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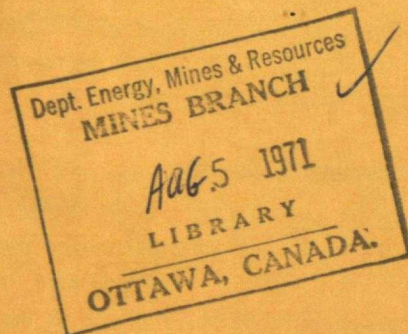
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THE INCINERATION OF
POLYMERS - A COMBUSTION ENGINEER'S
VIEWPOINT

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Canadian Combustion Research Laboratory

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THE INCINERATION OF POLYMERS - A COMBUSTION ENGINEER'S VIEWPOINT

by

F.D. Friedrich*

ABSTRACT

The incineration of polymers can present difficult combustion problems and can lead to the emission of corrosive or poisonous compounds into the atmosphere.

Typical municipal waste presently contains about 1.5% polymers, mostly in the form of plastic packaging materials. This can be adequately handled by well-designed municipal incinerators, and a typical system is described.

Industrial incineration of pure polymers presents more serious problems, and each case should be dealt with separately. The factors which should be considered are outlined, and the combustion properties of some common polymers are described. Sometimes pilot-scale research may be necessary to develop a suitable incineration system.

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Direction des mines

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L'INCINERATION DES POLYMERS - UNE VUE PAR UN INGENIEUR EN COMBUSTION

par

F.D. Friedrich*

RESUME

L,incinération des polymères peut présenter des problèmes difficiles en combustion et peut conduire à l'émission corrosive ou empoisonné des composés dans l'atmosphère.

L'ordure municipale typique contient présentement a peu près 1.5 pour cent de polymères surtout en forme de sacs plastiques. Ceux-ci peuvent être brûlés dans incinérateurs municipaux bien aménagés et un système typique est décrit.

L'incinération industriel de polymères purs présente des problèmes sérieux, et chaque problème doit être manié séparément. Les facteurs qui doivent être considérés sont expliqués, et les propriétés de combustion de certains polymères communs sont décris. Autrefois la recherche à l'échelle-pilote étaient nécessaire pour developer un système d'incinération convenable.

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CONTENTS

FIGURES

TABLES

INTRODUCTION

One of the ironies of affluence is that our wastes become a source of considerable embarrassment. This is true not only of the finished products that are discarded after they have served their usefulness but of the scrap material that is a byproduct of most manufacturing processes.

Man is creative by nature. When a problem arises, he is inclined to respond with an invention. This sometimes leads to an anomaly like the disposable garbage bag which contributes to the problem it helps to solve. His creativity also leads him to investigate in great detail how things can be made, while he pays very little attention to how they can be destroyed. The plastics industry is an excellent example; production-wise, it is a middle-aged industry with a highly developed technology but disposal wise, it is in its infancy.

In the past, our attitudes toward the reuse of waste material have been shaped by profit motivation. If it were possible to reuse waste profitably, it would be done. If economics favoured the use of virgin material, waste was disposed of as cheaply as possible, usually by dumping. It is only very recently that we began to learn from bitter experience how shortsighted our attitudes to waste disposal have been; how, for example, the few dollars per ton, saved by dumping municipal waste instead of incinerating it, can lead to inestimable damage to our environment.

Suddenly, then, industry is faced with a massive new problem; how to dispose of its many waste products without damage to the environment. For many of these products, incineration offers a temporary solution; temporary because, in all likelihood, within ten or twenty years emphasis will be on reuse and because incineration will be viewed with the same disfavour with which open dumping is viewed today. At present, the incineration of industrial waste is relatively new, at least in the polymer industry. The author found few papers dealing specifically with the incineration of polymers and none that were dated earlier than 1969. Though there remains much to learn, the incineration of polymers seems much less complicated than their manufacture. It is hoped that the following review will help to clarify the major factors which must be considered, the type of development work that may be necessary, and some of the pitfalls which must be avoided.

TABLE 1

Composition and Analysis of an Average Municipal Refuse[1]/

Component	Percent of All Refuse by Weight	Moisture (percent by weight)	Analysis (percent dry weight)						Noncombustibles[b]	Calorific Value (Btu/lb)
			Volatile Matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur		
Rubbish, 64%										
Paper	42.0	10.2	84.6	43.4	5.8	44.3	0.3	0.20	6.0	7572
Wood	2.4	20.0	84.9	50.5	6.0	42.4	0.2	0.05	1.0	8613
Grass	4.0	65.0	—	43.3	6.0	41.7	2.2	0.05	6.8	7693
Brush	1.5	40.0	—	42.5	5.9	41.2	2.0	0.05	8.3	7900
Greens	1.5	62.0	70.3	40.3	5.6	39.0	2.0	0.05	13.0	7077
Leaves	5.0	50.0	—	40.5	6.0	45.1	0.2	0.05	8.2	7096
Leather	0.3	10.0	76.2	60.0	8.0	11.5	10.0	0.40	10.1	8850
Rubber	0.6	1.2	85.0	77.7	10.4	—	—		2.0	11330
Plastics	0.7	2.0	—	60.0	7.2	22.6	—	—	10.2	14368
Oils, paints	0.8	0.0	—	66.9	9.7	5.2	2.0	—	16.3	13400
Linoleum	0.1	2.1	65.8	48.1	5.3	18.7	0.1	0.40	27.4	8310
Rags	0.6	10.0	93.6	55.0	6.6	31.2	4.6	0.13	2.5	7652
Street sweepings	3.0	20.0	67.4	34.7	4.8	35.2	0.1	0.20	25.0	6000
Dirt	1.0	3.2	21.2	20.6	2.6	4.0	0.5	0.01	72.3	3790
Unclassified	0.5	4.0	—	16.6	2.5	18.4	0.05	0.05	62.5	3000
Food Wastes, 12%										
Garbage	10.0	72.0	53.3	45.0	6.4	28.8	3.3	0.52	16.0	8484
Fats	2.0	0.0	—	76.7	12.1	11.2	0	0	0	16700
Noncombustibles, 24%										
Metals	8.0	3.0	0.5	0.8	0.04	0.2	—	—	99.0	124
Glass and ceramics	6.0	2.0	0.4	0.6	0.03	0.1	—	—	99.3	65
Ashes	10.0	10.0	3.0	28.0	0.5	0.8	—	0.5	70.2	4172
Composite Refuse, as Received										
All refuse	100	20.7	—	28.0	3.5	22.4	0.33	0.16	24.9	6203

[a] Data from [1].
[b] Ash, metal, glass, and ceramics.

[1]/ Taken from Table 1-3, Page 7, "Principles and Practice of Incineration". Ref. 1.

POLYMERS IN MUNICIPAL REFUSE

In any manufacturing plant, the engineer faced with disposing of production-line scrap may overlook the fact that the same problem exists for the plant's entire output. Sooner or later most of our manufactured goods complete their useful life, are discarded, and become a disposal problem. Household goods made of polymers such as synthetic fabrics, plastic packaging materials and rubber products are normally discarded into the household garbage can and are subsequently disposed of as municipal waste. Therefore, a review of the incineration of polymers should take into account the fact that tons of polymers are burned every day in municipal incinerators and their effect on municipal incineration should be noted.

Municipal Waste Composition and Trends

The composition and analysis of average North American municipal waste is given in Table 1(1). It can be seen that rubber and plastics together total 1.3% of the total. However, these figures were determined in 1962 and since that time the growth of the plastics packaging industry has resulted in a steadily increasing concentration of plastics in municipal waste. Plastics alone are reported to comprise 1.5 wt % of municipal waste in the United States at present and are estimated to comprise 3.3 wt % by 1976(2). It is likely that figures for Canada would be similar.

The Effect of Polymers on Municipal Incinerators

In general, designers and operators of municipal incinerators consider polymers in refuse to be an unavoidable nuisance. Though many polymers have a high calorific value, they tend to produce a great deal of smoke and products of partial decomposition may be highly toxic. To achieve clean and complete combustion, high furnace temperatures and intense mixing with combustion air must be provided. Thermoplastic compounds are likely to melt, run down into the grate and resolidify, thereby blocking the grate air openings. Self-extinguishing plastics require high temperatures for complete decomposition.

A more serious problem is the emission of dangerous pollutants. Though the sulphur content of rubber compounds is not likely to seriously increase the emission of SO_2 from incinerators, hydrogen chloride (HCl) from the decomposition of polyvinyl chloride may be emitted in concentrations exceeding the allowable limits. Also, HCl may corrode the incinerator and may adversely affect its efficiency.
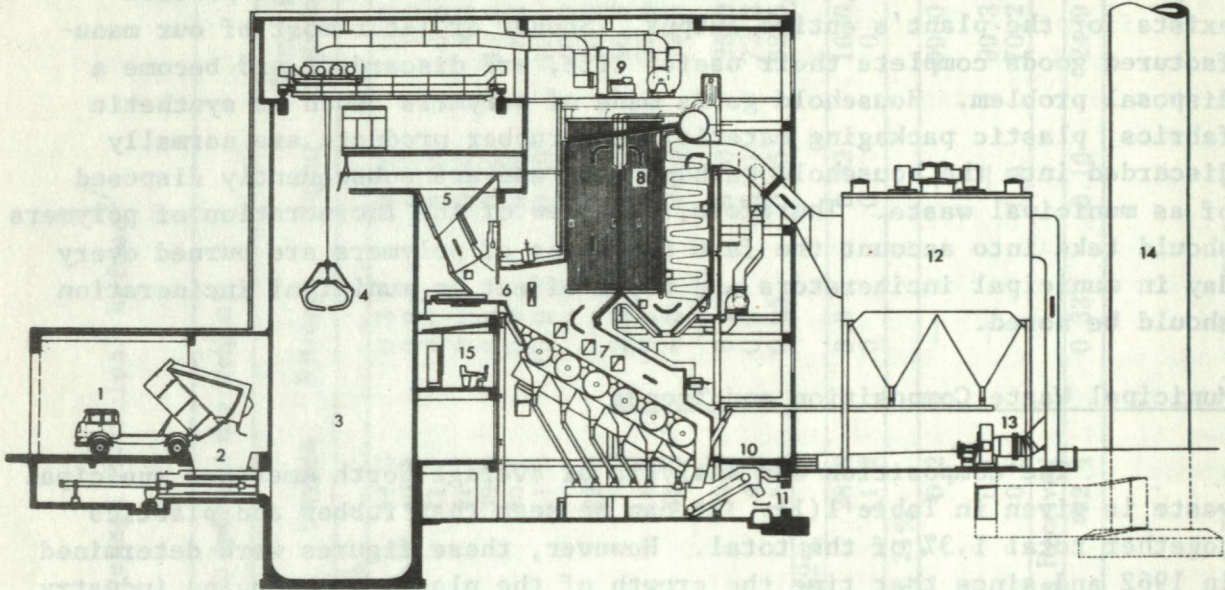
1 Truck airlock	8 Steam generator	3 x 6 tons/hr of refuse throughput
2 Bin charging	9 F.D. fan	14 kg./sq.cm.gauge supply pressure
3 Reception pit	10 Ash extractor	3 x 15 tons/hr of saturated steam
4 Refuse crane	11 Ash belt conveyor	
5 Refuse feed hopper	12 Flue-gas dust collector	
6 Refuse feeder	13 Flue-gas fan	
7 Roller grate of	14 Chimney	
"Düsseldorf System"	15 Control and supervisory centre	

Figure 1. Schematic cross-section of the municipal incineration plant
At Hagen, West Germany. Courtesy Vereinigte Kesselwerke,
A.G. Duesseldorf, West Germany.

None the less, municipal incinerators can usually cope with the concentration of polymers now found in municipal waste, provided the incinerators are properly designed. Probably the most important requirement is that the polymers be thoroughly mixed with the other waste in order to dilute objectionable polymer combustion properties. It is also important to provide high furnace temperatures (about 1800°F) and ample residence time at these temperatures. Controlled distribution of combustion air and sufficient over-fire turbulence are other factors which the designer must provide. The most common method of providing a measure of protection against corrosion is to cover with refractory those metal surfaces most prone to attack. At present, most municipal incinerators do not attempt to remove HCl from the flue gas. However, this may become necessary as the concentration of polyvinyl chloride in municipal waste continues to increase.

To clarify how the foregoing design considerations are applied in practice, it is expedient to examine a large, modern municipal incinerator. The author has chosen an example which is by no means unique; several satisfactory designs for large municipal incinerators have been reviewed elsewhere(3). However, the plant selected as an example is of particular interest because, in addition to the normal concentration of polymers in the waste, it burns substantial quantities of used tires.

The Municipal Incineration Plant at Hagen, West Germany

The Hagen incineration plant was commissioned in 1967 to incinerate the domestic and commercial waste from a population of 200,000(4). The plant comprises three incinerators, each having a throughput of 150 metric tons per 24-hr day. Normally, two units operate Monday through Friday, with the third unit serving as a standby. The incinerators are equipped with boilers for heat recovery; each boiler is capable of generating about 35,000 lb of steam/hr at 200 psig and 375°F. Waste oils and grease from service stations and other sources can also be fired into the incinerators by means of steam-atomizing burners.

Figure 1 shows a schematic cross-section of the plant. Solid waste, delivered by truck, is dumped into a large concrete bunker, where an overhead travelling crane mixes it with previously-delivered refuse and charges it to the incinerator hopper. A pusher mechanism at the bottom of the hopper controls the rate of feed to the incinerator grate. The grate consists of six rollers mounted in series on a 30° incline. The rollers are about 5 ft in diameter and 8 ft wide, each equipped with a reversible variable-speed drive to provide 0.0276 to 5.52 rph. The roller surfaces consist of cast iron segments mounted on a cylindrical framework; an assembled grate is shown in Figure 2. Slits between the grate segments
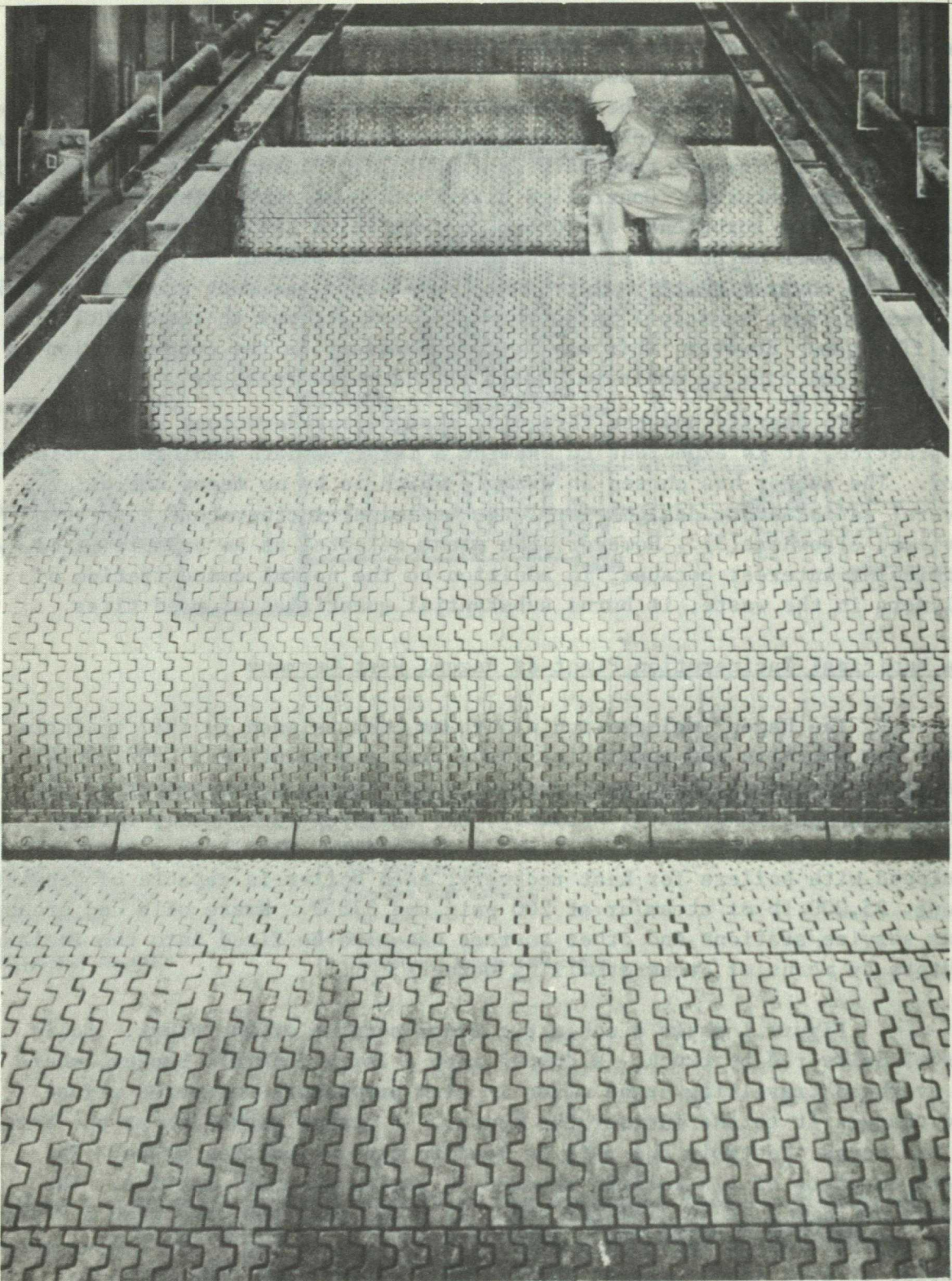
Figure 2.   A view of the Duesseldorf-System roller grate during assembly.
Courtesy Vereinigte Kesselwerke, A.G.   Duesseldorf, W. Germany.

permit combustion air to pass into the furnace. Combustion air is provided by a forced-draft fan via a series of windboxes, one connected to the underside of each grate roller, thus providing control of combustion air distribution.

The feeder lays a 3 to 4-ft bed of waste onto the first roller, where the waste is immediately exposed to intense radiation from the flames in the furnace, resulting in drying and surface ignition. As the waste is slowly tumbled forward by the rotation of the rollers, fresh surfaces are exposed, burning waste is mixed with unignited waste, and a fairly uniform fire-bed is maintained. The furnace incorporates a long refractory-covered rear arch which helps to maintain high gas temperature in the vicinity of the fire-bed, and contributes to complete burn-out. Generally the first roller serves as a drying and ignition zone, vigorous combustion occurs on the next three rollers, and the last two rollers provide a burn-out zone. The combustion air to each roller is adjusted accordingly. It will be noted from Figure 1 that the construction of the furnace is such that flames tend to sweep over the freshly charged waste.

The combustion residue is discharged from the last roller into a quench tank. From there it is conveyed to a crusher, ferrous metal is separated magnetically, and the remaining residue is screened. The metal recovered by the magnetic separator is sold as scrap, the coarse sizes of residue are sold as road fill, and the remainder is disposed of by landfill.

The lower part of the furnace is constructed of high-temperature refractory, with silicon carbide bricks immediately above the grate where abrasion is likely to be severe. The refractory helps to maintain furnace temperatures at the desired level of 1470°F minimum. Normally no support firing is required, but if the waste is very wet or otherwise low in calorific value, furnace temperature can be maintained by means of an oil burner located in the roof over the first grate roller. This burner also serves as an ignitor when the incinerator is brought on stream. Another burner in the rear wall can also be used as a support burner, but its main purpose is for firing the waste oils brought to the plant. Secondary air from a high-pressure blower is circulated through castings at the sides of the rollers to provide cooling, then injected over the fire to provide turbulence.

The refractory part of the furnace leads into a conventional 3-pass boiler. The first two passes are radiant sections which provide residence time for complete combustion of volatile matter. The third pass contains convection banks. The flue gas then passes through a large electrostatic precipitator and an induced-draft fan into a 200-ft stack. The electrostatic precipitators are 99% efficient and are guaranteed to limit the dust loading in the stack gas to 150 mg/Nm^3, the gas volume being corrected to 7% CO_2.

The grate residue is guaranteed to contain no more than 8% combustible and 0.3% putrescible.

Some of the steam generated in the boilers is supplied to various consumers in the plant and to a nearby municipal swimming pool. The remainder is dissipated in air condensers but will be available for sale to future commercial developments in the vicinity of the plant.

As mentioned previously, the Hagen incineration plant disposes of used automobile tires from the municipality it serves. A large shear is used to cut each tire into four pieces which are then dumped into the bunker and mixed with the other waste. Care is taken to avoid a large concentration of tires in an incinerator at one time. The combustion air distribution and the turbulence provided by the secondary nozzles seem to be adequate to incinerate the tires without smoke. Unfortunately, at the time the author visited this plant, no figures were available on the quantity of tires burned.

To protect the boiler against high-temperature corrosion the designer kept exposed metal surfaces out of the area where flame impingement was expected and selected steam conditions which would provide moderate tube metal temperatures. The danger of low-temperature corrosion was minimized by eliminating low-temperature heat exchange surfaces such as economizers and air heaters. A more recent trend in furnace construction is to bring tubes down the furnace walls along the grate rollers. These tubes are studded and covered with a thin layer of silicon carbide refractory to a height above the maximum flame travel. This construction eliminates much of the refractory in the lower part of the furnace. The refractory covering on the tubes is sufficient to maintain high furnace temperatures; furthermore, it protects the tubes against corrosion. At the same time the refractory is sufficiently cooled by the tubes to minimize slag build-up.

INDUSTRIAL INCINERATION OF POLYMERS

Combustion Properties

The foregoing has shown that polymers can be burned in municipal incinerators without serious difficulty, provided the polymers do not exceed about 2% of the total waste. Under these conditions no attention need be payed to the composition of the polymers or their combustion properties. However, industrial incineration is likely to involve waste containing high concentrations of polymers, perhaps 100% of one particular composition. In that case, the polymer composition and its combustion properties become of paramount importance. Therefore, some of the salient combustion characteristics will now be reviewed.

A. Calorific Values

Many polymers have calorific values higher than good-quality coal, as can be seen from the data published by Cheater(5), reproduced in Table 2.

TABLE 2

Calorific Value of Polymers[1]

Polymer	Calorific Value, Btu/lb
Polyisoprene	18,400
Nitrile rubber	17,000
Polyethylene	18,900
Polyisobutylene	18,900
Polystyrene	16,700
Polyvinyl chloride	9,400
SBR rubber	17,700
House coal	12,000

Natural rubber is 93% polyisoprene. Nitrile rubber is based on 3 parts butadiene and 1 part acrylonitrile. SBR rubber is based on 3 parts butadiene and 1 part styrene.

[1] From Table 2 of "Incineration of Rubber and Plastics Waste", Ref. 5.

Cheater points out that textbook calorific values for polymers can be misleading. The calorific value may be lowered or additives may be incorporated to make the polymer self-extinguishing. For example, polyvinyl chloride (PVC) has a calorific value higher than that of many low-grade coals used for power generation but it may require a substantial heat input to maintain PVC at a temperature sufficiently high for decomposition.

B. Products of Complete Decomposition

Rubber and plastics, the most common polymers, are composed primarily of carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, and sulphur. These are combined into repeating units which form the large molecules of polymers. The unit structure of some common plastics is shown in Table 3(6).

TABLE 3

Structural Units of Some Common Plastics[1]
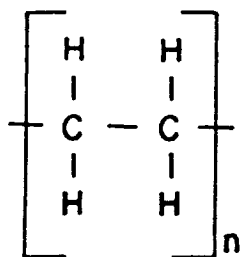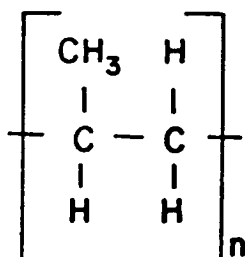
POLYETHYLENE   POLYPROPYLENE   POLYSTYRENE

POLYVINYL CHLORIDE   POLYTETRAFLUOROETHYLENE
(PVC)   (TEFLON)

[1] Taken from "Combustion Products of Organic Materials" Ref. 6.

If complete decomposition is achieved the products of combustion of polyethylene, polypropylene, and polystyrene are harmless, i.e., carbon dioxide and water vapour. On the other hand, complete decomposition of PVC releases chlorine which almost invariably unites with some of the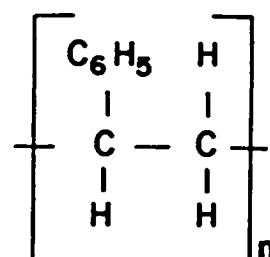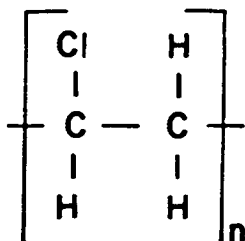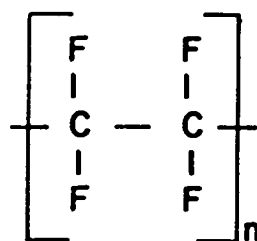 hydrogen to form hydrogen chloride (HCl). Similarly, complete decomposition of teflon yields hydrogen fluoride (HF). These compounds are corrosive as well as being serious pollutants, even in small concentrations. Rubber compounds often contain sulphur but usually in lower concentration than most fuels; the sulphur dioxide (SO_2) which may result from combustion is not likely to be a significant source of pollution.

However, the thermal breakdown of polymers is a complicated process and complete decomposition is not readily achieved. During incineration thermoplastics break down somewhat as follows: the solid melts to a liquid which depolymerizes to form hydrocarbon products. These hydrocarbons burn, if temperatures are high enough and if oxygen is present. Thermoset plastics, when incinerated, decompose without melting. The polymer bonds break in a number of places, leaving a mixture of simple molecules, including benzene rings (C_6H_5-). These, too, will burn under suitable conditions. During thermal decomposition, rubber also forms large quantities of compounds having benzene rings.

Many of the products of partial decomposition have high bond energies; therefore, high temperatures are necessary to complete the breakdown process. It may also happen that these compounds are decomposed by temperature but are subsequently chilled before they have an opportunity to oxidize. Therefore, high temperatures, adequate oxygen, and sufficient residence time must be provided simultaneously and, even under the best of circumstances, the flue gas is likely to contain significant quantities of unburned hydrocarbons and carbon particulates. Unfortunately, there is little precise information on the time/temperature relationships necessary for complete decomposition of common organic compounds.

C. Products of Partial Decomposition

Fire research has provided some useful information on what partial decomposition products the incinerator designer can expect if his design is inadequate(2, 7). There will, of course, be large quantities of smoke and dangerous concentrations of CO. PVC may yield phosgene ($COCl_2$) Various plastics may give off hydrogen cyanide (HCN) and ammonia (NH_3), though not in the high concentrations obtained from substoichiometric combustion of wool or silk.

Decomposition products of various materials are summarized in Table 4, and the relative toxicity of these products is given in Table 5.

TABLE 4

Decomposition Products of Various Polymers[1]

Material	Method of Testing	Oxygen O_2	Carbon Dioxide, CO_2	Carbon Monoxide, CO	Chlorine, Cl_2	Hydrogen Chloride, HCl	Carbonyl Chloride, $COCl_2$	Hydrogen Cyanide, HCN	Ammonia, NH_3	Hydrogen Sulphide, H_2S	Nitrous Fumes as NO_2	Notes
Melamine resin paper, or wool	Heated in a current of air and products passed over rate in cages.					Not analyzed						Demonstration that shows toxicity was due to carbon monoxide and not hydrogen cyanide.
Wood	5 lb burned in 110 ft^3 air	9.8	6.2	6.2	--	--	--	--	--	--	--	
Rubber	Insulation on cable in 5-1 flask	6.6-13.4	6.6-13.6	3.4-7.6	--	--	--	--	--	0.1	--	10% of hydrocarbons.
Wool	Heated in silica tube with a	6.6-14.2	4.6-9.2	0.5-5.0	--	--	--	1.3-2.5	1 3-2.6	0.02-0.40	--	
Silk	current of air	4.0-8.0	8.0-12.6	3.0-4.4	--	--	--	2.2-6.8	3.1-3.6	--	--	
Timber and fibre insulating board	Burning house	19.9	0.7	0.3	--	--	--	--	--	--	--	3 min from start.
		1.6	17.8	19.8	--	--	--	--	--	--	--	1.9% hydrogen 12 min from start.
		0.3	9.2	16.7	--	--	--	--	--	--	--	47% hydrogen 18 min from start.
Chlorinated methacrylate resin 27% chlorine	0.5 g at 550 C in 5 l air	n.d.	2.6	2.2	0.0	0.6	0.0005	--	--	--	--	
Polyvinyl chloride 57% chlorine	0.25 g at 550 C in 5 l air	n.d.	2.1	1.1	0.0	1.8	0.0005	--	--	--	--	
Polyvinyl chloride fabric	0.5 g at 550 C in 5 l air	n.d.	2.0	0.4	n.d.	2.9	n.d.	--	--	--	--	
Plywood	Heated at 550 C in 5 l air	2.8	17.1	3.6	--	--	--	--	--	--	--	3.4% hydrocarbons
Plywood PVC and flame-retardant paint	Heated at 550 C in 5 l air	2.1	17.1	5.1	--	3.1	--	--	--	--	--	
Plywood with polyester resin and flame-retardant paint	Heated at 550 C in 5 l air	2.6	14.7	13.2	--	3.8	--	--	--	--	--	
PVC coating only	Heated at 550 C in 5 l air	0.3	10.1	5.8	--	4.7	--	--	--	--	--	
Vinylidene coating only	Heated at 550 C in 5 l air	17.0	0.4	--	--	1.1	--	--	-- ..	--	--	
Foamed polyvinyl chloride	2-3 g heated electrically in 270 l air	20.7	0.16-0.35	0.023-0.040	0.0	0.005-0.023	0.0	0.001-0.003	0.002-0.003	--	0.001-0.002	Tests made to examine effects of blowing agents.
Foamed acrylonitrile		19.3	1.26-1.31	0.041	0.0	0.002	0.0	0.002	0.002	--	0.002	
Phenolic resin with fillers	As above	n.d.	n.d.	0.017-0.046	--	--	--	0-0.003	0.002-0.110	--	--	Carbon monoxide was highest with fillers
Melamine resin with fillers		n.d.	n.d.	0.012-0.075	--	--	--	0.002-0.25	0.006-0.180	--	--	such as wood, meal, and cotton.

[1] From Table D-2, Appendix D. "A Report on the Role of Plastics in Solid Waste". Ref. 2.

TABLE 5

Toxicity of Some Gases Which May Occur in Fires[1]

Effect	Concentration, parts per million								
	Carbon Monoxide, CO	Chlorine, Cl_2	Hydrogen Chloride, HCl	Carbonyl Chloride, $COCl_2$	Hydrogen Fluoride, HF	Hydrogen Cyanide, HCN	Ammonia, NH_2	Hydrogen Sulfide, H_2S	Nitrous Fumes as NO_2
Safe for several hours	100	0.35-1.0	10	1.0	1.5-3.0	20	100	20	10-40
Safe for 1 hour	400-500	4	50-100	--	10	50-60	100	--	--
Dangerous 1/2 to 1 hour	1500-2000	40-60	1000-2000	25	50-250	100-240	2500-4500	200	100-150
Fatal in 1/2 hour	4000	--	--	--	--	200-450	--	600	--
Rapidly fatal	--	1000	1300-2000	50	--	3000	5000-10,000	1000	200-700
Least amount causing throat irritation	--	15	35	3.1	--	--	408	100	62
Least detectable odor	--	3.5	--	5.6	--	--	53	10[a]	--

(a) Sense of smell lost after 2 to 15 minutes exposure to 100-150 ppm.

- 13 -

[1] From Table D-3, Appendix D. "A Report on the Role of Plastics in Solid Waste." Ref. 2

Design Considerations

It has been shown that the incineration of polymers can present rather more stringent problems than the incineration of municipal waste. Unfortunately the problems are substantially easier to identify than to solve and at the present state of the art, the author must content himself with offering the following rather general guidelines for the design of an incineration system:

1. The nature of the waste to be disposed of must be determined, that is, whether it is of uniform composition or is a mixture of compositions. The proportions of different compositions and the extent to which they are likely to change must also be taken into account. For example, an incinerator should not be designed to burn 50% flammable polyethylene and 50% self-extinguishing PVC if it occasionally must deal with 100% PVC. It is also important to know whether some wastes will be in liquid form.

2. The quantity of waste. to be disposed of, both average values and fluctuations, must be clearly established. Generally the average quantity per day will determine the size of incinerator required, whereas the fluctuations in quantity will establish the storage requirements.

3. The calorific value and combustion properties must be studied carefully. Unfortunately, the useful literature is limited in quantity but the work of Fenimore and Martin(8) gives some idea of the relative combustibility of various polymers. The physical nature of the waste must be taken into account; for example, a grate-type incinerator must be avoided for thermoplastic materials whereas a spray nozzle may be suitable for liquids. Size reduction of the waste prior to incineration may be necessary. Normally, pilot-scale combustion tests will provide useful guidance.

4. Incinerator construction offers considerable scope for novelty. It must first be decided whether the incinerator is to be operated batch-wise or continuously. Generally batch-type incinerators are most suitable for disposal rates up to 1 ton/hr, unless the waste is liquid A batch-type incinerator must have a convenient access for recharging but a continuous incinerator must have some form of stoking mechanism. The furnace should be refractory-lined to minimize chilling of partial decomposition products. Furnace volume will depend on the desired capacity and heat release rate. There is little guidance with respect to

the latter except in such as the Ontario incinerator code(9). Furnace configuration may vary. Rubber and thermoset plastics may be burned on grates; thermoplastic materials may be burned in chambers having no grates and in rotary kilns; liquids may be fired through modified oil burners but these are only a few of the possibilities. The main goal of furnace design is to ensure the necessary conditions of residence time, temperature, and mixing with air. If the furnace has a grate, adequate mixing can usually be achieved by controlled distribution of combustion air under the grate, together with overfire air through high-velocity overfire nozzles. If there is no grate, combustion air will have to be provided mainly by overfire nozzles with, perhaps, some underfire air tuyeres. Generally somewhere between 50 and 150% excess air should be provided. As mentioned previously, there is little guidance on the temperature and residence time necessary for complete incineration. The Ontario incinerator code suggests that furnace gases be subjected to 1800°F for at least 0.5 sec(9).

5. The rate and nature of support firing must be decided upon. Generally, burners using natural gas, liquified petroleum gas, or light fuel oil are most suitable for support firing. The burners should have flame safeguard systems and should be located so as to ignite the waste charge and to blanket the gases evolving from the waste. The rate of support firing will depend primarily on the amount and combustion properties of the waste being incinerated but will also depend on furnace construction. Cheater(5) suggests that the total heat input (calorific value of waste plus support firing) should be about 14,400 Btu per lb of waste. Therefore, polyvinyl chloride, having a calorific value of 9,400 Btu/lb, should have support firing to the extent of 5000 Btu/lb but nitrile rubber which has a calorific value of 17,000 Btu/lb would require no support firing.

6. The feasibility of heat recovery should be considered in relation to the need for cleaning stack gases. For example, if a fairly large incinerator were expected to have sufficient particulate matter in the flue gas to make electrostatic precipitators necessary, the gas would somehow have to be cooled to about 600°F before entering the precipitator. This could be done by massive dilution with air but then the fans and precipitator would have to be made larger to accomodate the increased volume. Such a situation could greatly improve the economics of cooling the flue gas by means of a waste heat boiler.

Conversely, corrosive components such as HCl in the flue gas might immediately rule out the possibility of using a waste heat boiler and heat recovery might be passed up in favour of a simple spray tower which would both clean and cool the flue gas.

Generally, the larger the incinerator, the more attractive heat recovery becomes, and it should be seriously considered for any continuous incinerator. Cheater describes an installation at a rubber plant which burns 700 lb/hr of old tires and produces 3,000 lb/hr of steam, sufficient to heat the plant. Although steam boilers or high-temperature water generators are the most common means of heat recovery, there are other alternatives. Gas-to-air convective heat exchangers may be used if the designer takes care to maintain safe metal temperatures. Radiant coolers may also be employed. A radiant cooler consists of a double-walled cylindrical vessel. The flue gas is passed through the center at moderate velocity while air or water is passed between the walls. Thus, heat transfer is largely by radiation. While radiant coolers are not very efficient, they are inexpensive and robust.

Permissible emission levels for the various pollutants can be obtained from the air pollution control authority having jurisdiction in a given case. The pollutants from the incineration of polymers are likely to be some or all of the following: CO_2, CO, NO, unburned hydrocarbons, particulate matter, SO_2 from polymers containing sulphur, HCl from polymers containing chlorine, and HF from polymers containing fluorine. As shown previously, it is also possible to produce hydrogen cyanide, phosgene, and ammonia but any incinerator in which emission of these compounds cannot be avoided should not be operated. Little can be done about CO_2 and SO_2. CO and unburned hydrocarbons can be kept within acceptable limits by high furnace temperatures together with turbulent mixing of excess air. The same is true of carbon particulate matter resulting from incomplete combustion. However, high temperatures and excess air tend to promote the formation of NO, so some compromise is necessary. The probable concentrations of HCl and HF can be determined by combustion calculations based on a representative analysis of the raw waste. For example, if pure PVC is incinerated, the concentration of HCl in the flue gas will be 79,000 ppm by vol under stoichiometric conditions and 40,800 ppm by vol at 100% excess air.

Similarly, the incineration of pure teflon will yield flue gas having a HF concentration of 301,500 ppm by vol under stoichiometric conditions and 265,000 ppm by vol at 100% excess air. If the concentration of acid gases such as HCl and HF is high, removal can be accomplished by spray towers using water or a mild caustic solution. Particulate matter may be removed by washers, cyclones, bag filters or electrostatic precipitators. The advantages and limitations of these devices are adequately covered in engineering handbooks such as the "Air Pollution Engineering Manual" (10).

To summarize, it is necessary to consider several factors in designing an incineration system. The most important of these are the composition of the waste, the quantity to be disposed of, its calorific value, its physical condition, the chemistry of its breakdown under high temperature conditions, and the nature of any corrosive or toxic compounds likely to be formed. On the basis of this information, decisions must be made concerning the necessary furnace temperature and residence time, the configuration of the incinerator, whether the incinerator should operate batchwise or continuously, the amount of support firing required, whether heat recovery should be incorporated, whether neutralizing sprays are required to deal with dangerous combustion products, and what form of gas cleaning is required. In many cases pilot-scale research will have to be carried out before a reliable system can be designed. An example is described in references 11 and 12.

CONCLUSIONS

Well-designed municipal incinerators can handle waste containing up to about 3% of halogenated polymers. Somewhat higher concentrations of carbon-hydrogen polymers can be burned successfully.

Industrial wastes such as 100% polymer scraps may present more complex problems, hence it is best to deal with each case separately. Halogenated polymers such as PVC are difficult to incinerate partly because they tend to be self-extinguishing and partly because they produce dangerous compounds which must be removed from the flue gas. Other polymers such as rubber have high calorific values and can be incinerated readily, if high temperatures and sufficient air are provided.

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