FINAL REPORT

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Environmental Protection Department

An Assessment of Dioxin Emissions in Hong Kong: *Final Report*

March 2000

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March 2000

Reference C1998

For and on behalf of
Environmental Resources Management

Approved by: S.M. LAISTER

Signed:

Position: Executive Director

Date: 6th March 2000

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CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

In November 1999 Environmental Resources Management (ERM) was commissioned by the Environmental Protection Department, Government of the Hong Kong Special Administrative Region (HKSAR) of The People's Republic of China, to undertake a study entitled *An Assessment of Dioxin Emissions in Hong Kong*. The objectives of the study, as detailed in the Terms of Reference (see *Annex A* for details), were as follows:

- to advise on the formation, source and health impacts of dioxins;
- to evaluate and assess the health impact of dioxin releases from the Chemical Waste Treatment Centre (CWTC);
- to evaluate and assess the potential health impact of dioxin emissions from the planned incineration facilities;
- to advise on dioxin control measures and their impacts on the adoption of incineration as an integral part of Hong Kong's waste management strategy.

The tasks to be undertaken in the course of the study were as follows:

1. To review ambient air monitoring data for dioxins in Hong Kong, and advise on the likely significant sources of dioxin.
2. To review existing emissions data, health assessment studies and assess whether the local community is being exposed to a dangerous level of dioxin generated by the existing waste management facilities.
3. To advise on the dioxin monitoring requirements including ambient monitoring and the monitoring of other dioxin sources considered to be significant.
4. To review and advise on the short and long term impacts of dioxin emissions, including the cumulative effect of existing and planned incineration facilities.
5. To advise on the control limit on dioxin emissions from the new incineration facilities in the light of international practice and of (4) above.
6. With respect to the CWTC, to audit the dioxin emission control mechanism, taking into account the future co-combustion of clinical waste.
7. To advise on the limit of exposure of the public to dioxin emissions from all significant identified sources, and on the risk, contingency and emergency

response measure in the event of any mal-operation leading to significant release of dioxins.

1.2 METHOD OF APPROACH

The Consultants have been provided with a number of reports pertaining to monitoring, EIA and risk assessment of waste management facilities in Hong Kong. These include the following:

- *Briefing Note for Baseline Dioxin and Furan Monitoring*, prepared by Camp Dresser & McKee International Inc (CDM), dated 4 November 1997.
- *Feasibility Study of Waste-to-Energy Incineration Facilities, Task 8: Baseline Conditions Interim Report*, prepared by CDM, dated 30 March 1998.
- *Feasibility Study of Waste-to-Energy Incineration Facilities, Task 8: Addendum to Baseline Conditions Interim Report*, prepared by CDM, dated 16 June 1998.
- *Feasibility Study of Waste-to-Energy Incineration Facilities, Site Assessment Report (Tit Cham Chau) Draft Final*, prepared by CDM, dated 25 January 1999.
- *Feasibility Study of Waste-to-Energy Incineration Facilities, Site Assessment Report (Tuen Mun Port) Draft Final*, prepared by CDM, dated 1 February 1999.
- *Feasibility Study of Waste-to-Energy Incineration Facilities, Site Assessment Report (Ha Pak Nai) Draft Final*, prepared by CDM, dated 23 April 1999.
- *Feasibility Study of Waste-to-Energy Incineration Facilities, Site Assessment Report (Lamma Island) Draft Final*, prepared by CDM, dated 2 March 1999.
- *Supplementary Environmental Impact Assessment for Clinical Waste Disposal at Chemical Waste Treatment Centre: Review of Existing Clinical Waste Management Practice*, prepared by ERM, dated 9 December 1998.
- *Supplementary Environmental Impact Assessment for Clinical Waste Disposal at Chemical Waste Treatment Centre*, prepared by ERM, dated 29 March 1999.
- *Chemical Waste Treatment Facilities Environmental Impact Assessment (Final Report)*, prepared by Waste Management International Inc and Dames & Moore, dated 19 April 1991.
- *Summary of ambient dioxin levels in Hong Kong*, Annex 1 of a submission by the Environmental Protection Department (EPD), dated 10 November 1999.
- *Summary of ambient air monitoring conducted by Enviropace Limited at Cheung Ching Estate under the CWTC contract (together with a copy of the 10th*

monitoring report), Annex 2 of a submission to ERM by the Environmental Protection Department (EPD), dated 10 November 1999.

- *Summary of stack gas volume and dioxin emission quantity for the CWTC incineration system*, Annex 3 of a submission to ERM by the Environmental Protection Department (EPD), dated 10 November 1999.

- *Summary of incineration ash quantity and dioxin content for the CWTC incineration system*, Annex 4 of a submission to ERM by the Environmental Protection Department (EPD), dated 10 November 1999.

- *Sludge Treatment & Disposal Strategy Study (Final Report)*, prepared by ERM, dated July 1999.

The Consultants have supplemented these documents with a range of information gathered from the technical literature, on environmental levels of dioxins, their behaviour in incineration systems, and their fate and transport in the environment. Based on this information, we have assessed the environmental impact of existing waste management operations (primarily, the CWTC) as well as the implications of the implementation of the waste reduction framework plan, in particular the provision of waste incineration facilities.

1.3 STRUCTURE OF THE REPORT

The remainder of this report is structured as follows:

- *Section 2* provides an introduction to the family of compounds described as "dioxins", their nomenclature, and standard means of reporting dioxin concentrations.

- *Section 3* assesses the likely sources of dioxins in Hong Kong, develops a tentative dioxin inventory for Hong Kong, and makes recommendations for the monitoring of dioxin releases.

- *Section 4* examines the ambient air monitoring data for Hong Kong, and compares the reported dioxin levels against measurements obtained elsewhere. The impact of future waste management operations is assessed, and the implications for current and future public health are discussed.

- *Section 5* advises on the selection of dioxin control mechanisms for the CWTC, the planned incineration facilities, and on monitoring requirements.

- *Section 6* discusses emergency response measures in the event of malfunctions.

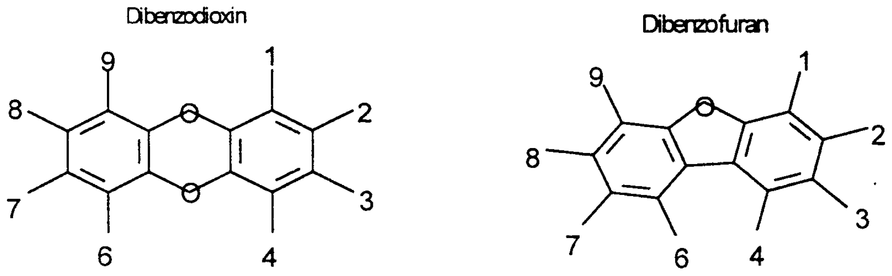
The report is supported by three annexes:

- *Annex A*, presenting the Terms of Reference for the study;
- *Annex B*, which provides background information on the environmental fate and behaviour of dioxins, as well as a summary of their toxic effects;
- *Annex C*, which discusses the fundamental principles and combustion studies informing the formation and emission of PCDD/Fs.

2.1 STRUCTURE AND COMPOSITION

The term "dioxin" is often used to denote a family of compounds known chemically as polychlorinated dibenzo-para-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Each compound comprises two benzene rings interconnected by oxygen atoms. In the case of PCDDs, the benzene rings are joined by two oxygen bridges, whereas in the PCDFs, the benzene rings are connected by a carbon bond and an oxygen bridge. *Figure 2.1a* depicts the basic structural formula of PCDDs and PCDFs, together with the numbering convention at the positions on the benzene rings where chlorine or other halogen atoms can be substituted.

Figure 2.1a ***Basic Structure of PCDDs and PCDFs***



There are 75 PCDDs and 135 PCDFs, each differing in the number and position of the chlorine atoms. Each individual PCDD or PCDF is termed a *congener* (giving 210 in total), while groups of congeners with the same number of chlorine atoms are called *homologues*. The number of congeners in each homologue group is shown in *Table 2.1a*. The homologue groups are often abbreviated for convenience; for example, tetrachloro CDDs and CDFs (PCDD/Fs with four substituted chlorine atoms) are abbreviated to TCDDs and TCDFs respectively, while the fully chlorinated octachloro congeners (eight substituted chlorine atoms) are abbreviated to OCDD and OCDF respectively.

2.2 INTERNATIONAL AND WHO TOXIC EQUIVALENT SCHEMES

PCDD and PCDF congeners with chlorine atoms in the 2, 3, 7 and 8 positions are of particular environmental concern, especially the tetrachloro-CDD congener 2,3,7,8-TCDD, which achieved notoriety following its release from the ICSEMA plant at Seveso, Italy in 1977.

Table 2.1a   Homologues and Congeners of PCDDs, PCDFs and PCBs

	Number of Congeners		
Homologue (Abbreviation)	**PCBs**	**PCDDs**	**PCDFs**
Monochloro(M)	3	2	4
Dichloro(D)	12	10	16
Trichloro(Tr)	24	14	28
Tetrachloro(T)	42	22	38
Pentachloro(Pe)	46	14	28
Hexachloro(Hx)	42	10	16
Heptachloro(Hp)	24	2	4
Octachloro(O)	12	1	1
Nonachloro	3		
Decachloro	1		
TOTAL	209	75	135

Table 2.2a   Toxic Equivalent Factors(I-TEFs)

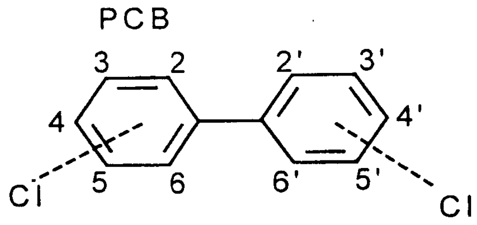
Congener	International I-TEFs	WHO TEFs
2,3,7,8-TCDD	1	1
1,2,3,7,8-PeCDD	0.5	1
1,2,3,4,7,8-HxCDD	0.1	0.1
1,2,3,7,8,9-HxCDD	0.1	0.1
1,2,3,6,7,8-HxCDD	0.1	0.1
1,2,3,4,6,7,8-HpCDD	0.01	0.01
OCDD	0.001	0.0001
2,3,7,8-TCDF	0.1	0.1
2,3,4,7,8-PeCDF	0.5	0.5
1,2,3,7,8-PeCDF	0.05	0.05
1,2,3,4,7,8-HxCDF	0.1	0.1
1,2,3,7,8,9-HxCDF	0.1	0.1
1,2,3,6,7,8-HxCDF	0.1	0.1
2,3,4,6,7,8-HxCDF	0.1	0.1
1,2,3,4,6,7,8-HpCDF	0.01	0.01
1,2,3,4,7,8,9-HpCDF	0.01	0.01
OCDF	0.001	0.0001
Coplanar PCBs		
3,4,4',5-TrCB	-	0.0001
3,3',4,4'-TrCB	-	0.0001
3,3',4,4',5-PeCB	-	0.1
3,3',4,4',5,5'-HxCB	-	0.01
2,3,3',4,4'-PeCB	-	0.0001
2,3,4,4',5-PeCB	-	0.0005
2,3',4,4',5-PeCB	-	0.0001
2',3,4,4',5-PeCB	-	0.0001
2,3,3',4,4',5-HxCB	-	0.0001
2,3,3',4,4',5'-HxCB	-	0.0005
2,3',4,4',5,5'-HxCB	-	0.00001
2,3,3',4,4',5,5'-HpCB	-	0.0001

Of the 17 PCDD and PCDF congeners with chlorine in the 2, 3, 7 and 8 positions, 2,3,7,8-TCDD is the most toxic, and by convention is assigned a toxicity rating of 1.0 (called a Toxic Equivalent Factor or TEF). The remaining 2,3,7,8-positional congeners are then assigned lower TEFs comparable to their toxicity, relative to that of 2,3,7,8-TCDD. The toxicity of any mixture of PCDDs and PCDFs, relative to 2,3,7,8-TCDD, can then be expressed by multiplying the concentrations of the 2,3,7,8-positional congeners present in the mixture by their respective TEFs. The resulting products for each congener are called Toxic Equivalents (TEQs), with units identical to that in which the concentrations of the individual congeners are expressed. The TEQ of the mixture is obtained by summing the individual TEQs.

While a number of toxicity rating schemes have been developed, the scheme that has been internationally adopted is that of NATO/CCMS (1988), under which the TEFs are termed International TEFs, or I-TEFs. The I-TEFs for the seventeen 2,3,7,8-positional congeners of PCDDs and PCDFs are presented in *Table 2.2a*; all other congeners that may be present in a sample are assigned a TEF value of 0.0. The summation of individual TEQs for a mixture of PCDDs and PCDFs is termed the International Toxic Equivalent or I-TEQ of the mixture.

A recent revision of the TEF scheme was undertaken by the World Health Organisation (Van den Berg *et al*, 1998) in connection with a review of the WHO recommended Tolerable Daily Intake (see *Annex B* for details). The proposed scheme includes coplanar congeners of polychlorinated biphenyls (PCBs) within the overall TEQ scheme, by defining TEFs for 12 coplanar PCBs on the basis that their mode of action and the responses elicited in biological systems parallel those of the 2,3,7,8-positional PCDD/Fs. These are listed in *Table 2.2a*, together with their proposed TEFs. The WHO-TEQ of the sample would be represented by the summation of the products of the concentrations of 17 PCDD/F congeners and 12 PCB congeners by their respective TEFs. The basic structure and positional numbering system for PCBs is presented in *Figure 2.2a.*.

Figure 2.2a *Basic Structure of PCBs*



2.3 NOMENCLATURE USED IN THIS REPORT

Throughout this report, "dioxins" are referred to in their correct nomenclature: as PCDDs, PCDFs, or as PCDD/Fs if the sample contains both PCDDs and PCDFs. Emissions of PCDDs and PCDFs to atmosphere and concentrations of PCDDs and PCDFs in stack gases and environmental media are given as total or individual congeners and homologues of PCDD/Fs, or as I-TEQs, depending on the manner in which they are reported in the data provided and in the technical literature. Most emission and environmental data post-1988 are generally reported solely as I-TEQs.

Concentrations of PCDDs and PCDFs are expressed as picogrammes (pg) or nanogrammes (ng) of the chemicals (generally expressed as I-TEQ) per gramme (g) of the medium or per cubic metre (m^3) if a gaseous medium. 1 pg is equal to 1/1,000,000,000,000 (1×10^{-12}) of a gramme (or one million millionth of a gramme) while 1 ng is equal to 1/1,000,000,000 (1×10^{-9}) of a gramme (or one part in one thousand millionth of a gramme).

3 SOURCES OF PCDD/FS IN HONG KONG AND MONITORING RECOMMENDATIONS

3.1 INTRODUCTION

In *Section 3*, the consultants address Task 3 of the Terms of Reference. The section commences with a brief discussion on the potential sources of PCDD/Fs and their propensity for emissions to the atmosphere. There follows a presentation of the UK PCDD/F emissions inventory, a comprehensive inventory covering a wide range of industrial and non-industrial activities and processes, together with the emission factors applied to each of the processes and activities of interest. In order to develop a tentative PCDD/F emissions inventory for Hong Kong, these emission factors were applied to activities and activity patterns identified as being present in Hong Kong. Both present and potential future emissions are estimated. The contribution of thermal waste treatment facilities to the total inventory is discussed.

Based on the identified sources, tentative monitoring requirements are suggested. These suggestions are in line with standard practice for monitoring of PCDD/F emissions from industrial processes operated elsewhere.

3.2 SOURCES OF DIOXINS

3.2.1 Natural and Man-made Sources

In 1980, following the discovery of PCDD/Fs in a broad range of environmental samples in both remote and industrially developed locations in the United States, the Dow Chemical Corporation put forward the Trace Chemistries of Fire hypothesis for their formation and occurrence. This hypothesis stated that in any situation where chlorine, carbon, hydrogen and oxygen came into contact with heat, PCDD/Fs could be formed as trace by-products. Hence, this suggested that these chemicals have been on earth since the advent of fire, and that both natural and man-made sources could release PCDD/Fs into the environment (Dow Chemicals, 1978).

Natural sources have been identified as releasing PCDD/Fs. For example, analysis of archived UK soil samples dating from the pre-1900s, before the large-scale manufacture and use of chlorinated chemicals, confirmed the presence of these compounds (Alcock *et al*, 1998b). Samples from 2,800 year old Chilean mummies (Ligon and Dorn, 1989) and from Japanese sediment samples dating from at least 6,100 years BC have also confirmed the presence of PCDD/Fs in historical times.

In addition, it has been postulated that biological formation of PCDDs and PCDFs is possible in sediments and soils, especially forest soils and sediments

(Rappe *et al*, 1997a; Hoekstra *et al*, 1999). Examination of PCDD/F congener profiles in uncontaminated forest soils and sediments and comparison with those of known sources has suggested that the presence of PCDD/Fs in these samples cannot be readily explained by inputs from man-made sources (Rappe *et al*, 1997b). Oberg *et al* (1992, 1993), Oberg and Rappe (1992) and Schramm *et al* (1996) have also noted the potential for the natural formation of PCDD/Fs in sewage sludge and compost under environmental conditions; these are synthesised by peroxidates from chlorinated organic precursors such as chlorophenols. The biochemical reactions in sewage sludge and compost favour the formation of HpCDD and OCDD, increasing the I-TEQ of the sample.

However, there is general agreement that man-made sources and activities are far greater contributors to the environmental burden of PCDD/Fs than natural processes, especially since the 1930s, from which time there has been a steady increase in environmental levels coinciding with the large scale production and use of chlorinated chemicals (Fortin and Caldbick, 1997; Alcock *et al*, 1998b). Man-made sources of PCDD/Fs can be divided into three main categories, broadly defined as follows (Fiedler, 1993):

- chemical processes;
- combustion processes;
- secondary sources.

Each of these sources are discussed in the following sections.

3.2.2 Chemical Processes

PCDDs and PCDFs can be formed as trace contaminants during the manufacture of a number of organic and inorganic chemicals and chemical products. The following conditions have been proposed under which PCDD/Fs are most likely to be formed:

- processes in which chlorine is present, either as a reactant or as a constituent of a reactant;
- process temperatures greater than 150℃, although leaching of paper pulp at 70℃ can also give rise to PCDD/Fs.
- presence of weak to strong alkaline conditions.

Applying the above criteria, the following processes have been ranked in order of importance as potential industrial sources of PCDD/F:

1. Processes involving chlorophenols and their derivatives.
2. Processes involving chlorobenzenes, further substituted chloroaromatic compounds and their derivatives.
3. Syntheses of chlorinated aliphatic compounds.

4. Processes where chlorine is part of the molecule in intermediate stages but not part of the final product.

5. Processes involving inorganic chlorine chemistry.

6. Process involving chlorine-containing catalysts and solvents.

These process conditions apply equally to the potential for PCDF formation, and have been adopted in a number of searches for potential sources of PCDD and PCDF emissions to the environment.

It should be noted that these criteria relate to the potential for PCDD/F formation in the product of a particular process. Generally, the product is a liquid or solid, and is retained within the reaction vessel. However, the potential for trace contamination of a product does not necessarily imply that the process will also release PCDDs and PCDFs to the atmosphere, reaction conditions may be such that emissions of these compounds to atmosphere may be negligible. Nevertheless, they may be released via other process discharges, for example in off-specification batches, liquid effluent or in solid residues.

3.2.3 Thermal Processes

Thermal processes differ from chemical processes in that the latter are conducted at relatively low temperatures, generally in the liquid phase. In thermal processes the reaction temperatures are typical of combustion-related processes (800℃ and above) but with the potential for some parts of the process train to be maintained at lower temperatures (generally after combustion or thermal treatment of the feed materials has taken place). Thermal or combustion processes include the following:

- ***Stationary sources***: incineration of various fuels (wood, coal, oil, etc) and wastes (chemical, municipal, clinical, sewage sludge, straw, etc), as well as foundries, sinter and secondary metal recovery facilities, fragmentisers, etc.

- ***Diffuse sources***: automobile exhausts, private home heating, smoking of cigarettes, etc.

- ***Accidental releases***: warehouse fires, fires involving polychlorinated biphenyls (PCBs), fires involving contaminated wood, etc.

The conditions which have been identified as being conducive to PCDD/F formation (through catalytic reactions) are as follows:

- presence of chlorine or of chlorine-containing compounds in the thermal/combustion system;

- temperatures in the system of between 250-400℃, and especially in the range 300-350℃ (Hagenmaier *et al*, 1987);

- type of pollution abatement equipment, especially plant maintained at between 250-400℃.

While the above temperature range has been shown to be the optimum for PCDD/F formation, gas phase reactions (as opposed to catalytic reactions) within the secondary combustion zone at 800-1,200℃ are also known to generate PCDD/Fs, but in very small quantities. The generation of PCDD/Fs in this high temperature range is balanced against the dominant process of destruction of PCDD/Fs caused by the high temperatures. Hence, the exposure of PCDD/Fs to the higher temperatures has the net result of significantly reducing their presence in a combustion gas stream.

3.2.4 Secondary Sources

Secondary sources of PCDD/F release include emissions from contaminated sites and landfills. In addition, soil and sediment in which PCDD/Fs can accumulate can also act as secondary sources of these chemicals by redistributing them via wind-blown dust and resuspension of sediments. Cycling of PCDD/Fs in the environment is thought to account for the majority of the measured environmental burden in the atmosphere. Around 90% of the measured deposition is thought to originate from PCDD/Fs that have been redistributed between air, water and soil, rather than arising as "new" emissions from the sources listed above (Rappe, 1992).

3.3 A PRELIMINARY PCDD/F INVENTORY FOR HONG KONG

3.3.1 National PCDD/F Emission Inventories

A number of countries have developed inventories of PCDD/F releases to atmosphere. Central to the compilation of an inventory is the estimation of emission factors, linking PCDD/F emissions with a unit of activity (for example, µg of PCDD/Fs (as I-TEQ) per tonne of waste incinerated, or µg of PCDD/Fs per kilometer travelled). These are typically obtained by sampling and analysing PCDD/F emissions from potential sources, and then averaging the measured emission factors across those particular activities to provide estimates of annual PCDD/F emissions on a national basis. In the absence of emission measurements within a particular activity or sector, national PCDD/F emission inventories rely initially on emission factors derived elsewhere, in order to develop preliminary inventories which can then be refined and updated by conducting appropriate sampling programmes.

The latter approach is adopted in the present study to develop a preliminary PCDD/F emissions inventory for Hong Kong, using as its basis the PCDD/F inventory of sources and where appropriate, emission factors derived for the UK (Eduljee and Dyke, 1996). *Tables 3.3a* and *3.3b* summarises the data, including the emission factors used to derive the UK national inventory.

Table 3.3a UK Inventory of PCDD/F Emissions to Atmosphere

Process	Emission Factor (μg I-TEQ/tonne)	Emissions 1994/95	Estimate (g I-TEQ) 2000
Coke production	0.3	2	2(2)
Coal combustion (ind/power)	0.04-4.8/0.06-0.32	5-67	5-67(2)
Waste oil combustion	2-6	0.8-2.4	0.8-2.4(2)
Wood combustion (cont/clean)	9-19/1-2	1.4-2.9	1.4-2.9(2)
Straw combustion	17-50	3.4-10	3.4-10(2)
Tyres combustion	18	1.7	1.7(2)
Landfill gas combustion	0.022	1.6-5.5	1.6-5.5(2)
Sinter plants	1.2-9.0	29-54	29-47
Iron and Steel	0.7-10	3-41	14
Non-ferrous metals	5-35	5-35	10
Cement manufacture	0.02-1.08(4)	0.2-11	0.2-11(2)
Lime manufacture	0.02-1.08(4)	0.04-2.2	0.04-2.2(2)
Glass manufacture	0.002-0.005	0.005-0.01	0.005-0.01(2)
Ceramic manufacture	0.002-0.005	0.02-0.06	0.02-0.06(2)
Halogenated chemicals	0.025(4)	0.02	0.02(2)
Pesticide production	0.01-0.025(4)	0.1-0.3	0.1-0.3(2)
MSW combustion (old/new)	184-231/0.8	460-580	15
Chemical waste combustion	5-30	1.5-8.7	0.3(3)
Clinical waste comb (old/new)	120-480/20-200	18-88	5
Sewage sludge combustion	9-77	0.7-6	0.9
Carbon regeneration	0.75	0.006	0.006(2)
Asphalt mixing	0.047	1.6	1.6(2)
PCP in timber processes	700-2500	0.8	0.8(2)
Crematoria	2.4-80 (per body)	1-35	1-35(2)
Domestic wood combustion	1-50	2-18	2-18(2)
Domestic coal combustion	2.1-9.3	20-34	20-34(2)
Traffic	see below	1-45	1-45(2)
Natural fires	1-28	0.4-12(1)	0.4-12(2)
Total		**560-1100**	**110-350**

Notes:

(1) Based on open fires data

(2) No reduction was assumed. This may not apply to future emissions from traffic and crematoria

(3) Assumed to comply with the Hazardous Waste Directive (0.1ng/m^3)

(4) μg I-TEQ per tonne of product

Table 3.3b Emission Factors for PCDD/F Releases from Traffic

Source	Emission Factor (μg I-TEQ/M km)
Cars	
• Leaded	1.1-220
• Unleaded (no catalytic converter)	0.36-21
• Unleaded (with catalytic converter)	0.36-13
• Diesel	0.65-10
Light vans	
• Petrol (leaded)	1.1-220
• Diesel	0.65-10
HGVs	
• Petrol	1.1-220
• Diesel	26-37
Large Buses (diesel)	26-37
Motorcycles (unleaded)	0.36-21

It is of interest to consider PCDD/F emissions from thermal waste treatment facilities in relation to other PCDD/F emitters. *Table 3.3c* summarises the data for key industrial emission sources in a number of national PCDD/F inventories.

Table 3.3c ***Percentage Contribution of Various Sources to National Emissions of PCDD/Fs (1995-97 estimates)***

Source	UK	US	Netherlands	Germany	Austria
MSW combustion	53-82	73	79	8-47	20-37
Chemical waste combustion	0.3	6	3.3	0.8-8	2-17
Clinical waste combustion	3-8	15	0.4	0.6-8	6-10
Sewage sludge combustion	<1	2	<1	<1	<1
Coal combustion (industrial)	1-6	NA	0.8	NA	<2
Secondary metals production	1-3	2	0.8	40-60	40-44
Sintering processes	5	2	5.4	2	NA
Wood combustion (industrial)	0.1-0.2	NA	2.5	NA	3-5

Notes:

(1) The calculated percentages are not strictly comparable since the national inventories encompass different source categories. UK data are from Eduljee and Dyke (1996). US data are from US EPA (1997). Other European data are from North Rhine-Westphalia State Environment Agency (1997).

(2) NA=Not available

(3) Secondary metals production includes copper smelting only

According to estimates of PCDD/F emissions to atmosphere in 1995/97, municipal waste incinerators contributed an average of 70% to the total emissions from industrial sources. However, the progressive implementation of Integrated Pollution Control in the UK, especially on thermal processes, was expected to result in significant reductions in PCDD/F emissions over the subsequent years. All new thermal waste disposal processes and thermal metallurgical processes must achieve an emission concentration of at least 1 ng I-TEQ m^{-3} (and strive towards a target of 0.1 ng I-TEQ m^{-3}) and old plant were required to meet this emission limit in the period leading up to the year 2000. This is in contrast to the circumstances in Hong Kong, where the CWTC commenced operation in 1993 with a 0.1 ng I-TEQ m^{-3} emission limit. For the UK inventory, the net effect is a reduction of annual emissions, from 560-1100 g I-TEQ a-1 to 110-350 g I-TEQ a-1. The largest reduction is effected through the imposition of the 1 ng I-TEQ m^{-3} emission level on clinical waste incinerators and municipal waste incinerators. The contribution from municipal waste incinerators was predicted to fall from its present range of 60-85% to approximately 6-18%.

The above inventory data, generally dating from the early 1990s, indicate that the dominant industrial source of PCDD/F emissions to atmosphere at that time can be attributed to municipal waste incineration. Future estimates based on more stringent emissions limits indicate that this particular emission source will drop to an average of 12% of industrial and non-industrial emissions. Hence, based on the current understanding of the fate and transport of PCDD/Fs in the environment, the contribution to the background intake from municipal waste incinerator emissions, the dominant emission source in most current inventories, should correspondingly decrease.

A recent update on the 1994/95 UK inventory confirmed the downward trend in PCDD/F emissions. Based on stack measurements between 1995 and 1997, Alcock *et al* (1998c) estimated that the emissions inventory for 1997 had decreased from 560-1100 g I-TEQ a-1 (see *Table 3.3a*) to 220-660 g I-TEQ a-1, with MSW incinerators contributing between 30-60% of total PCDD/F (I-TEQ) emissions as opposed to 53-82% in 1994/95.

3.3.2 Potential PCDD/F Sources in Hong Kong

The Consultants have conducted a preliminary screening level assessment of potential industrial and non-industrial sources of PCDD/F emissions in Hong Kong. *Table 3.3d* summarises our current understanding of the presence of potential current and future sources in Hong Kong. Activities which were identified as potential sources of PCDD/F emissions in Hong Kong were quantified. In compiling the inventory, the Consultants have discounted the following processes and activities:

- **Gas-fired power plants**. The nature of the feedstock, the lack of chlorine in the combustion system and the high combustion temperature suggest that gas-fired power plants are not significant PCDD/F emitters. The Consultants have not identified any data for PCDD/F emissions from gas-fired power station.

- **Landfill gas combusted in domestic premises**. In terms of the potential for PCDD/F emissions, the consultants have regarded landfill gas combusted in domestic premises as being equivalent to flaring of landfill gas, but at a far lower activity rate, overall PCDD/F emissions will be low. In any event, landfill gas will be treated prior to introduction into the Towngas network.

For the shortlisted processes and activities, the emission factors were selected from *Table 3.3a* and *Table 3.3b* or modified as appropriate, though preference was given to measured emissions as opposed to UK emission factors, where data for Hong Kong were available. A baseline of 1997 was selected as the most current year for which adequate activity data was available. Projected emissions for 2007 were estimated according to information on likely future activity patterns. Information on specific activities and sectors is provided below, where emission factors differ from those listed in *Table 3.3a* and *3.3b*.

- **MSW incineration**: the Consultants have assumed that a total projected incineration capacity of 1 million tonnes per annum will have been installed by 2007. The proposed new facilities will be operating to an emission limit of 0.1 ng I-TEQ m^{-3}. Assuming a nominal gas generation rate of 5,140 m3 $tonne^{-1}$, this results in an emission factor of 0.514 μg I-TEQ $tonne^{-1}$, rounded to 0.5 μg I-TEQ $tonne^{-1}$.

- **Sewage sludge incineration**: the UK emission factors of 9-77 μg I-TEQ $tonne^{-1}$ (dry) reflect the presence of both new and old plants, the former operating to an emission limit of 0.8 ng I-TEQ m^{-3}. However, these plants can operate to lower limits, and currently are typically guaranteed by equipment suppliers to operate within the 0.1ng I-TEQ m^{-3} emission limit applied to other types of waste combustors. Therefore in developing a PCDD/F inventory, the Consultants have applied an emission factor of 1 µg I-TEQ $tonne^{-1}$ (dry) to reflect PCDD/F emissions at 0.1 ng I-TEQ m^{-3}.

- **Chemical waste incineration**: since measured PCDD/F emissions were available for the CWTC, these were used directly to estimate annual emissions. For 1997, the CWTC monitoring data reports that 4.3 mg I-TEQ of PCDD/F was released, equal to 0.004 g I-TEQ a^{-1}.

- **Clinical waste incineration**: in future, the Consultants have assumed that clinical waste will be incinerated at the CWTC facility, which operates to a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. Assuming a gas flow of 30,000 m3 hr^{-1} from the combustion of clinical waste and an operating year of 8,000 hours, a mass emission of 0.02 g a^{-1} was calculated. This emission was added to the estimated emission of 0.004 g I-TEQ a^{-1} resulting from the combustion of chemical waste, giving a combined emission of 0.024 g I-TEQ a^{-1}.

- **Crematoria**: the PCDD/F emission limit for crematoria in Hong Kong is set at 1 ng I-TEQ m^{-3}, and this is unlikely to change in 2007. The emission factor for crematoria was developed by assuming a gas generation rate of 1,500 Nm3 per human body (Bremmer *et al*, 1994). An emission factor of 1.5 µg I-TEQ per body is calculated.

- **Animal carcass incineration**: it is assumed that the animal carcass incinerator will operate to a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. If it is further assumed that the same gas generation rate for humans also applies to animal carcasses, an emission factor of 0.15 µg I-TEQ $body^{-1}$ is estimated.

- **Cement manufacture**: the Consultants have developed an annual mass emission estimate from data provided by Green Island Cement (see notes attached to *Table 3.3d*), in preference to a mass emission calculated from UK emission factors.

The estimated PCD/F emissions for 1997 and 2007 are listed in *Table 3.3d*. It should be noted that the use of 1997 data does not necessarily influence the predictions for 2007, since different approaches were used for some sources.

According to the data in *Table 3.3d*, MSW incineration dominated the PCDD/F inventory in 1997, but the total inventory, i.e. the summation of all sources listed in the table (approximately 30 g I-TEQ a-1 in 1997), is far less than comparable inventories elsewhere. This is due to a combination of a lower level of population in Hong Kong (6.5 million as opposed to 60 million in the UK) and lower levels of industrial activity that have been traditionally associated with historical national inventories (eg. MSW and clinical waste incinerators, and secondary metal refining) and the absence of sources such as sinter plants. Currently operating thermal waste treatment processes in Hong

Kong are of relatively small scale, and the sole chemical waste treatment incinerator (the CWTC) introduced to Hong Kong in recent years has adopted technology and a PCDD/F emission limit (0.1 ng I-TEQ m^{-3}) that is presently regarded as constituting best practice in terms of PCDD/F emissions. The latter will also apply to the subsequent introduction in the coming years of the proposed MSW, clinical waste and sewage sludge incinerators. Therefore, the historical legacy of PCDD/F emissions due to the operation of thermal waste treatment processes has to a large extent been avoided.

Table 3.3d ***Estimated PCDD/F Emissions to the Atmosphere from the HKSAR (1997 and 2007)***

Sources	**Activity (1997)**	**Inventory (1997) (g I-TEQ)**	**Activity (2007)**	**Inventory (2007) (g I-TEQ)**
Industrial Sources				
Coal combustion (power)	6.1 MT	0.4-2.0	5.6 MT	0.3-1.8
Landfill gas combustion				
■ migrating gas	254,773 t CH4	0.2-0.3	145,000 t CH4	0.13-0.15
■ flared gas	17,662 t CH4	0.001	10,052 t CH4	0.001
■ combustion gas	NA	NA	NA	NA
Non-ferrous metal	27,450	0.1-1.0	27,450	0.1-1.0
Cement manufacture (a)	1,514,838 t clinker	0.32	1,514,838 t clinker	0.32
MSW combustion	116,508 t (old)	21-27	1,000,000 t (new)	0.5
Chem waste combustion	10,198 t (CWTC)	0.004 (b)	10,198 t (CWTC)	0.024 (c)
Clinical waste combustion	3,650 t (old plant)	0.4-1.8	5,290 t (CWTC)	(c)
Sewage sludge comb.	-		259,000 dry t	0.2
Asphalt mixing	84,050 t	0.004	84,050 t	0.004
Non-Industrial Sources				
Crematoria				
■ humans	16,250 bodies	0.024	20,750 bodies	0.031
■ animals	-		7,300 t (d)	0.015
Cars				
■ leaded	2,049 M km	0.002-0.45	-	-
■ unleaded (with cat)	2,237 M km	0.001-0.03	7,250 M km	0.003-0.09
■ diesel	2,515 M km	0.002-0.03	2,515 M km	0.002-0.03
■ LPG	-	-	2,600 M km	?
Light GVs (diesel)	2,000 M km	0.001-0.02	2,400 M km	0.002-0.04
Heavy GVs (diesel)	2,288 M km	0.06-0.09	2,557 M km	0.07-0.1
Buses (diesel)	612 M km	0.016-0.023	620 M km	0.016-0.023
Motorcycles	287 M km	0.0001-0.006	469 M km	0.0002-0.01
TOTAL		**23-33**		**2-4**

Notes:

(a) Assuming maximum operational conditions at 0.1ng I-TEQ/m3 limit., 7680hrs/year operation, 7000m3/min. flow rate (Green Island Cement, 6/1/00) and is not based on activity data.

(b) According to CWTC monitoring data, 4.3 mg I-TEQ of PCDD/F was released in 1997.

(c) Assuming maximum operational conditions at CWTC at 0.1ng I-TEQ/m3 limit., 8000hrs/year operation, 30000m3/hr flow rate (SEIA for CWTC, 29/3/99) and includes BOTH chemical and clinical waste incineration at the CWTC.

(d) Assuming average body weight of 70 kg, 7,300 t ≈ 100,000 bodies. For new plant, an emission factor of 0.15 µg I-TEQ body-1, corresponding to an emission of 0.1ng I-TEQ m^{-3}, is used.

The net reduction in PCDD/F emissions between the 1997 estimates and the projections for 2007, is primarily due to the closure of old MSW incineration plants. Despite the significant increase in the tonnage of MSW, clinical waste, sewage sludge and animal carcasses incinerated by 2007 as compared to 1997, the proposal by the EPD to operate these incinerators at a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} will still result in a net decrease in PCDD/F emissions relative to 1997. It is estimated that in 1999, with all of the old MSW incinerators decommissioned, the 1999 dioxin inventory would be approximately 2 to 6 g I-TEQ, assuming that all other activities were the same as in 1997. However, this would be a very preliminary estimate as there is incomplete activity data or information available for all the major sources in 1999.

3.3.3 Natural and Accidental Fires

To the emissions identified in *Table 3.3d* should be added emissions from accidental fires, natural fires, etc. Emission factors for these events are difficult to estimate with any degree of certainty. A detailed discussion is contained in HMIP (1995), in which an emission factor range of 1-28 µg I-TEQ per tonne of material consumed is derived for open natural fires. Bonfires also have the potential to release PCDD/Fs to atmosphere (Lorenz *et al*, 1996; Dyke *et al*, 1997). The same difficulty in estimating a PCDD/F emission factor applies in the case of accidental fires (HMIP, 1995). The potential for PCDD/F formation will depend on the combustion conditions, and on the presence or absence of chlorinated materials such as PVC. Contrasting PCDD/F emission estimates have been proposed, from 3 mg I-TEQ from a fire involving 200 tonnes of PVC and 500 tonnes of carpeting, to 13 kg of total PCDD/Fs from a fire involving 600 tonnes of rigid PVC (HMIP, 1995).

Further work is required to quantify PCDD/F emissions from these sources.

3.4 MONITORING OF POTENTIAL SOURCES

3.4.1 Routine Monitoring

Of the potential sources of PCDD/F emissions listed in *Table 3.3d*, the Consultants recommend that the stack gases from the following facilities should be subjected to routine monitoring:

- MSW incinerators;
- Clinical waste incinerators (if dedicated facilities are developed);
- Sewage sludge incinerator;
- Animal carcass incinerator;
- CWTC facility;
- Cement kilns.

Monitoring frequencies are not specified in the BPM Notes applicable in Hong Kong. A monthly stack monitoring frequency is adopted on the CWTC incinerator. For MSW and clinical waste incinerators, the proposed EU draft incineration directive specifies a minimum of one measurement every three months in the first twelve months of operation, and a minimum of two measurements per year thereafter. In Belgium, continuous monitoring of MSW incineration stack emissions is required, with analysis at least every two weeks.

The Consultants recommend a monthly sampling regime for the MSW and sewage sludge incinerators in the first year of operation. Thereafter, bimonthly sampling (i.e. one sample every two months) is suggested for the sewage sludge incinerator if the first year of operation indicates that the emission limit of 0.1 ng I-TEQ m^{-3} is not breached. It is recommended that monthly sampling of the MSW incinerators be continued after the first year of operation, in line with provisions currently in place on the CWTC plant. A tentative recommendation for the animal carcass incinerator is that the facility is monitored monthly for the first year of operation, and thereafter quarterly (i.e. one sample every four months) if the specified PCDD/F emission limit is not breached. For the cement kiln, bimonthly monitoring (i.e. once every two months) is recommended.

Reference should also be made to *Section 4.5* below in respect of analysis for co-planar PCBs.

3.4.2 Confirmatory Monitoring

Although coal combustion and landfill gas contribute a significant fraction of the total inventory, their emission factors relative to the sources listed in *Section 3.4.1* suggests that the magnitude of the annual mass of PCDD/Fs released is more a function of the high activity rate rather than high emission concentrations *per se*. For industrial sources like non-ferrous metal production, emission factors can be high, however the appropriate emission factors specific to the plants in Hong Kong are uncertain.

Hence, for these sources, the Consultants recommend a pilot sampling programme to verify the assumptions made in the compilation of the preliminary inventory, after which a routine sampling programme can be developed if appropriate.

4 PRESENT AND FUTURE AIR QUALITY AND PUBLIC HEALTH

4.1 INTRODUCTION

Section 4 addresses Tasks 1 to 4 of the Terms of Reference. In *Section 4.2* the PCDD/F ambient air quality measured at two urban sites is presented and compared against measurements obtained in other countries. *Section 4.3* introduces the measured PCDD/F emissions from the CWTC and assesses their impact on local air quality, as measured at three nearby locations. *Section 4.3* then assesses the impact of other existing waste management facilities on the general environment, based on the background ambient air measurements. *Section 4.4* extends the assessment to a consideration of the PCDD/F impact of the planned waste management facilities. *Section 4* ends with recommendations for monitoring of the ambient environment.

4.2 PRESENT AMBIENT AIR QUALITY

Ambient air quality has been measured by the Environmental Protection Department (EPD) at two urban locations (Tsuen Wan and Central/Western) since the beginning of 1997. A summary of the PCDD/F data, measured over 24 hour sampling periods and expressed as monthly averages in units of pg I-TEQ m^{-3}, is presented in *Table 4.2a*.

Table 4.2a Summary of Ambient Air PCDD/F Levels in Hong Kong

Year	Month	Dioxin Concentration (pg I-TEQ m^{-3})	
		Central/Western	**Tsuen Wan**
1997	July	0.063	0.098
	August	0.14	No data
	September	0.114	0.121
	October	0.110	0.246
	November	0.173	0.116
	December	0.131	0.192
1998	January	0.210	0.143
	February	No data	0.350
	March	0.100	0.132
	April	No data	No data
	May	0.037	0.036
	June	0.058	0.044
	July	0.021	0.023
	August	0.019	0.022
	September	0.046	0.060
	October	0.089	0.070
	November	0.108	0.096
	December	0.093	No data
1999	January	0.143	0.103
	February	0.469	1.149
	March	0.190	0.114
	April	0.048	0.078
	May	0.038	0.036
	June	0.031	0.056
	July	0.050	0.047

The median (50th percentile) concentrations of the total data set are 0.093 pg I-TEQ m^{-3} at Central/Western monitoring station, and 0.097 pg I-TEQ m^{-3} at Tsuen Wan. The 95th percentile concentrations at these monitoring stations are 0.21 and 0.34 pg I-TEQ m^{-3} respectively. In April 1997 the MSW incinerator in Hong Kong ceases operation, and in the same year the majority of clinical waste incinerators also ceased operation.

The data in *Table 4.2a* also illustrates the effect of seasonal variations in air movements over Hong Kong. During summer months (April - September) air movement has a predominantly southerly component, carrying clean air from over the ocean, whereas in the winter months (October - March) winds frequently enter Hong Kong from the industrialised mainland to the north. Therefore ambient PCDD/F levels are likely to be higher during the winter months than during the summer period. Inspection of the total data set in *Table 4.2a* shows this to be the case:

- Summer (April - September): 0.019-0.14 pg I-TEQ m^{-3} (median=0.047)
- Winter (October - March): 0.07-1.15 pg I-TEQ m^{-3} (median=0.132)

This trend is consistent with that of the levels of other pollutants such as PM10.

The measured PCDD/F levels can be compared against ambient air quality data for a selection of other locations, as summarised in *Table 4.2b*.

Table 4.2b ***Summary of Urban/Industrial Ambient Air Data for PCDD/Fs***

Country	**pg I-TEQ m^{-3}**	**Reference**
Belgium		
Ambient air - 6 sites	0.02-0.59	Wevers *et al*, (1993)
Germany		
Urban	0.07-0.35	Rappe (1993)
Close to major sources	0.35-1.6	Rappe (1993)
Rural/industrial - 5 sites	0.08-0.15	Konig *et al* (1993)
Sweden		
Urban/suburban	0.013-0.024	Broman *et al* (1991)
United Kingdom		
Urban - 4 sites (median/range)	0.10 (nd-1.8)	Duarte-Davidson *et al* (1994)
Slovakia		
Urban/industrial (geometric mean)	0.05-0.13	Stenhouse *et al* (1998)
Spain		
Urban (mean/range)	0.25 (0.07-0.53)	Abad *et al* (1997)
USA		
Urban (mean/range)	0.081 (0.016-0.21)	Riggs *et al* (1996)
Urban (mean/range)	0.25 (0.09-0.45)	Hunt *et al* (1997)
Japan		
Urban (summer) mean/range	0.79 (0.4-1.3)	Sugita *et al* (1993)
Urban (winter) mean/range	1.46 (0.3-2.9)	Sugita *et al* (1993)
Urban (mean/range	0.16 (0.08-0.28)	Seike *et al* (1997)
Australia		
Sydney/urban - 4 sites	0.02-0.06	Taucher *et al* (1992)
Korea		
Urban	0.029-0.69	Hyo-bang *et al* (1999)

The urban ambient air PCDD/F data for Hong Kong generally falls within the range of PCDD/F concentrations measured at other locations.

4.3 PCDD/F EXPOSURE FROM EXISTING WASTE TREATMENT FACILITIES

4.3.1 CWTC Emissions and Air Quality in the Vicinity of the CWTC

The Consultants have been provided with PCDD/F emissions data relating to the CWTC, covering the period May 1993 to September 1999. The data supplied were expressed as mg I-TEQ of PCDD/Fs in the total emission gas volume per month. Converting this data to units of ng I-TEQ m^{-3}, the resulting emission concentrations are listed in *Table 4.3a*.

Table 4.3a Calculated PCDD/F Emission Concentrations for the CWTC (ng I-TEQ m^{-3})

Month	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
January	-	0.099	0.009	0.028 (f)	0.008	0.018	0.019
February	-	0.021 (c)	0.009	0.007	0.015 (h)	0.010	0.274 (j)
March	-	0.005	0.003	0.006	0.014	0.017	0.036 (k)
April	-	0.001	Shutdown	0.008	0.007	0.050	0.007
May	0.001	0.012	0.007	0.015	0.047	0.026	0.082
June	0.002	0.025	0.018	0.010	0.093	0.014	0.056
July	0.002	0.004 (d)	0.011 (e)	0.022	0.013	0.013	0.003 (l)
August	(m)	0.017	Shutdown	0.067	0.041	(m)	0.012
September	0.025 (a)	0.005	0.024	0.040	0.044	0.009	0.010
October	0.024 (b)	0.030	0.009	0.068	0.034	0.003	-
November	(n)	0.006	0.028	0.025 (g)	0.033	0.214	-
December	(n)	0.008	0.010	0.034	0.002	0.020 (i)	-

Note:

(a) Average of 0.0227, 0.0280
(b) Average of 0.0322, 0.0158
(c) Average of 0.0144, 0.0266
(d) Average of 0.0028, 0.0044
(e) Average of 0.0178, 0.0036
(f) Average of 0.0265, 0.0299
(g) Average of 0.016, 0.027
(h) Average of 0.0154, 0.002, 0.028
(i) Average of 0.0057, 0.0063, 0.0355
(j) Average of 0.0991, 0.4495
(k) Average of 0.0252, 0.0476
(l) Average of 0.0025, 0.0039
(m) Sample contamination: result cancelled.
(n) Sampling system under test

The emissions listed in *Table 4.3a* may be compared against the stipulated emission limit for the CWTC, of 0.1 ng I-TEQ m^{-3}. As a frequency distribution, 98% of the measurements (93 out of 95 measurements) lie well within the emission limit, while 2% (2 out of 95 measurements) exceed the emission limit by a factor of 2-3.

The impact of CWTC emissions on local ambient air quality can be assessed by examining the ambient measurements reported in the *Tenth Monitoring Report* for the CWTC, undertaken at the following local sampling stations:

- A - Roof top of packaged waste reception building in CWTC;
- B - Roof top of administrative building in CWTC;
- C - Roof top of Ching Yung House of Cheung Ching Estate.

It should be noted however, that PCDD/Fs were sampled only at Station C. The majority of congener concentrations are reported as below the limit of detection. Using the reported limit of detection as a guide and converting measured concentrations to units of I-TEQ by applying values of TEF (see *Table 2.2a*) and a sampling volume of 300 m^3, the estimated concentrations in the ambient air samples in units of pg I-TEQ m^{-3} are listed in *Table 4.3b*.

Table 4.3b ***PCDD/F Measurements in Ambient Air Local to the CWTC (pg I-TEQ m^{-3})***

Congener	**Sampled (13/12/96)**	**Sampled (13/12/96)**
2,3,7,8-TCDD	(0.009)	(0.004)
1,2,3,7,8-PeCDD	(0.016)	(0.003)
1,2,3,4,7,8-HxCDD	(0.004)	(0.001)
1,2,3,7,8,9-HxCDD	(0.012)	(0.001)
1,2,3,6,7,8-HxCDD	(0.009)	(0.001)
1,2,3,4,6,7,8-HpCDD	(0.005)	(<0.001)
OCDD	0.002	(<0.001)
2,3,7,8-TCDF	0.015	(<0.001)
2,3,4,7,8-PeCDF	(0.092)	(0.007)
1,2,3,7,8-PeCDF	(0.007)	(0.001)
1,2,3,4,7,8-HxCDF	(0.025)	(<0.001)
1,2,3,7,8,9-HxCDF	(0.003)	(<0.001)
1,2,3,6,7,8-HxCDF	(0.023)	(<0.001)
2,3,4,6,7,8-HxCDF	(0.026)	(0.002)
1,2,3,4,6,7,8-HpCDF	0.009	(<0.001)
1,2,3,4,7,8,9-HpCDF	(0.001)	(<0.001)
OCDF	0.001	(<0.001)
TOTAL (at half the limit of detection)	**(0.13)**	**(0.01)**

Notes: Values in brackets are notional concentrations, based on the reported limit of detection for each congener.

The notional ambient air concentrations calculated in *Table 4.3b* range from 0.01-0.13 pg I-TEQ m^{-3} if half the limit of detection, the Consultant's preferred procedure, is applied as a notional concentration. Further data provided by Enviropace indicates that PCDD/F levels in summer and winter range from <0.002 to 0.17 pg I-TEQ m^{-3} and <0.0023 to 0.117 pg I-TEQ m^{-3}, respectively. Comparison against the ambient air concentrations reported in *Table 4.2a* and the urban locations in *Table 4.2b* (including an ambient concentration of 0.35-1.6 pg I-TEQ m^{-3} "close to major sources" in Germany) indicates unexceptional localised concentrations relative to the background urban ambient air concentrations, and a general lack of observable impact of the CWTC on the local environment.

In 1991, Waste Management International prepared an Environmental Impact Assessment (EIA) for the CWTC, which included an assessment of PCDD/F releases to the atmosphere. Dispersion modelling of the plume released from the 75 metre stack indicated that when the plant operated consistently (i.e. as an average over the year) at a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}, the maximum annual average ambient air concentration of PCDD/Fs would increase by 0.004 pg I-TEQ m^{-3} over the background, and that in residential areas, the increase would be in the region of 0.001 pg m^{-3}. This represents an approximately 1-4% increase in background concentrations, assuming the latter to be 0.1 pg I-TEQ m^{-3}. The stack monitoring data presented in *Table 4.3a* indicates that measured PCDD/F concentrations fall well below the notional emission release limit adopted in the EIA, on average by a factor of 10, indicating that as a maximum, stack emissions are likely to contribute 0.1-0.4% to existing ambient air background concentrations. This magnitude of increment falls well below the sampling and analytical uncertainties associated with existing monitoring systems, and cannot be distinguished from the background measurement.

Our analysis of the available data suggests that the operation of the CWTC has not adversely impacted the ambient environment in the vicinity of the plant, and by implication the operation of the plant has not adversely affected the health of exposed populations over and above the potential effects of background exposure.

4.3.2 Effect of the Existing Ambient Air Levels on the Intake of PCDD/Fs

Task 2 of the Terms of Reference also requires the Consultant to advise on the short and long term impacts on the local community of PCDD/F emissions from existing waste management facilities in Hong Kong.

The PCDD/F data supplied to the Consultants is limited to the ambient air data listed in *Tables 4.2a* and *4.3b*. To the extent that these data are inclusive of releases from all current waste treatment facilities in Hong Kong (and in the case of the data in *Table 4.3b*, inclusive of the local impact of the CWTC), an assessment of present ambient air quality is an appropriate surrogate for the assessment of impacts from current waste management facilities.

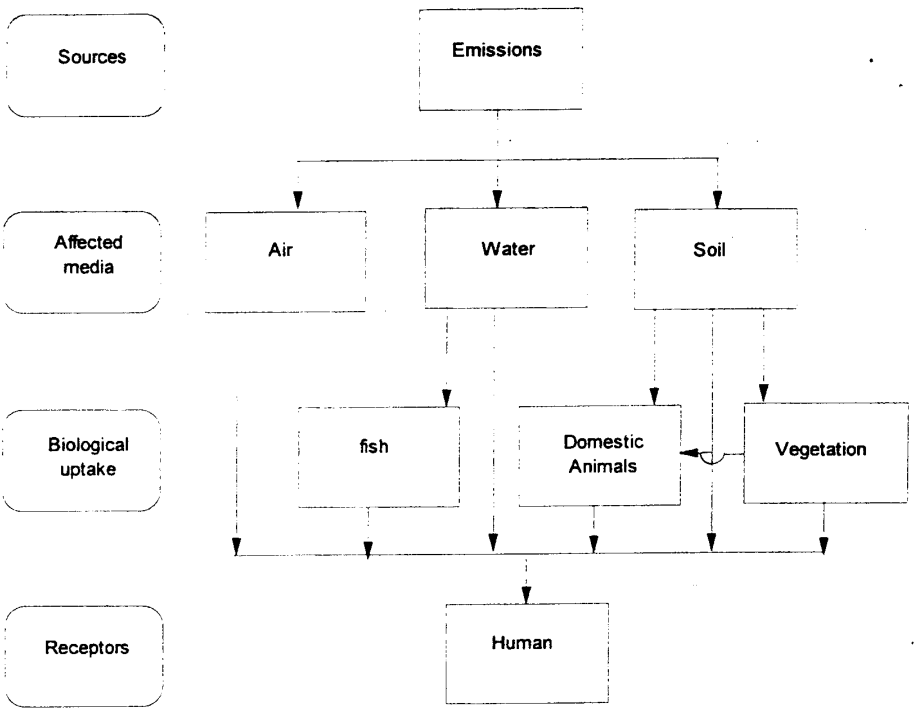
The lack of a discernible difference between the air quality local to the CWTC and the air quality measured at the Central/Western and Tsuen Wan monitoring stations suggests that the presence of the CWTC has not increased the background PCDD/F intake to any significant extent. As indicated above, this judgement is supported by the generally low PCDD/F emission concentrations measured in the CWTC stack gases.

In terms of the total dose experienced by exposed populations, it is necessary to appreciate that air quality *per se* is an insufficient indicator of public health. Following their release to atmosphere, PCDD/Fs partition into other environmental media. Humans in the vicinity of waste incinerators can be exposed via several direct and indirect pathways, via inhalation, the terrestrial and aquatic food chain, and through ingestion of soil and water impacted by the emissions (see *Figure 4.3a*).

It is now recognised that the food chain is responsible for the majority of PCDD/F uptake into humans, accounting for over 98% of the total uptake from the environment (Eduljee and Gair, 1996). Under exposure conditions typically encountered by the general population, direct contact with ambient air (i.e. via inhalation) contributes at most up to 2% of the total PCDD/F uptake. Therefore, any assessment of the appropriateness of a particular

PCDD/F emission concentration should take into account multimedia partitioning of these chemicals.

Figure 4.3a ***Multipathway Exposure to PCDD/Fs***



In the absence of measured data on other environmental media (soil, grass, food products) which would be in contact with or ingested by humans and thus contribute to the body burden of PCDD/Fs, and in the absence of ambient air data indicative of rural/agricultural environments in Hong Kong, we have estimated the typical inhalation dose experienced by an exposed individual by multiplying the 50th percentile concentration of PCDD/Fs in urban air (0.1 pg I-TEQ m^{-3}) by a nominal inhalation rate of 20 m^3 day^{-1}. The Consultants select the median PCDD/F concentration in urban air in preference to an arithmetic average of the data set in *Table 4.2a*, since environmental data tends to be log-distributed and the median provides a truer representation of mean concentrations than the arithmetic average. This calculation provides an estimate for the inhalation dose of 2 pg I-TEQ day^{-1}, or 0.03 pg I-TEQ kg^{-1} (bw) day^{-1} using a nominal body weight of 70 kg. The total intake is therefore estimated as 1.5 pg I-TEQ kg^{-1} (bw) day^{-1}, assuming the inhalation dose represents 2% of the total intake of PCDD/Fs. This estimate is almost certainly an over-estimate, since ambient air PCDD/F concentrations in rural and agricultural areas, where food production activities take place, would be at the lower end of the concentration range measured at the Central/Western and Tsuen Wan stations.

This notional total PCDD/F intake can be compared against estimated dietary intakes of PCDD/Fs in other countries (*Table 4.3c*). The conservative estimate of PCDD/F intake for Hong Kong is in line with estimates for dietary intakes in other countries. A more detailed assessment of exposure cannot be made without data on PCDD/F concentrations in environmental media other than air, and in food products.

Table 4.3c ***Estimated Dietary Intakes of PCDD/Fs per Day in Various Countries***

Country	**Dietary Intake (pg I-TEQ day-1)**	**Reference**
Canada	92	Birmingham *et al* (1989)
Germany	62-100	Malisch (1998)
Italy	260-480	Di Domenico (1990) (a)
Japan	63	Ono *et al* (1987)
Netherlands	70	Theelen *et al* (1993)
Norway	51-85	Becher *et al* (1998)
Russia	139	Maystrenko *et al* (1998)
Spain		Schuhmacher *et al* (1997) (b)
■ Catalonia	210	
■ Madrid	120	
■ Basque Country	128	
UK	70	Eduljee and Gair (1996)
United States	18-192	Schecter *et al* (1994)
Hong Kong	**105**	**This study (conservative estimate)**

Notes:
(a)117 pg I-TEQ day-1 if vegetables were excluded from the diet.
(b)Fruits and cereals contributed 35% of the total dietary intake in Catalonia.

Given the limitations of the data available for Hong Kong, a firm conclusion as to the likely PCDD/F dose experienced by exposed populations cannot be drawn. From the screening calculations performed in this report, it appears likely that the total intake of PCDD/Fs presently experienced by the population in Hong Kong is of the same order as for other countries. This intake *includes* the presence of current waste management facilities and other PCDD/F emitters. In general, the contribution of the former facilities to the total PCDD/F intake is, as a first approximation, proportional to the contribution of these facilities to ambient air ground level concentrations. From the screening calculations presented above, this contribution is likely to be in the region of 0.1-0.4% of the general background.

The tentative PCDD/F uptake of 105 pg I-TEQ day^{-1} via the foodchain calculated in this report equates to 1.5 pg I-TEQ kg^{-1} (bw) day^{-1} for a nominal individual with a body weight of 70kg. Assuming that conversion to WHO-TEQs is on a 1:1 basis and that coplanar PCBs contribute a further 1.5 pg WHO-TEQ from the diet (Alcock *et al*, 1998a), the total uptake of PCDD/Fs and coplanar PCBs in Hong Kong is 3 pg WHO-TEQ kg^{-1} (bw) day^{-1}. This can be compared against the Tolerable Daily Intake (TDI) recommended by WHO of 1 to 4 pg WHO-TEQ kg^{-1} (bw) day^{-1} (see *Annex B*). WHO recommend that every effort should be made to reduce intake towards the lower end of this range. While in other industrialised countries this can be achieved by lowering PCDD/F discharges to water and by further tightening PCDD/F emission limits on combustion sources, in the case of Hong Kong this course of action has been pre-empted by the adoption of the PCDD/F emission standard of 0.1 ng I-TEQ m^{-3}, and by the fact that the preponderance of food items consumed in Hong Kong are imported and are therefore out of the direct influence of local emission sources.

4.4 PCDD/F EXPOSURE TO PLANNED WASTE TREATMENT FACILITIES

4.4.1 Contribution of the Planned Waste Management Facilities to PCDD/F Levels

The proposed thermal waste treatment facilities are as follows:

- up to four or five MSW incineration facilities;
- co-incineration of clinical waste in the CWTC;
- a sewage sludge incineration facility; and
- an animal cremator.

The first issue to consider is whether cumulative dispersion modelling of all proposed facilities is necessary to obtain a picture of the overall effect of PCDD/F emissions on air quality in Hong Kong.

PCDD/Fs are persistent pollutants in the environment and their impact on human health occurs through long term exposure. Therefore, the key measure is the maximum annual average ground level concentration, which will also translate directly into the maximum deposition rate. With respect to the proposed MSW incineration facilities, the modelling exercise performed on each individual facility and presented in separate feasibility study reports, is a thorough one, in that each considers explicitly the local meteorological conditions and, in particular, the local wind fields. Given the complex topography of Hong Kong and the land sea interactions, this is a crucial aspect.

The dispersion modelling shows that the maximum deposition occurs approximately 1 km from each of the four proposed sites. The value of this maximum is greater than 5 times that of most other points within 10 km of the plant. Unless two sites are sited within 1 km of each other, the impact from one on ground level concentrations will be negligible in comparison to the other at the point of the maximum.

The PCDD/F contribution from other sources, as indicated by the background, is very difficult to quantify through modelling. Even with a comprehensive emission inventory and a good regional dispersion model, it is doubtful that the observed ground level concentrations and deposition rates could be replicated. Where this exercise has been attempted in other parts of the world, it is usually found that the PCDD/F modelling estimates are significantly less than the observed values (Rappe, 1992). This suggests either that the emission inventories are incomplete and there are missing sources, or that there is some feature of the environmental behaviour of PCDD/F which is not fully understood (for example, recycling between soil and air).

In this case, the best estimate of the worst case exposure to any individual is the estimate of the maximum concentration downwind of one of the facilities, coupled with the background concentration as given by monitoring data. In practice, the latter value will be much higher than the former. From an examination of the feasibility study reports, each of the four site's contribution to the maximum concentration appears to be estimated as approximately 0.001 pg I-TEQ m^{-3}, 1% of the background level of 0.1 pg I-TEQ m^{-3}. This contribution to the ambient environment applies in the case of each site, to the scenario relating to combustion of 6,000 t d^{-1} of waste.

From the inventory for Hong Kong as shown in *Table 3.3d*, it is apparent that the closure of existing facilities and development of the proposed facilities will result in a net improvement to the environment, and hence a net reduction in PCDD/F intake, albeit a relatively low reduction given the preponderance of imported food and the overwhelming impact of dietary exposure on the overall exposure profile. Therefore the future total intake of PCDD/Fs and coplanar PCBs is likely to be relatively insensitive to the development of the proposed facilities, remaining in the region of 3 pg WHO-TEQ kg (bw) day^{-1}, as estimated in *Section 4.3.2*.

4.5 MONITORING RECOMMENDATIONS

The Consultants recommend that monitoring of PCDD/F emissions at source be supplemented by monitoring of PCDD/F levels in vegetation, soil, dust and food items. Surveillance of the general environment and of the foodchain provides an important link between PCDD/F emissions and PCDD/F intake by humans. A detailed monitoring programme cannot be formulated at this stage, but some general principles can be set out as follows:

- It is suggested that four soil/dust and vegetation sampling sites be identified within 3 km of each of the proposed facilities, one site located at the point of maximum impact, another site in the dominant wind direction but at a further distance from the plant, one site in an infrequent wind direction as a control, and the final site at a location to be selected on the basis of the sensitivity of the receptor. The emission dispersion modelling conducted for each facility will provide the basis for site selection.

- The sites should be at locations that will remain undisturbed by human activity, so as to avoid confounding factors and interferences.

- At each sampling site, it is suggested that soil/dust and grass samples be collected on a biannual basis (i.e. twice per year) and analysed for PCDD/Fs.

- A selection of food items should be monitored for PCDD/Fs on a regular basis. These items should include dairy products, fish and meat, but the final selection will depend on local dietary habits.

Initially, it is suggested that a pilot food surveillance study be conducted. The results of this programme will provide information for the development of a more focused and long term surveillance programme. Following the pilot study, a regular three-yearly surveillance programme is suggested.

In view of the revisions of the WHO to the TEF scheme (see *Section 2*), it would be prudent to include measurements of co-planar PCBs in the pilot programme. The measurement of these chemicals can be continued or discontinued in the following surveillance programme, depending on the findings of the pilot programme and their contribution to the total WHO-TEQ of the samples.

In the event that co-planar PCBs are found to contribute significantly to the total WHO-TEQ of the sample, the Consultants recommend that a pilot source sampling programme be initiated, in which the monitoring recommendations in *Section 3.5* are supplemented by the additional analysis of these chemicals.

Furthermore, although the current ambient monitoring programme incorporates an adequate sampling frequency, it is recommended that the number f monitoring locations be increased to extend the coverage to a wider range of sites, for instance to rural areas and industrial areas.

5. DIOXIN CONTROL MECHANISMS

5.1 INTRODUCTION

Regulatory control of PCDD/F emissions has typically been addressed in two ways.

- By identifying what are believed to be the key design and operational parameters controlling emissions of PCDD/Fs, and stipulating suitable limits within which these parameters should be maintained.
- In addition to the above, imposing emission limits for PCDD/Fs in the stack gas.

For example, the proposed draft incineration directive of the European Union requires new municipal solid waste incinerators to be designed to the following specifications:

- The combustion gases should be maintained at a temperature of at least 850℃ for at least 2 seconds in the presence of at least 6% oxygen.
- PCDD/F emissions should be below 0.1 ng I-TEQ m^{-3}.

From a knowledge of the fundamental chemical and physical mechanisms of PCDD/F formation and their relationships to the prevailing physical and chemical conditions, it is possible to identify key operational parameters or surrogate emissions which can individually be correlated with PCDD/F emissions. Control of these parameters would therefore imply control of PCDD/F emissions.

The fundamental considerations for the control of PCDD/F emissions apply equally to MSW, chemical waste, clinical waste and sewage sludge incinerators. These aspects will be summarised in *Section 5.2*. In *Section 5.3* these principles will be applied to the audit of the dioxin control system on the CWTC, while in *Section 5.4* PCDD/F control on the proposed new facilities will be discussed. Finally, ash management issues will be addressed in *Section 5.5*. A detailed discussion of the principles and experimental/operational findings underlying the audits of the CWTC and of the planned facilities is contained in *Annex C*.

5.2 GOOD COMBUSTION PRACTICE AND BEST OPERATING PRACTICE

5.2.1 Formation of PCDDs and PCDFs in Combustors

Theoretical studies into the mechanisms of formation of PCDD/Fs in combustion systems, with the specific aim of elucidating emission control strategies, have suggested a mechanistic framework which provides a basis for the development of PCDD/F emission control strategies (Hagenmaier *et al*, 1987; Addink *et al*, 1998):

1. Incomplete combustion of organic wastes in the combustion chamber leads to the formation of organic fragments, commonly known as products of incomplete combustion (PICs), which serve as organic precursors to the dioxin/dibenzofuran molecule.

2. The waste provides a source of chlorine, and of metals. The latter are incorporated into flyash, which carries over to the cooler (250-400℃) post-combustion zone of the incineration system.

3. The organic precursors adsorb onto the surface of the flyash in the post-combustion zone, and following a complex sequence of reactions which are catalysed by metals (primarily copper) in the flyash, leading to the formation of PCDD/Fs along with other chlorinated trace organics.

In keeping with the above mechanistic framework, US EPA (1987) introduced the concept of Good Combustion Practice (GCP), the term being defined as "those combustion conditions which lead to low emissions of trace organic pollutants." Following a comprehensive study of three types of MSW incinerators the US EPA concluded in 1987 that low organic emissions could be achieved by a combination of good combustion control techniques and appropriate gas cleaning technology. The rationale for the application of GCP to the control of organic emissions was that the latter were the PICs. Hence, optimisation of combustion conditions to approach as closely as possible the theoretical ideal of complete combustion (ie combustion to carbon dioxide, water, etc), coupled with appropriate "end-of-pipe" control strategies, should lead to reductions in trace organic emissions. The US EPA recommendations for GCP fell into three categories:

1. Minimisation of organic emissions to atmosphere through optimum design of the combustor.

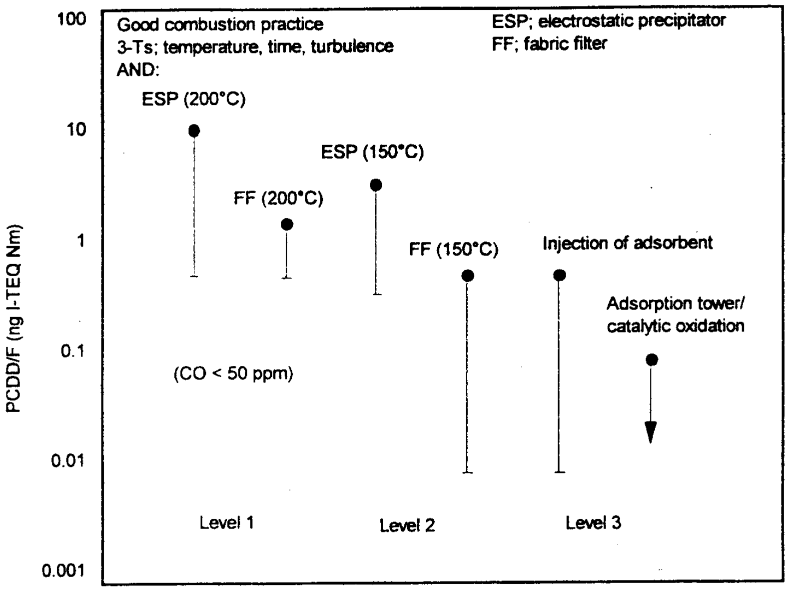
2. Operation of the combustor within its design specifications, with control systems to prevent excursions outside of the design envelope.

3. Monitoring and verification of combustion performance, with continuous surveillance of key design and operating parameters.

US EPA (1994) subsequently defined Best Operating Practice (BOP) as being the use of GCP combined with a temperature limitation of 350ë (approximately 175℃) on the inlet to post combustion control devices. Rapid quenching of the combustion gases to below 175℃ was also regarded as BOP.

Mechanistic considerations supply an underlying rationale for the requirements of GCP and BOP, many components of which were formulated before the reaction pathways were elucidated in laboratory experiments. The key to the implementation of GCP has been amply demonstrated in the bench scale studies and in full scale trials. The implementation of GCP, coupled with control of post-combustion conditions, can affect PCDD/F emissions as summarised in *Figure 5.2a* for an MSW incinerator (Hiraoka and Okajima, 1994).

Figure 5.2a ***Control of PCDD/Fs in MSW Incinerators (Hiraoka and Okajima, 1994)***



GCP, coupled with pollution abatement equipment maintained in the region of 200°C, will permit consistent achievement of PCDD/F emissions of 0.5-10 ng I-TEQ m^{-3}. Maintenance of GCP and operation of the pollution abatement equipment below 200°C will help achieve further reductions to 0.1 ng I-TEQ m^{-3} and below, as exemplified by the CWTC. Catalytic oxidation or treatment with activated carbon also enables emissions to be maintained below 0.1 ng I-TEQ m^{-3}.

5.2.2 *Summary of Key Operating Variables for PCDD/F Control*

To summarise the discussion in the preceding section and in *Annex C*, the key operating conditions pertaining to prevention of PCDD/F formation and minimisation of their release are as follows:

- **Feedstock and feed control:** attention to preparation of feedstock so as to avoid upset conditions within the combustor.

- **Maximisation of combustion efficiency**: adequate levels of temperature, residence time, supply of air (oxygen) and turbulence within the CWTC furnace, so as to ensure efficient burnout of the waste and minimisation of the formation of PICs.

- **Management of waste heat boiler conditions:** attention to the cooling regime for combustion gases and minimisation of flyash build-up.

- **Management of pollution control devices**: management of temperature regime and installation of appropriate PCDD/F removal processes.

- **Control and monitoring of system variables:** control and monitoring of critical parameters such as excess oxygen, CO levels, temperature, etc.

To the above we add a further design and facility management requirement, namely:

- **Emergency and failsafe systems:** the provision of design and management measures that ensure the failsafe response of the facility in the event of mal-operation or an emergency.

Each of these issues is addressed in the context of the current operating regime and the potential for co-incineration of clinical wastes with chemical wastes.

5.3 *AUDIT OF THE CWTC PCDD/F EMISSION CONTROL SYSTEM*

The above combustion and pollution control considerations can be applied to the operation of the CWTC, as discussed below.

5.3.1 *Feedstock and Feed Control*

Currently, the CWTC receives incinerable chemical and MARPOL wastes delivered in containers (primarily in 20 and 200 litre drums) or in bulk. Incinerable bulk wastes are stored in one of six storage tanks, two having capacity for one year's generation of MARPOL wastes, and the remaining four tanks having the capacity to hold 10 days deliveries of all other incinerable wastes. In addition, the facility maintains four blending tanks, each with one day's volume of feed to the incinerator. Packaged waste is fed into the kiln through a dedicated system.

The facility therefore has the necessary infrastructure to prepare feedstock for presentation to the incinerator according to established good practice (see *Annex C2*). Variations in individual liquid waste loads are smoothed by blending to a consistent feed composition, while solids are homogenised by shredding prior to introduction into the furnace, encouraging steady and consistent burnout by maximising contact with air. The low PCDD/F emissions (see *Table 4.3a*) provide confirmation of the generally stable operation of the plant.

With respect to future proposals for the co-combustion of clinical waste in the existing kiln system, the discussion in *Annex C2* notes that differences in feedstock composition are in themselves not the determining factor in influencing PCDD/F formation; rather, the means of presentation of the waste to the incinerator needs to appropriately reflect the particular physical characteristics of the waste. The Consultant's understanding of the options to be considered for the presentation of clinical waste to the kiln is as follows:

(1) ***Ram feeding system***: clinical waste will be loaded into a ram feed hopper controlled by load cells. When the appropriate amount of waste is introduced, a slide gate is released and the material is pushed into the kiln by the hydraulic ram. This feed system can be used for both clinical and chemical wastes.

(2) ***Continuous bulk feed system***: clinical and chemical wastes will be fed into a shredder via a feed hopper. The shredded waste will be introduced into the kiln.

(3) ***Modified feed chute system***: clinical and chemical bulk waste will be conveyed to a closed package chamber. A slide gate will be opened, permitting the packaged wastes to fall into the kiln.

In dedicated clinical waste incinerators, it is not customary to shred clinical waste bags and packages, since this practice has the potential to release and spread contamination onto feed equipment surfaces. Further, options (2) and (3) are more prone to blockages and plugging, leading to the potential for greater downtime and maintenance. With these provisos, any of the above systems is capable of ensuring controlled and even feeding of clinical waste into the kiln, in isolation or in conjunction with chemical wastes, though option (1), the ram feeding option, is to be preferred over the remaining feed options. It is of interest to note that the current draft of the proposed directive on the incineration of waste (98/0289/SYN), which is intended to regulate incineration of non-hazardous waste in the European Union, states in respect of infectious clinical waste that "[this waste] should be placed straight in the furnace, without first being mixed with other categories of waste and without direct handling". This statement favours option (1).

The Consultants conclude that the waste presentation systems proposed for the introduction of clinical waste to the CWTC kiln are appropriate for maintaining even and stable combustion conditions within the kiln, but express a preference for option (1). It has been proposed that the CWTC will co-incinerate clinical waste for 8-12 hours per day, and for the remaining period revert to the dedicated incineration of chemical wastes. This proposed operating regime, coupled with the type of feed system under consideration, is not anticipated to impact adversely on the stability of the combustion conditions within the kiln.

5.3.2 Maximisation of Combustion Efficiency

The critical parameters are combustion temperature, gas phase residence time, excess oxygen and turbulence within the kiln and secondary combustion chamber (SCC). The CWTC kiln operates at an average temperature of 1050℃ ± 100℃, while the SCC operates at an average temperature of 1,150℃± 25℃. For materials such as PCBs, the SCC exit temperature is maintained above 1,250℃. The gas phase residence time in the kiln is approximately 6 seconds. The SCC provides a further 4 seconds of residence time for combustion gases. Excess oxygen levels are maintained at 6%, relative to 12% CO_2.

These temperatures, gas phase residence times and excess oxygen conditions are appropriate both for the combustion of chemical waste, and for the combustion of clinical waste and carcasses. Temperature and residence times for dedicated clinical waste combustors are stipulated in the *Best Practicable Means Requirements for Pathological Waste Incinerators* (EPD, 1992) and the *Best Practicable Means Requirements for Incinerators* (EPD, 1991). The former BPM stipulates a minimum combustion temperature of 1,000℃, a minimum gas phase residence time of 1 second, and a minimum excess oxygen level of 6%. The latter BPM stipulates a minimum combustion temperature of 850℃, a minimum gas phase residence time of 2 seconds, and a minimum excess oxygen level of 6%. These conditions are comfortably met in the CWTC, as presently configured.

For solid wastes, the CWTC kiln provides a residence time that varies from 20 to 200 minutes (average of 80 minutes) depending on the rotational speed of the drum. This is sufficient for efficient burnout of solid and packaged clinical waste.

Turbulence within the combustion zone is essential to ensure complete mixing of the waste with air/oxygen and the prevention of PIC formation, and to prevent the formation of cold spots, streaming and short circuiting of the combustion gases through the kiln and SCC. Turbulence is characterised by the Reynolds Number, with a value above 10,000 signifying turbulent conditions. The Reynolds Number for the SCC of the CWTC is estimated as 55,800, indicative of highly turbulent gaseous flow conditions and a well mixed combustion gas.

The Consultants conclude that the combustion conditions presented by the existing CWTC kiln and SCC are appropriate for the co-incineration of clinical and chemical waste.

5.3.3 Management of Waste Heat Boiler Conditions

As noted in *Section 5.2* and in *Annex C3*, the combustion gases exiting the kiln and SCC must pass through a temperature window of 200 - 450℃ during cooling, a range in which the formation of PCDD/Fs is favoured if other conditions prevail (such as the presence of PICs and of flyash particles). As discussed in *Annex C4*, measures can nevertheless be taken to minimise the residence time of gases and flyash particles within this temperature window.

At the CWTC, the waste heat boiler is designed such that its exit temperature is maintained at 380℃, towards the high end of the PCDD/F formation window. Regular cleaning of the boiler tubes also minimises the potential for the build-up of flyash on the tube surfaces.

These operating practices are appropriate for both the combustion of chemical waste, and for the co-combustion of clinical waste within the CWTC.

Importantly, should be noted that during normal operation of the CWTC and during the course of the trial burn with clinical waste, the activated carbon injection system was not in use. The CWTC is nevertheless capable of meeting its PCDD/F emission limit with ease, further illustrating the efficacy of good combustion control in controlling PCDD/F formation and emissions.

5.3.4 Management of Pollution Control Devices

The discussion in *Annex C5* highlights the efficacy of particulate control and adsorptive systems in minimising PCDD/F emissions to atmosphere, in conjunction with control of combustion conditions and control of boiler operation. The CWTC employs a spray dryer in which a slurry of lime and water is injected into the hot gases exiting the waste heat boiler, followed by a fabric filter which captures particulate mater. Prior to the fabric filter, there is provision to inject activated carbon into the gas stream. This pollution control configuration represents standard practice for most modern incinerators; its efficacy in achieving the desired PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} is illustrated in general in *Figure 5.2a*, and for the CWTC in particular in the PCDD/F emission results listed in *Table 4.3a*.

This configuration is equally capable of cleaning the combined gas stream resulting from the co-incineration of clinical waste with chemical waste. For clinical waste incinerators with a capacity of greater than 1 tonne per hour, the PCDD/F emission limit stipulated in the relevant BPM note is identical to that which currently applies to the CWTC dedicated to the combustion of chemical waste; namely 0.1 ng I-TEQ m^{-3}. The trial burn conducted on the CWTC in November 1996 confirmed the ability of the current gas cleaning system on the CWTC to achieve this PCDD/F emission limit when clinical waste was introduced into the kiln. During the trial burn, two PCDD/F stack emission concentrations of 0.016 and 0.027 ng I-TEQ m^{-3} were measured, against a concentration range of 0.002-0.09 ng I-TEQ m^{-3} during normal operation (Hong Kong Productivity Council, 1996). It should be noted that the activated carbon injection system was not used during the trial burns.

At the CWTC, carbon injection is configured as two parallel and equivalent systems, each connected to a separate power supply and operating continuously but independently of each other. Failure or malfunction of one line results in the gases being diverted into the continuously operating back-up system without a time delay, thereby providing uninterrupted cleaning of the gas stream.

The Consultants conclude that the pollution abatement system of the CWTC is suitable for meeting the stipulated PCDD/F emission limit when clinical waste is co-incinerated with chemical waste.

5.3.5 Control and Monitoring of System Variables

Good Combustion Practice (GCP), relies crucially on control, measurement and monitoring of key operating variables (see *Section 5.2.1*). This includes feedback control of operating parameters such as kiln and SCC temperature, fabric filter temperature and excess oxygen, as well as interlocks that regulate feed addition and permit termination of the waste feed and controlled shutdown of the facility. For regulation and control of normal day-to-day operations, the CWTC monitors the following key operating parameters on a continuous basis, which have relevance to PCDD/F formation and emission:

- kiln temperature;
- SCC temperature;
- excess oxygen level;
- total dust in stack gas;
- CO_2 and CO in stack gas;
- total hydrocarbons in stack gas.

Monitoring of CO_2, CO and total hydrocarbon emissions and kiln/SCC temperatures provides the operator and regulator with a real-time record of the combustion history of the facility, and together with examination of the waste composition and feed rate, with the means to post-mortem abnormal events or emission levels. More importantly, these operating parameters must be maintained within the relatively narrow range indicative of good combustion conditions, through interactive feedback control.

The BPM Notes relating to the incineration of pathological wastes and general wastes stipulate a range of monitoring requirements. Those of relevance to PCDD/F formation and emissions include process monitoring of waste throughput, primary and secondary combustion temperatures, oxygen content, and in-stack monitoring of CO_2, CO and oxygen. The requirements are identical to those currently undertaken at the CWTC.

The Consultants conclude that the combustion control and monitoring capabilities of the CWTC are appropriate for the co-incineration of clinical waste with chemical waste.

5.3.6 Emergency and Failsafe Systems

To ensure that emissions of PCDD/Fs are controlled even during events when the CWTC incinerator has experienced plant malfunction, power failure or process upset conditions, it is necessary for the facility to have appropriately designed emergency response and failsafe systems in place. The CWTC is equipped with the following systems for a controlled emergency shutdown.

- **Interlocks for the termination of waste feeds** in the event of an electrical power outage, ID fan failure, excessive temperatures in the baghouse, loss of water supply (including to the boiler), loss of water and/or lime in the spray dryer.

- **An emergency generator** which is started in the event of a power outage, to apply power to the ID fan and to critical control systems.

- **An emergency water supply and backup lime slurry system** to replace loss of water or lime to the boiler and spray dryer respectively. The emergency supply will also regulate the temperature of the gases within the spray dryer.

- **Failsafe feed shutdown and associated interlocks**, for example to activate the emergency water supply in the event of the boiler and the baghouse inlet temperature exceeding set limits.

The facility also has controlled start-up procedures that ensure an orderly recovery to normal operating conditions following a process upset or emergency shutdown.

The above provisions have an influence on PCDD/F emissions during upset or emergency events. The thermal inertia within the kiln and SCC, together with termination of the waste feed, will permit residual waste trapped within the kiln to burn out under controlled conditions. Temperature control of the post combustion system and the continuing operation of the activated carbon, lime slurry and baghouse system will ensure that the combusted gases are cleaned prior to release to atmosphere via the stack.

For these reasons, the Consultants are of the view that during process upset conditions or emergency shutdown events, PCDD/Fs are unlikely to be released in quantities that will be detrimental to human health or the environment. Given the failsafe mechanisms in place, PCDD/F emissions are likely to remain within a relatively narrow range, even during abnormal operating events.

To date, in six years of operation, the CWTC facility has experienced nine unplanned shutdowns. None of these shutdowns were as a result of a furnace, boiler or spray absorber/fabric filter malfunction, and therefore PCDD/F emissions would not have been released in excess of their permitted limits during preparation for these events.

5.4 PCDD/F EMISSION CONTROL ON PLANNED FACILITIES

Task 5 of the Terms of Reference requires the Consultant to advise on the control mechanism on PCDD/F emissions to be set for the planned incineration facilities, taking into account international practice and the results of the health impact assessment. Firstly, the setting of an appropriate PCDD/F emission concentration will be discussed, followed by guidance on what control mechanisms might be suitable in order to meet the proposed emission limit. Ash management will be discussed in *Section 5.5*.

5.4.1 Setting a PCDD/F Emission Limit

International best practice does not distinguish between PCDD/F emission limits for MSW, chemical waste, clinical waste, or sewage sludge incinerators. Thus, the European Union's (EU) Directive on the incineration of hazardous waste (94/67/EC) stipulates a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}, while the proposed draft waste incineration directive (98/0289/SYN), applicable to MSW, clinical waste and sewage sludge incinerators also stipulates a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. National legislation in a number of European countries also apply this emission limit to the incineration of other waste types, for example:

- Belgium (MSW, sewage sludge, crematoria);
- Denmark (MSW, sewage sludge);
- Germany (MSW, sewage sludge, crematoria);
- Netherlands (MSW, clinical waste, sewage sludge).

An emission limit of 0.1 ng I-TEQ m^{-3} should therefore apply to facilities for the incineration of MSW, clinical waste and sewage sludge in Hong Kong. Importantly, facilities currently in operation can demonstrate compliance with this limit, as shown in *Table 5.4a* for a selection of MSW and sewage sludge incinerators currently operating in Europe.

The data in *Table 5.4a* have been extracted from literature supplied by manufacturers. All of the facilities listed in the table have been provided with a vendor guarantee with respect to compliance with a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. The case of co-incineration of clinical waste with chemical waste in the CWTC has been discussed in *Section 5.3*, and is in line with this limit value.

Dedicated animal carcass incinerators are less well characterised with respect to emissions of PCDD/Fs. However, on the basis that national legislation in some countries (for example, the UK IPC Guidance Note S25.01 on Waste Incineration) place a target PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} on these facilities, the Consultants recommend that this limit is placed on animal carcass incinerators in Hong Kong.

Table 5.4a ***PCDD/F Emissions of Selected MSW and Sewage Sludge Incinerators***

Facility/Location	**PCDD/F Emissions (ng I-TEQ m^{-3})**	**Pollution Abatement Equipment**
Sewage Sludge Incinerators		
Frankfurt (Germany)	0.002	SNCR, ESP, MSS
Dordrecht (Netherlands)	<0.01	SNCR, ESP, MSS, Z
Beckton/Crossness (UK)	0.007	FF, MSS. CFB (AC)
Knostrop (UK)	<0.02	ESP, MSS, Z
Belfast (UK)	0.003	ESP, MSS, AC
MSW Incinerators		
MVA Nürnberg (Germany)	<0.05	ESP, SA, FF
GAVI Wijster (Netherlands)	<0.1	ESP, SA, FF, MSS, CATOX
Ghent (Belgium)	<0.1	ESP, SA (AC), FF, MSS
Ingolstadt (Bavaria)	0.002-0.004	SA (AC), FF, MSS
Hägdalen (Stockholm, Sweden)	<0.1	FF (AC), MSS
SYSAV (Malmo, Sweden)	<0.1	FF (AC), MSS
Umea (Sweden)	<0.1	FF (AC), MSS
Clinical Waste Incinerators		
Redditch, UK	0.06	SA, CF

Facility/Location	PCDD/F Emissions (ng I-TEQ m^{-3})	Pollution Abatement Equipment

Notes:

AC=Activated carbon
CATOX=Catalytic oxidiser
CF=Ceramic filter
CFB=Circulating fluid bed absorber
ESP=Electrostatic precipitator
FF=Fabric filter
MSS=Multi stage scrubber
SA=Spray absorber with lime slurry
SNCR=Selective Non-Catalytic Reduction (for NOx control)
Z=Zeolite addition for mercury control

5.4.2 Combustion Conditions and Pollution Control Equipment

The discussion in *Section 5.3* with respect to the optimisation of combustion efficiency applies equally to the CWTC and to the proposed MSW and sewage sludge incineration facilities. According to information contained within the Feasibility Study of the waste-to-energy facilities, the proposed combustion conditions for the MSW incinerators are a minimum furnace temperature of 850℃, and a minimum gas phase residence time at this temperature of 2 seconds. An excess oxygen level has not been noted, but should be clearly stipulated; in this regard, a value of 6% is typically set. In the proposed EU draft waste incineration directive, these operating conditions apply both to MSW incinerators and to incinerators for the combustion of sewage sludge, and are therefore endorsed by the Consultants. For clinical (strictly, pathological) waste, the BPM Note applicable in Hong Kong stipulates a minimum SCC temperature of 1,000℃, a temperature which will be achieved in the CWTC when clinical waste is co-combusted with chemical waste.

Tuning to pollution control equipment, the Feasibility Study of the waste-to-energy facilities proposes a spray dryer and fabric filter combination for the MSW incinerators, into which lime slurry and powdered activated carbon will be introduced. This configuration is identical to the abatement system on the CWTC, and has been shown to be effective in meeting the PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. The MSW incinerators at Nürnberg and Wijster and the Beckton/Crossness sewage sludge incinerators have abatement systems similar to that proposed in the Feasibility Study, in conjunction with additional equipment for the control of mercury and NOx emissions. However, *Table 5.4a* indicates that other equipment configurations are also capable of meeting the PCDD/F emission limit.

On this basis, the Consultants consider it inappropriate to be overly prescriptive in defining a specific pollution abatement configuration for proposed waste incinerators in Hong Kong. It is sufficient to state that the PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} can be met by a range of pollution abatement configurations, and that currently operating plant can achieve this emission standard. Reference plants would be sought from vendors as part of the tender process thereby requiring a clear demonstration of good performance.

5.4.3 *Control and Monitoring of System Variables and Emissions*

The principles discussed in *Section 5.3.5* and *Section 5.3.6* with respect to the CWTC and the co-incineration of clinical waste apply equally to the proposed MSW, sewage sludge and animal carcass incinerators. The proposed facilities will require waste feed regulation and control of operating parameters such as primary chamber and SCC temperature, boiler temperature, abatement system temperature/pressure and excess oxygen. The proposed EU draft directive on waste incineration requires continuous measurements of the following parameters of relevance to PCDD/F formation and emission:

- temperature of the combustion chamber;
- excess oxygen level;
- CO in stack gas;
- total dust in stack gas;
- total organic carbon (TOC) in stack gas.

As indicated in *Section 5.3.5*, monitoring of CO_2, CO and TOC emissions and combustion temperature provides a real-time record of the combustion history of the facility.

The proposed incinerators will also be equipped with failsafe systems to ensure controlled responses and/or shutdown in the event of process upsets, plant malfunction or power failure. As a minimum, these will parallel the systems on the CWTC, and include interlocks for the termination of waste feeds, an emergency generator, and an emergency water supply.

Monitoring and testing frequencies for PCDD/F emissions are discussed in *Section 4.5*. In conjunction with stack monitoring, the Consultants also recommend that environmental monitoring be undertaken in the vicinity of each facility, as discussed in *Section 6.4*.

5.5 *ASH MANAGEMENT AND MONITORING*

5.5.1 *PCDD/F Content of Incinerator Ash and Control Levels*

As the design, management and control of waste incinerators has evolved over the past two decades, so the quality of ash produced by these facilities has improved with respect to PCDD/F content. The latter is a function of the overall operating regime of the facility, as illustrated in *Figure 5.5a* representing old MSW incineration plant, and *Figure 5.5b* representing modern facilities (IAWG, 1994). The former were potential net generators of PCDD/Fs relative to the quantity of these chemicals introduced into the incinerator via the waste feed. Consequently, PCDD/F levels could reach ≤20 µg I-TEQ g-1 in bottom ash from the incinerator grate, and 5-20 ng I-TEQ g-1 in flyash from the pollution control device. However, modern well-operated plant are net destroyers of PCDD/Fs, with less of these chemicals exiting the facility via the stack, in wastewater and in solid residues than is

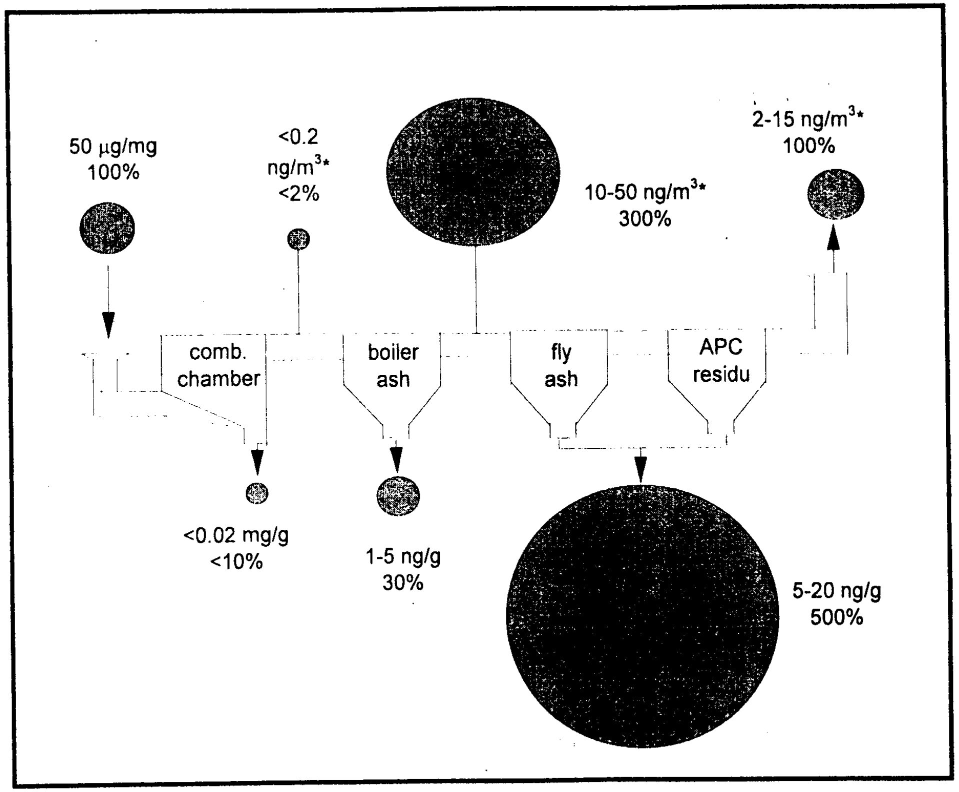


Figure 5.5a Concentrations (TE) and Balance of PCDD/PCDF in an old MSW Incinerator. (% = proportion of total inventory input to the system.)
** = raw gas concentration*

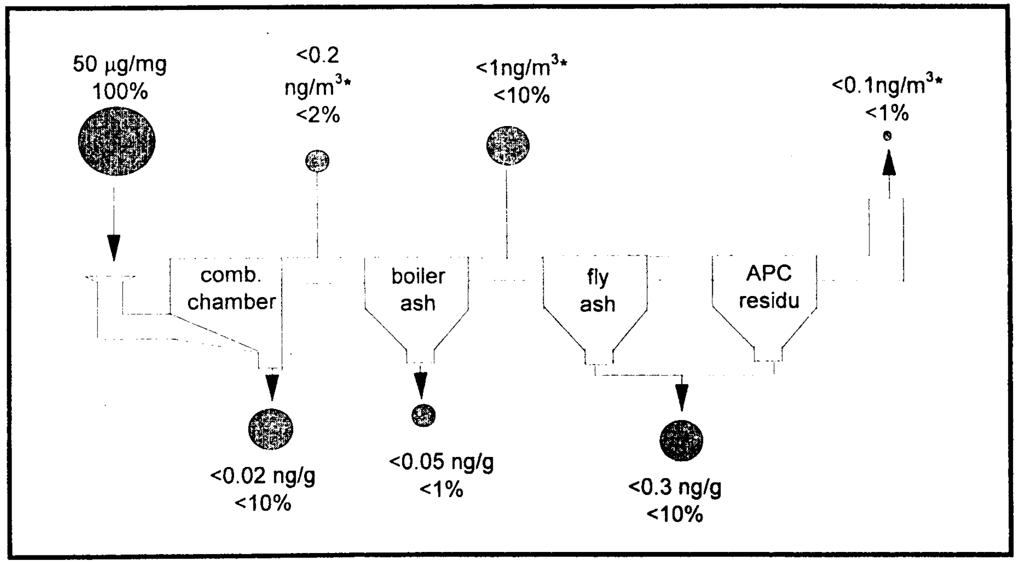


Figure 5.5b Concentrations (TE) and Balance of PCDD/PCDF in an modern MSW Incinerator. (% = proportion of total inventory input to the system.)
** = raw gas concentration*

introduced via the waste feed. Consequently, PCDD/F levels in ash have reduced significantly, and are typically ≤0.02 ng I-TEQ g^{-1} in bottom ash, and less than 0.3 ng I-TEQ g^{-1} in flyash from the pollution control device.

The expectations of PCDD/F concentrations in the ash from modern, well run incineration facilities are confirmed in the case of the CWTC. *Table 5.5a* summarises the PCDD/F content of combined bottom ash and flyash generated by this plant, as measured by Enviropace Limited on a monthly basis, prior to stabilisation.

Table 5.5a PCDD/F Content of CWTC Ash (Average Concentration, ng I-TEQ g^{-1})

Year/Month	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
January	-	0.05	0.05	0.06	0.06	0.013	0.006
February	-	0.05	0.05	0.06	0.06	0.004	0.005
March	-	0.05	0.05	0.06	0.06	0.003	0.006
April	-	0.05	0.163	0.06	0.06	0.025	0.009
May	0.05	0.05	0.085	0.06	0.06	0.005	0.004
June	0.05	0.05	0.062	0.06	0.06	0.004	0.006
July	0.05	0.05	0.043	0.06	0.06	0.017	0.015
August	0.05	0.05	0.072	0.06	0.01	0.032	0.006
September	0.05	0.05	0.047	0.06	0.018	0.008	0.015
October	0.05	0.05	0.023	0.06	0.025	0.035	-
November	0.05	0.05	0.346	0.06	0.014	0.014	-
December	0.05	0.05	0.038	0.06	0.011	0.019	-

The PCDD/F concentrations in *Table 5.5a* are well within the specified limit for ash quality at the CWTC, namely 1 ng I-TEQ g^{-1}. The consultants consider this to be an appropriate quality standard to apply to the proposed incinerators.

The proposed EU draft directive on waste incineration requires that the total organic carbon (TOC) content of the bottom ash be less than 3%, or their loss on ignition (LOI) less than 5% of the dry weight of the material. In the case of the CWTC, the TOC content of incineration residue is specified as 0.5%, but this applies to the stabilised residue rather than to the residue as generated. During the co-combustion trial burn, a target limit of <5% total hydrocarbons (THC) was set for the bottom ash. The trial burn produced THC measurements of 3%, 1.7% and 0.5% in bottom ash, well within the target limit.

5.5.2 Management of Ash

Incinerator ash, and boiler ash and flyash in particular, is a fine material that is susceptible to windblown dispersion if the material is not appropriately handled. On the proposed MSW incinerators the Feasibility Study recommends standard ash management techniques, which include wetting of bottom ash and flyash, collection of flyash in hoppers connected to the boiler and fabric filter discharge points by airlocks, and stabilisation of the flyash with cement-like materials. These management measures are appropriate for the proposed facilities.

5.6 *SUMMARY*

The discussion in this section has stressed that because of the inter-dependency of the operating variables and their interaction in terms of the effect on combustion conditions, control of only a selection of operational parameters to the exclusion of others is unlikely to provide an overall optimum in terms of minimising PCDD/F formation. All relevant operational parameters need to be controlled in concert in order to achieve the goals for Best Operating Practice (BOP) outlined in *Section 5.2*.

The Consultants conclude that the operating regime and pollution control configuration on the CWTC incinerator are appropriate for the co-combustion of clinical waste with chemical waste. The same principles should also be applied to the prevention of PCDD/F formation and control of emissions from the proposed MSW, sewage sludge and animal carcass incinerators. Operating experience gained in Europe has demonstrated that the proposed PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} can be met by a range of pollution abatement configurations.

6 SETTING EXPOSURE LIMITS AND EMERGENCY CONTROL

6.1 INTRODUCTION

Task 7 requires the Consultant to consider the limit of exposure to the public to PCDD/F emissions from all significant identified sources and the risk, contingency and emergency response measures in the event of any mal-operation leading to a significant release of PCDD/Fs.

Section 6.2 examines the propensity for non-steady state conditions in thermal waste treatment facilities, their potential influence on emissions of PCDD/Fs, and their subsequent environmental impact. *Section 6.3* advises on potential contingency measures at source that could be adopted in the event of an identified risk. Finally, *Section 6.4* advises on monitoring measures in the ambient environment to maintain an ongoing surveillance of facility operations and environmental quality.

6.2 ACCOUNTING FOR NON-STEADY STATE INCINERATION OPERATIONS

The underlying implication of the Task 7 is that fluctuations in facility PCDD/F emissions, whether as a result of unsteady operations or of a malfunction, can be so great as to affect the environmental quality and public health in the short term, and that a PCDD/F emission limit can be set that will act as a trigger for shut-down and/or external emergency action.

Concern has been expressed that a low frequency of stack sampling and over-reliance of "spot" sampling can mask potentially large variations in PCDD/F stack emissions. For example, De Fré and Wevers (1998) report that continuous sampling of an MSW incinerator over a two week period resulted in a calculated average PCDD/F emission concentration of 8.2-12.9 ng m^{-3} whereas a 6-hour sample taken during steady state operation resulted in a PCDD/F emission concentration of 0.25 ng m^{-3}, underestimating average emissions over this period by an order of magnitude. Emissions during upset conditions or during start-up or shut down can vary from those under steady state operating conditions. Referring to emissions of organics from municipal waste incinerators, Benestad *et al* (1990) measured emissions of PAH, PCDDs, PCDFs, bicyclic compounds and other polycyclic organic compounds that were ten times higher during start-up and shut down than during normal operation.

Similar results were obtained by Kawakami *et al* (1993) in respect of PCDD/F emissions from small intermittently operated MSW incinerators in Japan. In relation to other organic emissions, Yasuda and Takahashi (1998) measured PAH emissions from four municipal waste incinerators during start-up, normal operation and burn-out. The emission factor changed over the start-up and burn-out period and stabilised during normal operation, as shown in *Table 6.2a* for a step grate incinerator. There is a thirty-to sixty-fold difference between the average PAH emission factor during stable operation and during the initial start-up and burn-out phase. However, taking into account the time over which start-up and burn-out occurred relative to the period of stable operation, the mass of PAHs emitted during normal operation comprised 90% of the total PAHs emitted over the complete burn cycle.

Table 6.2a Change in PAH Emission Factor during Incineration of Municipal Waste in a Step Grate Incinerator (from Yasuda and Takahashi, 1998)

Sample No.	Combustion Period	Combustion Temperature (℃)	CO Concentration (ppm)	PAH Emission Factor (g^{t-1})
1	Startup	300-530	50-620	3.24
2		440-560	100-580	0.52
3		500-755	70-725	0.34
4	Combustion	760-830	100-520	0.08
5		750-850	80-260	0.05
6		820-970	60-500	0.05
7	Burn-out	550-740	80-1500	3.51
8		320-460	400-1250	1.38

Tejima *et al* (1993) measured PCDD/F releases from small batch-operated MSW incineration plants. Steady state daytime operations accounted for 67% of total daily emissions, while shut down and start-up accounted for 33% of daily emissions. Using a different night-time standby technique the furnace emitted 46% of the total daily emissions during start-up and shut down, 45% during normal daytime operations and 9% during the nighttime standby period. Emission factors measured during periods of start-up and shut down would have been an order of magnitude higher than if measured during normal daytime operations. Jager *et al* (1993) measured PCDD/F concentrations in the flue gas of a municipal waste incinerator that were 4-8 times higher during periods of "cold blowing" and "soot blowing" than during normal operation. These operations can extend over 40-60 minutes per activity.

In the light of these findings, the issue to be considered is whether maintenance activities such as boiler cleaning, as well as disrupted operations have the potential to significantly influence the total daily PCDD/F release from the facility. The examples provided above are primarily those of small, discontinuously operated thermal treatment facilities, where frequent start-ups, shut downs and the lack of thermal inertia within the furnace mitigate against steady state operation. Inconsistency of plant operating conditions and the lack of observance of the principles of Good Combustion Practice (GCP), as discussed in *Section 5.2*, are likely to be the main causes of such fluctuations in PCDD/F emissions. This is observed in the example provided in *Table 6.2a* in respect of PAH emissions, in which the highest emissions correspond to conditions of low temperature and high concentrations of CO, indicating poor combustion conditions within the furnace during the particular release episode. Conversely, the lowest PAH levels correspond to the highest combustion temperatures and the lowest CO emission levels. In the case of the CWTC, the waste feed is blended to achieve a more controlled and homogeneous mixture in terms of its physical and chemical composition, and hence combustion is expected to be better controlled. The facility is also not subject to frequent shutdowns and start-ups.

This issue is further developed in *Section 6.3*.

6.3 SETTING PCDD/F EMERGENCY RESPONSE EMISSION LIMITS

PCDD/Fs are persistent substances in soil, sediments and in biota (including humans). Except in the case of extreme, catastrophic exposure scenarios which are never encountered in the waste management industry, their adverse health effects, as well as estimated safe doses (such as the Tolerable Daily Intake, TDI) are typically expressed as a dose averaged over a lifetime. It follows that short term perturbations, fluctuations and exceedances in PCDD/F emissions from waste management facilities and other sources, such as those discussed in *Section 6.2*, need to be averaged over the remaining sampling events and over longer timescales before a judgement can be made as to the impact of these exceedances on the environment and on human health.

To illustrate the concept, inspection of *Table 4.3a* indicates that in 1999 the average PCDD/F emission concentration from the CWTC in the year to September is 0.055 ng I-TEQ m^{-3}. This average includes one exceedance of 0.274 ng I-TEQ m^{-3} in February 1999 against a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. In the months excluding February, the average PCDD/F emission concentration was 0.028 ng I-TEQ m^{-3}. Were the CWTC facility to have released PCDD/Fs at this average concentration in February 1999, then the resulting average emission concentration to September 1999 would also have been 0.028 ng I-TEQ m^{-3}. The cumulative emissions of PCDD/Fs are below the allowable emissions of PCDD/Fs, as the data in *Table 6.3a* illustrate.

Table 6.3a Cumulative emissions of PCDD/Fs from the CWTC in 1999

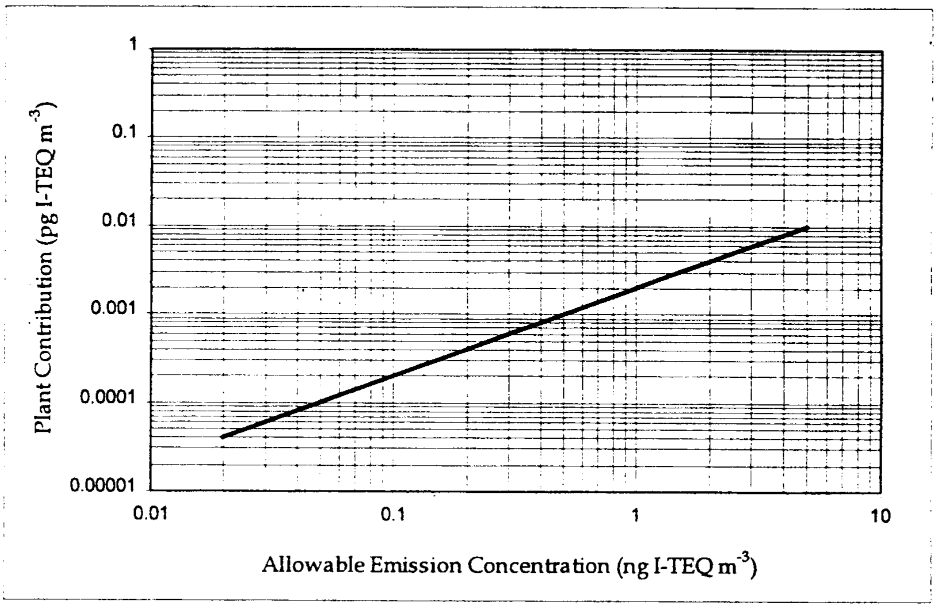
Month	Permitted PCDD/Fs Release at 0.1 ng I-TEQ emission limit (mg I-TEQ)	Measured PCDD/F Release (mg I-TEQ)
January	1.09	0.2054
February	0.76	2.0738
March	0.98	0.3566
April	0.88	0.0572
May	1.24	1.0134
June	0.99	0.5547
July	1.19	0.0316
August	1.18	0.1412
September	0.72	0.0731
TOTAL	**9.03**	**4.5071**

The PCDD/F emission concentration exceedance in February 1999 amounts to an emission of 1.31 mg I-TEQ over and above that which was permitted for that month, but the cumulative release to September 1999 of 4.5 mg I-TEQ is still 50% of the permitted release of 9.03 mg I-TEQ.

The impact of an incremental atmospheric loading of PCDD/Fs from incinerator emissions can be examined by reference to *Figure 6.3a,* in which the incremental annual average ambient air ground level concentration of PCDD/Fs resulting from facility emissions, ***at the point of maximum impact*** (the so-called "plant contribution") is plotted against the corresponding PCDD/F emission concentration. The graph has been prepared from the results of the dispersion modelling conducted by Enviropace on the CWTC, and on the planned MSW incinerators. Plant size is not a controlling factor, since stack heights are adjusted on a case by case basis to broadly result in the same magnitude of ambient air ground level concentrations irrespective of plant size (Eduljee and Gair, 1997).

Figure 6.3a indicates that at a PCDD/F emission concentration of 0.1 ng I-TEQ m^{-3}, each plant contributes a maximum annual average ground level concentration of approximately 0.0002 pg I-TEQ m^{-3} to the ambient air concentration, equivalent to approximately 0.2% of a background ambient air PCDD/F concentration of 0.1 pg I-TEQ m^{-3}. Were the facility to have operated *continuously* at emissions equivalent to 10 times the permitted limit (i.e. at 1 ng I-TEQ m^{-3}), then the incremental annual average plant contribution would increase to 0.002 pg I-TEQ m^{-3}, or 2% of the ambient air concentration.

Figure 6.3a** **Plant Contribution to PCDD/F Ambient Air Ground Level Concentrations



In the present case, the Brief asks for guidance on emergency response measures in the event of a mal-operation leading to a "significant" release of PCDD/Fs. Given that analysis of PCDD/F stack emission samples typically take 4-8 weeks before results are reported, any response measure can only be applied in retrospect, and possibly at a time when the plant has returned to steady state, "normal" operation. The Consultants therefore consider it appropriate to develop a hierarchy of response measures depending on magnitude of the reported exceedance.

In developing a hierarchy of response measures, the Consultants do not seek to condone or minimise the seriousness of a breach of an emission limit. Regulatory authorities in Hong Kong can apply a range of sanctions in the event of an exceedance being reported. If considered appropriate, Hong Kong EPD can exercise its prerogative to apply more stringent sanctions, including prosecuting the operator for a beach of licence conditions, or ordering closure of the plant, at any stage of its investigations into the exceedance.

The Consultants' approach in recommending response measures to an exceedance is based on the following assumptions:

(1) The stack emission analysis of any month is likely to be available during the next month's sampling event, defining the minimum time period within which a response can be initiated (i.e. in month 2). The maximum time period within which the plant will revert to compliance with the stated emission limit is 3 months from the date of sampling.

(2) Any remedial action on the plant will have been undertaken within a maximum of three months of the exceedance.

(3) In view of assumption (1) and the fact that health standards for PCDD/F represent exposure over the long term, the most appropriate averaging time to apply to plant emissions is the annual average ground level contribution.

On this basis, an exceedance is assumed to occur for a maximum time period of three months. Thus, if the plant operated at an emission of 5 ng I-TEQ m^{-3} for a maximum of three months and at an emission of 0.1 ng I-TEQ m^{-3} for the remaining 9 months of the year, the annualised emission of PCDD/Fs will be $[9(0.1)+3(5)]/12=1.3$ ng I-TEQ m^{-3}. From *Figure 6.3a*, this level of emission will contribute a maximum annual average ground level plant contribution of 0.003 pg I-TEQ m^{-3}, which amounts to an increment of 3% over an ambient air concentration of 0.1 pg I-TEQ m^{-3}.

The extent to which exceedances in PCDD/F stack emission concentrations continue to be "tolerable" will depend on a judgement as to what constitutes a "significant" release. Thus, if it is assumed that no facility should contribute more than 1% to the ambient atmospheric concentration of PCDD/Fs, averaged over a year, then from the above discussion and *Figure 6.3a*, an emission concentration of 2 ng I-TEQ m^{-3} would result in an annualised emission of 0.6 ng I-TEQ m^{-3} and a maximum annual average plant contribution of 0.001 pg I-TEQ m^{-3}. A PCDD/F emission of 2 ng I-TEQ m^{-3} could therefore be regarded as a trigger for undertaking a review of facility operational and control measures, the aim being to bring the facility back into compliance with the 0.1 ng I-TEQ m^{-3} emission limit by the next monthly sampling event. *Figure 6.3b* presents a suggested emissions management scheme, taking an emission of 2 ng I-TEQ m^{-3} to trigger intermediate and more detailed levels of action.

Note that exceedance of this trigger emission concentration, even over a prolonged period, does not imply a likely adverse environmental or health impact. Monitoring and recording of operational parameters such as temperature and CO concentrations will provide more immediate indications of potential instabilities in facility operations and might hence anticipate potentially higher emissions of PCDD/Fs prior to stack sampling. Given these real-time indicators of plant performance, the likelihood is that plant instabilities will have been addressed prior to the next sampling period, as is evident in the case of the CWTC (see *Table 4.3a*).

The Consultants believe this to be an appropriate approach to regulation of PCDD/F releases for the following reasons:

- Waste combustion plants will have been operating under a guaranteed PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} (see *Section 5.2* and *Section 5.3*). Therefore the expectation is that day-to-day emissions will be at or below this emission limit.

- Regular monitoring of emissions and key operating variables will forestall the likelihood of the facilities operating consistently at PCDD/F emission levels far beyond their design limits;

- Combustion facilities cannot be compared with plants in the chemical sector, such as the reactor at Seveso, where runaway chemical reactions have resulted in the production of PCDD/Fs and a catastrophic release. The type of feedstock and the temperature regime within the combustion system rule out this eventuality. Therefore, exceedances are anticipated to remain within a relatively narrow band.

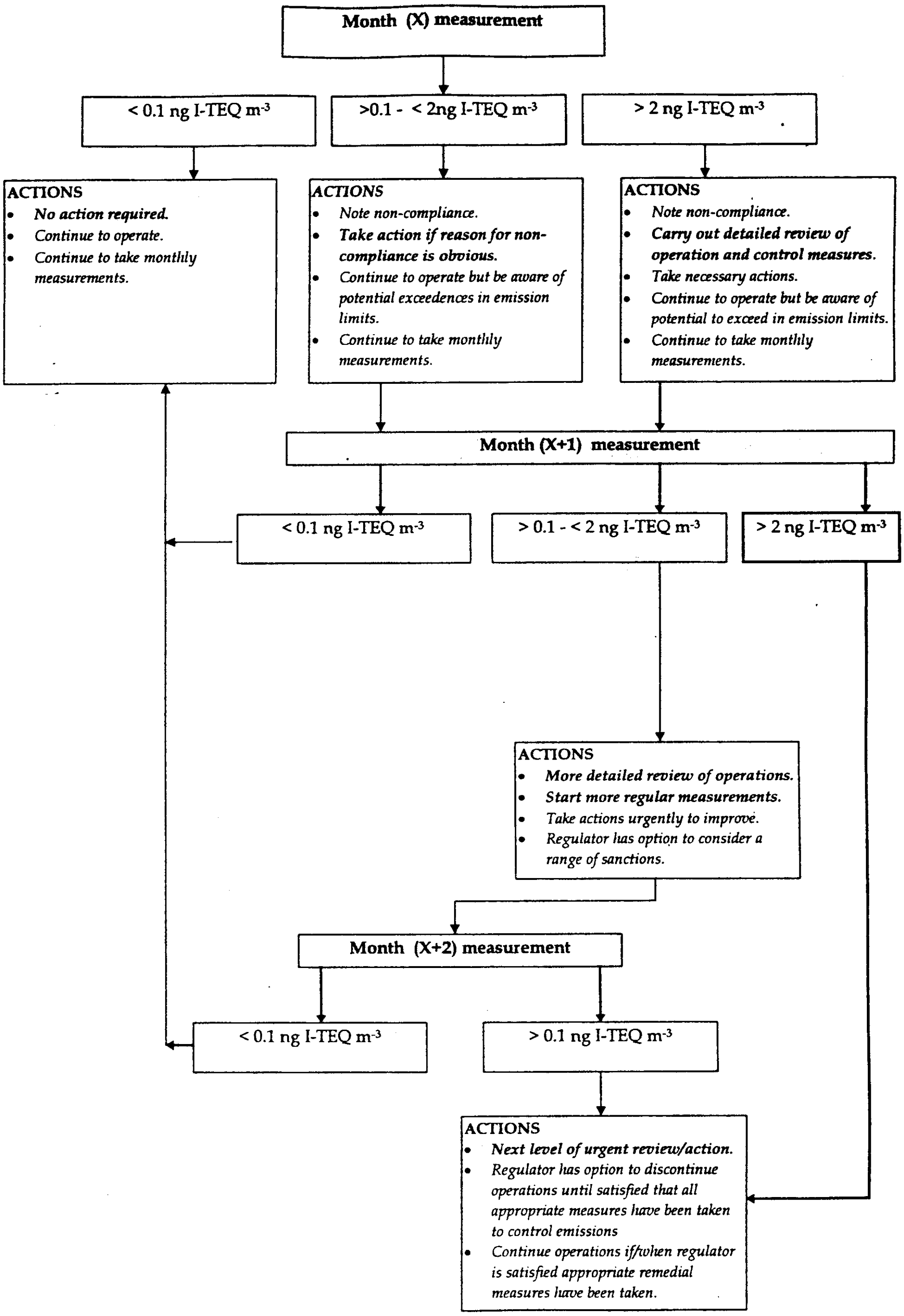
- The trigger for a review of control and operational procedures is expected to bring emissions back into compliance within one month of detection, based on the current sampling frequency of the CWTC.

- Emergency systems installed on the CWTC are such that emergency shutdown will be activated when the temperature regime in the furnace and in the baghouse system are less than optimal. Avoidance of these conditions will also ensure that excessive PCDD/F formation is mitigated (see *Section 5.3.6*).

As previously stated, the above response process does not prevent regulatory authorities in Hong Kong from applying more sever sanctions. The proposed response measures are intended to forestall the likelihood of the facility adding significantly to the ambient environmental burden of PCDD/Fs by stipulating a relatively low trigger level for initiation of remedial action.

This approach relies crucially on emission sampling times and frequencies. The current sampling frequency of CWTC emissions is once monthly, supported by continuous monitoring of CO and temperature. This sampling frequency is considered to be adequate in the light of the back-up continuous monitoring of key operational variables.

Figure 6.3b *Flow diagram of response options to emission measurement results*

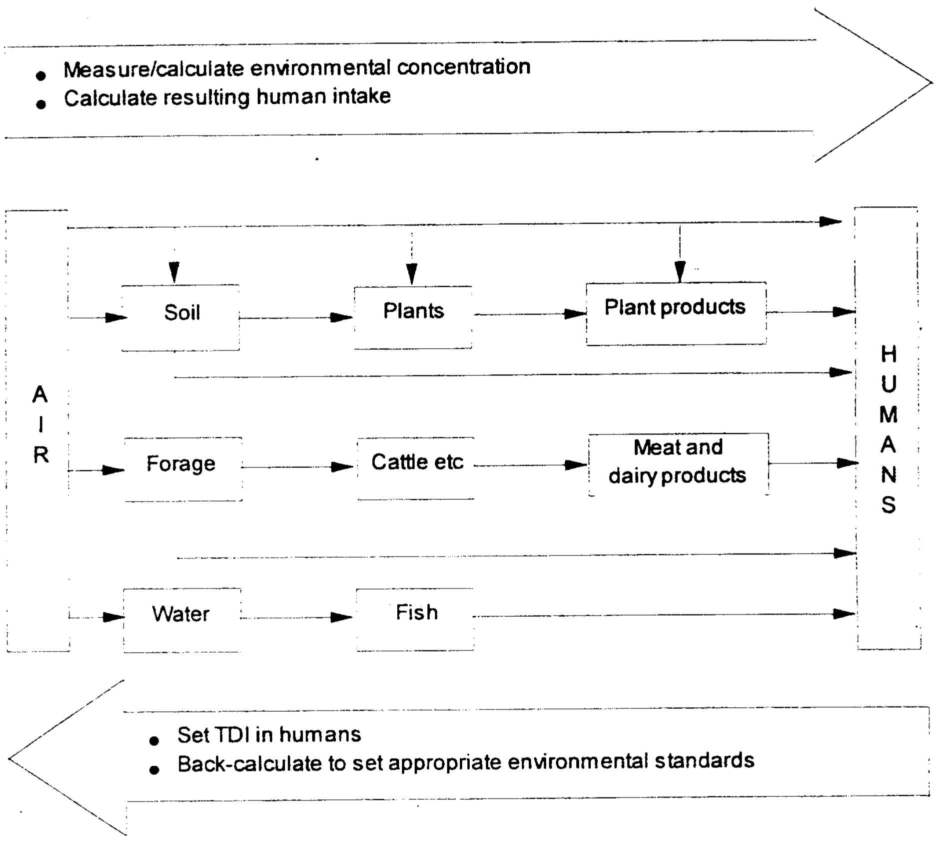


6.4 SETTING ENVIRONMENTAL LIMITS OF EXPOSURE

6.4.1 *A Multimedia Exposure Assessment Framework*

A detailed discussion linking atmospheric emissions from waste incinerators to the setting of environmental guidelines is contained in Eduljee and Gair (1997). *Figure 6.4a* summarises the multimedia exposure framework which can be used in the forward mode to assess the risk posed by exposure to facility emissions, and in reverse mode to set environmental guidelines, and ultimately facility emission guidelines. The framework permits both facility emission guidelines and environmental guidelines to be internally coherent and mutually consistent.

Figure 6.4a *A Risk Assessment Framework for Setting Environmental Standards*



The underlying rationale of the framework is that exposure risk is not solely a function of the ambient air concentration at a location impacted by facility emissions. Indeed, from the discussion in *Section 4.3.2* it is apparent that under typical exposure conditions experienced by the general population, direct contact with impacted air (i.e. via inhalation) is a minor pathway relative to the dominant secondary pathway of uptake via the foodchain. The framework permits the setting of PCDD/F environmental guidelines, for example in ambient air, which consider the implication of a release on the primary and subsequent uptake pathways (see *Figure 4.3a*).

Based on the framework illustrated in *Figure 6.4a*, Eduljee and Gair (1997) derived the indicative environmental guide values for PCDD/Fs in ambient air, soil, forage, water and milk presented in *Table 6.4a*, commencing with a Tolerable Daily Intake (TDI) of 10 pg I-TEQ kg (bw) day-1 as adopted in the UK, and using the following assumptions:

- The proportion of PCDD/Fs allocated to each environmental medium is determined by a congener-specific fate and transport model.
- The average UK dietary intake of foodstuffs is used to apportion the PCDD/F dose between meats, vegetable products, fruits, dairy products and fish.
- The individual doses from the media most proximate to the exposed person contribute the following percentages to the cumulative dose:

Inhalation:	0.5%
Milk:	25%
Meats and dairy products:	46%
Vegetables and fruits:	25%
Fish:	3%
Others (dermal contact, etc):	0.5%

- The cumulative PCDD/F dose experienced by an exposed individual (i.e. from all potential pathways) is 700 pg I-TEQ day-1, equivalent to a TDI of 10 pg I-TEQ kg (bw) day-1 for an individual of 70 kg body weight.

Table 6.4a ***Summary of Indicative Guide Values for PCDD/Fs (Eduljee and Gair, 1997).***

Medium	**Indicative Guide Value**	**Comments**
Ambient air	0.5 pg I-TEQ m^{-3}	Derived from a maximum daily intake equal to the TDI.
Soil	40 pg I-TEQ g^{-1} (dry wt)	Based on an assumed deposition period of 30 years, and on measured deposition velocity.
Forage	5 pg I-TEQ g^{-1} (dry wt)	Air to leaf transfer is the major PCDD/F uptake pathway at an assumed temperature of 10℃.
Water	1 pg I-TEQ 1^{-1}	Based on the air-water-fish-human pathway.
Milk	0.7 ng I-TEQ kg^{-1} whole milk	Equivalent to 17 pg I-TEQ g-1 milk fat, assuming 4% fat in whole milk.

Clearly, the contribution of each pathway (inhalation, ingestion and dermal contact) to the total exposure experienced by an individual is a function of the precise locational circumstances of the existing and planned thermal waste treatment facilities in Hong Kong, and of the specific dietary intakes of the general population. Thus, in a wholly urban setting the impact of facility emissions on primary food production, in particular meat and dairy products, is limited relative to that in a rural/agricultural setting, and therefore the contribution of PCDD/F exposure from inhalation (i.e. the allowable concentration of PCDD/Fs in air) will be greater. For the general population the ambient air guide value can generally only be varied within relatively narrow limits since it is not possible to neglect the ingestion pathway within the context of background exposure. However, since inhalation exposure contributes less than 2% of the total dose, the latter is least sensitive to a large variation in the PCDD/F ambient air concentration.

With respect to dietary intakes, geographical and cultural differences can significantly affect the contribution individual food types can make to the total intake of PCDD/Fs. For example, Ono *et al* (1987) estimated that 25% of the dietary intake of PCDD/Fs in Japan originated from the consumption of fish. In Spain, this pathway contributed 15% of the total PCDD/F dietary intake (Schuhmacher *et al*, 1997). Scandinavian countries have estimated higher contributions from fish; for example, 63% of the daily PCDD/F dietary intake in Finland (Vartiainen and Hallikainen, (1992)) and 40-50% of the dietary intake in Sweden, with particular exposed groups such as Baltic Sea fishermen experiencing six times the PCDD/F intake relative to the "average" Swede (Svensson *et al*, 1991). It is therefore important to consider the specific dietary practices in Hong Kong when modelling PCDD/F intakes.

6.5 RECOMMENDATIONS FOR HONG KONG

Since foodstuffs contribute the greatest proportion of the total daily intake of PCDD/Fs, national legislators have tended to focus on specific food products as surrogates for environmental quality. In particular, the PCDD/F concentration in the fat of milk and other dairy products is regarded as a sensitive indicator of general environmental well-being, and as a barometer of the human body burden of PCDD/Fs. Pasture accumulates PCDD/Fs primarily via direct transfer from the atmosphere into above ground plant parts. The subsequent uptake of PCDD/Fs by dairy cattle and incorporation into milk and dairy products offers a relatively simple means of monitoring the impact of the atmospheric loading of PCDD/Fs on humans.

Table 6.5a presents the data on countries that have developed guidelines relating to PCDD/F levels in milk and dairy fat, as well as to levels in related environmental media. The general veracity of the approach outlined in *Figure 6.4a* and applied in *Table 6.4a* is vindicated by the fact that were the TDI for the UK reduced from 10 pg I-TEQ kg^{-1} (bw) day^{-1} to the range of values proposed by the WHO (1-4 pg WHO-TEQ kg^{-1} (bw) day^{-1}) and currently adopted by some Scandinavian States (5 pg I-TEQ kg^{-1} (bw) day^{-1}, but discounting coplanar PCB congeners), then the proportionality between the PCDD/F dose from milk and the total dose indicates that the resulting PCDD/F concentration in milk fat reduces from 16 pg I-TEQ g^{-1} fat to 8 pg I-TEQ g^{-1} fat, generally in line with value of 5 pg I-TEQ g^{-1} recommended by those States (see *Table 6.5a*). The German guide value for PCDD/Fs in soil also corresponds to the modelled indicative guide value in *Table 6.4a*, while the Austrian target PCDD/F concentration in forage is similar to that derived in *Table 6.4a* for the same TDI of 10 pg I-TEQ kg (bw) day^{-1} as for the UK.

Extension of the above concepts to the specific case of Hong Kong is not appropriate owing to the general lack of indigenous agricultural land and of intensive farming. A small number of cattle (57 in 1997) are reared in Hong Kong, and therefore the total indigenous production of milk is low relative to the total quantity of milk consumed. The majority of foodstuffs are imported, and there are very limited opportunities for direct impacts of waste facility emissions on the foodchain.

Table 6.5a Summary of national PCDD/F environmental guidelines

Country	**Milk/Dairy (pg I-TEQ g^{-1} fat)**	**Pasture (ng I-TEQ kg^{-1} dw)**	**Soil (ng I-TEQ kg^{-1} dw)**	**TDI (pg I-TEQ kg (bw) day^{-1})**
Austria	-	3 in grass fed to dairy cows	-	10 (target value of 1)
Belgium	5/g milk fat for foods with >2% fat; 100/g food for foods with ≤2% fat	-	-	-
Denmark	-	-	-	5
Finland	-	-	2	5
France	Milk and dairy products not marketable if >5 (target of 1)	-	-	Target of 1
Germany	Milk and dairy products not marketable if >5. Limit value of 3, and target value of 0.9.	-	Between 5-40 grazing should be avoided if levels in foods increase	10 (target value of 1)
Netherlands	6 in milk and milk products	-	1000 (residential/agricultural); 100 (aquatic sediments); 10 (dairy farming)	10 (recommended to be reduced to 1)
Sweden	-	-	10 (sensitive use); 250 (less sensitive use) This legislation has not been used	5
UK	Milk not marketable if>17.	-	-	10

Under these circumstances, we recommend that the Hong Kong SAR Government considers supplementing the present ambient air monitoring programme with the institution of a regular monitoring programme encompassing grass and soils, the first tier of environmental media affected by emissions to atmosphere. Candidate locations would be those which are generally downwind of existing and proposed waste management facilities, and which will remain undisturbed over a period of years so that an unbroken temporal record of trends can be compiled. For comparison, a selection of background sites can be identified and monitored contemporaneously with the other sites. Candidate sites of both types can be identified from the pollutant dispersion contours developed for each facility.

Further, the Government may consider a pilot surveillance study of PCDD/Fs in indigenously produced and imported foods, in order to compile information on the concentration of PCDD/Fs in foods, and to ascertain the intake of PCDD/Fs via the foodchain. If necessary, the Government may then consider whether it is appropriate to set provisional limits for PCDD/Fs in indigenously produced food items such, as milk and dairy products and fish, and to continue with a regular food surveillance programme, in line with practice in Europe. This issue can be reviewed in the light of the proposed monitoring of food items and subsequent studies on dietary intake of PCDD/Fs in Hong Kong.

7 SUMMARY

This Section summarises the outcome of each of the tasks set the Consultant in the Terms of Reference, as detailed in *Annex A*.

7.1 TASK 1: LIKELY SIGNIFICANT SOURCES AND REVIEW OF AMBIENT PCDD/F DATA

7.1.1 Likely Significant Sources

The Consultants have compiled a preliminary PCDD/F emission inventory for Hong Kong, the results are presented in *Section 3.3*, and are based on our understanding of the principal industrial and non-industrial sources and their levels of activity. For a baseline of 1997, total PCDD/F emissions amounted to 23 to 33 g I-TEQ a^{-1} (excluding adventitious sources such as fires) of which an average of 85% is attributable to the incineration of MSW in old stoker boilers.

In order to estimate future emissions in 2007, it is conservatively assumed that an incineration capacity of 1 million tonnes of MSW will have been installed, together with the sewage sludge and animal carcass incinerators, and that clinical waste will be combusted in the CWTC facility. All these proposed facilities will operate to a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. The net outcome will be a reduction in PCDD/F emissions to 2 to 4 g I-TEQ a^{-1}, principally resulting from the closure of the old MSW incineration facilities.

The current and future PCDD/F inventory for Hong Kong is lower than for other national inventories per head of population, owing to a generally low level of combustion and industrial activity at present, but more significantly to the fact that Hong Kong has adopted a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} for all existing and proposed waste incineration facilities, in line with best practice elsewhere.

7.1.2 Review of Ambient Air Monitoring Data

In *Section 4.2*, the Consultants reviewed PCDD/F ambient air quality monitoring data collected at two urban sites, Central/Western and Tsuen Wan. The data for 1997-1999 indicated a strong seasonal trend, with ambient air levels higher during winter months when winds originated from the industrialised north. The median PCDD/F concentration at these sites was within the range of concentrations measured at other urban sites worldwide. Ambient air quality monitoring conducted by Enviropace in the vicinity of the CWTC elicited concentrations that were lower than PCDD/F concentration measured close to major sources in Germany and were typical of the reported concentrations at Tsuen Wan and Central/Western.

The data indicate that urban air quality in Hong Kong with respect to PCDD/F levels is similar to air quality in other urban locations elsewhere. In the vicinity of the CWTC, PCDD/F ambient air levels are indistinguishable from levels at background urban locations in Hong Kong, and lower than concentrations measured in the vicinity of major PCDD/F sources in Germany.

7.2 TASK 2: PCDD/F EMISSIONS AND HEALTH IMPACT OF EXISTING FACILITIES

PCDD/F emission data relating to the CWTC have been assessed in *Section 4.3.1*. Of the monthly measurements, 98% were well within the specified PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}. Two exceedances were recorded: 0.215 ng I-TEQ m^{-3} in November 1998, and 0.4495 ng I-TEQ m^{-3} in February 1999. Modelling of CWTC stack emissions indicated that the facility was likely to contribute a further 0.1 to 0.4% to existing ambient air concentrations. Current sampling and analytical methods are unable to achieve this level of discrimination, and the ambient measurements in the vicinity of the facility confirm the lack of a significant impact on local air quality (see *Section 7.1*).

With respect to other existing waste management facilities in Hong Kong, current ambient air PCDD/F concentrations are indicative of emissions from these and other sources. In *Section 4.3.2* the Consultants estimated the dietary intake of PCDD/Fs, the dominant intake pathway into humans, as 105 pg I-TEQ day^{-1} (equivalent to 1.5 pg I-TEQ kg^{-1} (bw) day^{-1}) although a high degree of uncertainty is associated with this estimate. This estimate lies within the range of PCDD/F intakes measured elsewhere. However, since the majority of food items consumed in Hong Kong are imported, PCDD/F emissions from waste treatment facilities in Hong Kong have only a peripheral influence on this intake pathway. The PCDD/F intake is increased to 3 pg WHO-TEQ kg^{-1} (bw) day^{-1} to allow for the inclusion of coplanar PCBs within the toxic equivalent calculation. This value falls within the tolerable daily intake (TDI) range recommended by the World Health Organisation (WHO) of 1 to 4 pg WHO-TEQ kg^{-1} (bw) day^{-1}.

7.3 TASK 3: PCDD/F MONITORING REQUIREMENTS

Monitoring requirements at individual sources are discussed in *Section 3.4*, while monitoring of the ambient environment is addressed in *Section 4.5*. With respect to the former, the type of source and suggested PCDD/F monitoring frequency is summarised in *Table 7.3a*.

Table 7.3a Stack Monitoring Recommendations for PCDD/F Emission Sources in Hong Kong

Sources	**Monitoring Frequency**
MSW incinerators	Monthly in year 1 and thereafter
Sewage sludge incinerator	Monthly in year 1, followed by one sample every 2 months
Animal carcass incinerator	Monthly in year 1, followed by one sample every 3 months
Cement kiln	One sample every two months
CWTC	Continue with monthly samples

The Consultants recommend that monitoring at source be supplemented with ambient monitoring of soil/dust and grass in the vicinity of the waste treatment facilities. It is suggested in *Section 4.5* that on the basis of the dispersion modelling conducted for each of the proposed facilities, three sampling locations be selected, two being in the downwind direction and one in an upwind direction to act as a control. At each of the sampling locations it is suggested that soil/dust and grass be analysed for PCDD/Fs on a biannual basis.

In addition, the Consultants recommend the institution of a food surveillance programme to record PCDD/F levels in both indigenous and imported food items. The food products should include fish, milk and dairy products, meats and vegetable products. Initially, a pilot study should be conducted to establish the scope and frequency of the ongoing surveillance programme.

If the analytical scope of the pilot programme is extended to include coplanar PCBs, this data will also allow a calculation of the intake of PCDD/Fs and dioxin-like PCBs via the foodchain, to compare against the WHO recommended tolerable daily intake of 1 to 4 pg WHO-TEQ kg-1 (bw) day-1. The contribution of coplanar PCBs to the total TEQ of the food samples will provide useful information for the overall management of PCDD/F intake via the diet, and will also indicate whether these chemicals should be included in the source sampling programme detailed in *Section 3.4*.

7.4 TASK 4: SHORT AND LONG TERM IMPACTS OF DIOXIN EMISSIONS

This task follows from Tasks 1 and 2, and is addressed in *Section 4* of the Report. The accumulative nature of PCDD/Fs and low levels of emissions indicated to the Consultants that the relevant impacts to be considered were chronic, long term impacts rather than acute, short term impacts. Firstly, the Consultants compared ambient air concentrations of PCDD/Fs measured in Hong Kong against data obtained at similar urban locations elsewhere. The results of this comparison have been summarised in *Section 7.1.2*. Secondly, in recognition of the fact that inhalation of PCDD/Fs from ambient air is generally a very minor uptake pathway into humans, the Consultants calculated a first order estimate of the dietary intake of PCDD/Fs, a pathway that typically accounts for > 98% of the total PCDD/F intake. This value was compared against the WHO tolerable daily intake for PCDD/Fs, as summarised in *Section 7.2*.

The impact of existing waste treatment facilities on public health was addressed in Task 2 (see *Section 7.2*). Insofar as the planned waste management facilities were concerned, the discussion in *Section 4.4* concluded that since the PCDD/F emissions inventory for Hong Kong indicated a net reduction in PCDD/F emissions, and hence a net improvement to the environment in Hong Kong. Furthermore, the dispersion modelling results indicated that PCDD/F emissions were not predicted to overlap significantly unless any two facilities were sited within 1 km of each other. Management of each facility should therefore focus on achieving an acceptable local ambient air ground level concentration of PCDD/Fs following their release from the stack. The dispersion modelling work predicted that each site treating 6,000 t d-1 would contribute a maximum of 0.001 pg I-TEQ m^{-3} to ambient air levels. The incremental environmental burden associated with these emissions is sufficiently low, such that even if two sites for incineration facilities were proximate to each other, the cumulative health impact of the emissions would not constitute a significant additional exposure.

7.5 TASK 5: CONTROL LIMIT ON DIOXIN EMISSIONS FROM THE NEW FACILITIES

Task 5 is addressed in *Section 5*, and specifically in *Section 5.4.1*. The Consultants recommend that a PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} be placed on the proposed facilities for the incineration of MSW, sewage sludge, and animal carcasses, as representing best practice in the industry. This emission limit should also apply to the management of clinical waste if this material is incinerated in a dedicated stand-alone facility rather than in the CWTC.

In *Section 5.4.1* the Consultants have listed waste incineration facilities that are operating to this limit with a range of pollution abatement configurations Reference plants meeting the required standards should be sought from vendors as part of the tendering process for the procurement of any new facilities. A PCDD/F emission limit of 0.1 ng I-TEQ m^{-3}, in conjunction with an appropriate stack height, will result in maximum ambient air ground level concentrations in the region of 0.001 pg I-TEQ m^{-3}, which as discussed under Task 4 above, is an incremental concentration which in the context of the background exposure is not regarded as being likely to impact adversely on public health.

7.6 TASK 6: AUDIT OF CWTC DIOXIN EMISSION CONTROL SYSTEM

Task 6 is addressed in *Section 5.3* of the Report. The Consultants have taken a broad view of what factors influence PCDD/F emission, and therefore have audited a number of control activities and design features upstream of the pollution abatement system. The key conclusions with respect to the proposed co-incineration of clinical waste are as follows.

- **Feedstock Control**: Of the three options for presentation of clinical waste to the kiln, the Consultants express a preference for option 1, the ram feeding system. This system should ensure the maintenance of even and stable combustion conditional in the kiln.

- **Maximisation of Combustion Efficiency**: The CWTC is operating at temperatures that are appropriate for the combustion of clinical waste, and will provide the combustion gases with sufficient residence time and turbulence to ensure good mixing with air and effective burnout of the waste.

- **Management of Waste Heat Boiler Conditions**: The CWTC boiler is designed for an exit temperature of 380℃, towards the high end of the PCDD/F formation window. Regular cleaning of the boiler tubes will also minimise the potential for build-up of flyash.

- **Management of Pollution Control Devices**: The configuration and management of the pollution control device on the CWTC facility is appropriate for the co-combustion of clinical waste, as was demonstrated in a trial burn when two PCDD/F emission concentrations of 0.016 and 0.027 ng I-TEQ m^{-3} were measured, well within the specified limit of 0.1 ng I-TEQ m^{-3}. It should be noted that the activated carbon ingestion system was not operational during the trial burn. There is sufficient redundancy designed into the pollution control system to ensure that the unit operates in the event of a malfunction.

- **Control and Monitoring of System Variables**: The CWTC monitors and records all the necessary kiln, secondary combustion chamber and stack discharge parameters for effective control of the combustion conditions.

- **Emergency and Failsafe Systems**: The CWTC has a comprehensive emergency response system to enable the facility to engage in a controlled shutdown sequence. All key malfunction options are linked through interlocks to termination of the waste feed, and diversion to emergency power and water supplies.

The Consultants conclude that the design and management of the CWTC is suitable for the co-incineration of clinical waste with chemical waste in a safe environment, and that the specified PCDD/F emission limit of 0.1 ng I-TEQ m^{-3} can be achieved.

7.7 TASK 7: ADVICE ON THE LIMIT OF EXPOSURE TO DIOXIN EMISSIONS

Task 7 is addressed in *Section 6* is the Report. Based on the judgement that cumulatively in a year no one facility should contribute more than 1% to the background ambient air concentration of PCDD/Fs on an annualised basis, the Consultants have suggested an emission concentration of 2 ng I-TEQ m^{-3} as a trigger for reviewing to appropriate levels of detail the facility's operational and control measures, with the intention of bringing the following month's emission measurement back to within the stated limit of 0.1 ng I-TEQ m^{-3}.

In concert with in-stack monitoring, the Consultants also recommend that the Hong Kong SAR Government institutes a food surveillance programme, commencing with a scoping exercise in the form of a pilot study. This has been discussed in *Section 7.3*. Milk is regarded in some countries as a particularly sensitive indicator of PCDD/F uptake, and dairy farms downwind of MSW incinerators are often placed on the surveillance programme. This scenario is unlikely to present itself in Hong Kong, but nevertheless the pilot study may identify alternative but equally viable biological matrices as PCDD/F pollution indicators.

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Annex A

Terms of Reference

Tender Ref. SW 99-069

SPECIAL CONDITIONS OF CONTRACT

Tender for the Provision of Services for An Assessment of Dioxin Emissions in Hong Kong

1. Background

1.1 The waste management system in Hong Kong has long been relying on landfill as the ultimate disposal means. With the current waste intake rate at the landfills of about 16,000 tonnes per day and the rising trend of waste growth, the existing landfills will likely be exhausted by 2015 and Hong Kong will be running out of land for waste disposal. If we do nothing to reverse this trend, we will need to find about 860 hectares of land for new landfills within the next 20 years. Finding suitable sites for the new landfills is very difficult given the many competing demands for the very limited land resources in Hong Kong. To overcome this problem, the Government of the Hong Kong Special Administration (HKSAR) issued a Waste Reduction Framework Plan (WRFP) in 1998. Among other recommendations on waste avoidance, minimization and recycling initiatives, the WRFP recommended the use of incineration as a bulk waste reduction means for municipal solid waste.

1.2 Apart from municipal solid waste, incineration is also recommended by the Sludge Treatment and Disposal Strategy Study as the most appropriate means of disposing the vast quantity of sewage sludge generated in Hong Kong. The infectious nature of animal carcasses has rendered the existing landfill disposal arrangement undesirable and there is plan to develop an animal cremator to cremate all the carcasses.

1.3 Recently, public concern was aroused by the dioxin incidences originated from the contamination of dairy products in Belgium, followed by the disclosure of two occasions where the Chemical Waste Treatment Centre (CWTC) failed to meet its dioxin emission standard of 0.1 ng/m3 during its monthly flue gas monitoring programme. Whilst the exceedence of dioxin emission was only for a short period of time and the level of exceedence was very low (less than 0.5 ng/m3), these incidences have attracted much public criticism on the potential health impacts caused by incineration.

1.4 In view of the above, it is considered necessary for the Government of HKSAR to provide some positive assurance to the public that the CWTC and any other dioxin sources, including the planned incinerators, will not pose any threat to the public health. As the formation and health impacts of dioxins are still under extensive investigation, it is advisable to invite the world's most renowned experts to assess Hong Kong dioxin baseline conditions and provide and unbiased view on the health impacts caused by dioxin emission from our waste management system. It is proposed to engage a consultant (hereafter called "Consultant") with in-depth knowledge on the dioxin issues, the Hong Kong environment and the waste management system adopted in Hong Kong to undertake the assessment work. To ensure the Consultant's findings are not biased, it is proposed to submit the Consultant's findings and recommendations (in the form of a comprehensive report) to an international dioxin Expert, for an independent review. The recommendations of the Expert, together with the Consultant's Report, will then be considered by the HKSAR Government and made known to the public.

2. Objectives of Study

2.1 The Consultant will be appointed to offer the Services with the following key objectives:

(i) Advise on the formation, source and health impacts of dioxins;

(ii) Evaluate and assess the health impact of any known dioxin sources in Hong Kong;

(iii) Evaluate and assess the potential health impact of the planned incineration facilities resulting from their dioxin emissions; and

(iv) Advise on dioxin control measures and their impacts on the adoption of incineration as an integral part of Hong Kong's waste management strategy.

3. The Services

3.1 Without prejudice to the generality of the above, the Services shall consist of the following tasks:

(i) To review the ambient dioxin monitoring data and advise the likely significant sources of dioxin in Hong Kong.

(ii) To review the existing emission data, health assessment studies of Hong Kong's waste facilities and to assess whether the local community is being exposed to a dangerous level of dioxin generated from the existing waste management facilities.

(iii) To advise on the dioxin monitoring requirements including ambient monitoring and the monitoring of other dioxin sources considered by the consultant to be significant.

(iv) To review and advise on both the short term and long term health impacts of dioxin emission taking into account the population density of Hong Kong, the possible cumulative effect from the existing and planned incineration facilities for municipal solid waste, sewage sludge, animal carcasses, clinical waste and chemical waste.

(v) To advise on the control mechanism on dioxin emission to be set for the planned incineration facilities taking into account international practices and the findings of task (iv) above. The dioxin control mechanism shall cover, but not limited to, the emission limit, dioxin suppression system, ash management, monitoring and testing regime.

(vi) To audit the dioxin emission control mechanism of the CWTC, taking into consideration that clinical waste will be co-incinerated with chemical waste at the CWTC in the future.

(vii) To advise on the limit of exposure of the public to emissions of dioxins from all the significant sources identified in task (i) above. Also to advise on the risk as well as the appropriate contingency and emergency response measure in the event of any mal-operation leading to release of significantly quantities of dioxin.

Annex B

Background Information on the Properties, Fate and Toxicity of PCDDs and PCDFs

CONTENTS

B1 INTRODUCTION

There is a voluminous literature on the effects of PCDDs and PCDFs on humans and the general terrestrial and aquatic ecosystem. Since there have been comprehensive reviews that are readily available (for example, WHO, 1989; Academie des Sciences, 1994; US EPA, 1994; Health Council, 1996; Mukerjee, 1998) the purpose of this annex is to summarise the physicochemical properties, environmental behaviour and toxic effects of relevance to this report and where appropriate to refer the reader to the primary references for further information or detail.

B2 PCDDS AND PCDFS IN THE ENVIRONMENT

B2.1 Physicochemical Properties

PCDDs and PCDFs are chemically stable, nonpolar and with low solubility in water, a low volatility and a high octanol-water partition coefficient. The latter property makes PCDDs and PCDFs highly lipophilic, preferentially partitioning onto the surface of solids such as soil, sediment and dust particles, and resulting in a high affinity for fats. The physicochemical properties are reviewed by Mackay *et al*(1992) and US EPA (1994). A selection of physicochemical properties is listed in *Table 2.2a.*

Table B2.2a A Selection of Average Physicochemical Properties of PCDD/Fs

Homologue Group	**Vapour Pressure (mm Hg at 25℃)**	**log Kow**	**Solubility (mg l^{-1} at 25℃)**	**Henry's Constant**
TCDD	8.1×10^{-7}	6.4	3.5×10^{-4}	1.35×10^{-3}
PeCDD	7.3×10^{-10}	6.6	1.2×10^{-4}	1.07×10^{-4}
HxCDD	5.9×10^{-11}	7.3	4.4×10^{-6}	1.83×10^{-3}
HpCDD	3.2×10^{-11}	8.0	2.4×10^{-6}	5.14×10^{-4}
OCDD	8.3×10^{-13}	8.2	7.4×10^{-8}	2.76×10^{-4}
TCDF	2.5×10^{-8}	6.2	4.2×10^{-4}	6.06×10^{-4}
PeCDF	2.7×10^{-9}	6.4	2.4×10^{-4}	2.04×10^{-4}
HxCDF	2.8×10^{-10}	7.0	1.3×10^{-5}	5.87×10^{-4}
HpCDF	9.9×10^{-11}	7.9	1.4×10^{-6}	5.76×10^{-4}
OCDF	3.8×10^{-12}	8.8	1.4×10^{-6}	4.04×10^{-5}

B2.2 PCDD/Fs in air

Particulate/vapour partitioning in the atmosphere is dependent on a number of factors but in particular on temperature, the total surface area of atmospheric aerosols available for adsorbing PCDD/Fs, and the congener-specific vapour pressure. A theoretical method for estimating vapour/particulate fractions had been developed by Bidleman (1988). Eitzer and Hites (1989), Hites and Harless (1991) and Kaupp *et al* (1994) have measured the partitioning of PCDD/Fs between the particulate and vapour phase in the ambient environment. On average, 50-75% of the TCDD/Fs are present in the vapour phase, compared with less than 4% of OCDD/Fs. The percentage of particulate bound 2,3,7,8-TCDD at 12℃ is 85%, falling to 50% at 25℃. Therefore the proportion of vapour phase PCDD/Fs would be expected to be higher in summer than in winter.

The residence time of PCDD/Fs in the atmosphere varies according to whether the congeners are in the vapour or particulate phase. PCDD/Fs are subject to photolysis, especially when present in the vapour phase. Podoll *et al* (1986) estimate the photolysis rate of 2,3,7,8-TCDD vapour to be 1 hour at 40℃. However, Mill *et al* (1987) and Koester and Hites (1992) observed that PCDD/Fs adsorbed onto flyash particles were highly resistant to photodegradation. Podoll *et al* (1986) estimated the half-life of vapour phase

2,3,7,8-TCDD to be approximately 200 hours. Kwok *et al* (1995) estimate vapour phase residence times of 3-9 days for PCDDs and 8-29 days for PCDFs. Particulate bound PCDD/Fs would generally be removed from the atmosphere by dry and wet deposition within 10-15 days or less.

B2.3 PCDD/FS IN SOIL

Atmospheric deposition is the principal route of entry of PCDD/Fs into soil. The high octanol-water partition coefficients of PCDD/F congeners results in these chemicals binding tightly to soil particles, approaching irreversibility over time (Puri *et al*, 1992). Congener half-lives are in the order of 10-20 years (Paustenbach *et al*, 1992; Mackay *et al*, 1992). Because of the strong binding to soil particles and the low solubility, PCDD/Fs are subject to few removal processes. Leaching in an aqueous medium is negligible, although relatively more so for the lower chlorinated homologues. In soil conditions where solvents and other organic carriers might be present (for example, in landfills) PCDDs and PCDFs can be mobilised to a greater extent. PCDD/Fs can also be mobilised in landfill leachate via adsorption onto very fine sub-micron particles suspended in the leachate.

Microbial attack and photodegradation of PCDD/Fs in soil under ambient conditions are not thought to be important removal processes. Highly engineered biological systems designed primarily for remediation purposes have demonstrated limited success in degrading 2,3,7,8-TCDD and some mono-, di - and tri-chloro CDDs (Bumpus *et al*, 1980; Hoffman *et al*, 1992). Adriaens and Grbic-Galic (1994) have examined the reductive dechlorination of PCDD/Fs by anaerobic cultures. Reduced penetration of sunlight beyond the immediate surface layer limits the effectiveness of photolysis of PCDD/Fs in soil. Miller *et al* (1989) have investigated the kinetics of degradation of the higher chlorinated PCDD/Fs, but under extreme conditions of light and temperature not encountered in Europe. Tysklind *et al* (1992) studied the photolysis of OCDD and OCDF in soil, and determined that 2,3,7,8-positional fragments were formed as byproducts. However, Watts *et al* (1991) found in laboratory experiments that in the presence of hydrogen ions the 2,3,7,8-positional congeners are preferentially attacked. There is no evidence that photolysis is increasing the proportion of toxic isomers in ambient soil (Eduljee and Townsend, 1987). Photodegradation and/or volatilisation are thought to be important removal mechanisms for fresh surface deposits of PCDD/Fs (Di Domenico *et al*, 1982). However, aged deposits or deposits that have been worked into the soil subsurface rapidly become virtually immobile (Freeman and Schroy, 1989; Hagenmaier *et al*, 1992).

B2.4 PCDD/FS IN AQUEOUS MEDIA

Atmospheric deposition is the principal route of entry of PCDD/Fs into the aquatic environment, though there is clear evidence of specific effluent streams contributing to localised elevations of PCDD/Fs downstream of receiving water bodies. These relate to pulp and paper mills using chlorine as a bleaching agent, and certain chemical manufacturing processes. The high octanol-water coefficient of PCDD/Fs results in rapid and preferential binding to sediments and to particulate matter and dissolved organic matter within the water column. The half-life of PCDD/Fs in the water column is estimated to be in the order of 2-4 days. The volatilisation half-life for 2,3,7,8-TCDD in open and closed water bodies is estimated to be in the region of 15-32 days (Podoll *et al*, 1986).

PCDD/Fs undergo photodegradation in the aqueous environment, and is especially rapid in the presence of hydrogen donors. Choudry and Webster (1989) estimate photolysis half-lives during summer in northern latitudes ranging from 1.8 days for 1,2,3,7-TCDD to 18 days for OCDD and 47 days for 1,2,3,4,6,7,8-HpCDD, compared with 1-225 days in winter (Atkinson, 1991). Friesen *et al* (1993) observed half-lives of 1.2 days and 0.19 days for 2,3,7,8-TCDF and 2,3,4,7,8-PeCDF respectively in lake water.

Microbial degradation, if present, is a slow process on PCDD/Fs (Matsumura and Benezet, 1973). Sediment-water studies indicate a half life of 550-590 days for the microbial degradation of 2,3,7,8-TCDD in water (Ward and Matsumura, 1978).

B2.5 TROPHIC BIOMAGNIFICATION OF PCDD/FS

The movement of PCDD/Fs from the primary environmental compartments (air, soil, sediments and water) into the natural and human foodchain is a highly significant consequence of the physicochemical properties of these chemicals. The foodchain represents the principal source of human exposure to PCDD/Fs in the general environment, accounting for over 95% of the total intake, with other exposure pathways (for example inhalation and dermal contact) collectively contributing no more than 5% of the intake. Movement to higher trophic levels is typically accompanied by biomagnification of PCDD/Fs in the receptor species.

Because of shorter food chains, biomagnification is less pronounced in the terrestrial ecosystem than in the aquatic environment. Kenaga and Norris (1983) estimated average bioconcentration factors for 2,3,7,8-TCDD from water to aquatic species of 1,000-7,000 compared with 2-25 for food and soil to terrestrial mammals. The uptake of PCDD/Fs from the background environment (air, water, sediments and soil) into fish, plants and into animals consumed by humans has been modelled by Hattemer-Frey and Travis (1991), Lorber *et al* (1994), US EPA (1994), Lorber (1995), McLachlan *et al* (1990, 1995), McLachlan (1995), Harad and Smith (1997) and Eduljee and Gair (1997). Accumulation in higher animal and human fat is limited to the seventeen 2,3,7,8-positional PCDDs and PCDFs; the remaining congeners are metabolised and/or eliminated from the body. Absorption efficiency varies with the degree of chlorination, approaching 70% for 2,3,7,8-TCDD and falling to 1-10% for OCDD and OCDF. The half-life of PCDDs and PCDFs in humans is in the order of 5-8 years (Poiger and Schlatter, 1986). Maternal transfer into infants via breast feeding is efficient; the level of bioaccumulating PCDD/Fs in the mother decreases by about 12% per month owing to lactation, and the absorption efficiency of PCDD/Fs from maternal milk into infants has been measured at 95% (Dahl *et al*, 1995).

Trophodynamic studies in the natural environment have established an increase in bioaccumulation with increasing trophic levels as dietary intake assumes greater importance. The highest accumulations has been recorded in top predator species dependent on the aquatic ecosystem. Magnification factors for fish-to-piscivorous bird eggs of 21 for 2,3,7,8-TCDD in herons and 11-32 for PCDD/Fs in eagles have been reported (Niimi, 1994).

B3 TOXICITY OF PCDDS AND PCDFS

B3.1 MECHANISM OF ACTION AND TOXIC RESPONSE

A large number of studies have been published on the potential for adverse effects on humans following exposure to PCDD/Fs, though the overwhelming majority of these studies relate to 2,3,7,8-TCDD. Comprehensive reviews are available (WHO, 1989; NATO/CCMS, 1991; Van den Berg *et al*, 1994). A particularly exhaustive review is contained in US EPA (1994). The toxic action of PCDD/Fs in humans is believed to be initiated by binding to the Aryl hydrocarbon hydroxylase (Ah) receptor, followed by translocation to the cell nucleus (Landers and Bunce, 1991; Enan *et al*, 1996a; Enan and Matsumura, 1996). Binding to DNA does not occur to any significant extent, indicating that PCDDs and PCDFs are promotors rather than initiators of carcinogenesis.

The most widely recognised response to acute and chronic exposure to PCDDs and PCDFs, particularly under occupational conditions, is chloracne. However, this condition is associated with high level exposure to PCDD/Fs and is not manifested in the general population. Other effects such as porphyria cutanea tarda have been observed in workers accidentally exposed to chemicals containing PCDD/Fs, but this condition is not unequivocally attributable to these chemicals - the host chemical, particularly hexachlorobenzene and trichlorophenol, has been implicated in the adverse effect. Among the general population chloracne, liver dysfunctions and other adverse effects were noted subsequent to the industrial accident at Seveso in 1976, but again this involved a short exposure to a very high dose of 2,3,7,8-TCDD - this congener is present as a minor component among the PCDD/Fs in the general environment, and is typically below the limit of detection in samples of PCP and its derivatives.

B3.2 CARCINOGENIC AND NON-CARCINOGENIC EFFECTS

The US EPA review of 1994 classed 2,3,7,8-TCDD as a "probable" human carcinogen on the basis of mechanistic considerations, unequivocal animal carcinogenicity, and limited human evidence. This interpretation has been generally accepted by other regulatory agencies; for example the UK Government regards 2,3,7,8-TCDD as a "possible" human carcinogen. However, the US EPA's assumption of a linear dose-response relationship at all dose levels has not been accepted outside of the US. All European regulatory agencies regard PCDD/Fs as carcinogenic promotors and define a Tolerable Daily Intake (TDI) on the basis of a No Observed Adverse Effect Level (NOAEL) derived from animal studies. In February 1997 the WHO classed 2,3,7,8-TCDD as a "known" human carcinogen, but continues to regard other PCDD/Fs as "not classifiable" despite a similar mode of action to 2,3,7,8-TCDD.

Other than carcinogenicity, PCDD/Fs exhibit immunotoxicological, reproductive and developmental effects in animals, but evidence from human epidemiological studies is less clear: there are large areas of uncertainty, not least in the interpretation of some of the key studies cited as evidence of adverse non-cancer effects, as representing "background" exposure. Recent epidemiological studies have focused on the anti-oestrogenic effects of PCDD/Fs and dioxin-like compounds (Birnbaum, 1994) and investigation of subtle developmental effects in infants and children. For example, Pluim *et al* (1996) investigated effects such as low birth weight and neurological disorders in a population of 38 healthy breast-fed infants in the Netherlands. The infants were divided into two groups according to the concentration of PCDD/Fs in their mothers milk: 9-28 ng I-TEQ kg-1 fat in the low exposure group, and 29-67 ng I-TEQ kg-1 fat in the high exposure group. A range of physical, neurological and developmental indicators were measured over the first six months of life. The study did not reveal any effects of exposure to background levels of PCDD/Fs, nor any statistically significant differences between the two groups. However, Pluim *et al* (1994) found relatively high thyroid and liver function effects among the high exposure group.

In a follow-up study by Ilsen *et al* (1996) psychomotor development and neuromotor functioning of the study group was assessed when the infants had reached the age of 2-2.5 years. Psychomotor development was normal in all the children, with no differences between the two exposure groups. However, the investigators measured suboptimal scores for neuromotor functioning in the high exposure group, postulating that these findings may be due to thyroxine aginistic action of dioxins, in accordance with earlier signs of relatively high thyroid function in the first 11 weeks of life in the high exposure group. Other cognitive and immunological effects in Dutch toddlers and children of school age have been studied by, for example, Vregdenhil *et al* (1999) and Weisglas Kuperus *et al* (1999). Whether any or all of these effects can be ascribed to dioxin exposure remains an open question, since other confounding factors are present (Neubert *et al*, 1999; Safe, 1999). Other studies on these issues are discussed in Health Council (1996).

Another study suggests that 2,3,7,8-TCDD follows multiple mechanistic pathways in animals, possibly manifested in gender differences in the mechanisms of toxicity (Enan *et al*, 1996b). In male animals 2,3,7,8-TCDD inhibited the addition of phosphorus to proteins within the cell nucleus while enhancing the transfer external to the nucleus, whereas in female animals the reverse process was favoured. Enan *et al* (1996b) suggest that in males the toxic effects of 2,3,7,8-TCDD may be initiated outside of the nucleus, while in females a nuclear factor may be involved.

In 1998 the WHO updated their 1989 study, and reported on their findings in late 1998 (van Leeuwen and Younes, 1998 - see below). The Health Council of the Netherlands (Health Council, 1996) reports that a proportion of the Dutch population already has body burdens of dioxin-like substances which are causing measurable effects to new-born infants and recommend that the TDI for PCDD/Fs should be reviewed downwards (see below).

B3.3 DOSE-RESPONSE

B3.3.1 General

In assessing the dose-response characteristics of chemicals, it is common practice to group chemicals into two categories; noncarcinogens and carcinogens. The assessment is then simplified to the consideration of these two broad categories of chemicals. The dose response relationship is fundamental to the interpretation of toxic effects; ie there is a direct relationship between the exposure intake, duration of intake and the severity of the toxic effect. The basic quantitative difference in risk assessment for carcinogens versus that for noncarcinogens centres on the concept of thresholds. Whereas noncarcinogens have thresholds below which they fail to induce any discernible adverse health effect, carcinogens are often assumed to have no such threshold; carcinogenic risk is dependent on total dose, independent of whether the dose occurs over a short or long time period.

In the case of potential human carcinogens such as PCDDs and PCDFs, this simplified view has to be refined. Carcinogens can be grouped into two categories: *genotoxic*, or carcinogens that operate through an initial effect on DNA or chromosomes that initiates cancer, and *nongenotoxic*, or carcinogens that operate through chronic cell damage. There are theoretical, mechanistic grounds for assessing genotoxic carcinogens with no-threshold dose-response models, while the available evidence for nongenotoxic carcinogens supports a dose-response as for noncarcinogens - ie a threshold does exist. The US EPA has traditionally assessed the dose-response characteristics of PCDDs and PCDFs as a genotoxic carcinogen (ie as a non-threshold initiator), and as a result has developed a risk-specific dose by linear extrapolation of the dose-response data. In contrast all European regulatory agencies, together with Canda and the WHO, regard the available toxicological data as indicating that PCDDs and PCDFs are nongenotoxic carcinogens (ie as threshold-based promotors) and have therefore applied safety factors to the animal data to derive a Tolerable Daily Intake. We examine these two approaches below.

B3.3.2 Risk-Based Dose-Response Analysis

For carcinogens the US EPA and other US agencies and research centres have developed estimates of cancer potency for 2,3,7,8-TCDD by applying the so-called linearised multistage model to estimate the largest possible linear slope (within the 95th percentile confidence limit) to extrapolate from high doses typical of experimental studies on rodents to the much lower doses typical of environmental exposures. This approach assumes a linear dose-response relationship between the origin and the upper 95th percentile confidence level on the doses. A carcinogenic potency factor called the *slope factor* is computed from the data which, when multiplied with the calculated intake of PCDD/Fs, produces an estimate of the incremental cancer risk to the individual as a result of exposure to the particular source. The risk is expressed as an estimated lifetime risk (probability) of the incidence of cancer.

Prior to their re-appraisal of the toxicity of PCDD/Fs, US EPA's slope factor for 2,3,7,8-TCDD was set at 156,000 (mg kg^{-1} day^{-1})$^{-1}$ based on the combined influence of a variety of tumor types at target organs observed in female Sprague-Dawley rats. For illustration, if an "acceptable" risk criterion of 10-5 (ie 1 in 100,000) is selected, then the corresponding dose will be 0.064 pg kg^{-1} bw day^{-1}, compared with the WHO's Tolerable Daily Intake (TDI) of 1-4 pg kg^{-1} bw day^{-1} obtained using a threshold-based analysis of the same dose-response data. Following the re-appraisal, US EPA (1994) set the slope factor for 2,3,7,8-TCDD at 100,000 (mg kg^{-1} day^{-1})$^{-1}$.

B3.4 Tolerable Daily Intake (TDI)

The approach adopted by European regulatory agencies has been to assess acute and chronic animal studies into the full range of noncarcinogenic (immunological, reproductive and developmental) and carcinogenic adverse health effects with the aim of identifying a No Observed Adverse Effect Level (NOAEL) or a Lowest Observed Adverse Effect Level (LOAEL), to which appropriate safety factors are applied to obtain a Tolerable Daily Intake (TDI) for PCDDs and PCDFs. The TDi is the daily dose of a chemical to which an individual may be exposed for a lifetime, and not be expected to develop adverse health effects.

European governments have developed a range of TDIs depending on the toxicological endpoints observed, and the safety factors applied at the endpoint. In 1982 the Netherlands derived a TDI of 4 pg I-TEQ kg^{-1} bw day^{-1} based on an identical NOAEL but with a safety factor of 250. The Health Council of the Netherlands (Health Council, 1996) subsequently recommended that the TDI be lowered to 1 pg I-TEQ kg^{-1} bw day^{-1}, while acknowledging that the average Dutch citizen is exposed to 2 pg I-TEQ kg^{-1} bw day^{-1} via the background environment. The recommended TDI is set on the basis of a Lowest Observed Adverse Effect Level (LOAEL) dose of 0.1 ng kg^{-1} bw day for 2,3,7,8-TCDD in baby rhesus monkeys (Rier *et al*, 1993) and a LOAEL of 0.13 ng kg^{-1} bw day^{-1} for 2,3,7,8-TCDD in marmosets (Neubert *et al*, 1992). Applying a factor of 2, a NOAEL of 0.05 ng kg^{-1} bw day^{-1} is derived. A further safety factor of 50 is applied to obtain a recommended TDI for humans of 1 pg I-TEQ kg^{-1} bw day^{-1}. In the view of the Health Council, the studies of researchers such as Plium *et al* (1996) indicate subtle immunological and motor-neurological effects in infants at background levels of exposure experienced by the mother, lending support to the lower recommended TDI. Importantly, the Health Council also note that these changes were within the normal range during the development of infants, and that breast-feeding on balance provides benefits to the infant that are not outweighed by the higher daily dose of PCDD/Fs experienced by the infant.

In Germany safety factors of 100^{-1},000 have been applied to obtain TDIs in the range of $1^{-1}0$ pg I-TEQ kg^{-1} bw day^{-1} with the lower end of the range being regarded as a non-statutory *precautionary* TDI, and the higher end as a *preventative* or *intervention* TDI (Schulz, 1993). The UK, France and Belgium adopted the WHO recommendation of 1990, of 10 pg I-TEQ kg^{-1} bw day^{-1}.

Sweden, Norway and Finaland adopted a TDI of 5 pg I-TEQ kg^{-1} bw day^{-1} using a NOAEL of 1,000 pg I-TEQ kg^{-1} bw day^{-1} and a safety factor of 200.

In the UK, the Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT, 1995) conducted a formal re-examination of the current TDI in the UK of 10 pg I-TEQ kg^{-1} bw day^{-1} in the light of the findings of the US EPA (1994) study. The COT also considered the primate study of Rier *et al* (1993) on which Health Council (1996) chose to base their revised TDI, but commented that in view of the small number of animals involved and the apparently high spontaneous background incidence of endometriosis in rhesus monkeys this study was in itself not sufficient to merit a revision of the current TDI. The COT concluded that the US EPA (1994) study did not provide a justification for a reduction in the current TDI, but recommended that the matter be kept under review.

In 1990 the WHO recommended a TDI of 10 pg kg^{-1} bw day^{-1} based on a NOAEL for primate reproductive performance of 1,000 pg I-TEQ kg^{-1} bw day^{-1} and a safety factor of 100. However, as noted above, in 1998 the WHO re-appraised their earlier assessment of the TDI for PCDD/Fs (van Leeuwen and Younes, 1998). Hormonal, reproductive and developmental effects were considered to be the most sensitive effects seen at low doses in animal studies, occurring at body burdens in rats and monkeys in the range of 10-50 ng kg^{-1} body weight (bw) per day. WHO considered human daily intakes corresponding with body burdens similar to those associated with adverse effects in animals to be in the same range (i.e. 10-40 mg kg^{-1} bw). Applying an uncertainty factor of 10 to this LOAEL, a TDI in the range of 1-4 pg TEQ kg^{-1} bw day^{-1} was established, but adopting a revised set of TEF factors for PCDDs and PCDFs. These are generally in line with the I-TEQ scheme of NATO/CCMS, except that in the WHO scheme the TEF for 1,2,3,7,8-PeCDD is set at 1.0, whereas in the I-TEQ scheme, this congener has a TEF of 0.5. Further, the revised TDI includes other dioxin-like chemicals such as the coplanar PCBs. The WHO TEF system is listed in *Section 2* of the main report.

WHO acknowledged that the general population was already exposed to background concentrations of PCDDs and PCDFs approaching or within this range of intake. WHO therefore recommended that every effort should be made to reduce exposure to the lower end of this range.

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Annex C

Review of PCDD/F Formation and Control Mechanisms

CONTENTS

C1 GOOD COMBUSTION PRACTICE AND BEST OPERATING PRACTICE

C1.1 FORMATION OF PCDDS AND PCDFS IN COMBUSTORS

Theoretical studies into the mechanisms of formation of PCDD/Fs in combustion systems, with the specific aim of elucidating emission control strategies, have suggested a mechanistic framework which provides a basis for the development of PCDD/F emission control strategies (Hagenmaier *et al*, 1987; Fangmark *et al*, 1995; Addink *et al*, 1998):

1. Incomplete combustion of organic wastes in the combustion chamber leads to the formation of organic fragments (PICs) which serve as organic precursors to the dioxin/dibenzofuran molecule.

2. The waste provides a source of chlorine, and of metals. The latter are incorporated into flyash, which carries over to the cooler (250-400℃) post-combustion zone of the incineration system.

3. The organic precursors adsorb onto the surface of the flyash in the post-combustion zone, and following a complex sequence of reactions which are catalysed by metals (primarily copper) in the flyash, lead to the formation of PCDD/Fs along with other chlorinated trace organics.

In keeping with the above mechanistic framework, US EPA (1987) introduced the concept of Good Combustion Practice (GCP), the term being defined as "those combustion conditions which lead to low emissions of trace organic pollutants." Following a comprehensive study of three types of MSW incinerators the US EPA concluded in 1987 that low organic emissions could be achieved by a combination of good combustion control techniques and appropriate gas cleaning technology. The rationale for the application of GCP to the control of organic emissions was that the latter were the products of incomplete combustion (PICs). Hence, optimisation of combustion conditions to approach as closely as possible the theoretical ideal of complete combustion (ie combustion to carbon dioxide, water, etc), coupled with appropriate "end-of-pipe" control strategies, should lead to reductions in trace organic emissions. The US EPA recommendations for GCP fell into three categories:

1. Minimisation of organic emissions to atmosphere through optimum design of the combustor.

2. Operation of the combustor within its design specifications, with control systems to prevent excursions outside of the design envelope.

3. Monitoring and verification of combustion performance, with continuous surveillance of key design and operating parameters.

From a regulatory standpoint, the most appropriate means of implementing GCP for minimisation and control of trace organic emissions is to frame a set of general rules which can be applied to all types of combustors. Five classes of criteria can be identified:

1. Design criteria (for example, requiring a minimum gas phase residence time of 2 seconds in the combustion zone).

2. Operational criteria (for example, requiring a minimum furnace temperature of 850℃, or maintenance of a minimum excess oxygen level in the combustion gas).

3. Measurement and control of surrogates such as CO and particulate emissions (for example, maintaining CO emission below 50 mg/m3)

4. Control regimes (restrictions of waste feeds; failsafe, interactive control systems; automatic shutdown procedures, etc).

5. Monitoring regimes (measurement and recording of combustion temperature; continuous monitoring of excess oxygen, CO emissions and combustion efficiency, etc).

The UK's Chief Inspector's Guidance Notes, and European Union Directives on incineration provide examples of regulatory requirements and/or guidance which incorporate aspects of the above five types of criteria for GCP.

C1.2 BEST OPERATING PRACTICE

US EPA (1994) subsequently defined Best Current Operating Practice (BOP) as being the use of GCP combined with a temperature limitation of 350°F (approximately 175℃) on the inlet to post combustion control devices. Rapid quenching of the combustion gases to below 175℃ was also regarded as BOP.

The principles of good combustion practice (GCP) in *Section 5.2.1* can be restated in a manner which better relates to the mechanistic aspects of PCDD/F formation and to operational and control regimes. Updating GCP to include catalysed heterogeneous reactions in the post-combustion zone, the following goals of GCP can be identified:

1. Maximise the destruction of organics in the combustion chamber, so as to prevent the carryover of uncombusted organics or products of incomplete combustion (PICs) into the post-combustion zone. This in turn will reduce the likelihood of PCDD/F formation in the post-combustion zone;

2. Minimise the potential for low temperature catalysed reactions in the post-combustion zone by minimising the time the gases and particulate matter spend in the temperature region 250-400℃ or by suppressing the catalytic activity of flyash.

3. Minimise emissions of PCDD/Fs by employing end-of-pipe control strategies.

In terms of developing control strategies relating to the control of PCDD/F formation and emissions, the above goals can be discussed under four headings:

- Control of feedstock
- Control of the combustion process
- Control of the post-combustion process
- End-of-pipe strategies

The combined control of combustion and post-combustion processes constitutes the equivalent of US EPA's Best Current Operating Practice (BOP) discussed above. In the following sections we draw out relevant observations concerning the fundamentals of PCDD/F formation in order to inform the development of potential control strategies.

C2 CONTROL OF FEEDSTOCK

C2.1 INTRODUCTION

Three issues are discussed under this heading:

(1) The effect that different feed materials might have on the propensity for PCDD/F formation in combustors;

(2) Whether restrictions in feedstock composition are likely to have a beneficial effect in terms of reduced PCDD/F emissions.

(3) Whether the manner in which the feedstock is presented to the combustor influences PCDD/F formation.

Each issue is discussed below.

C2.2 EFFECT OF DIFFERENT FEED MATERIALS

The fact that all waste types, and indeed all fuels, including fossil fuels such as coal, generate PCDD/Fs on combustion suggests a common reaction framework which applies to all combustors fired with any type of fuel or waste type. However, studies have indicated that flyash generated from MSW combustion and from the combustion of chemical waste differ in their catalytic activity, the former being more active per gramme of material (Naikwadi *et al*, 1993). This either reflects the compositional variations of different starting materials, or different combustion conditions under which these wastes are treated. For example, it is possible that the generally higher temperatures within a chemical waste incinerator results in a "sticky", sintered flyash surface with less active sites than flyash generated in a MSW incinerator.

In terms of PCDD/F control strategies, an important point is that combustors should be specifically designed to accept the waste in question, so as to ensure that the requirements of GCP and BOP are met regardless of the type of waste. Thus, a designer of a clinical waste incinerator should allow for the fact that medical waste invariably arrives at the facility in sealed bags or containers, that the composition of the waste could vary markedly from bag to bag, and that there is relatively little scope for inspection and equalisation of loads. The design of the waste reception and loading equipment, feed regime, and of the combustor will therefore be influenced by these considerations. In the case of the combustion of wood chips, other factors may be more important and result in a different design of the combustion system. The key point is that if GCP and BOP are observed, then the issue of waste type is of secondary importance.

C2.3 RESTRICTIONS IN FEEDSTOCK COMPOSITION

There has been considerable debate as to whether removal of chlorine-containing components (such as PVC from MSW) prior to combustion contributes to a lowering of PCDD/F emissions relative to a conventional incineration operation. The rationale for this suggestion is that chlorination reactions at post-combustion temperatures cannot proceed to completion and thus deliver maximum yields of PCDD/Fs if HC1 delivery to the reaction sites is reduced. In order to achieve the latter, the principal sources of chlorine in the feed material should be removed prior to combustion.

PCDD/F formation in combustors is a side-reaction which, in terms of percentage yield, is inconsequential relative to the dominant oxidative reactions between organic matter and chlorine in MSW and oxygen in combustion air. Literature sources indicate that the quantity of HC1 in process gases is at best a secondary determinant in influencing PCDD/F yields, and is much less important than the temperature-time window (Fangmark *et al*, 1993; Fangmark *et al*, 1994; Gullet *et al*, 1994).

PCDD/Fs are produced in trace quantities, and the demand for HC1 participating in the chlorination reactions is correspondingly very small. While removal of materials such as PVC could potentially result in a significant reduction in the total amount of HC1 generated by the combustion of MSW in the furnace, this will not necessarily impact on the small quantity required for PCDD/F formation. In other words, there is sufficient chlorine present in the remaining MSW, clinical waste, or other waste-based feedstock after removal of PVC to satisfy the requirements of the PCDD/F formation reactions, even under optimum formation conditions. PVC/plastics removal is therefore unlikely to affect emissions of PCDD/Fs, all other operational conditions remaining constant.

Trials on laboratory, pilot and full scale plant have tended to confirm the lack of a beneficial effect on PCDD/F emissions when chlorine-containing components of MSW and other waste types are withdrawn from the feedstock to a combustor (ASME, 1995; APME, 1994). As a strategy for controlling PCDD/F formation, our view is that removal of chlorine-containing materials such as PVC is unlikely to prove effective.

Similar arguments should apply to the likely effectiveness of strategies based on reducing levels of metals and potential organic precursors in the waste stream, at least with regard to influencing PCDD/F emissions. Removal or control of metals or sources of metals such as mercury and cadmium may still be necessary in order to achieve the required emission concentrations for these chemicals.

C2.4 PRESENTATION OF THE FEEDSTOCK

Mention was made above of the need to consider the manner in which the waste is presented to the combustor. The aim is to ensure that the requirements of GCP are met, once the waste has been introduced into the combustor.

Combustion is best controlled when the waste is homogeneous, both in physical and compositional terms. Thus, during industrial waste combustion this can be achieved by blending the incoming waste streams to a consistent, controlled composition prior to combustion. Solid material can be shredded prior to being fed into the incinerator in order to reduce particle size, and ensure increased contact with combustion air, and uniform burning.

Different types of waste will require different handling techiques. For example, clinical waste is invariably sealed at source, and shredding of this material prior to it being fed into the combustor would not be considered good practice. The principle, that the combustor and associated handling requirements should reflect the type of waste to be treated, remains an important consideration for the control of PCDD/F emissions.

C3 CONTROL OF THE COMBUSTION PROCESS

C3.1 INTRODUCTION

Conventional control strategies dealing with the combustion process are well summarised by US EPA's requirements for good combustion practice (GCP). There are two issues to be considered:

(1) Whether current knowledge of the fundamentals of PCDD/F formation provides either a justification for these requirements, or represents a conflict with presently held views on PCDD/F control;

(2) Whether some or all of these requirements need to be modified and/or supplemented with new requirements in the light of more recent knowledge.

C3.2 RELEVANCE OF CURRENT THINKING TO GOOD COMBUSTION PRACTICE

With respect to issue (1), current thinking on the mechanistic aspects of PCDD/F formation does not contradict the requirements for GCP as set out in *Section 5.2*, nor does it suggest that any of these requirements are superfluous. Precursor concentrations, temperature regimes, etc are directly impacted by operational practices which have been demonstrated in both bench scale and full scale tests to either reinforce or negate the goals set out for GCP in a predictable and reproducible manner. This issue is discussed further in *Section 5.7*.

As with feedstock preparation, uniform mixing of the waste with combustion air and adequate turbulence in the combustion chamber are important to ensure consistent and controlled combustion conditions. The use of computational fluid dynamic (CFD) modelling of incinerator plants is a means of simulating the material and energy distribution patterns in an incinerator, and is an excellent tool for visualising the flow patterns in an incinerator, and hence aiding in the design of plant configurations and control systems (Nasserzadeh *et al*, 1995).

C3.3 PCDD/F FORMATION MECHANISMS

With regard to issue (2), recent developments have provided evidence of in-flight formation of PCDD/Fs. Measured formation rates for in-flight formation have been much higher than those for static formation (Gullett *et al*, 1994; Altwicker, 1991; Konduri and Altwicker, 1994) but they inevitably apply over relatively short residence times of gas solid contact. Moreover, it has been proposed that the enhanced catalytic activity is associated with freshly produced ash, and that this activity diminishes inherently over periods of the order of 0.1-1 second (Konduri and Altwicker, 1994).

However, in-flight mechanisms may determine the ultimate PCDD/F emission levels that are achievable in well designed and operated plant, since it is very difficult to envisage a design that does not involve passing combustion gas with some particulate loading through the temperature window of 250-400℃. The application of in-flight calculations could assist in estimating potential limiting formation levels under various post-combustion scenarios (Gullett *et al*, 1994). Since the in-flight formation rate is in units of ng (total PCDD/F) g-1 (flyash) min-1, it follows that the current calculation method would prescribe low particulate loading and short residence time in the temperature window 250-400℃ as the measures most likely to minimise PCDD/F formation.

C4 CONTROL OF THE POST-COMBUSTION PROCESS

C4.1 INTRODUCTION

Several issues need to be considered in relation to control of the post-combustion stage of a combustor:

- Control of the temperature window in which optimum PCDD/F formation occurs: 250-400℃;
- Minimisation of the time particulate matter spends in the post-combustion zone;

Each issue is discussed in turn.

C4.2 CONTROL OF THE TEMPERATURE WINDOW FOR PCDD/F FORMATION

Bench scale and full scale trials are unequivocal in identifying post-combustion temperature as a key operational variable influencing the formation of PCDDs and PCDFs. There is now a general consensus that maintenance of post-combustion conditions in the gas cleaning system below about 200℃ is desirable.

There will always exist intermediate temperatures in sections of the post-combustion train between the furnace temperature (~850 - 1100℃) and the conditioner/ESP/fabric filter temperature (~200℃), notably in the boiler and economiser sections, and it therefore follows that PCDD/F formation cannot be entirely suppressed. However, good operating practice as currently recommended by equipment suppliers centres on cleaning of equipment surfaces subjected to temperatures within the formation range so that the residence time of particulate matter subjected to these temperatures is minimised (see below). Rapid cooling of the furnace gases with a water quench or by air atempuration such that all pollution abatement equipment temperatures post-boiler are maintained below 200℃ would minimise the potential for PCDD/F formation in particulate removal devices. Quench rates typically achieved by atempuration are sufficiently high to circumvent the formation of PCDD/Fs during the cooling process (Gullett *et al*, 1994).

C4.3 MINIMISING THE RESIDENCE TIME OF PARTICULATE MATTER

The operation of boilers, economisers, ESPs and other post-combustion equipment at around 300℃ is generally regarded as conducive to the production of high PCDD/F emissions. High formation rates in boilers, ESPs, etc appear to occur primarily due to high static formation on trapped particulates and in the case of ESPs, electrostatic enhancement of PCDD/F levels in the gas phase (Kolluri and Altwicker, 1994; Halasz, 1996) It follows that an important aspect of controlling emissions is the prevention of particulate build-up on plant and pipework operated in the temperature region associated with formation. This should be taken together with the minimisation of all gas-particulate contact in the formation temperature window. However, the requirement to cool combustion gases implies that such conditions, and hence some PCDD/F formation, cannot be eliminated entirely.

C5 END-OF PIPE STRATEGIES

These include the control of particulate emissions, adsorption of PCDD/Fs by activated carbon or other substrates, and decomposition of PCDD/Fs or catalytic destruction.

C5.1 CONTROL OF PARTICULATE EMISSIONS

As noted above, PCDD/F formation is via a surface-catalysed mechanism. It may therefore be thought that capture and removal of the particulate matter would necessarily result in a corresponding reduction in PCDD/F emission concentrations. If this logic were applied as a control strategy in isolation, it would suggest progressive lowering of particulate emissions as a simple means of PCDD/F emission control. Yet as a large number of studies have shown, it does not follow that a correlation between PCDD/F emissions and particulate emissions is necessarily observed in full-scale incinerators under all operating conditions. The reaction sequence is complex, and a number of variables affect the rate of formation and quantities of PCDD/Fs produced. For these reasons, particulate removal will not necessarily result in a proportional reduction in PCDD/F emissions. PCDD/F emissions can be controlled by means other than limiting particulate emissions (e.g. by controlling PCDD/F formation).

C5.2 ADSORPTIVE PROCESSES

The use of activated carbon, sprayed into a dry/semi dry scrubbing unit along with lime or less frequently packed in an adsorption unit positioned after the particulate removal device and prior to the stack, has become a standard component in gas cleaning trains as a means of PCDD/F control, on all sizes of plant fed with MSW or clinical waste. Other adsorptive media such as zeolites are also being tested. The inclusion of an adsorptive device in combustion systems fired with wood and agricultural wastes is not normally contemplated, and as noted above, an interesting issue to be resolved is whether different waste types generate flyash of different activities relative to PCDD/F formation.

C5.3 CATALYTIC DESTRUCTION

It has been reported that catalysts employed for the selective catalytic reduction (SCR) of NOx emissions also demonstrate the ability to decompose organohalogen compounds, including PCDD/Fs (Andersson *et al*, 1998). Successful pilot trials at MSW and hazardous waste incineration facilities indicated that PCDD/F emission concentrations of <0.1 ng I-TEQ m^{-3} could be achieved in the absence of ammonia when titanium dioxide-based SCR catalysts were maintained between 200-350℃.

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