A CHEMICAL INPUT-OUTPUT ANALYSIS OF MUNICIPAL SOLID WASTE INCINERATION

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ABSTRACT

This article comprises a detailed tabulated review from a chemical stand-point, of incineration and pyrolysis processes for disposal of municipal waste. Inputs are given on a descriptive basis by place and time and on a chemical basis. Products are detailed both overall, and on chemical, flyash, and residual ash bases, and a brief overview and trend description of the input-output data is included. A summary of how the output masses and concentrations relate to various air quality standards, and the degree of effectiveness of emission control devices which may be used to avoid exceeding these is also discussed.

Introduction

With per capita urban waste generation now reaching levels of 1.5 to over 5 pounds per day (Table 1) for the Western World, and decreased land availability for either dump or sanitary landfill disposal measures now used for more than 80 per cent of all municipal waste disposal, strong incentives for less land-intensive disposal practices have had to be developed [1]. Other factors associated with land disposal of refuse such as difficulties with pests, long continued gas evolution, percolation of a highly contaminated leachate and more or less unpredictable settling rates make such sites suitable only for highly specific end uses for some time after covering [2—4]. Salvage operations, and composting still dispose of less than 5 per cent of all North American solid waste [1], perhaps largely because of the requirement of highly

Table 1. Composition of Household Solid Wastes by Weight

	Canada		France	Sweden (4)	U.K. (4)	U.S. Average [1]
Component	B.C. Lower Mainland [5] %	Metro Toronto [6] %	Paris [7] %	%	%	%
Dust and Cinders	—	—	24.3	—	30-40	1.7
Paper	34.6	39.5	29.6	55	25-30	35.6
Organic Refuse	25.0	32.4	24.0	12	10-15	23.7
Wood	14.9	1.1	—	—	—	2.5
Metals	8.2	5.9	1.2	6	5-8	8.2
Glass	7.2	8.0	3.9	15	5-8	8.3
Rock and Rubble	3.6	7.9[a]	—	—	—	15.5[a]
Textiles	2.5	1.5	—	—	—	1.9
Plastics	1.7	2.6	—	—	—	1.1
Tires	0.5	1.1[b]	—	—	—	1.5[b]
Miscellaneous	—	—	14.0	12	5-10	—
Pounds per capita per day	1.9	5.3	1.8-2.2	1.3	1.5-1.8	4.4-5.6

[a] Classified as "yard waste."
[b] Includes leather in category.

capital or labour intensive sorting required without householder involvement [8—10]. Because of these multiple interactions, and also because much of the increased volume of per capita waste generated is of combustible packaging material, incineration in one form or another is being increasingly accepted for volume reduction to about 1.5 per cent of that collected, frequently with incorporated power recovery and partial salvage operations [11]. This trend has led to the rapid generation of a wealth of recent published data relating to the chemical processes involved in the thermal destruction of municipal waste and makes it highly appropriate at this time to consider an overview of the processes involved on the basis of a chemical input-output analysis.

Municipal Waste Composition

This review deals with material classified by the Incinerator Institute of America as "Type 2 Waste," described as *Refuse* and consisting in their terms of a mixture of roughly 50 per cent *Rubbish* (combustible waste: paper, cartons, rags, wood scraps, etc.) and 50 per cent *Garbage* (kitchen wastes: primarily animal and vegetable matter) [12]. This definition is a typical descriptive basis for the waste collected from residential sources. Reviews of various aspects of the material discussed here have appeared recently [13—16].

While the component distribution of municipal waste varies widely from even one locality to another and certainly from country to country, figures can be given for probable average or typical compositions. Table 1 summarizes the data available for the British Columbia lower mainland, and the Metropolitan Toronto areas, as representative of relatively young and older urban centres in Canada. Much greater wood waste, and much lower per capita waste generation appear to be the significant locality differences. Data for France, Sweden, and the United Kingdom are similar in volume and composition to that given for the B.C. lower mainland except for the notably higher ash content and lower paper content shown by the U.K. and France, and a much lower metals content for France. Figures for the United States parallel fairly closely the compositions and total volume found for Metropolitan Toronto, and represent a typical input description for much of the American-based incineration data reported here.

Refuse composition not only varies with place of collection but also with time as indicated by the long and short term historical data of Table 2. Here, for instance, is clearly shown the long term trend in the U.K. towards lower cinder content and higher paper content, and in consequence, much lower bulk densities. These trends, despite the small rise shown in the metal and glass components, combine to make incineration a more feasible proposition there both from the fuel value gained and volume

Table 2. Variations in Refuse Composition, Long and Short Term[a]

Component	U.K. Refuse Composition [16]			U.S. Refuse Composition, 1966 [17]			
	1934 %	1964 %	1966 %	Feb 21 %	April 5 %	June 1 %	June 23 %
Dust and Cinders	74.8	45.8	28.5	—	—	—	—
Paper	7.7	31.2	32.9	53	44	33	40
Organic Refuse	6.1	9.0	17.5	17.3[b]	25[b]	43[b]	39[b]
Metal	3.3	4.8	7.1	11	7	8	8
Glass	3.2	7.2	8.1	—	—	—	—
Glass, Building Rubble	—	—	—	12	7	10	9
Textiles	1.5	1.1	2.3	2	4	3	3
Plastics, Rubber	—	—	—	4	9	3	3
Wood Waste	—	—	—	1	3	1	7
Miscellaneous	3.2	0.9	3.7	—	—	—	—
Average density cwt/yd^3	5.76	3.73	2.63				

[a] Adapted from data in references given.
[b] In U.S. data, includes categories "garbage," and "yard waste" (grass, leaves, dirt).

reduction. The variation during a year for the example in the U.S., shows fluctuations largely brought about by a much larger garden waste input in summer, which not only raised the proportion of the organic refuse but although not tabulated, also the total refuse volume. Superimposed on this major influence is the variation in moisture content, which affected the weights of some of the components more than others during prolonged wet weather.

From a chemical standpoint, input-output analysis of incinerator operation, theoretical firing air calculations, and flue gas volume relationships, all can be more readily considered on the basis of the elemental composition of the refuse (Table 3). Two particular sets

Table 3. Approximate Gross Elemental Composition of Refuse

| Component | One Study [19] | | Altoona, Pa. [20] | Concentration Ranges | |
	As Fired %	Dry (calculated) %	Dry[a] %	As Fired [18] %	Dry [21] %
Non-metals:					
Carbon	27.6	34.5	34.7	15-30	34-48
Hydrogen	3.8	4.8	7.4	3-8	4.5-6.0
Oxygen	24.5	30.6	47.0	15-22	22-33
Nitrogen	0.3	0.4	0.7	0.2-1	0.7-1.2
Sulfur	0.1	0.1	0.2	0-0.1	0.2-0.4
Ash	23.7	29.6	10.0	7-26	12-38
Moisture	20.0	—	—	20-43	—
	100.0	100.0	100.0		
Fuel values (Btu/lb)					
as fired	5070			3000-6000	4800-5600
Dry				6500-8900	5600-8500

Selected Metals [22] : Lead-25.7-61.8 μg/g; Mercury-1.39-3.46 μg/g; Cadmium-1.5-7.9 μg/g; Zinc-96.2-166.1 μg/g.

[a] Original moisture content was 30.6%.

of analyses are given, the first recalculated on a dry basis for ease of comparison with the second, together with ranges that have been quoted both for an "as fired" (= as collected) condition and on a dry basis. Approximate fuel values are included as an indication of the levels of energy recovery possible in an integrated operation. Analyses for a few trace constituents in refuse are included as an aid to determining their disposition during and after the incineration process.

Incineration of Refuse

The efficiency of any particular incineration operation is related to uniformity of size of combustible material, number of combustion chambers, combustion temperature and time, and to the amount of air available. A variety of incinerator designs have been developed in attempts to optimize performance based on these factors [23], but for both efficiency of combustion and decreased emission levels a multiple chamber incinerator fitted with moving grates to reduce combustion gas channeling in the waste is probably optimum [24]. Material balance data for the gaseous and volatile products and solid-residues of incineration is presented in Table 4 for a conventional incinerator. Because of the multiple simultaneous analyses and mass or volume measurements required very few combustion product inventories were complete, or in the same units, but comparisons between different inventories can be made in a qualitative way on common combustion fuels and flue gases from a consideration of the respective chemical compositions.

Varied incinerator configurations, particular emission control measures used, if present, and relatively minor fluctuations in the refuse composition (Tables 5 and 6) charged all can effect changes

Table 4. Major Products of Incineration of One Ton Mixed Refuse

Stack Gases	Average Incinerator Without Reclamation [6]	Using 200% Excess Air[a] [25]		
	Pounds Per Ton	Pounds Per Ton	Volume, ft^3	Dry Volume
Carbon Dioxide	—	1,738	14,856	6.05%
Sulfur Dioxide	6.8	1	6	22 ppm
Carbon Monoxide	35.0	10	135	0.06%
Oxygen	—	2,980	35,209	14.32%
Nitrogen Oxides	3.0	3	23	93 ppm
Nitrogen		14,557	195,690	79.57%
Total Dry Gas		19,289	245,919	100.00%
Water Vapor		1,400	29,424	
Total		20,689	275,343	
Solids, Dry Basis				
Grate Residue		471		
Collected Fly Ash	22.8	17		
Emitted Fly Ash		3		
Grand Total		21,180		
Minor Emissions				
Hydrocarbons	2.7			
Polynuclear hydrocarbons	0.008			
Hydrogen Chloride	0.023			
Metals (as lead)	0.023			

[a] Dry air requirement 18,930 lb; moisture contribution from this, 250 lb.

Table 5. Minor Inorganic Components of Incinerator Flue Gas

Component	Incinerator feed origin	Quantities or concentrations	Reference citing
Carbon Monoxide	Refuse, Plastics	35-400 ppm	26
	Refuse	Trace, high 0.9%	17
		< 200 ppm	27
Carbon Dioxide	Refuse	6-7%, highs 11.5%	17
Ammonia	Refuse	0.44-10 ppm	26, 28
		0.3 lb/ton burned	29
		None	17
Nitrogen Oxides	Refuse, Plastics	0.15-1.5 ppm, 2.7 lb/ton burned	26
		2.1 lb/ton burned	11, 29
		55 mg NO_x/m^3	30
	Refuse	100 ppm (average)	17
	Refuse	2.5 lb/ton burned	31
	Refuse	150-250 mg "N_2O_3"/m^3 STP	32
Sulfur Dioxide	Refuse	0.25-1.2 ppm	26
		1.9 lb/ton burned	11
		80-90 ppm, high 192 ppm	17
	Refuse	740-1060 mg SO_2/m^3 STP	32
Sulfur Trioxide	Refuse	8% of SO_x emitted	33
Hydrogen Chloride	Refuse	330-1030 ppm	34
		10 ppm	35
	Refuse	455 ppm, corr. to 12% CO_2	36
	PVC alone	11 ppm, 6 ppm after scrubber	37
	Pure PVC	1180 lb/ton burned (theoret.)	38
	Refuse	300-600 mg/m^3 STP	32
	Refuse, 2% PVC	800 ppm	39
	Refuse	11-100 μg/m^3	40
Hydrogen Fluoride	Refuse	Not specified in abstract	27
		0.5 ppm	35
Hydrogen Sulfide	Refuse	No level specified	28
		None	17
Hydrogen Cyanide	Refuse	5.6-9.5 mg/m^3, incomplete combustion	41
		0.2-1.2 mg/m^3, complete combustion	41
		Trace, high of 3 ppm	17
Chlorine	Refuse	Not specified in abstract	42
	Refuse	< 0.2 ppm	36
	Refuse	Trace, high 2.5 ppm	17
	PVC alone	Laboratory, 60 ppm	37
		Pilot Plant, < measurable	37
Mercury	Refuse	100-5400 lb/year/incinerator	43
		None	17
Lead	Refuse	Contrib. approx. 1/40 of that of autos, U.S.	22
Fluorine	Plastics combustion	Suggested as possible products	29
Phosgene		Phosgene < 0.5 ppm	36
		Phosgene, chlorine, not found	27
		Phosgene, not found	17

Table 6. Minor Organic Components of Municipal Incinerator Flue Gas

Component	Incinerator feed origin	Quantities	Reference citing
Alcohols	Refuse	Not detectable	17
Formic Acid	Refuse	25-133 ppm	26
Organic Acids, as			
Acetic Acid	Refuse	0.6 lb/ton burned	29
	Refuse	100 ppm, for 12% CO_2	36
	Refuse	25-133 ppm, for 12% CO_2	44
Methyl Acetate	Refuse	5-137 ppm	26
Formaldehyde	Refuse, Plastics	1.1 lb/ton burned	29
	Refuse	0-9.9 $\times$ 10^{-4} lb/1000 lb. flue gas	45
	Refuse	1.4 $\times$ 10^{-3} lb/ton burned	31
Acetaldehyde	Refuse, Plastics	17-39 $\times$ 10^{-5} lb/ton burned	26
Aldehydes and			
Ketones	Refuse	5.9 ppm, for 12% CO_2	36
		10.8-82 ppm, for 12% CO_2	44
Hydrocarbons	Refuse, Plastics, Rubber	0.8-1.4 lb/ton burned	29
	Refuse	< 100 mg/N m^3	27
	Refuse	< 3 $\times$ 10^{-3} lb/1000 lb flue gas	45
	Refuse	< 1 lb/ton burned (as CH_4)	31
Polychlorinated			
Biphenyls	Refuse	0.30 μg per N m^3	43
		5.50 g/day from 80 tons refuse	29
Polynuclear			
Hydrocarbons:			31
Benzo(a)pyrene	Refuse	16 μg/kg particulate	
Pyrene	Refuse	1900 μg/kg particulate	
		31.3 μg/kg ash	
Benzo(e)pyrene	Refuse	80 μg/kg particulate	
Coronene	Refuse	60 μg/kg particulate	
Fluoranthene	Refuse	2200 μg/kg particulate	
		47.5 μg/kg ash	
Benz(a)anthracene	Refuse	90 μg/kg particulate	
Phenols	Refuse	0.08-1.2 ppm, for 12% CO_2	44

in the minor gaseous components of incinerator flue gas. This is apparent from Tables 5 and 6, which summarize these data. Much of the variation in the data are real chemical differences, the consequence of factors alluded to above, but some may also be put down to difficult analytical matrix problems for some of the constituents. Details of some of the methods used have been quoted [34]. However, by using these in conjunction with the overall mass balance picture of Table 4 it is still possible to usefully relate many of these small component discharges to the overall flue gases emitted.

Measures which can be taken to decrease many of the inorganic emissions have been demonstrated. Significant concentrations of

carbon monoxide, ammonia and hydrogen cyanide may be generated from reducing conditions or insufficiently high temperatures during incineration. Good mixing with somewhat more than the stoichiometric air requirement, plus combustion temperatures of around 850-1500°C preferably in conjunction with an after burner (second chamber), have been found adequate to control all three [32, 38]. Unfortunately, the same conditions tend to raise the emission levels of nitrogen oxides [31, 45] although decreasing the extent of excess air provided, and placing most of this *under* the fire helps significantly [45]. Sulfur dioxide emission is seldom a problem in incineration flue gases because the sulfur content of the feed, averaging 0.1 per cent, is much lower for example than even "low sulfur" coal containing from 0.7-1 per cent S. Sulfur trioxide forms much more slowly than the dioxide, hence levels discharged are lower still. The chlorine entering hydrogen chloride or chlorine discharges arises from the 0.04-0.16 per cent chlorine content of paper which is completely expelled on burning [32], and from sodium chloride, about 80 per cent of which is volatilized by reactions with metal ions and water (42) ($M^+ + Cl^- + H_2O \rightarrow$ $MOH + HCl$), and the rest remains in the ash [34]. Volatile metal constituents, such as mercury, in the refuse will be vaporized and discharged in the flue gases on incineration, and the emissions of metals such as lead are probably largely lost as particulate or adsorbed on particulates (see Table 9). The minor organic components detailed in Table 6 all arise under inadequate combustion conditions such as outlined for ammonia, and the same solutions apply.

The particulate emissions of any combustion source are defined by a knowledge of the mass emission rates, the particulate concentrations, and the particle size distribution. These are summarized in Tables 3 and 7, with concentrations quoted in both grains per cubic foot, and grams per cubic meter for ease of comparison with objectives and standards. While the large particle sizes tend to be far more readily noticeable on discharge and are relatively easily controlled, a significant fraction of the particulate, on a number or a mass basis, is below 5 micrometers (μm) in average diameter. It is this fraction, and particularly below about 2 μm, that is the most difficult to measure and control [46-48] and is hazardous for human exposure because natural protective measures are inadequate to prevent deep penetration on inhalation and retention in the alveoli [49].

For reference to any effect of particulate or agglomerated aerosols on inhalation, or fallout on truck farm or pasture land,

Table 7. Particle Size Range of Fly Ash Emitted From
Incinerators by Cumulative Weight

Particle size μm (microns)	Incinerator guideline [50] %	Lifford Works Birmingham[a] [17] %	Typical incinerator New York City [11] %	Averaged U.S. [51] %
< 2	13.5			
< 4	16.0			
< 5		23.0	12.0	
< 6	19.0			
< 8	21.0			
< 10	23.0	63.0	17.8	30.0
< 15	25.0		39.0	
< 20	27.5	81.0	42.4	35.0
< 30	30.0	88.0	44.3	38.0
< 40		90.0	56.8	39.5
< 60			70.0	47.0
< 90		85.6	87.7	55.0
< 120			94.2	61.0
< 150		93.94		66.0
> 120			5.8	39.0
For average concentration:				
grains/ft^3, NTP		0.386		1.61
grams/m^3, NTP		0.883		3.67

[a] Below 60 micrometers on a particle *count* basis.

typical chemical compositions of fly ash are given in Table 8.
Certainly if the mass emission rates were very large, the reported
concentrations of elements such as lead, mercury, and cadmium are
sufficient to be cause for concern. Elements which are not evenly
distributed by mass among the different particle sizes will effec-
tively be fractionated by any emission control measures, which in
general are characterized by poorer efficiencies for the smaller
particle sizes. While some compilations of elemental composition
versus a rough particle size breakdown into +200 and – 200 mesh
after rodmilling [52], or separation according to collected and
emitted flyash fractions [33], failed to show any clearly defined
tendency of this kind, at least cadmium, mercury and zinc have
been shown to strongly favour flyash adsorption [22] and, for
zinc at least, the – 325 mesh fraction of this [21].

Emission Control Requirements and Measures

The concentrations and mass emission rates of most of the
common polluting gases for small installations using emission
controls plus normal stack requirements, are low enough under

Table 8. Elemental Composition of Incinerator Fly Ash

Component	Arlington, Va. [53]	Jens-Rehm Study [54] %	Kaiser Study[a] [33] %	Johnson-Fluharty [22]
Organic Carbon	11.62%			
Silicon	18.64%	5+	36.3	
Aluminum	10.79%	1-10	25.7	
Iron	2.13%	0.5-5.0	7.1	
Sulfur, as SO_4^{2-}	Trace		8.0	
Calcium	4.70%	1.0+	8.8	
Magnesium	0.98%	1-10	2.8	
Titanium	2.24%	0.5-5.0	0.9	
Nickel	Trace	1-10		
Sodium	Trace	1-10	10.4	
Zinc	Trace	1-10		3872-4699 ppm
Barium	Trace	0.1-1.0		
Chromium	Trace	0.1-1.0		
Copper	Trace	0.1-1.0		
Manganese	Trace	0.1-1.0		
Tin	Trace	0.05-0.5		
Boron		0.01-0.1		
Lead	Trace	0.01-0.1		34.8-39.0 ppm
Beryllium		0.001-0.01		
Silver	Trace	0.001-0.01		
Vanadium		0.001-0.01		
Potassium	Trace			
Gallium	Trace			
Mercury	Trace			7.65 ppm
Molybdenum	Trace			
Tantalum	Trace			
Cadmium				9.5-12.7 ppm
Ignition loss	14.45%			
apparent specific gravity 2.58				

[a] Compositions quoted as the elemental oxides, not as the element.

favourable atmospheric conditions (a positive atmospheric tempera-
ture lapse rate and/or moderate winds) to not be a great cause for
concern. The very low sulfur content of refuse, for example,
generates sulfur dioxide concentrations in the flue gas easily dealt
with by standard stack engineering. However, in large metropolitan
areas where many point sources may contribute to the ambient
atmospheric pollutant loads, in areas subject to frequent stable
meteorological highs, or for very large installations, more stringent
emission controls may be required to achieve desired goals well
within local ambient air standards. For example, an inventory in
1967 showed that 26 per cent of the total hydrocarbon emissions
in that year for the State of Michigan arose from refuse burning
[55]. Table 9 summarizes the emission range data already detailed
and relates these to olfactory thresholds, Canadian and U.S.

Table 9. Incinerator Emissions of Polluting Gases Related to Ambient Air Standards, Olfactory Thresholds and Industrial Hygiene Requirements

Gas	Calculated flue gas concentration[a] range	Olfactory threshold [49, 57]	Canadian National Air Quality Objectives [56] Max. Acceptable		U.S. Federal Primary Ambient Air Standard [49]		Industrial hygiene requirements [57]
			Conc.	Averaging Time	Conc.	Averaging Time	
Sulfur Dioxide	48-330 ppm	0.5 ppm	0.02; 0.11 ppm	annual; 24h	0.03 ppm; 0.1	annual; 24h	5 ppm
Nitrogen Oxides	0.15-145 ppm	5	0.015[c]; 0.025[c] ppm	annual; 24	0.05 (as NO_2)	1h	50-100 (0.5h); 5 ppm (as NO_2)
Hydrogen Fluoride	0.5 ppm	50 ppm	—	—	—	—	3 ppm
Hydrogen Chloride	10-1030 ppm	1	—	—	—	—	5 ppm
Hydrogen Sulfide	—	0.5 ppb	—	—	0.03[b]	1h	20 ppm
Hydrocarbons	< 100 mg/Nm^3	100 ppm (benzene)	0.24 ppm	3	0.24 total	3h	500 ppm, aliphatic; 25 ppm, aromatic (as benzene)
Chlorine	<0.2	0.3 ppm	—	—	—	—	1 ppm
Particulates	0.88-3.7 g/m^3	—	70 $\mu g/m^3$; 120 $\mu g/m^3$	annual; 24	75 $\mu g/m^3$; 260 $\mu g/m^3$	annual; 24h	—
Formic Acid	25-133	—	—	—	—	—	5-10 ppm
Acetic Acid	<100	1.0	—	—	—	—	10 ppm
Formaldehyde	44	1.0	—	—	—	—	5 ppm
Ammonia	0.44-16	47	—	—	—	—	100 ppm
Carbon Monoxide	35-9000	None	13 ppm; 30 ppm	8; 1	9 ppm; 35 ppm	8h; 1h	100 ppm

[a] Taken from data of Tables 4-6, concentrations calculated by volume where not directly quoted.
[b] No U.S. Federal standard. California standard quoted.
[c] As total "photochemical oxidants."

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ambient air quality objectives, and, for purposes of operational hazards, the currently accepted industrial hygiene requirements.

The North American ambient air quality objectives have been set at least an order of magnitude lower than the olfactory thresholds experienced by most people, as is desirable from purely aesthetic considerations. The only exception, hydrogen sulfide, may be detected by the human nose at levels well below the currently accepted ambient air standards, evidence that at present acute and chronic toxicity considerations have taken precedence over aesthetic ones. Canadian and U.S. requirements agree with one another quite closely in most respects except for permissible particulate emissions, U.S. standards for a twenty-four-hour averaging time being currently half as stringent. While only hydrogen sulfide has an olfactory threshold in most people to be low enough to detect levels below ambient air standards, all except hydrogen fluoride and carbon monoxide provide reasonable initial warnings by smell of levels below the industrial hygiene requirement for an eight hour per day exposure. For some of these gases though, such as hydrogen sulfide and ammonia, the warning is only initial since desensitization of the sense of smell occurs more or less rapidly.

It is evident from Table 9 that flue gas concentrations are at least occasionally sufficiently greater than ambient air standards require, to as a minimum require careful consideration of stack height and location to avoid incinerator contributions to repeated infractions in dense urban areas. From the aesthetic point of view too, if it is realized that without emission controls fly ash particulate loss may amount to 0.4 per cent of the weight fired [17], or as a rough rule of thumb 8 per cent of the total residue, it becomes apparent that an invisible plume (not more than 0.05 grains/ft^3; 0.14 grams/m^3 is not merely a desirable visual objective [48]. Table 10 outlines some of the control capabilities of various types of collectors.

The particulate collection efficiency of dry collectors is relatively poor for the low cost settling chamber, which in effect may comprise no more than an enlarged section of the flue, to extremely efficient for the more complex and costly cyclones, bag filters, and electrostatic precipitators. However, none of the dry filters are able to achieve any better than a small amount of adsorptive removal of the gaseous emissions. Some improvement may be achieved by the simple expedients of adding a water spray to a cyclone or cloth filter, with some further improvement particularly for SO$_2$ which is only poorly collected in water, by

Table 10. Demonstrated Efficiencies of Various Types of Collectors

Collector Type	Mass Removal Efficiency [23] %	Particulates [46]	
		Mass Removal Efficiency %	Minimum Particle Size μm
Settling Chamber	34, 35	—	40
Wetted Baffles	53	—	—
Cyclone Collectors	70-80	80-90	5
Direct Impaction Scrubbers: (Venturi + Tray > Venturi > Tray alone > Spray Cyclonic)	94-96	97	1
Electrostatic Precipitators	99+	90	0.01
Bag Filters	99+	99	0.5

	Constituent	Gaseous Removal Efficiencies %
Single Scrubber [60]	fluorides, 3-4.5 ppm	98
Medium Energy Wet Scrubber [27]	NO_x	65
	SO_2	1.5
	HC1	95
	polynuclear hydrocarbons	95
	volatile metals	8
Wetted Cloth Filters [42]	HCl, 0.5 g/m^3	99+

adding a soluble alkaline substrate. In this respect, it has been noted that emissions of ammonia simultaneously with SO_2 or HCl are jointly removed with much improved efficiency in a wet collector [32, 37, 58]. But a medium to high energy scrubber, with adequate water treatment facilities, appears to be optimum if both particulate and pollutant gas removal are required from a single collection device. Rather than regulate from the standpoint of ambient air requirements, it is undoubtedly more straight-forward to regulate from a "required collection efficiency" stance [23].

Grate Ash From Incineration

The gross composition of grate ash is much less heterogeneous than the refuse feed (Table 11) and hence frequently lends itself to post-incineration reclamation at least for metals and glass [59, 60]. It also does not require any elaborate emission control measures to avoid involuntary discharges. Sanitary landfill [61, 62] has been advocated as the best method of disposal of incinerator residues, although simultaneous ocean borne incineration and dumping has

Table 11. Breakdown of the Ash Composition from a
Grate-type Municipal Incinerator [63]

Component	% Dry Weight
Iron: Cans, Wire & Massive	28.2
Non-ferrous Metals	1.4
Stones, Bricks	1.3
Ceramics	0.9
Carbon, as Charcoal, Carbonized Paper	8.3
Partly Burned Organics	0.7
Ash (see Table 9)	15.4
Glass	44.1

also received detailed study [64]. If ash is transported dry to land-
fill sites some dust loss may be incurred during vehicle transfers,
but this would represent a very small mass loss. Concern for the
ultimate disposition of the ash on burial with respect to soluble
and toxic components should be maintained as it is considerations
such as these that are leading to incineration as a viable option to
direct sanitary landfill. When grate ash is cooled by water quench,
the discharge water and the burial or ocean dumping site require
some consideration of the chemical composition to be aware of
and avert any possible serious side effects of the disposal operation
itself [64]. Table 12 gives typical ash compositions not only for
normal low temperature incineration, which contains a significant
carbon residue, but also for some high temperature slags where
the carbon content is reduced to near zero and the inorganic
components are fused, both effecting still further volume reduc-
tion than possible by conventional incineration. Possibly recent
efforts to determine the practicality of metals recovery from either
flyash [52] or hearth ash residues may shortly lead to both
enhanced potential for reclamation of metal values and at the same
time reduce the environmental impact of the residues when
ultimately disposed [59].

Refuse Pyrolysis

A relatively newer concept reduces many of the emission
problems of conventional municipal waste incineration by
separating the functions of burning (whether or not for energy
recovery), and ashing of the wastes [65], and has recently been
briefly reviewed [18]. The devices used to carry this out range
from fluid bed [66], or fixed bed [67] pyrolysis in the absence of

Table 12. Chemical Composition of Incinerator Residues

Compound	Low Temperature Ash		High Temp. Slags[a]	
	Klumb [68] %	Hrudey, Perry and Wellings[b] [69] %	Herbert [70] %	Composite Ranges [21] %
Carbon	—	13.7-22.9	—	—
Silicon Dioxide	39.9-58.1	10-20	43.0-49.9	60-62.4
Aluminum Oxide	6.1-26.9	5-15	8.7-24.9	7.6-13.6
Calcium Oxide	8.5-15.8	5-10	9.3-11.0	6.6-17.0
Iron Oxide	3.0-22.2	10-20	6.0-12.8	3.7-5.2
Sodium Oxide	3.1-19.2	—	3.2-3.3	3.0-9.4[c]
Titanium Dioxide	0.07-1.5	0.1-0.5	2.4-3.3	0.7
Magnesium Oxide	0.22-2.3	0.1-1.0	2.5-2.7	2.0-5.0
Phosphorus Pentoxide	0.99-2.0	0.1-0.5	2.0-2.4	0.7
Potassium Oxide	0.9-2.9	0.5-2.0	0.7-2.3	3.0-9.4[c]
Zinc Oxide	0.09-2.25	0.5-2.0	0.5-2.5	1.7
Barium Oxide	—	0.01-1.0	0.5-0.7	0.2
Lead Oxide	0.04-0.73	0.05-0.6	—	0.5
Copper Oxide	0.08-1.74	0.1-0.5	—	0.4
Manganic Oxide	—	0.1-0.5	—	0.2-1.0
Nitrogen	—	0.51-0.56	—	—
Sulfur	—	0.5-1.0	—	—
Chlorine	—	0.2-1.0	—	—
Tin	0.02-0.10	0.01-0.1	—	—
Others	—	—	—	1.9-2.0

[a] Incineration at temperatures of approx. 3500° F.
[b] Compositions quoted as the element, not as the elemental oxides.
[c] Includes potassium and sodium oxides.

air, pyrolysis in a deficiency of air [71, 72], pyrolysis with air in the presence of steam [73-76] utilizing the old water gas reaction to raise the fuel value of the gases produced, pyrolysis with pure oxygen [77], and the more imaginative suggestions that the pyrolysis products may be economically converted to oil [78, 79], pipeline gas, or methanol [80-83].

All these processes have the advantage that the gas volumes generated from the wastes are far lower than processes utilizing conventional incineration and that, in general, the particulate loadings are lower because of the in situ filtering action of the shredded feed above the actual pyrolysis zone. Hence, the gas cleaning equipment required can be much smaller and simpler, reducing the investment required for efficient emission control. As examples of the order of magnitude level of improvement of particulate emission levels achieved by pyrolysis even without emission control, 0.6 and 0.2 pounds of particulates per ton of waste have been reported for air/steam pyrolysis [74], and the

Purox oxygen pyrolysis system, respectively [77]. In contrast, conventional incineration, even *with* strict emission control, only achieves emission levels of around four pounds of particulates per ton of waste burned [23] (0.2 lb/1000 lb gas × 20,000 lb gas/ton waste). Efficient conventional incineration without emission control would result in something like twenty pounds of particulate discharge per ton of refuse burned (Table 4). Since a scrubber is normally used in the pyrolysis gas line (both to cool and to avoid blockage problems during the secondary combustion) there is every reason to expect that both the pyrolysis gas and the final boiler flue gas streams, in the event of secondary power recovery, should discharge far less than the 0.6 lb. per ton of waste quoted for a pilot operation [75].

The composition of the gases produced varies widely [18, 49, 79] but typical ranges are 25-50 per cent hydrogen, 13-25 per cent carbon monoxide, 12-22 per cent methane, and 10-18 per cent carbon dioxide together with smaller amounts of higher hydrocarbons [80]. The high carbon monoxide content makes pyrolysis gas somewhat less desirable than natural gas as a domestic fuel from purely toxicity considerations. However, with fuel values in the neighbourhood of 450-570 Btu per cubic foot [80], as an industrial fuel it would rank in the same range as carburetted water gas or coke oven gas, and about one half the heating value of natural gas. From 40-60 per cent of the total energy availability in the refuse is obtained from the fuel gas output [75]. The residual char too, containing 30-50 per cent carbon [78] retains a further potential fuel value of 5,000-8,000 Btu per pound [18], and in a cleaner burning form than the original refuse feed. Particulate matter and condensible oils scrubbed from the pyrolysis gases prior to pipelining for final combustion or storage, produces a liquid stream which requires at least phase separation and settling prior to discharge. The 1.5-2.5 gallons of oils per ton of refuse obtained in this way may readily be fired for supplementing pyrolysis heat requirements [80].

Precombustion removal of metals and glass for salvage increases the net calorific value for a given mass of feed and, at least in conventional incineration processes, has been found to reduce the metal vapour mass emission rate. This option is not attractive for small operations because of the low salvage values of the small volumes generated coupled with the significantly increased capital and operating costs and aggravated sanitary problems of this alternative. Also, with separated pyrolytic and combustor units metal vapour losses from the second stage would be expected to be

minimal (much lower than indicated in Table 4 for conventional incineration without reclamation).

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