

INCINERATION: BASIC TECHNICAL & ENVIRONMENTAL INFORMATION

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INTRODUCTION

Incineration is an industrial combustion process designed to reduce unwanted materials to simple solid and gaseous residues. Incineration differs though, from most commercial combustion processes in that heat generation is only of secondary interest. The primary goal is the total or partial destruction of unwanted materials. The degree to which this is achieved is central to the controversy surrounding commercial incineration operations. Incineration is also considered to be a process that reduces the volume of the wastes treated and thus simplifies disposal problems. The original unwanted materials can range from solid municipal refuse to highly toxic liquid and solid chemical residues. Incinerator designs are commercially tailored to address this variety of potential feedstocks.

Waste incinerator technology derives both from conventional combustion plant design and from technology originally employed for thermal treatment in bulk chemical or mineral processes. Various modifications are possible in order to closely configure plant to operational requirements imposed by the nature of the waste being processed. The most usual modifications allow the plant to operate at much higher temperatures than most driers or processors.

Much of the literature concerning incinerator design and operation, however, is not readily available in the open literature. Some specialist journals deal with combustion processes, but for the most part in conventional plant. A certain amount of information may be gathered from promotional literature released by the manufacturer. Some information is available from the so-called "grey" literature, for example USEPA reports and environmental impact assessments (EIAs). More recently, there has been a tendency on the part of the merchant incinerators to publish material in the refereed scientific literature. Published studies underwritten by commercial companies deal mostly with validation and control with particular reference to emissions and residues. They often relate too, to "test burns" which do not fully reflect conditions prevalent under normal operating conditions. There are concerns also about possible selectivity in the data released by these operators.

The literature itself falls into two broad divisions. One relates to municipal "mass burn" incinerators, the other to hazardous waste facilities. It quickly becomes clear that the information base concerning the former is very much more extensive than the latter probably due to the public accountability of the authorities which operate them. For both areas, though, much of the literature concerns emissions of two related groups of toxicologically important compounds: the chlorinated dioxins and dibenzofurans. These are not the only compounds of importance, however, merely the best studied.

This document is designed as an introduction to incineration plant. It does not pretend to be complete. It draws heavily on a number of key reviews of incineration. It does not consider the

ancillary facilities necessary to handle the various wastes consumed and generated although this is an important aspect of incinerator operation and subject to operational risk. It is intended as a basic overview of the technology used and a description of the processes involved in its operation. It also attempts to explain the environmentally important processes associated with incinerator operation with particular emphasis on emissions. In doing so, the broad divisions in the literature are followed.

MUNICIPAL INCINERATORS

Municipal incinerators constitute part of a strategic commitment to the use of landfill for the disposal of municipal solid waste (MSW). A mass burn incinerator can reduce the apparent mass of the feedstock by 70% and the volume by closer to 90%. This has obvious attractions given the decreasing availability of landfill sites in some countries and increasing quantities of waste being created. It is now routine, for example, for municipal incinerator ashes to be exported from the country of origin for disposal elsewhere. It is thought that exports of such ash from Switzerland to the UK are in excess of $100,000\text{t y}^{-1}$. Generally, this traffic seems set to grow. Municipal incinerators are well studied and an extensive literature exists. This serves to illustrate well the problems with emissions experienced with all incinerators, although actual mass balances vary considerably between installations.

a) Feedstock: Composition of Municipal Solid Waste.

Municipal solid waste plants operate across a range of capacity of between 10-3000 tons per day (TPD). Despite differences in the actual hardware, all have some common operating elements represented pictorially in FIGURE 1 [1]. In some cases the boiler is replaced by an air heat exchanger, and the excess heat dissipated directly to atmosphere. Only four of the 35 plants operating in the UK are fitted with energy recovery systems [2]. This is becoming less usual in new plant, since heat recovery from waste combustion is seen by manufacturers and operators alike as a positive selling point in the acceptability of these installations. It is worthy of note that this ethic is incorporated into the waste management schemes promoted by environmental groups. The Sheffield (UK) model scheme uses incineration followed by landfilling of ash as a final disposal method [3] although overall it emphasises reuse of waste components.

This otherwise laudable system must be seen as misguided with respect to the incineration component. The nature of MSW as a fuel and the difficulty of optimising operating conditions of the plant under such a potentially heterogeneous loading make undesirable emissions inevitable. TABLE 1 taken from Ref: [1] shows the estimated typical percentage composition of MSW in the United States. There is obviously some uncertainty as to precise percentages as shown in TABLE 2 taken from Ref: [4] but this probably reflects, in part, the normal variability of composition due to, for example, differences in contribution from rural and urban sources. The components of MSW then, vary widely in chemical makeup and in concentration in the waste stream. Heating value, overall, is low

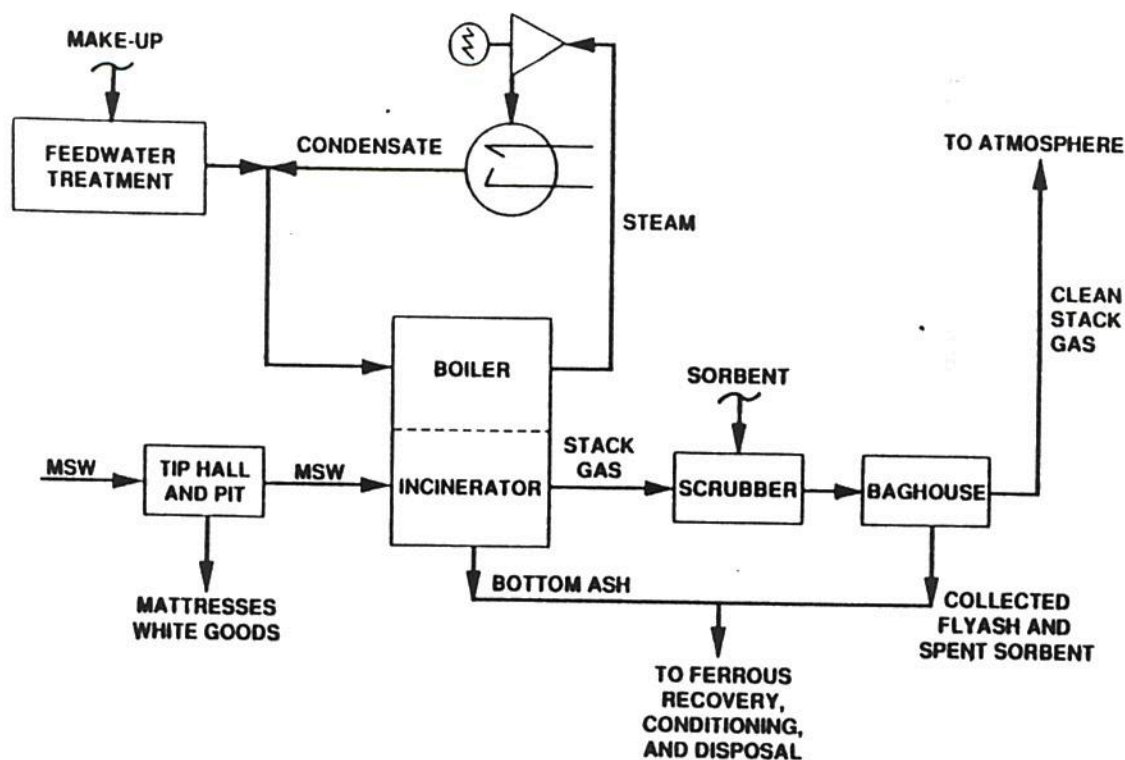


FIGURE 1: A general schematic diagram for the processing of Municipal Solid Waste (Source: REF: [1])

per unit mass, around 4000 British Thermal Units (BTU) per lb, but the masses may be considerable. The city of Paris, France generates some 2 million $t a^{-1}$ [5]. In the UK around 3 million $t a^{-1}$ of industrial wastes are incinerated at 35 dedicated plants, representing some 10% of annual national arisings. It is clear that full recycling would do much to alleviate the problem although on the basis of current projections (see Table 1) the impact of recycling schemes is of doubtful significance. This problem needs to be addressed.

The content of MSW reflects the society which generates it and as such it may be expected to include some lesser amounts of toxic and hazardous materials arising from household materials such as paints, glues and cleaners. A proportion of these may also arise from urban or rural light industry. Plastic convenience packaging content may be seen as indicative of societal trends, for example, the trend away from single income households [1]. The proportion of plastics found in Italian and US MSW at 5% by weight is around double that found in UK MSW. It has been estimated [10] that some 40% of paper production is used for packaging purposes. Paper constitutes 50% by weight of US MSW but only 20% in Italian MSW. The UK level is 38% by weight [1]. As a result of variability and heterogeneity of feedstock composition on a local basis it is simply impossible to continually operate an MSW incinerator under perfect conditions and a compromise is generally effected by blending of feed and operator adjustment of firing conditions as thought necessary.

Under less than optimum conditions the chemical reactions comprising the combustion process do not proceed to completion. This results in emissions which are of environmental concern. In addition there are trace components of the feedstock, in particular the metals, which may be mobilised by the incineration process. Here again, recycling and recovery could do much to alleviate the problems. An order of magnitude difference reported in the mercury levels in feedstock to two Swiss MSW incinerators was attributed to an efficient battery collection scheme reducing input to one of them [6].

| COMPONENT (%) | YEAR | | |
|------------------|------|------|------|
| | 1980 | 1990 | 2000 |
| Paper + card | 33.6 | 38.3 | 41.0 |
| Garden waste | 18.2 | 17.0 | 15.3 |
| Food waste | 9.2 | 7.7 | 6.8 |
| Plastics | 6.0 | 8.3 | 9.8 |
| Wood | 3.9 | 3.7 | 3.8 |
| Textiles | 2.3 | 2.2 | 2.2 |
| Rubber & leather | 3.3 | 2.5 | 2.4 |
| Glass | 11.3 | 8.8 | 7.6 |
| Metals | 10.3 | 9.4 | 9.0 |
| Misc. | 1.9 | 2.1 | 2.1 |

TABLE 1: Estimated percentage composition of municipal solid wastes for the years shown. Inspection of the figures suggests that recycling and waste reduction methods are likely to make little impact on the overall mass balance based on current projections. (SOURCE: REF: 1)

| COMPONENT (%) | | | |
|-------------------|------|--------------|------|
| Ferrous metal | 7.6 | cardboard | 3.5 |
| Aluminium | 1.1 | paper | 51.7 |
| Copper-base metal | 0.06 | putrescibles | 4.4 |
| Zinc-base metal | 0.14 | glass | 10.5 |
| plastics | 5.0 | misc. | 0.9 |
| leather & rubber | 0.7 | grit, dirt | 10.0 |
| fabrics | 1.8 | & ceramics | |
| wood | 2.6 | | |

TABLE 2: Composition of typical MSW showing metals by type in the waste. (SOURCE REF: 4) Note differences in proportions from TABLE 1 which partially reflect the degree of variation likely in this material

b) Municipal Incinerator Mass Balance

The easiest way to visualise the process of MSW incineration is to look at a mass balance schematic. FIGURE 2 [4] is one such mass balance calculated for a rocking grate incinerator treating some 920 tons (dry weight) of MSW per week. By adding all the tonnages of material produced as wastes it is obvious (even without the laws of thermodynamics) that this equates with the tonnage input. In fact this is inaccurate insofar as combustion will actually increase the mass of material due to chemical combination with oxygen. Scrubber brines represent a further mass increase although in the schematic only dissolved content of these is considered. This effectively explodes the myth of volume and mass reduction. They do not happen. What effectively happens is that the atmosphere is used to dilute and disperse the large quantities of process off-gases containing trace contaminants. Water soluble material is discharged to sewer. The residue is landfilled.

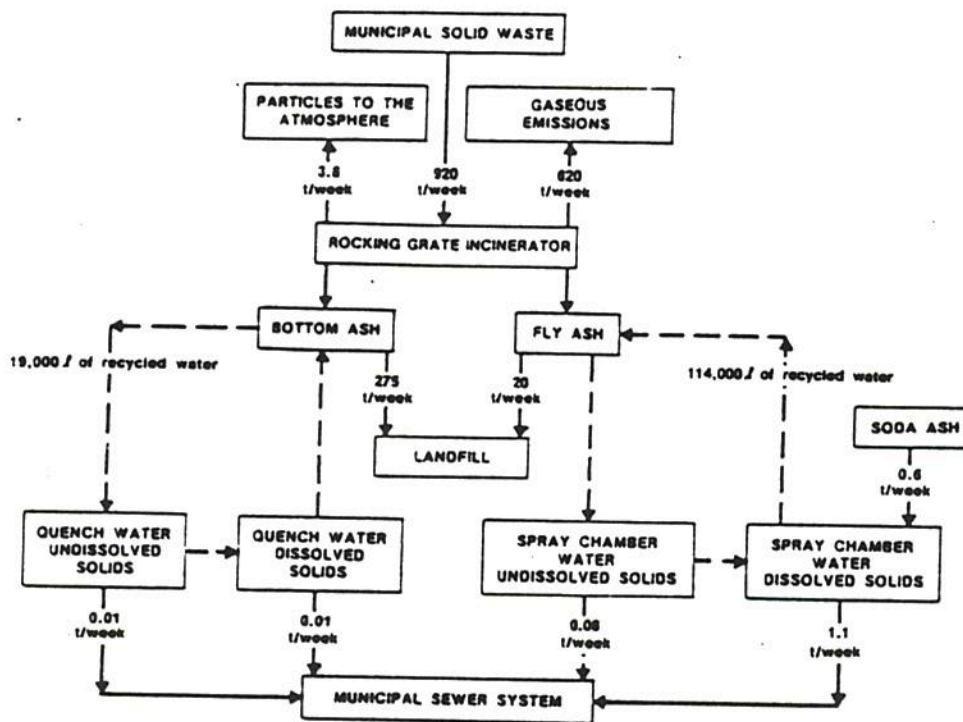


FIGURE 2: A theoretical mass balance for a municipal solid waste incinerator. The figures quoted are likely to be an underestimate since combination with oxygen will lead to increased mass of some materials (Source Ref: [4]).

Each of the waste elements discharged from the incinerator will contain quantities of associated contaminants. The mass balances of these are of importance since there are both human health and wider environmental implications. The studies serve additionally to exemplify the problems common to all incinerators.

i) Metal and Inorganic Substance Mass Balances

The mass balance of metals and inorganic substances in MSW incinerators has been well studied. Not all materials behave in the same way although behaviour is broadly predictable from a knowledge of individual and interactive chemical and physical properties of the materials concerned. FIGURE 3 taken from Ref: [6] illustrates this point, showing the percentage of given elements in the feedstock lost into flue gas after treatment, into fly ash and bottom ash/slag.

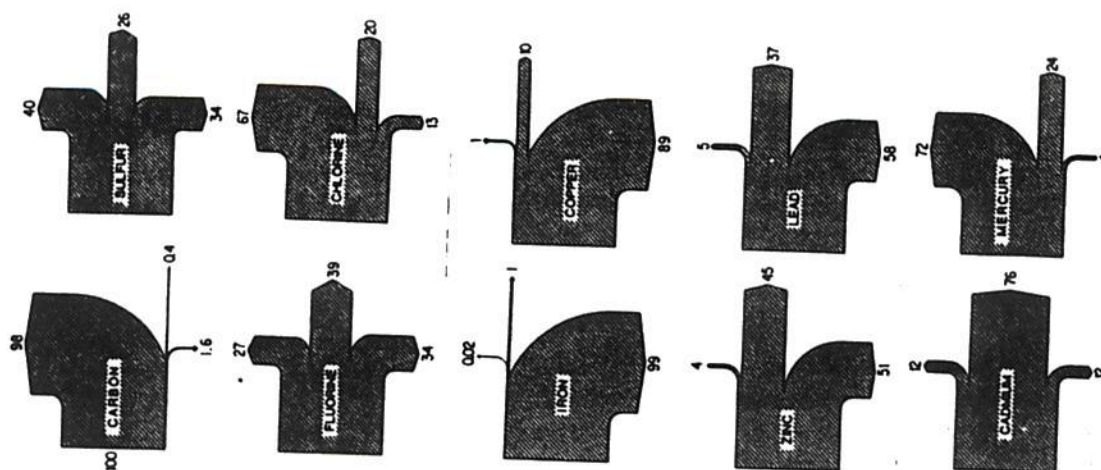


FIGURE 3: Mass balance of environmentally important inorganic substances in a municipal waste incinerator. Key: Δ To atmosphere, \square To electrostatic precipitator (ESP), \blacktriangledown To bottom ash (Source Ref: [6]).

Metals such as cadmium and mercury are only part of the inventory of metals fed to the incinerator. TABLE 3 shows the metal contents in the combustible fraction of MSW contained in pigments, inks, plastic stabilisers and whiteners in addition to metal levels in the raw materials. Non-combustible materials also make a contribution to the budget for metals such as cadmium. Also shown are the weekly outputs based on the flow rates shown in the schematic for FIGURE 2. Simple arithmetic shows that these installations have the potential to emit substantial quantities of metals to the atmosphere. Optimisation of the scrubbing systems will not solve the problem of highly contaminated ash. The chemistry of metals in incinerators is poorly understood. The speciation of the metals will be governed strongly by the speciation of chlorine, fluorine and sulphur [6]. In particular the high concentration of chlorine will tend to result in the formation of metal chlorides which are often both more volatile than the corresponding metal and more water soluble, thus rendering emission control more difficult. Given the different relationship between incinerator conditions and emissions of each individual metal, it is not likely to be possible to optimise conditions to uniformly remove all metals.

Mercury is a particular problem. Figure 3 indicates that a large proportion of this element is lost to atmosphere. It has been

estimated that waste incineration is responsible for the emission of some 20 tonnes of mercury to atmosphere per year in West Germany [7]. Mercury reduction has been identified as a priority in an extensive study of Swedish MSW incinerators [8]. While changing of temperature in key components of the plant may help minimise mercury emissions, it may cause problems with the emission of other materials. Things are not helped by the fact that mercury behaviour, despite much study, is still poorly understood [9].

The disposal of metal contaminated ashes to landfill can result in significant metal mobilisation due to leaching. This may be particularly problematic where incinerator ash is co-disposed with other wastes having or generating an acidic environment [11]. This may necessitate leachate treatment. Metals present in evaporated scrubber brines are likely to be present as chlorides and therefore easily mobilised. Scrubber brines disposed of to sewer will contribute a metal loading to sludges. Metal levels in sludges may prevent their use on land [12] contribute to ash disposal problems from sludge incinerators [13] and lead to further atmospheric emissions. Around 4% of UK generated sludge is incinerated at 5 dedicated plants in the UK [19]. Aerial emissions and aeolian transport are a poorly understood but important mobilisation pathway for metals in global terms [14]. It is thought that around 50% of the contaminants entering the North Sea, for example, do so from atmospheric deposition [15].

| ELEMENT | COMBUSTIBLE FRACTION ppm | FINE BOTTOM ASH kg week ⁻¹ | FLY ASH kg week ⁻¹ | ATMOSPHERIC PARTICLES kg week ⁻¹ |
|---------|--------------------------------|---|----------------------------------|---|
| Ag | 3 | 2 | 3 | 1 |
| Al | 9000 | 3000 | 2400 | 60 |
| Ba | 170 | 90 | 30 | 3 |
| Ca | 9800 | 2500 | 460 | 90 |
| Cd | 9 | 3 | 1 | 4 |
| Co | 3 | 4 | 2 | 0.05 |
| Cr | 55 | 32 | 23 | 2 |
| Cu | 350 | 28 | 10 | 8 |
| Fe | 2300 | 990 | 480 | 34 |
| Hg | 1.2 | 0.02 | 0.02 | ~1 |
| K | 1300 | 390 | 240 | ~50 |
| Li | 2 | 1 | 1 | ~0.1 |
| Mg | 1600 | 790 | 190 | 26 |
| Mn | 130 | 190 | 30 | 6 |
| Na | 4500 | 510 | 320 | 370 |
| Ni | 22 | 13 | 36 | 1 |
| Pb | 330 | 110 | 140 | 370 |
| Sb | 45 | 7 | 7 | 9 |
| Sn | 20 | 25 | 25 | 40 |
| Zn | 780 | 340 | 200 | 460 |

TABLE 3 Indication of the mass balance of metals in MSW incinerator feedstock and waste matrices. Feed levels are given in ppm, outputs in kg week⁻¹ (SOURCE: Ref[4])

Consideration of the behaviour and speciation of inorganic moieties can give some indication of the complexities of the reactions taking place in MSW incinerators. The element chlorine is judged to be of particular importance since this is related to the production of chlorinated organic compounds. Much is emitted to atmosphere. Levels can be controlled using slaked lime injection, but even so levels of HCl, a contributor to acid precipitation, may average 200mg Nm^{-3} of stack gas [8]. Studies of three Parisian MSW incineration plants with varying degrees of stack gas treatment have shown HCl levels of between 568 and 1095mg Nm^{-3} [5] in normal operation. A mass flow rate of 113 kg h^{-1} was calculated for the plant with the most effective treatment system. Swedish studies [8] of a number of plants have shown that while mean HCL values are relatively constant there may be large temporal variations in flue gas content at each plant. Declared chlorine content in raw MSW ranges between 0.45% by weight [1] and 0.7% [8]. There will also be formation of sulphur dioxide from sulphur present in the feedstock. Carbon dioxide is now identified as a "greenhouse" gas.

ii) Emission of organic compounds

Although municipal incinerators are important sources of heavy metals to the wider environment, they also emit substantial quantities of organic materials. The broad groups of compounds of concern [16] are the poly-nuclear aromatic hydrocarbons (PAHs) including chlorinated PAHs, chlorinated benzenes, chlorinated phenols, phthalates and dioxins. In addition smoke/gas condensates have been shown to have mutagenic activity which appears to be related to combustion conditions [17] and the production of PAHs. The relationship is far from clear however and some activity may be due to the large component of chlorinated compounds emitted with the flue gases [18]. At least 400 different organic compounds are known to be emitted with flue gases from MSW incinerators [19]. The most intensively investigated group of compounds are without doubt the poly chlorinated dibenzo-p-dioxins (PCDDs) and the poly chlorinated dibenzo-furans (PCDFs). This is due to the potentially serious health effects associated with these compounds [20; 21]. They were first reported in MSW ash in 1977 and since this time much effort has been directed at the mechanisms of their formation and the conditions under which they are formed. They were reported at levels of between a few and several thousand ng Nm^{-3} dry gas corrected to 10% CO_2 .

To date, the most exhaustive study of the behaviour of organic contaminants in a MSW incinerator and the associated pollution control train is probably that carried out on behalf of Environment Canada [22; 23]. Figure 4 taken from the report illustrates the budget for one of two pollution control train configurations tested at different temperatures. It is apparent that while a proportion of organics are arrested in the post combustion pollution control equipment, a substantial quantity may be emitted to atmosphere. Formation of the PCDDs and PCDFs is thought to take place predominantly in the lower temperature (300°C) areas of the

boiler/heat exchanger, catalysed by metal compounds on the surface of particulates [24]. PVC is an important source of the chlorine taking part in the *de novo* synthesis of these compounds [25]. These emissions are of concern with respect to public health [26]. There is some evidence that the inhalation of incinerator ash can cause elevated tissue levels of metals and deleterious changes in the lung of test animals [27]. Acute toxic effects of dioxins by this route have not been reported. There have been recent suggestions that the accepted models for dermal absorption, of significance to workers in ash disposal, that action levels for 2,3,7,8-TCDD have been set too high [28].

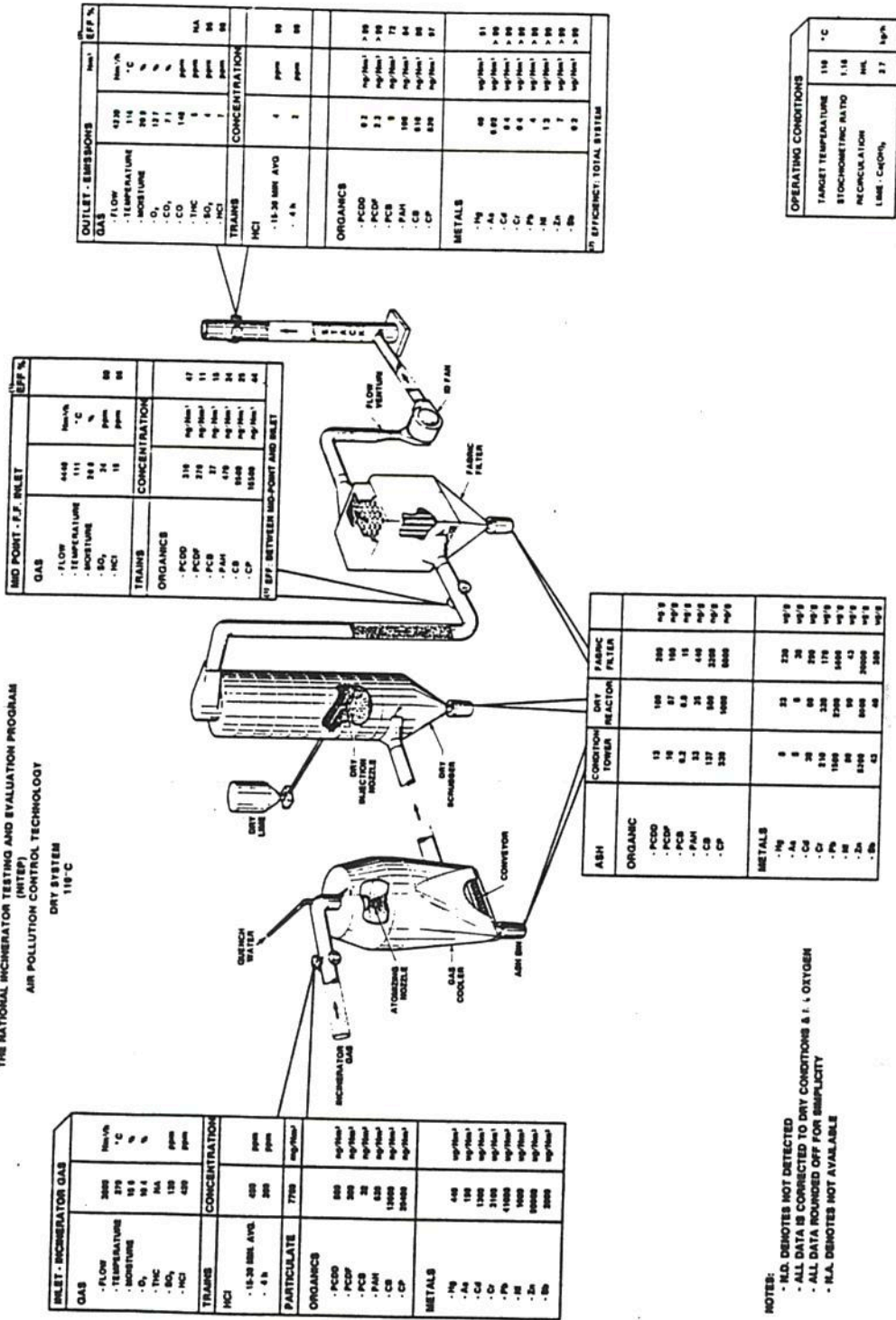
Other studies have shown that there are no real reliable indices for the production of chlorinated organics in these installations. For example monitoring of carbon monoxide in the stack gas appears to relate convincingly to levels of PAHs in the flue gas. The presence of CO and H₂ indicate incomplete combustion [8] in the installation. But, while low levels of CO equate with low levels of uncombusted hydrocarbons, the relationship is not similar for chlorinated compounds which are comparatively difficult to oxidise. The route of formation of these involves a variety of compounds as possible precursors including chlorobenzenes and chlorophenols [29; 30]. The evolution of free chlorine or chlorine radicals from chlorinated feedstock and its reaction with aromatic compounds may precede this but hydrogen chloride is evolved from combustion of many chlorinated compounds and also possibly from the reaction of NaCl with SiO₂ [26]. It is thought that the presence of high sulphur levels may inhibit the production of PCDDs and PCDFs [31].

The chlorinated aromatic emissions, specifically the PCDDs and PCDFs cannot be eliminated solely by controlling combustion conditions [8; 32] although running conditions can be optimised [33; 48]. This optimisation may extend to the processing of the feedstock to produce refuse derived fuel (RDF) and the removal of metals able to catalyse the formation of secondary products of combustion. This may also help with separation of materials for later reclamation. Significantly, [8] the use of RDF does not reduce the HCL content of the discharged flue gases. In any case, the composition, character and behaviour of the bulk of the total organic carbon residual in the stack gases, bottom ash and filter dusts is simply not known or understood [34]. Given the overall uncertainties, it is the view of some authorities [26] that municipal incinerators cannot be regarded as a proven technology.

c) Municipal incinerator technology

Mass burn technology is, unsurprisingly, considered by its vendors as a mature technology [1] and the US, for example, currently has 74 waste-to-energy plants with a combined operating capacity of some 38000 tons d⁻¹. If plant under construction and undergoing permitting procedures is considered this rises to 156,000 tons d⁻¹. Some 60% of the capacity is furnished by five suppliers. 37% of the total market is supplied by the manufacturers Ogden Martin and Waste Management/Signal Environmental Systems. Only one manufacturer currently offers an RDF system, all others are mass burn.

THE NATIONAL INCINERATOR TESTING AND EVALUATION PROGRAM
(INTERP)
AIR POLLUTION CONTROL TECHNOLOGY
DRY SYSTEM
119°C



NOTES:
 - N.D. DENOTES NOT DETECTED
 - ALL DATA IS CORRECTED TO DRY CONDITIONS & 3% OXYGEN
 - ALL DATA ROUNDED OFF FOR SIMPLICITY
 - N/A. DENOTES NOT AVAILABLE

FIGURE 4: Performance test results from a Canadian MSW incineration study showing metals and trace organics present at each stage of the combustion train in off gases and residues. (Source Ref: [23]).

A mass burn facility comprises a tipping hall/reception pit, the combustor itself and the pollution control train. Only the combustor plant will be considered at this stage, pollution control equipment will be dealt with later in the text. For the most part, incinerator plant is based around modular systems predominantly grate fired but sometimes rotary kiln. A review of the current state of the technology for Canada, Sweden and the UK may be found in Refs: [35; 36 & 37]. These reveal considerable differences in national policy. In Sweden the emphasis is on incineration (50% of arisings) while in the UK and Canada incineration of only 8-10% of MSW arisings takes place. In the UK however, use of landfill gas is an object of research as opposed to the use of combustion technology in Canada. Larger scale systems which can operate on a virtually continuous basis are coming increasingly into favour. Due to the modular design, together with the fact that design evolution is on an experiential basis, it is difficult to define a typical plant although each design type operates to common principles. Recently, a computer model has been constructed to simulate the operation of a MSW combustor on a simple basis [39]. Figure 5a (Ref: [1]) shows the gas travel and temperature profile of a Swedish MSW incineration plant based upon a reciprocating grate system (Figure 5b). Figure 6 shows a more detailed schematic [35] of the Edmonton, London MSW incinerator which generates electricity from the combustion of 1600 tons of MSW each working day. Both should be compared to the rotary kiln schematic for a US facility (Figure 7). This represents a step away from conventional boiler technology. The rotary kiln system for the combustion of MSW and hazardous industrial wastes owes much to high temperature mineral processing technology. Indeed both MSW [35] and hazardous waste [38] are used in the firing of cement kilns which are highly energy intensive.

The generation of refuse derived fuel (RDF) is becoming more widespread in some countries [8] as part of schemes to maximise both the energy output from MSW and the quantities of materials which can be recycled. Figure 8 shows the process rationale of such a scheme as in place at Kovik Sweden. Unfortunately, there appears to be considerable consumer resistance to the use of recycled materials which needs to be overcome. Moreover, [35] it seems that most community recycling schemes need to be underwritten by central funding if they are to be a success, ie commercially attractive. It is clear that insofar as the composition of MSW is a reflection of the society that generates it then any changes will have to arise as a result of societal changes. In a sense the same is true of industrial wastes. While these reflect the industrial processes in use in society, they also reflect an underlying demand for industrial products. A full discussion of process and product substitution is outside the scope of this document but it is central to the problems of waste generation and disposal including hazardous waste. The concept of clean production is considered by some authorities as axiomatic to future environmental protection strategies [40], given the inadequacies identified [41] in monitoring of contaminants entering the environment and of the legislative instruments used in enforcement.

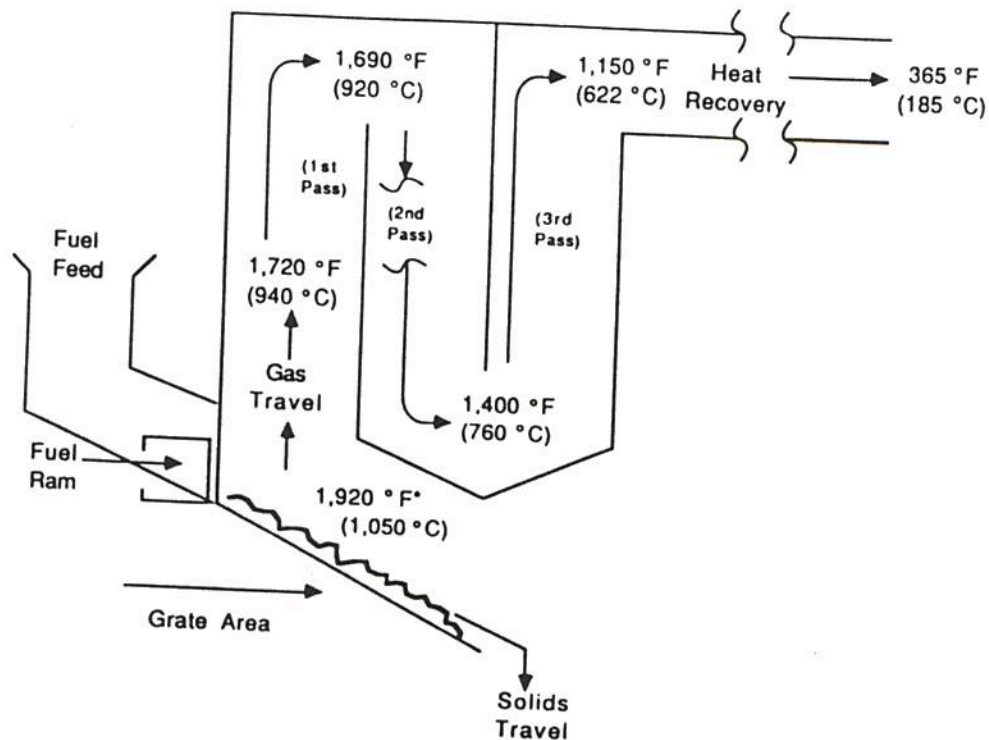


FIGURE 5a Temperature profile of the Hogdalen Municipal solid waste incineration plant, Sweden. This indicates that suitable temperatures for PIC formation occur in the post-heat exchange zone. (SOURCE Ref: [1])

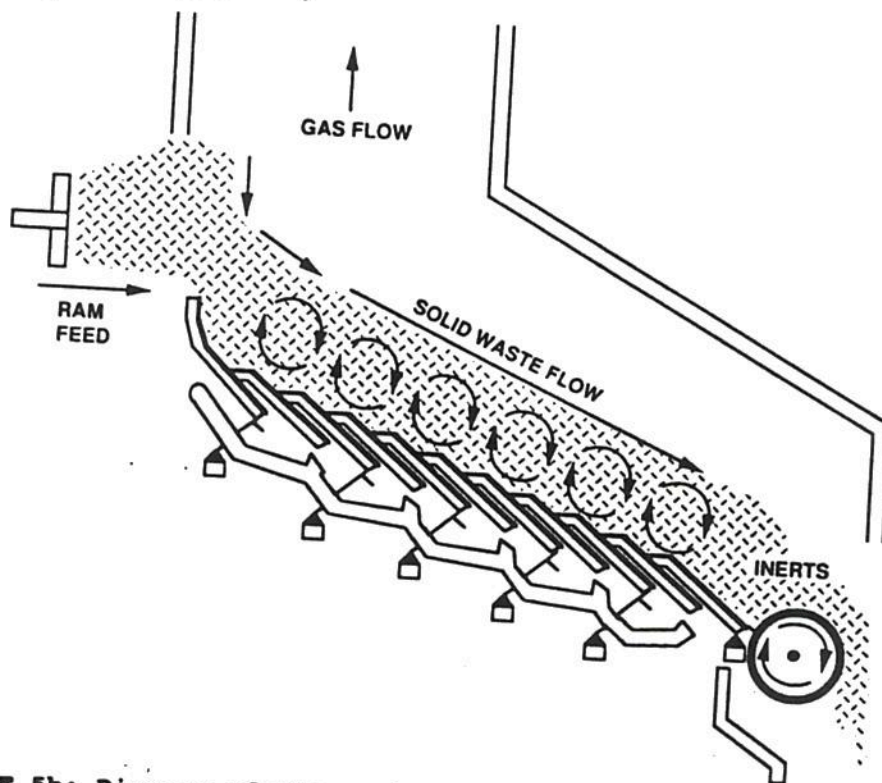


FIGURE 5b: Diagram of the reciprocating grate system at the Hogdalen plant designed to agitate the refuse to promote maximal burn-out. (SOURCE Ref: [1]).

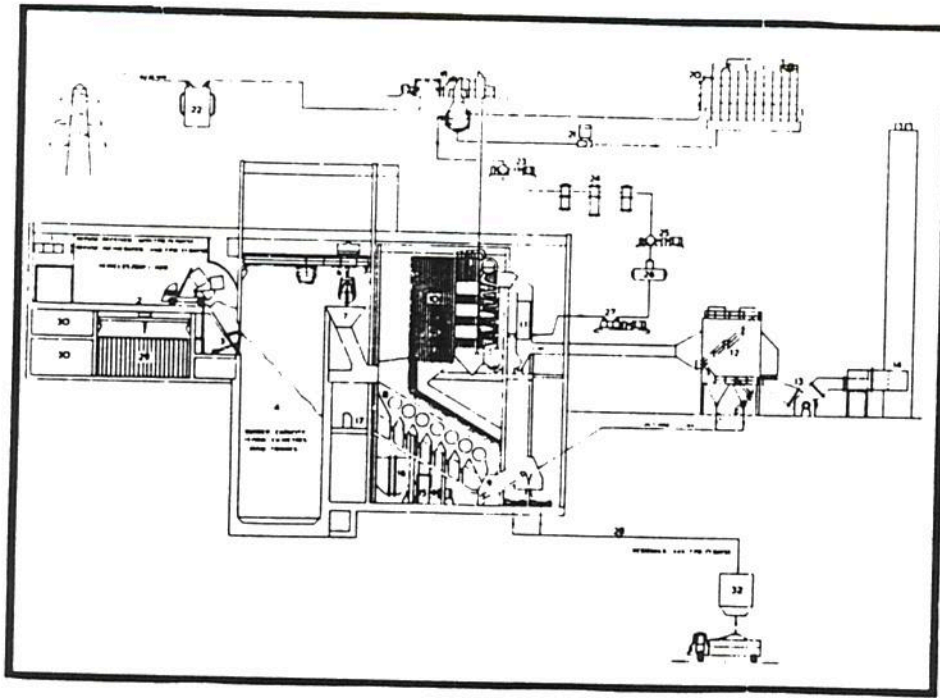


FIGURE 6: Diagram of the Edmonton, London MSW-energy plant showing the tipping hall, incinerator, heat exchange and flue gas treatment. (SOURCE Ref: 35).

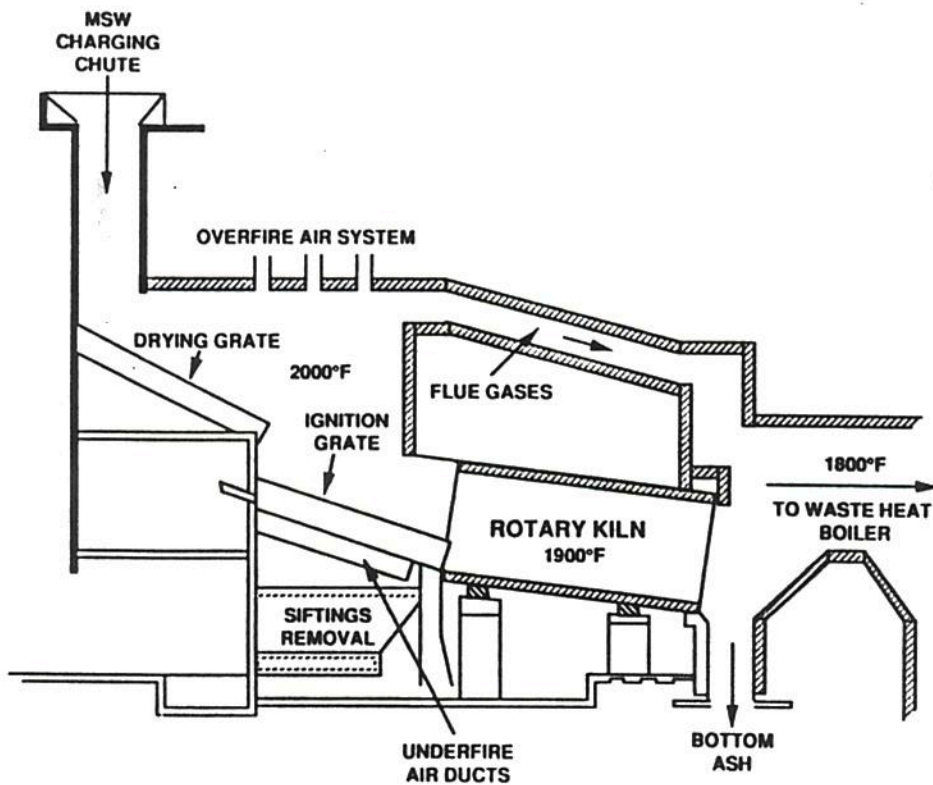


FIGURE 7: Temperature profile of a US Rotary Kiln MSW incinerator. (SOURCE Ref: [1]).

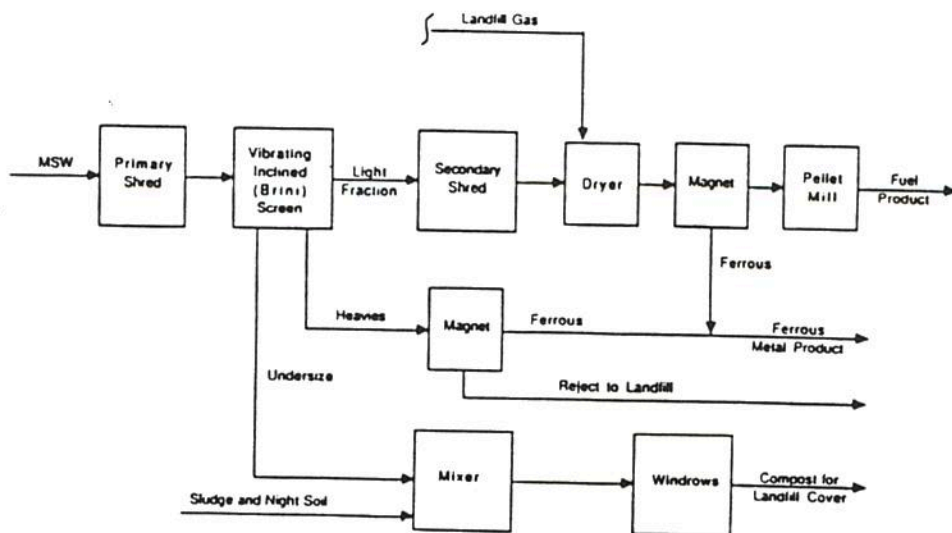


FIGURE 8: A process diagram for the production of refuse derived fuel (RDF) as used at the Kovik incinerator, Sweden. (SOURCE Ref: [1]).

HAZARDOUS WASTE INCINERATION

The literature concerned with hazardous waste incineration is less extensive than that for incineration of MSW. Nonetheless, what there is, in combination with various published EISs and government commissioned reports enables assembly of a useful overview. It is of note that hazardous industrial wastes are routinely incinerated in facilities that are not purpose designed. For example, the tar distilling and macadam industry uses industrial waste as a fuel source and in admixture to produce "cut back" tars and bitumen. Even oil fired heating plant may be employed for the purpose of disposing of waste oils from car servicing. "100 sec oil" is a mixture of waste and primary oils used in this way. It incorporates waste oils from vehicle servicing. These in turn are known to contain dioxins and other chlorinated compounds [45] which probably arise from chlorinated paraffins used as oil additives and from chlorinated "anti-knock" petrol additives [42] added to leaded fuel. Some waste oil, estimated at 40,000 tons y^{-1} [3] is burned directly without emission control in small space heaters in the UK alone. This is of significance when it is realised that few dedicated hazwaste incinerators have an annual capacity equal to this figure.

a) Feedstock: the composition of hazardous waste

The hazardous waste problem is something that we all contribute to directly in the course of our daily lives. It should come as no surprise that the indirect contribution through our consumption of industrial products is very much larger. Table 4, taken from Ref: [43] shows the annual arisings of incinerable wastes and those remaining after recycling and recovery in the US for 1983.

The incinerable waste remaining after recycling/recovery processes comprises some 18% of the total hazardous waste arisings

in the US. Another point of note is that around 21% of the total arising of incinerable waste is halogenated. This may of course not include some wastes contaminated with halogenated residues at low levels.

| WASTE TYPE | GENERATED (MMT) | %RECYCLED/ RECOVERED | REMAINING (MMT) |
|-----------------------------|--------------------|-------------------------|--------------------|
| Liquids | | | |
| Waste oils | 14.25 | 11 | 12.68 |
| Halogenated solvents | 3.48 | 70 | 1.04 |
| Non-halogenated | 12.13 | 70 | 3.64 |
| Organic liquids | 3.44 | 2 | 3.37 |
| Pest/herbicides | 0.026 | 55 | 0.012 |
| PCBs | 0.001 | 0 | 0.001 |
| TOTAL LIQUIDS | 33.33 | 38 | 20.74 |
| Sludge & Solids | | | |
| Halogenated sludges | 0.72 | 0 | 0.72 |
| Nonhalogenated | 2.24 | 0 | 2.24 |
| Dye & Paint sludges | 4.24 | 0 | 4.24 |
| Oily sludges | 3.73 | 5 | 3.54 |
| Halogenated solids | 9.78 | 0 | 9.78 |
| Non halogenated | 4.58 | 0 | 4.58 |
| Resins/latex | 4.02 | 65 | 1.41 |
| TOTAL SLUDGES/SOLIDS | 29.31 | 10 | 26.51 |
| Total incinerable waste | 62.64 | 25 | 47.25 |
| Total Hazwaste | 265.60 | 6 | 249.28 |

Table 4: Total incinerable waste generated by category in the US in 1983 and that remaining after recycling/recovery. The total arisings of hazardous waste are also shown. Source: Ref: [43].

b) The growth of hazwaste incineration

Incineration of industrial wastes has been practised for around a quarter of a century, with early dedicated units being based on municipal incinerator technology. Poor performance led to the development and use of rotary kiln technology of which the first units were constructed in Germany. Currently, there are four main types of plant in general use: Liquid injection incinerators, rotary kiln incinerators, fluidised bed incinerators and fixed hearth incinerators. The rotary kiln is by far the most flexible in terms of the spectrum of potential feedstock, and it has become the preferred installation for on-site and merchant applications.

There are at least 12 process contractors offering incineration technology in Europe and there are some 40 new incinerator plants projected for Europe in the near future [44]. It is inferred that much of this extra capacity is required for incinerating highly chlorinated waste no longer permitted for ocean incineration. Highly chlorinated waste must be diluted with non-chlorinated waste to avoid overwhelming the pollution control train in land based systems and while wastes of chlorine content of 70% have

been incinerated, most operators restrict this to 30% and blend the wastes to a heat value of 8000 BTU lb⁻¹ or more [43].

The same trend towards reliance on incineration processes for hazwaste is apparent in the US. Table 5 shows the number of existing and projected incinerators by type for the US taken from Ref [43].

| DESIGN TYPE | UNITS | | % Fitted with air pollution control |
|-------------------|------------|------------|-------------------------------------|
| | Reported | Projected | |
| Rotary Kiln | 42 | 45 | 90 |
| Liquid injection | 95 | 101 | 42 |
| Fume | 25 | 26 | 40 |
| Hearth | 32 | 34 | 38 |
| Fluidised Bed etc | 14 | 15 | - |
| TOTAL | 208 | 221 | 50 |

Table 5: Reported and Projected hazardous waste incinerator plant in the United States by type showing the percentage fitted with emission control equipment. Source Ref: [43] Only 18 are commercial off site incinerators, the rest being located on-site.

The United States tendency towards the use of incineration is possibly a result of pressure on landfill and an enforced duty of care through long term liability for landfill sites. Problems with groundwater contamination and the difficulties which led to the establishment of Superfund are of primary importance. Both in Europe and N. America the data imply considerable commitment to the continued growth of the incineration industry. In the United States [3] the normal time required for permitting new incineration facilities is some three years. This time, and the expense incurred in obtaining a permit can be increased by substantial amounts if there is public opposition to the facility. A similar situation exists in the UK where under EEC legislation an environmental impact study must be produced prior to construction being permitted. Although the local planning authority can turn down the planning application an appeals procedure involving the government Department of the Environment may then be instituted. A public enquiry then ensues to investigate the technical aspects of the application. Usually, participation in these fora requires substantial commitment of resources over a period of time. Moreover, a precedent problem is created if construction is allowed to go ahead on appeal. This is a growing problem generally in Europe and the whole objection and enquiry process is in danger of becoming little more than a method of delay rather than prevention. Involvement in the process may become very expensive. In the long term it is probably desirable to address the national policies underlying the proliferation of incinerator technology rather than become involved in single issues, with the concomitant dilution of resources that this entails.

c) Emissions from hazwaste incineration.

Proponents of hazardous waste incineration refer to it as an appropriate technology or as a proven technology. Certainly the operational principles are well established. Figure 9 (Ref: [1])

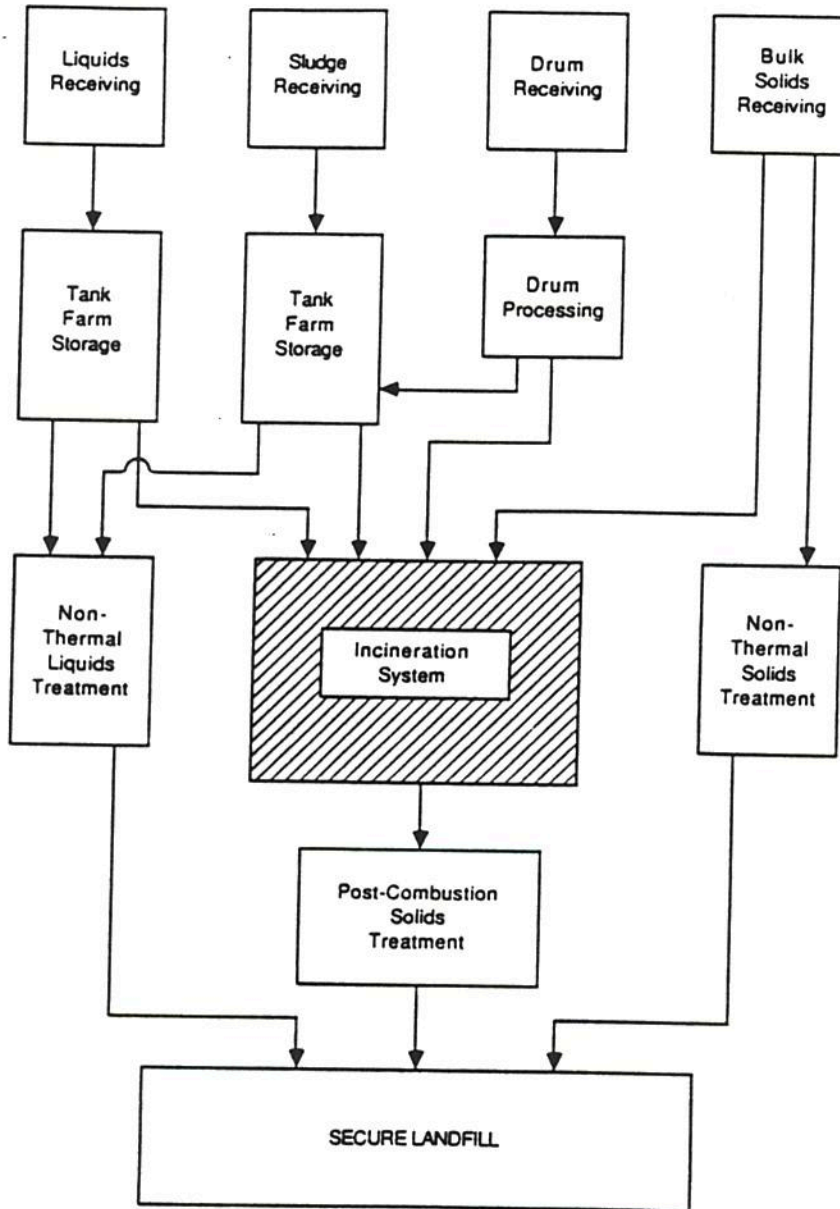


FIGURE 9: Process diagram of hazardous waste incineration facility. The storage operation allows blending of wastes to optimise incinerator operation. It is clear that there is still a requirement for post operation landfill disposal. All aspects of the operation are subject to finite risk. (SOURCE Ref: [1]).

shows the general scheme of operation in a hazardous waste facility. However, in the first case, this is little more than a non-scientific value judgment, in the second the technology is far from proven in the sense that it has not been shown not to have harmful effects. The literature is vague on this point despite doubts about emissions from hazwaste facilities [26]. Hazardous waste incinerators do emit dioxins and dibenzofurans. In this sense they are no different to the municipal incinerators. Residues of this type have been found from the combustion of PCBs and other hazardous waste [46; 47]. Although the data are acknowledged to be scarce it is generally considered [21] that emissions are likely to be comparable to those from a municipal incinerator. This allows no real conclusions to be drawn concerning hazwaste installations since PCDD & PCDF levels recorded in stackgases from municipal plant range over five orders of magnitude at 10,000 to less than 0.1 ng m^{-3} with a PCDD:PCDF ratio ranging from 1 to over 10 [48]. The limited data from Tier 4 of the US National Dioxin Study suggests that the same variation may apply to hazwaste incinerators as judged from ash values [49]. A suite of halogenated aromatic compounds has been identified in the off gases of the SAKAB incinerator in Sweden [50]. This was shown to be related to chlorine input in earlier work [51] and largely due to *de novo* synthesis in the boiler of the plant. Currently, construction of a more efficient filter system is underway at this plant to try and reduce these problems downstream of the offending unit. The SAKAB plant is often held up as an example of good incinerator technology in operation.

There is clearly a need to resolve the inadequacies in the database. In many respects the focus on PCDD/PCDF and primary organic hazardous component (POHC) emission from hazwaste facilities is unfortunate. Much of the data produced by incinerator operators has been directed at demonstrating that no appreciable problem exists with respect to these parameters. This has been successful in at least two cases in the UK [52; 53; 54; 55] despite some convincing preliminary epidemiological evidence of unusual incidence of twinning in humans and animals in the vicinity of one of these plants [56].

There is too a growing awareness that PCDDs and PCDFs arise from a number of different sources, the common element being the combustion of chlorinated compounds. The direct synthesis of these was recently demonstrated [79] by combusting hydrocarbons in a hydrogen chloride atmosphere. Initially incinerator operators promoted the "trace chemistries of fire theory" to explain levels of dioxin in the environment. This theory is falling increasingly into disrepute as archived and historical material is processed leading to the conclusion that current global burdens are a result of industrial chlorine chemistry [57; 58]. Recently, [59] there has been a tendency to try and rank the sources of these compounds. This leads to the conclusion that while incinerators are important point sources, their overall contribution of PCDDs and PCDFs to the environment is exceeded by the contribution from contaminated chlorophenols. In Germany it has been estimated that the contribution from pentachlorophenol is 100 times that of the 41 waste incineration plants in operation there. Congener

profiles of background levels tested in an industrialised region of Germany at the pg m^{-3} level indicated combustion sources as the primary source of the predominantly gas phase atmospheric burden [60]. In the US municipal incinerators have been identified as the major input.

This is not to say that PCDDs and PCDFs are not important, they are. Focussing only on this group of compounds rather than the problems of incineration as a whole may well lead to efforts to eliminate these materials from stack gas emissions and control their formation in ash, however, whilst the great number of other, largely uncharacterised emissions are ignored. Worse, the ubiquity of these materials as environmental contaminants and the absence as yet of definite ecosystem effects is likely to lead to calls to deregulate them as now seems to be the case in Canada. These substances undoubtedly pose a potential toxicological problem on a global scale, since in common with other organochlorines and volatile metals they may be transported over continental distances in the atmosphere [61].

A more holistic approach seems desirable, considering the whole waste cycle from generation to disposal and transport and handling of wastes and residues. The current economic drives towards the use of incinerators need to be explored and the alternatives evaluated. The concept of clean production needs to be promoted. In fact the arguments will be almost the same as those used to promote changes in the volume and type of municipal waste arisings to avoid the need for combustive disposal. Waste minimisation research is attracting increasing levels of central funding as its benefits become clearer [63] although there is some evidence that small businesses may have difficulty complying with the evolving stringent regulation [64].

c) Hazardous waste incineration technology

A rudimentary understanding of the principles and configuration of hazwaste incineration plant is useful in order to understand the principles of performance monitoring currently used. Most plants of interest are likely to be rotary kiln. Figure 10 (Ref: [43]) shows the basic configuration of a rotary kiln system Figure 11 shows a more detailed manufacturers drawing of such a plant with a waste heat boiler and flue gas cleaning section. The waste heat boiler may be omitted and a simple quench system fitted. Some processes such as the Vicarb process [62] incorporate both a boiler and a quench with a downstream acid recovery unit. The rotating kiln is essentially a cylindrical steel shell lined with a refractory, rotating on a slightly inclined horizontal axis at between 1-5rpm. Solid waste is fed by chute, sometimes in drums, to the front of the kiln. The feed access is usually set in a waterwall. Liquid waste or auxiliary fuel is injected through atomising burners to maintain the temperature in the range 900-1300°C. Excess air is supplied to 50-250% The kiln may be of the ashing or slagging type and after a residence time of 1-2 hours the ash/slag is removed for disposal. Figure 12 (Ref: [1]) shows the basic mechanisms involved in the thermal oxidation of solid waste supplemented with liquid fuel.

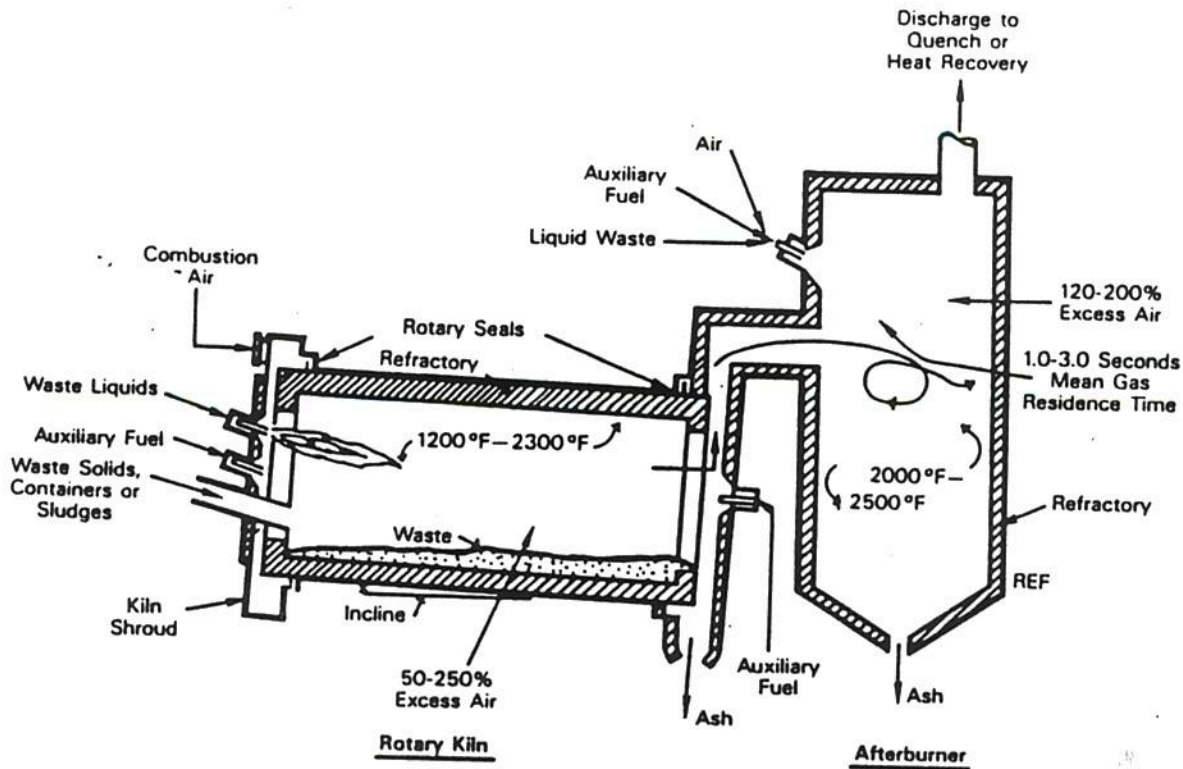


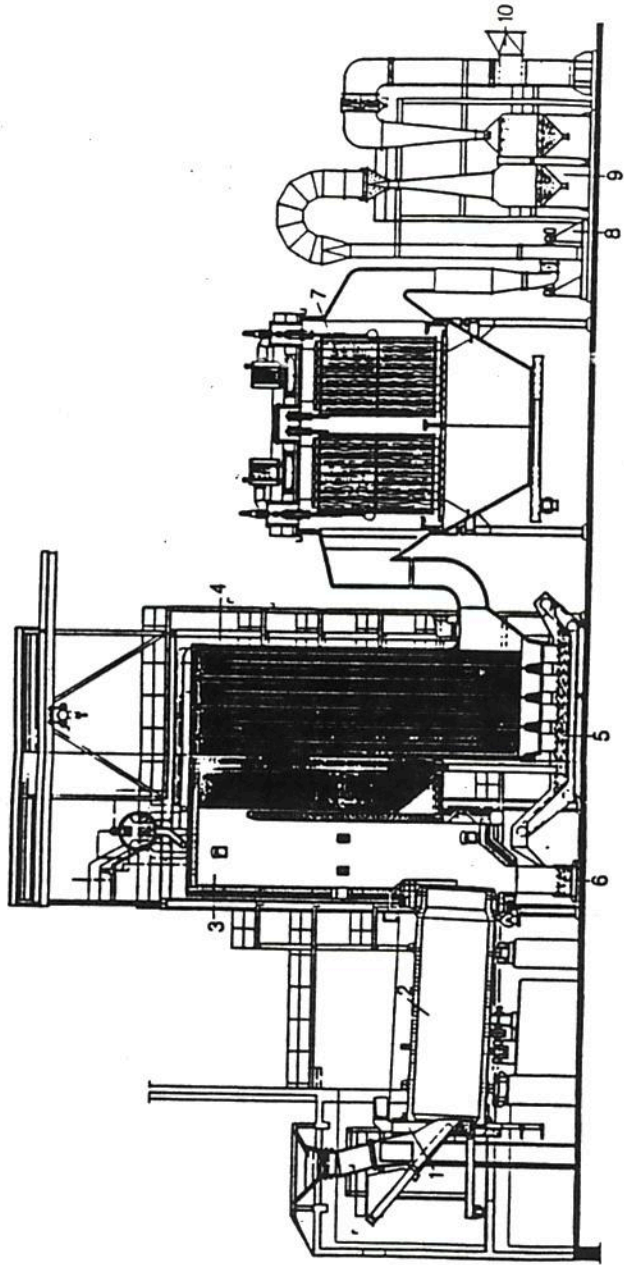
FIGURE 10: Process schematic and temperature profile for a rotary kiln hazwaste incinerator and attached afterburner. The various waste introduction points area shown (SOURCE Ref: [43])

On exit from the kiln the gases which are a mixture of vapours, derivatives of partial combustion and pyrolysis products pass to the afterburner where further fuel is injected to raise the temperature to 1400°C and 120-200% excess air is introduced. Aqueous waste is also introduced into the afterburner. The required temperature profile is maintained by manipulation of the various combustion parameters and the waste streams. Off gases from the secondary burn chamber exit to a quench or heat exchange system.

In controlling the incineration process the solid waste and slurry provide the base thermal load and the high calorific waste or auxiliary streams are varied to control the temperature profile. Theoretical considerations suggest that the minimum capacity of such a plant is in the region of $10,000 \text{ tons per } \gamma^{-1}$.

The most common type of fault reported from all incinerators is corrosion and occlusion of ancillary equipment. This has been reported from several municipal incinerators [35], from a radwaste incinerator [65] a variety of hospital and hazwaste incinerators [66] and a pharmaceutical waste incinerator [67]. The industry acknowledges that major problems with rotary kiln technology [68] include the high capital costs, high zonal mechanical and thermal stresses, uncontrolled air leakage at seals and slag build up. All can affect the adequate performance of the installation.

The crucial function of air emission control is accomplished by



- Feed silos
- Power plant
- Alkali burning chamber
- Waste heat recovery boiler
- Air removal
- Slag removal
- Electrostatic precipitator
- Induced draught fan
- Scrubber (two-stage)
- Stack connection

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FIGURE 11: Manufacturers diagram for a large capacity rotary kiln showing the main components of the plant.

the use of modular scrubbing equipment. It is not unusual for more than one type of system to be fitted. In some cases no control may be present where the waste stream is low ash/low halogen content, although this is becoming less common due to legislative requirements. Table 6 (Ref: [43]) shows distribution of air pollution control devices (APCDs) by type reported from US hazwaste incinerators.

| APCD type | Number | Percent |
|------------------------|--------|---------|
| Quench | 21 | 23.3 |
| Venturi Scrubber | 32 | 35.6 |
| Wet Scrubber | 7 | 7.8 |
| Wet ESP | 5 | 5.5 |
| Ionising wet scrubber | 5 | 5.5 |
| Not specified | 12 | 13.3 |
| Packed Tower | 18 | 20.0 |
| Spray Tower | 2 | 2.2 |
| Tray Tower | 1 | 1.1 |
| Other | 2 | 2.2 |
| None/unknown | 31 | 34.4 |
| Total systems surveyed | 90 | |

Table 6: APCDs reported by type from US hazardous waste incinerators. Source Ref: [43]

The most usual APCD train employed is a combination of a quench which cools and conditions the off gases with a high energy venturi scrubber to remove particulates. A packed tower adsorber removes acid gases and a final demist stage produces an invisible plume. Other systems in use include baghouses and electrostatic precipitators. None achieves full particulate removal and the relative efficiency of baghouses and ESPs is still the subject of considerable debate. Without doubt ESPs have worse penetration and fractional collection efficiency than baghouses. Venturi systems find little application in MSW incinerators due to the sizable pressure drops in the off gases required by their operation.

d) Process performance monitoring

This is carried out for three distinct reasons:

- 1) verification of performance standard (trial burns)
- 2) routine continuous monitoring
- 3) research and development

Figure 13 (Ref: [43]) shows the type of monitoring which may take place at each stage of the incineration train with a view to maintaining perceived optimum conditions. The major focus of

analysis in verification procedures is on POHCs in the stack gases. Levels of HCl and particulate emissions are also included.

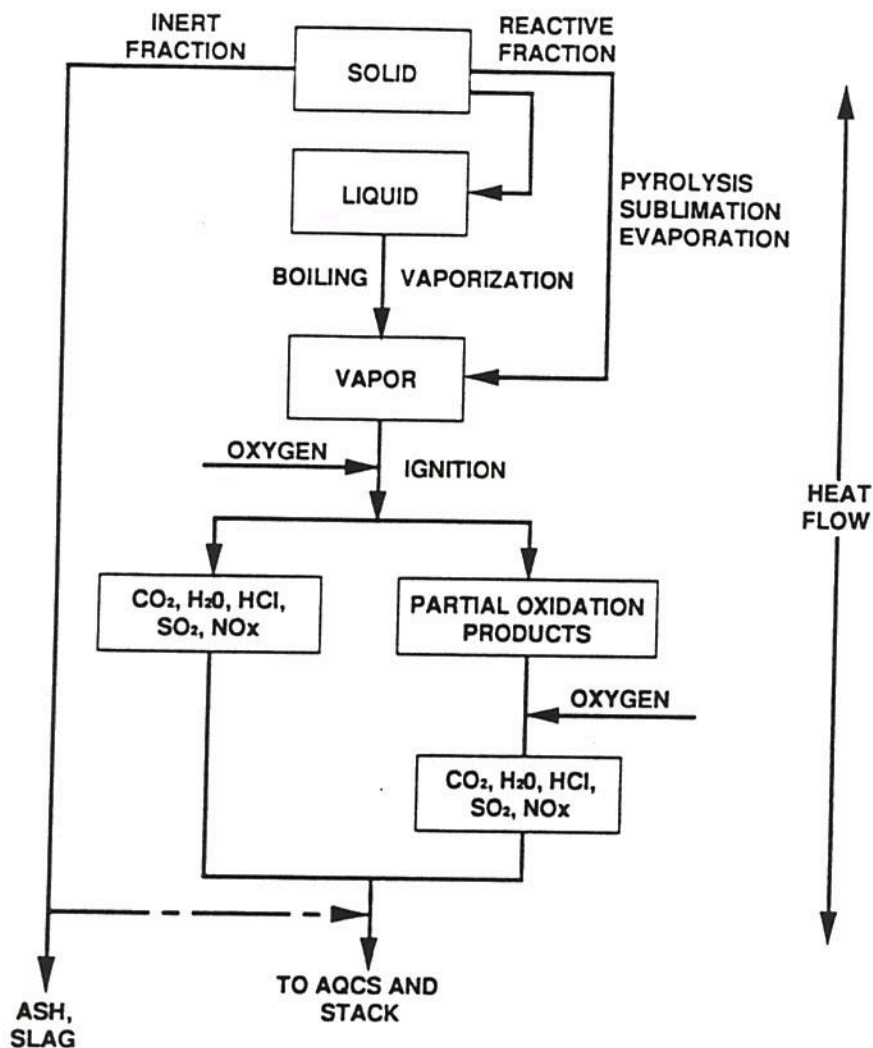


FIGURE 12: The broad mechanisms of combustion chemistry and process pathways for a hazardous waste incinerator. (SOURCE Ref [1]).

The use of trial burns and the methodology employed in monitoring them has been the subject of considerable debate and criticism [69].

A major criticism of the trial burn procedure is that it cannot fully account for the variety likely to be experienced in feedstock. Much of the technical process for trial burns derives from US practice defined under the Resource Conservation and Recovery Act (1976). This is becoming accepted generally as the methodology underpinning permitting procedures. Given that rotary kilns can, in theory, handle a wide variety of wastes it is unlikely that the conditions applicable to, for example, pesticides in one incinerator [70] will apply to general waste streams in another [71]. Indeed this latter authority describes problems in achieving the required destruction and removal

efficiency for just three designated POHCs in a waste stream containing between 0.8 and 31.23% chlorine by weight. At best this could be described as somewhat hit and miss with open reference being made to the "laws of nature" and the "Murphy factor" becoming involved, with the express implication that these normally play no part in incineration processes. These problems experienced under test burn conditions and the somewhat flippant attitude evident on the part of the investigators do not bode well for adequate evaluation of normal incinerator operation. The current methodology must be seen as establishing an "at best" overview under continuous operation. No account is made of periods

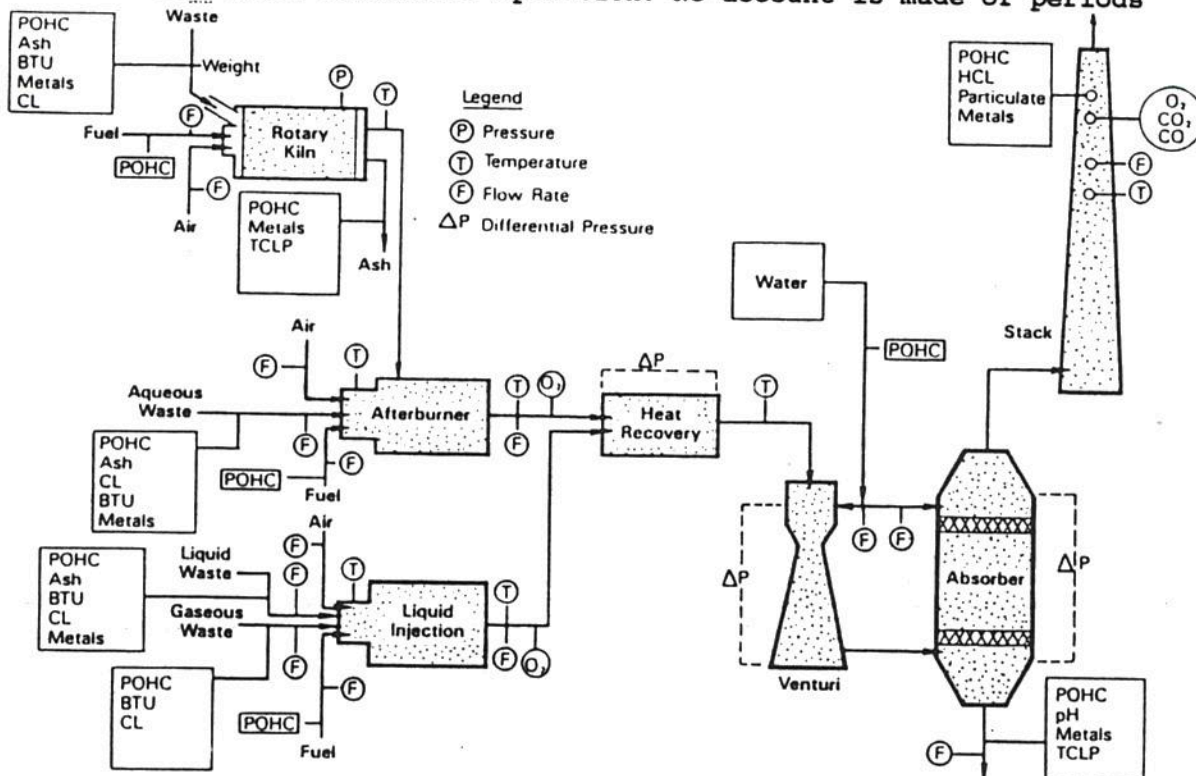


FIGURE 13: Possible sampling points for performance assessment of a hazardous waste incinerator showing types of measurements likely to be made at each point. The values obtained cannot generally be used as directly proportional indices. (SOURCE Ref: [43]).

of unusual operation or response to changes in feedstock. Moreover, [43; 72] while the sampling methodology is well established, there are many potential traps for the unwary or inexperienced. The technology is highly sophisticated and specific application driven determined. Professional judgement is a strong element in the decision about which sample train is likely to be the most suitable for a given purpose. This allows room for mistakes since it introduces a large element of subjectivity. Doubts about the accuracy and reliability of these methods which underpin the permitting procedure, must confer doubts upon the reliability of incinerator performance and their environmental safety in general.

A further cause for concern is that with complex wastes, materials justifying POHC designation may not be designated for the waste stream concerned, leading to uncontrolled emissions. This is part

of a wider problem concerning emissions which is not addressed by current trial burn methodology with its emphasis on POHC destruction and removal efficiency.

Emissions of organic materials from hazardous waste incinerators are known to include products of incomplete combustion (PICs) these may be fragments of POHCs or other organic chemicals in the feedstock. New compounds can be created downstream of the combustion zone as a result of part combustion followed by chemical recombination. In some cases impurities entrained in scrubber water or the air feed from ambient sources may be emitted and identified as PICs. The quantitative component of these can be measured in mg Nm^{-3} of stack gas. The German TA-Luft standards for incinerators, accepted worldwide as an achievable operating standard allow for the emission of 20 mg Nm^{-3} of organically bound carbon in the stack gases.

The compounds comprising this element remain largely unidentified and may be expected to vary according to the waste stream supplied to the kiln. Hence it is not possible to ascribe, with any certainty, environmental significance to this group. In any case, it is widely acknowledged that consensus on a definition of PICs has not been reached [43; 73]. This problem may be more serious than operators would like to believe and in any case is eclipsed by the current preoccupation with PCDDs and PCDFs. EPA studies (see: [43]) of hazardous waste facilities operating with waste and with auxiliary fuel only, identified 55 of the RCRA 400 POHC components in stack gases which nonetheless accounted for only a small proportion of the TOC component. The same lack of characterisation, then applies to TOC in hazwaste incinerator emissions as in MSW incinerators (see: [34]). This is of potential toxicological significance: if it is not possible to identify compounds then it is not possible to evaluate them toxicologically.

Given the analytical difficulties in analysing for PICs on a routine basis, there have been a number of attempts to establish usable surrogate measures. These have been largely unsuccessful. In the first place, the continuous methods used are simply not sensitive enough to detect and quantify low levels of compounds. Matrix and analytical interferences may be substantial. Other measures of stackgas components such as Carbon monoxide (CO) and total organic Carbon (TOC) may have some utility as parameters of operation [73]. Both are limited as indices of actual performance and there are shortcomings in measurement, normalisation and averaging of emissions of these compounds. Correlations of CO and TOC levels with PIC emissions are not quantitative. Moreover the PICs may require a higher temperature for destruction than the parent compounds. It is now accepted [74] that PIC formation is an inevitable function of POHC incineration and that highly chlorinated waste may form stable higher molecular weight chlorinated compounds with a high degree of reactive efficiency. Questions must arise too concerning unscheduled shutdowns. These are acknowledged to arise from problems as diverse as poor atomisation of waste, explosive reactions due to free liquid in the solids feed, and waste by-passing the flame [75]. This industry viewpoint considers incinerator operation to be "more an art than an exact science" dependent largely for success upon training and experi-

ence of personnel. There is obviously then great scope for operator error.

The PIC problem may be seen as fundamentally undermining the credibility of hazardous waste incineration technology as a proven and benign technology. It is unlikely to ever be satisfactorily resolved within a general toxicological frame of reference. Neither is there much hope that designs of incinerators will evolve to eliminate the emission problem.

The design philosophy of manufacturers tends to be highly conservative [76]. It is based on "rules of thumb" developed over a number of years of design and manufacture. The afterburner characteristics are regarded as particularly important. Much research goes into the operation of this stage but to date it appears that no predictive design model has emerged. Destruction and removal efficiency is the key variable considered. It is noted, further, that POHC DRE at any specific area in the kiln cannot be monitored from single point measurements and that results achieved for one plant cannot be generally applied to others. These authorities also suggest that exhaustive evaluation of the full behaviour of POHCs in such plant is not feasible. Laboratory studies [77] have confirmed the intuitively attractive direct relationship between desorption of POHC from solid waste and temperature. Evolution of PICs may occur if desorption of hydrocarbons leads to exceedence of the available oxygen present. This may take place as a small scale runaway reaction.

Further studies [78; 80] have confirmed the difficulties in elucidating kiln dynamics even under the relatively simple set of circumstances whereby only a single liquid POHC is processed. Solid processing is likely to lead to even greater complexity of internal behaviour of these plants and concomitant difficulty in deriving a workable design and general operation model. There is too, a great deal of uncertainty concerning the validity of extrapolating laboratory POHC combustion experiments to full scale incineration [81].

There is then, a lack of understanding of the way in which PICs are evolved in hazwaste incineration processes. Moreover, there is no reliable surrogate measurement which can be made. The processes taking place inside the kiln are not understood and as a consequence no predictive models can be derived on a general basis. It follows that incineration is not a proven technology.

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