MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

SEPTEMBER 2018

VOLUME 1

DECISION XXIX/4 TEAP TASK FORCE REPORT ON DESTRUCTION TECHNOLOGIES FOR CONTROLLED SUBSTANCES (ADDENDUM TO THE MAY 2018 SUPPLEMENTAL REPORT – REVISION)

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The text of this report is composed in Times New Roman.

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Foreword

September 2018 TEAP Report

The September 2018 TEAP Report consists of five volumes:

***Volume 1**: Decision XXIX/4 TEAP Task Force Report on destruction technologies for controlled substances (Addendum to the May 2018 Supplemental Report – Revision)*

***Volume 2**: Decision XXIX/8 on the future availability of halons and their alternatives*

***Volume 3:** MBTOC CUN assessment report (final report)*

***Volume 4:** Response to Decision XXVI/5(2) on laboratory and analytical uses*

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

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Executive Summary

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. 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 TEAP Task Force on Destruction Technologies (2018 TFDT) published its initial report in early April 2018. The 2018 TFDT specified in that report additional information that would be helpful to its assessment. Additional information became available and, as a result, a Supplemental Report was prepared, considering the new information, and submitted to the 40th Open-ended Working Group, in accordance with decision XXIX/4.

The 40th Open-ended Working Group formed a contact group, and following those discussions, TEAP was requested to provide additional information for the Thirtieth Meeting of the Parties, including on CO_2 emissions associated with energy consumption.

This Addendum to the Supplemental Report updates with additional information:

- The assessment of destruction technologies approved under decision XXIII/12 to confirm their applicability to HFCs (paragraph 1a, decision XXIX/4);
- The assessment of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances (paragraph 1b, decision XXIX/4).

The assessment criteria remain unchanged from the April 2018 TFDT report. The Supplemental Report noted the objective approach taken by the 2018 TFDT for consistency, and some of the limits to data availability for consideration by the parties.

This Addendum Report describes in new detail only the assessments for those destruction technologies for which additional information was provided.

This Addendum Report also outlines a few additional observations of the 2018 TFDT in finalising its assessments (see Chapter 2 of this report), and information on energy consumption for a destruction technology chosen as an example owing to its higher energy intensiveness compared to other destruction technologies.

A summary table of recommendations is presented in Chapter 4. The 2018 TFDT has indicated where insufficient data was available to assess adequately the destruction technologies against the performance criteria for emissions and for technical capability. For completeness, a summary of the final findings from the assessment of all destruction technologies is presented in Appendix 1. A summary table of data available to assess destruction technologies for the Addendum to the Supplement Report is presented in Appendix 2.

This Revision to the Addendum Report updates the September 2018 version in order to incorporate additional information that had been overlooked during the assessment, and some minor factual corrections. For ease of reference, updates to the September 2018 version of the Addendum Report are highlighted in grey throughout this Revision version.

1 Introduction

1.1 Decision XXIX/4, the Supplemental Report, and the Addendum to the Supplemental Report

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-40), on an assessment of destruction technologies, as requested 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;*

The TEAP Task Force on Destruction Technologies (2018 TFDT) published its initial report in early April 2018 (the April 2018 TFDT report). A summary of the 2018 TFDT recommendations was set out in Appendix 3 of that report, including a number of cases where technologies were recommended as “high potential” or “unable to assess”, based on the technical information available at the time the report was prepared. The 2018 TFDT specified in the report additional information that would be helpful to its assessment.

On behalf of the TEAP and its 2018 TFDT, the Ozone Secretariat invited those parties[1] that had made submissions in response to decision XXIX/4 to submit any additional information by email to enable the 2018 TFDT to assess and determine whether to revise its recommendations and publish them through a supplemental report for OEWG-40. The 2018 TFDT followed up directly with several parties and/or technology suppliers/owners in an effort to collect missing data that would enable it to complete its assessments. Several parties and/or technology suppliers/owners provided additional information. As a result of the additional information that became available, a Supplemental Report was prepared,

[1] Armenia, Australia, Canada, China, the European Union, Japan, Luxembourg, Mexico, the United States, and Venezuela.

considering the new information, and submitted to OEWG-40, in accordance with decision XXIX/4.

OEWG-40 formed a contact group, and following those discussions, TEAP was requested to provide additional information for the Thirtieth Meeting of the Parties, including on CO_2 emissions associated with energy consumption of destruction technologies.

The 2018 TFDT worked entirely by email and other electronic means in completing its reports. The 2018 TFDT co-chairs express their gratitude to parties, technology suppliers/owners and task force members in providing their assistance.

1.2 This Report

Additional information was provided by Australia, Colombia, the European Union, Japan, and the United States. The 2018 TFDT has reviewed the information provided, and on the assumption that it is accurate data based on real measurements from destruction technologies during testing or under normal operation.

This Addendum Report updates with additional information:

- The assessment of destruction technologies approved under decision XXIII/12 to confirm their applicability to hydrofluorocarbons (HFCs) (paragraph 1a, decision XXIX/4)
- The assessment of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances (paragraph 1b, decision XXIX/4)

This Addendum Report also outlines information on energy consumption for a destruction technology chosen as an example owing to its higher energy intensiveness compared to other destruction technologies, and a few additional observations of the 2018 TFDT in finalising its assessments (see Chapter 2 of this report).

Only non-confidential information has been referenced in this report. Efforts have been made to withhold commercially sensitive information from publication, when this preference was indicated to the 2018 TFDT.

The assessment criteria remain unchanged from the April 2018 TFDT report. The Supplemental Report noted the objective approach taken by the 2018 TFDT for consistency, and some of the limits to data availability for consideration by the parties.

This Addendum Report describes in new detail only the assessments for those destruction technologies for which additional information was provided.

Other information in the April 2018 TFDT Report, such as background to the decision, the assessment criteria, and previous assessments of destruction technologies, are not repeated.

A summary table of recommendations is presented in Chapter 4. The 2018 TFDT has indicated where insufficient data was available to assess adequately the destruction technologies against the performance criteria for emissions and for technical capability. For completeness, a summary of the final findings from the assessment of all destruction technologies is presented in Appendix 1. A summary table of data available to assess destruction technologies for the Addendum Report is presented in Appendix 2.

2 Additional considerations regarding the assessment of destruction technologies and recommendations

This chapter outlines a few additional considerations made by the 2018 TFDT in finalising its assessments. Unless otherwise elaborated or clarified here, the assessment criteria remain unchanged from the April 2018 TFDT report and are not repeated here (see Chapter 2 of the April 2018 TFDT report).

The 2018 TFDT has taken an objective approach to its technical assessments and recommendations, as outlined in section 2.3 of the April 2018 TFDT report, to ensure internal consistency in its technology assessments and also consistency with previous assessments. Although the 2018 TFDT has actively sought to identify data to complete its assessments, including consulting with technology suppliers/owners, in some cases complete data has not been available for assessment against performance criteria for a number of reasons:

- Some technologies destroy mixed waste streams, and so emissions data specific to HFCs destruction may not be available for these technologies.
- Emissions testing of destruction technologies may be performed only on proxy chemicals, followed by continuous monitoring of the operating conditions to meet local requirements (e.g. measuring opacity as an indicator of particulate levels).
- Some previously approved ODS destruction technologies are no longer in operation, and data on HFC destruction was not available.
- In some circumstances, emissions testing has not been feasible.

Parties may wish to consider these limiting factors when deciding whether to approve, or not, technologies for their applicability for HFCs destruction, or for possible inclusion on the list of approved destruction technologies, based on the balance of available information.

2.1 Considerations for reduction of particulate matter and carbon monoxide when destroying refrigerants with contaminant oils removed or not present

Particulate matter is formed in the thermal destruction of halocarbons through incomplete combustion of carbon-based fuels (e.g. natural gas, coal, wood, gasoline) used in the incineration process, or where co-disposal with other wastes is involved from its combustion. In parts of the furnace where combustion is not complete, combustible components of organic compounds are burned off, leaving the incombustible particulate matter entrained in the flue gas if not removed by appropriate air pollution control devices prior to release.

In contrast, conversion technologies irreversibly transform halocarbons to smaller components (e.g. hydrofluoric acid) or to larger molecules (e.g. vinyl monomers) without introducing fuels into the process to create incombustible particulate matter, especially if oil contaminants have been removed through a traditional reclaim process.

Particulate emissions could be reduced for conversion technologies and might meet the particulate performance criterion for HFC destruction if oil contaminants have been removed through a standard refrigerant purification process and the HFC chemical meets standards for new products. However, it is suggested that particulate analysis is carried out, and may be mandatory under local requirements.

In addition, the reactor cracking process is classified as an incineration technology because it uses a controlled flame to destroy ODS in an engineered device. However, the process is very different than conventional incineration because of the use of hydrogen and oxygen, as fuel and oxidant, avoids the generation of a large flue gas volume with consequent large emissions of pollutants and also enables the recovery of acid gases. Particulate emissions could be reduced and might meet the performance criterion for HFC destruction if oil contaminants have been removed. However, it is suggested that particulate analysis is carried out, and may be mandatory under local requirements.

In a Cement Kiln demonstration project for ODS destruction, it was noted that particulates are controlled by a bag house, where dust and particles are collected, while other emissions are expected to comply with local government requirements. Those emissions levels are higher than the performance criteria for emissions that have been used by TFDTs. The 2002 TFDT noted that emissions from cement kilns are typically very high, but the addition of ODS is unlikely to have any or little additional effect on those emissions[2]. Many parties require stringent monitoring of hazardous emissions from Cement Kiln facilities as reported in the demonstration project[3].

Similarly, carbon monoxide is formed in the thermal destruction of halocarbons through incomplete combustion of carbon-based fuels and oils (e.g. oils used with refrigerants) when oxygen is present, but it is insufficient to fully oxidize all of the carbon present. For processes that have no oxygen present from the halocarbon due to contamination (e.g. oils, water, air), and that do not introduce oxygen containing process gases (e.g. oxygen, water, air, steam, carbon dioxide and some fuels), carbon monoxide cannot be formed and analysis for carbon monoxide is unnecessary. For example, HFC-23 that is destroyed by argon plasma arc that is linked to a production process, with no oxygen present, would not produce carbon monoxide during the pyrolysis process.

2.2 Assessment of the Impact of Destruction of Fluorocarbons on Greenhouse Gases

The TFDT was asked to consider energy consumption, by evaluating whether the benefit of destroying an HFC outweighs the carbon dioxide emitted from the energy source required to operate the facility. The specific example of interest to the contact group was the operation of a plasma arc facility when destroying an HFC. Plasma arc facilities are known to require significant energy consumption during operation.

HFC destruction is a "direct emission", while the carbon dioxide related to energy use is an "indirect emission". Indirect emissions are influenced by the energy source. For example,

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[2] Fluorine and chlorine input rates need to be carefully controlled and impose a destruction capacity limit on the cement kiln. The above referenced cement kiln, with a capacity of 5000 t/day of clinker, would be limited by the theoretical chlorine limit to about 50 kg/h of CFC-12, which is still a reasonable feed rate. Cement kilns are not specifically established to handle or burn CFCs and halon wastes. Necessary modifications require equipment for feeding ODS in a controlled manner and monitoring hazardous emissions. A major public concern generally in relation to cement kilns is the magnitude of mass emissions of pollutants, especially particulates and carbon monoxide. However, the destruction of ODS is expected to have little or no additional effect on these emissions. (2002 TFDT)

[3] United Nations Industrial Development Organization: Demonstration Project for Disposal of Unwanted ODS in Mexico 2017, referring specifically to NOM-040-SEMARNAT-2002 limits.

energy produced from hydroelectric power would have a very small greenhouse gas footprint; energy produced by a coal-burning power plant would have a large greenhouse gas footprint.

According to the 2002 TFDT Report, plasma arc destruction processes are, as a group, the most energy intensive destruction processes evaluated. Despite this, destruction using this technology is still found to result in a significant greenhouse gas benefit. As this technology is one of the most energy intensive processes, other less energy intensive destruction technologies will have even larger negative greenhouse gas footprints. The high GWP of HFCs gives the operation of destruction facilities a very large negative greenhouse gas footprint. An example from an argon plasma arc facility follows.

[4]Example: HFC-134a destruction at an argon plasma arc facility[5]

An argon plasma arc facility would require approximately 250 kWh of electricity for the destruction and cooling processes used to destroy 60 kg of HFC-134a. An additional 9.6 kWh of electricity is consumed in the production of 15 Nm^3 of argon, which is used in this process[6].

The total 260 kWh would result in indirect emissions of 0.179 CO_2 tonnes based on the average carbon intensity in Mexico of 0.689 kg CO_2/kWh [7]. The destruction of 60 kg of HFC-134a would prevent 85.8 CO_2 equivalent tonnes[8], resulting in a benefit of a net **reduction** in CO_2 equivalent emissions of 85.6 tonnes.

Even if the carbon intensity is higher (e.g. 0.927 kg CO_2/kWh from coal burning energy production, as noted in the World Bank Report "Understanding CO_2 Emissions from the Global Energy Sector")[9], the result is the same. The impact from energy consumption associated with operating any destruction technology is negligible compared to the reduction in greenhouse gas emissions due to the destruction of HFCs.

Further information on the indirect emissions due to a number of destruction technologies is available in monitoring reports for CDM projects for the destruction of HFC-23[10].

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[4] This grey highlighted box has been updated in the Revision to the Addendum Report.

[5] Clean Development Mechanism Project Design Document Form (CDM-PDD) Quimobásicos HFC Recovery and Decomposition Project: 2004

[6] Nahkla *et al*., 2012, "Environmental Impacts of Using Welding Gas", *The Journal of Technology, Management, and Applied Engineering*, vol. 28, no. 3, July 2012 – September 2012, pp.2-11.

[7] Intergovernmental Panel on Climate Change Special Report on Oceans and Climate Change, Table 3.5 Carbon dioxide intensities of fuels and electricity for regions and countries. The carbon intensity for Mexico is noted as 0.689 kg CO_2 /kWh.

[8] Assuming HFC-134a has a global warming potential of 1430, as in IPCC Assessment Report 4.

[9] Understanding CO_2 Emissions from the Global Energy Sector (World Bank Report) http://documents.worldbank.org/curated/en/873091468155720710/pdf/851260BRI0Live00Box382147B00PUBLIC0.pdf

[10] Monitoring reports can be accessed at https://cdm.unfccc.int/Projects/projsearch.html.

3 Assessment of destruction technologies for which new information was provided

3.1 Assessment of approved destruction technologies for applicability to HFCs

This section 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";

New information was provided to the 2018 TFDT and assessed for Liquid Injection Incineration. The summary assessments for all of the destruction technologies are contained in Appendix 1.

3.1.1 Liquid Injection Incineration

DRE (99.995%) and emissions data are available that meet all of the performance criteria for HFC-134a destruction. Data were also available for HFC-23 destruction that meet all of the performance criteria. **Liquid Injection Incineration is recommended for *approval* for applicability to HFCs destruction, including for HFC-23.**

3.1.2 Rotary Kiln Incineration

The May Supplemental Report documented that the 2018 TFDT had several follow-up discussions with various technology owners after the April 2018 TFDT Report, including with an operator of Rotary Kilns. The operator did not have test data relating to the destruction of HFCs. A compliance test report was provided relating to the destruction of carbon tetrachloride and tetrachloroethylene using multiple sets of conditions. DRE, CO, dioxins/furans, particulates and HCl emissions met the performance criteria for destruction of these surrogate refractory halogenated organic chemicals. The relevant facility continuously monitors pH (for acid control), carbon monoxide, carbon injection (for dioxide/furans production), opacity (for control of particulates) and temperature (for DRE control) for destruction of all substances including HFCs. Feed rates are also controlled of various substances to further control emissions. This technology is also in compliance with local regulatory requirements.

Additional data provided by another operator of Rotary Kilns for the Addendum Report relates to the destruction of another surrogate refractory halogenated organic chemical, sulfur hexafluoride (SF_6), which has high thermal stability[11]. The DRE for SF_6 destroyed using this technology was reported to be higher than 99.99%.

Additional information provided for the Addendum Report notes that those facilities (related to the DRE data provided for SF_6) have continuous monitoring of chlorinated dioxins/furans, with measured levels meeting local regulatory requirements (0.01-0.08 ng ITEQ/Nm^3) (also well within the assessment criteria used by TEAP). Other pollutants (HF/HCl, CO,

[11] Philip H. Taylor & John F. Chadbourne (1987), "Sulfur Hexafluoride as a Surrogate for Monitoring Hazardous Waste Incinerator Performance", *Journal of Air Pollution Control Association (JAPCA)*, 37:6, 729-731, DOI: 10.1080/08940630.1987.10466260. http://dx.doi.org/10.1080/08940630.1987.10466260. [Accessed Oct. 11 2018].

particulates) are also monitored continuously and meet local regulatory requirements. At the time of completion of the Revision to the Addendum Report, the 2018 TFDT had yet to receive information verifying the destruction of HFCs. Data were also available from the 2002 TFDT report related to particulate and dioxins/furans emissions that meet the performance criteria for ODS destruction.

In the absence of data for HFC destruction, and with DRE and emissions data for the destruction of surrogate refractory halogenated organic chemicals (SF_6, carbon tetrachloride, tetrachloroethylene, ODS) that meet the performance criteria, according to the assessment criteria used by TEAP, **Rotary Kiln Incineration remains recommended as *high potential* for applicability to HFCs destruction, including HFC-23**.

3.2 Assessment of any other technology for possible inclusion in the list of approved destruction technologies

This section 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.

New information was provided and assessed for Thermal Decay of Methyl Bromide. The summary assessments for all of the destruction technologies are contained in Appendix 1.

3.2.1 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 of methyl bromide 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.

The Supplement to the April 2018 Task Force Report on Destruction Technologies provided an assessment of the technology against the performance and technical capability criteria, based on the information available at that time, which showed that DRE, HBr and particulate emissions meet performance criteria. A test to measure for brominated dioxins/furans emissions was not feasible in the circumstances, and CO emissions exceeded the performance criteria, based on the measurements made at that time.

Since then, the technology developer has made several modifications to the overall process, which have the objective of improving the overall combustion and scrubbing processes. New analytical measurements were provided for CO emissions only. Improvements to the combustion process have reduced CO emissions. The new analytical data provided confirms that CO emissions have been reduced compared to the data reported in the Supplement Report. The CO concentration in the exhaust gases was measured as 40 mg/m^3, based on an average of 3 analytical results corrected to standard conditions of dry gas at normal conditions of 0ºC and 101.3 kPa, and with the stack gas corrected to 11% oxygen. This meets the performance criterion and is considerably below the CO emissions (283 mg/m^3) reported for combustion without the new component.

In addition, the combustion process operating temperature has been reduced, but still remains in the range where dioxins/furans could be formed. The technology developer indicates that changes to improve combustion should not have impacted on the methyl bromide DRE, which was >99.99% for the previously reported destruction system operation. No data is available for the emissions of brominated dioxins/furans, and therefore no change in recommendation can be made.

In the absence of measured brominated dioxin/furan emissions, and with all other emissions and technical capacity meeting the performance criteria, **Thermal Decay of Methyl Bromide remains recommended as *high potential* for methyl bromide destruction.**

4 Recommendations

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 approved destruction technologies for their applicability to HFCs and any other technologies for possible inclusion on the list of approved destruction technologies). This table ***replaces*** recommendations presented in the previous April 2018 and May 2018 TFDT reports.

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%	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	Recommend for Approval	Recommend for Approval		
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	Recommend for Approval	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 Determined	Approved	Approved	Approved	Approved	Not Determined	Unable to Assess	Unable to Assess		

Nitrogen Plasma Arc	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	Recommend for Approval	Recommend for Approval		
Portable Plasma Arc	Approved	Not Determined	Approved	Approved	Approved	Approved	Not Determined	High Potential	Unable to Assess		
Chemical Reaction with H_2 and CO_2	Approved	Approved	Approved	Approved	Approved	Approved	Not Determined	Recommend for Approval	Recommend for Approval		
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	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	High Potential	High Potential		
Fixed Hearth Incinerator	Unable to Assess										
Furnaces	Unable to Assess										
Thermal Decay of Methyl Bromide	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	High Potential	Not Determined	Not Determined		
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 Access										

*DRE - Destruction & Removal Efficiency

Appendix 1: Summary assessments of destruction technologies

A1 Assessment of approved destruction technologies for applicability to HFCs

A1.1 Thermal Oxidation

A1.1.1 Cement Kilns

DRE (99.998%) and dioxin/furans data meet the performance criteria for the destruction of HFC-134a. Other emissions data were either unavailable or did not meet performance criteria. **Cement Kilns are recommended as *high potential* for applicability to HFCs destruction, including HFC-23**.

A1.1.2 Gaseous/Fume Oxidation

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.

A1.1.3 Liquid Injection Incineration

DRE (99.995%) and emissions data are available that meet all of the performance criteria for HFC-134a destruction. Data were also available for HFC-23 destruction that meet all of the performance criteria. **Liquid Injection Incineration is recommended for *approval* for applicability to HFCs destruction, including for HFC-23**.

A1.1.4 Municipal Solid Waste Incineration

No data from HFC destruction were available to the 2018 TFDT, and dioxins/furans emissions were higher than the performance criteria for ODS destruction, as noted in the 2002 TFDT report. **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**.

A1.1.5 Porous Thermal Reactor

Data for HFC-23 destruction were not available for this assessment. **Porous Thermal Reactor is recommended for *approval* for applicability to HFCs destruction except for HFC-23. Porous Thermal Reactor is recommended as *high potential* for applicability to HFC-23 destruction.**

A1.1.6 Reactor Cracking

No 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**.

A1.1.7 Rotary Kiln Incineration

The May Supplemental Report documented that the 2018 TFDT had several follow-up discussions with various technology owners after the April 2018 TFDT Report, including with an operator of Rotary Kilns. The operator did not have test data relating to the destruction of HFCs. A compliance test report was provided relating to the destruction of carbon tetrachloride and tetrachloroethylene using multiple sets of conditions. DRE, CO, dioxins/furans, particulates and HCl emissions met the performance criteria for destruction of these surrogate refractory halogenated organic chemicals. The relevant facility continuously monitors pH (for acid control), carbon monoxide, carbon injection (for dioxide/furans production), opacity (for control of particulates) and temperature (for DRE control) for destruction of all substances including HFCs. Feed rates are also controlled of various substances to further control emissions. This technology is also in compliance with local regulatory requirements.

Additional data provided by another operator of Rotary Kilns for the Addendum Report relates to the destruction of another surrogate refractory halogenated organic chemical, sulfur hexafluoride (SF_6), which has high thermal stability[12]. The DRE for SF_6 destroyed using this technology was reported to be higher than 99.99%.

Additional information provided for the Addendum Report notes that those facilities (related to the DRE data provided for SF_6) have continuous monitoring of chlorinated dioxins/furans, with measured levels meeting local regulatory requirements (0.01-0.08 ng ITEQ/Nm^3) (also well within the assessment criteria used by TEAP). Other pollutants (HF/HCl, CO, particulates) are also monitored continuously and meet local regulatory requirements. At the time of completion of the Revision to the Addendum Report, the 2018 TFDT had yet to receive information verifying the destruction of HFCs. Data were also available from the 2002 TFDT report related to particulate and dioxins/furans emissions that meet the performance criteria for ODS destruction.

In the absence of data for HFC destruction, and with DRE and emissions data for the destruction of surrogate refractory halogenated organic chemicals (SF_6, carbon tetrachloride, tetrachloroethylene, ODS) that meet the performance criteria, according to the assessment criteria used by TEAP, **Rotary Kiln Incineration remains recommended as *high potential* for applicability to HFCs destruction, including HFC-23**.

A1.2 Plasma Technologies

A1.2.1 Argon Plasma Arc

DRE (99.994%) and emissions data are available that meet all of the performance criteria for HFC destruction except for HFC-23. For HFC-23 destruction, DRE and emissions data meet the performance criteria except for CO, which did not meet the performance criteria. Therefore, **Argon plasma arc is recommended for *approval* for applicability to HFCs destruction except for HFC-23, and as *high potential* for HFC-23 destruction.**

A1.2.2 Inductively coupled radio frequency plasma

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

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[12] Philip H. Taylor & John F. Chadbourne (1987), "Sulfur Hexafluoride as a Surrogate for Monitoring Hazardous Waste Incinerator Performance", *Journal of Air Pollution Control Association (JAPCA)*, 37:6, 729-731, DOI: 10.1080/08940630.1987.10466260. http://dx.doi.org/10.1080/08940630.1987.10466260. [Accessed Oct. 11 2018].

A1.2.3 Microwave Plasma

Due to insufficient data for Hbeing available, **the 2018 TFDT is *unable to assess* Microwave Plasma for applicability for HFCs destruction**.

A1.2.4 Nitrogen Plasma Arc

DRE (99.99%) and emissions data are available that meet all of the performance criteria for HFC destruction, including for HFC-23. Therefore, **Nitrogen Plasma Arc is recommended for *approval* for applicability to HFCs destruction, including HFC-23.**

A1.2.5 Portable Plasma Arc

While DRE, HF, and CO emissions meet the performance criteria for HFCs destruction, data were not available for particulates and dioxins/furans emissions for HFCs destruction. No emissions data were available for HFC-23 destruction. **Portable Plasma Arc is recommended as *high potential* for applicability to HFCs destruction except for HFC-23. The 2018 TFDT is *unable to assess* Portable Plasma Arc for applicability for HFC-23 destruction.**

A1.3 Conversion (non-incineration) technologies

A1.3.1 Chemical Reaction with H_2 and CO_2

Refrigerants are reclaimed to saleable purity of refrigerants before processing. All gases from the processes are recycled back into the reactor. These process features suggest that only DRE should be relevant for the assessment, and thus meets the performance criterion. **Chemical Reaction with H_2 and CO_2 is recommended for *approval* for HFC destruction including HFC-23.**

A1.3.2 Gas Phase Catalytic De-halogenation

No dioxins/furans emissions data for HFCs destruction were available to the 2018 TFDT. 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.**

A1.3.3 Superheated steam reactor

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

A1.3.4 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**.

A2 Assessment of any other technology for possible inclusion in the list of approved destruction technologies in relation to controlled substances

A2.1 Thermal Oxidation

A2.1.1 Electric Heater

The available emissions data applies to HFCs destruction. Particulate emissions that meet the performance criteria were unavailable. No information was provided to indicate whether other controlled substances (CFCs, etc.) have been destroyed using this technology. **Electric Heater is recommended as *high potential* for HFCs destruction, including HFC-23.**

A2.1.2 Fixed Hearth Incinerator

Due to insufficient data being available, **the 2018 TFDT is *unable to assess* Fixed Hearth Incinerators** for possible inclusion on the list of approved destruction technologies.

A2.1.3 Furnaces Dedicated to Manufacturing

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

A2.1.4 Thermal Decay of Methyl Bromide

In the absence of measured brominated dioxin/furan emissions, and with all other emissions and technical capacity meeting the performance criteria, **Thermal Decay of Methyl Bromide is recommended as *high potential* for methyl bromide destruction.**

A2.2 Plasma technologies

A2.2.1 Air Plasma Arc

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

A2.2.2 Alternating Current Plasma (AC Plasma)

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

A2.2.3 CO_2 Plasma

Due to insufficient data being available, and no data that meets the performance criteria, **the 2018 TFDT is *unable to assess* CO_2 Plasma Arc** for possible inclusion on the list of approved destruction technologies. The 2002 TFDT reported emissions data for dioxins/furans for the destruction of ODS that meets the performance criterion, and emissions data for particulates that do not meet the criterion.

A2.2.4 Steam Plasma Arc

The 2018 TFDT has been unable to contact the technology owner. Due to insufficient data being available, **the 2018 TFDT is *unable to assess* Steam Plasma Arc** for possible inclusion on the list of approved destruction technologies.

A2.3 Conversion (or non-incineration) technologies

A2.3.1 Catalytic Destruction

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

A2.3.2 Chlorination/De-chlorination to Vinylidene Fluoride

This technology is part of a chemical manufacturing process and is not a destruction n process.

A2.3.3 Solid Alkali Reaction

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

Appendix 2: Summary of data available to assess destruction technologies for the Addendum Report

Table A2.1: Data available for the assessment of approved destruction technologies for their applicability to HFCs

Technologies Previously Approved by Parties	**HFCs (excluding HFC-23)**					**HFC-23***					**Capacity****
	DRE	**HF**	**CO**	**Particulates**	**Dioxins/ Furans**	**DRE**	**HF**	**CO**	**Particulates**	**Dioxins/ Furans**	
Cement Kiln	✓	⊘HF	X	X	✓	⊘	⊘	⊘	⊘	⊘	✓
Gaseous Fume Oxidation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Liquid Injection Incineration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipal Solid Waste Incineration (dilute sources)	⊘	⊘	⊘	✓	X	Not Relevant to HFC-23					✓
Porous Thermal Reactor	✓	✓	✓	✓	✓	⊘	⊘	⊘	⊘	⊘	✓
Reactor Cracking	✓	✓	✓	⊘	✓	✓	✓	✓	⊘	✓	✓
Rotary Kiln	⊘	⊘	⊘	✓	✓	⊘	⊘	⊘	✓	✓	✓
Argon Plasma Arc	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓
Inductively Coupled Radio Frequency Plasma	⊘	⊘	⊘	✓	✓	⊘	⊘	⊘	✓	✓	⊘
Microwave Plasma	⊘	⊘	⊘	✓	✓	⊘	⊘	⊘	✓	✓	⊘
Nitrogen Plasma Arc	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Portable Plasma Arc	✓	✓	✓	⊘	⊘	⊘	⊘	⊘	⊘	⊘	✓
Chemical Reaction with H_2 and CO_2	✓	Recycled	Recycled	Recycled	✓	✓	Recycled	Recycled	Recycled	✓	✓
Phase Catalytic De-halogenation	✓	✓	✓	✓	⊘	⊘	⊘	⊘	✓	⊘	✓
Superheated Steam Reactor	✓	✓	✓	⊘	✓	✓	✓	✓	⊘	✓	✓
Thermal Reaction with Methane	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘

*Data made available for HFC-23 is used as a proxy for all HFCs where data is unavailable for other HFCs

**Capacity for any substance is used for all substances

✓	Data available meets performance criteria
⊘	Data unavailable
X	Available data does not meet performance criteria
✓	2002 data available meets performance criteria
X	Neither 2002 data, nor any other available data, meets performance criteria and no other data is available
⊘HF	HF was not provided for HFC destruction; HCl data was provided for ODS destruction that met criteria

Table A2.2: Data available for the assessment of any other technologies for possible inclusion on the list of approved destruction technologies (all controlled substances)

Technologies Not Previously Approved by Parties	Controlled Substances					Capacity**
	DRE	HF/HCl/HBr	CO	Particulates	Dioxins/Furans	
Electric Heater	X	✓	✓	⃠	✓	✓
Fixed Hearth Incinerators	⃠	⃠	⃠	⃠	⃠	⃠
Furnaces Dedicated to Manufacturing	⃠	⃠	⃠	⃠	⃠	⃠
Thermal Decay of Methyl Bromide	✓	✓	✓	✓	⃠ Br	✓
Air Plasma Arc	⃠	⃠	⃠	⃠	⃠	⃠
AC Plasma Arc	⃠	⃠	⃠	⃠	⃠	⃠
CO_2 Plasma Arc	⃠	⃠	⃠	X	✓	⃠
Steam Plasma Arc	⃠	⃠	⃠	⃠	⃠	⃠
Catalytic Destruction	⃠	⃠	⃠	⃠	⃠	⃠
Solid Alkali Reactor	⃠	⃠	⃠	⃠	⃠	✓

*Data made available for HFC-23 is used as a proxy for all HFCs where data is unavailable for other HFCs

**Capacity for any substance is used for all substances

✓	Data available meets performance criteria
⃠	Data unavailable
X	Available data does not meet performance criteria
✓	2002 data available meets performance criteria
X	Neither 2002 data, nor any other available data meets performance criteria and no other data is available
	Methyl bromide destruction technology
⃠ Br	Brominated dioxins and furans unavailable; chlorinated meets criteria
⃠HF	HF was not provided for HFC destruction; HCl data was provided for ODS destruction that met criteria