group I, or Annex F substances shall occur only by technologies approved by the Parties.

From its beginnings, the parties to the Montreal Protocol have periodically requested the TEAP to assess and provide advice on destruction technologies in order to meet relevant requirements under the Protocol.

The First Meeting of the parties decided in Decision I/12F with regard to destruction:

(a) to agree to the following clarification of the definition of Article 1, paragraph 5 of the Protocol: “a destruction process is one which, when applied to controlled substances, results in the permanent transformation, or decomposition of all or a significant portion of such substances”;

(b) to request the Panel for Technical Assessment to address this subject for the Parties to return to it at its second and subsequent meetings with a view to determining whether it would be necessary to have a Standing Technical Committee to review and recommend for approval by the Parties methods for transformation or decomposition and to determine the amount of controlled substances that are transformed or decomposed by each method.

Decision II/11 established an Ad Hoc Technical Advisory Committee on Destruction Technologies under the Protocol’s Panel for Technical Assessment to analyse destruction technologies and assess their efficiency and environmental acceptability and develop approval criteria and measurements.

At the Fourth Meeting, parties decided in decision IV/11,

“2. to approve, for the purposes of paragraph 5 of Article 1 of the Protocol, those destruction technologies that are listed in Annex VI to the report on the work of the Fourth Meeting of the Parties which are operated in accordance with the suggested minimum standards identified in Annex VII to the report of the Fourth Meeting of the Parties unless similar standards currently exist domestically;

3. to call on each Party that operates, or plans to operate, facilities for the destruction of ozone-depleting substances:

(a) to ensure that its destruction facilities are operated in accordance with the Code of Good Housekeeping Procedures set out in section 5.5 of the report of the Ad Hoc

³ Annex C, Group I, relates to HCFCs, Annex F to HFCs, and Annex F, Group II to HFC-23, as listed in the Montreal Protocol.

Technical Advisory Committee on Destruction Technologies, unless similar procedures currently exist domestically; and

(b) for the purposes of paragraph 5 of Article 1 of the Protocol, to provide each year, in its report under Article 7 of the Protocol, statistical data on the actual quantities of ozone-depleting substances it has destroyed, calculated on the basis of the destruction efficiency of the facility employed;”

The Code of Good Housekeeping Procedures, adopted by decision IV/11 were later updated by decision XV/9 in Annex III to the 15th Meeting of the Parties. The Code was intended to provide additional guidance to facility operators with a brief outline of measures that should be considered to ensure that environmental releases of ODS through all media are minimized. This Code was also intended to provide a framework of practices and measures that should normally be adopted at facilities undertaking the destruction of ODS.

Parties have taken a number of related subsequent decisions to approve destruction technologies for the purposes of Montreal Protocol requirements. Over time, a list of destruction technologies approved by parties has been updated and included in progressive decisions, with the most recent list of approved destruction processes contained in the Annex to decision XXIII/12⁴, as presented in Table 1-1.

⁴ Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer, Eleventh edition (2017), Section 3.1, pg. 603.

Table 1-1: Current list of approved destruction technologies (2011) (Source: Annex to decision XXIII/12, reordered into destruction categories)

Technology	Applicability							Dilute Sources
	Concentrated Sources							
	Annex A		Annex B			Annex C	Annex E	
	Group 1	Group 2	Group 1	Group 2	Group 3	Group 1	Group 1	
Primary CFCs	Halons	Other CFCs	Carbon Tetrachloride	Methyl Chloroform	HCFCs	Methyl Bromide		
DRE*	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	95%
Cement Kilns	Approved	Not Approved	Approved	Approved	Approved	Approved	Not Determined	
Gaseous/Fume Oxidation	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Liquid Injection Incineration	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	
Municipal Solid Waste Incineration								Approved
Porous Thermal Reactor	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Reactor Cracking	Approved	Not Approved	Approved	Approved	Approved	Approved	Not Determined	
Rotary Kiln Incineration	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	Approved
Argon Plasma Arc	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	
Inductively coupled radio frequency plasma	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	
Microwave Plasma	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Nitrogen Plasma Arc	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Portable Plasma Arc	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Chemical Reaction with H ₂ and CO ₂	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	
Gas Phase Catalytic Dehalogenation	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Superheated steam reactor	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	
Thermal Reaction with Methane	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	

*DRE - Destruction & Removal Efficiency

Decision XXIX/4 takes into account the Kigali Amendment by requesting TEAP to provide an assessment of the destruction technologies to confirm their applicability to hydrofluorocarbons, as well as review any other technology for possible inclusion in the list of approved destruction technologies in relation to all controlled substances.

Within this history, this report builds on previous work by TEAP and its subsidiary bodies, including reports in 1992¹, 1995², 2002³, 2005⁴ and 2011⁵.

In 2002, a major assessment on destruction was undertaken by the TEAP Task Force on Destruction Technologies. The 2002 Task Force (2002 TFDT) developed screening criteria for the assessment of destruction technologies on the basis of:

1. Destruction and Removal Efficiency (DRE)⁶
2. Emissions of dioxins and furans (PCDDs/PCDFs)⁷
3. Emissions of other pollutants (acid gases, particulate matter, and carbon monoxide)
4. Technical capability

These performance and technical capability criteria are described further in Section 2.

These criteria have been used as the basis for assessing destruction technologies since 2002, and in this assessment. They constitute minimum performance criteria for the purposes of assessing technologies and making recommendations to the parties to the Montreal Protocol. The technical assessment can conclude that a generic type of destruction technology has demonstrated that it is capable of meeting these performance criteria based on actual data.

The assessment criteria are not intended to imply, in any way, a level of standards for pollutants emitted from destruction facilities. Local standards are established by governments within their regulatory regimes. Similarly, a recommended generic type of destruction technology assessed against these criteria does not imply that a specific facility can or will meet local standards for pollutant emissions, or even the assessment criteria, during actual operation. These are matters for operators and government agencies within national

¹ UNEP Report of the *Ad Hoc* Technical Advisory Committee on ODS Destruction Technologies. United Nations Environment Program, May 1992.

² UNEP Report of the Technology and Economic Assessment Panel ODS Disposal Subcommittee Workshop held in Montreal, Canada, May 2-3, 1995, June 1995.

³ UNEP Report of the Technology and Economic Assessment Panel, Volume 3B, Report of the Task Force on Destruction Technologies, April 2002.

⁴ UNEP Report of the Technology and Economic Assessment Panel, Progress Report, Response to Decision XVI/15, May 2005.

⁵ UNEP Report of the Technology and Economic Assessment Panel, Volume 1, Progress Report, TEAP Task Force Response to Decision XXII/10, May 2011.

⁶ Destruction and Removal Efficiency (DRE) has traditionally been determined by subtracting from the mass of a chemical fed into a destruction system during a specific period of time the mass of that chemical alone that is released in stack gases and expressing that difference as a percentage of the mass of that chemical fed into the system.

⁷ Polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)

regulatory frameworks. A recommendation for inclusion on the list of approved destruction technologies is also not an endorsement.

Only technical feasibility has been considered in this assessment, including technical capability. Costs (plant, maintenance, operation, cost per kg) and economic feasibility have not been taken into consideration in this assessment.

The TEAP, TOCs, and 2018 TFDT co-chairs and members, and the companies and organisations that employ them, do not endorse the performance, worker safety, or environmental acceptability of any of the destruction technologies discussed.

1.4 Submissions received

Submissions in response to decision XXIX/4, paragraph 2, were received from Armenia, Australia, Canada, China, the European Union, Japan, Luxembourg, Mexico, the United States, and Venezuela. A summary is contained in Appendix 1. The 2018 TFDT has considered and incorporated relevant information contained in those submissions. Where parties have confirmed that the information is non-confidential, this will be compiled in a separate document, in pdf format, and made available prior to the 40th Open-ended Working Group on the Ozone Secretariat website at the following link: <http://conf.montreal-protocol.org/meeting/oewg/oewg-40/presession/SitePages/Home.aspx>.

1.5 This assessment

In addition to considering the relevant information provided by parties in their submissions, the 2018 TFDT also conducted literature research, reviewed other publicly available information, and requested detailed clarifications and additional information from several parties and/or technology suppliers and owners. The 2018 TFDT has reviewed performance data provided to it in good-faith on the assumption that it is accurate data based on real measurements from destruction technologies during test or under normal operation.

The 2018 TFDT addressed decision XXIX/4 according to its two parts:

- An assessment of destruction technologies approved under decision XXIII/12 to confirm their applicability to HFCs (paragraph 1a)
- An assessment of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances (paragraph 1b)

In response to paragraph 1b, the 2018 TFDT considered destruction technologies of which it was aware, based on existing knowledge, literature, reports, or from parties' submissions.

The 2018 TFDT has indicated where insufficient data was available to assess adequately the destruction technologies under paragraphs 1a or 1b against the performance criteria and for technical capability.

Subsequent to publication of the advance copy of this report, additional information has been provided to the 2018 TFDT. As a result, it will be necessary to submit a supplemental report to the 40th Open-ended Working Group that incorporates the new information.

2 Assessment criteria

The 2002 Task Force on Destruction Technologies (2002 TFDT)¹ developed screening criteria for the assessment of destruction technologies for the purposes of the Montreal Protocol, and on the basis of:

1. DRE, which is a minimum of 95% for dilute sources (e.g. foams) and 99.99% for concentrated sources;
2. Emissions of dioxins and furans (PCDDs/PCDFs);
3. Emissions of other pollutants: acid gases (HCl, HF, HBr/Br₂); carbon monoxide (CO); and total suspended particulates (TSP);
4. Technical capability, where the technology has demonstrated destruction on at least a pilot scale or demonstration scale, and for which the processing capacity is no less than 1.0 kg/hr of the substance to be destroyed, whether ODS or a suitable surrogate.

The first three refer to technical performance criteria selected by the 2002 TFDT as measures of potential impacts of the technology on human health and the environment. The technical capability criterion was selected to indicate the extent to which the technology has been demonstrated to be able to dispose of ODS (or a comparable recalcitrant halogenated organic substance such as polychlorinated biphenyl (PCB)) effectively and on a commercial scale.

The following sections outline in more detail the performance criteria and technical capability against which the destruction technologies have been assessed. The 2018 TFDT has considered the 2002 performance criteria and also taken into account previous assessments of ODS destruction technologies, to confirm the applicability of approved destruction technologies to HFCs, in response to decision XXIX/4 paragraph 1a, and other technical considerations based on more recent international developments.

2.1 Performance criteria

The performance criteria developed by the 2002 TFDT are summarized in Table 2-1.

¹ UNEP Report of the Technology and Economic Assessment Panel, Volume 3B, Report of the Task Force on Destruction Technologies, April 2002.

Table 2-1: Summary of Technical Performance Criteria

Performance Qualification	Units	Concentrated Sources	Diluted Sources (e.g. foams)
DRE	%	99.99	95
PCDDs/PCDFs	ng-ITEQ/Nm ³	0.2	0.5
HCl/Cl ₂	mg/Nm ³	100	100
HF	mg/Nm ³	5	5
HBr/Br ₂	mg/Nm ³	5	5
Particulates (TSP)	mg/Nm ³	50	50
CO	mg/Nm ³	100	100

Notes to the table:

All concentrations of pollutants in stack gases and stack gas flow rates are expressed on the basis of dry gas at normal conditions of 0°C and 101.3 kPa, and with the stack gas corrected to 11% O₂ (as referred to by normal cubic metre, Nm³).

ITEQ – international toxic equivalency used for PCDDs and PCDFs.

TSP – total suspended particles

These criteria represent the minimum destruction and removal efficiencies and maximum emission of pollutants to the atmosphere demonstrated by technologies to enable their recommendation to the parties to the Montreal Protocol for approval as ODS destruction technologies. These criteria were developed after an earlier decision of Parties to the Montreal Protocol, taken at their Fourth Meeting, on “suggested minimum standards” for the operation of destruction facilities (see Appendix 2).

The performance criteria serve as a benchmark for comparison purposes. They are not standards, nor do they meet internationally accepted emissions limits for pollutants. They were developed only for the purposes of screening and recommending generic technologies that might be considered technically capable of meeting acceptable limits of pollutant emissions. Operators of destruction technologies are required to meet local emissions controls, and a recommendation or an approval under the Montreal Protocol does not guarantee that local requirements can or will be met. There may be other concerns or emissions of interest to governments at their national levels. In addition, the performance of technologies are plant and operation specific. Emissions management is a matter for operators and government agencies within national regulatory frameworks.

Waste ODS are typically classified as hazardous wastes, and relevant legislation imposes additional requirements, nationally, or regionally (European Union), and may also be subject to international reference guidance (Basel Convention) in terms of emissions performance, including other potential emissions and sources of emissions and monitoring.

2.1.1 Chlorinated dioxins and furans

PCDDs and PCDFs (chlorinated dioxins and furans) are generally released to the environment as mixtures of these compounds. The scientific community developed a system of toxic equivalency factors (TEFs) which relate the biological potency of compounds in the dioxin

and furan family (dioxins/furans) to the reference tetrachlorodibenzo-p-dioxin (TCDD) compound. The concentration of each specific compound is multiplied by its corresponding TEF value, and the resulting potency-weighted concentration values are summed to form an expression of the mixture's overall toxic equivalence (TEQ). The International Toxic Equivalents (ITEQ) scheme was established by NATO in 1988. More recently the TEFs were re-evaluated by the World Health Organisation and the revised TEQ scheme is generally universally accepted, with the updated TEFs used in the TEQ calculation.² Some of the data reviewed by the 2018 TFDT quotes TEQ values.

The performance criterion for chlorinated dioxins/furans of 0.2 ng ITEQ Nm³, as defined by the 2002 TFDT, lay between the more stringent requirements in some countries (<0.1 ng ITEQ Nm³) and less stringent requirements in other countries at that time. In response to decision XXII/10, the 2011 TEAP Task Force (2011 TFDT)³ reviewed this performance criterion and concluded that a limit of 0.1 ng ITEQ Nm³ would be closer to the global industry norm. However, the 2011 TFDT also noted that there may be some existing approved destruction technologies that might not satisfy this criterion, and that a review might be required. The 2011 TFDT concluded that parties may wish to consider consultation on a revision to the dioxins/furans criterion. No decision was taken by parties in relation to such a revision. The Basel Convention in its guidance applicable to Persistent Organic Pollutants (POPs) under the Stockholm Convention also requires an emission limit of 0.1 ng TEQ/Nm³ for chlorinated dioxins/furans for atmospheric emissions.

The TEQ scheme updated by the WHO for dioxins and dioxin-like substances (including chlorinated dioxins/furans) is generally accepted with an international emission limit of 0.1 ng TEQ/Nm³. However, the performance criterion for recommending destruction technologies for approval by parties under the Montreal Protocol is <0.2 ng ITEQ/Nm³. As in previous reviews, the 2018 TFDT has continued to use the performance criterion for chlorinated dioxins/furans (PCDDs/PCDFs) of 0.2 ng ITEQ Nm³ for concentrated sources and 0.5 ng ITEQ Nm³ for diluted sources as defined by the 2002 TFDT, for this assessment. Parties may wish to consider a review of this performance criterion to make it consistent with the lower WHO TEQ level.⁴

² See TOXICOLOGICAL SCIENCES 93(2), 223–241 (2006) REVIEW. The 2005 World Health Organization Re-evaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-Like Compounds. This paper gives an indication of the quantitative impact of the 2005 changes on WHO TEF values in some selected biotic samples. *“In general, it can be concluded that the changes in 2005 values have a limited impact on the total TEQ of these samples with an overall decrease in TEQ ranging between 10 and 25%. In view of this average impact of 10–25%, it should be realized that many duplicate GC-MS analyses for these compounds also have an uncertainty that can fall in the range of 10–25%.”* In conclusion, the future or retrospective use of TEQ with revised Toxic Equivalent Factors (TEF) instead of ITEQ should have little if any impact on the evaluation of technologies screened-in or screened-out for the dioxins/furans performance criterion.

³ UNEP Report of the Technology and Economic Assessment Panel, Volume 1, Progress Report, TEAP Task Force Response to Decision XXII/10, May 2011.

⁴ Toxicol Sci. 2013 Jun; 133(2): 197–208: Polybrominated Dibenzo-p-Dioxins, Dibenzofurans, and Biphenyls: Inclusion in the Toxicity Equivalency Factor Concept for Dioxin-Like Compounds; Martin van den Berg et al. In 2011, a joint World Health Organization (WHO) and United Nations Environment Programme (UNEP) expert consultation took place, during which the possible inclusion of brominated analogues of the dioxin-like compounds in the WHO Toxicity Equivalency Factor (TEF) scheme was evaluated. The use of similar interim TEF values for brominated and chlorinated congeners for human risk assessment is recommended, pending more detailed information in the future.

2.1.2 Brominated and mixed halogenated dioxins and furans

The 2011 TFDT also considered methyl bromide destruction and the potential formation of poly-brominated dibenzo-*p*-dioxins and poly-brominated dibenzofurans (PBDD/PBDF, or brominated dioxins/furans). The 2011 TFDT noted that, in 1998, an expert group had recommended the adoption of the same limits for brominated dioxins/furans as for chlorinated dioxins/furans.

In addition, in 2010 the UK Committee on Toxicity concluded that the available evidence suggests that mixed halogenated compounds (dioxins/furans containing chlorine and bromine) are less toxic than the equivalent chlorinated compounds.⁵

Analysis of brominated and mixed chlorinated/brominated dioxins/furans would be appropriate due diligence under circumstances where they may be formed and may be mandatory under local requirements.

2.2 Considerations for performance criteria relevant to approved destruction technologies for their applicability to HFCs

The following section outlines considerations for performance criteria relevant to the assessment of destruction technologies for their applicability to HFCs. Based on its technical assessment, the 2018 TFDT has concluded that no *additional* performance criteria are necessary for assessing destruction technologies for the destruction of HFCs.

2.2.1 DRE⁶, emissions of other pollutants, and technical capability

The DRE, emissions of other pollutants, and technical capability of the 2002 TFDT performance criteria are equally applicable to HFCs, particularly as many ODS already contain fluorine and a criterion is already included for HF emissions. In fact, the generation rate of HF from some ODS has been shown to be similar to that from some HFCs⁷, as calculated based on stoichiometry and shown in Table 2-3.

⁵ Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT). 2010 COT statement on Occurrence of Mixed Halogenated Dioxins and Biphenyls in UK Food.

⁶ The 2018 TFDT notes the discussion on the use of the more comprehensive Destruction Efficiency (DE) parameter in the 2011 TFDT, which accounts for all release paths as opposed to just in exhaust gases in the cases of DRE. The 2018 TFDT supports the continued use of DRE, and in this case its equivalency to DE, based on the low potential for detectable undestroyed ODS or HFCs to be found in solid or liquid releases from destruction processes.

⁷ Calculated based on stoichiometry.

Table 2-3: HF Generation Rates

Substance		HF generation kg HF/kg substance destroyed
CFC-12	CF ₂ Cl ₂	0.33
HCFC-22	CHF ₂ Cl	0.46
CFC-115	C ₂ F ₅ Cl	0.65
Halon-1301	CF ₃ Br	0.40
HFC-134a	C ₂ H ₂ F ₄	0.78
HFC-143a	C ₂ H ₃ F ₃	0.71
HFC-23	CHF ₃	0.86

The 2018 TFDT has applied the same performance criteria established for ODS for DRE, emissions of other pollutants (acid gases, carbon monoxide, and total suspended particulates), and technical capability to the destruction of HFCs, and also taken into consideration the previous assessments of approved ODS destruction technologies.

2.2.2 Fluorinated dioxins and furans

As any high temperature process used to destroy ODS has associated with it the potential formation (as unintended by-products) of dioxins/furans, depending on the process and operating parameters, it is important to consider if fluorinated dioxins/furans could be formed from HFCs, and indeed other ODS-containing fluorine. In addition, applying the same performance parameter, as used for chlorinated and brominated species, requires some knowledge of the relative toxicity of fluorinated dioxins/furans.

A published study⁸ has shown that it is much more difficult to form fluorinated dioxins, under conditions where chlorinated dioxins are formed. No fluorinated dioxins were detected in municipal fly ash, and no fluorinated dioxins were detected if fluoride was added to the fly ash followed by heat treatment. Under similar conditions, with addition of chloride, chlorinated dioxins/furans were detected. No fluorinated dioxins were detected from CFC-11 or polytetrafluoroethylene (PTFE) at temperatures in the range of 550-750°C. Therefore, the techniques that are successfully employed to minimize the formation of chlorinated dioxins should similarly apply to any possible fluorine analogues, particularly as it has been shown to be much more difficult to form fluorinated dioxins, under conditions where chlorinated dioxins are formed.

There are several papers^{9,10,11,12} that show that 2,3,7,8-TFDD (a fluorinated dioxin) has dioxin-like activity. However, it appears to be metabolized and excreted much faster than its

⁸ Weber, R, Schenk, D, Schmitz, H-J, Hagenmaier A and Hagenmaier, H. "Polyfluorinated dibenzodioxins and dibenzofurans – synthesis, analysis, formation and toxicology." *Chemosphere*, 30, 629 – 639, 1995.

⁹ Schmitz, H-J, Weber, R, Hagemmaier, A, Hagenmaier, H, Poellinger, L and Schrenk, D. "2,3,7,8-Tetrafluorodibenzo-p-dioxin: a potent agonist of the murine dioxin receptor" *Environmental Tox & Pharmacol*, 3, 105 - 113, 1997.

¹⁰ Weber, R, Schmitz, H-J, Schenk, D, and Hagenmaier, H. "Metabolic degradation, inducing potency and metabolites of fluorinated and chlorinated-fluorinated dibenzodioxins and dibenzofurans" *Chemosphere*, 34, 29 – 40, 1994.

chlorinated analogue, which suggests that the overall severity of any toxic effect may be much less. It may be concluded that setting the same emission performance criteria for 2,3,7,8-TFDD and the other fluorinated dibenzodioxins and dibenzofurans, as for chlorinated and brominated dioxins/furans, would be a conservative precautionary approach.

Analysis of fluorinated dioxins/furans would be appropriate due diligence under circumstances where they may be formed and may be mandatory under local requirements.

2.2.3 Consideration of previous assessments of approved ODS destruction technologies

There are three types of destruction technologies that have been approved for ODS destruction. Thermal oxidation (or incineration) is the use of controlled flame combustion to destroy substances in an engineered device. Plasma arc destruction generally occurs by pyrolysis in an oxygen reduced environment at significantly higher temperatures than thermal oxidation and differ from each other in the type of inert gases employed, the method of heat generation to create the plasma, and the plasma torch/process containment vessel design. Conversion (or non-incineration) technologies are those that primarily rely on chemical transformation to destroy substances.

The 2018 TFDT has used the following requirements to assess a technology that was previously approved for ODS for its applicability to HFCs destruction.

- The DRE must be a minimum of 99.99% for concentrated sources or 95% for dilute sources.
- The HF emissions must be demonstrated to be less than 5 mg/Nm³ and CO emissions less than 100 mg/Nm³ for HFCs destruction.

Thermal oxidation and plasma arc technologies that have already met the criterion for chlorinated dioxins/furans for ODS destruction are considered capable of meeting the same performance criterion when used for HFCs destruction. The available data for thermal oxidation and plasma arc technologies suggests that fluorinated dioxins/furans are much more difficult to form, and not formed under conditions where chlorinated dioxins are formed. However, since HFCs may contain ODS impurities or be part of a mixed waste, dioxins/furans analysis would be appropriate due diligence, and may be mandatory under local requirements.

For particulates (TSP), approved ODS thermal oxidation and plasma arc destruction technologies are considered capable of meeting the same performance criterion when used for HFC destruction. However, it is suggested that particulate analysis is carried out, and may be mandatory under local requirements, as particulates may be introduced by other waste streams introduced co-destroyed with ODS or HFCs.

Incineration and plasma destruction processes operate at high temperatures linked to a rapid quench that minimises the formation of dioxins/furans. Conversion (or non-incineration) technologies transform halocarbons under a range of operating conditions, often at lower temperature than incineration, using specific reactants to achieve the conversion of ODS

¹¹ Weber, R, Kuhn, T, Hagenmaier, H and Hafelinger, H. "ab initio MO Optimisation of Molecular Structures of Fluoro- and Chloro-substituted Dibenzo-p-dioxines and the effect of Halogen Substitution at the 2,3,7,8-positions on Metabolic Attack." Z. Naturforsch. 52b, 1418 – 1431, 1997.

¹² Conrad, D, Golor, G, Neubert, D and Rotard, W. "Organohalogen Compounds", 29, 406, 1996.

(including conversion to saleable products like acids, vinyl monomer etc.). Due to the unique and varied methods involved in conversions technologies, the 2018 TFDT considers it necessary that these technologies demonstrate they can meet all of the emissions performance criteria.

2.2.4 Destruction of mixed streams of ODS and HFCs

Many parties already undertake destruction of waste HFCs. Typically, these are destroyed using the same processes that are used for ODS destruction, and the processes must meet the same emissions and performance regulatory requirements that also apply to ODS destruction. One technical issue for mixed ODS and HFCs streams is the presence of halons or methyl bromide, as molecular bromine tends to be formed, which is very difficult to remove from the exhaust gases and the presence of bromine can significantly alter the process parameters (HTOC 2014 Technical Note 5)¹³. Mixed streams already have to take into account, or screen for, the presence of other wastes, such as hydrocarbons and lubricants.

2.3 Technical capability

2.3.1 Technical capability for ODS destruction

As well as demonstrating the above performance criteria, destruction technologies must also demonstrate that they are technically capable at an appropriate scale of operation. In practical terms, this means that a technology is demonstrated to achieve the recommended DRE while satisfying the emissions criteria outlined above. The 2002 TFDT established that an ODS destruction technology would be considered technically capable if it meets the following minimum criteria:

- It has been demonstrated to have destroyed ODS to the technical performance criteria, on at least a pilot scale or demonstration scale (*recommended for approval*); or
- It has been demonstrated to have destroyed a refractory chlorinated organic compound other than an ODS, to the technical performance criteria, on at least a pilot scale or demonstration scale, which indicates that the technology is considered to have a high potential for application with ODS but has not actually been demonstrated with ODS (*recommended as high potential*); and
- The processing capacity of an acceptable pilot plant or demonstration plant must be no less than 1.0 kg/hr of the substance to be destroyed, whether ODS or a suitable surrogate.

The 2005 TEAP Response to Decision XVI/15¹⁴ further clarified that a destruction technology might have a high potential for ODS destruction when the technology was not demonstrated specifically on this category of ODS but was considered likely to be applicable based on the evidence of destruction of other substances (i.e. refractory halogenated organics) and on professional judgment.

¹³ UNEP Halons Technical Options Committee 2014, Technical Note 5 on Halons Destruction, pg. 2.

¹⁴ UNEP Report of the Technology and Economic Assessment Panel, Progress Report, Response to Decision XVI/15, May 2005.

The 2002 TFDT Report indicated that the Task Force considered that it was reasonable for technologies that had been demonstrated to satisfy the criteria for one type of CFC could be recommended for the destruction of all CFCs and HCFCs, and that a technology that had been demonstrated to satisfy the criteria for one type of halon could be recommended for destruction of all halons. The 2002 TFDT did, however, consider it necessary that the stack (exhaust) gases be tested for each new ODS destroyed to ensure that the DRE and emission requirements are satisfied, since some CFCs, for example, are more easily destroyed than others. This is relevant for thermal oxidation and plasma technologies but not necessarily for conversion (or non-incineration) technologies.

Finally, the 2011 TFDT also reviewed a small scale portable plasma destruction packaged unit, which can have a capacity as low as 1 kg/hour for some ODS (e.g. CFC-12). Even though this is equivalent to the minimum feed rate defined by the 2002 TFDT as a 'screen in' criterion, the portable unit is designed to be at an appropriate commercial scale for its intended application and has similar process characteristics to larger scale nitrogen plasma arc destruction units. A detailed discussion on throughput capability is contained in Appendix B of the report of the 2002 TFDT¹⁵.

2.3.2 Technical capability for HFC destruction

A similar approach has been applied by the 2018 TFDT to the assessment of approved destruction technologies for confirming their applicability and potential applicability to HFCs.

- It is an approved thermal oxidation or plasma arc destruction technology for ODS, which has demonstrated that it meets the particulates and dioxins/furans emissions criteria for ODS destruction, and has been demonstrated to have destroyed HFCs to the technical performance criteria for DRE, HF and CO, on at least a pilot scale or demonstration scale (*recommended for approval*); or
- It is an approved conversion (or non-incineration) technology for ODS, or a destruction technology specifically developed for HFCs, that has been demonstrated to have destroyed HFCs to the technical performance criteria for DRE, HF, CO, particulates, and dioxins/furans, on at least a pilot scale or demonstration scale (*recommended for approval*); or
- It is an approved destruction technology (including for conversion technology) for ODS but has not actually been demonstrated to have destroyed HFCs to the technical performance criteria, on at least a pilot scale or demonstration scale (*recommended as high potential*); or
- It has been demonstrated to have destroyed a refractory halogenated organic compound, in gaseous or liquid form, other than an ODS or HFCs, to the technical performance criteria, on at least a pilot scale or demonstration scale, but has not actually been demonstrated with HFCs (*recommended as high potential*); and
- The processing capacity of an acceptable pilot plant or demonstration plant must be no less than 1.0 kg/hr of the substance to be destroyed, whether HFC or a suitable surrogate.

¹⁵ UNEP Report of the Technology and Economic Assessment Panel, Volume 3B, Report of the Task Force on Destruction Technologies, April 2002.

It is important to note that the higher fluorine content of HFCs may impact the operability, productivity and/or performance of the technology, and adjustments may be needed for approved ODS destruction technologies to process waste HFCs.

The submissions from the United States and the European Union indicate that either they use the destruction of surrogate chemicals (such as carbon tetrafluoride) to demonstrate DRE (United States) or they recommend operational parameters (e.g. maintaining temperatures above 1200°C for a minimum residence time of 2 seconds for thermal oxidation technologies) (European Union).

The European Union submission states that HFC incineration systems operating at or above 1200°C, with residence times of at least two seconds, ensure decomposition¹⁶ of HFC/HCFC and minimize the formation of unwanted combustion products such as dioxins/furans, carbonyl halides (COF₂, COCl₂) and hydrocarbons. The proposal that specific incineration facility operating conditions might be used as an assurance of meeting DRE and emissions limits highlights the importance of operating at conditions sufficient to meet those criteria.

The submission by the United States (in its Appendix D) explains that the U.S. EPA established a system for ranking the thermal stability of hazardous wastes for the purposes of developing methods for testing the DRE of hazardous waste incinerators, a thermal stability index. Hazardous waste incinerators in the United States are required to demonstrate the ability to destroy hazardous wastes (including chlorinated and fluorinated compounds that are regulated as hazardous wastes) to a DRE of > 99.99 percent (40 CFR 266.104 *Standards to Control Organic Emissions*). In general, hazardous waste incinerator operators test the incinerator using one or more principle organic hazardous constituent (POHCs) as surrogates for all other hazardous waste compounds. If the incinerator demonstrates the ability to destroy the surrogate to a DRE of > 99.99 percent, the incinerator is assumed also to have the ability to destroy any other compounds ranked lower on the thermal stability index. HFC-23 is a Stability Class 2 compound. CFC-11, -12, -113, and HCFC-22, Halon-1301, and HFC-161 are ranked as Stability Class 3 compounds.¹⁷

The 2018 TFDT considers that it is reasonable for thermal oxidation and plasma arc destruction technologies that have been demonstrated to satisfy the criteria for one type of HFC from Annex F, Group 1 could be recommended for the destruction of all HFCs from Annex F, Group 1, provided destruction conditions (destruction temperature and residence times, as applicable) are met for each HFC to be destroyed. The 2018 TFDT also recommends that exhaust gases to be tested for each new HFC destroyed to ensure that the DRE and emissions requirements are satisfied, as some HFCs listed in Annex F, Group 1 are more easily destroyed than others.

The 2018 TFDT considers that HFC-23 (Annex F, Group 2) can act as a proxy for all HFCs in Annex F, Group 1. However, if a destruction technology has been demonstrated to satisfy the criteria for HFCs from Annex F, Group 1, it cannot necessarily be recommended for the destruction of HFC-23, due to the relatively higher thermal stability of HFC-23¹⁸.

¹⁶ This is stated in the Reference document on best available techniques for Waste incineration, 2006 (http://eippcb.jrc.ec.europa.eu/reference/BREF/wi_bref_0806.pdf) as well as demonstrated by the existing technologies for trifluoromethane (HFC-23) destruction (<http://cdm.unfccc.int/Projects/projsearch.html>).

¹⁷ “ODS Destruction in the U.S. and Abroad”, February 2018, https://www.epa.gov/sites/production/files/2018-03/documents/ods-destruction-in-the-us-and-abroad_feb2018.pdf, accessed March 2018.

¹⁸ A complete table of HFC thermal stabilities was not available to the 2018 TFDT. Relevant data is contained in: ‘Appendix D: Incinerability of HFCs of the United States’ submission in response to decision XXIX/4, paragraph

2.4 Considerations for performance criteria relevant to methyl bromide destruction technologies

2.4.1 Methyl Bromide Destruction

No destruction technology has yet been approved for methyl bromide destruction. Even so, six Parties have reported destruction of methyl bromide to the Ozone Secretariat (see section 2.4.1.1).

The 2011 TFDT reviewed the performance criteria in general for destruction technologies, and also considered a minimum DRE criterion for methyl bromide destruction¹⁹. The 2011 TFDT concluded that having reviewed the limited data available, that there was no technical reason why the DRE should be set at an initial figure that differed from that used for the destruction of other concentrated sources of ODS (i.e. >99.99%). The 2011 TFDT reviewed two technologies related to methyl bromide²⁰. This DRE would be relevant to the destruction step of any multi-step process. No decision was made by the parties related to a destruction criterion for methyl bromide. For some destruction technologies (e.g. plasma arc), the presence of bromine may impact on process parameters and molecular bromine may be formed, which is difficult to remove from exhaust gases.

Destruction of methyl bromide can occur for reasons different to those for other ODS, e.g. minimising the health effects of toxic methyl bromide atmospheric emissions from fumigation processes to the surrounding environment. However, when assessing methyl bromide destruction technologies for approval under the Montreal Protocol, it is important to remember that this assessment is not for health reasons but for the purposes of meeting Montreal Protocol reporting obligations, if that is a desired outcome. Emissions reduction through methyl bromide destruction at a DRE of >99.99% would take normal fumigation concentrations to below typical threshold limit values (TLVs) but possibly above many jurisdictions' environmental limits.

Methyl bromide is also very different chemically from other ODS. Most halons and chlorofluorocarbon ODS are chemically stable and relatively non-toxic to humans. In contrast, methyl bromide is in use as a fumigant because of its toxicity, and its inherent high chemical reactivity (and as compared to CFCs, HCFCs and HFCs). Methyl bromide is easily attacked by nucleophiles, such as reactive oxygen, sulphur and nitrogen groups (e.g. –OH, –SH and –N)

2; Tsang, W., Burgess Jr., D. R., and Babushok, V. (1998) *On the Incinerability of Highly Fluorinated Organic Compounds, Combustion Science and Technology*, 139:1, 385-402; The available data allows the conclusion that HFC-23 is the most thermally stable HFC.

¹⁹ The relevant text of the Decision for methyl bromide is as follows:

1. To request the Panel and the relevant technical options committees, in consultation with other relevant experts, for consideration at the thirty-first meeting of the Open-ended Working Group and with a view to possible inclusion in the Montreal Protocol handbook:

a. To evaluate and recommend the appropriate destruction and removal efficiency for methyl bromide.

²⁰ An Argon plasma arc technology was reviewed by the 2011 TFDT (High Potential) (and also in the 2014 CTOC Assessment Report). This stated that “its DRE is over 99.6% with 2-3% of methyl bromide recovered. Brominated dioxins and furans were detected in the emissions. The technology remains as ‘not determined’ for methyl bromide in the list of approved technologies. The second technology reviewed by the 2011 TFDT is described as adsorption of methyl bromide on activated carbon and subsequent destruction by chemical, biological or thermal means. Since the technology is not linked with any specific destruction technology, the Task Force did not believe that the submission could be considered within the scope of an assessment of destruction technologies.

in solution, giving methylated products and bromide ion. This reactivity allows simple low temperature destruction technologies to be developed, without the risks of production of toxic dioxins/furans. Methyl bromide is also easily attacked by radicals at relatively low temperatures, such as with ozone or catalytic combustion.²¹

2.4.1.1 Quantities of methyl bromide destroyed

While there are currently no approved technologies for methyl bromide destruction, methyl bromide destruction has been reported to the Ozone Secretariat under Article 7 data reporting. Data has been incomplete, but cumulatively, between 1996 and 2016, 938 tonnes of methyl bromide destruction were reported by six Parties²², and with destroyed quantities being reported, by one or more Parties, each year since 2005.

In addition, the 2010 TEAP Progress Report Volume 2 noted that the United States had destroyed 10,531 tonnes of methyl bromide between 1996 and 2003²³. Furthermore, the 2016 Toxics Release Inventory²⁴ shows a total of 112.6 tonnes of methyl bromide releases as fugitive and stack releases in the United States, with 1,499.8 tonnes destroyed on-site in the category ‘Chemical Industry’, with none reported from the ‘Food’ sector. In 1994, the Food sector had reported venting of 209 tonnes, while the Chemical Industry vented 1006 tonnes, recycled 350 tonnes and destroyed 85 tonnes²⁵. Details of the recycling and destruction processes were not given.

2.4.1.2 Destruction technologies used for methyl bromide

The 2010 and 2014 MBTOC Assessment reports, and the United States’ submission in response to this decision (Decision XXIX/4), discuss methyl bromide destruction and the technologies used.

Bulk methyl bromide destruction technologies

For the destruction of bulk methyl bromide, the United States’ submission stated that two commercial destruction facilities destroyed methyl bromide in the 2010 to 2016 period using:

- Gas/Fume Oxidation
- Rotary Kiln Incineration

In addition to those facilities that destroy ODS commercially, some companies destroyed methyl bromide on-site from 2010 to 2016, either as a by-product of manufacture or when it is used as raw material in a manufacturing process. The technologies used by some facilities were not disclosed, but the destruction technologies reported to be used are:

²¹ Jonathan Banks, MBTOC member, personal communications, March 2018.

²² Brazil, Czech Republic, France, Germany, The former Yugoslav Republic of Macedonia, United States of America

²³ UNEP/OzL.Pro/Workshop.3/INF/1, 26 June 2009, “ODS Destruction in the United States of America and Abroad (May 2009), Prepared by ICF International for U.S. EPA’s Stratospheric Protection Division”: Table 10: Reported Kilograms of ODS Destroyed by Type, as Reported in TRI (1991 – 2003).

²⁴ Toxics Release Inventory 2016, <https://www.epa.gov/toxics-release-inventory-tri-program>, accessed March 2018.

²⁵ Toxics Release Inventory, <https://www.epa.gov/toxics-release-inventory-tri-program/tri-basic-data-files-calendar-years-1987-2016>, accessed March 2018.

- Fume/Vapour (conventional thermal incineration)
- Other Incineration/Thermal treatment
- Rotary Kiln with Liquid Injection Unit
- Other Rotary Kiln

The 2010 TEAP Progress Report noted that catalytic oxidisers were one of the destruction technologies used.

Further information on emissions data for dioxins/furans, CO, particulates, and HBr/Br₂, applicable to the commercial hazardous waste facilities, would be needed for the 2018 TFDT to evaluate if Rotary Kiln and Gas/Fume Oxidation could be recommended for approval for methyl bromide destruction. In addition, further information would be required for those facilities that destroy methyl bromide as a by-product if they were to be assessed.

Methyl bromide capture and/or destruction immediately after fumigation use

In the context of fumigation, methyl bromide destruction can occur as part of a multi-step process, where methyl bromide is used for fumigation, extracted, and then destroyed. Methyl bromide can also be exhausted after fumigation, collected/captured (e.g. by adsorption onto activated carbon), and then processed, reused and/or disposed. In both cases, the methyl bromide is recovered from the fumigation chamber prior to destruction, reuse or disposal.

Methyl bromide during fumigation is used at diluted concentrations for pre-plant soil (20-100 g/m²) and commodity and structure fumigation (typically 24-128 g/m³), where a significant amount (e.g. over 20%) of methyl bromide can be destroyed naturally during the fumigation process and a further quantity lost as fugitive emissions. Losses during commodity and structure treatments can be substantial²⁶. The methyl bromide remaining in the head space of a chamber or structure after fumigation can be either extracted and captured or extracted and destroyed. However, the desorption of methyl bromide from the commodity/structure over time, and other issues related to the fumigation process, lead to inefficiencies in the recovery of the methyl bromide. Several technologies, which use either processes described above, are available or being evaluated for commodity and structural fumigations, although none are effective for soils.

The practices associated with methyl bromide fumigation need to be taken into account when considering whether a technology can demonstrate methyl bromide destruction that is acceptable from the standpoint of minimising emissions to the atmosphere. While methyl bromide can be recovered after fumigation, the losses during commodity and structure treatments can be substantial, and removal of the remaining methyl bromide from the fumigation can be an inefficient process. For this reason, the DRE of methyl bromide for a multi-step fumigation, extraction, and destruction process needs to consider the efficiency of the extraction and destruction process together. While the DRE of the destruction step should be at least 99.99% to minimise exhaust emissions (as for concentrated sources, and as for other ODS), the 2018 TFDT considers a lower DRE may be more appropriate for the

²⁶ Losses can occur at a number of points in the process: 1) fugitive loss before and during application from the supply cylinder; 2) fugitive loss (leakage) from the during the exposure period; 3) reversible physical sorption on the treated commodity, materials and enclosure fabric; 4) irreversible chemisorption on to reactive components of materials within the enclosure; 5) venting at the end of the exposure. Most of these losses can be minimised, but not eliminated, with good practice. The loss of methyl bromide varies widely with individual circumstances. With best practice, weakly absorbing treated materials and favourable conditions, more than 50% of applied dosage can remain in the gas phase at end of exposure.

combined extraction/destruction steps for processes where there are inherent inefficiencies in the recovery of methyl bromide from the fumigation chamber.

Methyl bromide can be exhausted directly into a destruction system or, as stated in the 2014 MBTOC Assessment Report, a number of methods have been investigated or developed to capture methyl bromide after fumigation operations. Capture on activated carbon was reported as the main system in full-scale commercial use. The captured methyl bromide can be recovered in liquid or gaseous form, and then either destroyed, e.g. by incineration, or converted into inert products or made available for reuse. MBTOC reported that various technical options were being assessed at that time. Without capture and/or destruction, the methyl bromide used for fumigation would be emitted directly to atmosphere.

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

With specific regard to methyl bromide from fumigation, the DRE, as defined by MBTOC in 2006, is only a measure of the destruction process itself²⁷. The September 2006 TEAP Report on 2006 Critical Use Nominations: Final Report²⁸ contains submissions reported under Decision XVII/11 from Australia and the United States on the operating efficiencies (DE, DRE, RDE²⁹) for fumigation, recovery and destruction, as part of a multi-step process. The

²⁷ UNEP 2006 Report of the Methyl Bromide Technical Options Committee, Assessment Report 2006, pg. 82.

²⁸ Report of the UNEP Technology and Economic Assessment Panel, Evaluations of 2006 Critical Use Nominations for Methyl Bromide and Related Matters, Final Report, September 2006, Chapter 4, pg. 103 and Table 11. Operating efficiencies and costs per kg of methyl bromide destroyed for systems submitted under Decision XVII/11 summary.

²⁹ According to the Report of the UNEP Technology and Economic Assessment Panel, Evaluations of 2006 Critical Use Nominations for Methyl Bromide and Related Matters, Final Report, September 2006, Chapter 4 (see also MBTOC Assessment Reports 2006, 2010, 2014): "Technically, the recapture and destruction of methyl bromide from fumigations has similarities with the recapture and destruction of CFCs from foams. Both are dilute sources. Both suffer losses between their application or discharge from the concentrated supply to the time where recapture may be carried out in practice. In one key aspect recapture of used methyl bromide is much less difficult than recapture from used foams. Used methyl bromide is held in the sealed fumigation chamber ready for convenient recapture; used foams have to be gathered and transported to a recapture or destruction facility.

The efficiency of recapture/destruction can be described in several ways. For dilute methyl bromide sources, the same general concepts may be applied as for dilute CFC sources. These are the overall Destruction Efficiency (DE), the Recovery and Destruction Efficiency (RDE) and the Destruction and Removal Efficiency (DRE). Decision XVII/11 specifically requests information on DRE. These various measures of efficiency of destruction, and thus ozone protection, are defined (TEAP 2002, 2005) thus:

- Destruction Efficiency (DE) is determined by subtracting from the mass of a chemical fed into a destruction system during a specific period of time the mass of that chemical that is released in stack gases, fly ash, scrubber water, bottom ash, and any other system residues and expressing that difference as a percentage of the mass of the chemical fed into the system.
- Destruction and Removal Efficiency (DRE) has traditionally been determined by subtracting from the mass of a chemical fed into a destruction system during a specific period of time the mass of that chemical alone that is released in stack gases and expressing that difference as a percentage of the mass of that chemical fed into the system.
- Recovery and Destruction Efficiency (RDE) is given by the quantity of the chemical destroyed in the destruction system as a percentage of that present in situ prior to the start of the destruction system. This measure includes losses in segregation, decommissioning, mechanical recovery and incineration or other destruction process.

various efficiencies reported were >88% to 99.9%. However, the DE for the carbon-based systems, at least, are based on the assumption that the destruction system used (thiosulfate washing or incineration) is 100% efficient and that there are no inadvertent losses during the destruction process. Measurements in support of this assumption were not supplied. The capture technology³⁰ alone reviewed by the 2011 TFDT achieved a recovery rate of 96.02% over an extended period (16 months).

Destruction systems for methyl bromide following fumigation, proposed or in commercial use, have included absorption into ethylene diamine, decomposition with ozone after adsorption onto activated carbon, absorption and destruction into sodium thiosulphate solution and relatively low temperature catalytic combustion.

A recent press release³¹ described the performance of commercial facilities in Florida and California, which use a two-stage system; capture and a destruction system. It uses activated carbon adsorption followed by an inline thiosulfate scrubber that chemically destroys over 94% of the methyl bromide collected.

In conclusion, for methyl bromide, the DRE of the destruction step alone should be at least 99.99% to minimise exhaust emissions (like for concentrated sources, and for other ODS). However, at present, there are two key approaches used to destroy methyl bromide following fumigation that could potentially be assessed against a lower efficiency criterion. Therefore, the 2018 TFDT considers a lower efficiency may be more appropriate for the combined extraction/destruction steps due to inefficiencies expected in the recovery of methyl bromide from the fumigation chamber.³²

With specific regard to methyl bromide from fumigation, the DRE is a measure of the recapture/destruction process itself, while the DE is a measure of the complete process. The DE includes losses from leakage and reaction on the commodity, as well as inefficiencies in removing the substance (methyl bromide) from the fumigation enclosure for input to the recapture/destruction system. Leakage losses will be emissions to the atmosphere and thus ODS emissions not controlled by a destruction process.”

³⁰ Nordiko Quarantine Systems Pty Ltd described as adsorption of methyl bromide on activated carbon and subsequent destruction. TEAP May 2011 Progress Report.

³¹ Marlton, N.J., July 13, 2016 /PRNewswire/ -- Value Recovery, Inc. (VR), a company supplying emission controls to the fumigation industry, announced today that it achieved an unprecedented milestone for controlling methyl bromide used to kill invasive insects hitchhiking on imported and exported goods. <https://www.prnewswire.com/news-releases/destruction-of-ozone-depleting-methyl-bromide-used-for-imports-and-exports-300298291.html>, accessed March 2018.

³² The 2002 TFDT defined a DRE for foam destruction based on what could be achieved for a recovery step for the foam blowing agent followed by destruction and concluded a DRE of 95% for foam destruction was appropriate. The 2002 TFDT determined that 95% of ODS could be recovered from foam. Once recovered, the ODS could be destroyed at a DRE of 99.99%. Following this approach, a lower efficiency for a multi-step fumigation process may also be required for methyl bromide.

3 Assessment of approved destruction technologies to confirm their applicability to HFCs

3.1 The assessment of approved destruction technologies

This chapter addresses paragraph 1a of decision XXIX/4:

“An assessment of the destruction technologies as specified in the annex to decision XXIII/12 with a view to confirming their applicability to hydrofluorocarbons”;

The current list of approved destruction processes is contained in the Annex to decision XXIII/12, as presented in Table 1-1.

Chapter 2 outlines the performance and technical capability criteria against which the approved technologies have been assessed to confirm their applicability to HFCs.

Data used to assess the approved destruction technologies applicability to HFCs came from a variety of sources, including parties’ submissions, publicly available information, and additional information requested from several parties and/or technology suppliers and owners.

3.2 Thermal Oxidation

Thermal Oxidation or Incineration is the use of controlled flame combustion to destroy substances in an engineered device. The technologies have been developed for the dedicated incineration of ODS, co-incineration of ODS along with other waste or whether the ODS are incinerated in a manufacturing process. For example, liquid injection incineration, gaseous flume oxidation, porous thermal reactor, and reactor cracking are integrated into process plants for halogenated by-product destruction, including for ODS and in most cases for HFCs, such as HFC-23.

Material of construction of equipment used in thermal oxidation facilities need to be compatible with acids, particularly HCl and HF especially due to HF formation in exhaust gases due to HFC destruction to avoid excessive downtime for maintenance.

3.2.1 Cement Kilns

This is a manufacturing process that produces Portland cement by heating calcium (usually limestone), silica and alumina (typically clay or shale) and iron (steel mill scale or iron ore) in cement kilns to temperatures of up to 1500°C. Under this intense heat, the raw materials blend to form a pebble-like substance called “clinker” which is later cooled and ground with a small amount of gypsum to produce cement. A comprehensive process description is provided in the 2002 TEAP report.

At the time of writing, no specific DRE or relevant emission data were available for assessment of HFC destruction against the performance criteria. **Cement Kilns are recommended as high potential for applicability to HFCs destruction, including HFC-23.**

There are reports of destruction of ODS foams in Cement Kilns; however, no data was made available to the 2018 TFDT.

3.2.1.1 Experience with HFC destruction

Two Parties have reported use of this technology for destruction of HFCs. Mexico has reported general emission data applicable to destruction of HFC-23 and HFC-134a in a cement kiln but no actual DRE values nor general emissions for pollutants have been

submitted for comparison against the performance criteria for this assessment. Japan has reported the use of cement kilns and lime calcination furnaces for the destruction of refrigerants generally without any specific emission performance or DRE data provided. No data was reported by Parties on quantities of HFCs destroyed.

3.2.1.2 Assessment of applicability to HFCs using performance criteria

At the time of writing, no specific DRE or emission data for assessment against the performance criteria were available.

3.2.1.3 Technical capability for destruction of HFCs

The technology offers relatively high throughput capacity for the destruction of ODS and HFCs. Reported throughput capacities of 50 kg/hr were recorded in Mexico for HFC-23 and HFC-134a. Japan reports throughputs applicable to F-gases generally in the range of 10-50 kg/hour. Limitations on throughput are assumed to be largely determined by the tolerance of the primary commercial process products to chlorine and fluorine content in the overall feed, given potential negative impacts on product quality and operation. The 2002 TFDT report indicates that conservative limits of 0.015% chlorine and 0.25% fluorine in the overall mass feed may apply, noting that this may increase on a facility specific basis, depending on the type of process and specific control parameters.

In terms of overall assessment of this technology, it is concluded that, in principle, cement kilns equipped with suitable feed infrastructure and modern air pollution control technology would likely be capable of destruction of HFCs meeting the performance criteria.

3.2.1.4 Other considerations

This technology utilizes manufacturing infrastructure already available in Non-Article 5 and Article 5 countries which may provide an option for destruction of HFCs in countries that might not have other national destruction options. Performance for destruction with HFCs (as with ODS) should be viewed as facility specific. A discussion of advantages and risks applicable to cement kilns is provided in the 2002 TFDT report and remains applicable.

3.2.2 Gaseous/Fume Oxidation

Gaseous/Fume Oxidation uses a refractory-lined combustion chamber with the flume stream heated by an auxiliary fuel such as natural gas. The 2002 TFDT report process description indicates typical combustion chamber temperatures of >1,100°C and 1-2 second resident times for destruction of CFCs. This technology is primarily applied within production facilities, typically fluorochemical manufacturing plants, for the destruction of by-products waste streams, and is designed for continuous operation as an integrated part of the overall plant process scheme or alternatively to take such material from storage facilities where practical.

A study of ODS destruction submitted by the United States³³, reported the use of this technology in that country at one commercial facility that is applied to a large range of CFCs and HFCs, as well as methyl bromide, and at 15 production facilities applied to CCl₄ and methyl bromide. Globally, it is also reported to be applied to a number of CDM projects for HFC-23 destruction.

³³ Submission from the United States, *ODS Destruction in the United States and Abroad*, Prepared for the U.S. EPA by ICF, February 2018.

Given the availability of information on demonstrated destruction of HFCs that meet the performance criteria, **Gaseous/Fume Oxidation is recommended for approval for applicability to HFCs destruction, including HFC-23, using HFC-23 data as a proxy for other HFCs.**

3.2.2.1 Experience with HFC destruction

The technology is reported to be in general use for HFC-23 destruction in fluorochemical production facilities, including CDM projects associated with HCFC-22 manufacturing plants.³⁴

3.2.2.2 Assessment of applicability to HFCs using performance criteria

Emissions data, obtained for a facility in the Republic of Korea, is provided in a CDM reference monitoring report from 2010 applicable to destruction of 123 tonnes of HFC-23. The report indicates a measured DRE of 99.9995% for HFC-23 destruction³⁵. This data supports the applicability of the technology to HFCs generally.

3.2.2.3 Technical capability for destruction of HFCs

Capacity information for HFC-23 is available in the CDM project design documents for HFC-23 destruction. As an example, an annual destruction capacity for a waste stream containing about 90% HFC-23 and 10% HCFC-22 is 660 tonnes annually, equivalent to approximately 80 kg/hr. The capacity required is determined by the instantaneous HCFC-22 production rate.³⁶ The 2002 TFDT report indicates a capacity range for CFC-12 and HFC-22 of 165 kg/hr at a facility in Japan which provides a further indication of potential capacity. However, it is anticipated that this would vary among facilities given design capacity would be plant specific. Systems are specifically designed to cope with the high fluorine content.

3.2.2.4 Other considerations

The application of the technology to HFCs destruction requires the materials of construction and design to be compatible with HF. As is the case with ODS destruction, dioxins/furans emissions should be carefully monitored, particularly for waste streams that contain chlorinated substances.

3.2.3 Liquid Injection Incineration

Liquid injection incinerators are usually single-chamber units with one or more waste burners, into which the liquid waste is injected, atomized into fine droplets, and burned in suspension. Tangential firing is frequently used to promote turbulent mixing. This is followed by a quench step, in which acid gases are recovered for neutralization. Exhaust gases are directed to an absorber, and dry and/or wet scrubbers.

³⁴ The CDM project website can be searched by project type and some versions of the monitoring reports contain emissions data as well as DRE data see <https://cdm.unfccc.int/Projects/registered.html>

³⁵ HFC Decomposition Project in Ulsan Monitoring Period Number: 20 (1st Monitoring Period in 2nd Crediting Period) 1 January 2010 to 31 July 2010. <https://cdm.unfccc.int/Projects/DB/JQA1094478108.13/CP/3HXJJOFD0FFDT9DDK7H1GA219RJRQ3/iProcess/SGS-UKL1325763645.23/view>

³⁶ See, for example, the Project Design Document for Project 0001: Project for GHG emission reduction by thermal oxidation of HFC 23 in Gujarat, India. <https://cdm.unfccc.int/Projects/DB/SGS-UKL1092749325.58/view>

The submission by the United States³⁷ indicates 3 commercial hazardous waste facilities employing this technology that are used for ODS destruction (CFC-11, CCl₄), and 11 applications of this technology in fluorochemical plants, either directly or in combination with rotary kiln incineration for the destruction of a wide range of ODS (CFC-11, CCl₄, HCFC-22, HCFC-141b, methyl bromide). Japan has reported data on process plant application for destruction of HFC-134a, HFC-410A, HFC-407C, HFC-404A, HFC-502, and HCFC-124, including a statement that supports meeting the performance criteria for DRE, as well as performance data from an unidentified facility.

The 2002 TFDT reported dioxins/furans emissions data that were higher than the performance criteria for ODS destruction. At the time of writing, no data were available to confirm dioxins/furans emissions for HFC-134a destruction, and no data were provided for HFC-23 performance or destruction, therefore, **Liquid Injection Incineration is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.2.3.1 Experience with HFC destruction

The only facility specific information reported by the Parties for this technology used for HFCs destruction, with supporting performance data available, relates to an unidentified facility in Japan, which is said to have been used for a wide range of HFCs. However, only data related to the destruction of HFC-134a was provided.

3.2.3.2 Assessment of applicability to HFCs using performance criteria

The only HFC destruction performance data presently available to undertake a performance criteria assessment has been supplied by Japan for an unidentified production facility with a capacity of 22 kg/hr, operating temperature of 1,249°C and residence time of 1.44 sec, with achieved DRE of 99.995%, for the destruction of HFC-134a. The 2018 TFDT is working to confirm reported dioxins/furans emissions, which were reported to be higher than the performance criteria. Emissions of other pollutants were within the performance criteria.

3.2.3.3 Technical capability for destruction of HFCs

The 2002 TFDT report indicates a capacity range for CFC-12 of 10 kg/hr at a facility in Japan. Current information reported by Japan indicates a capacity of 22 kg/hr. In general, it is anticipated that this would vary between facilities and may be constrained by the impact of higher fluorine content depending on facility specific design.

3.2.3.4 Other considerations

The application of this technology to HFCs should consider the impact of potentially higher acid gas generation associated with HFC combustion, particularly HF, on the operation of facilities, a factor that may limit destruction capacity.

The technology is able to handle a wide range of liquid or vapour wastes, has high turndown ratios and no moving parts. The technology is limited to treating wastes that can be pumped and atomized through the burner and is therefore well suited to handling HFCs generally.

3.2.4 Municipal Solid Waste Incineration

Solid materials including foams are transferred to a bin that feeds the waste onto a moving grate. Combustion air is drawn through the refuse pit, preheated and introduced into the

³⁷ Submission from the United States, *ODS Destruction in the United States and Abroad*, Prepared for the U.S. EPA by ICF, February 2018.

combustion zone through the moving grate. Hot gases from the combustion of the waste are typically cooled in a waste heat boiler and then cleaned, either by a spray drier and bag house or by a dry electrostatic precipitator. In order to obtain low dioxins/furans emissions, advanced air pollution control systems use spray-dry scrubbers with activated carbon injection, followed by bag houses. The combustors may be refractory lined or, as in many newer systems, the walls may be water-cooled to recover additional heat. More details are available in the 2002 TFDT Report.

Apart from the listing of the technology as used for refrigerant (assumed to be foam) destruction in Japan, at the time of its report, the 2018 TFDT was not aware of other information specific to this technology and its application to HFCs.

The overall assessment of this technology is that it is likely qualified for application to foam waste with HFC blowing agent to the same degree that it is assumed to apply to foam with ODS blowing agents.

No dioxins/furans emissions data were available to the 2018 TFDT at the time of this writing, and the dioxins/furans emissions were higher than the criteria for ODS as noted in the 2002 TFDT. **Municipal Solid Waste Incineration is recommended as high potential for applicability to destruction of dilute HFC sources (except for HFC-23), specifically for the destruction of HFC blowing agents in foam.**

3.2.4.1 Experience with HFC destruction

No HFC destruction data for dilute waste streams have been reported by the Parties or was otherwise available for assessment.

3.2.4.2 Assessment of applicability to HFCs using performance criteria

No HFC specific performance data is currently available to undertake a performance criteria assessment, although in principle it would be anticipated that the technology should meet the performance criteria, and to the same degree that it does for ODS in dilute sources such as blowing agents in foams.

3.2.4.3 Technical capability for destruction of HFCs

Information from Japan indicates that municipal incineration facilities offer capacities in the range of 10-120 kg/hr, a capacity that is assumed to apply to a dilute waste stream, such as foam. The 2002 TFDT Report indicates capacities of over 400 kg/hr for foams.

3.2.4.4 Other considerations

The application of the technology to dilute HFC wastes, such as foams, should consider the impact of potentially higher acid gas generation associated with HFC combustion, particularly HF, on the operation of facilities. Based on the original 2002 TFDT assessment, this technology requires sophisticated air pollution control systems to achieve pollutant emissions within the performance criteria, although this was achievable under strict operating conditions. These qualifications are also relevant for HFCs destruction and should be taken into consideration for the operation of specific facilities, particularly with respect to dioxins/furans, HC, HF and particulate emissions.

3.2.5 Porous Thermal Reactor

This is a combustion process using a natural gas/air fuel mixture in a relatively small combustion chamber or reactor (300 to 1100 mm in diameter) that, once it is heated, runs on an exothermic basis at quoted temperatures of up to 1,500°C. The reactor is filled with small carbon balls and the process forces the gas stream through small pores between the balls to

foster self-ignition and maximize complete combustion. Exhaust gas quenching involves a high-performance carbon liquid to air heat exchanger directly after combustion, which is said to exclude priority pollutant combustion gases. Acid residues such as HCl can either be collected for commercial use or neutralization. For HFC destruction, the process is also claimed to produce industrial grade HF.

While the commercial information from the technology proponent declares its applicability to HFCs, no specific material on the technology was submitted by Parties and has been obtained directly from a technology owner.

Porous Thermal Reactor is recommended for approval for applicability to HFCs destruction, except for HFC-23, for which no data was available for assessment. Porous Thermal Reactor is recommended as high potential for applicability to HFC-23 destruction.

3.2.5.1 Experience with HFC destruction

Information supplied by a technology owner elaborates on its application in the test and pilot plants for the destruction of a variety of chemicals including HFC-134a.

3.2.5.2 Assessment of applicability to HFCs using performance criteria

HFC performance data is applicable to HFC-134a, as supplied by the technology owner for the test and pilot plants it operates with the capacities noted above. The data applies to operating temperatures of >1,200°C and a residence time of 0.2 seconds and is stated as achieving 99.99% DRE. Emissions of other pollutants also met the performance criteria.

3.2.5.3 Technical capability for destruction of HFCs

Current facilities operate range from 10 -100 kg/hr which appears to be applicable to HFCs. No information was provided regarding specific commercial installations capacities for HFCs destruction.

3.2.5.4 Other considerations

This technology appears to offer a number of advantages including comparatively high energy efficiency, low energy requirements, rapid start up allowing flexible batch operation, being specifically designed using corrosion resistant materials (graphite), compact design, scalable for a variety of demand requirements, and offering recovery of industrial grade HCl and possibly HF.

3.2.6 Reactor Cracking

The process utilises a cylindrical, water-cooled reactor made of graphite, and an oxygen–hydrogen burner system that achieves reactor temperatures of up to 2,000°C. As such, it avoids the generation of a large flue gas volume with consequent large emissions of pollutants, as well as enabling the recovery of acid gases. The 2002 TFDT Report provides a more complete process description.

In the 2002 TFDT report, its application to HFC was reported although performance data provided was limited to the destruction of ODS. Although no data was reported for particulates this was estimated to be about 10 mg/Nm³ uncorrected for O₂, consistent with other low volume processes.³⁸ More recently, the technology has been reported to have been

³⁸ UNEP Report of the Technology and Economic Assessment Panel, Volume 3B, Report of the Task Force on Destruction Technologies, April 2002, Appendix A, page 73.

applied to a CDM project for HFC-23 destruction, which provide direct data supporting application to HFCs (as described below).

At the time of writing, no specific emission data for particulates were available for assessment against the performance criteria³⁹. **Reactor Cracking is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.2.6.1 Experience with HFC destruction

The 2002 TFDT Report make general reference to application of the technology to HFCs, and it has been identified as being a thermal oxidization technology applied to CDM projects, including SRF Limited in Rajasthan, India for the destruction of HFC-23, and at the Solvay plant referenced in the 2002 TFDT Report.

3.2.6.2 Assessment of applicability to HFCs using performance criteria

Emission performance data was obtained from the following sources: a) SRF's 13th CDM Monitoring Report⁴⁰ for the period January to March 2008, during which 252 tonnes of HFC-23 was destroyed that indicates a DRE of >99.99%, based on the guarantee provided by the technology supplier. In addition, the HFC-23 in the exhaust gases was measured and found to be below the detectable limit.⁴¹

Another technology supplier provided representative data for HFC-23 destruction applicable to a feed rate of 100 kg/hr, reactor temperature >1,200°C, residence time of 2 seconds and exhaust gas flow rate of 40 Nm³/hr, achieving a DRE of 99.99%.

Excluding particulates, emissions data provided met the performance criteria.

3.2.6.3 Technical capability for destruction of HFCs

The capacities quoted in the 2002 TFDT Report are 200/kg/hr. The capacity stated by one technology supplier is 100 kg/hr when applied to HFC-23.

3.2.6.4 Other considerations

This technology appears to offer a number of advantages, particularly for ODS and HFC destruction within production facilities, including high capacity, being specifically designed using corrosion resistant materials (graphite), high DRE potential, low emission performance (particularly for dioxins/furans), and offering recovery of technical grade acid gases.

Facility specific performance testing may be recommended as various operating conditions can significantly impact DRE and emissions.

³⁹ The 2002 TFDT provided an estimate of the particulates concentration for this process that meets the performance criteria.

⁴⁰ Project 0115 : GHG emission reduction by thermal oxidation of HFC 23 at refrigerant (HCFC-22) manufacturing facility of SRF Ltd, <https://cdm.unfccc.int/Projects/DB/DNV-CUK1129901204.48/view>

⁴¹ Project 0115: for example, see monitoring report 28 01/07/2012 to 30/09/2012 Appendix 4. As the concentration is below the limit of detection then a conservative value is applied leading to the >99.99% DRE, <https://cdm.unfccc.int/Projects/DB/DNV-CUK1129901204.48/view>

3.2.7 Rotary Kiln Incineration

Rotary kiln incinerators are refractory-lined rotating cylindrical steel shells mounted on a slight incline from horizontal. Most rotary kilns are equipped with an afterburner that ensures complete destruction of exhaust gases. Hydrocarbon fuels are typically used as an energy source. Rotary kilns are most frequently incorporated into the design of commercial incinerator facilities.

The European Union submission identifies rotary kilns as the technology used for destroying HFCs, with specific reference to HFC destruction at facilities in Poland, the Czech Republic and, Finland. The United States' submission reports that ODS destruction undertaken at 4 commercial facilities and 5 production plant facilities. Canada reported that all ODS and HFCs collected in its national program were being destroyed at two rotary kilns, one in Canada and one in the United States (although the 2018 TFDT believes that the United States facility used may be a fixed hearth incinerator). The quantity and types of HFCs destroyed from Canadian sources were provided (HFC-32, -125, -134a, -143a, -152a) for the years 2016 (127 tons) and 2017 (93 tons).

No HFC performance data is presently available to undertake a performance criteria assessment on rotary kiln incineration, therefore, **Rotary Kiln Incineration is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.2.7.1 Experience with HFC destruction

Experience with the application of rotary kilns for HFC destruction is reported in the European Union and North America, as reported by Parties. However, emission performance and DRE data for HFCs destruction have not been identified to enable an assessment against performance criteria.

3.2.7.2 Assessment of applicability to HFCs using performance criteria

No HFC performance data is presently available to undertake a performance criteria assessment on rotary kiln incineration, notwithstanding the reported application of the technology in Europe and North America where national regulations applied to such facilities would generally be more stringent than the TEAP performance criteria, and in the case of North America may require higher DREs. On that basis, in principle, it would be anticipated that the technology should meet the performance criteria, subject to facility specific qualifications, feed limits on chlorine and fluorine, and utilisation of higher combustion chamber temperatures and longer residence times.

3.2.7.3 Technical capability for destruction of HFCs

The capacities for ODS and HFCs will vary substantially depending on design size, tolerance to chlorine and fluorine content in the overall waste feed, and sophistication of the air pollution control system, particularly for dioxins/furans capture. Commercial units typically utilised for halogenated wastes have overall design capacities between 20,000 to 70,000 tonnes/year (3 to 10 tonnes/hr) although there are significant numbers of smaller units in commercial operation usually for non-halogenated wastes. Larger commercial units might indicatively have ODS, and potentially HFC, capacities of 10 to 200 kg/hour depending on the above factors. Recent test burn results for an MLF project in Colombia on a small (1 tonne/hr), but well equipped, commercial rotary kiln showed capacity limits for CFCs of 3-5 kg/hr, largely due to limitations on chlorine and particularly fluorine content in the feed, which were imposed to meet HCl and HF emission limits identical to the TEAP performance criteria, with DRE substantially exceeding 99.99%. This capacity is anticipated to be less for HFCs due to potentially higher HF emissions. The Colombian experience underlines an

overall caution that small rotary kilns are more prone to marginal or non-compliant performance when destroying ODS, and likely also HFCs.

3.2.7.4 Other considerations

Rotary kiln incineration is general technology applicable to the destruction of a wide range of wastes. More sophisticated variants of the technology tend to operate at higher temperatures (> 1,100°C) and longer secondary combustion chamber residence times (>1 sec). They are more likely to be equipped with advanced air pollution control systems and continuous environmental monitoring capability. These facilities are qualified more typically for the destruction of a wide range of halogenated waste as a co-disposed waste stream in relatively small quantities. The qualification of the technology is highly facility specific and may entail facility specific compliance test burns.

3.3 Plasma Technologies

Plasma arc destruction generally occurs by pyrolysis in an oxygen reduced environment at significantly higher temperatures than thermal oxidation. Plasma arc technologies tend to differ from each other in the type of inert gases employed, the method of heat generation to create the plasma, and the plasma torch/process containment vessel design. The pyrolysis process inherently offers high destruction efficiencies and can generally be assumed to have low exhaust gas emissions, particularly for dioxins/furans, although this requires process specific evaluation.

A concern raised in the literature is the “interconversion” of an ODS or HFC to another ODS or HFC. For example, under some conditions, the DRE of CFC-12 (CCl₂F₂) was measured as 99.9998% although this was accompanied by a conversion of 25% of the input CFC-12 to CFC-13 (CClF₃). According to the literature, replacing oxygen with steam reduces interconversion reactions to a negligible level. Interconversion should be taken into account when determining the DRE, according to the 2002 TFDT Report. It is recommended that destruction technologies should be operated to avoid interconversions and generation of other HFCs. It is further recommended that, in the absence of data, evaluation of interconversion be undertaken on a plasma arc technology specific basis.

Limitations associated with this technology are their relatively high energy input requirements, need for assured consumable supply in some cases, the general requirement for disposal of halide air emission treatment residues, and in some cases high technical support and maintenance requirements.

3.3.1 Argon Plasma Arc

This pyrolysis process mixes liquid or gaseous waste directly with an argon plasma jet (“in flight”) generated by an electric plasma torch. Argon prevents reactions with the torch components. Waste is rapidly heated in the reaction chamber (a flight tube) to about 3,000°C where pyrolysis occurs. Pyrolysis is followed by rapid alkaline quenching to less than 100°C, which limits the formation of dioxins/furans, followed by exhaust gas passing through a caustic scrubber prior to release. A recently introduced refinement of technology is understood to involve additional off-gas treatment.

Argon plasma arc is a well-established technology with more than 25 years of experimental and commercial experience in the destruction of CFCs, HCFCs, halons and HFCs. Worldwide it is understood that 12 units are operated commercially, largely for ODS and HFC destruction, including in Australia (4 units), Japan (4 units), Mexico (2 units), and the United States (2 units), with reported development projects in Canada and in the Russian Federation and/or Belarus associated with a GEF project.

The technology was specifically identified in the submission from Australia for application to HFCs, with supporting information provided by two operators/technology suppliers. Additional data applicable to HFC destruction in the United States uses the same technology. It was also identified in Mexico's submission as being applied to HFCs with limited supporting performance data. Canada identified a refrigeration servicing company that is in the process of developing a plant for ODS and HFC refrigerant destruction.

At the time of writing, either emissions data are higher than performance criteria (for CO) or are presently unavailable to undertake a performance criteria assessment, therefore, **Argon plasma arc is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.3.1.1 Experience with HFC destruction

As indicated above, the technology is understood to have application in at least three countries (Australia, Mexico and the United States), with Mexico and the United States facilities having available performance demonstration data for comparison with the performance criteria. It may also be utilized for refrigerant destruction in Japan. The HFC destruction applications identified are HFC-134a and HFC-23 in Mexico (the latter for a CDM project) and HFC-23 in the United States. Mexico reported 26.7 tonnes of HFC-134a destroyed over a 3-month period in 2015, and, with reference to one monitoring period for the CDM project, 52.4 tonnes HFC-23 during and 3-month period in 2009, with a reported DRE of >99.9999%⁴². Australia is understood to destroy a variety of HCFC/HFC blends, which currently contain 87% HFCs.

3.3.1.2 Assessment of applicability to HFCs using performance criteria

Performance data, while not entirely complete, were submitted for HFC destruction at facilities in Mexico and the United States for the destruction of HFC-134a and HFC-23. DRE > 99.99% was indicated in all cases. No dioxins/furans results were included in any case, and CO emissions were either not reported or higher than the performance criteria.

3.3.1.3 Technical capability for destruction of HFCs

The advertised capacities range from 70-150 kg/hr generally with the only actual data on HFCs as listed above being in the range of 60 to 90 kg/hr for HFC-23. The actual destruction rate for the CDM project is about 25 kg/hr for HFC-23 but this is about 90% purity and contains HCFC-22⁴³.

3.3.1.4 Other considerations

This technology is sized for placement at generation sources and/or at a commercial waste management service supplier's site. Technology suppliers noted the technologies high level of automation and minimum supervision requirements, as well as safety associated with rapid shut down capability to avoid losses of ODS or HFCs. The fact that it does not rely on co-disposal offers an advantage of being dedicated to niche speciality destruction applications. Interconversion to another CFC or HFC during destruction would need to be suppressed. Data available for a unit destroying CFC-12 demonstrates the elimination of interconversion reactions to CFC-13. However, no data for interconversion reactions associated with HFCs is available.

⁴² Project: 0151 Quimobásicos HFC Recovery and Decomposition Project, Monitoring Report: 31st December 2008 to 30th March 2009, <https://cdm.unfccc.int/Projects/DB/DNV-CUK1138260062.21/view?cp=1>

⁴³ Destruction rate calculated from actual destruction in a 3-month period. See the Monitoring Report for: 31st December 2008 to 30th March 2009, <https://cdm.unfccc.int/Projects/DB/DNV-CUK1138260062.21/view?cp=1>

Supporting utility infrastructure in the form of a robust electrical power supply and steam generation capability, as well as the availability of consumables, such as argon and caustic soda/sodium hydroxide is required. Disposal of exhaust gas treatment residuals is also a consideration. The technology is also relatively sophisticated, requiring access to high level technical support.

3.3.2 Inductively coupled radio frequency plasma

This technology involves a gaseous waste stream being fed through a plasma torch where temperatures of 10,000°C are achieved in a 185 kW inductively coupled radio frequency torch. The gases enter directly into the destruction reactor maintained at about 2000°C for about 2 seconds with exhaust gases being cooled and scrubbed with caustic solution to remove acid gases. This technology was approved for ODS destruction following a recommendation in previous TFDT reports, in which a complete process description is provided. At that time, it was stated that it had been used commercially in Japan since 1995 for destruction of ODS and HFCs.

Information submitted by Japan indicated that the operators that were originally understood to have used this destruction technology are no longer registered, and at the time of writing no data is available for its application to HFCs in Japan.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Inductively Coupled Radio Frequency Plasma for applicability for HFCs destruction.**

3.3.2.1 Experience with HFC destruction

No current information is available on application of this technology to HFCs, noting that it was reportedly used to destroy HFCs in Japan in 2002.

3.3.2.2 Assessment of applicability to HFCs using performance criteria

At the time of writing, no performance data for HFC destruction was available, which does not allow an assessment against the performance criteria.

3.3.2.3 Technical capability for destruction of HFCs

No current information is available that demonstrates capacities for this technology for HFC destruction. The 2002 TFDT report stated capacities in the range of 50-80 kg/hr for CFCs. This is based on the absence of any data specific to HFCs and information from Japan that facilities based on this technology are no longer registered for use.

3.3.2.4 Other considerations

No other considerations are noted.

3.3.3 Microwave Plasma

This plasma arc process involves feeding microwave energy into a specially designed coaxial cavity to generate a thermal plasma under atmospheric pressure. The coaxial design is claimed to promote plasma stability. Argon is used to initiate the plasma but otherwise the process requires no gas to sustain the plasma. A mixture of ODS and potentially HFCs with water vapour is fed to the plasma and is broken down at temperatures exceeding 6000°K with the formation of HCl, HF, CO and CO₂, followed by scrubbing of acid gases. It was approved for ODS destruction in the 2002 TEAP report in which a complete process description is provided. At that time, it was stated that it was being used commercially in Japan for destruction of CFCs.

Information submitted by Japan indicated that the destruction operators that were originally understood to have used this technology are no longer registered.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Microwave Plasma for applicability for HFCs destruction.**

3.3.3.1 Experience with HFC destruction

No information is available on application of this technology to HFCs.

3.3.3.2 Assessment of applicability to HFCs using performance criteria

No performance data is available that supports this technology meeting the criteria for HFC destruction.

3.3.3.3 Technical capability for destruction of HFCs

No current information is available respecting facility capacities for this technology. The 2002 TEAP TF report stated capacities in the range of 2 kg/hr. for CFCs.

3.3.3.4 Other considerations

No other considerations identified.

3.3.4 Nitrogen Plasma Arc

This process is similar to argon plasma arc except that nitrogen is used as the working gas. A thermal plasma generated by a DC plasma torch operating with water-cooled electrodes decomposes ODS and HFCs. Liquefied gases can be fed directly from their pressurized storage into the reactor, while liquids are first transferred to a pressure vessel and transferred with compressed air to an evaporator before being fed to the reactor. Gases from the plasma are fed to an oxidation tube in which ODS and HFCs are first reacted with steam to be decomposed into CO, HF and HCl. Air is introduced into the bottom of the tube to oxidize CO to CO₂. The temperature at the reactor nozzle is estimated to be in the range from 1400°K to 2500°K depending on the amount of steam appropriately supplied for desirable destruction. The reaction gas mixture is immediately quenched in a scrubber followed by absorption of acid gases using calcium hydroxide in water.

Information submitted by Japan indicated that the destruction operators that were understood to have used this technology are no longer registered in Japan. The technology is used for HFC-23 destruction in China.

Information available at the writing of this report indicated that reported particulate and HF emissions are above the performance criteria, therefore, **Nitrogen Plasma Arc is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.3.4.1 Experience with HFC destruction

The technology is utilized in China at HCFC-22 production facilities for the destruction of HFC-23 and emissions and DRE data is available on the CDM project website.

Representative amounts of HFC-23 destroyed at this plant over approximately 3-month periods in 2008 and 2009 were 52.62 tonnes and 42.45 tonnes respectively. No current information is available on application of this technology to HFCs in Japan historically noting the 2002 TFDT report indicates it has been applied to HFCs in Japan.

3.3.4.2 Assessment of applicability to HFCs using performance criteria

Performance data on the application at the above facility in China is available through periodic CDM project documents and monitoring report. Emission performance data for two monitoring periods and a recent test program on HFC-23 are available. The CDM project design document indicates that the design DRE is greater than 99.99%⁴⁴. Two monitoring reports were selected⁴⁵ and these provide data for all relevant emissions apart from particulates. The emissions data for HF and particulates are reported as higher than the performance criteria. Emissions for other pollutants meet the performance criteria. Based on the monitoring reports, the DRE appears to be >99.99%.⁴⁶

3.3.4.3 Technical capability for destruction of HFCs

The 2002 TEAP TF report indicated a capacity of 10 kg/hr for ODS destruction. The monitoring reports for the CDM project in China indicate a capacity for HFC-23 destruction of about 20kg/hr.

3.3.4.4 Other considerations

No other considerations are identified.

3.3.5 Portable Plasma Arc

This category of plasma arc technology was introduced in the 2011 TFDT report as an approved for ODS destruction and applied specifically to a small-scale unit (<2 kg/hr), marketed by a company in Japan. This process appears to be a variant of nitrogen plasma arc involving a DC based plasma torch and simple caustic scrubber for exhaust gases. A more detailed description of the process is not available, presumably for proprietary reasons.

In its current submission, Japan identifies this as a technology in use for HFC destruction and supplied some supporting performance data assumed to be applicable to HFCs.

Data were not available for HCl and dioxins/furans emissions at the time of writing of this report. **Portable Plasma Arc is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.3.5.1 Experience with HFC destruction

The technology is marketed as capable of destruction for refrigerant including HFCs. Data reported is assumed to apply to HFCs although the specific HFC to which it applies was not identified. Japan reported destruction of CFC-12, HCFC-22, HFC-134a, R-410A, and R-407C by this technology.

⁴⁴ See the Project Design Document page 9 for project 0767: HFC23 Decomposition Project at Zhonghao Chenguang Research Institute of Chemical Industry, Zigong, SiChuan Province, China, <https://cdm.unfccc.int/Projects/DB/JQA1163409153.5/view>

⁴⁵ Project 0767: HFC23 Decomposition Project at Zhonghao Chenguang Research Institute of Chemical Industry, Zigong, Sichuan Province, China, Monitoring Report 4 November 26, 2007 to February 25, 2008 and Monitoring Report 8 May 1, 2009 to July 25, 2009, <https://cdm.unfccc.int/Projects/DB/JQA1163409153.5/view>

⁴⁶ For Monitoring Reports 4 & 8 no HFC-23 was detected in the exhaust gases, which would imply DREs of 100%. For the purposes of conservative reporting required for CDM projects, the limit of detection values were applied, giving DREs of 99.988% and 99.984%. However, applying exhaust gas concentrations of HFC-23 at half the limit of detection would result in DREs of >99.99%.

There is at least one MLF ODS destruction demonstration project related to this technology and it has been utilized for demonstration purposes in several countries although no information is available on its sustained use.

3.3.5.2 Assessment of applicability to HFCs using performance criteria

Performance data made available by Japan on an unidentified HFC operating at 1,500°C and 0.13 second residence time. The DRE meets the performance criteria. However, data is not available for HCl and dioxins/furans emissions.

3.3.5.3 Technical capability for destruction of HFCs

The portable unit is specifically intended for application at the source of end of life ODS and HFC refrigerants, generated at locations like refrigeration servicing and reclaim centres. Given the setting, capacities are low (<2kg/hr) and tailored to anticipated periodic and relatively low generation rates.

3.3.5.4 Other considerations

In a discussion with Japan and the supplier, it was recommended that this technology be included under the category of Nitrogen Plasma Arc above.

3.4 Conversion (or non-incineration) technologies

As a general category of technology, conversion (or non-incineration) technologies are those that primarily rely on chemical transformation converting halocarbons sometimes to other saleable products (e.g. acids, vinyl monomers etc.).

3.4.1 Chemical Reaction with H₂ and CO₂

Thermal reaction of fluorocarbons with hydrogen and carbon dioxide results in an irreversible transformation to hydrogen halides (e.g. hydrochloric acid (HCl) and hydrofluoric acid (HF)) and/or halide salts. The destruction process is intended to produce and collect saleable bi-products (HCl and HF); minimizing HCl, HF, and CO levels in the stack (exhaust) gases.

Conversion data for a number of CFCs, HCFCs, and HFCs (including HFC-23) were provided by the technology supplier.

In the absence of emissions data demonstrating it meets the performance criteria for particulates and dioxins/furans, **Chemical Reaction with H₂ and CO₂ is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.4.1.1 Experience with HFC destruction

The technology supplier furnished data showing conversion of a number of HFCs, HCFCs, CFCs, and hydrocarbons, including HFC-23 and other HFCs.

3.4.1.2 Assessment of applicability to HFCs using performance criteria

The technology owner has provided test data for the conversion of a number of CFCs, HCFCs, and HFCs. The data shows that the process meets the performance criteria for HF, HCl, and CO emissions. The technology owner reports that the DRE is 99.99% or greater and that reported emissions are below the TEAP performance criteria; however, not all requested emissions data was provided.

3.4.1.3 Technical capability for destruction of HFCs

Although the process was described in 2011 as semi-commercial, the technology supplier reported to the 2018 TFDT that it intends to have fully commercial operations utilizing this process in late 2018 or early 2019. A demonstration project was approved by the Executive Committee in 2017 with UNDP as the implementing agency.

This technology has reportedly been tested at a throughput rate of 7kg/hr.

3.4.1.4 Other considerations

Technology owner reports that the conversion unit is a self-contained system and no caustic is needed for neutralization for HF and HCl, which are collected and sold⁴⁷.

3.4.2 Gas Phase Catalytic De-halogenation

The gas phase catalytic de-halogenation process destroys CFCs over a proprietary metal oxide catalyst at 400°C, at atmospheric pressure. The HCl and HF produced are absorbed in a lime solution.

Japan provided the following data related to HFC destruction following a request for information. The data is not from the same system for which data was provided in earlier reports referencing its previous application to ODS in the 2002 TFDT report. However, it appears to be a similar process falling into this general category. Japan reported that CFCs, HCFCs and HFCs were destroyed by this process, including HFC-134a, HFC-245fa, R-404A, R-407C, R-407D, R-407E, R-410A, R-R-507A, R-417A and R-508A. HFC destruction data was provided by Japan.

No dioxins/furans emissions data for HFCs destruction were available to the 2018 TFDT at the time of writing. The 2002 TFDT report noted that the TFDT believed that the dioxins/furans emissions would be comparable to those from rotary kilns, although also had no actual emissions data available. **Gas Phase Catalytic De-halogenation is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

3.4.2.1 Experience with HFC destruction

Approximately 10 metric tons per year have been destroyed by this process annually, including HFC-134a, HFC-245fa, R-404A, R-407C, R-407D, R-407E, R-410A, R-507A, R-417A and R-508A.

3.4.2.2 Assessment of applicability to HFCs using performance criteria

The DRE reported is 99.99%. A flue gas volume of 73.2 Nm³/h was estimated for a system destroying 4 kg/h, with emissions below the performance criteria except that it is noted that no dioxins/furans emission data is available.⁴⁸

⁴⁷ <http://www.midwestrefrigerants.com/> shows simulation of conversion process and collection of by-products

⁴⁸ The 2002 TFDT Report stated that it was claimed by the technology supplier that no dioxins or furans are produced in the process, although the process operates at a temperature that would generally result in the formation of PCDD/PCDFs. "PCDD/F emissions may be expected to be comparable to those from rotary kilns."

3.4.2.3 Technical capability for destruction of HFCs

At the time of writing, the technical capability relating to destruction of HFCs has not been reported. The 2002 TFDT reported that the process had been demonstrated to successfully destroy CFCs, PFCs, and PCBs at capacity of 1 kg/h.

3.4.2.4 Other considerations

At the time of writing, no other considerations were specifically reported for this process.

3.4.3 Superheated steam reactor

In the super-heated steam reactor process, decomposition of halocarbons takes place in the gaseous phase at elevated temperatures. Halocarbons, steam, and air are first mixed and then preheated to around 500 °C, before being fed into a tubular-type reactor, whose wall is electrically heated at 850-1000 °C. The decomposition, mainly by hydration, produces HF, HCl, and CO₂. The exhaust gas is led to a scrubber cooler where the exhaust is quenched by washing with a Ca(OH)₂ solution and the acids are neutralized. As a result of the quenching of the exhaust, the concentrations of dioxins/furans are minimized. This technology may be viewed by some as a thermal oxidation technology. Additional information was provided by the Japanese government and a technology owner.

In the absence of emissions data demonstrating it meets the performance criteria for particulates, **Superheated Steam Reactor is recommended for high potential for applicability to HFCs destruction, including HFC-23.**

3.4.3.1 Experience with HFC destruction

Japan has a commercial facility and provided data through the Japanese government. The process was reportedly used to destroy HFCs as early as 2002, as noted in the 2002 TFDT report. The installations of the superheated steam reactors were installed in 11 sites in Japan as captive destruction facilities.

This technology has reportedly been tested at a throughput rate of 12.4 kg/hr.

3.4.3.2 Assessment of applicability to HFCs using performance criteria

It appears that the Superheated Steam Reactor meets the minimum qualifications for both DRE and dioxins/furans emissions, but does not meet the criteria for particulates, according to the data reported at facilities in Japan and in China⁴⁹.

Two sets of data were reported for facilities in Japan and China. In one case, the DRE was reported as being greater than 99.99% while in the other case, no DRE was provided. No dioxins/furans data were reported in one case, and in the other they were reported as below the TEAP criteria.⁵⁰ Particulate emissions were not reported in one case and reported as higher than the performance criteria in another.

⁴⁹ Project 0193: HFC23 Decomposition Project of Zhejiang Juhua Co., Ltd, P. R. China, <https://cdm.unfccc.int/Projects/DB/DNV-CUK1135255248.44/view>

⁵⁰ Project 0193: see for example Monitoring Report 8: Dec 31, 2007 to Apr 30, 2008, <https://cdm.unfccc.int/Projects/DB/DNV-CUK1135255248.44/view>

3.4.3.3 *Technical capability for destruction of HFCs*

Japan and China have commercial facilities. The reactor has been used to destroy CFCs, HCFCs, and HFCs, including HFC-23. The installations of the super-heated steam reactors are installed at 11 sites in Japan as captive destruction facilities.

The application of this technology to HFC-23 destruction was broadly identified by China in its submission and in more detail in the Project Design Document and Monitoring Reports for the CDM Project. The quantity of HFC-23 reportedly destroyed in a monitoring period Dec 31, 2007 to Apr 30, 2008 was 181.33 tonnes, which equates to a capacity of about 60 kg/hr.

3.4.3.4 *Other considerations*

It is theoretically possible that superheated steam reactors might have even better performance with even higher operating temperatures.

Key advantages of the process are its high destruction efficiency and its low emissions of pollutants, which result from its high operating temperature, quench cooling of process gases and the low flue gas volume. The process is claimed to be easy to maintain because of its simple design, and safe to operate because it operates under negative pressure. The compact nature of the process permits its application in mobile destruction facilities and it is applicable to all but ODS-containing foams.

The key disadvantage is the need to dispose of halide salts resulting from neutralization of acid gases, although technology to recycle the CaF_2 would reduce this impact.

3.4.4 Thermal Reaction with Methane

This technology, which formed part of the submission from Australia, transforms fluorocarbons to fluorinated vinyl monomers, and was included on the list of approved technologies for ODS in 2011. The generic technology is currently being developed to treat HFC waste, including HFC-23. HFC destruction and performance data has been requested and reported as unavailable at the time of writing.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Thermal Reaction with Methane to confirm its applicability to HFCs destruction.**

3.4.4.1 *Experience with HFC destruction*

At the time of writing, information regarding the current or historical experience with HFC destruction using this technology has not yet been provided to the 2018 TFDT.

4 Assessment of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances

This chapter addresses paragraph 1b of decision XXIX/4:

“A review of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances;”

The destruction technologies discussed in this chapter are not included on the current list of approved destruction processes, contained in the Annex to decision XXIII/12 and as presented in Table 1-1.

Chapter 2 outlines the performance and technical capability criteria against which the destruction technologies have been assessed for possible inclusion on the list of approved technologies.

A number of destruction technologies, not included on the list of approved technologies, were mentioned in parties' submissions, either in a specific way with supporting data provided, or in a general way. The 2018 TFDT has made efforts to locate operating examples of these technologies and/or gather any available information where possible. For some destruction technologies, inadequate information was available to assess against the performance and technical capability criteria. It appears that some technologies are also no longer in commercial use.

Data used to assess the destruction technologies came from a variety of sources, including parties' submissions, publicly available information, additional information requested from several parties and/or technology owners, and previous assessments undertaken by TEAP, CTOC and TFDTs.

4.1 Thermal Oxidation

4.1.1 Electric Heater

This is a previously unidentified technology marketed by a Japanese company that was introduced in the submission by the Japan. Based on the material presented this appears to be a form of flameless combustion process operating in a reduced oxygen environment with reactor chamber heating supplied by electric heater elements. Operating temperatures inside a reactor are in the range of 900-1,200°C. Exhaust gases are passed through a wet scrubber prior to release. It appears to be a small self-contained modular unit with a foot print of approximately 1 m² and a height of 1.9 m. suggesting portability and application at smaller generation locations. A feed rate range of liquid HFC in the range of 100-300 l/min (as vapour). is noted in the supplied materials.

The submission by Japan in the form of presentation material from the supplier indicates that it is designed for HFC destruction with specific reference to HFC-32, HFC-41, HFC-125 and HFC-23. This material also indicates that it is produced commercially with deliveries 237 units in Japan, China, Singapore and Malaysia of which 74 are used for HFC-32 destruction and 55 are used for HFC-41 destruction. The remainder are used for HFC-23 by-product destruction.

Particulate emissions that meet the performance criteria are unavailable at this time. Additional DRE and more elaboration on the measurement of emission results would be

useful, noting the general reporting of nil results. **Electric Heater is recommended as high potential for applicability to HFCs destruction, including HFC-23.**

4.1.1.1 Experience with destruction

As noted above Japan has reported the application of this technology to a range of HFCs and provided specific performance data for HFC-125 and HFC-23, as described below. Commercial application is also reported for HFC-32 and HFC-41 without performance data. No data was reported on quantities of HFCs destroyed.

4.1.1.2 Assessment using performance criteria

Data on performance has been presented indicating DRE values >90% with graphical data indicating increasing DRE obtained with increasing reactor temperature and lower feed rates. In the case of HFC-125 DRE appears to approach 99% for reactor temperatures of 1,050°C and feed rates of 50 l/min. For HFC-23, DRE appears to exceed 99% and may meet the 99.99% requirement for reactor temperatures over 1,100°C and feed rates of up to 300 l/min.

4.1.1.3 Technical capability for destruction of controlled substances

The technology is declared as offering a throughput capacity for the destruction for HFC-23 of <2 kg/hr. As noted above, throughput appears to be limited by ensuring sufficient residence time in combination with a sufficiently high reactor temperature to obtain a compliant DRE.

4.1.1.4 Other considerations

The main advantages identified for this technology is what appears to be a relatively simple design, potential utility to destroy a variety of halogenated chemical wastes at source, safety associated with the absence of open flames and its small foot print and portability. The main identified disadvantages appear to be the need for operating discipline to ensure sufficiently low feed rates, associated longer resident times and high reactor temperatures to ensure sufficiently high DRE to meet performance criteria associated with the need to maintain higher operating temperatures. This may also negatively impact the operational life and reliability of reactor components, particularly the heater element.

4.1.2 Fixed Hearth Incinerator

Fixed Hearth Incinerators are commonly used in the United States for ODS destruction. The United States' submission provided the following description of this technology:

“Fixed hearth incinerators function similarly to rotary kiln incinerators but utilize fixed combustion chambers to destroy liquid wastes at temperatures ranging from 760 – 980°C. Solid wastes are placed in the primary combustion chamber where they are burned; the residue ash is removed from the primary chamber, and the by-product gases move into the secondary combustion chamber for further destruction. While fixed hearth incinerators are typically utilized to incinerate sewage sludge, medical wastes, and pathological waste, they can also be used to destroy ODS (ICF 2009a)¹.”

ODS processed at two facilities in the United States in 2010-2016 was reported to be CFC-11, CFC-12, CFC-113, CCl₄, HCFC-21, HCFC-22, HCFC-123. The maximum rate for a fixed hearth incinerator in Illinois is about 12,000 kg/hour of ODS.

¹ “ODS Destruction in the United States of America and Abroad”, prepared by ICF International for the U.S. Environmental Protection Agency, May 2009. Available online at: http://unep.ch/ozone/data_reporting/USA-Decision-XX-7-ODS-Destruction.pdf

No other data to assess the technology was provided. Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Fixed Hearth Incinerators** for possible inclusion on the list of approved destruction technologies. Also, the operating temperature appears to be lower than recommended in the European Union submission for destruction of HFCs.

4.1.3 Furnaces Dedicated to Manufacturing

The European Union submission provided the following description of this technology:

“All incineration and co-incineration (furnaces dedicated to manufacturing like: lime calcination furnace, electric furnace, etc.) technologies that comply with the following conditions:

- the temperatures in the oxidation chamber are equal or above 1200°C
- and the retention time of HFC is at least two seconds; the criteria of the destruction established by the Task force on destruction technologies in May 2002, are met; should be included in the list of approved destruction technologies.”

The 2002 TFDT screened out this type of technology (Blast Furnaces) and did not recommend for them approval for the list of approved destruction technologies. The 2002 TFDT described some promising results for DRE performance with one example of ODS destruction. However, there was no data for HF and no reference to destruction of any fluorine containing compounds, possibly due to concerns regarding the attack on furnace and stove refractory material due to HF. Most importantly, there did not appear to be any reported destruction of refractory compounds in blast furnaces at the time, which was thought to be due to the risk of product contamination by the waste. This raised a serious question for the 2002 TFDT about the technical capability of this destruction process. No new data is available to re-assess the technology.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Furnaces Dedicated to Manufacturing** for possible inclusion on the list of approved destruction technologies.

4.1.4 Thermal Decay of Methyl Bromide

The technical application submitted by one company (Australia) is described as a portable system for the capture and destruction of methyl bromide, at locations where it is used as a fumigant. The technology is based on destruction by thermal decay in a single pass destruction step, followed by conversion of the by-products through a water-based scrubbing system. This technology is more than a capture system alone and, based on the information provided, falls within the scope of an assessment as a destruction technology.

Further information has been requested in order to assess the technology adequately against the performance and technical capability criteria.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Thermal Decay of Methyl Bromide** for possible inclusion on the list of approved technologies. The TEAP would welcome data to enable it to complete an assessment of this technology.

4.2 Plasma technologies

4.2.1 Air Plasma Arc

The United States' submission provided the following description of this technology:

“Air plasma arc technology destroys CFCs and HCFCs by injecting them into a reaction chamber filled with air, liquefied petroleum gas, and water. The air is heated to about 1,300°C in a plasma generator, and the CFCs and HCFCs are broken down into H₂, H₂O, CO, CO₂, HCl, and HF. These resulting gases are cooled by water injection once they leave the reaction chamber and are scrubbed in a spray tower. The acids are washed out of the gases as calcium chloride and fluorspar by adding calcium hydroxide to the mixture. The gas is washed a second time in a packed bed to ensure that all acids are removed. The gas is released through a stack after passing through a wet electrostatic precipitator, the fluorspar is removed as sludge in a settling tank, and the calcium chloride solution is either used for dust reduction on gravel roads or is disposed (ICF 2009a).

An experimental air plasma destruction facility is located in Sweden destroying CFC-11, CFC-12, and HCFC-22 at a rate of about 300 kg/hour (ICF 2009a). This is the only known air plasma facility.”²

No other data to assess the technology was provided. Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Air Plasma Arc** for possible inclusion on the list of approved destruction technologies.

4.2.2 Alternating Current Plasma (AC Plasma)

The European Union submission provided the following description of this technology:

“The AC plasma is produced directly with 60 Hz high-voltage power but in other respects is similar to the inductively coupled RF plasma. The system is electrically and mechanically simple and is thus claimed to be very reliable. The process does not require argon and can tolerate a wide variety of working gases, including air or steam, as plasma gases and is claimed to be tolerant of oil contamination in ODS.”

The 2002 TFDT screened in this technology but did not recommend it for approval for inclusion on the list of approved destruction technologies, due to technical capability questions at the time. No data is available to re-assess the technology.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess AC Plasma Arc** for possible inclusion on the list of approved destruction technologies.

4.2.3 CO₂ Plasma

The European Union submission provided the following description of this technology:

“A high-temperature plasma is generated by sending a powerful electric discharge into an inert atmospheric gas, such as argon. Once the plasma field has been formed, it is sustained

² “ODS Destruction in the United States of America and Abroad”, prepared by ICF International for the U.S. Environmental Protection Agency, May 2009. Available online at: http://unep.ch/ozone/data_reporting/USA-Decision-XX-7-ODS-Destruction.pdf

with ordinary compressed air or certain atmospheric gases depending on the desired process outcomes.

The temperature of the plasma is well over 5,000°C at the point of generation into which the liquid or gaseous waste is directly injected. The temperature in the upper reactor is about 3,500°C and decreases through the reaction zone to a precisely controlled temperature of about 1,300°C.

A special feature of the process is the use of CO₂, which is formed from the oxidation reaction, as the gas to sustain the plasma.

The process has demonstrated high DREs with refractory compounds at a reasonably high demonstration rate. Mass emission rates of the pollutants of interest are low, primarily because of the low volume of flue-gas produced by the process.”

The 2002 TFDT screened in this technology but did not recommend it for approval for inclusion on the list of approved destruction technologies, due to particulates emissions higher than the performance criteria from a small-scale facility. No data is available to re-assess the technology, and it is understood that the technology owner has not pursued the technology beyond the pilot scale.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess CO₂ Plasma Arc** for possible inclusion on the list of approved destruction technologies.

4.2.4 Steam Plasma Arc

Steam plasma arc has been reported as a plasma destruction technology that injects CFCs, HCFCs, halons and PFCs into high temperature steam into a 1,300°C reactor. H₂ and CO are formed under the plasma plume, which are oxidized to CO₂ and H₂O through addition of small amounts of air in a separate zone. The gas stream is then rapidly quenched to prevent any reformation of dioxins/furans. The DRE was reported to be over 99.9999 percent when CFC-12 was applied. The CTOC assessed this technology and reported that it met the performance criteria for ODS destruction in its 2014 Assessment Report.^{3,4}

The 2018 TFDT has been unable to contact the technology owner to verify the earlier assessment for all of the performance criteria. Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Steam Plasma Arc** for possible inclusion on the list of approved destruction technologies.

4.3 Conversion (or non-incineration) technologies

4.3.1 Catalytic Destruction

This process is described as catalytic destruction of fluorocarbons at modest temperatures, using a catalyst to assist the conversion. It has been used to destroy fluorocarbons from foams.

³ Submission from the United States, *ODS Destruction in the United States and Abroad*, Prepared for the U.S. EPA by ICF, February 2018.

⁴ UNEP 2015 Report of the Chemicals Technical Options Committee, Assessment Report 2014, June 2015.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Catalytic Destruction** for possible inclusion on the list of approved destruction technologies.

4.3.1.1 Experience with destruction

Several commercial plants are operating in Sweden, Denmark, and the United Kingdom. An appliance recycling plant with ODS destruction capabilities is operating the technology in the United States according to the United States' submission.

4.3.1.2 Assessment using criteria

The 2011 TFDT assessed this destruction technology. In its assessment, the DRE claimed for the technology was 99.9%, which did not qualify the technology for approval under the performance criteria. The dioxins/furans performance was reportedly 0.2 ng ITEQ Nm³, which meets the criteria. On the basis of the reported DRE, the 2011 TFDT was unable to recommend it for approval, recommending it instead as high potential.

However, the United States' submission makes the general statement that this technology has been demonstrated to operate in accordance with the performance criteria. The 2018 TFDT does not have performance data to verify this assessment.

4.3.2 Chlorination/De-chlorination to Vinylidene Fluoride

The United States' submission provided information about the conversion of HFC-152a to vinylidene fluoride (or vinyl fluoride), which is a commercial chemical production process used at chemical production plants in the United States, where HFC-152a is either a feedstock or a chemical intermediate. The HFC-152a undergoes a chlorination and de-chlorination process to produce the vinylidene fluoride. This technology is part of a chemical manufacturing process and not a destruction process.

4.3.3 Solid Alkali Reaction

This technology destroys halogenated compounds by a vapour phase chemical reaction using an alkali metal vapour, alkaline earth metal vapour, or a combination of the two, in a heated reactor to produce mineralized or solid products. Information about this technology was provided on request by Japan.

In 2002, two technologies that appear to be similar were screened out by the 2002 TFDT: Chemical Reduction of ODS Using Metallic Sodium on a Solid Substrate and Aerosol Mineralisation of CFCs by Sodium Vapour Reduction developed by the National Institute of Standards and Technology, Maryland, USA.

Due to insufficient data being available at the time of writing, **the 2018 TFDT is unable to assess Solid Alkali Reaction** for possible inclusion on the list of approved destruction technologies.

4.3.3.1 Experience with destruction

At the time of the writing, information regarding the current or historical experience using this technology has not yet been provided to the 2018 TFDT.

4.3.3.2 Assessment using performance criteria

The DRE reported is 99.99% (an unspecified substance). A flue gas volume of 7Nm³/h was estimated for a system destroying 4 kg/h and estimates of the emissions were tabulated. It is

noted that no dioxins/furans or particulates emissions data is available. The converted substance was not identified in the information provided.

4.3.3.3 Technical capability for destruction of controlled substances

At the time of writing, information regarding the current or historical technical capability has not yet been provided to the 2018 TFDT.

4.3.3.4 Other considerations

The production of solid products, such as halide salts and particulate carbon, yields numerous advantages in the collection and disposal of the resulting products.

5 Recommendations for list of approved destruction technologies

The existing list of approved destruction technologies is shown in the table below in green. Recommendations relevant to this assessment are shown in the table below in red (for the assessment of the applicability of approved destruction technologies to HFCs and any other technologies for possible inclusion on the list of approved destruction technologies). Appendix 3 presents a written summary of the recommendations included in Chapters 3 and 4.

Technology	Applicability										
	Concentrated Sources									Dilute Sources	
	Annex A		Annex B			Annex C	Annex E	Annex F			Annex F
	Group 1	Group 2	Group 1	Group 2	Group 3	Group 1	Group 1	Group 1	Group 2		Group 1
Primary CFCs	Halons	Other CFCs	Carbon Tetrachloride	Methyl Chloroform	HCFCs	Methyl Bromide	HFCs	HFC-23	ODS	HFCs	
DRE*	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	99.99%	95%	95%	
Cement Kilns	Approved	Not Approved	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Gaseous/Fume Oxidation	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	Recommend for Approval	Recommend for Approval		
Liquid Injection Incineration	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Municipal Solid Waste Incineration										Approved	High Potential
Porous Thermal Reactor	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	Recommend for Approval	High Potential		
Reactor Cracking	Approved	Not Approved	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Rotary Kiln Incineration	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential	Approved	
Argon Plasma Arc	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Inductively coupled radio frequency plasma	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	Unable to Assess	Unable to Assess		
Microwave Plasma	Approved	Not	Approved	Approved	Approved	Approved	Not	Unable to	Unable to		

		Determined					Determined	Assess	Assess		
Nitrogen Plasma Arc	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Portable Plasma Arc	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Chemical Reaction with H ₂ and CO ₂	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Gas Phase Catalytic De-halogenation	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Superheated steam reactor	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	High Potential	High Potential		
Thermal Reaction with Methane	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	Unable to Assess	Unable to Assess		
Electric Heater								High Potential	High Potential		
Fixed Hearth Incinerator	Unable to Assess										
Furnaces								Unable to Assess			
Thermal Decay of Methyl Bromide							Unable to Assess				
Air Plasma Arc	Unable to Assess										
Alternating Current Plasma	Unable to Assess										
CO ₂ Plasma	Unable to Assess										
Steam Plasma	Unable to Assess										
Catalytic Destruction											Unable to Assess
Chlorination/De-chlorination to Vinylidene Fluoride	Not a destruction technology										
Solid Alkali Reaction	Unable to Assess										

*DRE - Destruction & Removal Efficiency

Appendix 1: Summary of submissions received from parties in response to Decision XXIX/4

Submissions were received from Armenia, Australia, Canada, China, European Union, Japan, Luxembourg, Mexico, United States, and Venezuela. TEAP has responded to requests for technology assessment and incorporated relevant information into this assessment. The substantive parts of parties' submissions will be compiled in a separate document, in pdf format. The document will be posted in time for the 40th Open-ended Working Group on the Ozone Secretariat website at the following link: <http://conf.montreal-protocol.org/meeting/oewg/oewg-40/presession/SitePages/Home.aspx>.

Party	Article 5 or non-Article 5 party	Destruction Technology Type Referenced in the Submission (Proponent, if mentioned)	Approved Technologies: Assessment for applicability to HFCs destruction	New Technology: Assessment for possible inclusion on list of approved technologies
Armenia	A5	No destruction technology – for information	N.A.	N.A.
Australia	Non-A5	Argon Plasma Arc (one company)	✓	
		Argon Plasma Arc (one company)	✓	
		Thermal Reaction with Methane	✓	
		Thermal Decay of Methyl Bromide		✓
Canada	Non-A5	Rotary Kiln Incinerator	✓	
		Argon Plasma Arc	✓	
China	A5	Nitrogen Plasma Arc	✓	

		Superheated Steam Reactor	✓	
European Union ⁶⁶	Non-A5	Incineration Technologies (Cement kilns, Gaseous/ Fume oxidation, Liquid injection incineration, Porous Thermal Reactor, Reactor cracking, Rotary kiln incineration)	✓	
		Incineration and co-incineration (furnaces dedicated to manufacturing, e.g. lime calcination furnace, electric furnace) technologies meeting the following conditions: <ul style="list-style-type: none"> the temperatures in the oxidation chamber are equal or above 1200°C and the retention time of HFC is at least two seconds; the criteria of the destruction established by the Task force on destruction technologies in May 2002. 		✓
		Plasma Technologies (Argon Plasma Arc, Inductively Coupled Radio Frequency Plasma, Microwave Plasma, Nitrogen Plasma Arc, Portable Plasma Arc)	✓	
		AC plasma (Alternating Current Plasma)		✓
		CO ₂ plasma arc		✓
		Non-incineration technologies (Chemical Reaction with H ₂ and CO ₂ , Gas Phase Catalytic Dehalogenation, Superheated Steam Reactor, Thermal Reaction with Methane)	✓	
Japan	Non-A5	Liquid Injection Incineration	✓	
		Electric Heater		✓
Luxembourg	Non-A5	No destruction technology – for information	N.A.	N.A.

⁶⁶ The European Union submission included a general summary of a range of destruction technologies reported to destroy ODS and/or HFCs.

Mexico	A5	Argon Plasma Arc	✓	
		Cement Kiln	✓	
United States ⁶⁷	Non-A5	Incineration Technologies (Cement kilns, Gaseous/Fume oxidation, Liquid injection incineration, Municipal Solid Waste Incineration, Porous Thermal Reactor, Reactor cracking, Rotary kiln incineration)	✓	
		Fixed Hearth Incinerator		✓ (ODS)
		Plasma Arc Technologies (Argon Plasma Arc, Inductively Coupled Radio Frequency Plasma, Microwave Plasma, Nitrogen Plasma Arc, Portable Plasma Arc)	✓	
		Air Plasma Arc		✓
		Steam Plasma Arc		✓
		Non-incineration technologies (Chemical Reaction with H ₂ and CO ₂ , Gas Phase Catalytic Dehalogenation, Superheated Steam Reactor, Thermal Reaction with Methane)		✓
		Chlorination/De-chlorination to Vinylidene Fluoride		✓
		Catalytic Destruction		✓
Venezuela	A5	Cement Kiln	✓	

⁶⁷ The United States' submission included a general summary of a range of destruction technologies reported to destroy ODS and/or HFCs.

Appendix 2: Decision IV/11, Annex VII: Suggested minimum standards for the operation of destruction facilities

At their Fourth Meeting in 1992, in decision IV/11, parties decided upon suggested minimum standards for the operation of destruction facilities:

2. To approve, for the purposes of paragraph 5 of Article 1 of the Protocol, those destruction technologies that are listed in Annex VI to the report on the work of the Fourth Meeting of the Parties which are operated in accordance with the suggested minimum standards identified in Annex VII to the report of the Fourth Meeting of the Parties unless similar standards currently exist domestically;

The suggested minimum standards contained in Annex VII to the Fourth Meeting report are presented in the table below. These standards were subsequently reviewed and updated by the 2002 TFDT, resulting in the 2002 technical performance criteria outlined in section 2.1.

Decision IV/11, Annex VII of the report of the Fourth Meeting of the Parties

<i>Pollutant</i>	<i>Stack Concentration</i>	<i>Comments</i>
<i>PCDD/PCDF</i>	<i><1.0* ng/m³</i>	<i>Frequency, method of sampling, and limit for the ODS that is being destroyed as recommended by national regulatory agencies</i>
<i>HCl</i>	<i><100 mg/m³</i>	
<i>HF</i>	<i>5 mg/m³</i>	
<i>HBr/Br₂</i>	<i>< 5 mg/m³</i>	
<i>Particulates</i>	<i>< 50 mg/m³</i>	
<i>CO</i>	<i><100 mg/m³</i>	<i>Continuous emission monitoring with 1 hour rolling average</i>
<i>ODS</i>		<i>Atmospheric releases of ODS shall be monitored at all facilities with air emission discharges (where applicable) to ensure compliance with the recommendations of the report of the ad hoc Technical Advisory Committee on Destruction Technologies.</i>

** Toxic equivalence using international method. Emissions limits are expressed as mass per dry cubic metre of flue gas at 0°C and 101.3 kPa corrected to 11% O₂.*

Appendix 3: Summary of Recommendations in Chapters 3 and 4

Appendix 3 summarises the written recommendations included in Chapters 3 and 4, with corresponding numbered heading references. In the Word version of this document, the headings below are hyperlinks to the relevant section in the body of the report.

3.2.1 Cement Kilns

At the time of writing, no specific DRE or relevant emissions data were available for assessment of HFC destruction against the performance criteria. Cement Kilns are recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.2.2 Gaseous/Fume Oxidation

Given the availability of information on demonstrated destruction of HFCs that meet the performance criteria, Gaseous/Fume Oxidation is recommended for approval for applicability to HFCs destruction, including HFC-23, using HFC-23 data as a proxy for other HFCs.

3.2.3 Liquid Injection Incineration

The 2002 TFDT reported dioxins/furans emissions data that were higher than the performance criteria for ODS destruction. At the time of writing, no data were available to confirm dioxins/furans emissions for HFC-134a destruction, and no data were provided for HFC-23 performance or destruction, therefore, Liquid Injection Incineration is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.2.4 Municipal Solid Waste Incineration

No dioxins/furans emissions data were available to the 2018 TFDT at the time of this writing, and the dioxins/furans emissions were higher than the criteria for ODS as noted in the 2002 TFDT. Municipal Solid Waste Incineration is recommended as high potential for applicability to destruction of dilute HFC sources (except for HFC-23), specifically for the destruction of HFC blowing agents in foam.

3.2.5 Porous Thermal Reactor

Porous Thermal Reactor is recommended for approval for applicability to HFCs destruction, except for HFC-23, for which no data was available for assessment. Porous Thermal Reactor is recommended as high potential for applicability to HFC-23 destruction.

3.2.6 Reactor Cracking

At the time of writing, no specific emission data for particulates were available for assessment against the performance criteria. Reactor Cracking is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.2.7 Rotary Kiln Incineration

No HFC performance data is presently available to undertake a performance criteria assessment on rotary kiln incineration, therefore, Rotary Kiln Incineration is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.3.1 Argon Plasma Arc

At the time of writing, either emissions data are higher than performance criteria (for CO) or are presently unavailable to undertake a performance criteria assessment, therefore, Argon plasma arc is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.3.2 Inductively coupled radio frequency plasma

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Inductively Coupled Radio Frequency Plasma for applicability for HFCs destruction.

3.3.3 Microwave Plasma

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Microwave Plasma for applicability for HFCs destruction.

3.3.4 Nitrogen Plasma Arc

Information available at the writing of this report indicated that reported particulate and HF emissions are above the performance criteria, therefore, Nitrogen Plasma Arc is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.3.5 Portable Plasma Arc

Data were not available for HCl and dioxins/furans emissions at the time of writing of this report. Portable Plasma Arc is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.4.1 Chemical Reaction with H₂ and CO₂

In the absence of emissions data demonstrating it meets the performance criteria for particulates and dioxins/furans, Chemical Reaction with H₂ and CO₂ is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.4.2 Gas Phase Catalytic De-halogenation

No dioxins/furans emissions data for HFCs destruction were available to the 2018 TFDT at the time of writing. The 2002 TFDT report noted that the TFDT believed that the dioxins/furans emissions would be comparable to those from rotary kilns, although also had no actual emissions data available. Gas Phase Catalytic De-halogenation is recommended as high potential for applicability to HFCs destruction, including HFC-23.

3.4.3 Superheated steam reactor

In the absence of emissions data demonstrating it meets the performance criteria for particulates, Superheated Steam Reactor is recommended for high potential for applicability to HFCs destruction, including HFC-23.

3.4.4 Thermal Reaction with Methane

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Thermal Reaction with Methane to confirm its applicability to HFCs destruction.

4.1.1 Electric Heater

Particulate emissions that meet the performance criteria are unavailable at this time. Additional DRE and more elaboration on the measurement of emission results would be useful, noting the general reporting of nil results. Electric Heater is recommended as high potential for applicability to HFCs destruction, including HFC-23.

4.1.2 Fixed Hearth Incinerator

No other data to assess the technology was provided. Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Fixed Hearth Incinerators for possible inclusion on the list of approved destruction technologies. Also, the operating temperature appears to be lower than recommended in the European Union submission for destruction of HFCs.

4.1.3 Furnaces Dedicated to Manufacturing

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Furnaces Dedicated to Manufacturing for possible inclusion on the list of approved destruction technologies.

4.1.4 Thermal Decay of Methyl Bromide

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Thermal Decay of Methyl Bromide for possible inclusion on the list of approved technologies. The TEAP would welcome data to enable it to complete an assessment of this technology.

4.2.1 Air Plasma Arc

No other data to assess the technology was provided. Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Air Plasma Arc for possible inclusion on the list of approved destruction technologies.

4.2.2 Alternating Current Plasma (AC Plasma)

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess AC Plasma Arc for possible inclusion on the list of approved destruction technologies.

4.2.3 CO₂ Plasma

Due to insufficient data that meets the performance criteria available at the time of writing, the 2018 TFDT is unable to assess CO₂ Plasma Arc for possible inclusion on the list of approved destruction technologies.

4.2.4 Steam Plasma Arc

The 2018 TFDT has been unable to contact the technology owner to verify the earlier assessment for all of the performance criteria. Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Steam Plasma Arc for possible inclusion on the list of approved destruction technologies.

4.3.1 Catalytic Destruction

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Catalytic Destruction for possible inclusion on the list of approved destruction technologies.

4.3.2 Chlorination/De-chlorination to Vinylidene Fluoride

The United States' submission provided information about the conversion of HFC-152a to vinylidene fluoride (or vinyl fluoride), which is a commercial chemical production process used at chemical production plants in the United States, where HFC-152a is either a feedstock or a chemical intermediate. The HFC-152a undergoes a chlorination and de-chlorination process to produce the vinylidene fluoride. This technology is part of a chemical manufacturing process and not a destruction process.

4.3.3 Solid Alkali Reaction

Due to insufficient data being available at the time of writing, the 2018 TFDT is unable to assess Solid Alkali Reaction for possible inclusion on the list of approved destruction technologies.