UNITED NATIONS
ENVIRONMENT PROGRAMME

AD-HOC TECHNICAL ADVISORY COMMITTEE ON ODS DESTRUCTION TECHNOLOGIES

May 1992

UNITED NATIONS

ENVIRONMENT PROGRAMME

AD-HOC TECHNICAL ADVISORY COMMITTEE ON ODS DESTRUCTION TECHNOLOGIES

May 1992

ACKNOWLEDGEMENT

I wish to thank all members of the Committee, the observers from governments, industry, and the research institutions, and all of the others who participated. Their contributions and cooperation were essential to our success in carrying out our mandate.

Mr. Abe Finkelstein
Chairman
United Nations Environment Programme
Ad-Hoc Technical Advisory Committee on
ODS Destruction Technologies

CONTENTS

Appendices

EXECUTIVE SUMMARY

AD-HOC TECHNICAL ADVISORY COMMITTEE ON ODS DESTRUCTION TECHNOLOGIES

At the second meeting of the Parties to the Montreal Protocol, held in London in June 1990, it was decided to establish an ad-hoc technical advisory committee (TAC) on destruction technologies for ozone-depleting substances (ODS). The TAC was requested to carry out a review of such technologies; make recommendations as to their approval criteria; consider related environmental issues; and examine other pertinent aspects. The most significant findings of the TAC, based on data provided in large part by its members and observers, are as follows.

- **ODS Destruction Program:** Further acceleration in the phase-out of production and consumption of ODS is likely to accentuate the need for a global destruction program. A higher profile and priority for the endorsement of destruction technologies under the Montreal Protocol seems advisable.

- **Global Destruction Capacity:** A preliminary conclusion was reached that worldwide destruction capacity by approved technologies appears to be inadequate to meet demand. Because of uncertainties with available data, it is recommended that periodic reassessments of this capacity be carried out.

- **Destruction Efficiency (DE):** The DE standard proposal of ≥99.99% is readily achievable in well-designed and operated destruction facilities. This DE strikes a balance between very high efficiency (≥99.9999%) destruction facilities available to a limited market, and high efficiency (≥99.99%) facilities available to a majority of the potential world market. Given the projected low recovery rates of ODS prior to delivery to a destruction facility, this trade-off is considered quite insignificant.

- **Recommended Destruction Technologies:** The only destruction processes currently recommended for approval by the TAC are within the thermal oxidation category. Six processes are recommended, however, not all may be appropriate for all classes of ODS. The recommended processes are:

  - ***Liquid Injection Incinerators;***
  - ***Reactor Cracking;***
  - ***Gaseous/Fume Oxidation;***
  - ***Rotary Kiln Incinerators;***
  - ***Cement Kilns; and***
  - ***Municipal Solid Waste Incinerators (foams only).***

- **Environmental Impact:** Assessment of environmental issues indicates that use of efficient, well-operated destruction facilities, that are equipped with modern pollution control systems and operated to achieve the "suggested minimum standards" developed by the TAC, should negate damage to the environment from ODS destruction. It is important that these "suggested minimum standards" be adopted in countries that do not have, as yet, appropriate standards to apply.

- **Compliance:** Destruction facilities that use approved technologies should submit appropriate test data, which demonstrate achievement of the DE standard, to their national regulatory agency. National regulatory agencies should submit to the Ozone Secretariat a list of approved destruction facilities, along with annual reports of ODS quantities destroyed in accordance with Article 7.3 of the ammended Montreal Protocol. Parties to the Montreal Protocol who operate, or plan to establish, ODS destruction facilities in their countries should commit themselves to enforce compliance with the destruction efficiency and environmental standards defined in this report.

- **New Technologies:** Emerging technologies may have economic and regional benefits, and their development should be actively encouraged.

- **UNEP Advisory Committee:** Because of the many uncertainties associated with the calculation of global ODS production and destruction capacities, it is recommended that the UNEP Ozone Secretariat establish an Advisory Panel to meet on a periodic basis to:

  - ***reassess ODS destruction capacities;***
  - ***evaluate emerging technology submissions;***
  - ***review report submissions; and***
  - ***prepare recommendations for the annual review of the Parties.***

- **Fugitive Losses of ODS:** To minimize the largest potential source of ODS emissions from destruction facilities, the TAC recommends that efforts be made to achieve "zero" losses through the adoption of the "good housekeeping practices" presented in this report.

TECHNICAL ADVISORY COMMITTEE ON ODS DESTRUCTION TECHNOLOGIES

Country	Name/Position/Affiliation
CANADA (Chairman)	Mr. Abe Finkelstein Chief, Clean Air Technologies, Environment Canada
AUSTRALIA (Rapporteur 2nd. Mtg.)	Dr. Peter Wailes Deputy Chief, CSIRO, Division of Chemicals and Polymers
CHINA	Prof. Feng Yun Gong Deputy Chief Engineer, Shanghai Institute of Organo-Fluorine Materials
GERMANY	Dr. Holger Brackemann, Federal Environment Agency
JAPAN	Dr. Koichi Mizuno Head, Environmental Technology Laboratory, National Institute for Resources and Environment
RUSSIA	Dr. Victor G. Temchenko Deputy Director, State Institute of Applied Chemistry
SINGAPORE (Rapporteur 3rd. Mtg.)	Dr. Steve M.F. Lai Director, Materials Technology Division, Singapore Institute of Standards and Industrial Research
SWEDEN (Monitoring Sub-Chair)	Mr. Jan Bergstrom President, Milokonsulterna i Studsvik Ab
UNITED KINGDOM (Regulatory Sub-Chair)	Mr. Les Baker Director, Rechem Environmental Services
UNITED STATES (Technologies Sub-Chair)	Mr. Robert E. Hall Branch Chief, Air and Energy Engineering Research Laboratory, United States Environmental Protection Agency
ZAIRE	Mr. Kabeya Mukenyi Directeur de la protection de l'environnement

OBSERVERS	
Country	**Name/Position/Affiliation**
CANADA (Rapporteur 1st. Mtg.)	Mr. Tony Kosteltz Head, Air Pollution Control, Environment Canada
CONGO	Mr. Nkaya-Loubaki, Direction générale de l'environnement
FRANCE	Mr. Michel J. Perrot Manager, Incineration Department, John Zink Sarl
GERMANY	Mr. Siegfried Unger Project Manager, DOW Deutschland Inc.
INDIA	Dr. A.V. Rama Rao Director, Indian Institute of Chemical Technology
MALAYSIA	Mr. Azman Zainal Abdin Lecturer, Department of Environmental Sciences, Universiti Pertanian Malaysia
The NETHERLANDS	Mr. Antony Beekwilder Senior Process Engineer AKZO Engineering
The NETHERLANDS	Mr. Wim J.M. Sprong Air Directorate, Ministry of Housing Planning and Environment
RUSSIA	Mr. Evgueni F. Outkine Interagency Ozone Commission, The CIS Hydrometeorlogical Committee
UNITED STATES	Mr. Keith J. Herbert Director, Allied-Signal Inc.
UNITED STATES (Technologies Contractor)	Mr. Kirk E. Hummel Project Engineer, Radian Corporation
UNITED STATES	Mr. Gene H. Irrgang Manager Market and Product Development, T-Thermal Europe Ltd.
UNITED STATES	Mr. Maurice Oubre Technical Manager, DOW Chemical Louisiana

UNEP Ozone Secretariat	Mr. K. M. Sarma, Coordinator Dr. P. S. Low, Scientist

CHAPTER 1

INTRODUCTION

1.1 Background

The worldwide goal of complete elimination of the consumption of chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and certain transitional substances was established as a result of constantly expanding international scientific knowledge about the phenomenon of ozone layer depletion and its impacts on human health and the environment. There has been a continuing acceleration of the pace of technological progress necessary to phase out the use of these substances through combined international efforts by governments and the industries concerned.

The Montreal Protocol on Substances that Deplete the Ozone Layer, which came into force on 1 January 1989, provided for the establishment of four international panels to carry out a comprehensive review process. The four assessment/review panels were: Environmental; Scientific; Economic; and Technical.

A review of the status of the technology for destroying CFCs and halons was included in the mandate of the Technical Review Panel. In its report of 30 June 1989, the Panel described the status of the technology for the destruction of CFCs and halons but did not attempt to elaborate criteria for approving destruction techniques. The Panel concluded that there were many techniques currently available, and many more under development, but that the establishment of approval criteria required detailed technical consideration of each individual technique. The Panel also noted that the incentive of a production credit for CFCs and halons that are destroyed, as provided for in the Montreal Protocol, combined with the increasing desire to better protect the ozone layer, will be a driving force for the development of environmentally acceptable disposal or destruction practices and techniques. Thus, the Panel recommended the establishment of a dedicated Working Group under UNEP to develop a management system that could provide invaluable information and guidance on assignment of responsibility and liability for collecting and disposing of banked CFCs and halons. As well, the Panel could establish criteria for siting and approving the various destruction technologies. The Panel suggested that such criteria could include:

- performance standards for incinerators or other destruction techniques;
- tracking procedures;
- sampling and analytical methods;
- process, environmental, and emission monitoring requirements;
- air emission standards;
- ash residue disposal requirements;
- wastewater disposal requirements;
- operating procedures;
- methods for handling and storage of waste inventory;
- emergency shut down procedures; and
- contingency plans.

Under Decision 12F(b) of the first meeting, the Parties agreed to return to this subject at their second and subsequent meetings to determine whether it would be necessary to have a Standing Technical Committee to review, and recommend for approval by the Parties, methods for transformation or decomposition, and to determine the amount of controlled substances that are transformed or decomposed by each method.

In accordance with Decision II/11 of the second meeting of the Parties, it was agreed:

- ***To establish an ad-hoc technical advisory committee (TAC) on destruction technologies and to appoint its Chairman, who shall appoint in consultation with the Secretariat up to nine other members on the basis of nomination by Parties. The members shall be experts on destruction technologies and selected with due reference to equitable geographical distribution;***

- ***The committee shall analyze destruction technologies and assess their efficiency and environmental acceptability and develop approval criteria and measurements. The committee shall report regularly to meetings of the Parties.***

Certain other provisions of the Montreal Protocol are pertinent to the work of this Technical Committee. Under Article 7, Reporting of Data, each Party is to provide data to the Secretariat on its annual production, and separately, the amounts destroyed by technologies approved by the Parties. Under Article 9, Research, Development, Public Awareness, and Exchange of Information, destruction of controlled and transitional substances is one of the areas for cooperation and exchange of information. The cost of destruction of ODS is one of the end-use costs included in the indicative list of categories of incremental costs (Decision II/8 Financial Mechanisms) adopted at the second meeting of the Parties, and, lastly, Resolution II, Transitional Substances, of the Resolution by the Governments and the European Communities at the second meeting of the Parties provides, *inter alia*, that transitional substances should, to the degree possible, be collected and prudently destroyed after of their final use.

1.2 Committee Composition

In accordance with Decision II/8B of the second meeting of the Parties, Canada was appointed to Chair the Ad-Hoc Technical Advisory Committee on Destruction Technologies. On 23 April 1991 the Ozone Secretariat accepted the nomination by the Government of Canada of Mr. Abe Finkelstein, Technology Development Branch, Environment Canada, as Chairman. A list of experts nominated by their respective governments was also received from the Ozone Secretariat, and subsequently ten candidates were selected. The membership, including observers, consisted of:

	MEMBERS
Australia:	**Dr. Peter Wailes**
China	**Prof. Feng Yun Gong**
Germany	**Dr. Holger Brackemann**
Japan	**Dr. Koichi Mizuno**
Russia	**Dr. Victor G. Temchenko**
Singapore	**Dr. Steve M.F. Lai**
Sweden	**Mr. Jan Bergstrom**
United Kingdom	**Mr. Les Baker**
United States	**Mr. Robert E. Hall**
Zaire	**Mr. Kabeya Mukenyi**

	OBSERVERS
Canada	**Mr. Tony Kosteltz**
Congo	**Mr. Nkaya-Loubaki**
France	**Mr. Michel J. Perrot**
Germany	**Mr. Siegfried Unger**
India	**Dr. A.V. Rama Rao**
Malaysia	**Mr. Azman Zainal Abidin**
The Netherlands	**Mr. Anthony Beekwilder**
The Netherlands	**Mr. Wim J.M. Sprong**
Russia	**Mr. Evgueni F. Outkine**
UNEP	**Dr. Pak Sum Low**
United States	**Mr. Gene H. Irrgang**
United States	**Mr. Keith J. Herbert**
United States	**Mr. Kirk E. Hummel**
United States	**Mr. Maurice Oubre**

Mr. K. M. Sarma, Coordinator of the Ozone Secretariat, was an ex-officio member of the Committee and worked closely with it on behalf of the Ozone Secretariat. A list of the membership and observers including affiliation, address, and phone and facsimile numbers is given in Appendix H.

1.3 Mandate

Based on Decision II/11 of the second meeting of the Parties, the mandate was discussed and further developed during the first meeting of the Committee, and adopted as follows:

"To review CFC/halon destruction technologies and to develop criteria to assess their appropriate DE limits; acceptable environmental impacts; approval requirements; necessary monitoring procedures; and present the findings with recommendations of the most appropriate destruction technologies to the fourth meeting of the Parties to the Montreal Protocol."

1.4 Function of the Committee

The Committee met three times: 19-23 August 1991 in Nairobi, Kenya; 19-21 November 1991 in Frankfurt, Germany; and 17-20 February 1992 in Singapore.

- Committee members contacted relevant industries in their countries to inform them of committee activities and of the opportunity to make presentations.

- Technologies that convert ODS to alternative environmentally safe compounds were given preference over destruction technologies. Destruction technologies that include energy recovery or chemical recovery were given preference over simple destruction. Storage technologies were not considered by the committee. A standardized evaluation criteria was developed to assess both existing destruction technologies and emerging designs.

- The committee was divided into three subgroups. The first group, "Technologies," developed criteria to evaluate and select the most appropriate destruction technologies. Group two, "Monitoring," developed sampling and analytical criteria to ensure that facilities could be adequately monitored to ensure compliance with national regulations. The final group, "Regulations," developed the regulatory criteria that should be adopted by Parties to ensure that designs do not pose environmental or health concerns.

- The Committee agreed to limit its scope to the inflows and outflows at the gates of a destruction facility. Process efficiencies were specified but overall facility destruction requirements were not recommended. Compliance monitoring of facilities, environmental impact analysis, and transportation issues were examined as part of the scope of the Committee.

- The second meeting in Frankfurt included the three day meeting plus two days of facility tours. In addition to Committee members, participants included representatives from manufacturers of ODS, destruction equipment suppliers, facility operators, and observers from environmental agencies of developed and developing nations. Data on inventories and banked quantities of ODS, as well as information on available destruction facilities, were presented by all Committee members present. Three presentations were made by industries: Allied Signal Inc; T-Thermal Inc; and John Zink Sarl.

- By the conclusion of the third meeting, the Committee was successful in establishing approval criteria for ODS destruction technologies that balance state-of-the-art incinerator designs with technologies readily available in developing countries. These criteria, which will form the basis for Parties to obtain credits for the destruction of ODS, also take into account the capabilities of both developed and developing nations. The major issues dealt with included destruction technology reporting format, agreed definitions, and final report preparation.

1.5 Definitions

These definitions have been specifically drafted for this document. They should be used only when interpreting this report because they may differ from definitions found elsewhere.

ODS: All controlled substances as defined in Paragraph 4 of Article 1 of the amended Montreal Protocol, as well as transitional substances as defined in paragraph 9 of Article 1 of the amended Montreal Protocol.

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

Consumption: Production plus imports minus exports of ODS.

Destruction Process: Any combination of equipment, including piping and instrumentation, that is used to destroy ODS. Included in the process are any add-on or supplementary pollution control equipment required to minimize product and environmental releases.

Destruction Facility: The total activity of process and supplementary operational requirements connected with the receiving of ODS material together with their sampling, storage, handling, preparation, and their destruction via the process(es) itself. The term generally refers to the location on which these activities are sited.

Product Releases: Any ODS in the products leaving a destruction facility (e.g. carbon tetrachloride in hydrochloric acid produced by a destruction facility).

Environmental Releases: Any release into the environment (multi-media; via air, water, and land). These release streams are commonly referred to as air emissions, wastewater discharges, and solid residues.

Wastewater: Any aqueous release from a process into the environment. Uncontaminated water and/or rainwater collected at a facility are excluded as releases.

QA/QC: Program of quality assurance and quality control to ensure compliance with national regulations on environmental and product releases.

Feedstock: ODS used in a chemical process. Any ODS not transformed in the chemical process must go to an approved destruction process in order to be exempt from production. (Feedstock can come directly from an ODS production unit, from a unit in which the ODS is a by-product, or from ODS that is first used in other ways and recovered).

Destruction Technologies: Processes that transform ODS to non-ODS with a DE $\geq$99.99%. ODS to a destruction process can come from a unit in which the ODS are by-products or can be ODS that are first used in other ways and recovered.

Existing Technology: Any technology commercially demonstrated to destroy ODS.

Emerging Technology: Any technology demonstrated in the laboratory, bench, or pilot scale, or any commercial technology developed to destroy other compounds, but not yet proven to be effective at destroying ODS.

Recommended Technology: Any destruction technology recommended by the TAC for approval by the Parties to the Montreal Protocol.

Approved Technology: Any destruction technology approved by the Parties to the Montreal Protocol.

Incinerator: An engineered device using controlled flame combustion to thermally destroy ODS. Examples of incinerators include rotary kilns, liquid injection incinerators, and high temperature furnaces.

Destruction Efficiency: The overall destruction of ODS is calculated on the basis of the total weight of ODS into the process, minus the sum of the ODS in all products, by-products, and environmental releases, divided by the ODS input. (DE is reported as a percentage.)

Fugitive Losses: Releases to the environment from miscellaneous sources such as flanges, valve packing, seals, safety devices, etc. Quantities are to be estimated through the use of good engineering practices.

Housekeeping: Specific actions taken to minimize environmental releases of ODS. Measures normally referred to as "good housekeeping practices" are listed in Chapter 5.

PCDD/PCDF: Refers to two categories of trace organics, polychlorinated dibenzo-paradioxins and polychlorinated dibenzofurans. Test results will be given using the toxicity equivalency factors for specific congeners based on the new International Method.

Particulates: Includes solids and condensable organics (aerosols). Measurable sub-micron particles are included.

STP: Refers to condition at standard temperature and pressure (i.e. 0°C; 101.3 kPa).

Reference Level: Air emission limits, unless otherwise noted, are referenced to 11% oxygen by volume on a dry basis in the off-gas stream.

By-product: A chemical substance produced without specific commercial intent during the manufacturing or processing of another chemical substance or mixture.

CHAPTER 2

OZONE-DEPLETING SUBSTANCES (ODS)

2.1 Introduction

In this chapter, the ODS included in the TAC study are identified, as are the internationally agreed-on Ozone-Depleting Potential (ODP) of these substances. Global consumption estimates of stored and available (banked) ODS for selected countries are presented. The ODS banked inventory data are based on values provided by individual countries and on a total world estimate based on UNEP world consumption data. Finally, an assessment of global ODS destruction capacity is given.

The TAC agreed that there was a need to establish what quantities of ODS were available for destruction. The following reasons for establishing ODS inventories were noted:

- ***To establish the type of material available for destruction;***

- ***To estimate the ODS destruction potential;***

- ***To assess available destruction capacity; and***

- ***To estimate destruction costs and a time frame.***

The quality of information gathered by TAC members in their countries varied considerably. This information, the 1986 national estimates reported to the Ozone Secretariat for those countries not represented on the TAC, and other data sources explained below were employed in preparing these inventories.

The TAC did not undertake to verify any inventory information because another UNEP technical committee has the task of reporting ODS production statistics. The available data were subjected to additional interpretation to estimate the end uses and banked quantities of ODS available for destruction. The error in these estimates is considered large, although it has not been quantitatively established. Therefore, the inventory data should only be used as a rough estimate of the quantities available for destruction.

The global distribution pattern of ODS banked materials is important for two reasons. First, regional destruction capacities should correlate with the regional availability of ODS material. Second, the issue of transporting ODS-containing material to destruction facilities may be more significant if many countries do not have ODS destruction capability. The TAC believes that transportation may be an issue, especially if the economics of constructing destruction facilities are not favourable on a small scale. This may be an important issue for developing countries.

2.2 List of Ozone-Depleting Substances

The ODS (CFCs, halons, carbon tetrachloride, and methyl chloroform) discussed in this report and shown in Tables 2-1 and 2-2 are those listed as Group I and II of Annex A, and Groups I, II, and III of Annex B, entitled "Controlled Substances," in the amended Montreal Protocol. The HCFCs referred to in the report and shown in Table 2-3 are those

TABLE 2-1. OZONE-DEPLETING POTENTIAL OF CONTROLLED SUBSTANCES LISTED IN ANNEX A OF THE MONTREAL PROTOCOL.

Group I	Substance	Ozone-Depleting Potential
$CFCl_3$	(CFC-11)	1.0
CF_2Cl_2	(CFC-12)	1.0
$C_2F_3Cl_3$	(CFC-113)	0.8
$C_2F_4Cl_2$	(CFC-114)	1.0
C_2F_5Cl	(CFC-115)	0.6
Group II	**Substance**	**Ozone-Depleting Potential**
CF_2BrCl	(halon-1211)	3.0
CF_3Br	(halon-1301)	10.0
$C_2F_4Br_2$	(halon-2402)	6.0

These numbers are estimates based on existing knowledge and will be reviewed and revised periodically.

listed as Group I in Annex C, entitled "Transitional Substances," in the Montreal Protocol.

The Ozone-Depleting Potential (ODP) represents the amount of ozone destroyed by emissions of a gas over its entire atmospheric lifetime (i.e. at steady state) relative to that destroyed by emissions of the same mass of CFC-11. The ODP of a particular substance is a function of the number of chlorine or bromine atoms it contains and its ability to reach the stratosphere intact (atmospheric lifetime). ODP is defined in modelling calculations shown below. For HCFCs identified as transitional substances in Table 2-3, ODPs are shown opposite those substances for which an ODP has been developed.

2.3 Global Consumption

Article 7 of the amended Montreal Protocol requires Parties to supply data on the production, imports, and exports of ODS. The data are reported to the Ozone Secretariat but held in absolute confidence and are therefore not available for dissemination. For that reason, the estimates given in this section are based on data made available to the TAC, and they vary as to coverage and reporting year. The global consumption of ODS was obtained from data presented in the UNEP Technology and Economic Assessment Panel Report (1). The UNEP report estimates that current production of CFCs is approximately 60% of the base 1986 level. However, it should be noted that data for Eastern Europe and some developing countries are not yet accurately compiled.

$$\text{ODP} = \frac{\text{Globally averaged ozone depletion due to }\underline{\text{x}}}{\text{Globally averaged ozone depletion due to CFC-11}}$$

TABLE 2-2. OZONE-DEPLETING POTENTIAL OF CONTROLLED SUBSTANCES LISTED IN ANNEX B OF THE MONTREAL PROTOCOL.

Group I	**Substances**	**Ozone-Depleting Potential**
CF_3C1	(CFC-13)	1.0
C_2FC1_5	(CFC-111)	1.0
$C_2F_2Cl_4$	(CFC-112)	1.0
C_3FC1_7	(CFC-211)	1.0
$C_3F_2Cl_6$	(CFC-212)	1.0
$C_3F_3Cl_5$	(CFC-213)	1.0
$C_3F_4Cl_4$	(CFC-214)	1.0
$C_3F_5Cl_3$	(CFC-215)	1.0
$C_3F_6Cl_2$	(CFC-216)	1.0
C_3F_7Cl	(CFC-217)	0.6
Group II	**Substances**	**Ozone-Depleting Potential**
CCl_4	carbon tetrachloride	1.1
Group III	**Substances**	**Ozone-Depleting Potential**
$C_2H_3Cl_3$	1,1,1-trichloroethane (methyl chloroform)	0.1

Additional sources of data for historical ODS consumption are available (2-7).

Annual estimates of the worldwide consumption of certain ODS are presented in Table 2-4 and shown in Figures 2-1 and 2-2. The quantities consumed are presented on a basis of actual (unweighted) consumption and weighted consumption by ODP. The base year for the data varies from 1988 to 1991. In nearly all Western countries, carbon tetrachloride consumption is dominated by its use as a feedstock for CFC-11 and -12; therefore, carbon tetrachloride consumption is expected to decline concurrent with the phase-out of CFCs production.

Annual estimates for end-use applications of CFCs are presented in Table 2-5 and shown in Figures 2-3 and 2-4. The reference year varies from 1988 to 1991. The relative end-use consumption was uncertain because each of the UNEP Technical Options Committees calculated the approximate end-use CFCs consumption, which may not exactly match CFCs producer estimates. CFCs used in solvents, as aerosols, or in various other applications are considered to be dispersive. Solvent emission controls and solvent recycling are available and have been practiced, but most solvent is emitted in less than 6 months. Little or no capture of CFCs in other uses is practiced. In addition, before expens-

TABLE 2-3. TRANSITIONAL SUBSTANCES LISTED IN ANNEX C OF THE MONTREAL PROTOCOL.

Group I	Substance	Ozone-Depleting Potential[a]
$CHFCl_2$	(HCFC-21)	
CHF_2Cl	(HCFC-22)	0.055
CH_2FCl	(HCFC-31)	
C_2HFC1_4	(HCFC-121)	
$C_2HF_2Cl_3$	(HCFC-122)	
$C_2HF_3Cl_2$	(HCFC-123)	0.02
C_2HF_4Cl	(HCFC-124)	0.022
$C_2H_2Cl_3$	(HCFC-131)	
$C_2H_2F_2Cl_2$	(HCFC-132)	
$C_2H_2F_3Cl$	(HCFC-133)	
$C_2H_3FCl_2$	(HCFC-141)	0.11
$C_2H_3F_2Cl$	(HCFC-142)	0.065
C_2H_4FC1	(HCFC-151)	
C_3HFCl_6	(HCFC-221)	
$C_3HF_2Cl_5$	(HCFC-222)	
$C_3HF_3Cl_4$	(HCFC-223)	
$C_3HF_4Cl_3$	(HCFC-224)	
$C_3HF_5Cl_2$	(HCFC-225)	0.025/0.033
C_3HF_6Cl	(HCFC-226)	
$C_3H_2FCl_5$	(HCFC-231)	
$C_3H_2F_2Cl_4$	(HCFC-232)	
$C_3H_2F_3Cl_3$	(HCFC-233)	
$C_3H_2F_4Cl_2$	(HCFC-234)	
$C_3H_2F_5Cl$	(HCFC-235)	
$C_3H_3FCl_4$	(HCFC-241)	
$C_3H_3F_2Cl_3$	(HCFC-242)	
$C_3H_3F_3Cl_2$	(HCFC-243)	
$C_3H_3F_4Cl$	(HCFC-244)	
$C_3H_4FCl_3$	(HCFC-251)	
$C_3H_4F_2Cl_2$	(HCFC-252)	
$C_3H_4F_3Cl$	(HCFC-253)	
$C_3H_5FCl_2$	(HCFC-261)	
$C_3H_5F_2Cl$	(HCFC-262)	
C_3H_6FCl	(HCFC-271)	

[a] These ODP values have been compiled from the literature.

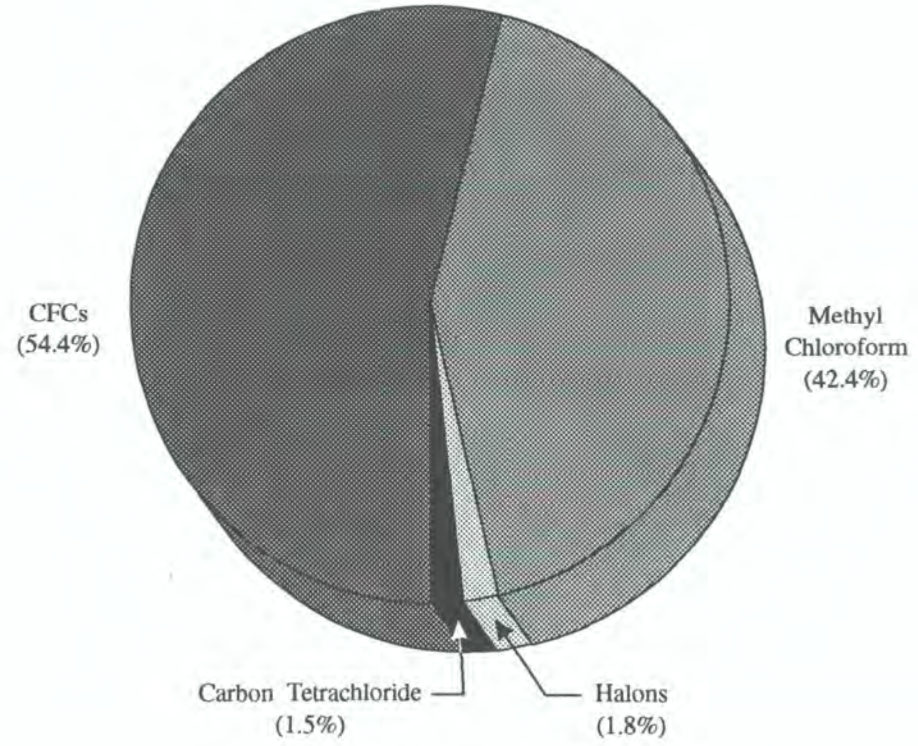


Figure 2-1. Total Estimated Consumption of ODS Worldwide (1,398,000 t, unweighted).

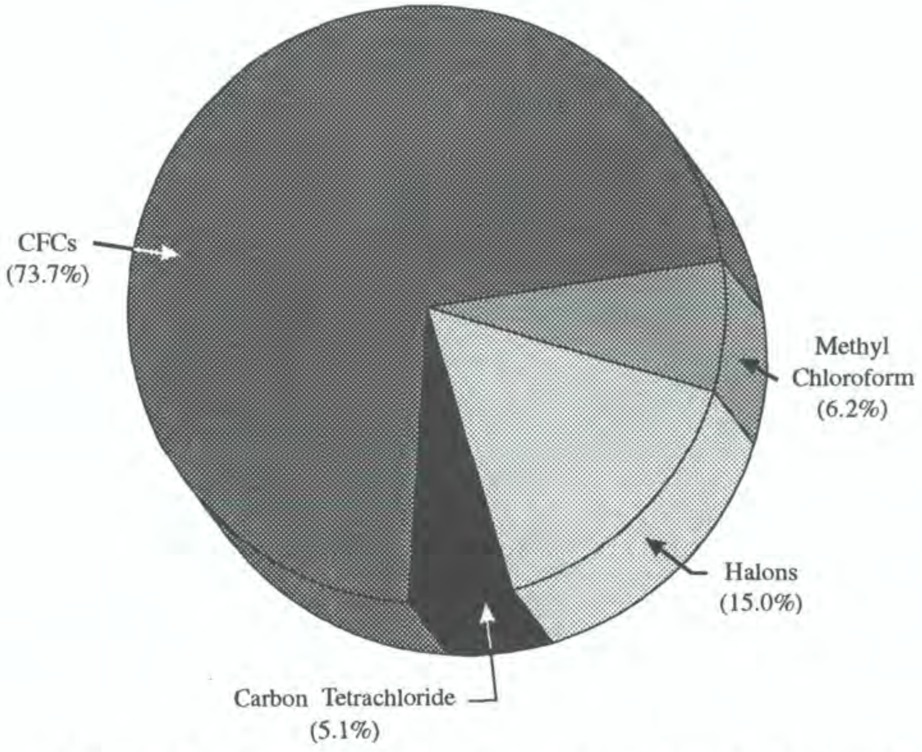


Figure 2-2. Total Estimated Consumption of ODS Worldwide (940,000 t, weighted).

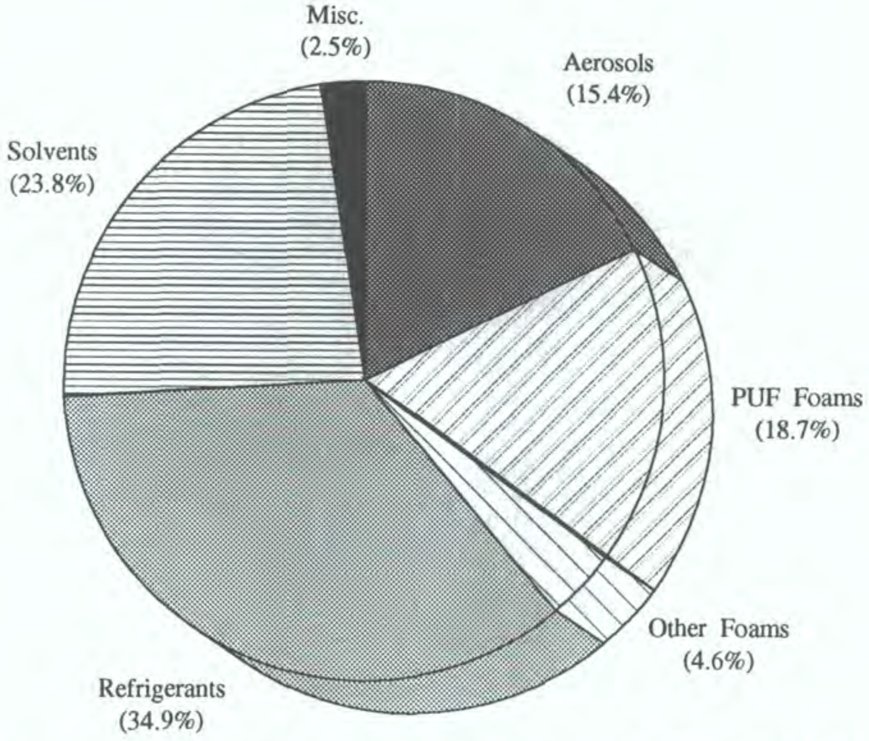


Figure 2-3. Total Estimated Consumption of CFCs Worldwide (747,000 t, unweighted).

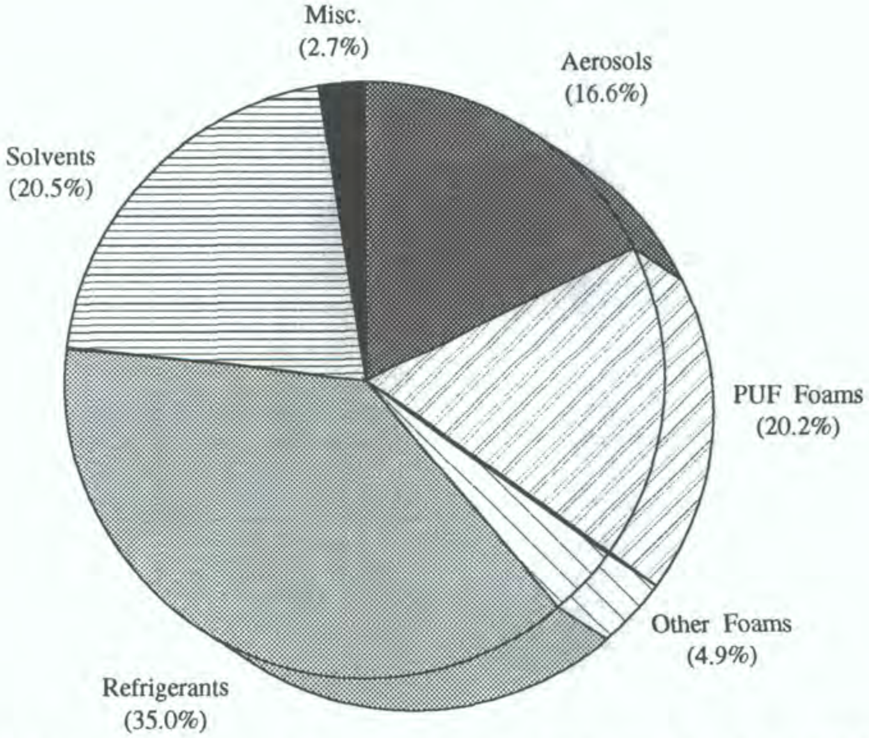


Figure 2-4. Total Estimated Consumption of CFCs Worldwide (693,000 t, weighted).

TABLE 2-4. ESTIMATED WORLDWIDE CONSUMPTION OF OZONE-DEPLETING SUBSTANCES (t x 1000).

Compound	Unweighted	Weighted[a]
CFCs	747[b]	693
Halons	25[c]	141
Carbon Tetrachloride	44[d]	48
Methyl Chloroform	582[e]	58

[a] According to ODP as shown in Tables 2-1 and 2-2.
[b] 1991 UNEP Technology and Economic Assessments Panel Report (1).
[c] 1990 data (6).
[d] 1988 data (1), 96% of CCl_4 assumed to be feedstock.
[e] 1988 data (1).

TABLE 2-5. ESTIMATED WORLDWIDE CONSUMPTION OF CFCS BY END-USE (t x 1000).[a]

Compound	Unweighted	Weighted
Aerosols	115	115
Foams		
PUF[b]	140	140
Other Foam	34	34
Refrigerants	261	242
Solvents	178	142
Miscellaneous	19	19
Total CFCs	747	692

[a] Source: 1991 UNEP Technology and Economic Assessment Panel Report (1).
[b] PUF = polyurethane foam.

TABLE 2-6. ESTIMATED BANKED QUANTITIES OF ODS (t x 1000, UNWEIGHTED).

Compound	Canada[a]	U.S.[b]	Japan[c]	Germany[d]	Sweden[e]	Australia[g]	China[h]	Netherlands[i]	World[j]
CFCs									
Refrig/AC	70	560	31	25	1.9	77	7.9	1.8	970
Rigid Foam	57	530	32	80	13	2	32	18	920
Other Foam (Open Cell/ Aerosol)			1.3	10					120
Solvent		59	62	40					120
Halons									
Halon: Total Flooding	1.7	31	1.63	2.5	1.2[f]	2.7	0.25	1.5	57[k]
Halon: Portable	0.8	15	0.1	7	0.07[f]	8	11.7	1.5	60[k]
Methyl Chloroform[l]	0	0	0	0	0	0	0	0	0
Carbon Tetrachloride[l]	0	0	0	0	0	0	0	0	0

[a] 1988 estimates (14).
[b] 1990 estimates based on material balance approach (updated from US EPA estimates for 1988)
[c] Verbal communication with Dr. K. Mizuno (18 February 1992).
[d] 1988 estimates (with some 1986 estimates) (15).
[e] Estimates (most recent year) (16).
[f] 1985 estimates (17).
[g] 1990 estimates (18).
[h] 1988 estimates (19).
[i] Estimates (most recent year) (20).
[j] Worldwide estimates of banked CFCs for 1988 (CMA reporting companies only) (2, 3).
[k] Worldwide estimates of banked halons for 1988 (6).
[l] Banked quantities of methyl chloroform and carbon tetrachloride are both assumed to be zero because production is either consumed as feedstock or promptly emitted.

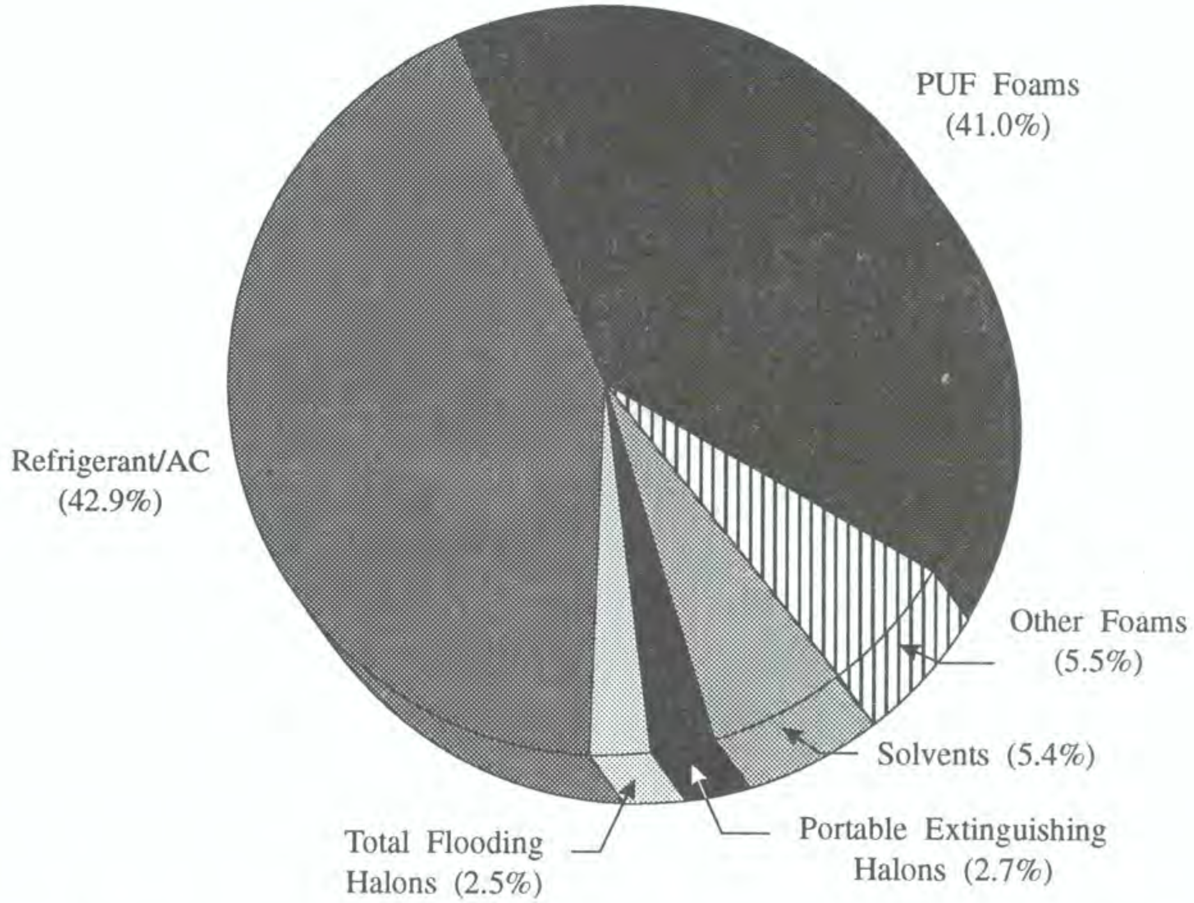


Figure 2-5. Total Estimated Bank of ODS Worldwide (2,247,000 t, unweighted).

ive recovery devices are installed, the use of CFCs in these applications will be phased out. Refrigeration, including stationary and mobile air conditioning, and certain rigid foams are the end uses with possible banks of CFCs.

Data on the consumption and banked quantities of HCFCs are sparse. The Alternative Fluorocarbon Environmental Acceptability Study (AFEAS) has taken over the function of collecting worldwide data formerly performed by the Chemical Manufacturers Association Fluorocarbon Program Panel.

A report for AFEAS was prepared by KPMG Peat Marwick on HCFC-22 consumption and banked quantities (8). The AFEAS/KPMG Peat Marwick report only analyzes the "dispersive" uses (i.e. it excludes chemical intermediate use). For 1989, the AFEAS report estimates that a total of 220,000 t of HCFC-22 were produced. Nearly 90% was used in the "medium-term" (1-10 year) emission category. The worldwide unreleased or "banked" quantity of HCFC-22 in 1989 was estimated to be 482,000 t.

2.4 Banked ODS

Table 3-6 presents the most recent estimates for banked inventories of ODS which are also shown in Figure 3-3. These data were collected for this study, and the reference year varies from 1985 to 1992, depending on the source of the data. Banked quantities of carbon tetrachloride and methyl chloroform were not estimated because the amounts are insignificant. More than 96% of the methyl chloroform produced is emitted in less than 6 months (5). More than 96% of the carbon tetrachloride produced is captively consumed in the production of CFC-11 and -12 and is, therefore, not emitted (9). Two categories are reported for halons - flooding systems and portable fire extinguishers. Globally, halons represent 5% of the total estimated unweighted bank of ODS.

Because of several complicating factors, the quantity of ODS that potentially would be destroyed in the future is highly speculative. Some of these factors are:

- ***Uncertainty about the recoverable fraction of banked ODS;***

- ***Changes in the relative amount of recovered ODS that are recycled, used in conversion processes, and sent to destruction processes; and***

- ***Changes in regulatory stringency and timing that would accelerate the retirement of equipment that requires ODS.***

The banked quantities of ODS are substantial, but for many reasons, only a small fraction of the bank will be destroyed. For example, when estimating the potential supply of CFCs and halons for destruction, several assumptions were made. One was that the source or supply of material for destruction was rejected material that was otherwise unsuitable for recycling or reclamation. It was also assumed that the only banked CFCs recovered would be what was regularly produced from the servicing or retirement of equipment. Another key assumption was that the fraction of CFCs rejected after recovery can range from 1 to 10%. This may be due to such possibilities as:

- ***Mixtures of CFCs that cannot be economically separated;***

- ***Other contamination;***

- ***Increased costs for recycling or reclamation; and***

- ***Changes in supply and demand.***

This fraction could increase over time. As equipment is retired and the demand for refrigerant for servicing of existing equipment diminishes, the relative fraction available for destruction might be expected to increase. The supply of halons for destruction was assumed to be negligible, based on information in the UNEP Halons Technical Options Committee Report (6).

The destruction of CFCs from insulating foam in refrigerators has recently been demonstrated in Germany (and other European countries). National policy in Germany will require that CFCs banked in refrigerator insulating foam be destroyed. Germany will also ban the use of methyl chloroform. Although the recovery and recycling of refrigerants is encouraged, further ODS bans will add to the bank for destruction.

In conclusion, although the banked quantities are large, at present only a small fraction will probably ultimately be destroyed. Most of the banked ODS will be gradually emitted from equipment during its use. This could be reversed, however, if an accelerated phase-out schedule led to the premature retirement of equipment or if prohibitions on existing use, rather than production, were enacted.

TABLE 2-7. COMMERCIAL/PUBLIC HAZARDOUS WASTE INCINERATION CAPACITY ESTIMATE.

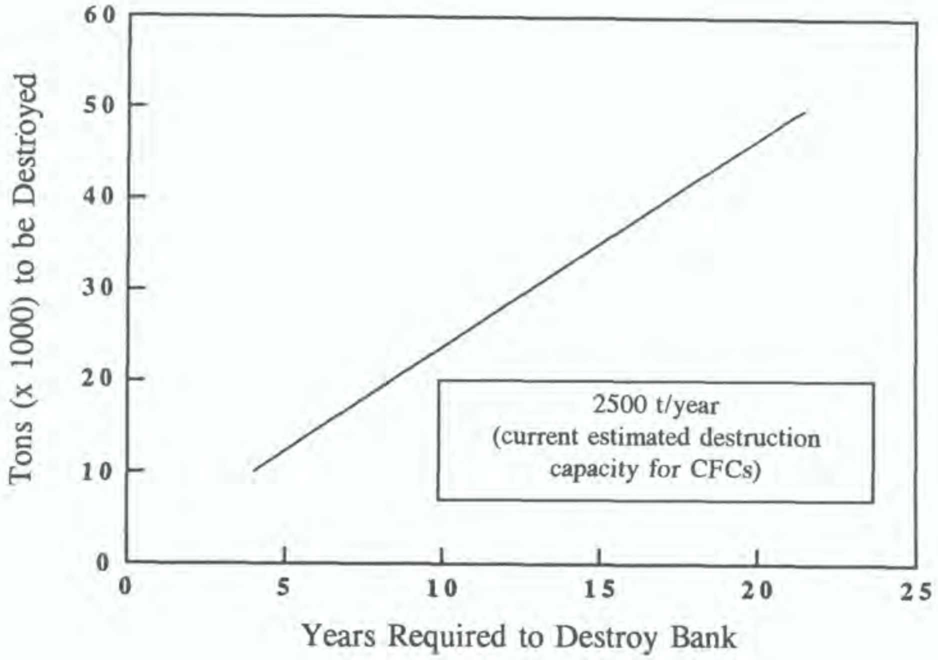
Country	Number of Facilities	Total Hazardous Waste Incineration Capacity (t/year)	Estimated Available Waste Incineration Capacity (t/year)[a]
AUSTRALIA	0	0	0
AUSTRIA	1	90,000	9,000
BELGIUM	1	60,000	6,000
CANADA	3	109,000	10,900
COMMONWEALTH OF INDEPENDENT STATES	N/A[b]	N/A	N/A
DENMARK	1	95,000	9,500
FINLAND	1	88,000	8,800
FRANCE	9	433,000	43,300
GERMANY	7	415,000	41,500
JAPAN	7	320,000	32,000
THE NETHERLANDS	1	100,000	10,000
SWEDEN	1	42,000	4,200
UNITED KINGDOM	4	140,000	14,000
UNITED STATES	16	636,000	63,600
TOTAL	52	2,528,000	252,800

[a] Assumes that current capacity is already operating at 90% of capacity (10% available capacity).

[b] N/A = not available.

2.5 Global ODS Destruction Capacity

Because of the large quantities of banked ODS, the TAC felt that the current capacity for destroying ODS should be estimated. A rough estimate was made by assembling the available data on current worldwide hazardous waste incineration capacity, then factoring this capacity by an approximate halogen loading. Sources of the data for this estimate consisted of published reports and studies (10-13) and direct industry contacts. In the process of assembling the data on hazardous waste incineration capacity, it became apparent that halogen loading capacity varied considerably for different facilities. For example, at incineration facilities without proper refractory or acid gas scrubbing systems, halogen loading is generally limited to less than 1%, perhaps less than 100 ppm (parts per million). The maximum halogen loading also depends on whether heat is recovered, the age of the facility, and local regulatory requirements. Conversely, at



Assumptions:

- There is approximately 50,000 t currently available for destruction based on 5% of the recoverable bank. This excludes foams, halons, aerosols, and solvents as they are not likely to be destroyed or do not represent a significant bank.

- The total available worldwide destruction capacity for ODS in commercial/public hazardous waste incinerators is 2500 t/year. This is based on utilizing 10% of the total capacity (for reporting countries) for ODS and feeding a maximum of 1% by weight of CFCs in the ODS (to prevent damage due to fluorides).

Figure 2-6. Timescale for Destruction of Banked CFCs Based on Current Capacity.

facilities with specially designed units (as found at some ODS production plants), halogen loadings in the range of 10% by weight (wt%) or greater of the feed were reported. Thus, these estimates should only be considered as a best guess.

For the purposes of this estimate of the current capacity for destroying ODS, only commercial hazardous waste incinerators and publicly owned regional incinerators were included. All other types were excluded. These estimates and tabulations are admittedly incomplete due to lack of data from some countries. Because of uncertainties with available data, periodic reassessment of capacity should be carried out.

Worldwide, it was estimated that more than 50 commercial or public hazardous waste incineration facilities are currently in operation. Table 2-7 summarizes the number of facilities and their incineration capacity for those countries for which data were available. The worldwide commercial and public incineration capacity may be as high as 3.0 million t/year. Estimated available waste incineration capacity was taken as 10% of total capacity (i.e. typical commercial hazardous waste incinerators are already operating at approximately 90% of capacity). Maximum halogen content in the waste feed can vary from very low to 10% or more. Examples include specific facilities such as AVR-Netherlands with limits of 4.5 wt% Cl and 0.45 wt% F for the total mix. Individual lots with up to 45 wt % Cl and 20 wt % F are accepted as standard procedure. Facilities shown in Appendix A are reported to accept anywhere from 0 to 25% halogen in the waste feed. These estimates reflect the assumptions about halogen content as applied to total waste-feed capacity. In reality, some of the facilities may be designed to handle solids and sludges, and the capacity available for liquid or gas injection may be less. Assuming an average of 10% available capacity over the entire population of commercial/public hazardous waste incinerators (with a maximum 2 wt% of chlorine-containing wastes, and 1 wt% of fluorine-containing wastes), the worldwide available annual incineration capacity is estimated to be approximately 5000 t/year (for chlorinated waste) and 2500 t/year (for fluorinated waste).

Based on the above assumptions, and as shown in Figure 2-6, we conclude that:

- ***There is insufficient destruction capacity worldwide to destroy all stockpiles of CFCs by the year 2000.***

- ***It appears that it would take approximately 20 years to destroy the current stockpile at the present capacity.***

- ***Further acceleration in the phase-out of production and consumption of ODS is likely to accentuate the need for a global destruction program.***

CHAPTER 3

TECHNOLOGIES

3.1 Introduction

The TAC identified general categories of potential ODS destruction technologies and considered a number of specific ODS destruction technologies, including potential or emerging technologies.

Destruction technologies and feedstock uses are both legal ways to eliminate ODS and in principle both ways should meet the same criteria. However, a recommendation for a destruction efficiency (DE) of ≥99.99% is not appropriate for feedstock processes because they are generally much less efficient. Therefore, it has been recommended that unconverted ODS from a feedstock process be destroyed by an approved destruction technology to be fully exempt from production as defined in paragraph 5 of Article 1 of the Montreal Protocol.

The recommended DE of ≥99.99% is appropriate for thermal oxidation type processes. This DE applies to the input and output of the destruction processes itself, and not the rest of the facility. To minimize the environmental losses of ODS, the TAC developed a Code of Good Housekeeping procedures for destruction facilities. It is recommended that a similar Code be used to minimize environmental losses of ODS from feedstock facilities.

3.2 Commercial or Public Incineration Versus Captive Incineration

The use of commercial or public versus captive incineration facilities was examined, and some advantages and disadvantages for destroying ODS were noted. Commercial or public incineration facilities are those available for a fee or toll to commercial or public organizations to destroy hazardous substances or ODS. A captive incineration facility is generally constructed by an industrial operator for a specific purpose and is generally not available to the commercial or public sector.

One advantage of commercial facilities is their flexibility to handle a wide variety of waste streams, including ODS wastes. These facilities represent existing waste disposal capacity that is available to virtually anyone willing to pay for disposal. Permitted facilities will have a high destruction efficiency. Also, because many commercial or public incinerators already encounter some halogen loadings in their waste feed, they have acid gas scrubbing systems. Finally, operators of commercial or public hazardous waste incinerator are trained to handle chemical wastes.

One possible disadvantage of relying on commercial or public facilities for disposal of ODS is that some units may lack fluoride-resistant construction. Rapid refractory damage may occur in these units and result in premature downtime. Storage losses could be greater because ODS wastes might be stockpiled so that they could be incinerated just before a planned shutdown. Another possible disadvantage is that these facilities might not have the proper infrastructure to handle destruction of ODS.

One advantage of destroying ODS in captive incinerators is that some of these incinerators were specifically designed for ODS compounds. Therefore, they may be equipped with robust refractory material or designed for its easy replacement. A relatively uniform waste feed may result in consistent performance and fewer upsets. Captive units normally have a higher rate of resource recovery, and those located at ODS production facilities probably have more direct access to ODS materials. Finally, captive hazardous waste incinerators will have personnel trained in handling chemical wastes.

The disadvantages of captive, dedicated incinerators include the possibility that site operating permits may prohibit the destruction of wastes from off-site sources, and make them unavailable to the public. Also, because some are integrated into one or more chemical process units, the excess capacity available to destroy other wastes may be limited.

3.3 Existing Technologies

Thermal oxidation (or incineration) is an engineered process that employs high temperatures (900°C or greater) to destroy organic compounds. Typically, the waste or hazardous material must be combustible. For example, it is common practice to blend the waste to obtain a minimum heating value of 3500 cal/g (14.6×10^9 J/kg). However, the halogen-containing ODS have very low heating values (because they are nonflammable). Therefore, if concentrations are high, they may require supplemental fuel (natural gas, fuel oil, propane) to maintain the high temperatures needed for destruction. The primary overall products of the thermal destruction of ODS are CO_2, H_2O, HCl, and HF, and, in addition, HBr (and/or Br_2) from the destruction of halons.

By-products also may be produced from the thermal oxidation of ODS as a result of incomplete combustion or the combustion of other compounds present in the wastes. Incomplete combustion products include carbon monoxide, carbon, hydrocarbons, organic acids, and any other waste constituents or their partially degraded products that escape thermal destruction in the incinerator. In well-designed and operated incinerators, these products of incomplete combustion (PICs) are emitted in minute amounts.

Several types of thermal oxidizers are commercially available for destroying hazardous wastes. These include liquid injection incinerators, rotary kilns, fluidized bed incinerators, and multipurpose incinerators (21). Liquid injection incinerators and rotary kilns have been commercially demonstrated to meet the UNEP Destruction Efficiency (DE) requirements; therefore, they are qualified, recommended, destruction technologies. However, they must be equipped with certain features that enable them to destroy ODS in a reliable and environmentally acceptable manner. These features include:

- ***Proper construction materials throughout;***

- ***Scrubber design capacity for halogen acid gases; and***

- ***Entire system designed and operated to prevent or minimize the formation of PICs.***

Because of the corrosive acid gases (HF, HCl, or HBr) formed in the destruction process, proper construction materials must be employed throughout the entire system (incinerator and downstream gas scrubbing equipment). Examples of critical areas for proper materials include HF-resistant (high alumina) refractory lining and binder in combustion chambers through the quench area, and corrosion-resistant (such as fibreglass-reinforced plastic or "FRP") scrubber internals. Fluorides require, as well, a special lining for the FRP. The gas scrubbing sections of liquid injection and rotary kiln incinerators are essentially the same. Properly designed gas scrubbing will use electrostatic precipitators (ESPs), baghouses, venturi scrubbers, packed bed scrubbers, or plate tower scrubbers to control particulate matter and acid gas. Packed and plate tower scrubbers do not remove particulate matter very efficiently. For liquid injection incinerators, packed bed or plate tower are more commonly used to absorb soluble acid gases such as HCl. Rotary kiln incinerators with a higher particulate loading tend to employ high-energy venturi scrubbers, followed by a packed or plate scrubber, to remove both fine particulate matter and acid gas. For the maximum control of acid gases, the contacting liquid may be either water or a basic solution (sodium bicarbonate or hydroxide). If acid recovery is desired, water is used as the scrubber liquid. If sludge recovery is desired, a calcium-based scrubbing solution can be used to precipitate a sludge or solid that can be disposed of or reclaimed.

Residence time and temperature have an effect on PIC formation and destruction. To minimize the formation of PICs, adequate residence time (generally one to two seconds), high temperatures, excess O_2, and adequate turbulence or mixing of the compounds to be destroyed is required (22). For the complete destruction of ODS, an adequate hydrogen source (methane or propane fuel gas, or water vapour) is required to promote the conversion of halogens to the acid gas form (HCl or HF) instead of free halogen gas (Cl_2 or F_2).

The incineration of bromine-containing halons may form HBr and Br_2. The formation of free halogen Br_2 is favoured, even with an adequate hydrogen source, and is difficult to absorb in the acid gas scrubber. The Test Burn Report for the incineration of ethylene dibromide (EDB) at Rollins Environmental Services (Texas) provides some data that might be useful for destroying halons (23). Previous researchers found that incinerating halogen-containing waste in conjunction with sulfur-containing waste produces beneficial results. The SO_2 produced during the process apparently reduces the halogens that are present to the corresponding hydrogen halide, and no free halogens are detected.

At high temperatures, the sulfuric acid decomposes via an endothermic reaction to SO_2 and H_2O, as shown in the two-step reaction below:

$$2\ H_2SO_4 \xrightarrow{\Delta} 2\ SO_3 + 2\ H_2O \quad (1)$$

$$2\ SO_3 \overset{\Delta}{\rightleftarrows} 2\ SO_2 + O_2 \quad (2)$$

At high temperatures, the equilibrium reaction (equation 2) is displaced to the right, thus favouring decomposition of SO_3.

During the combustion of brominated hydrocarbons such as ethylene dibromide (EDB), the EDB decomposes at high temperatures as follows:

$$C_2H_4Br_2 + 3\ O_2 \xrightarrow{\Delta} 2\ CO_2 + 2\ H_2O + Br_2 \quad (3)$$

Bromine gas (Br_2) is formed rather than HBr because bromine has a lower electronegativity than chlorine. The Br_2 formed in equation 3 reacts with the SO_2 formed in equation 2 and water to produce HBr and H_2SO_4:

$$Br_2 + SO_2 + 2\ H_2O \longrightarrow 2\ HBr + H_2SO_4 \quad (4)$$

This reaction (equation 4) proceeds both in the gas and liquid phases. In the gas phase (i.e. at high temperatures), the sulfuric acid further decomposes as shown in equations (1) and (2).

This technique is also described in a paper by Whiting and Irrgang (24). The authors recommend the introduction of a sulfur-bearing waste or an auxiliary fuel source containing sulfur (such as fuel oil) when incinerating brominated wastes. They explain that the sulfur, from the SO_2 in equation (4), can minimize the formation of hypobromite in the scrubbing solution:

$$Br_2 + 2\ NaOH \rightleftarrows NaBr + NaBrO + H_2O \quad (5)$$

Whiting and Irrgang (24) also describe an alternative approach that involves the direct addition of a neutralizing agent into the incinerator itself, which rapidly and continually removes acid gases from the equilibrium gas stream:

$$HBr + NaOH \rightleftarrows NaBr + H_2O \quad (6)$$

In effect, the equation is no longer reversible and high conversion of HBr is possible. The addition of NaOH to the furnace is not possible if a waste heat boiler is used because it causes excessive fouling with NaBr or NaCl.

3.4 Categories of Destruction Technologies

The TAC identified from the reports of its members a total of ten general categories of potential ODS destruction technologies (Table 3-1). These represent all the currently known potential technologies from around the world. Appendix C contains a summary listing of all the potential destruction technologies within the categories.

3.5 Recommended Technologies

The only destruction processes currently recommended for approval by the TAC are within the thermal oxidation category. Six processes are recommended, however, not all may be appropriate for all classes of ODS. The processes recommended for approval are:

- ***Liquid Injection Incinerators;***
- ***Reactor Cracking;***
- ***Gaseous/Fume Oxidation;***
- ***Rotary Kiln Incinerators;***
- ***Cement Kilns; and***
- ***Municipal Solid Waste Incinerators (Foams Only)***

3.5.1 Liquid Injection Incinerators

Liquid injection incinerators are usually single-chamber units with one or more waste burners, but they may include the liquid injection stages of a multiple chamber incineration facility. A liquid injection incinerator consists of a refractory-lined combustion chamber. A simplified illustration of a complete system is shown in Figure 3-1. Liquid injection incinerators are suitable for wastes with a low ash content, and may be used for any combustible liquid, vapour, or pumpable slurry or sludge (25, 26). These incinerators may be vertically fired (upfired, with the burner on the lower end firing upward; or downfired, with the burner on top and a wet quench zone on the bottom) or horizontally fired. The vertical, downfired unit is preferred when wastes are high in inorganic salts and ash content; horizontal units may be used with low-ash waste. Liquid wastes are injected through the burner(s), atomized to fine droplets, and burned in suspension. A waste with a low heating value (such as ODS) may be injected into the flame zone through a separate atomizing nozzle. Atomization, using gas-fluid nozzles with air or steam pressure, is used to convert the liquid to a gas before combustion. A swirl or vortex burner with tangential entry is preferred by some vendors and combustion experts because its highly turbulent (and compact) flame zone allows a higher release of heat without having the flame impinge on the walls. Problems of flame stability may

TABLE 3-1. GENERAL CATEGORIES OF DESTRUCTION TECHNOLOGIES.

1. Thermal Oxidation
    a. Gaseous/Liquid Thermal Oxidation
    b. Rotary Kiln
    c. Multipurpose (Municipal Solid Waste Incineration)
    d. Cement Kilns
    e. Miscellaneous
        Fluidized bed
        Waste gasification
        "Burn Box" technology
2. Catalytic Processes
    a. Oxidation
    b. Hydrogenation
3. Pyrolysis by Rotary Kiln
4. Chemical Destruction
    a. Reaction with Elemental Metals
    b. Reaction with Metal Oxides
5. Supercritical Water Oxidation
6. Wet-Air Oxidation
7. Plasma Destruction
8. UV Photolysis
9. Biological Processes
10. High-Energy Radiation

result when large volumes ($\geq 40\%$) of CFCs or other ODS are injected into the burner.

Advantages: Wide range of liquid or vapour wastes, high turndown ratio, no moving parts.

Disadvantages: Limited to wastes that can be atomized through the burner, susceptible to plugging.

Availability: Several vendors provide liquid injection incinerators for hazardous wastes.

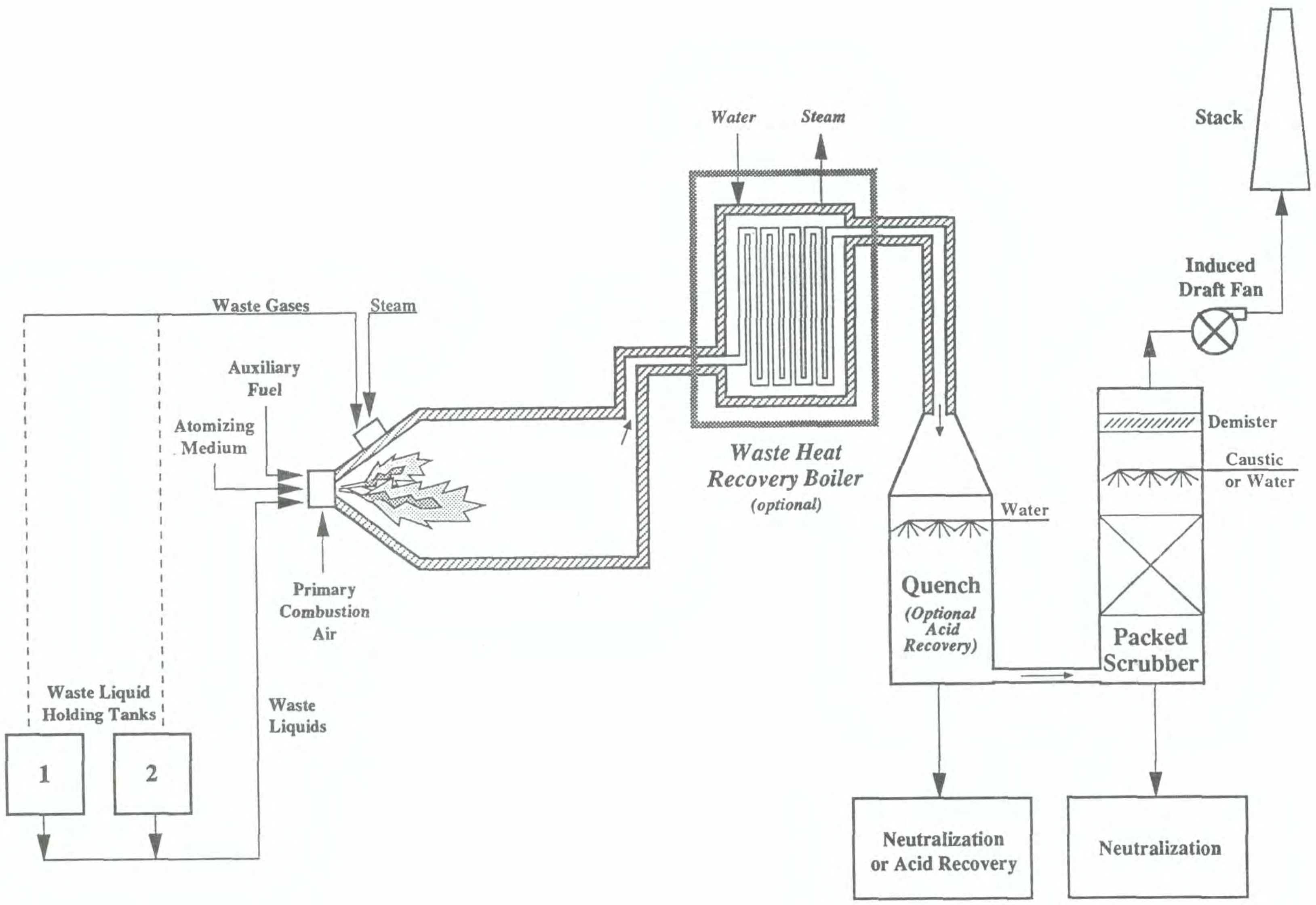


Figure 3-1. Liquid Injection Incinerator.

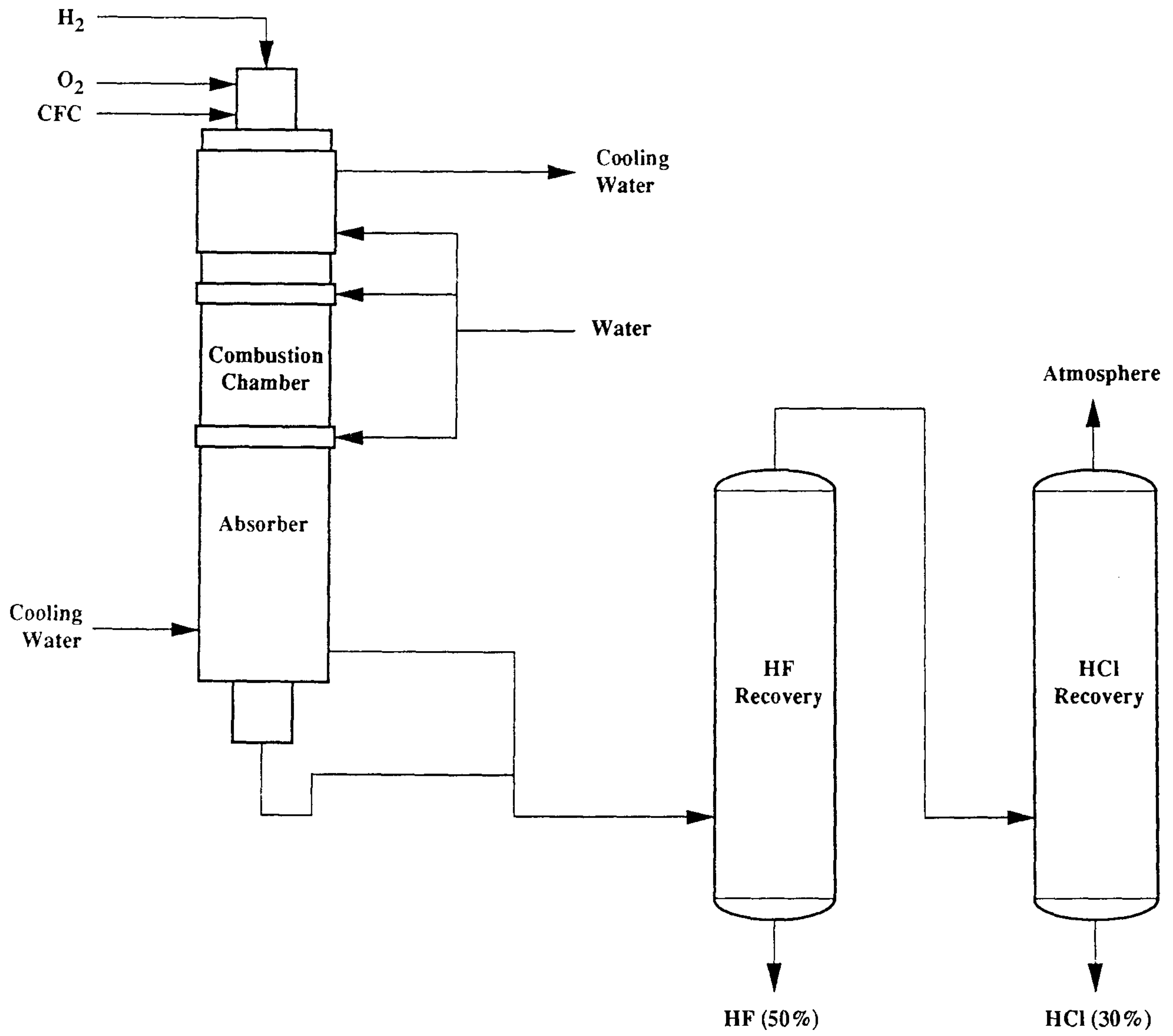


Figure 3-2. Reactor Cracking Process.

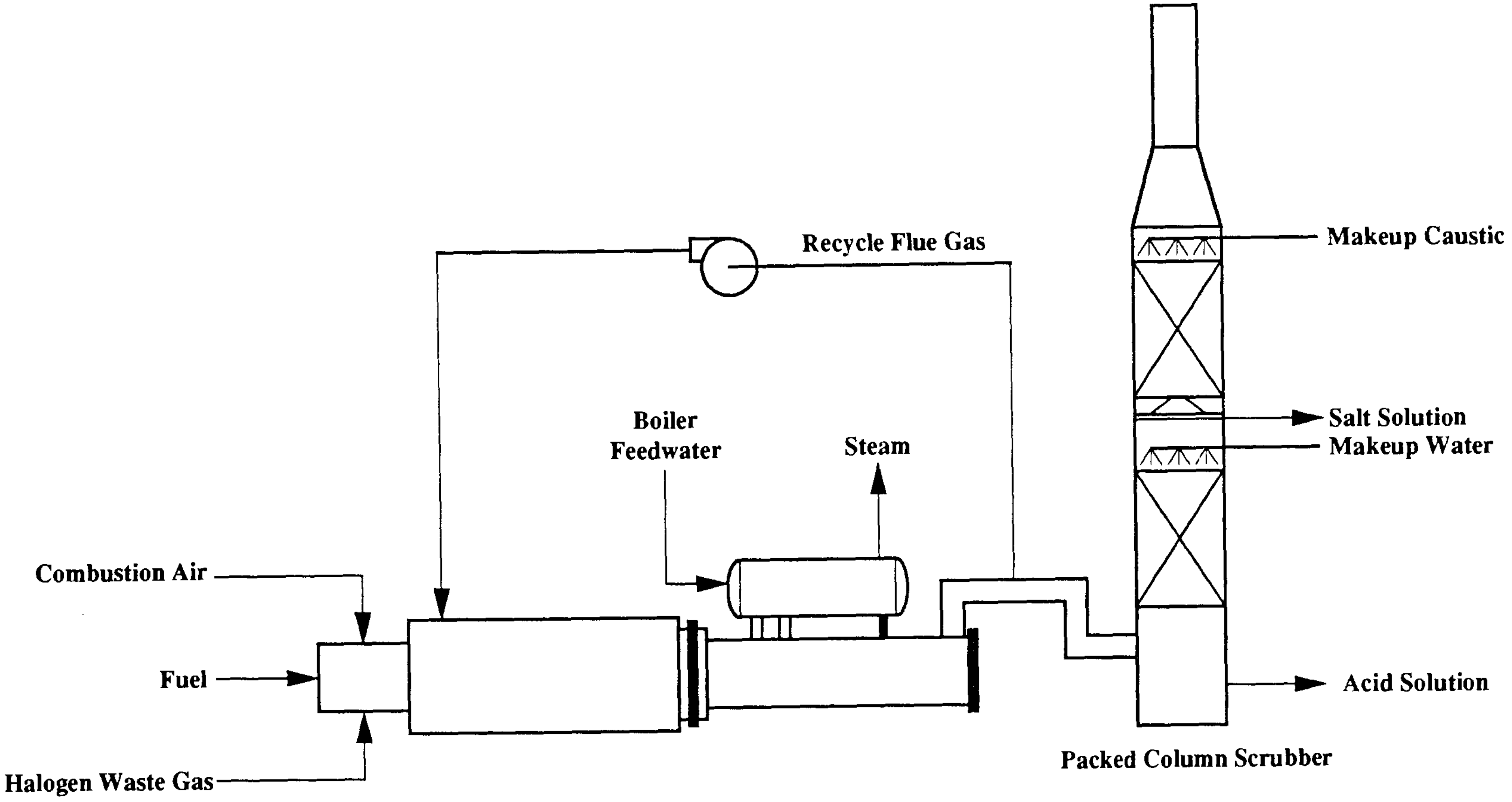


Figure 3-3. Gaseous/Fume Oxidation.

In the United States alone, 14 manufacturers existed in 1985 (22). However, if only those firms with experience in halogenated wastes, particularly CFCs, were considered, the number of qualified vendors would be sharply reduced.

Destruction efficiency: Trial burn testing of the Resource Conservation Recovery Act (RCRA) hazardous waste incinerators in the United States using CFCs or other ODS as the principal organic hazardous constituent (POHC) has shown destruction efficiencies ≥99.99%. Appendix E contains representative trial burn data for liquid injection incinerators.

Commercial systems that meet the criteria:

- ***Liquid Injection Incinerators such as exist at several production plants for CFCs or HCFCs*** . These are downfired refractory-lined liquid injection incinerators with a quench tank.

3.5.2 Reactor Cracking

Reactor cracking is a patented process developed by Hoechst AG, Frankfurt, Germany (EP 0 212 410 Bl dated 4 August 1986). A simplified block diagram is shown in Figure 3-2. The process uses a cylindrical, water-cooled reactor made of graphite, and an oxygen-hydrogen burner system. The reactor (combustion) chamber is directly flanged to an absorber.

This process has been operated since 1983 to treat waste gases from production of CFCs. The waste gases consist of CFCs, HCFCs, and HFCs. These gases are broken down into hydrofluoric acid (HF), water, hydrochloric acid (HCl), carbon dioxide, and chlorine. The absorber cools the cracked products to a temperature that allows a crude HF stream to be drawn from the absorber. The HF is subjected to further treatment in a purification column to obtain 50 to 55% HF, which is marketable. The gaseous components are subsequently fed to a gas scrubber to obtain 30% HCl. Any chlorine still contained in the residual gas is removed by further scrubbing. The resulting waste gas essentially only consists of CO_2, O_2, and water vapour.

The rated throughput ranges from 800 to 1600 t/year. The reaction pressure is 110 kPa, and the temperature in the reaction chamber is above 2000°C. Safety considerations require that a fuel flow control and regulation system is used because the burner is operated with an explosive gas mixture. The equipment is designed with corrosion-resistant materials, and those parts most susceptible to corrosion (such as burner parts) are easily replaced.

Advantages: Energy input by means of an oxygen-hydrogen flame, which limits formation of NO_x; high cracking temperature and high destruction efficiency; rapid cooling, which prevents the formation of PCDD/PCDF; and recovery of hydrofluoric and hydrochloric acid.

Disadvantages: Limited to gaseous wastes, possibly susceptible to plugging.

Availability: Proprietary technology patented by Hoechst AG (Frankfurt, Germany). Hoechst is presently considerably expanding the existing reactor cracking capacity.

Destruction Efficiency: Based on presently measured values, the reactor cracking process is capable of a DE ≥99.99%. To provide a more specific figure with greater accuracy, further measurements based on different analytical methods would be needed.

3.5.3 Gaseous/Fume Oxidation

This method uses refractory-lined combustion chambers for the thermal destruction of waste vapour streams (most often volatile organic carbons (VOCs) or other vapour wastes). A simplified diagram is shown in Figure 3-3. The fume stream is heated to temperatures of 650 to 1100°C using auxiliary fuel such as natural gas or fuel oil. A combustion temperature near 1100°C is required for most ODS compounds. Combustion air (excess oxygen) is provided for oxidation. Gaseous residence times in fume incinerators should be approximately 1-2 s. If halogenated waste vapours are incinerated, an acid gas scrubber is required. Three common types of fume incinerators are direct flame, recuperative, and regenerative.

The simplest example of a fume incinerator is the direct flame incinerator. This type of incinerator is similar both to the second-stage fired afterburner on a two-stage rotary kiln system, and to many liquid injection incinerators. The direct-flame fume incinerator consists of only the burner and combustion chamber.

Recuperative fume incinerators use heat exchangers in the flue gas outlet stream to preheat the incoming waste vapour feed stream, or the combustion air, or both. These heat exchangers can provide energy recovery of approximately 70% of the enthalpy in the flue gas, and result in reduced fuel consumption. Both plate-and-frame and shell-and-tube heat exchangers are commonly used.

According to industry sources, gaseous or fume incinerators have been used for the thermal destruction of ODS and other halogenated organic compounds. Fume incinerators are almost always privately operated, and are typically found in manufacturing plants or chemical process plants (handling process off-gas or vent streams). They are seldom used at commercial hazardous waste incinerator facilities, probably because of the excessive expense of transporting low-density fumes and vapours to an off-site incinerator.

Advantages: Fume incinerators are capable of processing a wide variety of waste vapours, and may incorporate energy recovery to minimize fuel costs. Fume incinerators are designed for continuous operation, and are a simple, proven technology. Some of the ODS (e.g. CFC-12, -114, or -115) are gases at ambient temperature and pressure. These compounds could be destroyed in the gas phase by bleeding them from their pressurized storage container into a fume incinerator.

Disadvantages: Only limited test data are available to demonstrate compliance with UNEP panel-recommended DE requirements. Examples of test data include the Energy and Environmental Research Corporation (EER) testing for the United States Environmental Protection Agency (US EPA) (which demonstrated DE ≥99.999%), and Japanese laboratory research on vapour-phase incineration. Industrial fume incinerators in some countries (i.e. United States) are not regulated as hazardous waste incinerators, and are therefore not required to demonstrate destruction efficiencies ≥99.99%. Acid gas scrubbers are still required.

Present stage of technology: Commercially available.

3.5.4 Rotary Kiln Incinerator

Rotary kiln incinerators are refractory-lined rotating cylindrical steel shells mounted on a slight incline from horizontal (27). Figure 3-4 is a simplified diagram of a complete system. These types of incinerators are capable of handling a wide variety of liquid and solid wastes. Both dry ash and slagging rotary kilns are available. The rotation of the

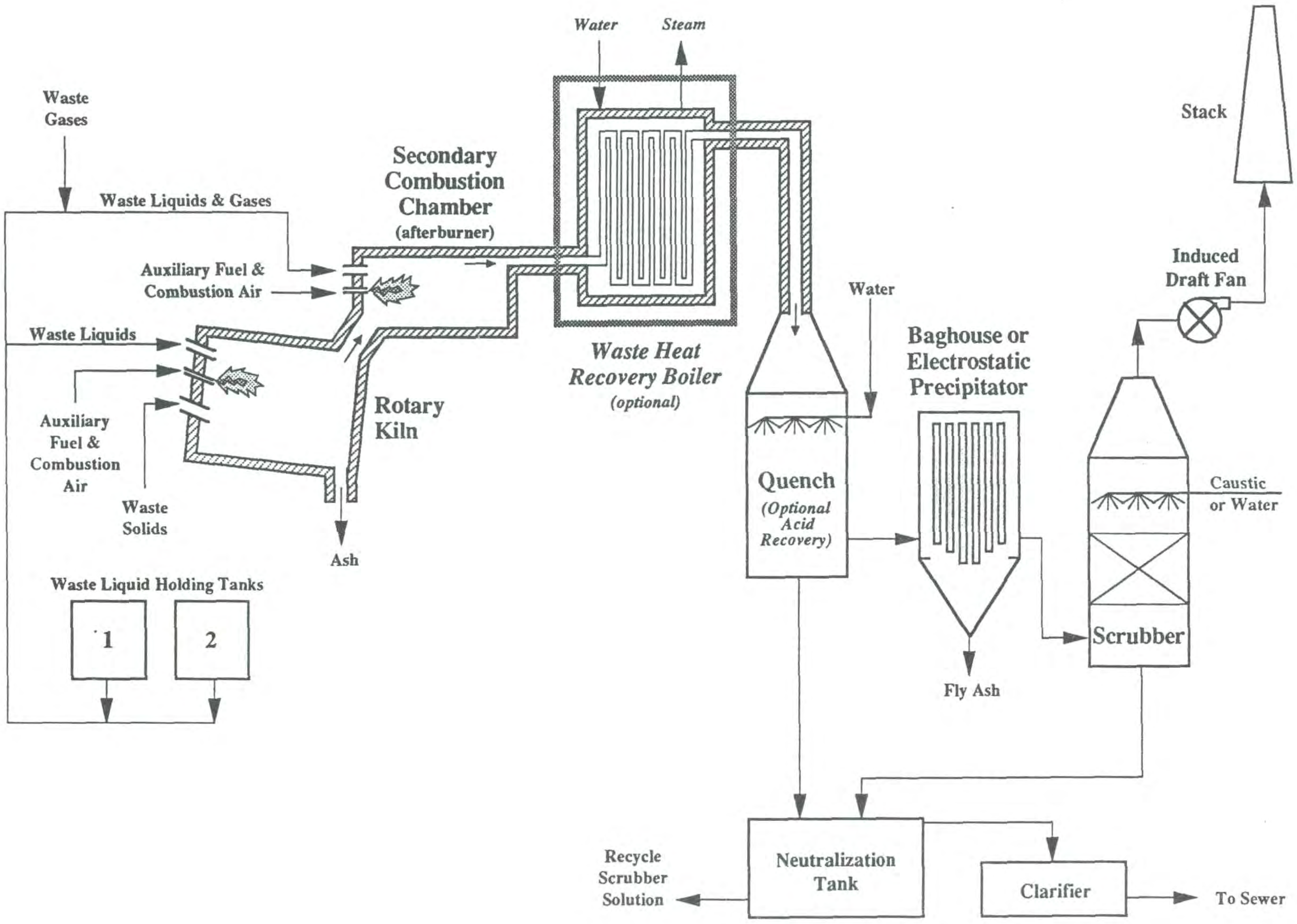


Figure 3-4. Rotary Kiln Incinerator.

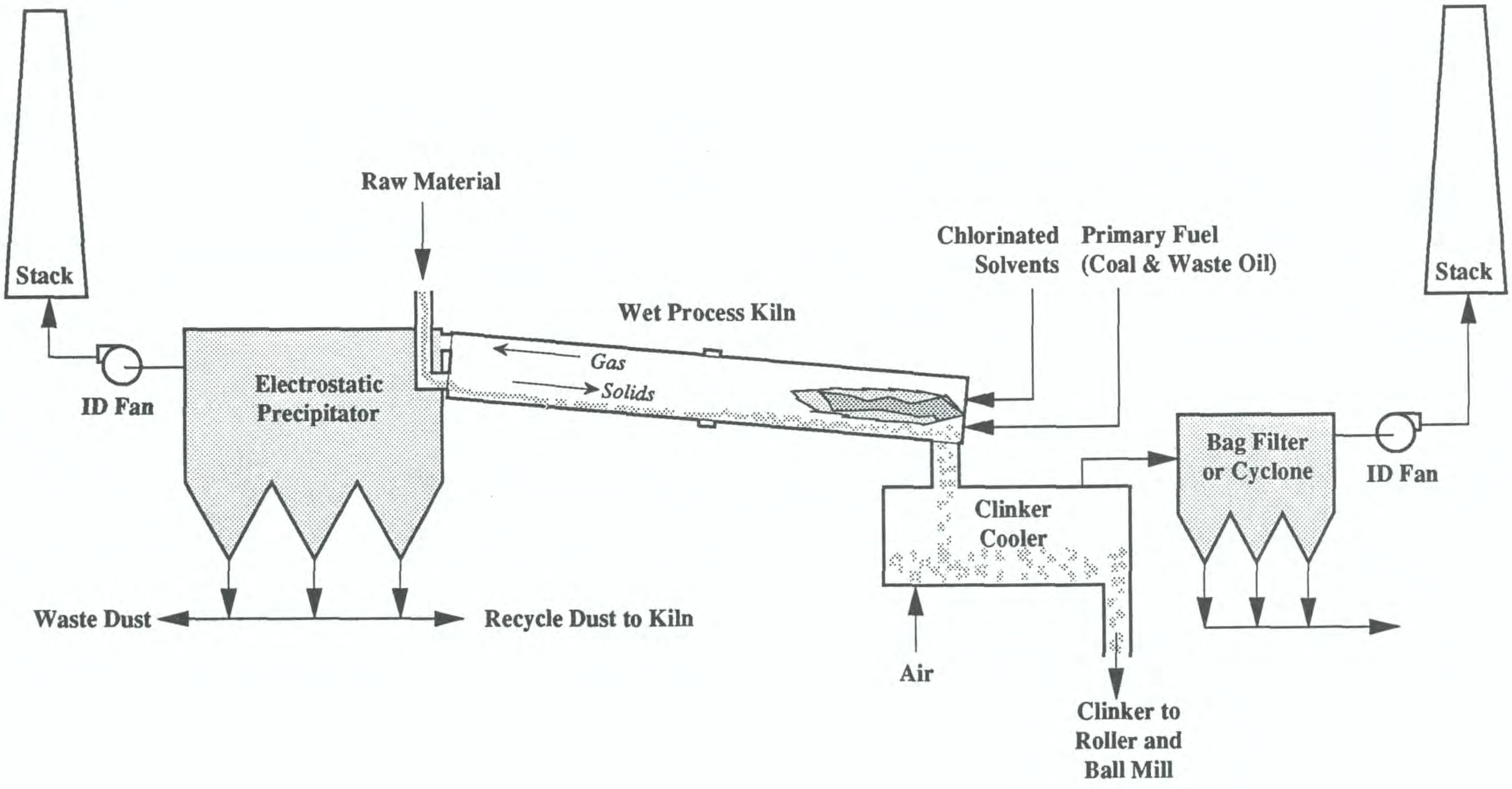


Figure 3-5. Cement Kiln.

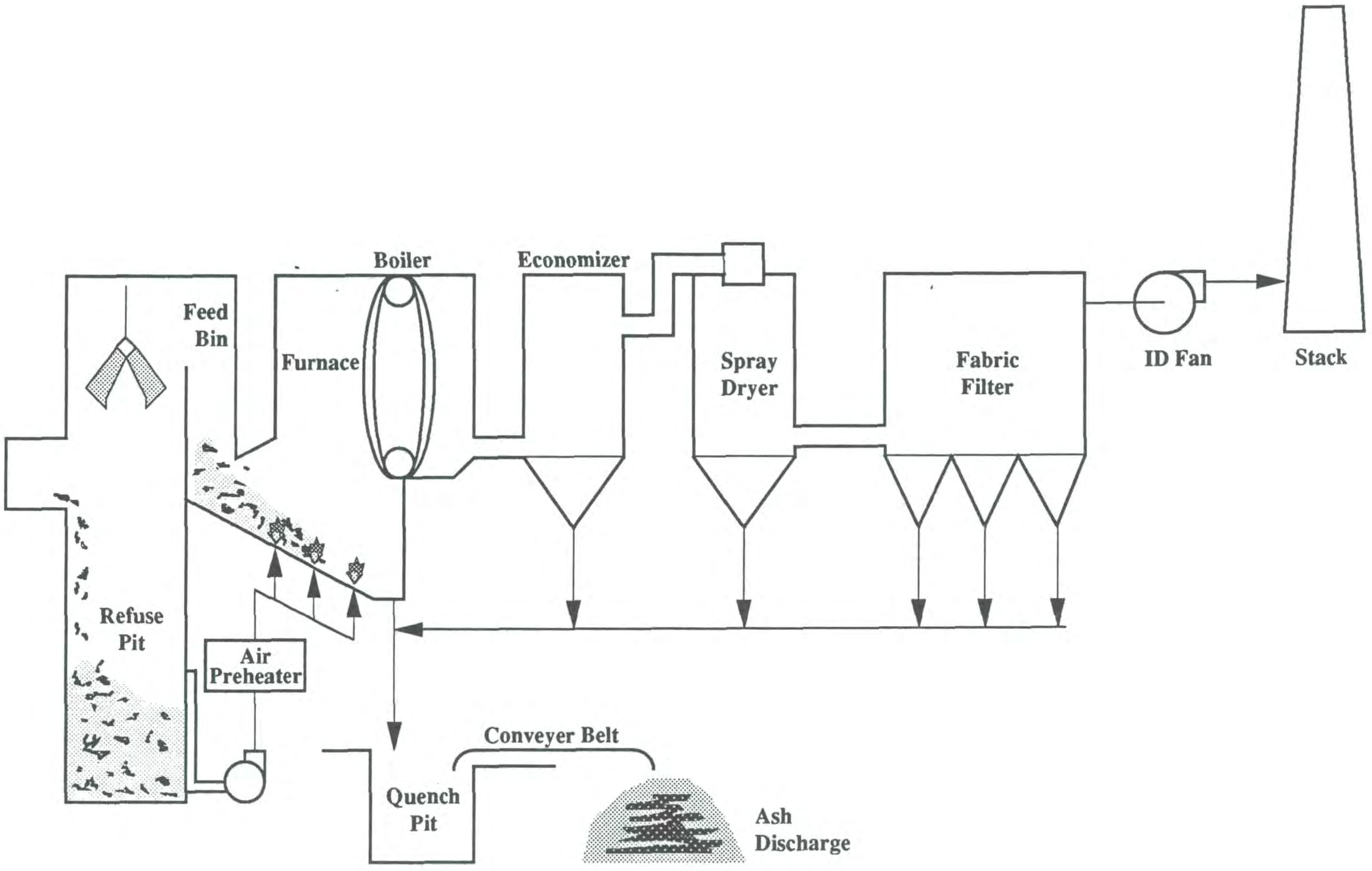


Figure 3-6. Municipal Solid Waste Incinerator.

shell enhances waste mixing, and the incline causes the ash or molten slag to drop out.

Most rotary kiln incinerators have at least two combustion chambers: a rotating kiln and an afterburner. The afterburner is located immediately after the rotating kiln section and is used to ensure the complete combustion of exhaust gases before they are discharged to the gas scrubbing section. The afterburner is also fired with auxiliary fuel to maintain the high temperature. The rotary kiln section may convert the solid wastes to gases through a series of volatilization, pyrolysis, and partial oxidation steps (25). The afterburner is needed to complete the gas-phase combustion reactions. The arrangement of the rotary kiln burner and waste feed can be either concurrent (burner located at front end where waste is fed) or counter current (located at the end opposite to the burner). Liquid materials such as CFCs, halons, and other ODS can be fed into the rotary kiln section or into the afterburner chamber. The latter case is similar to a liquid injection incinerator, where the fluid is atomized in the burner or combustion zone. Rotary kilns have been used to destroy all forms of hazardous waste (gas, liquid, solids, or sludge). Because of their flexibility, rotary kilns are most frequently incorporated into the design of off-site commercial incinerator facilities.

Advantages: Ability to retain and tumble wastes for complete combustion; can handle a wide variety of liquid and solid wastes in any combination; can accept drums or bulk containers; is adaptable to a variety of feed mechanisms.

Disadvantages: High capital costs, high maintenance costs.

Destruction efficiency: Trial burn testing of RCRA hazardous waste incinerators in the United States using CFCs or other ODS as the POHC has shown destruction efficiencies ≥99.99%. Appendix E contains representative trial burn data for rotary kiln incinerators.

3.5.5 Cement Kilns

Cement kilns have been used to burn chemical industrial wastes (28-32). A simplified diagram for a cement kiln is shown in Figure 3-5. Existing cement kilns, when properly operated, can destroy most organic chemical wastes, including PCBs. In the burning zone of a cement kiln, temperatures of over 1500°C are achieved. Gas residence times in the kiln may be up to 10 s, which ensures destruction efficiencies for organic compounds of ≥99.99%. The reaction of acid gases with alkaline materials in the kiln may produce high removal efficiencies of HCl (greater than 99%) without additional acid gas control equipment. A few tests have been conducted using CFC-113 to demonstrate organic destruction and removal efficiencies (22). These tests consistently showed greater than 99.99% destruction. Nearly every country has an existing domestic cement manufacturing industry. Therefore, it is advantageous to use this industry to destroy ODS. At most cement manufacturing plants, chlorine and fluorine are present in relatively low concentrations in the raw materials and fuels. Each cement plant will have a different tolerance for these halogens. Some of the factors that determine this tolerance include: (1) the type of kiln system used; (2) the concentration of halogens in the baseline raw materials and fuels; and (3) the types of cement products manufactured at the site. In general, most cement plants could tolerate the controlled addition of halogens (e.g. ODS); however, this must be evaluated on a case-by-case basis.

Several studies have been conducted on the effects of halogens on the cement kiln process. Fluoride can be beneficial to the cement manufacturing process because it allows the cement-producing reactions, which take place in the hottest portion of the cement kiln, to occur at lower temperatures. Theoretically, the addition of fluoride could result in reduced fuel consumption for the cement manufacturer. At higher levels, however, fluoride can have negative effects on cement quality. The addition of fluoride to the system must, therefore, be carefully controlled. As a broad generalization, the approximate maximum fluoride content is 0.25 wt% of raw material (33). An example of what this might mean for an average cement kiln with an annual clinker (product) output of 907,000 t/year is that the fluoride limitation for destruction of CFC-113 would be approximately 7500 t/year.

Chlorine is usually regarded as an unwanted constituent by the cement manufacturer. However, as a result of the use of chlorinated waste fuels, the cement industry has significant experience accommodating chlorine. Occasionally, chlorine is added to the process to aid in the production of low-alkali cement. Usually, however, chlorine creates operating problems by forming volatile alkali chlorides that vaporize in the hot portions of the kiln and recondense in the cooler sections. When present in sufficient concentrations, these alkali chlorides can cause accretions (rings or solids buildup). The rate of removal of the alkali chlorides with the clinker, or with the cement kiln dust, limits the maximum amount of chlorine that can be fed to the kiln.

In general, newer preheater-precalciner kilns are expected to have the lowest tolerance for chlorine. Wet process kilns and long, dry process kilns will often have a higher tolerance for chlorine loading. The variety of cement kiln types operating around the world makes generalizations difficult. The theoretical maximum chlorine input to a cement kiln is 0.015 wt% of the raw material (33, 34). However, because chlorides are removed from the system by various process modifications, the actual chlorine tolerance in most cement kilns is much higher (29, 30). An example of what the lower (theoretical) limit might mean for an average cement kiln with an annual clinker (product) output of 907,000 t/year is that the chloride limitation for CFC-113 destruction would be approximately 240 t/year.

It appears that the destruction of ODS in cement kilns is possible and may be beneficial. The use of ODS would require careful analysis and metering of the wastes to avoid compromising the quality of the cement product or creating operating problems.

Advantages: Large existing capacities; cement kilns exist in numerous countries.

Disadvantages: Chlorine and fluorine input rates have to be carefully controlled; cement kilns are not set up to handle or burn CFCs/halon wastes.

Destruction efficiency: Trial burn testing of hazardous waste handling cement kilns in the United States has shown destruction efficiencies ≥99.99%. Representative trial burn data for cement kilns appear in Appendix E.

Present stage of technology: Commercially available.

3.5.6 Municipal Solid Waste Incinerators (Foams Only)

This class of equipment includes three major types of systems: mass burn, modular, and refuse-derived fuel (RDF) fired (35). A typical mass-burn waterwall combustor is shown in Figure 3-6. Also, the municipal solid waste incinerator (MSWI) may be a moving-grate type (common in the United States and the European Economic Community) or fluidized-bed (common in Japan).

Mass burn combustors burn municipal solid waste that has not been preprocessed, except to remove items too large to pass through the feed system. In addition, there are two types of grate incinerators: waterwall and refractory-wall designs. Newer units are primarily of the waterwall design, which recovers heat for the production of steam.

Modular combustors also burn waste without preprocessing it, but they are smaller in size. These systems are most commonly of the two-chamber, controlled-air type. Waste is fed by batches into the primary chamber, which is operated with air at substoichiometric levels (usually 40% of theoretical). As hot, fuel-rich gases pass to the secondary combustion chamber, they are mixed with excess air to complete the burning process. Both primary and secondary chambers are usually equipped with auxiliary fuel burners (for startup and temperature maintenance).

The destruction of CFC-containing rigid polyurethane foam, together with municipal solid waste, was tested in Germany (36). The tests were conducted in two mass burn combustors: a small (0.25 t/h) test incinerator with a stoker grate, and a full-scale (10 t/h) incinerator with a roller grate. Temperatures in the combustors were between 850 and 950°C. The destruction efficiencies were ≥99.99% in all cases. The foam throughput varied from 1 to 3% by weight, which is the result of the low density and high heating value of the foam. Taking into account the CFCs content in the foam (approximately 6.5% by weight), the CFCs feed concentration was always less than 2000 ppmw.

Potential areas of concern for multipurpose incinerators used to destroy ODS foams include:

- ***Limitation of type of allowable ODS waste feed. MSWIs have only been demonstrated for destroying CFCs in waste PUF. Rigid PUF may contain variable amounts of CFC-11 blowing agent (the range is typically 5-15% by weight).***

- ***Controlled waste feed rate requirement. MSWIs have only been demonstrated for destroying PUF at an overall waste feed content of 2 wt% or less. Also, the PUF must be added regularly.***

- ***Acid gas control requirement. Some MSWI facilities are not equipped with acid gas control. New or reconstructed large municipal waste combustors in the United States are required to meet an HCl emission limit of 25 ppmv at 7% oxygen, or 95% control of the HCl (37). For smaller plants, the limits are defined as HCl removal to 25 ppmv at 7% oxygen, or 80% control. Acid gas control is achieved either by using a spray dryer followed by a fabric filter (large systems) or by using dry sorbent injection followed by an electrostatic precipitator (ESP) or fabric filter.***

- ***Potential dioxin formation. The potential formation of dioxins and furans across the ESP has been an area of concern. In other experiments, the formation of dioxins and furans was independent of the amount of organic chlorine in the MSWI waste input. These tests were conducted to estimate the influence of polyvinyl chloride (PVC) in the waste on emissions from a MSWI.***

Advantage: Proven technology for the disposal of PUF from refrigeration; large existing capacity.

Disadvantages: Building foams may not be as easily collected for incineration; not all municipalities have MSWIs; limited quantities of chlorides and fluorides for combustion; difficult to document quantity of PUF fed into incinerator.

Destruction efficiency: Trial burn testing was performed in Germany. Representative trial burn data for multipurpose (MSWI) incinerators are available (36).

Present stage of technology: Commercially available.

3.6 Emerging Technologies

Of the general categories for destruction technologies shown in Table 3-1, numbers 1e and 2 through 10 are classified by the TAC as emerging technologies. Whereas some have been commercially demonstrated to varying degrees, none has been demonstrated to meet the UNEP destruction efficiency (DE) requirements. A brief description of the emerging technologies appears in Appendix F (Emerging Technologies).

3.7 Economic Considerations

Existing facilities are limited to North America, Western Europe, and Japan. As soon as there is sufficient economic incentive, combined with the regulatory demand, new facilities will appear in other parts of the world. The following factors will be pertinent to the establishment of new facilities:

- ***Commercial availability;***
- ***Performance verification to UNEP DE requirements;***
- ***Capital and operational costs;***
- ***Energy penalties or savings; and***
- ***Safety characteristics.***

Based on discussions with commercial operators of hazardous waste incinerators, it is estimated that destruction costs for ODS will vary between USD0.50/kg and USD2.00/kg. The cost variation is dependent on a number of factors such as:

- ***Type of ODS;***
- ***Quantity;***
- ***Operating costs;***
- ***Frequency of delivery;***
- ***Availability of destruction facility; and***
- ***Permit costs.***

The TAC encourages facility operators to minimize disposal costs to ensure that ODS are destroyed in approved facilities.

The extensive list of emerging technologies, whose costs, performance, safety and environmental characteristics will be different, should enable the cost effectiveness of ODS destruction to improve over time. Actual costs in different parts of the world will depend on many technical and local variables, such as interest rates, energy prices, and labour costs. Overall, the cost of destroying ODS will probably represent a relatively minor part of country programs to eliminate the use of ODS.

CHAPTER 4

TECHNOLOGY APPROVAL MECHANISM

4.1 Approval Criteria

The principal mandate of the TAC was to review ODS destruction technologies and to develop approval criteria for assessing their appropriate destruction efficiency (DE). In accordance with the mandate, approval criteria were established by the Standards/Monitoring Subgroup and presented to the full committee for consideration and adoption. The TAC recommended that all destruction technologies meeting the established DE criteria should be eligible for approval. Key elements necessary in obtaining approval of a destruction technology are:

- ***The technology must be available on a commercial scale or demonstrated on a pilot scale with a maximum scale-up factor of 200 times. If the scale-up factor is greater than 200, separate approval must be obtained.***

- ***The commercial or pilot scale technology must be demonstrated to achieve the UNEP mandated ≥99.99% destruction efficiency (DE) for ODS.***

- ***The technology must comply with national regulatory requirements for air emissions, liquid effluents, and solid waste residues.***

In accordance with the definition of commercial scale, a minimum pilot scale unit of 10 kg/h ODS feed capacity, which has achieved the UNEP DE standards, can be approved for scale up to a maximum of 200 times. For example, a pilot plant unit that has successfully met the UNEP DE standard at an ODS feed rate of 10 kg/h could be approved for a commercial scale unit up to a maximum ODS feed rate of 2000 kg/h. The full-scale commercial unit must also meet the UNEP DE standard (compliance test).

The UNEP DE limit for incineration of ≥99.99% (also known as four nines) was based on a review of test results from a number of facilities worldwide. Based on the aforementioned test results, it was determined that a DE of ≥99.99% is readily achievable at a well-operated incineration facility.

4.2 Submission Procedures For Technology Approval

The TAC undertook an extensive review of available technologies as part of its mandate. Based on this review, the TAC prepared a list of all potential destruction technologies worldwide (Appendix C). In preparation of this list, TAC members were instructed to contact authorities in their respective countries and update all materials available. Given the level of participation and the diligent attempt made at identifying technologies, the TAC believes that a majority of destruction technologies currently available are included in this list. Technologies inadvertently overlooked and emerging innovative new technologies will have the opportunity to apply for approval status under the submissions procedures that have been established. The following sections outline the preferred option for ensuring that UNEP is made aware of on-going technological developments and should address any oversights that have been made. The process assumes that this UNEP Committee or a

TABLE 4-1. APPLICATION CHECKLIST.

	Included	Not Applicable
A. GENERAL INFORMATION		
1. Location		
2. Current name, phone number, fax number		
3. Current scale (laboratory, pilot plant etc.)		
B. DESIGN INFORMATION		
1. Treatment type (oxidation, biological etc.)		
2. Process type (batch, continuous)		
3. Feed type (gas, liquid, solid)		
4. Reactor conditions: Temperature (°C) Pressure (kPa) Residence time (s)		
5. Rated throughput - total/ODS (t/day)		
6. Destruction efficiency for ODS (%)		
7. Energy recovery		
8. Unit requirements - unit ratios		
9. Process flow diagram		
C. ENVIRONMENTAL RELEASES		
1. Air emissions - composition, quantity		
2. Liquid effluents - composition, quantity		
3. Solid residues - composition, quantity		
4. Monitoring frequency: Gaseous, PICs, Particulates, ODS Liquids Solids		
D. TRIAL TEST DATA		
1. Description - feeds, conditions, duration, etc.		
2. Trial results		
3. Sampling and analytical		
4. Calculations - DE, other		

subgroup would meet on a periodic basis to evaluate any submissions received by the Ozone Secretariat and to prepare recommendations for the annual meeting of the Parties. A number of destruction technologies have been demonstrated to destroy only individual or certain classes of ODS or a certain physical form of ODS (e.g. foams). Approval and credit will be given for these technologies only when the criteria in 4.1 are met.

The TAC has identified the following technologies that can be considered for approval:

- ***Municipal solid waste incinerators are appropriate for the destruction of foams containing CFCs.***

- ***The feedstock processes listed in Appendix D are appropriate for the destruction of certain ODS mentioned therein.***

4.2.1 Existing Technologies:

Any technology that meets the destruction efficiency requirements (Chapter 4.1) and has the potential to comply with the suggested minimum standards (Chapter 5) will be considered for approval. The Parties seeking approval must submit a complete description of the technology to the UNEP Ozone Secretariat. Parties intending to utilize technologies not shown on the list of approved technologies will have until 30 September 1994 to apply for approval. If approved, credit will be given retroactive to the date that this Committee's report was accepted by the Parties to the Montreal Protocol. Otherwise, credit will not be given for the related ODS destroyed.

4.2.2 Emerging Technologies:

As for existing technologies, the organization or individual seeking approval must submit a complete description of the technology to UNEP Ozone Secretariat as noted above for existing technologies. No time restrictions apply in this case.

4.3 Reporting Requirements

Facilities that employ approved technologies and destroy ODS shall submit, to their national regulatory agency, data required for compliance with the destruction efficiency and environmental standards criteria. National regulatory agencies shall then submit a list of approved facilities that were judged to be in compliance, along with their annual reports on quantities of ODS destroyed in accordance with Article 7.1 of the Montreal Protocol.

4.4 Technology Approval Applications

Applications for approval of technologies should be submitted to UNEP in report form. The report should provide UNEP, and the persons delegated to assess it, with sufficient information to enable them to recommend approval of the process by the Parties. The report should provide a comprehensive description of the process itself, together with the circumstances and conditions under which it has been tested. Monitoring and test arrangements should be described, and the results given. The report must demonstrate that these results indicate compliance with the necessary DE level of $\geq 99.99\%$ specified as a prerequisite for approval. Table 4-1 is a checklist of items that should be addressed in the report.

Whereas approval of technologies must be primarily based upon attainment of the specified DE, and detailed facility operation standards are a matter for national regulatory authorities, the Parties must take into account the wider environmental impact potential of new technologies. Applicants must therefore address the question of discharges of other substances resulting from the operation of the technology and report areas of significant environmental impact.

CHAPTER 5

STANDARDS, CODES, AND MONITORING

5.1 Introduction

An assessment of monitoring requirements, and associated standards, for the destruction of ODS, was included in the mandate of the TAC. The purpose of this assessment was to identify potential risks to the environment from destruction processes and therefore avoid or reduce any consequent environmental damage. The TAC addressed this subject from the premise that the UNEP does not have regulations or guidelines because it refers to the right of countries to establish and apply their own guidelines or regulations. However, because some countries that are Parties to the Montreal Protocol may not have established any suitable standards, the TAC has endeavoured to develop what may be regarded as basic requirements in this situation. The limits are based upon information presented by regulatory agencies represented on the TAC and are intended to ensure destruction facilities adhere to the general philosophy of the Montreal Protocol. This philosophy, which was adopted by the TAC, states that destruction of any ODS must be accomplished in a manner that does not further degrade the environment (e.g. global warming, acid deposition, toxics, etc.). Accordingly, the following recommendations are provided to assist national regulatory agencies to develop criteria to ensure that all ODS destruction facilities comply with this general philosophy.

The standards were developed with the primary intention of providing national regulatory bodies with an indication of the environmental pollutants and emissions levels that may be released from a well-operated destruction facility. It is recognized by the TAC that in most cases site-specific environmental conditions will often dictate the level of allowable emissions permitted into the environment. However, the TAC cannot address site-specific issues and therefore has proposed these minimum standards for consideration by the Parties to the Montreal Protocol that do not currently have standards.

Thermal oxidation processes, are the only technologies recommended for approval by the TAC. Based on information presented to the TAC by operators of destruction facilities and by equipment manufacturers, it was generally agreed that incineration processes must be properly designed and operated to limit the formation of pollutants resulting from the products of incomplete combustion. Furthermore, the standards proposed are based on actual field test data at commercial operating facilities resulting from the incineration of products containing ODS. The TAC also recognizes that it is beyond its scope and ability to recommend emission standards for all possible pollutants that may be discharged during incineration of ODS. Accordingly, the proposed standards are based on the specific emissions that are a direct result of ODS incineration in thermal oxidation processes. As new technological processes are approved, additional revisions may be required to ensure that pollutants that are not presently identified are assimilated into these standards.

5.2 Suggested Minimum Standards

Destruction technologies that utilize auxiliary fuels (e.g. coal, oil, and gas) for energy production and/or destruction requirements

TABLE 5-1. SUGGESTED MINIMUM STANDARDS: AIR EMISSIONS.

Pollutant	Stack Concentration	Comments
PCDD/PDCF	$< 1.0^{a}$ ng/m^3	Frequency, method of sampling, and limit for the ODS that is being destroyed as recommended by national regulatory agencies
HCl	< 100 mg/m^3	
HF	< 5 mg/m^3	
HBr/Br$_2$	< 5 mg/m^3	
Particulates	< 50 mg/m^3	
CO	< 100 mg/m^3	Continuous emission monitoring with 1 hour rolling average
ODS		Atmospheric releases of ODS shall be monitored at all facilities with air emission discharges (where applicable) to ensure compliance with the recommendations of this report.

[a] Toxic equivalence using international method. Emissions limits are expressed as mass per dry cubic metre of flue gas at 0°C and 101.3 kPa corrected to 11% O_2.

or utilize reagents/catalysts for process operations, can generate a multitude of pollutants. The TAC agreed that it was beyond its ability to address all potential environmental releases arising from these destruction technologies especially because no data from operating facilities were available. Therefore, the TAC agreed to limit its scope to those pollutants of concern (e.g. PCDD/PCDF) and surrogates (e.g. CO) that are common to all thermal destruction systems. The "suggested minimum standards" listed in Table 5-1 represent a balance between state-of-the-art incineration/air pollution control systems and thermal destruction facilities that may be available in developing nations.

The emission standards in Table 5-1 are based on submissions of actual field test results at full scale facilities equipped with modern pollution control systems. Carbon monoxide (CO) and particulate matter (PM) are also included in the standards as these parameters, in a number of test programs, have demonstrated their ability to act as surrogates for the efficient operation of the combustion process and associated control equipment. Furthermore, both CO and PM are readily measured and provide a relatively low-cost method of ensuring that good combustion is maintained.

5.3 Environmental Issues

This section addresses the environmental concerns associated with potential releases to the air, receiving waters, and land. Pollutants of concern to the TAC are those that would evolve as a direct result of the presence of chlorine, fluorine, or bromine in the ODS.

5.3.1 Air Emissions

By-products from the thermal oxidation of ODS may arise from incomplete combustion and from the combustion of other compounds present in the wastes. The incomplete combustion products include carbon monoxide, carbon, hydrocarbons, organic acids, and any other waste constituents or their partially degraded products that escape thermal destruction in the incinerator. In well-designed and operated incinerators, these PICs are emitted in minute amounts.

Most air emissions originate directly from thermal destruction processes and are released to the atmosphere through stacks, which are well-defined point sources. Such emissions should be monitored to confirm the recommended destruction efficiency (DE) given in Section 4.1.

Other sources of air emissions at a destruction facility are not well defined and may be numerous. These emissions are commonly referred to as "fugitive losses." Employment of good housekeeping practices (Section 5.5) at a facility should minimize fugitive losses and ensure that ODS are not inadvertently released into the environment prior to destruction. The TAC recommends that all operations within a facility employ good housekeeping practices to minimize releases of ODS into the environment. As a consequence the Committee developed the following guidelines for facility operators :

- ***Objectives are "Zero" losses;***

- ***The adoption of "Good Housekeeping Practices" are recommended;***

- ***Fugitive losses are to be estimated through best available engineering practices.***

Air pollutants, of concern to the TAC, that directly result from the combustion of ODS and various fuels can be classified into the following two categories: toxics; and acid gases.

Toxics The most important toxic emissions that may result from incineration of ODS are a family of compounds commonly referred to as dioxins and furans. Tests sponsored by the US EPA, ESA, and T-Thermal Inc. have shown that unacceptable dioxin levels can be formed if CFCs are incinerated in inadequately designed or poorly operated incinerators, or if a very large percentage (e.g. 50%) of the waste feed is comprised of ODS material. The tests have shown that dioxin/furan levels can be virtually eliminated by using incinerators of good design, by using good combustion practices, and by feeding appropriate levels of ODS into the waste stream.

Acid Gases Halogens contained in ODS are converted to hydrogen-halides (HF, HCl, HBr) in thermal destruction processes, if an adequate hydrogen source (e.g. methane, propane, or water vapour) is available to promote this reaction instead of the formation of free halogens. Incineration of bromine containing halons can form Br_2 as well as HBr because the formation of elementary bromine is favoured. The equilibrium of HBr and Br_2 in the incineration process can be shifted toward HBr by creating a reducing atmosphere in the combustion chamber (e.g. by adding sulfur containing waste). Gas scrubbing systems are required for the removal of the hydrogen-halides from the raw gas. The contacting liquid may be either water or a basic solution, which is commonly used in different types of scrubbers. It is difficult to absorb bromine in an acid gas scrubber. In the case of significant amounts of bromine in the raw gas, other scrubbing techniques must be used (e.g. adding SO_2 to reduce Br_2 to HBr).

5.3.2 Liquid Effluents

The TAC recommends that all facilities should either be designed for either "zero" discharge or employ on-site treatment for all liquid effluents prior to disposal. Deep well injection of liquid effluents as a disposal practice is not favoured by the TAC unless it meets the disposal criteria established for that specific site and meets stringent subsurface formation requirements established by the local regulatory agencies.

5.3.3. Residue Disposal

Several types of solid residues can be generated in the thermal destruction processes or in the subsequent treatment of off-gas or liquid effluents. The composition of these residues is highly variable and dependent on the composition of other waste being destroyed in conjunction with ODS, and on fuel characteristics, type of waste containers, and process operating variables. In some cases, it is possible to produce useful by-products (e.g. in the form of CaF_2). Other destruction technologies would employ various materials for promoting chemical reactions. The TAC therefore recommends the periodic assaying of the solids produced (e.g. process reagents, catalysts, etc). Facilities should be designed to meet the regulations of national regulatory agencies for the disposal of any solids.

5.4 Environmental Trade-Offs

The TAC has considered a number of environmental trade-offs in preparing this report. Thermal destruction facilities, although utilizing the most effective technology to date, are known to generate a number of pollutants of concern. These pollutants may impact on other environmental issues such as air toxics, acid deposition, etc. However, well-designed and operated incineration systems are available for disposal of ODS at a number of locations around the world. Furthermore, these facilities are immediately accessible for ODS destruction.

Many incinerators in developed countries are known to have destruction efficiencies that exceed the $\geq 99.99\%$ as proposed by the TAC. However, the destruction efficiency recommended was based on a balance between very high efficiency ($\geq 99.9999\%$) destruction facilities available to a limited market and high efficiency ($\geq 99.99\%$) facilities available to a majority of the potential world market. Given the projected low recovery rates for ODS prior to delivery to a destruction facility, this trade-off is considered quite insignificant.

5.5 Code of Good Housekeeping

To provide additional guidance to facility operators, the TAC prepared a "Code of Good Housekeeping" as a brief outline of what should be considered to ensure that environmental releases of ODS through all media are minimized. This Code is also intended to provide a framework of practices and measures that should be adopted at facilities undertaking the destruction of ODS.

Not all measures will be appropriate to all situations and circumstances, and as with any Code, nothing specified should be regarded as a barrier to the adoption of better or more effective measures if these can be identified.

5.5.1 Predelivery

This refers to measures that may be appropriate prior to any delivery of ODS to a facility.

- Facility operator to generate written guidelines on ODS packaging/containment criteria, together with labelling and transportation requirements. These guidelines to be provided to all suppliers/senders of ODS prior to agreement to accept such substances.

- Facility operator to seek to visit and inspect proposed senders stocks and arrangements prior to movement of the first consignment. This is to ensure awareness on the part of the sender of proper practices, and compliance with standards.

5.5.2 Arrival at Facility

This refers to measures to be taken at the time ODS are received at the facility gate.

- Immediate check of documentation prior to admittance to facility site, coupled with preliminary inspection of the general condition of the consignment.
- Where necessary, special or "fast-track" processing/repackaging facilities may be needed to mitigate risk of leakage/loss of ODS.
- Arrangements should exist to measure gross weight of consignment at the time of delivery.

5.5.3 Unloading from Delivery Vehicle

This refers to measures to be taken at the facility in connection with unloading ODS. It is generally assumed that ODS will normally be delivered in some form of container, drum, or other vessel that is removed from the delivery vehicle in total. Such containers may be returnable.

- All unloading activities should be carried out in properly designated areas, to which restricted personnel access applies.
- Areas should be free of extraneous activities likely to lead to, or increase the risk of, collision, accidental dropping, spillage etc.
- Materials should be placed in designated quarantine areas for subsequent detailed checking and evaluation.

5.5.4 Testing and Verification

This refers to the arrangements for detailed checking of the consignments of ODS prior to destruction.

- Detailed checking of delivery documentation should be done, along with a complete inventory, to establish that delivery is as advised and appears to comply with expectation.
- Detailed checks of containers should be made both in respect of accuracy of identification labels etc, and of physical condition and integrity. Arrangements must be in place to permit repackaging or "fast-track" processing of anything identified as defective.
- Sampling and analysis of representative quantities of ODS consignments should be carried out to verify material type and characteristics. All sampling and analysis should be carried out using approved procedures and techniques.

5.5.5 Storage and Stock Control

This refers to matters concerning the storage and stock control of ODS.

- ODS materials should be stored in specially designated areas, subject to the regulations of the relevant local authorities.
- Locations of stock items should be identified through a system of control that should also provide a continuous update of quantities and locations as stock is destroyed, and new stock is delivered.

5.5.6 Measuring Quantities Destroyed

- It is important to be aware of the quantities of ODS processed through the destruction equipment. Where possible, flow meters or continuously recording weighing equipment for individual containers should be employed. As a minimum, containers should be weighed "full" and "empty" to establish quantities by difference.

- Residual quantities of ODS in containers that can be sealed, and are intended to be returned for further use, shall be allowed. Otherwise, containers shall be purged of residues and/or destroyed as part of the process.

5.5.7 Facility Design

This refers to basic features and requirements of plant, equipment, and services deployed in the facility.

- In general, any destruction facility should be properly designed and constructed in accordance with the best standards of engineering and technology, and with particular regard to the need to minimize, if not eliminate, fugitive losses.

- ODS Pumps: Magnetic drive, sealess, or double mechanical seal pumps should be installed to eliminate environmental releases resulting from seal leakages.

- Valves: Valves with reduced leakage potential should be used. These include quarter-turn valves or valves with extended packing glands.

- Tank Vents (including Loading Vents): Filling and breathing discharges from tank/vessels should be recovered or vented to a destruction process.

- Piping Joints: Screwed connections should not be used, and the number of flanged joints should be kept to a minimum that is consistent with safety and the ability to dismantle for maintenance and repair.

- Drainage Systems: Areas of the facility where ODS are stored or handled should be provided with sloped concrete paving and a properly designed collection system. Water that is collected should, if contaminated, be treated prior to authorized discharge.

5.5.8 Maintenance

- In general, all maintenance work should be performed according to properly planned programs, and should be executed within the framework of a permit system to ensure proper consideration of all aspects of the work.

- ODS should be purged from all vessels, mechanical units, and pipework prior to the opening of these items to the atmosphere. The contaminated purge should be routed to the destruction process, or treated to recover the ODS.

- All flanges, seals, gaskets and other sources of minor losses should be checked routinely to identify developing problems before containment is lost. Leaks should be repaired as soon as possible.

- Consumable or short-life items, such as flexible hoses and couplings must be monitored closely, and replaced at a frequency that renders the risk of rupture negligible.

5.5.9 Quality Control and Quality Assurance

- All sampling and analytical work connected with the ODS, the process, and the monitoring of its overall performance should be subject to quality assessment and quality control measures in line with some recognized practices. This should include at least occasional independent verification and confirmation of data produced by the facility operators.

- Consideration should also be given to the adoption of quality management systems and environment quality practices covering the entire facility.

5.5.10 Training

- All personnel concerned with the operation of the facility (with "operation" being interpreted in its widest sense) should have training appropriate to their task.

- Of particular relevance to the ODS destruction objectives is training in the consequences of unnecessary losses, and training in the use, handling, and maintenance of all equipment in the facility.

- All training should be carried out by suitably qualified and experienced personnel, and the details of such training should be maintained in written records. "Refresher" training should be conducted at appropriate intervals.

5.6 Code of Transportation

In the interest of protecting the stratospheric ozone layer, it is essential that used ODS and products containing ODS be collected and moved efficiently to facilities practicing approved destruction technologies. For transportation purposes, used ODS should receive the same hazard classification as the original substances or products. The following proposed code of transportation for ODS from customer to destruction facilities is provided as a guide to help minimize damage caused to the ozone layer as a result of ODS transfers.

It is important to supervise and control all shipments of used ODS, and products containing ODS, according to national and international requirements to protect the environment and human health. To ensure that ODS and products containing ODS do not constitute an unnecessary risk, they must be properly packaged and labelled. Instructions to be followed in the event of danger or accident must accompany each shipment to protect human beings and the environment from any danger that might arise during the operation.

Notification of the following information must be provided at any intermediate stage of the shipment from the place of dispatch until its final destination. When making notification, the notifier shall supply the information requested on the consignment note, with particular regard to:

- The source and composition of the ODS, and products containing ODS, including the customer's identity;

- Arrangements for routing and for insurance against damage to third parties;

- Measures to be taken to ensure safe transport and, in particular, compliance by the carrier with the conditions laid down for transport by the member states concerned;

- The identity of the consignee, who should possess an authorized centre with adequate technical capacity for the destruction; and

- The existence of a contractual agreement with the consignee concerning the destruction of ODS and products containing ODS.

This code of transportation does not apply to the disposal of ODS-containing rigid insulation foams. The most appropriate way to dispose of such products may be by incineration in municipal waste incinerators.

5.7 Monitoring

Where national standards do not exist, the TAC recommends adoption of the following monitoring guidelines to ensure that destruction processes operating with an approved technology meet the suggested minimum standards contained in this report:

- All sampling and analysis of ODS and other required pollutants, including dioxins and furans, shall be carried out using ISO-standards.

- ISO-standards for reference measurement methods and the calibration of automatic measurement systems shall also be applied.

- Parties may use their own standards after having demonstrated that the results are comparable with results using ISO-standards.

- While awaiting the elaboration of ISO-standards, national standards shall apply.

- If no national or ISO-standards are available corresponding US EPA-methods can be used.

5.7.1 Measurement of ODS

Operators of destruction facilities should take all necessary precautions concerning the storage and inventory control of ODS containing material received for destruction. Prior to feeding the ODS to the approved destruction process, the following procedures are recommended:

- The mass of the ODS containing material must be determined.

- Representative samples should be taken where appropriate to verify that the concentration of ODS matches the description given on the delivery documentation.

- Samples should be analyzed by an approved method. If no approved methods are available, the adoption of US EPA methods 5030 and 8240 is recommended.

- All records from these mass and ODS concentration measurements must be documented and kept in accordance with ISO 9000 or equivalent.

5.7.2 Control Systems

Operators shall ensure that destruction processes are operated efficiently to ensure complete destruction of ODS to the extent that it is technically feasible for the approved process. This shall include the use of appropriate measurement devices and sampling techniques to monitor the operating parameters, burn conditions, and mass concentrations of the pollutants that are generated by the process.

Gaseous emissions from the process must be monitored and analyzed using appropriate instrumentation. This should be supplemented by regular spot checks using manual stack-sampling methods. Other environmental releases, such as liquid effluents and solid residues, require laboratory analysis on a regular basis.

The continuous monitoring recommended for on-going process control, including off-gas cleaning systems, is as follows:

- Measurement of appropriate reaction and process temperatures.

- Measurement of flue gas temperatures before and after the gas cleaning system.

- Measurement of flue gas concentrations for oxygen and carbon monoxide.

Any additional continuous monitoring requirements are subject to the national regulatory authority that has jurisdiction. The performance of on-line monitors and instrumentation systems must be periodically checked and validated. When measuring detection limits, error values at the 95% confidence level must not exceed 20%.

At no time during the destruction process must the measured pollutants exceed the acceptable minimum standards stated in this report. The approved processes must be equipped with automatic cut-off control systems on the ODS feed system, or be able to go into standby mode whenever:

- The temperature in the reaction chamber is below 850°C.

- The required minimum destruction conditions stated in the performance specifications cannot be maintained.

5.7.3 Performance Measurements

The ODS destruction efficiency, for a process within an approved facility, as well as for other environmental releases, shall be validated at least once every 3 years. Once a destruction facility has been fully commissioned (new or rebuilt) the process must undergo a complete validation to ensure that all facility characteristics are completely documented and demonstrated to meet UNEP requirements. At least three test runs per condition shall be used to determine the limitation of ODS concentrations in the feed and the optimum facility operating conditions. Only those test runs for the optimum condition need to be reported to the appropriate regulatory body.

Tests shall be done with known feed rates of a given ODS-compound or with well-known ODS mixtures. In cases where a destruction process incinerates halogen containing wastes together with ODS, the total halogen load shall be calculated and controlled. Three tests results, each of at least 6 h duration must be completed.

The destruction efficiency (DE) recommended means that less than 0.1 g of total ODS will enter the environment from flue gas emissions, liquid effluents, and solid residues, when 1000 gram ODS are fed into the process. A detailed analysis of stack test results should be made available to verify emissions of halogen acids and PCDD/PCDF. In addition, a site-specific test protocol should be prepared and made available for inspection by the appropriate regulatory authorities. The sampling protocol shall report the following data from each test:

- ODS feed rate,

- Total halogen load in the waste stream,

- Residence time for ODS above 850°C,

- Oxygen content in flue gas,

- Gas temperature in combustion chamber,

- Flue gas flow rate,

- Carbon monoxide in flue gas,

- ODS content in flue gas,

- Effluent volumes and quantities of solid residues discharged,

- ODS concentrations in the effluent and solid residues, and

- Concentration of PCDD/PCDF, dust, HCl, HF, and HBr in the flue gases.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS, AND PROPOSALS

6.1 Conclusions

6.1.1 Environmental Implications

The latest science on the pace of ozone layer depletion, and the emerging evidence of consequent damage to human health and the environment, add increased impetus to the establishment and implementation of a global ODS destruction program under the auspice of UNEP. The strong possibility of a further acceleration of internationally agreed reductions in consumption of ODS, under the amended Montreal Protocol, make it probable that the time frame for the establishment of the destruction program is much shorter than was originally thought.

6.1.2 Technologies

The only processes currently recommended for approval by the TAC are within the thermal oxidation category. Six processes are recommended, however, not all may be appropriate for all classes of ODS. The processes recommended for approval are:

- ***Liquid Injection Incinerators;***
- ***Reactor Cracking;***
- ***Gaseous/Fume Oxidation;***
- ***Rotary Kiln Incinerators;***
- ***Cement Kilns; and***
- ***Municipal Solid Waste Incinerators (foam only).***

6.1.3 ODS Global Destruction Capacity

The Committee has come to the preliminary conclusion that worldwide destruction capacity of ODS by approved technologies is inadequate to destroy the estimated global quantities of banked material available for destruction. This conclusion is uncertain due to the questionable validity of various assumptions made on the estimates of available destruction capacity, and on the potential quantities of ODS to be destroyed.

6.1.4 Environmental Issues

The TAC assessed monitoring requirements and associated standards for ODS destruction to identify potential risks to the environment, and to avoid environmental degradation that could be caused by destruction processes. The areas of concern addressed by the TAC were: air emissions of toxic substances and acid gases; fugitive losses of ODS; liquid effluents; and solid residues. In addition, impacts on other major environmental issues such as global warming and acid deposition were also considered. However, the use of well-designed and operated destruction processes and the application of the suggested minimum standards given in Chapter 5 of this report, should ensure that the potential for damage to the environment is kept to a minimum.

6.1.5 Approval Procedures for Emerging Technologies

Emerging and innovative new technologies offer the possibility of increasing global destruction capacity while potentially reducing the costs of ODS destruction. Furthermore, such technologies may provide a good solution to the problem of establishing destruction facilities in those countries where they are not yet available. Chapter 4 of this report contains the recommended approval mechanism for emerging technologies.

6.2 Recommendations

The TAC offers the following recommendations for consideration by the Parties to the Montreal Protocol:

1. In view of the accelerating pace of ODS phase-out, it is recommended that a high priority be given to the establishment of a UNEP sanctioned ODS destruction program under the Montreal Protocol.

2. Thermal oxidation in liquid injection incinerators, reactor cracking, gaseous/fume oxidation, rotary kiln incinerators, cement kilns, and municipal solid waste incinerators (foams only) are technologies for destruction of ODS that are recommended for approval.

3. Due to the uncertainties involved in assessing the global quantities of ODS banked for destruction and global destruction capacity, the TAC urges the UNEP Ozone Secretariat to establish an advisory Committee or a subgroup to meet on a periodic basis to:

- ***reassess ODS destruction capacities;***
- ***evaluate emerging technology submissions;***
- ***review report submissions; and***
- ***prepare recommendations for the annual review of the Parties.***

4. The minimum standards for air emissions, liquid effluents, and residue disposal given in Chapter 5 of this report are recommended for adoption by those countries that do not have such standards.

5. Parties to the Montreal Protocol should actively encourage, and perhaps provide an incentive for, research and development in emerging technologies for ODS destruction.

6. Destruction facilities that use approved technologies should submit appropriate test data, which demonstrate achievement of the DE standard and compliance with the environmental standards defined in this report, to their national regulatory agency.

7. National regulatory agencies should submit to the Ozone Secretariat a list of approved destruction facilities, along with annual reports of ODS quantities destroyed in accordance with Article 7.1 of the Montreal Protocol.

8. Parties to the Montreal Protocol that operate, or plan to establish, ODS destruction facilities in their countries should commit themselves to enforce compliance with the destruction efficiency and environmental standards defined in this report.

9. The Code of Good Housekeeping procedures described in this report should be utilized by destruction facility operators to minimize environmental losses of ODS.

6.3 Proposals to the Montreal Protocol

The TAC recommends that the following proposals be approved either as an amendment or as a clarification decision by the Parties to the Montreal Protocol with respect to the destruction of ODS:

Proposal 1

Paragraph 5 of Article 1 of the Montreal Protocol states the following:

"Production" means the amount of ODS produced, minus the amount destroyed by technologies to be approved by the parties and minus the amount entirely used as feedstock in the manufacture of other chemicals. The amount recycled and reused is not to be considered as "production."

The TAC understands that destruction technologies and feedstock uses are both legal ways to eliminate ODS and in principle both ways should meet the same criteria. However, the recommendation for a destruction efficiency of ≥99.99% is not appropriate for feedstock processes because they are generally much less efficient. Therefore, it is recommended that unconverted ODS from a feedstock process be destroyed by an approved destruction technology to be fully exempt from production.The recommended DE of ≥99.99% is appropriate for thermal oxidation type processes. This DE applies to the input and output of the destruction processes itself, and not to the rest of the facility. Consequently, to minimize environmental losses of ODS, the TAC developed a Code of Good Housekeeping procedures for destruction facilities. It is recommended that a similar Code be used to minimize environmental losses of ODS from feedstock facilities.

Proposal 2

Several chemical processes produce substantial quantities of ODS as an unintentional by-product. For these processes to continue operating after the phase-out of ODS, an acceptable method for handling by-product ODS must be available. The TAC recommends that unintentional by-product ODS be handled as recommended in Proposal 1.

APPENDIX A. COMMERCIAL/PUBLIC HAZARDOUS WASTE INCINERATORS.

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Comment
CANADA	Swan Hills	Swan Hills, Alta.	1 x RK + 1 x Rocking	19,000	
	Laidlaw	Montreal, Que.	Liq. Inj.	40,000	Limited to 0.2% Cl
	Laidlaw	Sarnia, Ont.	Liq. Inj.	50,000	Limited to 2.0% Cl
UNITED STATES	Rollins Environmental	Bridgeport, CT	1 x RK + AB		
	Rollins Environmental	Baton Rouge, LA	1 x RK + AB	24,100	
	Rollins Environmental	Deer Park, TX	2 x RK + AB	89,100	1% F max
	Chemical Waste Mgmt.	Chicago, IL	1 x RK + AB		
	Chemical Waste Mgmt.	Port Arthur, TX	1 x RK + AB	136,400	
	Tradewaste Incineration	Sauget, IL	1 x RK + AB	14,400	0.45% F max
	Aptus	Coffeyville, KS	1 x RK + AB		
	Aptus	Aragonite, UT	1 x RK + AB		
	GSX	Roebuck, SC	Liq. Inj.	41,800	10% Cl max
	Ross	Grafton, OH	1 x RK + AB		
	Ensco	El Dorado, AR	1 x RK + AB	11,400	
	LWD	Calvert City, KY	1 x RK + AB	28,200	
	LWD	Calvert City, KY	Liq. Inj.	13,200	
	Stauffer (Rhone Poulenc)	Hammond, IN	Liq. Inj.		

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Comment
UNITED STATES (cont'd)	Stauffer (Rhone Poulenc)	Baton Rouge, LA	Liq. Inj.		
	Thermal KEM	Rock Hill, SC			
UNITED KINGDOM	Rechem International	Fawley	1 x RK + AB	40,000	
	Rechem International	Pontypool	Multiple Chamber	30,000	
	Cleanaway Ltd.	Ellesmere Port	1 x RK + AB	50,000	
	Leigh Environmental	Killamarsh, Derbyshire	Liq. Inj.	20,000	
GERMANY	Hessiche-Industriemull (HIM)	Biebesheim	3 x RK + AB	60,000	
	Edelhoff-Stadtereinigung	Bramsche	1 x Liq. Inj.	12,000	100 t/year Cl
	Gesellschaft BS in Bayern (GSB)	Ebenhausen-Baars	2 x RK + AB	80,000	
	Abfallverbrennungs-gesellschaft (AVG)	Hamburg	2 x RK + AB	100,000	
	Gesellschaft fur Abfallbeseitigung (AGR)	Herten-Sud	2 x RK + AB	60,000	
	Zweckverband Sondermullplatze (ZVSMM)	Schwabach	1 x RK + AB	30,000	10% Cl max
	GSB	Schweinfurt	2 x RK + AB	75,000	10% Cl max

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Comment
GERMANY (cont'd)	Brandenburg (SMVA)	Schoneiche	1 RK + AB	30,000	
NETHERLANDS	AVR-Chemie	Rozenburg	2 x RK + AB	100,000	4500 t/year CCl_4, 450 t/year CFC, 450 t/year Halon
FRANCE	TREDI	Homborg Center	Liq. Inj.	3,000	
	SARP Industrie	Limay Center	2 x Liq. Inj.	80,000	5 to 7% Halogen
	GEREP	Mitry-Compans Center	Liq. Inj.	25,000	7% Halogen
	TREDI	Saint Vulbas Center	1 x RK + AB	30,000	25 to 60% Halogen
	EMC Group	Strasbourg	1 x RK	40,000	2% Halogen
	EMC Group	Salaise	2 x RK	82,000	2 to 25% Halogen
	SARP/SIAP	Bassens	1 x RK	23,000	5 to 7% Halogen
	SOLAMAT	Rognac	1 x RK	40,000	2 to 5% Halogen
SWEDEN	SAKAB	Norrtorp, Kumla	1 x RK + AB	42,000	
DENMARK	Kommunekemi	Nyborg	2 x RK + AB	95,000	1% Cl max
FINLAND	Finlands Problemavfall	Riihimaki	2 x RK + AB	88,000	
AUSTRIA	EBS	Vienna	2 x RK	90,000	
JAPAN	Kanegafuchi	Takasago, Hyogo	Liq. Inj. (LW-PCB) Liq. Inj. (LW-LE & -HE)	4,500 8,000	

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Comment
JAPAN (cont'd)	Osaka Kankyo Shori Center	Sakai and Osaka	2 x RK + AB	54,000	
			1 x Batch	63,000	
	Kowa Seiko	Kitakyushu/Fukuoka	1 x RK + AB	25,200	Cl - cmpds max 100%
			2 x Liq. Inj.		
	Kureha Kankyo	Iwaki/Fukushima	1 x RK + AB	22,400	
			1 x Fixed Bed	2,200	
	Kanbara Tank Cleaning	Fukuyama/Hiroshima	2 x RK + AB	126,000	Cl max 50%
					F max 3%
	Nomura Kosan	Rubeshibe/Hokkaido	1 x Liq. Inj.	280	Cl max 5%
	Miyama	Nakano/Nagano	1 x RK + AB	13,400	Cl max 1.0%
			1 x Fixed Bed	1,300	F + Cl max 1.0%
BELGIUM	Indaver NV	Antwerpen	1 x Liq. Inj.	10,000	Limited ODS capacity
			1 x RK + AB	50,000	Substantial ODS capacity

APPENDIX B. CAPTIVE HAZARDOUS WASTE INCINERATORS

APPENDIX B. CAPTIVE HAZARDOUS WASTE INCINERATORS.

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Chlorinated Capacity (t/year)	Fluorinated Capacity (t/year)
BELGIUM	John Zink France 0390 04	Jemeppe	Gas (VC + DC)			N/A
CANADA	3M Canada	London, Ont.	1 * RK	22,000		
	Ford Motor	Oakville, Ont.	1 * RK	23,000		
	General Motors	Oshawa, Ont.	1 * RK	63,000		
	DOW Canada	Fort Sask., Alta.	Liq./Gas Inj.	80,000	80,000	N/A
	DOW Canada	Sarnia, Ont.	Liq./Gas Inj.	40,000	40,000	N/A
CHINA	Shanghai Chlor-Alkali	Shanghai	Liq./Gas Inj.			120
	Shanghai Insecticide	Shanghai	Liq./Gas Inj.		144	
	Lian-yun-gang Insecticide	Jiang-Su	Liq./Gas Inj.		144	
	Hang-Zhou Insecticide	Zhe-Jiang	Liq./Gas Inj.		144	
	Jie-nan Chemical	Shang-don	Liq./Gas Inj.			96
	Hong-he Chemical	Si-chuan	Liq./Gas Inj.		144	
	He-jiang Natural Gas Plant	Si-chuan	Liq./Gas Inj.		144	
	Chong-qing Insecticide	Si-chuan	Liq./Gas Inj.		144	
	Chen-guang Chemical	Si-chuan	Liq./Gas Inj.			80
	Zhu-Zhou Chemical	Hu-nan	Liq./Gas Inj.			96
	Xing-huo Chemical	Jiang-xi	Liq./Gas Inj.			96

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Chlorinated Capacity (t/year)	Fluorinated Capacity (t/year)
CHINA (cont'd)	Fu-xin 611th Factory	Liao-ning	Liq./Gas Inj.			120
UNITED STATES	DuPont Chambers Works	Deepwater, NJ	Liq. Inj			
	ICI Americas	Bayonne, NJ	Liq. Inj			
	Ausimont	Thorofare, NJ	Liq. Inj	2,800	N/A	240.8
	Atochem	Calvert City, KY	Liq. Inj			
	Vulcan Chemicals	Wichita, KS	Liq. Inj	2,000	20	N/A
	Vulcan Chemicals	Geismar, LA	Liq. Inj	16,600	3,320	N/A
	PPG Industries	Lake Charles, LA				
	Dow Chemical USA	Freeport, TX				
	Dow Chemical USA	Plaquemine, LA				
	Dow Chemical USA	Pittsburg, CA				
	IT/McGill Job 130318	Burkville, AL	Liq. Inj.		unknown	unknown
	IT/McGill Job 130205	Theodore, AL	Liq. Inj.		unknown	N/A
	IT/McGill Job 130069	Palo Alto, CA	Gaseous/Fume Incin.		unknown	N/A
	IT/McGill Job 130184	Vine Hill, CA	Liq. Inj.		unknown	unknown
	IT/McGill Job 70749	Calvert City, KY	Liq. Inj.		unknown	N/A
	IT/McGill Job 130231	St. Gabriel, LA	Liq. Inj.		unknown	N/A
	IT/McGill Job 130076	Hamilton, MS	Gaseous/Fume Incin.		unknown	N/A
	IT/McGill Job 130215	Greenville, NC	Liq. Inj.		unknown	N/A
	John Zink SO 37837	Richmond, CA	Liq. Inj.		unknown	N/A

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Chlorinated Capacity (t/year)	Fluorinated Capacity (t/year)
UNITED STATES (cont'd)	John Zink SO 40068	Muskegon, MI	Liq. Inj.		unknown	N/A
	John Zink SO 40774	Baltimore, MD	Liq. Inj.			
	John Zink SO 52237	Houston, TX	Liq. Inj.			
	John Zink SO 71361	Mt. Pleasant, TN	Liq. Inj.			
	John Zink SO 91582	Geismar, LA	Liq. Inj.			
	John Zink SO 91880	Lake Charles, LA	Gaseous/Fume Incin.			
	John Zink SO 97418	Garyville, LA	Gaseous/Fume Incin.			
	John Zink TG-S73874	Chambersworks, NJ	Gaseous/Fume Incin.			
	John Zink TG-S72478	Institute, WV	Gaseous/Fume Incin.			
NETHERLANDS	Shell	Botlek	Liq. Inj	8,000	8,000	N/A
	Akzo	Botlek	Liq. Inj	33,000	33,000	N/A
	Akzo	Delfzijl	Liq. Inj	11,000	11,000	N/A
	ARAMI	Delfzijl	Liq. Inj	825	825	N/A
FRANCE	John Zink France 1282 01	Tavaux	Gaseous (VCM)		unknown	N/A
	John Zink France 0787 01	Couternes	Liq. Inj.			N/A
JAPAN	Asahi Glass	Chiba & Kashima/Ibaraki	3 x Liq. Inj.	11,500	11,200	280
	TOSOH	Shinnanyo/ Yamaguchi	1 x Liq. Inj.	20,200	12,100	

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Chlorinated Capacity (t/year)	Fluorinated Capacity (t/year)
JAPAN (cont'd)	Daikin	Osaka	1 x Fixed Bed	840		1.68
	Kanto Denka	Shibukawa/Gunma	1 x Liq. Inj.	900	600	
	Mitsui Toatsu	Nagoya/Aichi	1 x Liq. Inj.	5,600	5,500	
SPAIN	Hoechst Iberica					
	Atochem Espana					
BRAZIL	Dupont Brazil					
	Hoechst do Brazil					
	Dow Chemical					
GERMANY	Schering	Bergkamen	RK + AB	12,500		
	Hoechst	Frankfurt/Main	2 x RK	44,000		1,600
	Bayer	Brunsbuttel		20,000		
	IMC-Chemie	Ibbenburen		372		
	Richard Buchen	Koln		3,120		
	Ford-Werke	Koln	Roller grate	31,000		
	Bayer	Krefeld	2 x RK	30,000		
	Bayer	Leverkusen	2 x RK Multiple hearth furnace	a) 40,000 b) 30,000 c) 45,000	a) 6,000 b) 0 c) 9,000	
	Dynamit Nobel	Leverkusen		26,000		
	BASF	Ludwigshafen	7 x RK	170,000		
	Behring-Werke	Marburg	RK	8,400		
	Chemisch Werke Hüls	Marl	RK	17,000		

Country	Name	Location	Type of Unit	Total Capacity (t/year)	Chlorinated Capacity (t/year)	Fluorinated Capacity (t/year)
GERMANY (cont'd)	BASF Farben und Fasern	Munster-Hiltrup	RK	7,000		
	Hoechst	Offenbach	2 x RK Liq. Inj.	35,000		
	Hoechst	Gendorf	Liq. Inj.	1,000	1,000	1,000
	Richard Buchen	Wesseling				
	UR Braunkohlen-kraftstoffe	Wesseling				
	Wacker-Chemie	Burghausen/Selzach	2 Muffle furnaces, RK	33,000		
	Widdig	Neiderkassel	RK	2,000		
	DOW Deutschland	Stade	RK	30,000 (30-60%)		
	Kali-Chemie					
CZECHOSLOVAKIA	Spolana	Nerotovice	Liq. Inj.			
KOREA	Posco					
	Lucky Advanced Material					
	Han Yang Chemical					
	Korea Pacific Chemical Corp.					
	John Zink TG-S67589	Yeochunchi	Gaseous/Fume Incin.			
THAILAND	John Zink France WD 0690 01	Map Ta Phut	Gaseous/Fume Incin.			
	TPC					

APPENDIX C. POTENTIAL DESTRUCTION TECHNOLOGIES

APPENDIX C. POTENTIAL DESTRUCTION TECHNOLOGIES.

General Category Name	Subcategory	DE	Recovery of By-products	Status	Recom-mend for Approval	Country	Source
A. Thermal Oxidation	1. Gaseous Liquid Thermal Oxidation/Hydrolysis						
	● Liquid Injection Incineration (On-Site or Off-Site Commercial)	≥99.99%	Occasionally	Commercial	Yes	Several	
	● Reactor for cracking CFCs/HCFCs/HFCs	≥99.99%	Yes	Commercial	Yes	Germany	Hoechst, AG
	● Gaseous/Fume Oxidation	≥99.99%	Occasionally	Commercial	Yes	Several	AK 20
	2. Rotary Kiln (On-Site or Off-Site Commercial)						
	● Hazardous Waste Incinerator	≥99.99%	Occasionally	Commercial	Yes	Several	
	3. Multipurpose (MSWI)						
	● Incineration of PUF with MSWI	≥99.99%	No	Full-scale testing	Yes	Several	Kernforschungs zentrum
	4. Cement Kilns	≥99.99%	No	Commercial for other wastes	Yes	Several	

General Category Name	Subcategory	DE	Recovery of By-products	Status	Recom-mend for Approval	Country	Source
	5. Miscellaneous						
	● Fluidized Bed	Unknown	Unknown	Commercial for other wastes	No	USA	Ogden Environ. (Circul. Bed)
	● Waste Gasification	Not reported	No	Mobile demo unit	No	Austria	Voest-Alpine
	● Controlled Combustion (Burn Boxes)	Unknown	No	Commercial for other wastes	No	USA	MG Indst; CEMI
B. Catalytic Processes	1. Oxidation						
	● HDC Catalyst	≥99%	No	Commercial for other wastes	No	USA	Allied-Signal Industrial Catalyst
	● Direct Catalytic Oxidation	≥99%	No	Development	No	Japan	NIRE
	● Catalytic Decomposition	Approx. 100%	No	Lab Scale	No	Japan	Kyoto University
	● Catalytic Hydrolysis	Approx. 100%	No	Lab scale	No	Japan	NIRE

General Category Name	Subcategory	DE	Recovery of By-products	Status	Recom-mend for Approval	Country	Source
	2. Hydrogenation						
	● Selective Hydrodechlorination	80-100%	Yes	Lab Scale	No	Japan	Hokkaido University
	● Direct Contact Hydrogenation	Unknown	Unknown	Bench Scale	No	USA	UOP
C. Pyrolysis	Rotary Kiln	Unknown	Possible	Unknown	No	Germany	FBD/BKMI
D. Chemical Destruction	1. Reaction with Elemental Metals						
	● Chemical Destruction of CFCs with Sodium	≥99%	Not presently	Lab Scale	No	Germany	Degussa
	● Reductive Destruction by Dehalogenation	≥99%	No	Lab Scale	No	Japan	Kyoto Institute of Technology
	● Steel Smelter	Unknown	No	Unknown	No	Germany	Dornier
	● Molten Iron Reactor	≥99.9999%	Yes	Bench Scale	No	USA	MMT,Inc. (Molten Metal Technology)
	● P-CIG (Molten Iron)	Unknown	No	Pilot plant/demo plant	No	Sweden	MEFOS

General Category Name	Subcategory	DE	Recovery of By-products	Status	Recom-mend for Approval	Country	Source
	2. Reaction with Metal Oxides						
	● Chemical-thermal destruction with $CaAl_2O_3$ or SiO_4	≥99- 99.999-9%	Yes, HCl	Pilot plant	No	Germany	Nukem
	● Metal Oxide Conversion (pebble bed)	≥99.999%	No	Lab Scale	No	Australia	CSIRO
E. Super-critical Water Oxidation	1. Supercritical Water Hydrolysis	Approx. 100%	No	Lab Scale	No	Japan	NCLI
	2. Supercritical Water Oxidation	≥97%	No	No demo unit	No	USA	ABB Lummus-Crest/MODAR
F. Wet Air Oxidation	Wet Air Oxidation	≥99%	No	Commercial	No	USA	ZIMPRO
G. Plasma Destruction	1. Corona Discharge	Unknown	No	Pilot Scale	No	USA	US EPA
	2. Inductively-Coupled R.F. Plasma	≥99.9%	No	Pilot Scale	No	Japan	NIRE
	3. Thermal Plasma	Unknown	No	Lab Scale	No	Japan	Tokyo Institute of Technology
	4. Plasma Arc	Unknown	No	Pilot Scale	No	Australia	CSIRO

General Category Name	Subcategory	DE	Recovery of By-products	Status	Recom-mend for Approval	Country	Source
H. UV Photolysis	1. Photochemical Degradation	Unknown	No	Unknown	No	Japan	NCLI
	2. Decomposition by UV Irradiation	Approx. 100%	No	Lab Scale	No	Japan	Toshiba R&D
	3.(Photo-) Dechlorination	Approx. 100%	No	Lab Scale	No	Japan	Hosei University
	4. Photocatalytic Degradation	Unknown	No	Unknown	No	USA	Nutech & Sandia
	5. Photochemical Oxidation	≥95-99%	Unknown	Lab Scale	No	USA	Process Technologies, Inc.
I. Biological Processes	1. Degradation by Microbial Treatment	Approx. 100%	No	Lab Scale	No	Japan	NIES
J. High Energy Radiation	1. Conversion by Ionic Radiation	Unknown	Yes, HCFCs/ HFCs	Lab Scale	No	Japan	GIRIN

APPENDIX D

FEEDSTOCK PROCESSES

The following processes are considered feedstock processes.

Some examples for carbon tetrachloride (CCl_4) are:

- Catalytic Processes (Hydrogenation - Butamer process): In this process, CCl_4 is fed to the Butamer reactor (primarily used for isomerizing n-butane to isobutane) to maintain the activity of the Butamer catalyst (platinum). The CCl_4 is hydrogenated to CH_4, with formation of by-product HCl. Conversion efficiency is reported to be 99.99%.

- Perchloration: CCl_4 is used as a feedstock for production of perchloroethylene and hydrochloric acid. An example of this process is when CCl_4 is first used to recover Cl_2 from plant tail gas. This CCl_4 is later sent to the perchloration process. No data were available on conversion efficiency.

- Hydrogenation: CCl_4 is contacted with H_2 over a catalyst to form chloroform and HCl. This is a bench scale process.

For HCFC-22 only:

- Pyrolysis: This is a commercial process in a feedstock use, whereby HCFC-22 is non-catalytically pyrolyzed at 590-900°C to produce tetrafluoroethylene as a feedstock for polytetrafluoroethylene.

For HCFC-142b only:

- Pyrolysis: This is a commercial process in a feedstock use, whereby HCFC-142b is pyrolyzed to produce vinylidene fluoride as a feedstock for polyvinylidene fluoride. The HCFC-142 is produced with methyl chloroform as a feedstock.

For CFC-113 only:

- Catalytic Dechlorination: This is a commercial process in a feedstock use, whereby CFC-113 is reacted over a copper catalyst at 550°C to produce chlorotrifluoroethylene as a feedstock for polychlorotrifluoroethylene.

APPENDIX E. TRIAL BURN TEST DATA

The test burn data presented in this appendix are reproduced as submitted to the Committee.

pounds x 0.4536 = kilograms
tons (short) x 907.18 = kilograms
tons (long) x 101.6 = kilograms
BTU x 1055 = Joules
temp (°C) = 5/9 (temp °F - 32)

LIQUID INJECTION INCINERATORS

Facility: Ausimont (formerly Pennwalt)

Location (City, State): Thorofare, New Jersey

Test Dates: 6-19-89 to 6-22-89

Incinerator Type: Liquid Injection (T-Thermal LV-5 Sub-X)

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	HCFC-141b	27.17 lb/hr avg	99.993	3.47%

HCl: Emission Rate = 0.0834 lb/hr, 99.97% removal efficiency
2.69 ppm in off-gas
(HF = <0.29 ppm)

Particulate: 0.0063 gr/DSCF at 7 % O2

Waste Feeds:	Type	Feed Rate
Condition 1	Liquid/Gas	782 lb/hr

Test Run Time: unknown

Temperature: 2095 deg F

Residence Time (gas): 2.36 seconds (average for all three runs)

Comments:
Rated throughput: 9.42 short ton/day
5,000,000 BTU/hr firing rate

Facility: DuPont Central Scrubbed Incinerator

Location (City, State): La Porte, Texas

Test Dates: 08-12-88 to 10-05-88

Incinerator Type: Liquid injection

POHCs:	Compound Name:	Feed Rate:	DRE %:	% of Feed:
	CCl_4	Total Cl	99.99995	Total Cl
	o-dichlorobenzene (O-DCB)	550 lb/hr	99.99	1.5%

HCl:

Emission 0.75 lb/hr
Removal efficiency 99.9%

Particulate: 0.038 gr/DSCF at 7% O_2

Waste Feeds:	Type:	Feed Rate:
	Aqueous	45 gal/min
	Organic	4.5 gal/min

Test Run Time: 2 to 7 hours

Temperature: 1858 deg F

Residence Time (gas): Not available

Comments: DRE for O-DCB was below 99.99 for 5 out of 21 runs.

Facility: E. I. duPont de Nemours and Company Inc. incinerator

Location (City, State): Louisville, Kentucky

Test Dates: 03-31-87 to 04-04-87

Incinerator Type: Liquid injection incinerator with 2 cooling chambers, 3 falling-film absorbers, a fume scrubber, mist eliminator and induced draft fan.

POHCs:	Compound Name:	Feed Rate:	DRE %:	% of Feed:
	CCl_4	Total HCl input 976 lb/hr	99.9959	47%
	Toluene		99.9964	

HCl: Emission rate 13.2 lb/hr (removal efficiency 98.61%)

Particulate: 0.184 gr/dscf at 7% O_2

Waste Feeds:	Type:	Feed Rate:
	Liquid organic waste	2,068 lb/hr

Test Run Time: Not available

Temperature: 1,075 deg C

Residence Time (gas): 0.3 sec

Comments: Numbers are average of seven runs. One run did not meet DRE criteria. Total heat input 18.5 MMBTU/hr.

Facility: GSX (Thermal Oxidation Corp.)

Location (City, State): Roebuck, South Carolina

Test Dates: 3-17-87 to 3-26-87

Incinerator Type: Liquid Injection incinerator with waste heat boiler, baghouse filter venturi quench, acid fume scrubber, demister

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CCl4	251.9 lb/hr	99.999	3.5%
	Tetrachloroethylen	321.6 lb/hr	99.999	4.4%
	Methyl Ethyl Keton	64.9 lb/hr	>99.999	0.9%
	CFC-11	600 lb/hr	99.999	8.3%

HCl: 0.241 lb/hr in off-gas
(Removal efficiency greater than 99.9% HCl)

Particulate: 0.00677 g/dscf at 7 % O2

Waste Feeds:	Type	Feed Rate
	Liquid	

Test Run Time: Approximately 1-1/2 hours

Temperature: 1,800 deg F

Residence Time (gas): unknown

Comments: 16,500,000 BTU/hr firing rate
(10 MMBTU/hr in vaporizer burner, 6.5 MMBTU/hr in oxidizer burner)

Facility: ICI Americas, Inc.				
Location (City, State): Bayonne, NJ				
Test Dates: 6-19-90				
Incinerator Type: Liquid Injection incinerator (LV-3 Incinerator)				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1:	HCFC-22	37.86 lb/hr	>99.9992	N/A
HCl: Condition 1:		0.01122 lb/hr		
Particulate:	0.0122 gr/DSCF		at 7 % O2	
Waste Feeds:	Type	Feed Rate		
Condition 1:	unknown	N/A		
Test Run Time:	1 hrs per run, 3 runs per condition			
Temperature:	unknown			
Residence Time (gas):	unknown			
Comments:				

Facility: Olin Chemicals

Location (City, State): Lake Charles, LA

Test Dates: May 14, 15, 16, 17 & 18, 1991

Incinerator Type: N/A

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Condition 1	Carbon Tetrachloride	38.2 lb/hr	99.995	1.2
Condition 2	Carbon Tetrachloride	63.1 lb/hr	99.997	1.3
Condition 3	Carbon Tetrachloride	58.2 lb/hr	99.995	1.3
Condition 4	Carbon Tetrachloride	44.9 lb/hr	99.997	1.0

HCl:			
	Condition 1	0.358 lb/hr	>99.99% Removal
	Condition 2	0.930 lb/hr	>99.99% Removal
	Condition 3	0.482 lb/hr	>99.99% Removal
	Condition 4	0.540 lb/hr	>99.99% Removal

Particulate:		at % O2
Condition 1	.002518 gr/dscf	
Condition 2	.007990 gr/dscf	7%
Condition 3	.008463 gr/dscf	
Condition 4	.0065557 gr/dscf	

Waste Feeds:	Type	Feed Rate
Condition 1	TDI	3156 lb/hr
Condition 2	TDI	4703 lb/hr
Condition 3	TDI	4510 lb/hr
Condition 4	TDI	4419 lb/hr

Test Run Time:

Approximately 2 hours per run per condition

Temperature: Condition 1 – 1969 F, Condition 2 – 2380 F
Condition 3 – 2249 F, Condition 4 – 2369 F

Residence Time (gas): N/A

Comments:

No Schematic Available

Facility: PPG Industries, Inc.

Location (City, State): Lake Charles, LA

Test Dates: March 3 & 4, 1988

Incinerator Type: Liquid Feed, 2 Incinerators

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Condition 1	Carbon Tetrachloride	944.718 lb/hr	99.9985	11.2%
Condition 2	Carbon Tetrachloride	709.221 lb/hr (total feed)	99.9991	8.8%

HCl:

Condition 1	0.00512 lb/hr	Primary and secondary scrubbers
Condition 2	0.00590 lb/hr	Primary and secondary scrubbers

Particulate: at % O2

N/A

Waste Feeds:	Type	Feed Rate
Condition 1		
Gas Vent Feed	Gas	66070 SCFH
Liquid Feed	Liquid	10.5 GPM
Condition 2		
Liquid Feed	Liquid	10.0 GPM
Gas Vent Feed	Gas	71222 SCFH

Test Run Time:

Run 1 – 1 hour
Run 2 – 1 hour
Run 3 – 1 hour

Temperature: Condition 1 – 2650 F both/Condition4 2 – 2443 F No. 1; 2401 F No. 2

Residence Time (gas): N/A

Comments:

Facility: Rechem International Ltd

Location (City, State): Pontypool, South Wales, UK

Test Dates: 16 and 23 May 1991

Incinerator Type: Multiple chamber (liquids chambers Used)
Wet Quench/alkali scrubber/2 Wet electrostatic
Precipitors/Plume Reheat.

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	Halon 1211	100 Kg/hr	> 99.9999	3.0
		332 Kg/hr	> 99.9999	10.0

HCI: < 2.0 mg/m3 HF < 1.0 mg/m3

Particulate: 25 mg/m3 (Range 20 -30) at % 02

Waste Feeds:	Type	Feed Rate
	Liquid + solid	Total Circa 2200 Kg/hr

Test Run Time: 100 Kg/hr 2 Hours / 332 Kg/hr 1 Hours

Temperature: 1130^{0}C

Residence Time (gas): 6 Seconds

Comments: No Free Bromine emission Detected

Facility: Rechem International Ltd				
Location (City, State): Pontypool, South Wales UK				
Test Dates: 24th October 1991 and 20th November 1991				
Incinerator Type: Multiple chamber (liquids chambers Used) Wet Quench/alkali scrubber/2 Wet electrostatic Precipitators/Plume Reheat.				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	Halon 1211	500 Kg/hr	> 99.9999	15.0
	Halon 1301	1000 Kg/hr	> 99.9999	30.0
HCI: < 2.0 mg/m3	HF < 1.0 mg/m3			
Particulate: Circa 30 mg/m3		at	% 02	
Waste Feeds:	Type	Feed Rate		
	Liquid + solid	Total Circa 3300 Kg/hr		
Test Run Time: About 1 hr each				
Temperature: 1140 - 1150^{0}C				
Residence Time (gas): 6 Seconds				
Comments: No Free Bromine emission Detected				

Facility: Shell Chemical

Location (City, State): Norco, LA

Test Dates: June 7, 8, 9, 1984

Incinerator Type: Liquid Injection

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Condition 1	Carbon Tetrachloride	9.09 gpm	>99.99	N/A
Condition 2	Carbon Tetrachloride	1.18 gpm	>99.99	N/A
Condition 1 (Retest)	Carbon Tetrachloride	9.12 gpm	>99.99	N/A

HCl:	Condition 1	.438 lb/hr	>99% removal
	Condition 2	.0015 lb/hr	>99% removal
	Condition 1 (R)	.563 lb/hr	>99% removal

Particulate:	at % O2
< 0.08 gr/DSCF (all tests)	7%

Waste Feeds:	Type	Feed Rate
N/A	N/A	N/A

Test Run Time:

N/A

Temperature: 1700 F (All tests)

Residence Time (gas): N/A

Comments:

No Schematic Available

Facility: Thermal KEM (formerly Stablex)				
Location (City, State): Rock Hill, South Carolina				
Test Dates: 12-01-86 to 12-06-86				
Incinerator Type: Liquid injection				
POHCs:	Compound Name:	Feed Rate:	DRE %:	% of Feed:
	CCl_4		99.993	Chloride 22.2%
	Trichloroethylene		99.996	
	Perchloroethylene		99.995	
HCl: Emission rate 0.99 lb/hr (removal efficiency 99.88%)				
Particulate: 0.062 gr/dscf		at 7% O_2		
Waste Feeds:		Type:	Feed Rate:	
		Liquid	1,828 lb/hr	
		Solid	1,891 lb/hr	
Test Run Time: 3 hours				
Temperature: 2,220 deg F				
Residence Time (gas): Not available				
Comments: Average of 5 runs.				

Facility: Velsicol Chemical Corporation Memphis Plant

Location (City, State): Memphis, Tennessee

Test Dates: 11-08-88 to 11-12-88

Incinerator Type: Liquid injection

POHCs:	Compound Name:	Feed Rate:	DRE %:	% of Feed:
	CCl_4 C_2Cl_4 C_2Cl_6 C_6Cl_6	Chlorine Feed rate 650 lb/hr	99.97 99.998 99.998 99.998	Chlorine 50.7%

HCl: 0.154 lbs/hr

Particulate: 0.0071 gr/dscf at 7% O_2

Waste Feeds:	Type:	Feed Rate:
		1282 lb/ hr

Test Run Time: Not available

Temperature: 2000 deg F

Residence Time (gas): Not available

Comments: Six runs. Three runs had DRE for CCl_4 below 99.99.

Facility: Vulcan Chemicals

Location (City, State): Wichita, Kansas

Test Dates: 4-16-91 to 4-19-91

Incinerator Type: Liquid Injection incinerator with waste heat boiler, water scrubber and caustic scrubber.

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	38.0 lb/hr avg	99.9981	5.61%
Condition 2	Carbon Tet	39.9 lb/hr avg	99.9949	4.53%

HCl: Condition 1: 0.432 lb/hr, 99.92% Removal
Condition 2: 0.944 lb/hr, 99.87% Removal

Particulate: 1: 0.0104 gr/DSCF at 7 % O2
Condition 2: 0.0123 gr/DSCF at 7 % O2

Waste Feeds:	Type	Feed Rate
Condition 1	Liquid/Gas	677 lb/hr
Condition 2	Liquid/Gas	880 lb/hr

Test Run Time:
Condition 1: Approx. 4.1 hr per run (3 runs per condition)
Condition 2: Approx. 4.9 hr per run (3 runs per condition)

Temperature:
1000 deg C

Residence Time (gas):
3 seconds

Comments:
Rated throughput: 6.0 short ton/day
3,000,000 BTU/hr firing rate

Reported PIC Emissions (PCDD/PCDF)

Facility: Vulcan Chemicals				
Location (City, State): Geismar, Louisiana				
Test Dates: 10-15-90 to 10-19-90				
Incinerator Type: Liquid Injection incinerator with water scrubber and caustic scrubber				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 2:	Carbon Tet	135.7 lb/hr	99.9999	N/A
Condition 3:	Carbon Tet	155.3 lb/hr	99.99988	N/A
HCl: N/A				
Particulate:	unknown		at	% O2
Waste Feeds:	Type	Feed Rate		
Condition 2:	Groundwater Phase	1801 lb/hr		
Condition 3:	Hex Feed	2076 lb/hr		
	Groundwater Phase	1522 lb/hr		
Test Run Time:	2 hrs per run, 3 runs per condition (6 hrs per condition)			
Temperature:	1093 deg C			
Residence Time (gas):	3 seconds			
Comments:	Rated throughput: 50 short ton/day 8,000,000 BTU/hr firing rate			

ROTARY KILN INCINERATORS

Facility: Aptus Environmental Services				
Location (City, State): Coffeyville, KS				
Test Dates: 8-15-90 to 8-30-90				
Incinerator Type: Rotary Kiln				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	422 lb/hr avg	99.9959	4.09%
Condition 2	Carbon Tet	631 lb/hr avg	99.9968	5.48%
Condition 3	Carbon Tet	419 lb/hr avg	99.9966	3.37%
HCl:	Condition 1	0.0967 lb/hr	99.99% removal	
	Condition 2	0.211 lb/hr	99.98% removal	
	Condition 3	0.408 lb/hr	99.96% removal	
Particulate:	Condition 1	0.0037 gr/DSCF	at	7 % O2
	Condition 2	0.0037 gr/DSCF	at	7 % O2
	Condition 3	0.0017 gr/DSCF	at	7 % O2
Waste Feeds:	Type	Feed Rate		
Condition 1	Liquid	10,310 lb/hr		
Condition 2	Liquid	11,521 lb/hr		
Condition 3	Liquid/Solids	12,428 lb/hr		
Test Run Time:	unknown			
Temperature:				
Condition 1	Kiln = 1502 deg F; SCC = 2128 deg F			
Condition 2	Kiln = 1494 deg F; SCC = 2166 deg F			
Condition 3	Kiln = 1568 deg F; SCC = 2071 deg F			
Residence Time (gas):	unknown			
Comments:	No compounds of interest for Condition 4			

Facility: Chemical Waste Management				
Location (City, State): Chicago, IL				
Test Dates: 7-6-89 to 7-11-89				
Incinerator Type: Rotary Kiln incinerator				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	317 lb/hr avg	99.9985	2.69%
HCl: Removal efficiency = 99.95% Emission rate = 0.76 lb/hr				
Particulate:	Condition 1 = 0.0511 gr/DSCF		at 7 % O2	
Waste Feeds:	Type	Feed Rate		
Condition 1	Solids/Liquids	11,781 lb/hr avg		
Test Run Time:	2 hours per run (4 runs per Condition)			
Temperature:	Kiln: 1742 deg F Secondary Combustion Chamber: 1910 deg F			
Residence Time (gas):	unknown			
Comments:				

Facility: Chemical Waste Management				
Location (City, State): Port Arthur, Texas				
Test Dates: 01-05-90 to 01-28-90				
Incinerator Type: Rotary kiln with after burner				
POHCs:	Compound Name:	Feed Rate:	DRE %:	% of Feed:
	Carbon Tetrachloride	Total POHC	99.99964	Up to 10%
	Tetrachloroethylene	1340 lb/hr	99.99994	Chlorine
	1,1,2-Trichloroethane		99.99989	
	Chlorobenzene		99.99996	
HCl: Removal efficiency 99.81%				
Particulate: 0.54 lb/hr		at 7% O_2		
Waste Feeds:		Type:	Feed Rate:	
		Aqueous	7109 lb/hr	
		Energetic Sludge	5158 lb/hr	
		Energetic Liquid	2932 lb/hr	
		Solid	6970 lb/hr	
Test Run Time: 4 hour				
Temperature: 1825 deg F				
Residence Time (gas): Not available				
Comments:				

Facility: Doe K-25 Facility

Location (City, State): Oak Ridge, Tennessee

Test Dates: 06-01-88 to 06-09-88 and 06-14-89 to 06-14-89

Incinerator Type: Rotary Kiln Incinerator

POHCs:	Compound Name:	Feed Rate:	DRE %:	% of Feed:
	CFC-11	Total	99.998	11%
	$C\,Cl_4$	R-Cl	>99.9988	
	Hexachloroethane	321 lb/hr	>99.9974	

HCl:

Emission Rate 0.128 lb/hr
Removal Efficiency 99.92%

Particulate: 0.027 gr/dscf at 7% O_2

Waste Feeds:	Type:	Feed Rate:
	Kiln liquid	825 lb/hr
	SCC liquid	630 lb/hr
	Aqueous	350 lb/hr
	Soil	950 lb/hr
	Sludge	170 lb/hr

Test Run Time: 2 to 5 hr

Temperature: Kiln temperature 1572 deg F; SCC temperature 1878 deg F

Residence Time (gas): Not available

Comments: Five tests were run in 1988. Three tests were run in 1989. The values reported are the average of those runs.

Facility: Dow Chemical Company – Vinyl II Plant

Location (City, State): Plaquemine, LA

Test Dates: September 22, 23 & 24, 1987

Incinerator Type: Rotary Kiln

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Condition 1	Carbon Tetrachloride	N/A	99.99858	20.92
Condition 2	Carbon Tetrachloride		99.99945	24.87

HCl:

Condition 1 2.23 lb/hr
Condition 2 1.66 lb/hr

Particulate:	at % O2
Condition 1 – 77.5 mg/cu mt	
Condition 2 – 67.8 mg/cu mt	7%

Waste Feeds:	Type	Feed Rate
N/A	N/A	N/A

Test Run Time:

N/A

Temperature: Condition 1 – 1083 C Condition 2 – 1271 C

Residence Time (gas): N/A

Comments:

Facility: Dow Chemical				
Location (City, State): Midland, MI				
Test Dates: 4-17-89 to 4-21-89				
Incinerator Type: Rotary Kiln				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	118 lb/hr avg	99.99979	50
	Chlorobenzene	122 lb/hr	99.999425	50
Condition 2	Carbon Tet	6025 lb/hr avg	99.99993	98.7
	Chlorobenzene	79.5 lb/hr	99.999525	1.3
HCl:				
Condition 1		0.48 lb/hr		99.68 % Removal
Condition 2		3.54 lb/hr		99.93 % Removal
Particulate: 0.00836 to 0.0111 gr/DSCF			at 7 % O_2	
Waste Feeds:	Type	Feed Rate		
	Waste Liquids	230 to 6100 lb/hr of CCl_4 & Chlorobenzene		
	Solids (containers)	20 to 60 lb/hr of CCl_4 & Chlorobenzene		
Test Run Time:	20 hours at each condition			
Temperature:	Condition 1: Kiln = 700 degC, SCC = 950 degC Condition 2: Kiln = 950 degC, SCC = 950 degC			
Residence Time (gas):				
Comments:				

Facility: E.I. duPont

Location (City, State): LaPlace, LA

Test Dates: August 21 – 28, 1989

Incinerator Type: Rotary Kiln and Liquid Injection in Parallel

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Freon 113	Trichlorotrifluoroethane	248.42 lb/hr	>99.9999	5.28
Carbon Tetrachloride	----------	925.94 lb/hr	99.9995	19.68

HCl:
5.106 lb/hr

Particulate:	at % O2
0.0261 gr/dscf	7%

Waste Feeds:	Type	Feed Rate
Organics	Liquid	4,705 lb/hr

Test Run Time:
N/A

Temperature: Liquid Incinerator – 1339 C, Rotary Kiln – 779 C

Residence Time (gas): N/A

Comments:

Above Results are Averages of 9 Runs.

Facility: Dow Chemical Company, Environmental Operations Plant

Location (City, State): Plaquemine, LA

Test Dates: November 17, 18, 19 & 20, 1987

Incinerator Type: Rotary Kiln

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Condition 1	Carbon Tetrachloride	670.8 lb/hr	99.99980	50.4
Condition 2	Carbon Tetrachloride	712.3 lb/hr	99.99970	51.8

HCl:

Condition 1	0.055 lb/hr
Condition 2	0.032 lb/hr

Particulate:

	at % O2
Condition 1 – 63.7 mg/cu mt	
Condition 2 – 19.0 mg/cu mt	7%

Waste Feeds:	Type	Feed Rate
Condition 1		
Burner	Liquid	7549.2 lbs/hr
Packs	Solid	6088.7 lb/hr
Condition 2		
Burner	Liquid	7337.7 lb/hr
Packs	Solid	7795.7 lb/hr

Test Run Time:

N/A

Temperature: Condition 1 – 1241 F Condition 2 – 1509 F

Residence Time (gas): N/A

Comments:

Facility: Eli Lilly and Company				
Location (City, State): Clinton, IN				
Test Dates: 2-14-89 to 2-17-89				
Incinerator Type: Rotary Kiln				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	66.6 lb/hr avg	99.9947	0.79%
Condition 2	Carbon Tet	37.6 lb/hr avg	99.997	0.64%
Condition 3	Carbon Tet	57.8 lb/hr avg	99.9992	0.77%
Condition 4	Carbon Tet	45.6 lb/hr avg	99.9985	0.54%
HCl: Condition 1:		0.237 lb/hr		99.99% Removal
Condition 2:		0.0062 lb/hr		99.99% Removal
Condition 3:		0.021 lb/hr		99.99% Removal
Condition 4:		0.306 lb/hr		99.98% Removal
Particulate: Condition 1:		0.0345 gr/DSCF	at 7 % O2	
	Condition 2:	0.026 gr/DSCF	at 7 % O2	
	Condition 3:	0.0429 gr/DSCF	at 7 % O2	
	Condition 4:	0.0268 gr/DSCF	at 7 % O2	
Waste Feeds:	Type	Feed Rate		
Condition 1	Liquids	8474 lb/hr		
Condition 2	Liquids	5871 lb/hr		
Condition 3	Liquids	7481 lb/hr		
Condition 4	Liquids	8418 lb/hr		
Test Run Time:	Approx 8 hours at each condition			
Temperature:	unknown			
Residence Time (gas):	unknown			
Comments:	Condition 1 had one run (out of four) with DRE less than Four 9's Condition 3 had no run times given No temperature data for all four conditions			

Facility: PPG Industries

Location (City, State): Circleville, OH

Test Dates: 1-11-88 to 1-15-88

Incinerator Type: Rotary Kiln

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	35.08 lb/hr avg	99.995	0.57%
Condition 2	Carbon Tet	37.67 lb/hr avg	99.996	0.57%
Condition 3	Carbon Tet	40.42 lb/hr avg	99.98	0.46%

HCl: Condition 1:	0.243 lb/hr	99.83% Removal
Condition 2:	0.225 lb/hr	99.86% Removal
Condition 3:	0.237 lb/hr	99.87% Removal

Particulate: Condition 1:	0.01335 gr/DSCF	at	7 % O2
Condition 2:	0.00385 gr/DSCF	at	7 % O2
Condition 3:	0.00456 gr/DSCF	at	7 % O2

Waste Feeds:	Type	Feed Rate
Condition 1	Solids/Drums	6114 lb/hr (Run I, 4)
Condition 2	Solids/Drums	6639 lb/hr (Run II, 3)
Condition 3	Liquids	8875 lb/hr

Test Run Time:

Approx 8 hours at each condition

Temperature:

Condition 1: Kiln = 1100 deg C, SCC = 900 deg C
Condition 2: Kiln = 1010 deg C, SCC = 900 deg C
Condition 3: Kiln = 1100 deg C, SCC = 930 deg C

Residence Time (gas):

Comments:

Condition 1 had one run (out of four) with DRE less than Four 9's
Condition 3 had two runs (out of four) with DRE less than Four 9's

Facility: Rechem International Ltd				
Location (City, State): Fawley Southampton, UK				
Test Dates: 19-20 February 1991				
Incinerator Type: Rotary Kiln + A B Wet Quench/Alkali Scrubber/ Two wet electrostatic Precips(in series) + Plume Reheat.				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	Halon 1301	37 Kg/hr	> 99.99	0.9
	Halon 1211	276 Kg/hr	> 99.99	6.9
HCI: < 2.0 mg/m3 HF < 1.0 mg/m3				
Particulate: 9 mg/m3			at	% 02
Waste Feeds:	Type	Feed Rate		
	Liquid + Solid	Total circa 4000 Kg/hr		
Test Run Time: Approx 1 1/2 hrs each				
Temperature: Around 1150 ^{0}C				
Residence Time (gas): 5 Seconds				
Comments: DRE % computation limited by analytical sensitivity for residues. No Free bromine emissions detected.				

Facility: Rollins Environmental Services

Location (City, State): Baton Rouge, LA

Test Dates: October 12, 1988

Incinerator Type: Rotary Kiln

POHCs:	Compound Name	Feed Rate	DRE%	% of Feed
Feed A	Carbon Tetrachloride	122.4 lb/min	99.99986	7.7%
Feed D	Carbon Tetrachloride	158.3 lb/min (Total Feed Rate)	99.99986	<3.8 mg/k

HCl:

0.184 lb/hr 99.99% removal

Particulate:	at % O2
0.016 gr/dscf	7%

Waste Feeds:	Type	Feed Rate
Feed A	Liquid Blend	122.4 lb/min
Feed D	Thermalox Wastewater	158.3 lb/min

Test Run Time:

2 hours for each run (3 runs).

Temperature: Afterburner – 1856 F Kiln Exit – 1627 F

Residence Time (gas): N/A

Comments:

No Schematic Available

Facility: Rollins Environmental Services

Location (City, State): Bridgeport, New Jersey

Test Dates: 6-7-88 to 6-8-88

Incinerator Type: Rotary Kiln incinerator

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	Carbon Tet	44.27 lb/hr	99.9994	N/A
	HCFC-22	6.37 lb/hr	99.9992	N/A

HCl: N/A

Particulate: 0.0293 g/dscf at 7 % O2

Waste Feeds:	Type	Feed Rate
	Sludge	
	Freon Gas	

Test Run Time: unknown

Temperature: 1600 - 2000 deg F

Residence Time (gas): unknown

Comments:

Facility: Rollins Environmental Services (Incinerator Train I)				
Location (City, State): Deer Park, Texas				
Test Dates: 7–14–87 to 7–18–87				
Incinerator Type: 3.6m Slagging Rotary Kiln incinerator and Liquid Injection furnace				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CCl4	unknown	99.9995	approx. 20% average
HCl: Removal efficiency > 99.9% on all tests Maximum emission rate = 3.75 lb/hr on Day 3				
Particulate:	RCRA Fraction	0.0139 g/dscf	at 7 % O2	
Waste Feeds:	Type	Feed Rate		
	Industrial waste PCB Liquid T–ox Wastewater Sludge Aspirated water			
Test Run Time:	3 runs per day for 5 days = 15 runs total			
Temperature:	Kiln: typical 1800 – 2000 deg F (minimum 1500 deg F) Liquid Injection Afterburner: typical 2250 deg F (minimum 1800 deg F)			
Residence Time (gas):	> 2 seconds at 1800 deg F			
Comments:	Rated throughput: Rotary Kiln = 13,200 lb/hr Heat Release: Rotary Kiln = 80 MMBTU/hr Rated throughput: Afterburner = 10,200 lb/hr Heat Release: Afterburner = 100 MMBTU/hr			

Facility: Rollins Environmental Services (Incinerator Train II)				
Location (City, State): Deer Park, Texas				
Test Dates: 5-20-88 to 5-25-88				
Incinerator Type: 4.4m Slagging Rotary Kiln incinerator, Rollins Rotary Reactor, and Liquid Injection furnace				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CCl4	unknown	99.9999	unknown
HCl: Emission rate = 2.44 lb/hr average (summary did not report removal efficiency) Cl2 emission rate = 2.38 lb/hr average				
Particulate:	(4.19 lb/hr average particulate emissions)	0.014 g/dscf	at 7 % O2	
Waste Feeds:	Type	Feed Rate		
	unknown			
Test Run Time:	3 runs per day for 5 days = 15 runs total			
Temperature:	Kiln: typical 1800 - 2000 deg F (minimum 1500 deg F) Rollins Rotary Reactor: typical 1600 deg F (minimum 1200) Liquid Injection Afterburner: typical 2250 deg F (minimum 1800 deg F)			
Residence Time (gas):	> 2 seconds at 1800 deg F For Rollins Rotary Reactor: liquid/gas residence time = approx. 5 seconds			
Comments:	Rated throughput: Rotary Kiln = 12,000 lb/hr Heat Release: Rotary Kiln = 120 MMBTU/hr Heat Release: Rollins Rotary Reactor = 33.5 MMBTU/hr Rated throughput: Afterburner = 8,000 lb/hr Heat Release: Afterburner = 60 MMBTU/hr			

Facility: Ross Incineration

Location (City, State): Grafton, Ohio

Test Dates: 10-20-88 to 10-28-88

Incinerator Type: Rotary Kiln incinerator

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
Condition 1	Carbon Tet	1320 lb/hr avg	99.9998	6.77%
Condition 2	Carbon Tet	1353 lb/hr avg	99.9999	6.73%
Condition 3	Carbon Tet	1348 lb/hr avg	99.9999	6.88%
Condition 4	Carbon Tet	819 lb/hr avg	99.9998	6.35%
Condition 5	Carbon Tet	1270 lb/hr avg	99.9999	8.52%
Condition 6	Carbon Tet	1247 lb/hr avg	99.9999	8.66%

HCl: Removal efficiency > 99.8% on all tests
Maximum emission rate = 2.16 lb/hr for Condition 1

Particulate: Maximum = 0.0504 gr/DSCF at 7 % O2

Waste Feeds:	Type	Feed Rate
Condition 1	Solids/Liquids	19,500 lb/hr avg
Condition 2	Solids/Liquids	20,100 lb/hr avg
Condition 3	Solids/Liquids	19,600 lb/hr avg
Condition 4	Liquids	12,900 lb/hr avg
Condition 5	Solids/Liquids	14,900 lb/hr avg
Condition 6	Solids/Liquids	14,400 lb/hr avg

Test Run Time:
Average of 12 hours per Condition (3 to 4 runs per Condition)

Temperature:
Kiln: typical 1900 - 2200 deg F (minimum 1897 deg F)
Secondary Combustion Chamber: typical 2000 deg F (minimum 1700 deg F)

Residence Time (gas):
unknown

Comments:

Facility: Trade Waste Incineration (Div. of Chemical Waste Mgmt, Inc.)

Location (City, State): Sauget, IL

Test Dates: unknown

Incinerator Type: Rotary Kiln incinerator and secondary combustion chamber

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CFC-11	8.5 kg/hr	> 99.99	approx. 0.45%

HCl: Removal efficiency > 99.2%
Approx. emission rate = 14 kg/hr (based on "... less than 0.76% of incin. feed")

Particulate: < 0.023 g/Nm^3 at 11.7 % O2

Waste Feeds:	Type	Feed Rate
	Solid waste Liquid waste	

Test Run Time: unknown

Temperature:
Kiln: not reported
Liquid Injection Afterburner: continuously > 982 deg C (avg of 1038 deg C)

Residence Time (gas): Design is 2.2 seconds at 982 deg C

Comments:
Rated throughput: Total System = 4167 lb/hr (based on estimate of 50 short tons/day in 1992).
Heat Release: Total System = 50 MMBTU/hr

CEMENT KILNS

Facility: Lone Star Industries Cement Plant

Location (City, State): Oglesby, IL

Test Dates: December 1983

Incinerator Type: Cement Kiln - Dry

Capacity: 1450 ton/day of clinker (product)

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CFC-113	21.3 kg/hr	99.999	0.76% (avg)
	1,1,1-TCA	34.4 kg/hr	99.999	1.22% (avg)
	Toluene	91.3 kg/hr	99.995	3.25% (avg)
	MEK	43.8 kg/hr	99.999	1.56% (avg)
	Dichloromethane	10.9 kg/hr	99.965	0.39% (avg)

HCl: Removal efficiency: Not reported

Emissions: 4.85 and 12.04ppm

Particulate: 544 lb/hr at unknown % O2

Waste Feeds:	Type	Feed Rate
	Liquid	2810 kg/hr (avg)

Test Run Time: 6 hrs per day (2 valid runs)

Temperature: Kiln: 2500 - 2600 deg F avg. operating temperature

Residence Time (gas): Not reported

Comments: Pollution Control System: Electrostatic Precipitator (malfunctioning) and cyclone.

Facility: General Portland Cement Plant

Location (City, State): Los Robles, CA

Test Dates: 1982

Incinerator Type: Cement Kiln – Dry
Capacity: 1750 ton/day of clinker (product)

POHCs:	Compound Name	Feed Rate	DRE %	% of Feed	
	Dichloromethane	Not reported	>99.99	Not reported	
	1,1,1-TCA	Not reported	99.99	Not reported	
	1,3,5-Trichloroben	Not reported	>99.95	Not reported	(Not de
	Xylene	Not reported	>99.99	Not reported	exhaus
					on det

HCl: Removal efficiency: > 99% removal
Emissions: 1.03 lb/hr

Particulate: Not reported at 0.5 to 1.3 % O2

Waste Feeds:	Type	Feed Rate
	Liquid	Not reported

Test Run Time: Not reported

Temperature: Kiln: Operating temperature range not reported

Residence Time (gas): Not reported

Comments: Pollution Control System: Fabric filter

Facility: *Stora Vika Cement Plant*				
Location (City, State): Stora Vika, Sweden				
Test Dates: February 7–17, 1978				
Incinerator Type: Cement Kiln – Wet Capacity: 620 ton/day of clinker (product)				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CFC–113	85 kg/hr	99.99986	unknown
HCl: Removal efficiency: Not reported				
Particulate:		110 mg/Nm^3	at unknown	% O2
Waste Feeds:	Type	Feed Rate		
	Liquid	85 kg/hr		
Test Run Time:	3 hrs			
Temperature:	Kiln: 860 – 870 deg C (avg. 866 deg C)			
Residence Time (gas):	Not reported			
Comments:	1. Pollution Control System: Electrostatic Precipitator 2. Facility was closed in 1982.			

Facility: Ciments Lafarge (French Cement Kiln)				
Location (City, State): Frangey, Yvonne province				
Test Dates: unknown				
Incinerator Type: Semi-dry Cement Kiln				
POHCs:	Compound Name	Feed Rate	DRE %	% of Feed
	CCl4	13.7 kg/hr	> 99.9999	1.08%
HCl: unknown				
Particulate:	unknown		at	6 % O2
Waste Feeds:	Type	Feed Rate		
	Liquid			
Test Run Time:	unknown			
Temperature:	unknown			
Residence Time (gas):	unknown			
Comments:	Dry gas output: 63,000 Nm^3/hr Actual outlet stack concentration CCl4 = 0.1 ug/Nm^3 Source: de Montgailhard, J.D., and G. Chahine. "L'incineration des dechets industriels en cimenterie"			

APPENDIX F

EMERGING TECHNOLOGIES

CONVENTIONAL THERMAL OXIDATION

Fluidized Bed Incinerator

Fluidized bed incinerators consist of a single refractory-lined vessel partially filled with particles such as sand, alumina, or limestone (38). Bubbling bed and circulating bed types are distinguished by the extent of solid entrainment. Fluidized beds have been used historically in the petroleum industry (fluid catalytic cracking), and for processing nuclear waste, spent cook liquor, wood chips, and sewage sludge disposal. Major subsystems include the fuel burner, air supply, and feed system for liquid and solid wastes.

The bubbling bed type requires a waste feed with a minimum heating value of 10,000 kJ/kg to sustain 850°C. The design temperature range within the bed is 450-1000°C. Newer designs employ an air preheater to raise combustion air temperature to 425-650°C.

The circulating bed type of unit has not been used extensively for hazardous waste incineration. However, these units offer certain advantages - in particular, high velocity and turbulent flow of solids, which results in a high degree of back mixing. The enhanced heat and mass transfer create a high combustion efficiency. Primary fluidization air is introduced through the bottom of the combustion chamber, and secondary air is added further up to maintain entrainment and provide air staging for NO_x control. Discharge from the combustion chamber is sent to a hot, refractory-lined cyclone to separate solids for recycling.

Advantages: Simple design with low maintenance cost; high combustion efficiency; compact design; low gas temperature results in relatively low levels of NO_x formation; bed mass provides large surface for reaction, and maintains uniform temperature.

Disadvantages: Bed diameter and height are limited by current designs; potential problems with ash removal; high operating costs; limited to certain waste types; highly halogenated wastes may cause bed to agglomerate; relatively unproven for destroying ODS; low operating temperature may not be appropriate for destroying ODS.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Waste Gasification

This process has been developed for destroying chemical wastes and has an annual design capacity of 5000 t of waste (39). In the first section of the gasifier (approx. 1600°C), the waste feed and hot combustion gases are fed concurrently and form a molten ash bath. The gases from this section are then drawn through a hot coke bed in the second section where any unconverted halogenated hydrocarbons are decomposed. Before the product gas can be used as a low heating value fuel, it must be passed through a gas cleaning section to remove additional particulate matter, halogen acids, and H_2S. The molten ash bath is allowed to drip into water, where it forms a glass-like agglomerate for disposal.

Although this facility has been in operation for over 7000 h, destruction testing for CFCs has been very limited and halons have not been tested. Advantages of this process include the fact that halogens are converted to halogen acids and not free halogens, the formation of dioxins or furans is unlikely, there are low levels of NO_x generation, the process can handle a wide variety of waste feeds, and inert solids are fixed in a non-leachable agglomerate. Some disadvantages include the limited/nonexistent testing for ODS, the fact that the gas treatment section is not yet well developed (especially for this application), and the system consumes coke, which may introduce additional ash and sulfur to the system.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Gas Injection Oxidation/Hydrolysis ("Burn Box")

The controlled combustion process (known as "burn box") consists of a small fume incinerator and is used at semiconductor fabrication plants to destroy toxic process off-gases such as arsine, silane, and nitrogen trifluoride (NF_3). Corrosive exhaust gases are quenched with excess air and routed to large wet scrubbers. Two United States vendors are beginning a testing project to evaluate the DE for CFCs (in conjunction with DuPont).

Advantages: This system has already been commercialized as a packaged fume incinerator for similar compounds.

Disadvantages: Test data are not available to demonstrate compliance with UNEP DE requirements; downstream quench air and acid gas scrubber are still required.

Present stage of technology: Not demonstrated, but possible future option as a small-scale destruction process.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

CATALYTIC PROCESSES

Oxidation

Halohydrocarbon Destruction Catalyst (HDC):

This process uses a new catalyst that is more active, stable, and insensitive to inhibition by halogens than conventional supported noble-metal or chromia-alumina catalysts (40, 41). This process uses supplemental water vapour or hydrocarbons to provide a hydrogen source. The HDCs achieved ≥99% DE of CCl_4 at about 335°C (compared to 535°C for a chromia-alumina reference catalyst). A full-scale system is scheduled for startup at a purified terephthalic acid (PTA) plant in Taiwan (42), and another unit is believed to be operating in California. This system, which includes an air-to-air recuperative heat exchanger, is believed to be the industry's first such system.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Direct Catalytic Oxidation of Halogenated Hydrocarbons:

This process employs a proprietary catalyst to oxidize halogenated hydrocarbons completely to CO_2 and HCl (43). The catalyst is more active than chromia-alumina types and does not employ a noble metal. This process also uses supplemental water vapour or hydrocarbons to provide a hydrogen source. Stable activity has been observed over thousands of hours. This catalyst has not yet been demonstrated on CFCs. Another catalyst vendor also reportedly has a catalyst for organic chloride service.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Catalytic Decomposition of Halogenated Organics:

This research project is investigating the conversion of 1,2-dichloroethane and CFC-12 on a wide range of catalytic materials (44). Tested catalysts included metal oxides (Co and Mn), acid catalysts (SiO_2-Al_2O_3,or TiO_2-SiO_2), zeolites, Nb_2O_5, and noble metals.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Catalytic Hydrolysis of CFCs:

This research project involves testing a variety of catalysts in a fixed bed continuous flow reactor (44). Gaseous CFCs and water vapour are mixed and fed to a 9-mm ID quartz reactor. The results so far indicate that dealumination of the zeolite support material may occur. This may be due to the formation of volatile $AlCl_3$ and subsequent conversion to AlF_3. Conversions of CFC-113 varied from 15% to nearly 100%.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Hydrogenation

Selective Hydrodechlorination of CFC-113:

This research is investigating the reaction of CFC-113 with H_2 over a Ni-SiO_2 catalyst at 450°C to form CFC-1113 (chlorotrifluoroethene) (44). The CFC-1113 is catalytically dechlorinated with H_2 over Ti/Pd-SiO_2 at 250°C to form HFC-1123 (trifluoroethene), which can be reacted with HF to form HFC-134a. This is a potential conversion process.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Direct Contact Hydrogenation:

This is a new process developed by UOP and proposed for a hazardous waste treatment facility in the Netherlands (45). The process is designed for the selective removal of contaminants such as halogens, sulfur, and nitrogen. Undiluted waste is mixed with hydrogen at elevated temperature (up to 350°C) and pressure (up to 5470 kPa). The mixture then goes to a fixed-bed catalytic reactor (where organically bound chlorine is converted to HCl and then removed).

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

PYROLYSIS PROCESSES

Pyrolyzing Rotary Kiln

This process involves an externally heated stainless steel rotary kiln, that uses air locks on the inlet and discharge to prevent air from entering the kiln (26). The pyrolyzing rotary kiln operates at a lower temperature than a conventional rotary kiln, and maintains an oxygen-free environment in the kiln.

The combination of these two factors produces the following claimed advantages:

- Organic materials are pyrolyzed to produce a char residue and product gas typically composed of methane, higher-boiling hydrocarbons, carbon monoxide, carbon dioxide, and hydrogen. The product gas can be burned for energy recovery or treated for the recovery of condensible hydrocarbons.

- The reducing atmosphere in the kiln eliminates the production of SO_x and NO_x in the product gas. It also prevents the oxidation of metals, and allows their recovery in elemental form rather than as oxides.

- The pyrolysis section of the kiln operates at a temperature of about 500°C. Although this temperature is sufficient to decompose organic material, inorganic materials are generally not affected. This reduces the volatilization of heavy metals and the production of undesirable byproducts from the decomposition of inorganic constituents.

- Acid gases can be removed in the kiln by adding lime, thereby significantly reducing the need for air pollution control equipment.

Pyrolysis gases are passed through a cyclone for particulate removal and then burned at 1200°C in a combustion chamber. The combustion chamber provides a residence time of 1 s to destroy all organic constituents.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

CHEMICAL DESTRUCTION

Reaction With Elemental Metals

Chemical Destruction of CFCs with Sodium:

Gaseous CFCs are fed to a ceramic cartridge (Al_2O_3) that is coated with sodium metal kept under an inert atmosphere. The halogen reacts with the sodium and forms solid products that remain on the cartridge. Reaction products can be washed off the cartridge, which can then be recoated with sodium for subsequent use. External energy is not needed for this reaction, which is regulated by the inflow velocity of the gases. The reaction temperature and pressure are 500-600°C and 100 kPa, respectively, and the destruction efficiency is $\geq 99\%$. This technology was developed in Germany and to date has only been tested on the laboratory scale; it should be commercially available during the next five years (46).

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Complete Destruction of CFCs by Reductive Dehalogenation:

The principle of this process is the transformation of organic halogens into halide salts by reductive elimination through electron transfer (44). Either an ammoniac solution (Birch Reduction) or an ethereal solution of alkali-metals and naphthalene (Naphthalenide Method) can be used as the electron source for the reaction. The efficiency of the method appears to be better for chlorinated compounds than for fluorinated compounds; almost complete removal of chlorine atoms versus approximately 50% removal of fluorine atoms. The actual process varies depending on the CFCs being destroyed and whether it is gaseous or in solution. Basic research of the Naphthalenide

Method is almost complete and could be used for small-scale destruction of CFCs. Pilot-scale testing has not yet been started for larger quantities.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Dornier Incineration Process in Steel Smelter:

The Dornier process first reduces the volume of the waste by pyrolyzing the organic material at 700°C in a rotary kiln (47). The waste is then fed into a molten-steel bath at 1600°C to reduce the wastes to their elemental constituents. Any copper, nickel, carbon, or oxygen is absorbed by the steel. The reaction gas, which contains hydrogen, chlorine, and vapourized metals (lead, tin, and cadmium), is scrubbed and condensed. Any calcium, magnesium, manganese, chromium, and aluminum will form a floating oxide slag. Because the carbon and oxygen do not contact the gas, dioxins and furans are not generated. The first pilot plant is expected to be in operation in a West German steel plant in 1992.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Molten Metal Technology (MMT):

Catalytic extraction processing (CEP) uses a molten metal bath, such as iron, at about 1650°C to dissociate wastes into their atomic constituents (48). The waste is injected with oxygen into a reactor containing the metallic solvents. Once the bath has been initially heated, the temperature can be maintained by the addition of organic waste and oxygen. During the process, silicates and inorganic material accumulate in the slag; heavy metals remain in the bath; and elements such as carbon, hydrogen, nitrogen, and oxygen evolve as gases. Three end products can be recovered from the process depending on the feed: metals; gases such as chlorine, fluorine, hydrogen, and oxygen; and a ceramic phase that can be used as aggregate or in abrasives. The process may also yield by-products (0-5% of the total feed) that need to be disposed of as landfill.

The process has been applied to hazardous wastes that contained metals, halogens, and cyanide and a destruction efficiency of ≥99.99999% has been reported. Testing was conducted at a Gary, Indiana steel facility for feed rates from 5000 to 100,000 t/year. Limitations of the technology include: wastes that contain more than 90% water, and the fact that radioactive wastes cannot be processed. Advantages include: the CEP is considered a resource recovery and recycling technique; it can handle wastes that are traditionally difficult to combust; it does not generally require auxiliary fuel, can handle wastes without preprocessing, and does not result in PICs. Bench-scale tests are currently in progress and, if successful, a prototype unit is anticipated over the next 6 months to a year.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Pressurized Coal Iron Gasification (P-CIG):

P-CIG is a process for the gasification of coal that is injected into a slag-covered iron bath along with oxygen (17). The temperature of the melt is approximately 1450°C. This process has been tested on a laboratory scale for destruction of halons. The results from the test indicated that halons were destroyed and converted to iron salts ("dust"). A proposed test will evaluate the process on the pilot scale for 1 week.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Reaction with Metal Oxides

Chemical-Thermal Destruction of Halogenated Hydrocarbons (HHC):

This process feeds halogenated, higher-chlorinated, hydrocarbons (HHC) into a reactor along with granular reagents such as calcium silicate or calcium oxide (46). The reactor is maintained under an inert atmosphere at about 700°C and 98 kPa. Halogens are thermally released from the HHCs and are then chemically bound to the solid reagent. The granules can then be dehalogenated with superheated steam to recycle the granular reagent and produce hydrochloric acid (or the corresponding halogenated acid). The process also produces a chlorine-free exhaust gas that is combusted, and particulate emissions that are incinerated or removed for disposal. Dioxins have not been detected in either the gaseous or solid reaction by-products.

A destruction efficiency of $\geq 99.9999\%$ has been achieved in a pilot plant. A commercial facility is expected to be in operation in 2-3 years.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Reaction of CFCs with Metal Oxides:

This process involves the reaction of organic halogen compounds with metal oxides such as alumina (Al_2O_3) at 500-800°C. One group actively studying this process is in Australia (University of Sydney). This group has funds to build a demonstration plant, and is emphasizing the conversion of organic halogen compounds to useful materials (49).

In the United States, this process was tested at the Solar Energy Research Institute (50). The products of the reaction include $AlCl_3$ and AlF_3 (along with CO_2). The viability of the process has been examined by considering its thermodynamic equilibrium, and the investigators believe that the metal chlorides are stable products. Preliminary testing was conducted at the bench scale.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

SUPERCRITICAL WATER OXIDATION

This process involves using water at supercritical conditions [i.e. temperature maintained above 374°C (705°F) and pressure greater than 2.2×10^4 kPa with oxygen to rapidly oxidize organic compounds (26). In the supercritical state, gases are completely miscible in the water, which eliminates the mass transfer limitations typically encountered in two phase systems. Aqueous waste is pressurized by a diaphragm pump and fed to the oxidation reactor. Also fed are pressurized air or oxygen, and sodium hydroxide. The organics are rapidly oxidized to water and carbon dioxide. Chlorine in the organics reacts with the caustic to form sodium chloride. A second-stage oxidizer converts any residual carbon monoxide in the gaseous effluent.

In the United States, a company is conducting engineering studies for three proposed installations, and claims the method has been proven in two 2000 L/day pilot plants. The technology has been demonstrated to destroy up to $\geq 99.9999\%$ of the organic wastes, but because of its costly high-pressure equipment it is expected to be economic only on wastes such as PCBs, dioxins, and hexachlorobenzene (51). A research program on supercritical water oxidation at Sandia National Laboratory Combustion Research Facility (Livermore, California) is testing aqueous wastes, including organic streams with halogenated hydrocarbons (52). A research program for destroying CFCs using supercritical water oxidation is also underway in Japan at the National Chemical Laboratory for Industry (NCLI) (44).

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

WET AIR OXIDATION

Wet air oxidation operates on the principle that the rate of oxidation of organic compounds is significantly increased at higher pressures. Thus, by pressurizing an aqueous organic waste (pressures approach 10,000 kPa), heating it to temperatures of 300°C, and then introducing atmospheric oxygen, an incomplete liquid phase oxidation reaction is produced, which destroys most of the organic compounds (25). This process exhibits varying levels of destruction efficiency, depending on the waste. It is often used as a pretreatment step. The process becomes thermally self-sufficient when the chemical oxygen demand of the influent reaches 20,000 to 30,000 mg/L. The process has not been demonstrated on highly halogenated hydrocarbons.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

PLASMA SYSTEMS

Plasma chemical processes have been known to be highly effective in promoting oxidation, enhancing molecular dissociation, and producing free radicals to enhance a chemical reaction. The extremely high temperatures of the plasma create a reactive species from stable compounds; thus, plasma methods are expected to completely decompose CFCs, which are chemically stable (53).

Plasmas are generated in a gas by an electrical discharge from high-voltage electrodes or by microwave or radio radiation induction. The temperature and transport properties of each plasma depend on the pressure of the gas. This allows a flexible destructive capacity for various hazardous waste materials.

Plasma systems for destruction of CFCs include corona discharge, radio-frequency (RF) induced plasma, and arc discharge reactors. Plasma systems are currently under development in several countries, including Australia (CSIRO), France (Aerospatiale), Germany (Krupp Mak AG), Japan (NIRE; Tokyo Institute of Technology), Switzerland (MGC Plasma), and United States (Retech; Westinghouse).

CORONA DISCHARGE

This process uses a high-voltage AC or DC discharge to generate an ionized corona field (54). Corona process applications emphasize either the ions produced or the energy of the electrons producing the plasma. The ions that are produced depend on the polarity of the discharge and the gas mixture characteristics, and the electron energies depend on the method of generating the corona and the gas mixture characteristics.

A destruction efficiency of 67% was achieved for trichloro-trifluoroethane ($C_2Cl_3F_3$ or CFC-113) using a nanosecond pulsed corona reactor. This reactor applies a high pulsed voltage to destroy the CFCs by employing a positive DC power supply that is altered to produce a short pulse length with an extremely fast rise time (i.e. a nanosecond order pulse). The conditions for this destruction test were 500 ppm CFC-113 with 7.9 s of residence time in the reactor.

A black powder-like deposit and a high-molecular-weight compound like tar were deposited on the reactor electrode and surface. The reaction products have not yet been identified.

The development status for applying corona discharge to CFCs destruction is laboratory scale.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

RADIO-FREQUENCY (RF) INDUCED PLASMA SYSTEM

This process applies a radio frequency of 4 MHz up to 15 kW to a copper core to decompose the CFCs. The CFCs are mixed, passed through a quartz tube together with water vapour, and mixed with argon gas that has been converted to the plasma state. The temperature at the centre of this plasma reaches as high as 10,000 K (44).

A destruction efficiency of 97% was achieved for trichlorofluoromethane (CCl_3F or CFC-11) at a concentration of 2.2% with water at an argon feed rate of 40 L/min and 13.2 kW of input power. HCl, HF, and CO_2 were detected in the effluent gas. The reaction proceeds according to the equation,

$$CCl_3F + 2H_2O \rightarrow CO_2 + 3HCl + HF \quad (1)$$

Extremely small amounts of disproportionation products such as CF_4, CCl_2F_2, CCl_3F, and CCl_4 and polymerization products such as C_2- and C_3-chlorofluorocompounds were present.

In the absence of water, the destruction of CFC-11 decreased to 62% and carbonaceous material composed of C, Cl, and F atoms was produced. The disproportionation and polymerization products mentioned above were also increased.

Hydrogen and oxygen (instead of water) also react with CFC-11. CFC-113, carbon tetrachloride (CCl_4), and trichloroethylene ($CCl_2 = CHCl$) also decompose in a similar manner to CFC-11.

Advantages of this process are:

- Nonselective destruction: application to waste CFCs;
- Sure and rapid destruction;
- Treatment of a large amount of CFCs;
- Continuous destruction;
- Atmospheric operation; and
- Applicable to gas, liquid, and solid (powder) forms of CFCs.

The developmental status of RF plasma is laboratory scale.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

ARC DISCHARGE

This process uses a thermal argon plasma generated by a DC arc discharge at atmospheric pressure. The system is smaller and simpler than the RF plasma system (44). Near 100% decomposition of dichlorodifluoromethane (CCl_2F_2 or CFC-12) occurs according to the reaction:

$$CCl_2F_2 + 2H_2 + 0.5O_2 \rightarrow CO + 2HCl + 2HF \quad (2)$$

The conditions for this experiment were a discharge power of 3.2 kW with flow rates of 10 L/min Ar and 0.3-2.0 L/min CFC-12.

Carbonaceous material was not observed for these experimental conditions. A trace of COClF was observed by mass spectroscopy. The decomposition of CFC-12 with H_2O (flow rate of 0.45-1.50 mL/min), rather than H_2 and O_2, formed an ether-soluble tar that deposited on the wall because of the incomplete mixing of the water in the plasma.

Two plasma destruction devices (30 kW and 150 kW) have been built and tested in Australia, and a prototype industrial plant (150 kW) is under construction (49). The work to date has focused on chlorinated phenols and phenoxy acids. Destruction efficiency on these materials has been ≥99.99999% (7 nines). Development work on other halogenated compounds (including CFCs and halons) is scheduled to begin in 1992.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

ULTRAVIOLET (UV) PHOTOLYSIS

Photochemical Degradation:

A low-pressure mercury lamp has been used as a UV light source to degrade CFCs into carbon dioxide, chlorine, and fluorine (44). The CFCs are mixed with air to allow complete oxidation. In some cases, with insufficient illumination or available oxygen, phosgene, unidentified polymers, and acetic acid were also formed. With additional illumination and/or oxygen, most of these byproducts were also degraded. At this point, research has been limited to the laboratory. However, a 4-year project, which also includes building a prototype apparatus, has been initiated to further study the reaction mechanism.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Dechlorination Process of Chlorofluorocarbons or Compounds Containing Chlorine With or Without UV Irradiation:

Reacting CFCs or chlorinated compounds (RCl) with sodium alcolate solution (MeONa) in alcohol, and usually under UV irradiation, can decompose the reactants into precipitated sodium chloride and an ether (44). The resulting ethers may be suitable for use as solvents. The reaction proceeds at room temperature and under atmospheric pressure. Eight of the eleven compounds tested required UV irradiation (CFC-11,12,113,112, and 115; HCFC-123,112; and carbon tetrachloride); whereas the other three compounds were decomposed at room temperature without the UV irradiation (HCFC-22,123a, and chloroform). The decomposition efficiency in all cases was found to be 100%. The process development has been experimental thus far, with bench-scale testing planned for the near future.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Decomposition of CFCs by UV Irradiation:

This process uses a UV lamp with a cooling jacket inside a reaction vessel that contains a solution of CFCs (44). Four compounds have been tested: CFC-11, CFC-113, carbon tetrachloride, and trichloroethylene. The main products of the reaction are inorganic salts such as NaCl or NaF. It appears that chlorine is eliminated more easily than fluorine in the decomposition process, which is currently in the fundamental stages of development.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Photocatalytic Degradation of Organic Wastes:

Organic wastes, such as 2,4-dichlorophenol or nitrobenzene, have been decomposed using titanium dioxide (TiO_2) and UV irradiation (55). The reactor vessel contains a stainless steel jacket and a UV lamp mounted axially within the jacket. The TiO_2 is coated on a fiberglass mesh that is wrapped around the lamp to provide the catalyst for the reaction. As the waste is pumped through the jacket it is decomposed into nontoxics, such as carbon dioxide and water. Hydrogen peroxide can be added to prevent TiO_2 deactivation; it also increases the reaction rate of the waste decomposition. Commercialization should occur in the near future.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

Photochemical Oxidation:

This proprietary process is currently under development by Process Technologies, Inc. (Boise, Idaho). The process has only been described in general terms. It involves a batch or continuous reaction occurring at 20-40°C at essentially ambient pressure. Using photochemical oxidation, the developers have found DEs of greater than 95%, with possible enhancements to achieve ≥99%. The only inputs to the process are CFCs or other ODS, and electricity. Outlet streams have not been described.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

BIOLOGICAL PROCESSES

Bacterial decompositions of CFCs are useful because microbial reactions are carried out at room temperature and atmospheric pressure (44, 56, 57). These studies indicate that methyl chloroform can be biotransformed by reductive dehalogenation. This process occurs with some bacteria that are methanogenic (anaerobic methane utilizing). The breakdown of methyl chloroform may be to 1,1-dichloroethane. This may be further degraded to chloroethane. Biological transformation was not observed in aquifer sampling under aerobic or denitrifying conditions.

Developmental status of microbial treatment is pilot scale.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

HIGH-ENERGY RADIATION

In this process, a saturated hydrocarbon (n-hexane, n-octane, or cyclohexane) is dissolved in a 1.0-10.0 M CFCs ($CFCl_2CF_2Cl$ or CF_3CCl_3) solution (44). The resulting solution is sealed into a pyrex tube after degassing, and irradiated with a gamma radiation dose of 1.0- 10.0 Mrad at room temperature. For a CFC-113/n-hexane system, the main products after irradiation are a mono-chlorinated alkane ($C_6H_{13}Cl$) and a mono-hydrogenated CFC (CF_3CCl_2H). HCl is also found as a by-product. A G-value (number of product molecules/100eV) is 3-4, but recalculated as 600 if the calculation is based on energy absorbed by only the solute.

The hydrogenated CFCs are considered as substitutes of the actual CFCs because they are easily degraded in the stratosphere. Any saturated alkane may serve as the solute if soluble in the CFC.

Development status of high-energy radiation is laboratory scale; no experiments have been done from the technological point of view. Separation of the hydrogenated CFC from the reaction mixture and recycling of the unreacted species are still under study.

Reason for not recommending for approval: Not demonstrated on ODS on a commercial scale.

APPENDIX G

TECHNICAL ADVISORY COMMITTEE MEETING SUBMISSIONS

MEETING NUMBER 1,

NAIROBI, KENYA, 20-22 AUGUST 1991.

M1. List of attendees.

M2. United States: Report No. EPA 600/7/89/011.

M3. United States: Report No. EPA 600/2-89-037.

M4. Australia: Two Tables of inventory data.

M5. Japan: Inventory data (4 pages).

M6. Canada: Copies of overheads prepared for first meeting.

M7. UNEP: Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer. Ozone Secretariat, UNEP, May 1991.

M8. Scientific Assessment of Stratospheric Ozone: 1989 (Vol. 1), World Meteorological Organization, Global Ozone Research and Monitoring Project - Report No. 20.

M9. Scientific Assessment of Stratospheric Ozone: 1989 (Vol. 2), Appendix: AFEAS Report, World Meteorological Organization, Global Ozone Research and Monitoring Project - Report No. 20.

M10. Economic Panel Report - Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP, July 1989.

M11. Electronics Cleaning, Degreasing, and Dry Cleaning Solvents Technical Options Report, Summary Report, UNEP Solvents Technical Options Committee, 30 June 1989.

M12. Final Report of the Technology Review Panel, August 1989.

M13. Final Report of the Halons - Technical Options Committee, UNEP Montreal Protocol Assessment Technology Review, 11 August 1989.

M14. CFCs for Aerosols, Sterilants and Miscellaneous Uses, Technical Options Report, Technical Options Committee, 30 June 1989.

M15. Environmental Effects Panel Report - Pursuant to Article 6 of the Montreal Protocol on substances that deplete the ozone layer under the Auspices of the United Nations Environment Programme (UNEP), One of Four Assessment Panel Reports, November 1989.

M16. Report of the third meeting of the Parties to the Montreal Protocol on substances that deplete the ozone layer, Nairobi, 19-21 June 1991 (UNEP/Ozl.Pro.3/11).

M17. Report of the Secretariat on the reporting of data by the Parties in accordance with Article 7 of the Montreal Protocol - Report prepared pursuant to Article 12(c) of the Montreal Protocol, Nairobi, 19-21 June 1991 (UNEP/Ozl.Pro.3/5).

M18. Destruction Technology of CFC's - Second Interim Report of the Working Group for Emissions Control and Destruction Technology. Committee for Protection of Stratospheric Ozone Layer Working Group for Emissions Control and Destruction Technology, Japan, January 1990.

M19. Ozone Depletion and its Effects: Tropical Focus. International Conference on Tropical Ozone and Atmospheric Change; 20-23 February 1990, Penang, Malaysia.

M20. Germany: Copies of overheads used in presentation.

M21. Potential Destruction Technologies For Chlorofluorocarbons and Halons.

M22. Investigations on the Decomposition of CFCs in Municipal Solid Waste Incinerators.

M23. CFCs and Halons: Alternatives and the Scope for Recovery for Recycling and Destruction.

M24. Description of Hoechst CFC-Combustion Plant.

M25. Japan: Overheads used for presentation.

M26. Destruction Technologies of CFCs (Interim Report).

M27. Incineration of CFC-12 by Burner Methods.

M28. Liquid - Waste PCB Disposal by High-Temperature Thermal Destruction Technology.

M29. High-Temperature Thermal Destruction of Liquid-Waste PCBs.

M30. Sweden: The Destruction of Halons in the Nordic Countries.

M31. U.S.S.R. Overheads used for presentation.

MEETING NUMBER 2,

FRANKFURT, GERMANY, 18-22 NOVEMBER 1991.

M1. Japan: Destruction Technologies of Substances that Deplete the Stratospheric Ozone Layer, November, 1991.

M2. CFC Statistics in Japan - 1

M3. The Netherlands: Destruction Technology for CCl_4 as Used in AKZO Salt and Basic Chemicals Site DELFZIJL-NL an Example of Thermal Oxidation, November 1991.

M4. Information on the Butamer Process.

M5. CFC Action Programme, Annual Report, 1990.

M6. Potential Destruction Technologies for CFCs and Halons.

M7. Banked in the Netherlands.

M8. Canada: Canadian Inventory Data on ODP Substances.

M9. Destruction Facility in Canada.

M10. Australia: Estimated Banked Substances for 1990, Australia.

M11. Australian Technology.

M12. Germany: Global Carbon Tetrachloride Supply/Demand Balance.

M13. Banked Ozone-depleting Substances Inventory in Germany.

M14. CFC Destruction Technologies Developed and/or in-use in Germany.

M15. Example of CTC as Feedstock in the Manufacture of other Chemicals.

M16. Singapore: Consumption of CFCs and Halons by Type.

M17. Sweden: Banked CFCs in Sweden.

M18. United States: Update CFC/Halon Destruction Report: Task C.

M19. Regulatory sub-group report to the Committee at the second meeting, 'Suggested Minimum Standards.'

M20. Allied Signal - Catalytic Oxidation as a Destruction (Keith Herbert) Technology for CFCs and Halons.

M21. Jan Bergstrom (Sweden): Monitoring Programs for CFC Destruction Facilities, Outline of Basic Requirements.

M22. Report from Regulatory and Monitoring Sub-committee meeting.

M23. Report from Technologies Sub-committee meeting.

M24. Proposed Code of Good Housekeeping for Minimizing Fugitive Emissions from Destruction Facilities.

M25. Destruction Technology of CFC Developed in China, Shanghai Institute of Organo-Fluorine Materials, Fax received at meeting.

M26. Estimation of Production and Consumption of CFC & Halon in China, Fax received at meeting.

M27. Inventory of Banked CFCs & Halons in China (1988), Fax received at meeting.

MEETING NUMBER 3,

SINGAPORE, 17-20 FEBRUARY 1992.

M1. Time article, 'The Ozone Vanishes', 17 February 1992.

M2. ODS consumption statistics for Malaysia.

M3. Analysis of foam samples in The Netherlands.

M4. Forecast of world demand for CFCs, HCFCs and HFC from a UNEP Technical Panel report.

M5. Dioxin results from recent T-Thermal testwork.

M6. Additional information on commercial facilities in Belgium.

M7. Incinerators for industrial waste in Japan.

M8. CFC data for Zaire.

M9. CFC report for China.

M10. Butamer process description from The Netherlands.

M11. Interim findings: 'Second Airborne Stratospheric Expedition,' NASA report, 3 February 1992.

M12. Listing of toxic waste incinerators in France.

M13. Summary of rotary kiln ODS destruction units in some European countries.

M14. Some information on biological processes.

M15. 'Disposing of PUF in Waste Incineration Plants', Information from Germany.

M16. Handouts from Canada, 'Determination of ODS Emissions' and 'Destruction of Polyurethane Rigid Foams.'

M17. Comments from Germany on draft Radian report.

M18. United States paper, 'Experimental Investigation of PIC Formation in CFC Incineration.'

M19. Paper from T-Thermal on; 'Dioxins - Can Chemical Waste Incineration Systems Achieve Acceptable Emissions?'

M20. Radian information on recent trial burn data.

M21. Hoechst submission to the UNEP Committee on 'CFC Destruction Technologies Developed and/or In-use in Germany.'

M22. Paper on 'Scaleup of Chemical Processes.'

M23. Paper on 'L'incineration des Dechets Industriels en Cimenterie.'

M24. Trial burn data for Rechem International Ltd.

M25. AKZO paper on Aramide Maatschappij Vof, 'Description of the Company, Production and Products in Connection with the EEC Legislation on the Montreal Protocol.'

LIST OF MATERIAL DISTRIBUTED ON THE UNEP DRAFT REPORT

E1. Proposed definition on "Feedstock."

E2. Final version on "Definitions," 19 February 1992.

E3. An addition for Chapter 4.1 on "Production" and the "Entirely used" statement.

E4. Final version of Chapter 5, 20 February 1992.

E5. Revised version of Chapter 6.

E6. Proposed write-up on "Monitoring."

E7. Revised write-up on "Toxics" for insertion in Section 6.2.

E8. Proposed amendment to the Montreal Protocol on "By-product ODS."

E9. Proposed statement on "Technologies" for the Section 7.1, "Conclusions."

E10. Comments on draft report by Dr. Low, UNEP Ozone Secretariat.

APPENDIX H

MEMBERS OF TECHNICAL ADVISORY COMMITTEE

Technical Advisory Committee

Country	Name/Position	Tel./Fax.	Address
CANADA (Chairman)	Mr. Abe Finkelstein Chief, Clean Air Technologies	Tel: 819-953-0226 Fax: 819-953-4705	Environment Canada Unit 100, Asticou Centre, 241 Cite des Jeunes Hull, Quebec, K1A 0H3
AUSTRALIA	Dr. Peter Wailes Deputy Chief	Tel: 03 542 2478 Fax: 011-613 562 9876	CSIRO, Division of Chemicals and Polymers, Private Bag 10, Clayton, Victoria 3168
CHINA	Prof. Feng Yun Gong Deputy Chief Engineer	Tel: 021 4340154 021 4342458 Fax: 011 8621-4333401	Shanghai Institute of Organo-Fluorine Materials, 4411 Long Wu Road, Shanghai, 200241 P.R. China
GERMANY	Dr. Holger Brackemann	Tel: 0-30 89/03-2407 Fax: 011-11493089032285	Federal Environment Agency, Umweltbundesamt, Bismarckplatz 1, W-1000 Berlin 33
JAPAN	Dr. Koichi Mizuno Head, Environmental Technology Laboratory	Tel: 81 298-58-8270 Fax: 011-810298543049	National Institute for Resources and Environment, Agency of Industrial Science and Technology, Ministry of International Trade and Industry, 16-3 Onogawa Tsukuba Ibaraki, 305
RUSSIA	Dr. Victor G. Temchenko Deputy Director, State Institute of Applied Chemistry	Tel: 232-55-23 Fax: (812) 233-89-89 (812) 232-20-27	Research Production Association "State Institute of Applied Chemistry" 14 Dobrolyobov ave. 197198 St. Petersburg
SINGAPORE	Dr. Steve M.F. Lai Director, Materials Technology Division	Tel: 65 772-9550 Fax: 011-65 779 4359	Singapore Institute of Standards and Industrial Research, 1 Science Park Drive, Singapore, 0511, Kent Ridge, PO Box 1128
SWEDEN	Mr. Jan Bergstrom President	Tel: 46 155 22501 Fax: 01146 1551 0384	Miljokonsulterna i Studsvik Ab, PO Box 154 S-61124 Nykoping

Technical Advisory Committee

Country	Name/Position	Tel./Fax.	Address
UNITED KINGDOM	Mr. Les Baker Director, Rechem Environmental Services	Tel: 44 703 898 915 Fax: 011 44703897 282	RECHEM International Ltd., Charleston Rd. Hardley Hythe Southampton Hampshire, S04 6ZA
UNITED STATES	Mr. Robert E. Hall Branch Chief, Air and Energy Engineering Research Laboratory	Tel: 919-541-2477 Fax: 919-541-0554	United States EPA (MD-65), 86 Alexander Dr. Research Triangle Park, N.C. 27711
ZAIRE	Mr. Kabeya Mukenyi Directeur de la protection de l'environnement	Tel: 243 12 33250 33251 Fax: 011 874 150 3261 c/o UN in NYC 212 906 6501	Ministère de l'Environnement Conservation de la nature et tourisme B.P. 790 Kinshasa, Limete

OBSERVERS

Country	Name/Position	Tel./Fax.	Address
CANADA	Mr. Tony Kosteltz Head, Air Pollution Control	Tel: 819 953 2844 Fax: 819 953 9029	Environment Canada Unit 100. Asticou Centre 241 Cite des Jeunes Hull, Quebec, K1A 0H3
CONGO	Mr. Nkaya - Loubaki, P. Eng.	Tel: 83-30-46 Fax: 011 83-71-50	Direction générale de l'environnement, B.P. 958 Brazzaville, Congo
FRANCE	Mr. Michel J. Perrot Manager, Incineration Dept.	Tel: 33 1 39984512 Fax: 33 1 34111528	John Zink Sarl 11, rue Guy-Moquet Zone industrielle 95104 Argenteuil
GERMANY	Mr. Siegfried Unger Project Manager	Tel: 04146 91 2443 Fax: 011 0414 691 2424	Dow Deutschland, Inc. Postfach 1120, D 2160 Stade Germany
INDIA	Dr. A.V. Rama Rao Director	Tel: 853 289 or 853 403	Indian Institute of Chemical Technology, Uppal Road Hyderabad-500 007 AP
MALAYSIA	Mr. Azman Zainal Abdin Lecturer, Dept. of Environmental Sciences	Tel: 03-9486101 Fax: 011 6003 948 3745	Department of Environmental Sciences, Universiti Pertanian Malaysia, 43400 UPM Serdang

Technical Advisory Committee

Country	Name/Position	Tel./Fax.	Address
THE NETHERLANDS	Mr. Antony Beekwilder	Tel: 31-85-664844 Fax: 011 318 566 5345	AKZO Engineering PO Box 9300 6800 SB Arnhem
THE NETHERLANDS	Mr. Wim J.M. Sprong	Tel: 31-70-3174378 Fax: 011 317 0317 4449	Ministry of Housing, Physical Planning and Environment, PO Box 450 2260 MB Leidschendam
RUSSIA	Mr. Evgueni F. Outkine USSR Interagency Ozone Commission	Tel: 252 08 08	The USSR Hydrometeorlogical Committee, 12 Paolik Morozov St., Moscow
UNITED STATES	Mr. Keith J. Herbert Director	Tel: 918-266-1400 Fax: 918-266-3251	Allied-Signal Inc., PO Box 580970, Tulsa, Oklahoma 74158-0970
UNITED STATES	Mr. Kirk E. Hummel	Tel: 512-454-4797 Fax: 512-345-9684	Radian Corporation, PO Box 201088, Austin, Texas 78720-1088
UNITED STATES	Mr. Gene H. Irrgang Manager Market and Product Development	Tel: 0252-21811 Fax: 0252 21355	T-Thermal Europe Ltd., Stafford House, Station Rd., Aldershot Hants GU11 1BA
UNITED STATES	Mr. Maurice Oubre Technical Manager	Tel: 504-389-8953 Fax: 504-389-8160	Dow Chemical, Louisiana Highway 1, PO Box 150 PLAQM, Plaquemine, LA. 70765-0150

UNEP Ozone Secretariat	Mr. K.M. Sarma Coordinator, Dr. Pak Sum Low, Scientist	Tel: 25-42-521928 Fax: 011 254 252 1930	PO Box 30552, Nairobi, Kenya

APPENDIX I

REFERENCES

1. UNEP. Report of the 1991 Technology and Economic Assessment Panel. December 1991. ISBN 92-807-1314-0.

2. Chemical Manufacturers Association (CMA). Production, Sales and Calculated Release of CFC-11 and CFC-12 Through 1989. FC139-066. Washington, D.C., 8 April 1991.

3. CMA. Production, Sales and Calculated Release of CFC-113, CFC-114 and CFC-115 Through 1988. FC139-054. Washington, D.C., 12 November 1990.

4. Gamlen, P.H., B.C. Lane, P.M. Midgley, and J.M. Steed. The Production and Release to the Atmosphere of CCl_3F and CCl_2F_2 (Chlorofluorocarbons CFC 11 and CFC 12). Atmospheric Environment, 20(6): 1077-1085, 1986.

5. Midgley, P.M. The Production and Release to the Atmosphere of 1,1,1-Trichloroethane (Methyl Chloroform). Atmospheric Environment, 23(12): 2663-2665, 1989.

6. Halons. Peer Review Draft Report by the Halon Technical Options Committee. United Nations Environment Programme, July, 1991.

7. Global Carbon Tetrachloride Supply/ Demand Balance. Item M12 submitted by Germany to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

8. KPMG Peat Marwick. 1970-1989 Production and Sales of HCFC-22 for Dispersive Uses. Prepared for Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), Washington, D.C., June 1991.

9. Economic Panel Report. Montreal Protocol on Substances that Deplete the Ozone Layer. United Nations Environment Programme, July 1989.

10. Vogel, G.A., A.S. Goldfarb, R.E. Zier, and A. Jewell. Incinerator and Cement Kiln Capacity for Hazardous Waste Treatment. Nuclear and Chemical Waste Management, 7(1): 53-57, 1987.

11. Frost and Sullivan, Inc. Hazardous Waste Alternate Technologies. Report A2042. Winter 1990.

12. Brunner, C.R. European Hazardous Waste Incinerators. Provided by Dr. P.Lemeiux (USEPA/AEERL).

13. Coopers & Lybrand Deloitte. CFCs and Halons: Alternatives and the Scope for Recovery, for Recycling and Destruction. Report for Department of Trade and Industry (United Kingdom).

14. Canadian Inventory Data on ODP Substances. Item M8 submitted by Canada to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

15. Banked Ozone Depleting Substances in Germany. Item M13 submitted by Germany to the UNEP Ad-hoc Technical Advisory

Committee on CFC Destruction Technologies, November, 1991.

16. Banked CFC in Sweden. Item M17 submitted by Sweden to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

17. Bergstrom, J., R. Harju, and E. Hyden. The Destruction of Halons in the Nordic Countries. Miljorapport 1990:1E prepared for Nordic Council of Ministers, 1990.

18. Estimated Banked Substances for 1990, Australia. Item M10 submitted by Australia to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

19. Inventory of Banked CFCs & Halons in China (1988). Item M27, telefax received at 2nd Meeting of the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

20. Banked in The Netherlands. Item M7 submitted by The Netherlands to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

21. Oppelt, E.T. Thermal Destruction of Hazardous Waste. Presented at the USA/Spain Joint Seminar on Treatment and Disposal of Hazardous Waste, Madrid, Spain, 19-22 May 1986.

22. PEI Associates. Handbook: Permit Writer's Guide to Test Burn Data (Hazardous Waste Incineration). EPA-625/6-86-012, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1986.

23. RES(TX) EDB Test Burn Program Emission Test Results: Volume I. Final report. Prepared by Alliance Technologies. A-88-035. Bedford, Massachusetts, 1988.

24. Whiting, K.J., and G.H. Irrgang. When is an Incinerator Not an Incinerator? Presented at 1990 Incineration Conference, San Diego, California, 14-18 May 1990.

25. Cheremisinoff, P. Waste Incineration Pocket Hand Book. Pudvan Publishing Co., Northbrook, Illinois, 1987.

26. Rich, G., and K. Cherry. Hazardous Waste Treatment Technologies. Pudvan Publishing Co., Northbrook, Illinois, 1987.

27. Oppelt, E.T., Incineration of Hazardous Waste: A Critical Review. JAPCA 37(5): 558-586, May 1987.

28. PEI Associates. Guidance Manual for Co-Firing Hazardous Wastes in Cement and Lime Kilns. Contract No. 68-02-3995 (Work Assignment No. 12) for U.S Environmental Protection Agency, Cincinnati, Ohio, July 1985.

29. Waste Burning: An Inside Look. Rock Products, July 1988 (p.63-84).

30. Lauber, J.D. Burning Chemical Wastes as Fuels in Cement Kilns. JAPCA, 32(7): 771-777, July 1982.

31. MacDonald, L.P., D.J. Skinner, F.J. Hopton, and G.M. Thomas. Burning Waste Chlorinated Hydrocarbons in a Cement Kiln. Report No. EPS 4-WP-77-2 prepared for Environmental Protection Service, Fisheries and Environment Canada, March 1977.

32. Bolstad, J.N., J.T. Chehaske, M. Branscome, C.W. Westbrook, and R.G. Mournighan. Test Results of Hazardous Waste Combustion in Two Cement Kilns. Presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, Michigan, 16-21 June 1985.

33. Miller, F.M. Minor Elements in Cement Clinker. (undated, unpublished)

34. Ingebrigtsen, N., and J.O. Haugom.

Waste Firing in Cement Kilns: Operational Experience in Firing Waste in a 4 Stage Heater. Presented at 1988 IEEE Cement Industry Conference, Quebec, Canada, 24-26 May 1988.

35. Radian Corporation. Municipal Waste Combustion Industry Profile - Facilities Subject to Section 111(d) Guidelines. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 16 September 1988.

36. Vehlow, J., et al. Disposing of Puf in Waste Incineration Plants, Kern forschungszentrum Karlsruhe GmbH, Zentralverband der Elektrotechnik-und Elektronikindustrie e.v. (undated).

37. Radian Corporation. Municipal Waste Combustors - Background Information for Proposed Standards: Post Combustion Technology Performance. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, August 1989.

38. Theodore, L., and J. Reynolds. Introduction to Hazardous Waste Incineration. John Wiley & Sons, New York, New York, 1987.

39. Nesraad b.v. Potential Destruction Technologies for Chlorofluorocarbons and Halons. Prepared for Dutch Ministry of Housing, Physical Planning and Environment, December 1990.

40. Lester, G.R. Catalytic Destruction of Hazardous Halogenated Organic Chemicals. Presented at the 82nd Annual Meeting and Exposition of the Air and Waste Management Association, Anaheim, California, 25-30 June, 1989.

41. New Catalysts Destroy Volatile Organics at Lower Incineration Temperatures. Chemical Engineering, July 1989 (p.19).

42. Catalytic Oxidation System Zaps VOCs. Chemical Engineering Progress. December 1991 (p.14).

43. Kittrell, J.R., C.W. Quinlan, and J.W. Eldridge. Direct Catalytic Oxidation of Halogenated Hydrocarbons. Journal of the Air and Waste Management Association, 41(8): 1129-1133, August 1991.

44. Destruction Technologies of Substances That Deplete the Stratospheric Ozone Layer. Item M1 submitted by Japan to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

45. A New Way to Detoxify Liquid Organic Wastes. Chemical Engineering, August 1989 (p.11).

46. CFC Destruction Technologies Developed and/or In Use in Germany. Item M14 submitted by Germany to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

47. Wastes Suffer a Hot and Steely Death. Chemical Engineering, September 1990 (p.23).

48. Roy, K.A. Molten Metal Technology Destroys Wastes, Recovers Valuable Constituents. Hazmat World, July 1991 (p.62).

49. Australian Technology. Item M11 submitted by Australia to the UNEP Ad-hoc Technical Advisory Committee on CFC Destruction Technologies, November, 1991.

50. Blake, D.M., and R. Burrows. A Non-Incinerative Process for the Destruction of CFCs. Draft Internal Research Statement. Solar Energy Research Institute, Golden, Colorado, August 1988.

51. Supercritical Water System Destroys "Problem" Wastes. Chemical Engineering, November 1990 (p.19).

52. Supercritical Water Gets A Vote of Confidence at Sandia. Chemical Engineering, November 1990 (p.19).

53. Ondrey, G., and K. Fouhy. Plasma Arcs Sputter New Waste Treatment. Chemical Engineering, December 1991 (p.32).

54. Yamamoto, T. et al. Control of Volatile Organic Compounds by an AC Energized Ferroelectric Pellet Reactor and a Pulsed Corona Reactor. Report prepared by Research Triangle Institute for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1989.

55. A Shining Example: Catalytic Degradation of Waste Organics. Chemical Engineering, September 1990 (p. 17).

56. Vogel, T.M. and P.L. McCarty. Abiotic and Biotic Transformations of 1,1,1-Trichloroethane under Methanogenic Conditions. Environmental Science and Technology, 21(12): 1208, 1987.

57. Klecka, G.M., S.J. Gonsior, and D.A. Markham. Biological Transformations of 1,1,1-Trichloroethane in Subsurface Soils and Groundwater. Environmental and Toxic Chemistry, 9: 1437-1439, 1990.