MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

MAY 2018

SUPPLEMENT TO THE APRIL 2018 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*

This report is the Supplement to the April 2018 Decision XXIX/4 TEAP Task Force Report on destruction technologies for controlled substances (2018 TEAP Report, Volume 2).

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Executive Summary

The TEAP Task Force on Destruction Technologies (2018 TFDT) published its initial report in early April 2018. A summary of the 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.

Additional information became available and, as a result, it was necessary to prepare this Supplemental Report, taking into account the new information, and submit it to the 40th Open-ended Working Group. In addition to considering the relevant new information provided, the 2018 TFDT also continued to conduct literature research, reviewed other publicly available information, held discussions with technology suppliers/owners, and sought clarifications where necessary.

This Supplemental Report updates:

- The assessment of destruction technologies approved under decision XXIII/12 to confirm their applicability to HFCs (paragraph 1a, decision XXIX/4, see Chapter 3 of this report)
- 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, see Chapter 4 of this report)

This Supplemental Report outlines a number of general, additional observations and considerations made by the 2018 TFDT in finalising its assessments (see Chapter 2 of this report). Unless otherwise elaborated or clarified in Chapter 2 of this Supplemental Report, the assessment criteria remain unchanged from the April 2018 TFDT report. The Supplemental Report also notes the objective approach taken by the 2018 TFDT for consistency, and some of the limits to data availability for consideration by the parties.

A summary table of recommendations is presented in Chapter 5. The 2018 TFDT has indicated where insufficient data was available to assess adequately the destruction technologies against the performance criteria and for technical capability. A summary table of data available to assess destruction technologies for the Supplemental Report is presented in Appendix 1.

1 Introduction

1.1 Decision XXIX/4 and 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 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;*

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, as proposed in decision XXIX/4. The 2018 TFDT followed up directly with several parties and/or technology suppliers/owners in an effort to track down missing data that would enable it to complete its assessments. Several parties and/or technology suppliers/owners provided additional information.

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

As a result of the additional information that became available, it was necessary to prepare this Supplemental Report, taking into account the new information, and submit it to OEWG-40.

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

1.2 This Report

In addition to considering the relevant new information provided by parties and technology suppliers/owners, the 2018 TFDT also continued to conduct literature research, reviewed other publicly available information, held discussions with technology suppliers/owners, and sought clarifications where necessary. The 2018 TFDT has reviewed the information provided in good-faith and on the assumption that it is accurate data based on real measurements from destruction technologies during test or under normal operation.

This Supplemental Report updates with relevant new information:

- The assessment of destruction technologies approved under decision XXIII/12 to confirm their applicability to hydrofluorocarbons (HFCs) (paragraph 1a, decision XXIX/4, see Chapter 3)
- 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, see Chapter 4)

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 Task Force.

This Supplemental Report outlines a number of general, additional observations and considerations made by the 2018 TFDT in finalising its assessments (see Chapter 2 of this report). Unless otherwise elaborated or clarified in Chapter 2 of this Supplemental Report, 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).

Other background information to the April 2018 TFDT Report, such as background to the decision and previous assessments of destruction technologies, are not repeated here (see Chapter 1 of the April 2018 TFDT report).

A summary table of recommendations is presented in Chapter 5. 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. A summary table of data available to assess destruction technologies for the Supplemental Report is presented in Appendix 1.

2 Additional considerations regarding the assessment of destruction technologies and recommendations

This chapter outlines a number of 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 when destroying refrigerants with contaminant oils removed

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.

2.2 Considerations for collection of halocarbons for destruction

Chemical manufacturing sites may have integrated on-site destruction facilities, which are used to avoid emissions to atmosphere. Since these systems are integrated, emissions will be very low. Some such facilities may also accept controlled substances from off-site for destruction.

Facilities that do not have integrated destruction systems may have a process to collect halocarbons from manufacturing equipment[2] and store them in a separate container or tank while awaiting destruction. Refrigerants, fire suppression agents, solvents and other chemicals are also collected during servicing, maintenance and at the end of the useful commercial life of the product or equipment that contains them. Since these processes may not be completely self-contained, there may be emissions of halocarbons during the collection process. Emissions during collection can range from less than 0.1% to much higher levels. This excludes any emissions that may occur during the routine operation of, for example, a refrigeration system.

Similarly, methyl bromide emissions can occur at a number of points in the fumigation use process: 1) fugitive loss before and during application from the supply cylinder; 2) fugitive loss (leakage) 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.

As noted in the April 2018 TFDT report, the Destruction and Removal Efficiency (DRE) is traditionally calculated by subtracting the mass of a chemical released in stack gases from the original amount fed to the system. DRE does not take into account losses during the collection process or use phase. For example, although a controlled substance might be collected, transferred to larger cylinders or tanks and destroyed at a destruction facility that has a DRE with greater than 99.99% efficiency, there could be significant emissions during the collection and transfer process.

The 2018 TFDT only considered the traditional calculation of DRE and did not consider losses during the use or collection of halocarbons in its analysis of destruction technologies, including HFC-23 or methyl bromide destruction technologies.

2.3 Precautions for the destruction of flammable refrigerants using thermal and plasma technologies

Historically, refrigerants and other substances controlled by the Montreal Protocol have been characterized as non-flammable[3] by The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34. Some HFCs added to the list of controlled substances in 2016 are considered flammable or mildly flammable (A2 or A2L following

[2] These systems may have integrated piping and storage facilities and have minimal losses.

[3] Although classified as non-flammable, there are some circumstances that non-flammable refrigerants may burn. Appropriate precautions should always be taken when handling, storing and using refrigerants.

ASHRAE Standard classifications). Since flammable HFCs or flammable refrigerant blends may be destroyed using approved destruction technologies[4], it will be important for technology operators to take appropriate precautions in equipment design and operation for handling, storage and destruction of flammable refrigerants.

Although, some destruction technology operators are accustomed to handling and destroying flammable substances, others are not. One option may be for facilities to blend refrigerants with other substances to reduce the flammability of the mixture destroyed. Also, in some cases, safety protocols and procedures would be required to avoid the possibility of flammable mixtures with air.

Plant sites that have integrated incineration facilities might require flame arrestors to ensure that the flow rate of flammable substances into the system is faster than the flame front speed, so that the moving flame front could return back down a pipe. For A2Ls, the flame front or speed is very low. There is much less likelihood of a flame front moving back into a tank of bulk fluid, particularly with liquid injection and liquified gases under pressure.

Operators of other incineration technologies that destroy mixed streams of waste may be more accustomed to the handling and destruction of flammable substances. For plasma arc destruction technologies or conversion technologies, flammable mixtures may be less of a concern if no air is injected into the process.

Regardless of the destruction process, safe handling of flammable refrigerants to be destroyed by any technology should be analysed by the facility operator. Risk should be assessed, appropriate precautions should be taken, and adherence to local standards and codes should be ensured.

2.4 Considerations for the assessment of methyl bromide destruction technologies

2.4.1 Destruction of methyl bromide following fumigation

As stated in the April 2018 TFDT report, destruction of methyl bromide can occur as part of a multi-step process where, following the fumigation, the methyl bromide is extracted, and destroyed. Methyl bromide can also be collected/captured (e.g. by adsorption onto activated carbon) after fumigation, 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/m^2) and commodity and structure fumigation (typically 24-128 g/m^3), where an amount of methyl bromide is destroyed naturally during the fumigation process and a further amount lost as fugitive emissions.

At present, destruction systems are not commonly employed in conjunction with methyl bromide fumigation. Most of the currently employed commercial fumigation operations vent methyl bromide directly to the atmosphere. The 2014 Methyl Bromide Technical Options Committee (MBTOC) Assessment report estimated that for most commodity and structural fumigations an average of 15% of the applied dosage of methyl bromide is consumed by reaction during fumigation (irreversible chemisorption). An additional amount of the applied dosage of methyl bromide remains as residual on the treated commodity (reversible physical adsorption) or is lost as fugitive emissions through leakage (8% under best practice) from the

[4] For example, pure components or blends containing HFC-32, HFC-152a, or HFO-1234yf, or HFO-1234ze, or blends containing hydrocarbons.

enclosure. Up to 70% of applied methyl bromide remains available in the headspace of the enclosure for potential recovery (or is otherwise vented directly to the atmosphere). The reversibly adsorbed methyl bromide, that is eventually released from the commodity, is also potentially recoverable. Of the methyl bromide not consumed by fumigation, MBTOC has stated that up to 90% of the remainder is potentially available for recovery and subsequent destruction, reuse or disposal.

The April 2018 TFDT report outlines a number of considerations and previous deliberations by the MBTOC regarding possible definitions of overall operating efficiencies for these multi-step processes that take into account lower efficiencies due to fugitive emissions in the fumigation and extraction steps. The 2002 TFDT also 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 the amount present in foams. Once recovered, the ODS could be destroyed at a DRE of 99.99%. The April 2018 TFDT report mentioned that, following this general approach, a lower efficiency for the overall multi-step fumigation process might be considered suitable for methyl bromide. Nevertheless, the 2018 TFDT has concluded that for methyl bromide, as for concentrated sources of other ODS and HFCs, the DRE of the destruction step alone should be at least 99.99% to minimise emissions.

A technology submitted by one company (Australia) is of the general multi-step type that extracts and then destroys methyl bromide after fumigation. The 2018 TFDT assessed the destruction step alone of this technology (i.e. thermal decay of methyl bromide) against the DRE criteria of 99.99% or above. It did not attempt to quantify the efficiency of the fumigation and extraction steps of the process or any associated fugitive emissions. This approach is considered consistent with the mandate of decision XXIX/4, to undertake an assessment of the efficiency of the destruction technology itself (not ancillary parts of an overall process, such as related ODS use, collection and delivery into the destruction technology). This approach is also considered practical, as the DRE of the destruction step can be objectively determined and then used consistently for comparison purposes with other methyl bromide destruction technologies used as part of multi-step fumigation processes of varying types.

2.4.2 Brominated and mixed halogenated dioxins and furans

As mentioned in the April 2018 TFDT report, the 2011 TFDT 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] The April 2018 TFDT report indicated that 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.

The 2018 TFDT investigated technically and economically feasible analytical methods for testing brominated dioxins/furans, and mixed chlorinated/brominated dioxins/furans, and any

[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.

associated issues with available analytical methods. Analytical tests for brominated dioxins/furans are in irregular demand, and few laboratories in the world are equipped to undertake them. There are also a range of intrinsic challenges associated with this analysis.

Brominated dioxins/furans exhibit different properties than the chlorinated species due to the larger size of the bromine atom, and the weaker strength of the carbon–bromine bond compared with the carbon–chlorine bond. In comparison to the chlorinated dioxins/furans, the brominated species have higher molecular weights, higher melting points, lower water solubilities and lower vapour pressure. They are believed to bioaccumulate similarly to the chlorinated species but may be less persistent in the environment and more sensitive to UV degradation.

In a 2008 review, Hagberg[6] noted that, principally, electron impact high resolution mass spectrometry had been employed in almost all scientific literature published in the previous decade, and usually in combination with high resolution gas chromatography and single ion monitoring to enhance sensitivity. Brominated dioxins/furans are identified in a sample by comparison with isotopically-labelled internal standards. The available range of labelled brominated (or mixed chlorinated/brominated) species is likely to be limited to a handful of species, which could make determination of a broad range of brominated (and mixed) dioxins/furans impractical. Brominated dioxins/furans also have properties that make them sensitive to high temperatures that, along with the potential for UV degradation, requires special treatment to avoid the species degrading under conditions sometimes used for gas chromatography. There appears to be limited information available in the literature about the separation of the different brominated dioxin/furan species using gas chromatography. These technical complexities mean that a very limited number of laboratories specialise in this analysis and build internal expertise that is then marketed at a commercial cost premium.

In summary, the analysis of brominated dioxins/furans is technically specialised, costly, and not widely available. In addition, given the large number of possible mixed chlorinated/brominated species, it is likely that any mixed species might be close to the limits of analytical detection where chlorine availability is low in the waste stream.

For technologies that are used to destroy chlorinated ODS, the measurement of chlorinated dioxins/furans is well established. For technologies that have been used to destroy chlorinated ODS or brominated ODS separately, the determination of chlorinated dioxins/furans might be an appropriate determinant for the performance of the destruction technology for brominated ODS. However, for new technologies, that are only used to destroy brominated ODS, this approach (determining chlorinated dioxins/furans) may not be a reasonable determinant of likely dioxins/furans emissions under operation due to the absence, or insignificant quantities, of chlorinated substances in the waste. Nevertheless, where practicable, the use of a suitable chlorinated species as a proxy to measure the likely performance for dioxins/furans for destruction of brominated species may be appropriate where brominated dioxins/furans analysis is not available. All other performance criteria should be evaluated.

For the assessment of the technology thermal decay of methyl bromide (see section 4.1.4), brominated dioxins/furans analysis was not technically and economically feasible in the circumstances, although chlorinated dioxins/furans analysis was performed (and within performance criteria).

[6] Hagberg, J., Analysis of brominated dioxins and furans by high resolution gas chromatography/high resolution mass spectrometry, Journal of Chromatography A, 1216 (2009) 376–384.

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";

3.2.1 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**.

3.2.2 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.

3.2.3 Liquid Injection Incineration

DRE (99.995%) and emissions data are available that meet all of the performance criteria for HFC-134a destruction. No data were available for HFC-23 performance or destruction; therefore, **Liquid Injection Incineration is recommended for *approval* for applicability to HFCs destruction except for HFC-23, and as *high potential for* HFC-23 destruction.**

3.2.4 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**.

3.2.5 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.**

3.2.6 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**.

3.2.7 Rotary Kiln Incineration

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

3.2.7.1 Considerations for performance criteria assessment

The 2018 TFDT had several follow-up discussions with technology owners, including with an operator of Rotary Kilns. Although, they did not have test data related to the destruction of HFCs, they provided a compliance test report related to the destruction of carbon tetrachloride and tetrachloroethylene at multiple sets of conditions. DRE, CO, dioxins/furans, particulates and HCl emissions can meet the performance criteria for destruction of these proxy chemicals.

The site 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.

Data were available from the 2002 TFDT report related to particulate and dioxins/furans emissions that meet the performance criteria.

3.3 Plasma Technologies

3.3.1 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.**

3.3.2 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.**

3.3.3 Microwave Plasma

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

3.3.4 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.**

3.3.5 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. **<u>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.</u>**

3.4 Conversion (non-incineration) technologies

3.4.1 Chemical Reaction with H_2 and CO_2

<u>Chemical Reaction with H_2 and CO_2 is recommended for *approval* for HFC destruction including HFC-23.</u>

Additional substantive information was provided by the technology owner for the 2018 TFDT Supplemental Report. The technology owner noted that refrigerants are first reclaimed to saleable purity of refrigerants before processing. Further, that all gases from the processes are recycled back into the reactor. Pressure relief devices are used on the reactors and other vessels as a means for pressure relief. These process features suggest that only DRE should be relevant for the assessment, and thus meets the performance criterion.

3.4.2 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. **<u>Gas Phase Catalytic De-halogenation is recommended as *high potential* for applicability to HFCs destruction, including HFC-23.</u>**

3.4.3 Superheated steam reactor

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

3.4.4 Thermal Reaction with Methane

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

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.

For all except one (Thermal Decay of Methyl Bromide) of the technologies outlined in the April 2018 TFDT report, no additional information was provided for the Supplemental Report. Only the recommendation for Thermal Decay of Methyl Bromide has been updated to reflect the new information provided. Otherwise the recommendations for the remaining technologies are unchanged.

4.1 Thermal Oxidation

4.1.1 Electric Heater

The available emissions data applies to HFCs destruction. Particulate emissions that meet the performance criteria were unavailable. Additional DRE and more elaboration on the measurement of emission results would be useful, noting the general reporting of nil results. 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.**

4.1.2 Fixed Hearth Incinerator

No other data to assess the technology were provided. 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. Also, it is noteworthy that the operating temperatures appear to be lower than recommended in the European Union submission for optimal destruction of HFCs.

4.1.3 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.

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 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.

Further information has been received to enable a more complete assessment of the technology against the performance and technical capability criteria.

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. **Thermal Decay of Methyl Bromide is recommended as *high potential* for methyl bromide destruction.**

4.1.4.1 Description of the technology

The technology to destroy methyl bromide uses an industrial diesel engine configured with a scrubbing system and a control system with inlet and outlet gas sensors. The methyl bromide is drawn into the diesel engine at a controlled rate, compressed, and then diesel fuel is injected. The combustion raises the pressure to about 60 atmospheres and the temperature to about 2600 ºC. The high temperatures and pressures increase the decomposition rate. The initial exhaust temperature is about 520 ºC. After the methyl bromide has been destroyed, the exhaust gases, at about 100 to 200 ºC, are passed into a multi-stage scrubbing system to neutralise HBr acid with a base agent.

4.1.4.2 Experience with destruction

The commercial sized system had been operated for 40 hours with a feed rate of >1 kg hour. The DRE is measured based on the composition analysis of the exhaust gas flow exiting the water-based scrubbing system and the feed rate of the methyl bromide into the diesel engine. A 33 m^3 sealed container (used for fumigation processes) was filled with 32 g/m^3 of methyl bromide, in total the container contained 1056 g or 1.056 kg of methyl bromide. The container was connected to the destruction system via a 100 mm diameter flexible hose. The feed rate of the methyl bromide into the diesel engine is controlled. At the exhaust outlet, after the scrubber, a sample line was inserted, which was connected to a sample pump. Several samples were drawn at set intervals, and the content of methyl bromide in the exhaust gases determined. Analysis was carried out by an independent laboratory. The system is fitted with monitoring sensors in the air systems that will detect the level of methyl bromide entering and hydrogen bromide leaving the system. Based upon the measurement results, it automatically manages the input level of methyl bromide.

4.1.4.3 Assessment using performance criteria

A methyl bromide destruction test, with 4 different analyses at set intervals, resulted in destruction of 100% (for 3 analyses) and 99.89% for the other analysis. 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 the difference as a percentage of the mass of that chemical fed into the system.[7] Therefore, it can be concluded that the DRE for this technology is >99.99%.

The analytical capability at an independent laboratory was available for chlorinated dioxins/furans where the destruction tests were carried out (New Zealand). However, the analytical standards and complete methodology was unavailable for brominated dioxins/furans.

Modern industrial diesel engines have been investigated for chlorinated dioxins/furans formation[8], as low levels of chlorine are present as contaminant. The paper reports typically

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[7] April 2002 TEAP Task Force on Destruction Technologies Report, page 30.

[8] Emissions of PCDD/Fs, PCBs, and PAHs from a Modern Diesel Engine Equipped with Catalyzed Emission

about 150 ppb chlorine in diesel fuel, and tests were conducted on fuel with 600 ppb chlorine and also at 10 ppm chlorine to determine if chlorine concentration affected chlorinated dioxins/furans generation. A range of tests with and without catalysts systems indicated that chlorinated dioxins/furans emissions were very low, at or near detection limits and well within the same range. Other results[9] reported in the paper, for modern diesel engines equipped with emission control system configurations, also indicated that fuel doped to 8.4 ppm chlorine did not yield an increase in chlorinated dioxins/furans formation. The paper suggests that for a modern diesel engine, both with and without catalytic exhaust treatment, chlorinated dioxins/furans emissions are near zero levels. It also concluded that it may be possible to discern the differences in chlorinated dioxins/furans emissions from engines equipped with modern diesel emission control systems, however, the emissions of chlorinated dioxins/furans from these modern engines are so low that making an accurate comparison of different test configurations is difficult, even with today's ultra-trace analytical techniques.

The methyl bromide destruction using the diesel engine was investigated for chlorinated dioxins/furans generation. The analytical results found chlorinated dioxins/furans almost all below the limit of detection, consistent with the data reported in the literature. Some further investigation may be necessary to establish if brominated dioxins/furans might be formed.

The bromine loading for destruction is significantly higher than the background chlorine loading, by a factor of about 10,000. While the modern industrial engines minimise chlorinated dioxins/furans to near the limit of detection, there is insufficient data, currently, to draw a conclusion about brominated dioxins/furans formation.

The results reported by the National Vehicle and Fuel Emissions Laboratory also indicate that modern diesel emission control technology is very effective at significantly reducing NO_x, HC, CO, and PM emissions, showing greater than 90% reduction, and with the PM emissions approaching zero.

The particulate analysis used sampling according to United States Environmental Protection Agency USEPA Method 5. The methyl bromide destruction showed very low particulates, with a measured concentration of about 2 mg/m^3, well below the performance criterion.

Analytical data for HBr emissions shows that no HBr was emitted following multi-stage scrubbing, confirming that the scrubber system neutralises all HBr, and that the technology meets this performance criterion.

The CO concentration in the exhaust gases was measured as 283 mg/m^3 based on an average of 3 analytical results corrected to standard conditions of dry gas at normal conditions of 0 ºC and 101.3 kPa, and with the stack gas corrected to 11% oxygen. The emissions are within the range expected for a modern industrial diesel engine but do not meet the performance criterion. The CO emissions data provided by the manufacturer for the industrial engine used for destruction reports CO emissions at a similar concentration to those measured during methyl bromide destruction. The Euro VI standard of European Union for heavy-duty

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Control Systems Christopher A. Laroo, Charles R. Schenk, L. James Sanchez, and Joseph McDonald, National Vehicle and Fuel Emissions Laboratory, United States Environmental Protection Agency, 2565 Plymouth Rd., Ann Arbor, Michigan 48105, United States, dx.doi.org/10.1021/es104220f | Environ. Sci. Technol. 2011, 45, 6420–6428.

[9] Liu, Z. G.; Wall, J. C.; Barge, P.; Dettmann, M. E.; Ottinger, N. A. Investigation of PCDD/F emissions from mobile source diesel engines: impact of copper zeolite SCR catalysts and exhaust after treatment configurations. Environ. Sci. Technol. 2011, 45 (7), 2965–2972.

vehicles for CO is 1.5 g/kW-hr[10], which is similar to the CO emissions quoted by the manufacturer for the industrial engine used for the destruction.

4.1.4.4 Technical capability for destruction of methyl bromide

The smallest commercial system achieves >1 kg/hr destruction rate.

4.1.4.5 Other considerations

The main advantage of this technology is that it is portable and can be used at different fumigation sites. Currently, there is insufficient information to comment on any disadvantages.

4.2 Plasma technologies

4.2.1 Air Plasma Arc

No other data to assess the technology was provided. 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.

4.2.2 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.

4.2.3 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.

4.2.4 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.

4.3 Conversion (or non-incineration) technologies

4.3.1 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.

[10] The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems, Ibrahim Aslan Resitoglu, Kemal Altinisik, Ali Keskin, Clean Techn Environ Policy (2015) 17:15–27 DOI 10.1007/s10098-014-0793-9

4.3.2 Chlorination/De-chlorination to Vinylidene Fluoride

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

4.3.3 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.

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 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* the recommendations presented in the April 2018 TFDT report.

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	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	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	High Potential		
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 of data available to assess destruction technologies for the Supplemental Report

Table A1: 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: 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	✓	✓	X	✓	⦸ 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