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AIR POLLUTION EMISSIONS AND CONTROL TECHNOLOGY: PACKAGED INCINERATORS

by

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ABSTRACT

This study was initiated to assess air pollution emissions from packaged incinerators and to determine the best practicable technology for their control. There are an estimated 10,000 packaged incinerators currently in use in Canada. They are manufactured in capacities up to 900 kg/hr and are used to dispose of solid waste generated by a variety of industrial, commercial, institutional and residential sources.

In the past, poor combustion was a characteristic of packaged incinerators and the resulting emissions of smoke, fly ash and odour were an affront to many communities. In recent years improvements in design and operation have produced a new generation of packaged incinerators which have essentially eliminated these undesirable characteristics.

The design and operating features which yield good combustion performance are discussed and the types and quantities of air pollutants emitted by well-controlled units are tabulated.

RÉSUMÉ

La présente étude avait pour objet d'examiner les émissions polluantes des incinérateurs autonomes et de déterminer les meilleures techniques praticables pour les limiter. On évalue à 10 000 le nombre de ces incinérateurs, au Canada. Leur capacité peut atteindre 900 kg/h et ils servent à éliminer les déchets solides produits par diverses sources industrielles, commerciales, institutionnelles et résidentielles.

Dans le passé, ces incinérateurs étaient caractérisés par une mauvaise combustion qui entraînait des émissions de fumée, de cendres volantes et d'odeurs désagréables pour de nombreuses collectivités. Au cours des dernières années, avec les améliorations de la construction et de l'exploitation, ces caractéristiques indésirables ont pratiquement été éliminées.

La présente étude traite des caractéristiques de la construction et de l'exploitation qui donnent une bonne combustion et présente, sous forme de tableaux, les types et les quantités de polluants atmosphériques dégagés par les dispositifs couplés à de bons dispositifs antipollution.

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1.1 Scope

This study deals with the control of air pollutant emissions from packaged incinerators burning solid waste. These on-site incinerators with capacities up to 900 kg/hr have found broad application in burning combustible wastes from commercial and industrial operations across Canada. This study examines the two principal types of packaged incinerators currently in use and the factors which influence their air pollutant emissions.

1.2 Purpose

The purpose of this study is to assess the technology available for the control of air pollutant emissions from packaged incinerators.

1.3 Methods

The study examines the combustion process as it applies to packaged incinerators and discusses the importance of design, operation and waste characteristics in the formation of air pollutants. The results of emission tests gathered from the literature and incinerator manufacturers are used to compare the two principal incinerator types.

2 THE ROLE OF PACKAGED INCINERATORS

2.1 Applications

The problem of solid waste disposal is one which faces every commercial and industrial operation and every public institution and residence in Canada. The common objective in each case is to remove the waste from the site. Ideally, this should be accomplished in a manner which is both efficient and convenient.

There is no single best method for waste disposal. Numerous systems are available and the number of new techniques and improved hardware grows annually. Still, the most common method is storage of the material on-site and then periodic collection by public or private haulers for transfer to the municipal disposal area. The second most popular alternative involves the use of an on-site incinerator to burn the waste. Thus only the remaining ash need be removed from the site. For an incinerator to be of use, waste must be combustible. This is a common characteristic of many waste substances.

Other alternatives which could bridge the gap between generation and final disposal are compaction, shredding or pulping of the waste. The choice of method will depend primarily on cost, convenience and the degree of sanitation required. Incineration has a number of desirable characteristics; principally, reduction of the weight and volume of refuse. The residue is compact and sterile and is, therefore, both sanitary and convenient to store and handle. In certain applications energy can be recovered from the waste in the form of steam or hot water.

A few disadvantages may offset the benefits of incineration: the capital expense of the equipment, the requirement for auxiliary fuel and trained personnel, and the potential for air pollution emissions.

2.2 Waste Types and Sources

Packaged incinerators are found in many different sectors of business and industry. A rough estimate puts their number at about 10,000 in Canada.

Users are generally grouped into four broad categories: industrial, commercial, institutional and residential. Industrial sources include manufacturing plants and warehouses. The type of waste generated depends on the materials used and products manufactured, but could include plastic or textile scraps and wood shavings. Warehouses generate wooden pallets and crates, and cardboard cartons and packing material.

Incinerators for commercial businesses can be found in office buildings, department stores, supermarkets and restaurants. The waste comes from wastebaskets, confidential documents, paper and plastic packaging material, spoiled garden produce or table scraps.

A wide variety of wastes are found in institutions such as hospitals, homes for the aged, schools, laboratories and crematoria. The waste will consist of disposable cloth and plastic items such as bandages, surgical gowns and syringes; human and animal tissue from surgical operations; infectious animal bedding and dead animals from research labs and dog pounds. Finally, residential users of packaged incineration equipment would include homes, apartment buildings and small communities.

Obviously there are a great many types of waste material. To simplify discussion of wastes, the Incinerator Institute of America (IIA) classified wastes into categories according to physical and chemical properties and the way they behave upon incineration. The IIA classification has been revised and expanded by the Canadian Standards Association.[1] The revised classification appears in Table 1. The *solid* waste types are designated A to K in the CSA classification. Packaged incinerators can accept any of these types. Often, the waste is composed of several waste types, in which case it can be described according to the percentage of each waste type present.

2.3 Incinerator Capacity

The capacity of packaged incinerators is usually rated as the number of pounds of a specific waste burned per hour. Units have been manufactured with capacities greater than 900 kg/hr, however 90% of all units are rated at less than 225 kg/hr with the average capacity in the order of 100 kg/hr.[2]

A manufacturer will have several different capacity ratings for the same incinerator, depending on the type of waste to be burned. For instance, one model rated at 145 kg/hr for type A waste could be rated at 165 kg/hr for type B and 130 kg/hr for type C waste. This is because wastes burn at varying rates depending on their moisture content, heating value, density, volatile content and the amount of air and auxiliary fuel used. While there are analytical methods for estimating an

TABLE 1 CLASSIFICATION OF WASTES

Type	Description	Examples
A	Cellulosic solids, up to 15 percent moisture (wet basis)	dry paper cardboard boxes wooden pallets furniture photographic film
B	Cellulosic solids, 10 - 50 percent moisture (wet basis)	wet paper moist sawdust damp rags or clothing residential refuse bark
C	Cellulosic solids, over 40 percent moisture (wet basis)	fruits & vegetables garden trimmings kitchen wastes
D	Plastics & asphaltic solids, non-halogenated	polyethylene containers polystyrene toys asphalt shingles waxes
E	Plastics & asphaltic solids, halogenated	PVC (polyvinyl chloride) DDT powder
F	Rubber	tires
G	Animal materials	leather hair & wool feathers glue fur
H	Animal & human wastes	manure dried sewage sludge
I	Non-combustible solids	glass cans ashes and sand salt crockery metal objects
J	Pathological materials	hospital dressings disposable bedding & gowns
K	Pathological remains	dead animals parts of humans & animals
L	Cadavers, coffin encased	
M	Organic liquids with under 30 percent water	used automotive oils solvents alcohols
N	Organic liquids with over 30 percent water	phenol water separation sludge liquid sewage
O	Fumes	solvent vapours refinery tail gas drying oven fumes
P	Particulates, gas-borne	smoke
Q	Radioactive materials	*
R	Special wastes	**

* A waste shall be classified as Type Q if it is a radioactive material as defined by the Radiation Protection Bureau, Department of National Health and Welfare.

** A waste may be classified as Type R if it is a distinct type other than those recognized in Types A to Q, or if it has critical characteristics that require special recognition.

incinerator's burning rate, most manufacturers rely on experience or actual tests to establish the capacity of their models on different waste types.

3 INCINERATION PROCESS

3.1 Fundamentals

An incinerator is simply a furnace in which waste material is burned. The main difference between the combustion of solid waste and that of other solid fuels is in the purpose. Coal and wood are burned for heat production and steam generation, so thermal efficiency is an important factor. On the other hand, because incineration is a method of disposal, thermal efficiency is not important. In fact, the heat generated by the process limits the capacity of the incinerator and, for some types of incinerators, makes treatment of the flue gases more complex.

Besides this fundamental difference, the non-homogeneity of the waste with respect to size, moisture content and heating value requires special attention and thus differentiates incineration equipment from that used for burning coal or wood.

Packaged incinerators require a heat resistant refractory enclosure into which the waste material and combustion air are fed. The waste is ignited, usually by an auxiliary fuel burner, and the products of the reaction are ash and flue gases containing pollutants.

The quantity of pollutants in the flue gas is related, among other things, to the completeness of the combustion in the incinerator. The combustion process is complex and not entirely predictable. Briefly, it begins with the heat from an ignition burner or the already burning waste raising the temperature of the raw refuse and driving off moisture. Once the waste is dry, continued heating brings its temperature into the pyrolysis range which is about 260°C for cellulose. The volatile content of the waste begins to be released in the form of pyrolysis gases. If combustion air is present in the bed, as it usually is, the oxygen will react with the gases to form carbon dioxide, carbon monoxide, hydrogen, water and unburned pyrolysis gases. With the volatile products driven off, the fixed carbon or char fraction of the refuse combines more slowly with the combustion air to form carbon oxides. Once the char is exhausted the only remaining product is inorganic ash.

The gases which rise from the top of the refuse bed often contain unoxidized pyrolysis gases and partially burned solid particles. To complete the combustion of these products and bring them to their final equilibrium products, carbon dioxide and water vapour, the flue gases must be subjected to an oxidizing environment.

Oxygen is thus essential to the combustion process. Air, the most convenient source of oxygen, is invariably used in packaged incinerators and is added to an incinerator in several places. When supplied beneath the refuse bed it is called underfire air and when added above the refuse bed, overfire air. Air is often added in a separate chamber or flue gas passage remote from the refuse bed, in which case it is termed secondary air.

It is most important to mix the combustion air intimately with combustible gases from the refuse bed. This can be achieved by having the air/gas mixture flow through restricted passages and make abrupt right angle turns. The increases in velocity and directional changes create turbulence and thus induce mixing.

A more efficient method of mixing employs high velocity air jets. This technique uses the momentum of the jets to impart turbulence and, at the same time, supply oxygen for combustion.

A minimum temperature is necessary for the gas phase reaction to proceed to completion in a specified residence period. At higher temperatures the reaction takes place more rapidly. Most packaged incinerators are designed to operate in the 650° to 980°C range. Some difficult to burn wastes require higher temperatures. Auxiliary fuel is used to keep the combustion gases at operating temperature, particularly at the beginning and end of the burning cycle when the temperature of the combustion gases is at a minimum. Auxiliary fuel is usually natural gas but light oil and LPG are also used.

Sufficient time for mixing of the reactants and for the reaction to come to equilibrium is provided by a residence chamber in which the flue gases are held at operating temperature for up to 0.5 second before they leave the incinerator.

Packaged incinerators are designed to create all the conditions necessary for complete combustion of the waste. The success of the design is usually reflected in the amount of pollutants emitted from the stack. The majority of the pollutants are products of incomplete combustion and thus good incinerator design plays an important role in controlling air pollutants.

There are two principal designs currently on the market; the multiple-chamber incinerator which became prominent in the mid-nineteen fifties and the controlled air incinerator which was introduced commercially in the late nineteen sixties.

3.2 Multiple-Chamber Incinerator

As the name implies, multiple-chamber incinerators are composed of three independent chambers or zones, as depicted in Figure 1. Waste is charged intermittently into the ignition chamber. Charging may be done manually or with a mechanized loader. Each new charge is dried and ignited by the previous one sometimes assisted by an auxiliary burner. Underfire combustion air is supplied through a fixed cast iron grate while overfire air enters through natural draft ports usually located in the charging door.

Combustion gases flow through the flame port into the mixing chamber. Secondary air is supplied by natural draft and a second auxiliary burner is provided to maintain combustion gas temperatures. This chamber is sized to create a high gas velocity to induce mixing of the combustion gas with the secondary air.

From the mixing chamber the gases pass under a curtain wall into the combustion chamber. This chamber is sized for low gas velocity, and provides retention time for complete combustion of gaseous

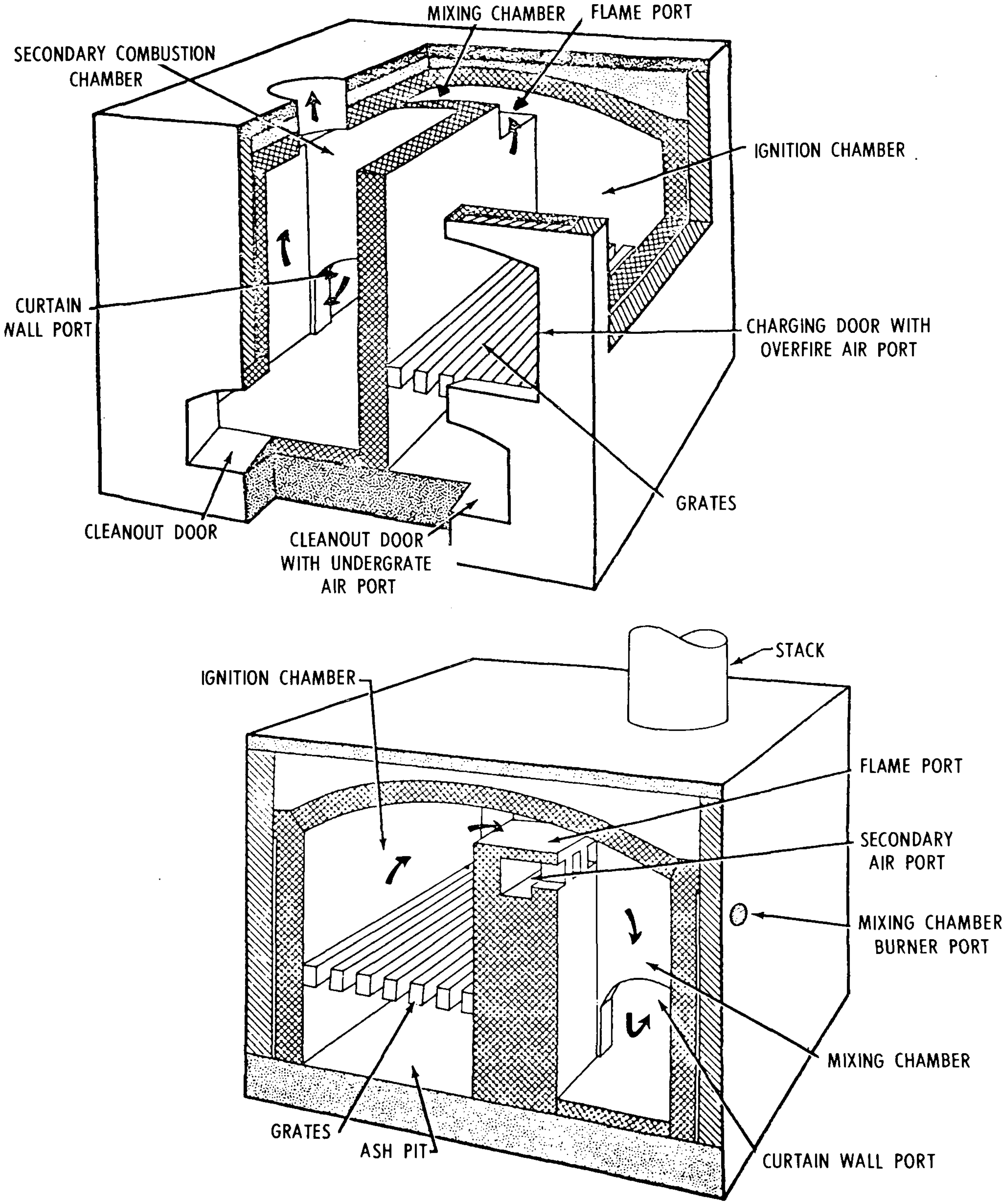


FIGURE 1 MULTIPLE-CHAMBER INCINERATOR

pollutants and particulate matter. The low velocity in this chamber encourages settling of the larger particles. The combustion products then pass out of the furnace into the stack or breeching.

3.3 Controlled Air Incinerator

Controlled air incinerators are characterized by an airtight ignition chamber, compact afterburner and forced combustion air supply. The main features are illustrated in Figure 2.

Some controlled air incinerators are designed to store waste for an entire day. Once the unit is full, the waste is ignited and burned with no further additions to the waste charge. The unit is allowed to cool and is then manually cleaned prior to the next day's operation.

Alternatively, the incinerator may be designed to be charged periodically while in operation. In this case an air lock feeder is used to charge the waste and prevent unwanted air from entering the ignition chamber. Restricting the admission of air to the ignition chamber is essential for the proper operation of the controlled air incinerator.

An auxiliary burner is provided in the ignition chamber to start the burning cycle and to increase the burning rate when the material is wet or compact. Forced underfire air is supplied by a blower through a series of small holes (tuyeres) in the refractory floor of the ignition chamber or along the walls close to the floor. No cast iron grate is used.

Overfire air is not added in the ignition chamber. The combustible rich gases rising from the top of the refuse bed are conducted to an afterburner chamber usually mounted on top of the incinerator or incorporated in the stack. High velocity air jets in the afterburner add oxygen and create turbulence. An auxiliary burner maintains the desired temperature of the mixture and the stack serves as the residence chamber for completion of combustion.

3.4 Design Comparison

The fundamental difference between the controlled air incinerator and the multiple-chamber design lies in the amount of combustion air supplied and the manner in which it is admitted. Each kilogram of waste material requires a stoichiometric (theoretical) quantity of air to combine with the combustibles in the waste. For example, cellulose, the most common waste constituent, requires 5.1 kg of air for each kg of cellulose. If it were burned with just that quantity of air and there were no heat losses, the combustion products would reach a temperature of 1930°C. Temperatures in this range would damage the ignition chamber walls and thus the temperature must be reduced. Ignition chambers are usually designed for temperatures in the 540° to 980°C range.

Figure 3 (p. 16) illustrates how the temperature of the combustion products varies with combustion air supply. Excess air is expressed as the percentage of air which is excess to stoichiometric requirements. From Figure 3 it can be seen that the gaseous products reach a maximum temperature at 0 percent excess air or under stoichiometric conditions. With less than stoichiometric air the temperature decreases due to incomplete combustion of the waste. With more than stoichiometric air the temperature decreases because of dilution with excess air.

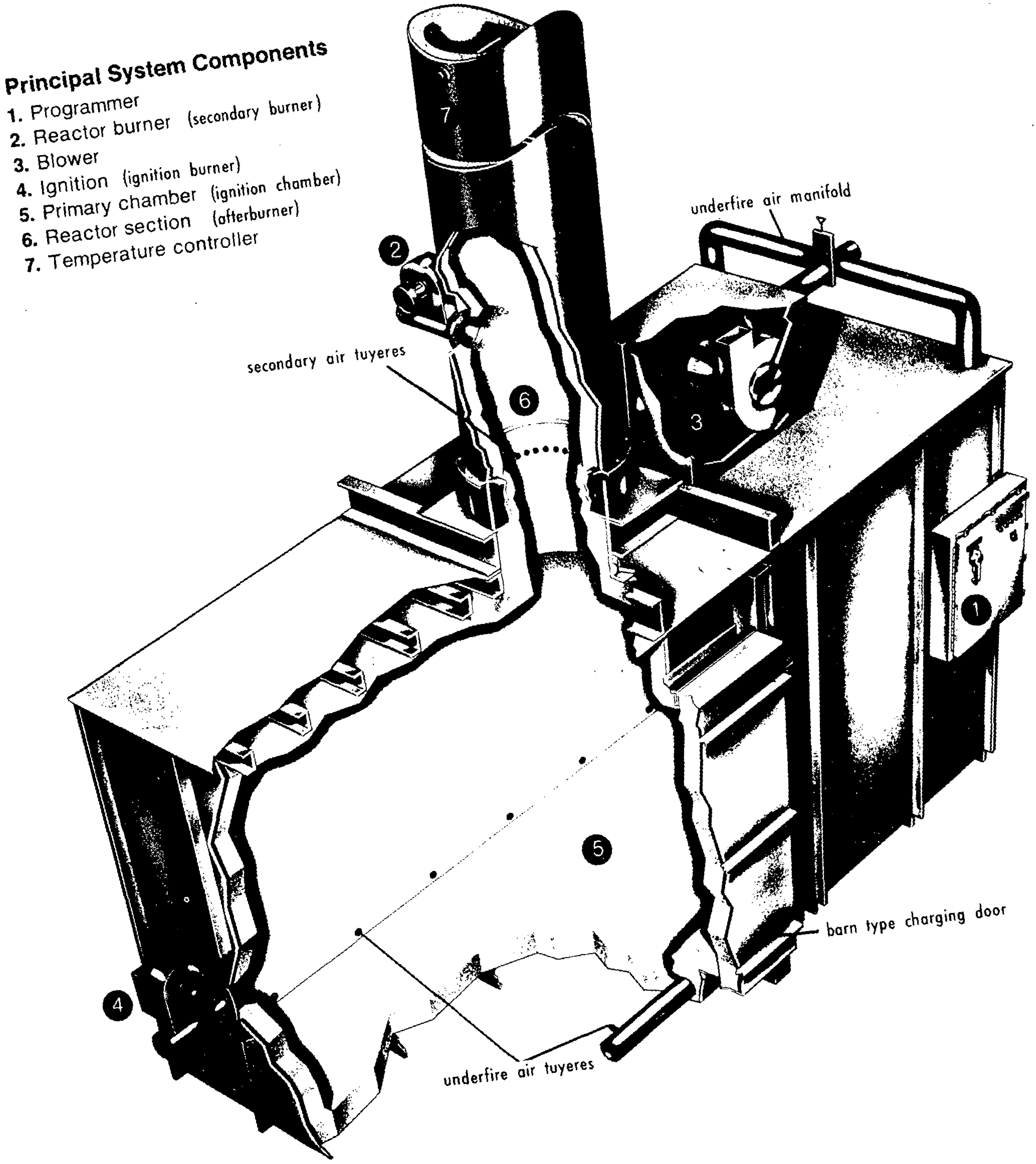


FIGURE 2 CONTROLLED AIR INCINERATOR
(Courtesy Plibrico (Canada) Ltd.)

Consequently, there are two approaches to keeping the gas temperature in the ignition chamber in the desired range. The multiple-chamber incinerator uses the excess air approach while the controlled air incinerator starves the combustion reaction by using less than the stoichiometric quantity of air. By starving the reaction, the volatile fraction of the waste is gasified. The combustible gas is subsequently combined with air and burned in the afterburner. The char portion of the waste burns in the ignition chamber and supplies heat for the gasification process. Energy from the waste is thus released throughout the incinerator. This eliminates the need for cooling air in the ignition chamber and reduces the requirement for auxiliary fuel in the afterburner.

Combustion air is supplied in multiple-chamber incinerators by the natural draft created by the stack. The air enters through adjustable ports located above the grate, in the ash pit beneath the grate, and in the mixing chamber. Air also leaks in around charging and cleanout doors and enters through the charging door when waste is added. Auxiliary burners also add to the excess air. Total excess air is commonly 200 to 400 percent.

In controlled air incinerators, combustion air is supplied by a fan and is admitted through tuyeres in ignition chamber floor or walls and in the afterburner. Usually a single fan is used to supply both locations. Butterfly or guillotine dampers are installed in the ducts to regulate flow. The gasification process is very sensitive to the quantity of air supplied. A forced draft system can be more closely regulated than a natural draft one, and for this reason a combustion air fan is invariably part of a controlled air incinerator.

Forced combustion air in the afterburner provides a rapid and efficient method of adding oxygen and mixing it with the combustion gases from the ignition chamber. Total excess air used in controlled air incinerators is generally between 100 and 200 percent.

3.5 Operation

An incinerator operator's main duties are to charge the incinerator with waste and to clean out the ash. These functions, particularly the charging operation, have a significant effect on air pollution emissions. With the multiple-chamber incinerator, the operator is required to charge small batches of waste every 5 to 10 minutes so that the aggregate equals the hourly rated capacity. Prior to charging, the refuse bed should be carefully stoked away from the charging door and then the new charge placed on the grate close to the door. Even with the careful observance of the proper procedure, the stoking action disturbs the bed, creating fly ash emissions. The large quantity of air entering the ignition chamber due to frequent opening of the charging door reduces the temperature throughout the incinerator and leads to incomplete combustion of the organic particulate matter and gases.

Proper operation of a multiple-chamber incinerator requires constant attendance by the operator. Often the operator has other duties which prevent him from following proper routine. Some installations have no full time operator; instead, persons delivering the waste have responsibility for charging. More often than not, proper procedure is not followed and charging is done infrequently with large batches of waste.

Rapid volatilization of a large quantity of waste can overtax the incinerator's ability to supply and mix secondary combustion air. The result is a rich black plume of unburned volatiles. With time the volatilization rate decreases to the point where sufficient oxygen is available and the plume disappears. However, if more waste is not added, the temperature within the incinerator will decrease. When it falls below the ignition temperature of the particulate and gaseous combustibles, a white smoke plume results. Ignition temperatures are usually in the 425° to 650°C range, depending on the waste and the other combustion variables.

The multiple-chamber incinerator relies heavily on the operator for optimum air pollution performance. Because of the inconvenience of the proper operating procedure and the exacting requirements which serve only air pollution control, proper operation is the exception rather than the rule. Continued surveillance on the part of the air pollution control agency is necessary to maintain a minimum standard of operation. Apartment house incinerators as a group were so poorly operated and maintained that they are now prohibited by legislation in major cities in North America.

Many of the operating problems of the multiple-chamber incinerator which resulted in air pollution were solved by the introduction of the single batch controlled air incinerator. In many instances a whole day's waste is collected and delivered to the incinerator over a few hours. The large ignition chamber of the controlled air incinerator acts as a storage bin during the collection period, after which the door is sealed and an automatic burning cycle is started. The cycle continues throughout the night and in the morning the cooled ash may be removed by the operator. A timer controls the sequencing of burners and combustion air blowers. Because no waste is added during the cycle, an operator is not required and air pollution emissions are minimized. While this mode of operation is suitable in many instances, there are situations where it is desirable to charge the incinerator during the burning cycle. This reduces the size of incinerator required to handle a day's waste. It is accomplished by adding a mechanical loader to the standard controlled air model. There are several loader designs, most of which incorporate a hopper, ram and guillotine charging door. As the waste arrives at the incinerator, it is placed in the hopper. When the hopper is full a cover is lowered over it, the guillotine door opens and the ram pushes the waste into the incinerator. The lid, together with the waste plug, limits air entering the ignition chamber. Overcharging is prevented by sizing of the hopper and limiting the frequency of the ram cycles.

Charging during the burning cycle disturbs the refuse bed and increases air leakage. However, emission tests show no significant increase in particulate emission rates for this type of operation.

The addition of a mechanical loader increases incinerator capacity considerably. The ash build-up becomes the limiting condition in the ignition chamber. With some types of low ash material, such as cardboard, it is possible to operate 24 hours per day, 6 days per week before cleanout is necessary. With other types of waste more frequent cleaning is required. For instance, municipal refuse can be charged at rated capacity for only about 10 hours before the chamber becomes full.

Ash removal has presented a problem in packaged incinerators, particularly controlled air types. With multiple-chamber incinerators, ash is removed manually with hoe and shovel through ash doors conveniently located around the incinerator. Doors are a major source of air leakage and so controlled air incinerators usually incorporate only one door which serves for both loading and cleanout. On small controlled air units, cleanout can be accomplished from outside the unit with a shovel or vacuum cleaner. Larger models, however, may be up to 6 metres long, requiring that the operator enter the incinerator and shovel the ash into barrels or tubs inside the unit. This can be hazardous at times because of hot walls, pockets of glowing ash, dust and noxious gases.

An alternative particularly suitable for outdoor installations is to mount a large hoe on the front of a vehicle and by manoeuvering the vehicle in front of the incinerator the hoe can be introduced and ash raked out onto the ground or into a container. Water sprays are used outside the unit to suppress dust. This method is simple and effective but sometimes hard on refractory.

A relatively new development offered by some manufacturers is an automatic ash discharge system. With this system the charging ram forces new waste into the ignition chamber pushing the previous charge across the floor. The waste is reduced to ash by the time it reaches the opposite end of the chamber. The ash then drops into a quench tank or an ash pit where it is removed without allowing air to leak back into the unit.

On any controlled air incinerator the initial adjustments to combustion air flow rate and cycle timing should be made to suit the individual character of waste to be burned. Combustion air is usually supplied by one blower and divided between ignition chamber and afterburner by dampers. The ratio should be adjusted so that the quantity of air supplied to the ignition chamber does not result in a volatilization rate that will demand more oxygen than can be supplied in the afterburner. The volatilization rate reaches a maximum shortly after the waste is lit, or after a new batch is charged. If the primary air rate is too high it will be evident at this time. Black smoke will be emitted, or flaring may occur at the top of the stack. Smoke may also be observed puffing out from around the charging door. This condition can be corrected by reducing the air supplied to the ignition chamber and increasing the air to the afterburner until smoking ceases. Smoke free operation can be obtained with as little as 1 percent oxygen in the flue gas. The air flow rates should be adjusted, however, so that the oxygen content never falls below 4 percent to provide a margin of safety. The oxygen content of the flue gas is easily measured with a hand held oxygen analyzer.

Too much secondary air will lower the gas temperature in the afterburner. This is particularly critical at the beginning and end of the burning period when heat from the ignition chamber is at a minimum. If the temperature falls below the ignition temperature of the smoke and organic gases, they will not burn and a white plume will result. This condition can be corrected by reducing the quantity of air supplied to the afterburner. If this results in insufficient air during peak volatilization periods, then the primary air must be reduced to slow volatilization. Alternatively, the auxiliary burner capacity could be increased.

Auxiliary fuel use in the afterburner provides about 4650 kJ/hr for each kg/hr of rated waste burning capacity. Depending on the manufacturer and the type of waste to be burned, the auxiliary burner may have a rating in the range of 2330 to 6980 kJ/lb of waste burned. Some large incinerators are equipped with high-low fire burners to provide quick preheat and to conserve fuel. With either type, the capacity must be sufficient to preheat the afterburner to about 540°C in a reasonable time before the waste is ignited. The burner should not be so large that, during normal operation, it creates such a high stack temperature that it must be shut off to protect the refractory. It is important that the burner operate continuously throughout the burning cycle. An auxiliary burner is required in the ignition chamber to light the waste and to increase the burning rate when the waste is wet. With dry waste, the burner remains on only long enough to start combustion. With wetter wastes, larger quantities of auxiliary fuel are necessary and burners remain on throughout the burning period.

Pathological waste is one of the wettest types to be burned in packaged incinerators. Moisture content averages 85 percent. Auxiliary fuel usage in the ignition chamber is usually 11630 kJ/kg of waste. Because of the low combustible content, the waste does not gasify under a starved air atmosphere as dryer wastes do in controlled air incinerators. Consequently, precautions limiting air leakage are not as critical and air lock charging is not necessary. Because of the similarity of operation with pathological waste, particulate emissions from both controlled air and multiple-chamber styles are comparable.

A stack is an essential part of any incinerator. It is used to create draft in the ignition chamber and carry away combustion products. Draft is most important in multiple-chamber incinerators because it induces flow of combustion air. With controlled air incinerators, air leakage is kept to a minimum but excessively high draft, as sometimes occurs when incinerators are located in the basements of tall buildings, can create sufficient leakage to upset the less than stoichiometric condition in the ignition chamber. For these reasons, all multiple-chamber incinerators and controlled air incinerators with stacks higher than 60 feet should be equipped with a barometric damper. In the latter case the damper should be located at sufficient distance beyond the afterburner to prevent quenching of the gases before combustion is complete.

Both incinerator types should also be equipped with a damper that blocks the stack during cleanout to prevent the escape of light ash particles.

4 AIR CONTAMINANT EMISSIONS

4.1 Pollutant Formation

There are a variety of pollutants emitted from packaged incinerators. These fall into three categories: particulate matter (both inert and combustible), combustible gases and non-combustible gases. Particulate matter is usually defined as finely divided liquid or solid material, other than uncombined water. Particulate matter from incinerators is commonly referred to as smoke and fly ash. Fly ash is a term used to describe large particles which are of sufficient size to be seen individually by the naked eye. Smoke is a collection of much smaller particles which reduces light transmission and decreases visibility.

Particulate emissions from packaged incinerators are primarily a result of entrainment of waste particles in the combustion gases and, to a lesser extent, they result from condensation of volatile metals and pyrolysis gases.

It has been found that the entrainment of particles from the refuse bed increases with gas velocity in the ignition chamber, particularly the underfire air velocity (4). Because of the smaller volumes of air used in the controlled air incinerator, fewer particles are lifted from the refuse bed, consequently particulate emissions are lower.

The particles, both organic and inorganic, are lifted from the refuse bed. The organic fraction, being combustible, will be reduced or eliminated if suitable conditions are maintained in the afterburner of a controlled air incinerator, or the mixing and combustion chambers of a multiple-chamber incinerator. The inorganic fraction will not be affected by the combustion process, but will be carried out in the flue gas of either type incinerator. The ash content of the refuse influences the particulate emission rate, because a higher proportion of the material entrained in the flue gas will be inorganic and thus not affected by combustion.

Combustible gases are an intermediate product in the combustion of solid fuel. They are created by the pyrolysis of the volatile fraction of the waste and by partial oxidation of the pyrolysis gases and char. There are numerous gases formed in this process; the main ones are carbon monoxide, hydrogen, hydrocarbons (principally methane, aldehydes, ketones), organic acids and ammonia. These gases will be oxidized in the afterburner section, if proper combustion conditions are maintained. When conditions are deficient, however, a portion will escape to atmosphere as air contaminants. These gases are undesirable primarily due to their odorous and irritant qualities. Some cause other adverse physiological effects and some contribute to photochemical smog reactions.

There are three main non-combustible gases and contaminants emitted from packaged incinerators: nitrogen oxides (NO_x), sulphur oxides and hydrogen chloride. Nitrogen oxides are formed by combustion of nitrogen-bearing waste material and by high temperature oxidation of nitrogen in the combustion air. The concentration of NO_x in the flue gas is relatively low, compared to that from fossil fuel fired sources, primarily because of the relatively low operating temperature of incinerators.

Sulphur dioxide and hydrogen chloride emissions result from the combustion of sulphur- and chlorine-bearing waste constituents. Rubber is the most common sulphur bearing material, while plastic packaging, wire insulation and construction materials made from polyvinyl chloride (PVC) are the most common chlorine-bearing constituents. Other materials such as food waste, wood, grass and leaves contain trace amounts of both sulphur and chlorine. The sulphur content of rubber is about 1 or 2 percent while the chlorine content of PVC is 58 percent. Not all the sulphur or chlorine present in the waste is released in the flue gas; some reacts with the ash and remains in the incinerator. The proportion emitted varies, but the average amount is about 60 percent of the available sulphur or chlorine.

4.2 Emission Rates

Typical emission rates for well designed and operated multiple-chamber and controlled air incinerators are listed in Table 2. These emission rates were derived from manufacturer's emission test reports and other test results reported in the literature. Listed also are emissions from single chamber incinerators. These preceded the multiple-chamber and controlled air types and were typified by the lack of a secondary combustion chamber. Although this design has now been supplanted, average emission rates have been included to illustrate the improvement achieved by the more recent designs.

TABLE 2 EMISSIONS FROM PACKAGED INCINERATORS*

Pollutant	Controlled Air	Multiple Chamber	Single Chamber
Particulate Matter (dry filterable) (g/kg)	0.6	1.2	7.7
Particulate Matter (condensible) g/kg	0.3	1.0	4.2
Particulate Matter (total) g/kg	0.9	2.2	11.9
Carbon Monoxide g/kg	Neg.	1.8	99 to 496
Organic Acid (acetic) g/kg	N.A.	0.4	<2
Aldehydes (formaldehyde) g/kg	N.A.	0.09	3 to 32
Hydrocarbons (methane) g/kg	Neg.	<0.5	N.A.
Nitrogen Oxides g/kg	1.6	1.1	<0.05

* From emission test reports on file with Combustion Sources Division and from References 5 and 6

Neg. – Negligible
N.A. – Not Available

The emission rates shown in Table 2 are expressed as grams of pollutant emitted per kilogram of waste burned. Particulate matter has been divided into two categories, dry filterable and condensible. This refers to the sampling technique usually employed to measure particulate emissions. The dry filterable portion is collected at a temperature above 120°C in the nozzle, probe, cyclone and filter of the sampling train. The condensible portion is collected in wet impingers suspended in an ice bath. Complete details of the sampling apparatus and procedure are contained in "Standard Reference Methods for Source Testing: Measurement of Emissions of Particulates from Stationary Sources'' report EPS 1-AP-74-1. Compliance with particulate emission regulations is usually based on the dry filterable portion only. Subsequent references to particulate matter will refer only to that fraction.

Particulate matter is the main pollutant and also the best indicator of incinerator performance. The average particulate emission rate for well designed and operated controlled air incinerators is 0.6 g/kg, as opposed to 1.2 g/kg for multiple-chamber incinerators and 7.7 g/kg for single chamber incinerators.

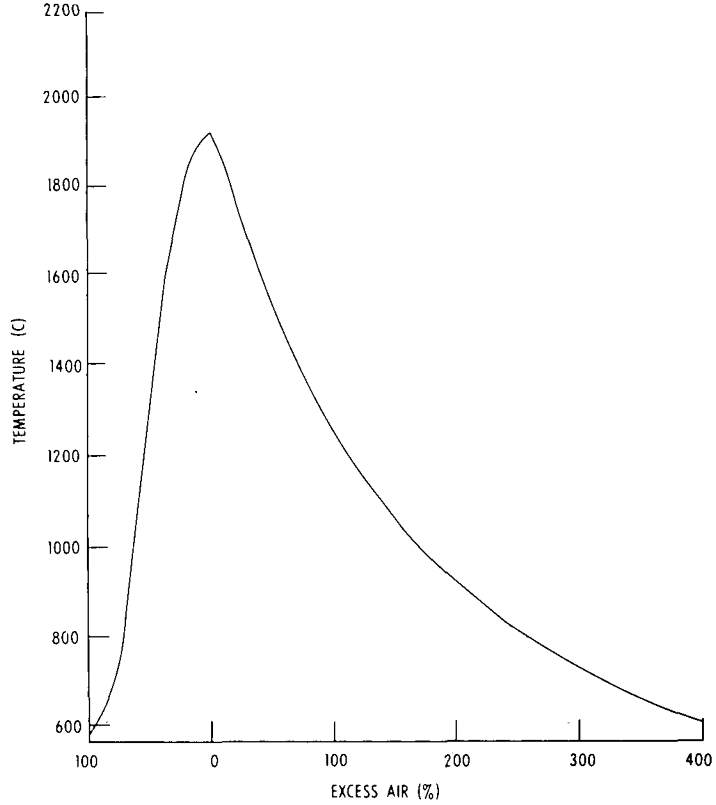
Figure 4 is a histogram derived from fifty-eight particulate emission tests conducted on controlled air incinerators by nine different manufacturers. Each box represents one test run. The results are grouped according to the type of waste burned during the test: cellulosic, pathological and industrial. The industrial wastes include nylon, oil soaked filters and wire insulation. As can be seen from the average and median particulate emission rates, the tests conducted with cellulosic and industrial waste have similar emission rates. The number of tests reported for pathological waste incinerators is small. However, they indicate a higher emission rate for this type of waste. The difference is probably related to the different charactertistics of pathological waste and the changes in incinerator operation necessary to handle the waste. Pathological waste is normally composed of 85 percent water, 10 percent combustible material and 5 percent ash. It is not possible to gasify this waste in the same manner as drier material. Substantial quantities of auxiliary fuel are necessary to destroy pathological material in a reasonable length of time. For maximum effect, auxiliary burners impinge directly on the waste. This procedure tends to disturb the inorganic part of the waste and entrain it in the flue gas.

4.3 Emission Control

Emissions from packaged incinerators are controlled in several ways. Inorganic particulate matter can be prevented from entering the flue gas stream by reducing the quantity of combustion air and consequently the gas velocity in the ignition chamber. With little turbulence in this chamber, few particles are lifted from the refuse bed. Combustible particulate matter and gases are controlled with afterburning. Afterburners which use forced combustion air can optimize combustion conditions and provide efficient reduction of organic emissions in a minimum of space.

Proper operation is essential in emission control. The incinerator must be adjusted for the type of waste burned and the operator should follow proper operating procedure, particularly with respect to charging. Incinerators that are charged in a single batch and operate on a timed cycle, and incinerators that regulate charging and air admission by mechanical means, remove much of the responsibility for emission control from the operator. These incinerators will provide a more consistant level of emission performance.

It is possible to reduce particulate emissions from multiple-chamber incinerators to the levels achieved by controlled air units by adding a flue gas scrubber. This combination has the additional advantage of removing some gaseous constituents from the flue gas. However, scrubbers increase operation and maintenance requirements and lower reliability. They also produce liquid effluent that has to be treated and recycled. For these reasons, the multiple-chamber incinerator and scrubber combination



FIGURE, 3 ADIABATIC TEMPERATURES OF CELLULOSE COMBUSTION WITH EXCESS AIR VARIATIONS [3]

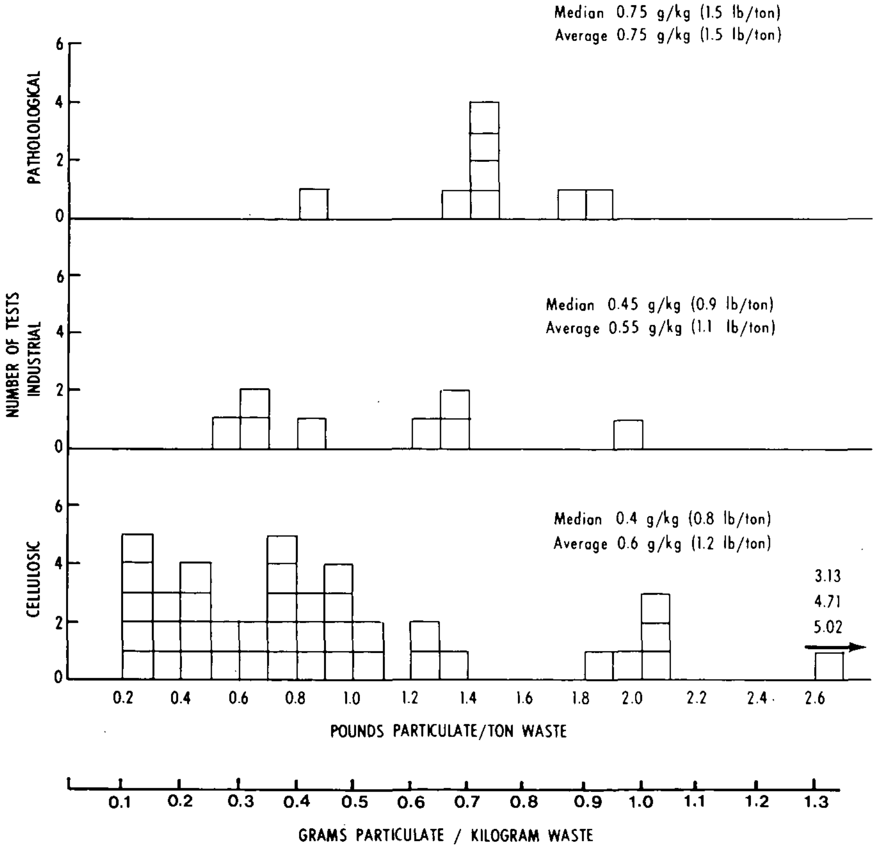


FIGURE 4 DISTRIBUTION OF PARTICULATE EMISSIONS FROM CONTROLLED AIR INCINERATORS

is not as desirable as the controlled air incinerator for control of particulate emissions and combustible gases.

Incinerators that burn waste containing chlorine or sulphur will emit hydrogen chloride and sulphur dioxide respectively. Usually the most effective method of controlling these emissions is to segregate the offending waste constituents and dispose of them in some other manner. There are, however, incinerators that are designed to burn autombile tires or PVC insulation from copper wire. In applications such as these and in situations where segregation of the chlorine- or sulphur-bearing constituents is not possible, flue gas scrubbers can be used to remove hydrogen chloride or sulphur dioxide.

If an incinerator without a scrubber were to burn waste containing 0.25 percent PVC or 20 percent rubber, then considering the various factors influencing hydrogen chloride and sulphur dioxide emissions, the incinerator would emit 80 ppm of hydrogen chloride corrected to 12 percent CO_2 (0.87 grams of HCl per kilogram of waste) or 180 ppm of sulphur dioxide corrected to 12 percent CO_2 (3.6 grams of SO_2 per kilogram of waste) respectively. In practice, the concentrations would be higher due to chlorine and sulphur in the other waste constituents and auxiliary fuel.

5 CONCLUSIONS

5.1 General

There are thousands of packaged incinerators in Canada operated by commercial, industrial, institutional and residential users to dispose of a wide variety of solid wastes. They emit particulate matter, carbon monoxide, hydrocarbons, organic acids, ammonia, nitrogen oxides, sulphur dioxide and hydrogen chloride. Many of these pollutants are products of incomplete combustion and can be satisfactorily controlled through good incinerator design and operation. Other pollutants such as sulphur dioxide and hydrogen chloride are not products of incomplete combustion but result from the decomposition of sulphur- and chlorine-bearing waste materials. Their removal requires physical or chemical treatment of the incinerator flue gas.

5.2 Emission Control Technology

The controlled air incinerator, because of its combustion design and automated operation, consistently emits less combustion related pollutants than the multiple-chamber incinerator. For this reason properly designed controlled air incinerators should be used for all new installations where the waste is composed of types A to L in the CSA classification and the required capacity is 900 kilograms or less per hour.

Existing installations may be either controlled air or multiple-chamber types or some other specialized design. In any case, existing units should perform at least as well as a properly designed and operated multiple-chamber incinerator. Units which do not meet this standard should be upgraded through internal modifications or additions. When this is not practicable, the unit should not be operated.

Emissions of hydrogen chloride and sulphur dioxide can be controlled by removing sulphur- and chlorine-bearing materials from the waste. Alternatively, these gases may be scrubbed from the flue gas. Because installations requiring flue gas scrubbers are few and often custom designed to suit the waste properties, selection of appropriate scrubbing equipment is best done on an individual basis.

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