



PDHonline Course C508 (4 PDH)

An Introduction to Solid Waste Incineration

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An Introduction to Solid Waste Incineration

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AN INTRODUCTION TO SOLID WASTE INCINERATION

1. INTRODUCTION. This course is an Introduction to the basics of disposal of solid waste by incineration.

2. BASICS OF INCINERATION

2.1 DEFINITION AND DESCRIPTION OF INCINERATION PROCESS.

2.1.1 DEFINITION. Incineration is a controlled combustion process for reducing solid, liquid, or gaseous combustible wastes primarily to carbon dioxide, water vapor, other gases, and a relatively small, noncombustible residue that can be further processed or land-filled in an environmentally acceptable manner.

2.1.2 DESCRIPTION. The incineration of solid waste involves a sequence of steps in the primary process, which includes drying, volatilization, combustion of fixed carbon, and burnout of char of the solids, which is followed by a secondary process, the combustion of the vapors, gases, and particulates driven off during the primary process.

3. CLASSIFICATION AND CHARACTERIZATION OF WASTE.

3.1 WASTE CLASSIFICATION. Four types of waste are identified here. The basic properties and descriptions of these four types are presented in Table 1.

3.2 WASTE CHARACTERIZATION. Detailed combustion characteristics are needed for the calculation of heat balances for the incinerator. For design purposes, the most important characteristics are the higher heating value, moisture content, and percent of inert material in the waste.

3.2.1 Maintaining minimum moisture is important as the energy required to dry the waste reduces the energy available to volatilize vapors and provide the necessary gas temperatures to complete the destruction of the unburned gases, vapors, and particulates.

3.2.2 Plastic wastes typically have a high specific-heating value (i.e., Btu/lb). The composite waste Btu content is therefore sensitive to the percent of plastics and other dry, high-Btu material (e.g., cardboard, paper, etc.) in the incinerator feedstock. Tables 2 and 3 provide combustion data on some materials in domestic and commercial wastes. Table 2 shows the nominal composition of discards in municipal waste (household waste).

3.2.3 The percentages of components in the waste which is to be combusted must be determined on the basis of a waste characterization analysis.

3.3 HEATING VALUE OF WASTES AND FUELS.

3.3.1 HEATING VALUE. The heating value for combustible materials may be presented in many ways. Table 3 lists the "as-fired" heating values generally assigned to different types of waste, some chemicals, and major constituents in municipal-type, and industrial-type, wastes. Table 5 lists the chemical analyses of some municipal, residential, and commercial wastes and indicates the higher heating values of the combined waste stream for as-received, moisture-free, and ash-free material. Table 6 lists the proximate analysis of 30 different components in municipal and commercial waste.

3.3.2 EFFECT OF MOISTURE ON HEATING VALUE. Since moisture is in effect water, a non-burnable component in the waste, it is important that the water content be kept to a minimum. All water in the feed stock must be vaporized in the drying phase of combustion.

3.3.2.1 Vaporization of water requires a nominal 1000 Btu/lb. Type-2 waste, containing 50% by weight water, requires approximately 12% of its heating value to dry the waste, and another 10% to raise the temperature of the water vapor to the required temperature for complete combustion.

3.3.2.1.1 Where practical, the addition of moisture should be prevented by providing covers on disposal containers to keep out rain and snow .

3.3.2.1.2 Alternative methods for the disposal of wet food waste and landscape wastes will also help to improve the quality of the waste stream. Note the difference between the as-discarded and the dry-basis values for the items listed in table 6.

3.3.2.2 Table 7 shows the ultimate analysis of these same constituents. Table 3-8 shows the ultimate analysis of some plastics commonly used in consumer products and containers and compares them with fuels used in power generation and space heating.

3.3.3 Effect of Preprocessing and of Source Separation/Collection for Recycle Programs on the Fuel Value.

3.3.3.1 The practice of preprocessing waste to remove inert materials, many of which are recyclable, is increasing as more communities and states are requiring waste stream recycling .

3.3.3.2 Incinerator operators are finding this to be advantageous because it removes up to 20% of the waste that is non-burnable and which often creates ash-handling equipment difficulties.

3.3.3.2.1 Processing the waste to produce an enhanced fuel product, called Refuse-Derived Fuel (RDF), raises the fuel heating value.

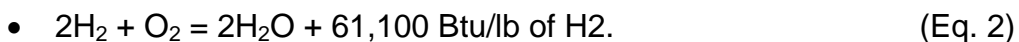
3.3.3.2.2 If the waste is processed for both optimization of recyclable materials recovery (i.e., remove recyclable paper, cardboard, and plastic) and fuel beneficiation (i.e., remove glass, aluminum, steel and inerts), the heating value drops. The end product may now consist of only 43-55% of the original waste. Table 3-9 shows the effect of processing and materials recovery/recycle on the heating value of waste.

4. OXIDATION.

4.1 BASIC CHEMISTRY. Incineration is an oxidation process, where organic constituents react with oxygen and release heat during the process. Combustion may be defined as the rapid chemical combination of oxygen with the combustible elements of a fuel.

4.1.1 The two major combustible chemical elements of significance are carbon and hydrogen. Chlorine and sulfur are usually of minor significance as sources of heat, but they (primarily chlorine) are usually the major constituents concerning corrosion and pollution.

4.1.1.1 Carbon and hydrogen, when burned to completion with oxygen, unite according to equations 1 and 2.

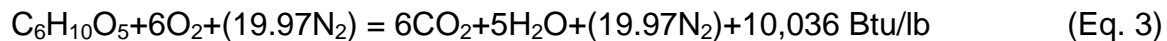


2.66 lb of oxygen (or 11.5 lb of air) are required to oxidize one pound of carbon and produce 3.66 lb of carbon dioxide. Similarly, 8.0 lb of oxygen (or 34.6 lb of air) are required to oxidize one pound of hydrogen and produce 9.0 lb of water vapor.

4.2 STOICHIOMETRY. The ratio of the actual amount of oxygen supplied in the oxidation process to the amount actually required is called the Stoichiometric Ratio (S.R.). In the examples given, the S.R.= 1.0. The heat released (i.e., 14,100 Btu/lb when

carbon is oxidized, or 61,100 Btu/lb when hydrogen is oxidized) raises the respective products of combustion, plus other gases present, to high temperatures.

4.2.1 The burning of compounds containing oxygen require less air since the compound already contains some oxygen that will be made available during the combustion process. A typical waste stream component like cellulose, a major constituent in paper products, is destroyed according to equation 3.



4.2.2 Because oxygen is present in the "fuel," only 5.1 lb of air per pound of cellulose are required to completely oxidize the cellulose. The theoretical amount of combustion air will produce the highest temperature combustion product gas temperature (i.e., an adiabatic gas product temperature of 3,250⁰F).

4.3 EFFECT OF EXCESS AIR.

4.3.1 Since air is the usual source of the oxygen, excess amounts of air will dilute the gases and reduce the temperature of the gases. When mass burning unprocessed municipal waste, approximately 7.5 lb of air (S.R.1.0) are required to burn 1 lb of waste. Any processing that improves the fuel quality (i.e., removal of non-combustibles and high-moisture-content materials) will increase the heating value of the remaining waste and the specific air demand (i.e., pounds of air per pound of material actually being burned).

4.3.1 Figure 1 shows the relationship between calculated flame temperature, stoichiometric ratio, and moisture content in the waste.

4.4 EFFICIENCY.

4.4.1 The objectives of combustion in an incinerator are the complete destruction of the organic constituents to form harmless gases and the prevention of the release of any

harmful material to the environment. Efficient conversion of the heat released into useful energy, though important, is secondary to safe and efficient destruction of the waste.

4.4.2 The oxidation of the combustible elements requires a temperature high enough to ignite the constituents, mixing of the material with oxygen, or turbulence and sufficient time for complete combustion, (i.e., the three "Ts" of combustion). Proper attention to these three factors can produce destruction/conversion efficiencies of 99.9%-99.95% in well-operated incinerators.

4.5 EXCESS AIR.

4.5.1 High-efficiency destruction (oxidation) of any combustible material requires that more oxygen be present than what is required by the chemistry of the process. Since combustion is a chemical process, the rate of oxidation is contingent upon many factors that can make the reactions occur at a faster or slower rate. The percent of excess oxygen present and available to the reaction is one of these factors.

4.5.1.1 In general, combustible gases and vapors require less excess oxygen to achieve high-efficiency oxidation than do solid fuels due to the ease of mixing and the nature of the compounds in the gases and vapors.

4.5.1.2 Solid fuel materials, because of the more complex processes involved in their combustion, require more excess air and more time.

4.5.2 Quantities of excess air have been determined empirically for different fuels and are given in table 10.

4.5.3 Increasing the quantity of excess air beyond the percentages indicated does not benefit the combustion process and lowers the gas temperature thereby reducing the efficiency of the downstream heat-recovery process.

4.5.3.1 The best combination of combustion efficiency and energy recovery when mass burning municipal waste in a large water-wall incinerator has been observed to occur with a system S.R. of 1.4 to 1.5.

4.5.3.2 The secondary combustion chambers in modular and packaged incinerators achieve their highest destruction efficiency at S.R.s of 1.5 to 2.0.

5. MECHANISM OF COMBUSTION.

5.1 PRIMARY COMBUSTION PROCESS. The thermal destruction of waste (or any other solid fuel with significant moisture content) is accomplished in four phases as described below:

5.1.1 PHASE ONE. The first phase is the drying phase that occurs in the initial heating of the heterogeneous material. Moisture is driven off as the material is heated past the vaporization temperature of water. Drying is usually complete by the time the material has reached 300°F.

5.1.2 PHASE TWO. The second phase is the volatilization of vapors and gases which occurs as the temperature of the waste continues to rise. Vapors and gases diffuse out as their respective volatilization temperatures are attained. Those vapors and gases having low flash points (i.e., the temperature at which a specific gas or vapor will ignite) may react with primary combustion air to burn at the surface of the bed of waste. If excess oxygen is not available, as in the case of starved-air incinerators, the low-temperature volatilization of vapors and gases may react to form other hydrocarbons and/or partially oxidized compounds (i.e., carbon monoxide, etc.). These compounds must be burned later in the secondary combustion process where there is sufficient oxygen for complete combustion. The higher flash point gases and vapors will most likely burn only after they have been swept up in the gas flow and subsequently ignite when they are exposed to their respective ignition temperatures. How well they are destroyed will depend upon their being subjected to their requisite "three T" conditions

in the higher temperature zones of the furnace. The flash point for the gases and vapors driven off in this phase of the primary combustion process ranges from approximately 500 to 1,300oF, which is usually several hundred degrees higher than their respective volatilization temperatures. Consequently, combustion of the gases and vapors occurs some distance above the bed in a zone where there is sufficient temperature and oxygen for them to be oxidized. If either or both conditions are not met, the partially oxidized vapors and gases will be carried through the system until the right conditions for completion of the oxidation process are met. Table 11 shows the ratios of air to weight of solids to burn different types of solid waste.

5.1.3 PHASE THREE. The third phase in the burn-down of solids is the in-place oxidation of the burnable solids left after the vapors and gases have been volatilized. The remaining, partially oxidized cellulose, lignins, and other hydrocarbon solids, when further heated, oxidize to form carbon dioxide and water vapor. This portion of the combustion process occurs in or on the bed in a fairly violent manner. In excess-air systems, the residues from this phase are incompletely burned carbon (char) and inert non-combustibles. Starved-air systems will also have some unburned hydrocarbons.

5.1.4 PHASE FOUR. The fourth phase in the process involves the final burn-down of char and the consolidation and cooling of the inert residues, known as bottom ash (metals and ceramic oxides; primarily alumina, silica and calcia, plus lesser amounts of other oxides; see table 12). This material is the end product, which, after a short period of cooling on the hearth/grate, is dumped into the ash-receiving system. In small units, the ash may be dumped directly into a dry collection hopper. In large units, the grate continually dumps the ash into the ash quench pit where it is cooled by water.

5.2 SECONDARY COMBUSTION.

5.2.1 The final destruction process requires specific conditions. The secondary combustion zone (i.e., secondary combustion chamber in packaged and modular units and the high temperature secondary combustion zone in large field-erected units) must

provide the desired temperature, turbulence, and excess air required to achieve complete destruction of all the unburned gases, vapors, and particulates released from the primary combustion process.

5.2.1.1 The complete destruction of high-flash-point, low-heat-content vapors and particulates requires more time and greater turbulence than does the complete destruction of the more easily burned materials.

5.2.1.2 The secondary combustion zone or chamber in which this final combustion process occurs is therefore designed to provide a sufficient volume to achieve the high-temperature residence times required to complete the oxidation of these harder-to-burn materials.

5.2.1.3 By maintaining the temperatures and oxygen partial pressure in the secondary combustion zones well above the requisite minimum conditions, the reactions involved in the complete destruction of the high-flash-point and/or the low-heat-of-combustion compounds is allowed to proceed at a rate fast enough to assure a high degree of destruction during the limited residence time in this zone or chamber.

5.2.2 Common practice in the design of secondary combustion chambers for municipal waste incinerators is to provide a nominal minimum of 1 to 2.5-seconds gas residence time and nominal secondary gas temperatures in the range of 1,800 to 2,000°F. Also, since the combustion of these volatiles will not be complete unless sufficient oxygen is available, additional air is introduced.

5.2.2.1 For unprocessed municipal solid waste (MSW), the optimal percent excess air required to achieve high destruction efficiency and high-efficiency energy recovery in a large waterwall furnace is approximately 40-50% (i.e., a Stoichiometric Ratio of 1.4 to 1.5, which provides an atmosphere containing 6.6%-7.7% excess oxygen).

5.2.2.2 The smaller modular and packaged units achieve their highest destruction efficiencies with 50-100% excess air, or greater (i.e., a stoichiometric ratio of 1.5 to 2.0). They pay for this higher dilution of exhaust gas by having lower efficiency energy recovery.

5.2.2.3 Introduction of this amount of excess air has been found to be necessary in order to supply the necessary partial pressure of oxygen required to achieve the highest destruction efficiency practical for the conglomeration of materials in municipal waste.

5.2.3 TIME FOR PRIMARY COMBUSTION AFFECTED BY THE METHOD OF BURNING.

5.2.3.1 The time required for complete burndown of municipal solid waste in the primary combustion chamber is a function of how the solid waste is fed into the system. The time required varies from six hours to a few minutes, depending upon the design of the furnace and the method used for feeding and supporting the waste while it is being burned.

5.2.3.1.1 MASS BURN SYSTEMS. These systems are the dominant type used to burn solid waste. A mass burn system uses a hearth or a grate to support a large mass of raw or processed waste as it is progressively burned down. The burndown process typically requires a nominal four to six hours from the time the waste is introduced into the primary combustion chamber until the ash is discharged. Incinerators operating under oxygen-deficient conditions (starved-air primary combustion mode) require longer burn-down times than the furnaces operating in the oxygen-rich condition (excess-air primary-combustion mode).

5.2.3.1.2 Injection-Fed, Dispersed-Bed System. This type of feed and method of distributing the waste as it is being burned is used in the fluidized-bed incinerator. Because the waste is diluted as it is rapidly distributed throughout the volume of the fluidized bed, much less time is required for complete destruction. The thermal

destruction of waste in a fluidized-bed incinerator requires essentially the same sequence for progressive destruction of the material, but instead of occurring in discrete zones, all of the processes occur simultaneously in a single large bed. Air and small particles of waste are continuously injected at a high rate into the bed, and ample oxygen is always available to all parts of the bed. This allows each distinct piece of waste to undergo its drying, volatilization, oxidation of the gases and vapors, combustion of organic solids, and complete burn-down of the char in all parts of the bed at the same time. Residence time for destruction of the small, (-2 inch), sized waste in the 1,500 °F bed is of the order of minutes.

5.2.3.1.3 CO-FIRING OF REFUSE-DERIVED FUEL (RDF). Co-feeding and co-firing of specially prepared refuse, RDF, with coal in a coal-fired boiler allows the waste to be destroyed at a rate comparable with that of burndown of the coal fed to the boiler furnace. This method of destruction of waste requires that the waste be sized, prepared, and fed into the furnace in a manner that assures that the 10-20% by weight of waste will burn down at a rate faster than that required for the 80-90% by weight of coal, for which the boiler was originally designed. Thus, a spreader stoker furnace burning 2-in. coal is co-fired with 0.75-1.5 in.-diameter pellets or cubes of RDF. Suspension-fired boiler furnaces firing pulverized coal are co-fired with fluff RDF.

5.2.4 SPECIAL DESIGN CONSIDERATIONS.

5.2.4.1 In the case of incinerators used to burn hazardous substances, a minimum residence time of 2 seconds at a minimum of 1,800 °F is used in the design criteria for achieving the 99.99% destruction efficiency required by law for hazardous waste incinerators. Some states are also requiring this higher efficiency destruction on municipal waste incinerators in order to assure the destruction of dioxins.

5.2.4.2 Toxic materials may be formed during primary combustion by the reaction of partially burned hydrocarbons with chlorine and must be destroyed in the secondary combustion process.

5.2.4.3 Figure 2 shows the relationship of destruction efficiency of biphenyls and chlorobenzenes (autogenous ignition temperature of 1,3190F and 1,2450F, respectively), with time and temperature.

5.2.5. MECHANICAL FEATURES USED TO ACHIEVE PROCESS CONTROL. The design of a mass burn furnace requires special provisions:

5.2.5.1 Controlled introduction of air at the appropriate locations above and below the bed is required in order to accomplish the drying, volatilization, and combustion processes in the respective zones of the combustion chamber.

5.2.5.2 Incinerators with primary combustion chambers operating in the starved-air mode require proportionately larger amounts of secondary air. This larger amount of air tends to cool the gases and requires that an auxiliary burner be provided to heat and maintain the gases at the required temperature. Typically, the less the amount of air delivered to the primary chamber (i.e., starved-air mode), the more air and the greater the auxiliary burner (either oil or natural gas fired) input to the secondary. This requires that the starved-air units (SAU) be provided with a larger volume secondary chamber than their comparable capacity excess-air unit (EAU). Table 13 lists the typical air distribution for primary and secondary combustion chambers/zones for modular and field-erected incinerators.

5.2.6 CHAMBER GEOMETRY AND INSULATION. Well-designed units make provision for the necessary features (i.e., insulation, size and shape of the chambers, etc.) for attaining and maintaining the temperatures desired in the respective zones of the furnace. For this reason, a primary chamber designed to operate in the starved-air mode will use a different configuration and type of insulation than a unit designed for operation in the excess-air mode.

5.2.7 CHAMBER VOLUME/GAS RESIDENCE TIME.

5.2.7.1 The combustion chamber must be sized to provide adequate residence time for complete destruction. The time required in the primary chamber is a function of the characteristics of the waste, the type of charging used, and the mode of operation (e.g., the starved-air mode requires more time than does the excess-air mode).

5.2.7.1.1 Of principal interest to the furnace designer is the projected hourly throughput required, the average moisture in the waste, and the major constituents, including the percentage of inerts and highly combustible materials.

5.2.7.1.2 Best performance is obtained by providing as uniform a feeding of the waste to the primary combustion chamber as possible. Similarly, allocation of space in the secondary chamber is a function of the volume of the total gas throughput and the need to provide the necessary 1.0 to 2.5 seconds of residence time, at temperature, before the gases are discharged to the downstream components.

5.2.8 TURBULENCE. Turbulence takes on two forms in the waste combustion process, slow agitation of the solid waste and turbulent mixing of gases and air in the gas combustion zones.

5.2.8.1 Continuous and/or routine agitation of the solid waste during the drying and volatilization phases assures that material in the lower part of the bed will not be insulated from the heat and gases sweeping over the top of the bed. By providing some physical means (usually a patented grate system) for the continual turning of the waste, the drying process will proceed at a more uniform rate.

5.2.8.2 Excessive and violent agitation of the bed by vigorous turning or by high-velocity flow of air up through the bed can be detrimental. Although drying may be more rapid and the waste is more frequently exposed to the radiated heat from the chamber walls, the lightweight ash and partially burned material on the surface could be excessively agitated.

5.2.8.2.1 Vigorous agitation will result in excessive amounts of solids being carried up with the gases. Some of these solids (e.g., flakes of paper and partially burned lightweight material) will burn with the gases as they enter the secondary zone and end up as fly ash. However, some of this solid material will continue to burn long after it leaves the secondary zone simply because it takes much longer to oxidize the solid material than it does to oxidize the gases. Unless special equipment is provided, the burning material may cause fires in the bag house.

5.2.8.2.2 Aside from the fire potential, the excess solid particulate creates problems by fouling the heat transfer surfaces and by producing additional loading to the gas cleanup system.

5.2.8.2.3 Release of these unburned artifacts can also contribute to the adverse emissions from waste incinerators. The release of dibenzo-p-dioxins (dioxins) and dibenzofurans (furans) has been associated with this condition; it has been postulated that the airborne unburned carbon provides the sites for reaction of the chlorine gas released from the oxidized, chlorine-containing waste with other unburned hydrocarbons to form any number of chlorinated hydrocarbons, including small amounts of dioxin and furan.

5.2.9 SECONDARY CHAMBER TURBULENCE.

5.2.9.1 High turbulence in the secondary combustion zone is necessary in order to assure proper mixing of the organic vapors and gases with the secondary combustion air. Complete mixing assures that the oxidation reaction proceeds to completion, since all of the carbon and hydrogen in the gases and vapors can come in contact and react with an adequate supply of air (oxygen) to convert these hydrocarbons into carbon dioxide and water vapor.

5.2.9.2 Improper design and/or operation of the devices intended to provide proper turbulence in the solids and the gases will retard and impede the drying, volatilization,

and oxidation processes critical to high-efficiency destruction of municipal solid waste. This results in low throughput, a high percent of unburned material in the ash, and serious emissions problems. Improper operation of a well-designed furnace by excessive loading or improper balance of the draft system can produce the same effect.

6. COMBUSTION PROCESS CONTROL.

6.1 PROCESS CONTROLLED BY DESIGN.

6.1.1 The most recent combustion research indicates that the best correlation to complete destruction of individual compounds is the unique combination of the "3 Ts" required for that specific compound. Thus, a design for a municipal waste furnace that does not provide for neither the careful control and monitoring of the envelope of three "Ts" required for the constituents in MSW nor the proper apportionment of air can only expect poor performance, excessive maintenance problems, and the release of unacceptable levels of pollutants to the environment.

6.1.2 Fortunately, the reactions involved in the combustion process can be modified significantly by restricting/balancing the flow of air during the different stages/phases of the combustion process.

6.2 EFFECT OF AIR CONTROL ON THE PRIMARY COMBUSTION PROCESS.

6.2.1 The four phases in the thermal destruction of waste by oxidation release chemical compounds generated from these reactions that can be altered by the conditions under which these compounds are formed. The amount of air available to the process will determine how far each different stage or phase can go through to completion, assuming all other conditions are met. Excess amounts of air has drawbacks as well.

6.2.2 DRYING PHASE. Since this phase involves the driving off of absorbed and bound moisture in the waste, this phase of the combustion process does not produce

energy, but it does produce products (water vapor and excess air) that can have a negative effect on subsequent phases of the total oxidation process. It is, therefore, advantageous to provide only the necessary heat and air required to remove as much moisture from the bed/fuel as is practical. The air-control system must inject only that amount of air needed to dry the waste, since this same air will be used downstream to provide oxygen to the other phases of the combustion process. Excessive amounts of air (i.e. more than is required for drying) will only upset the balance needed to control the subsequent phases).

6.2.3 VOLATILIZATION PHASE. Depending upon the availability of air, the chemical compounds released as the rising temperature reaches and exceeds the respective volatilization temperatures may or may not burn. Careful apportionment of air will determine how these reactions proceed. Typically, a primary combustion zone/chamber operating with a S.R. of 0.5 to 0.9 will provide less air through the bed and thus produces less agitation of the bed; as a result, fewer particulates are released from the bed. Also, the less the released gases and vapors are oxidized, the greater the amount of gases and vapors that will survive unburned through the primary combustion zone; as a result, a greater amount will be available as fuel in the secondary combustion zone. At lower gas temperatures, less NO_x is likely to form, and it will take longer to achieve the completion of this volatilization phase. The lower temperature and larger volume of unburned gases will require additional heat be supplied to the secondary combustion chamber in order to ensure that the requisite temperature for final destruction is attained and maintained. On the other hand, primary combustion zones/chambers operating with a S.R. of 0.95 to 1.1 will produce more particulate matter, because almost twice as much air is passing through and around the bed. In addition, the chamber will operate at higher temperatures since more of the gases and vapors will burn in and above the bed, resulting in higher levels of NO_x. It will also discharge smaller amounts of unburned gases and vapors to the secondary zone chamber, although they will be at a very high temperature and will therefore probably not require significant additional heat beyond that provided by the unburned gases and vapors as they are burned in the secondary combustion process. Even when operating with a primary combustion chamber S.R. of

1.0 to 1.1, the primary combustion gases will still contain significant amounts of CO and other partially burned combustible gases, vapors, and particulates. This fuel, when burned, will contribute enough heat to the secondary combustion process that usually there is no problem maintaining the gas temperature well above the minimum temperature of 1,600°F for autogenous combustion of the gases and vapors. This is true even when additional air for secondary combustion is added to raise the S.R. to the desired 1.4 to 1.5.

6.2.4 IN-PLACE OXIDATION OF BURNABLE SOLIDS. This third phase of the primary combustion process produces the hottest zone of the bed. It is controlled by introducing only enough air to complete the burndown of the nonvolatile organic materials. Insufficient air in this stage will mean that these materials will go unburned, only be partially burned, and/or will require a longer time for burndown. If the burndown is not completed in this phase, it will occur concurrent with and compete for the air in the burndown of the char in the last stage. Any material not burned will mean that heat will not be generated and effectively lost to this stage of the process. Excess air during this stage will produce hotter combustion products because of the higher rate of combustion, which will also produce more NO_x. The higher agitation caused by greater air flow will produce more fly ash in the gases.

6.2.5 CHAR BURNDOWN. This phase normally requires only enough air to achieve final destruction of the carbonaceous material remaining after the burning of the hydrocarbon during the third stage. Insufficient combustion air at this stage will mean that the ash residues will contain excessive amounts of carbon. Thus, the primary combustion process will not have achieved maximum volume and weight reduction in the waste destruction process, and the ash residues will be biologically active since it contains organic material. Excessive air to this stage will achieve the desired destruction of the carbon, but it will also introduce more air into the primary chamber, which will counter the effect of trying to maintain the control of air introduced to the system in the other stages. Since this final stage requires the lowest percentage of the

primary combustion air, the effect of introducing moderate levels of excess air in this stage has the least effect on the total system.

6.3 EFFECT OF AIR CONTROL ON SECONDARY COMBUSTION.

6.3.1 Since this is the last of the two processes, the secondary combustion process is designed to provide the final destruction and "polishing" of the combustion gases to achieve as benign a discharge gas as possible. This requires that the amount of air and the points of introduction to the secondary combustion process be closely controlled.

6.3.2 Large water-wall incinerator systems may achieve the highest destruction rates, produce the lowest CO concentrations (below 30-50 ppm), and have the highest combustion efficiency, with exit gas S.R.s of 1.4 to 1.5 and secondary gas temperature maintained above 1,6000F for 1.0 to 2.0 s. (see figure 3).

6.3.3 The smaller modular and packaged incinerator units achieve their best performance with exit gas S.R.s of 1.5-2.0 and exit gas temperature in the 1800-20000F range. To attain these temperatures with the higher air dilution, auxiliary burners must be used.

6.4 EFFECT OF AIR CONTROL ON EMISSIONS.

6.4.1 Control of the stoichiometry, temperature and time relationship in the secondary combustion process have been shown to be the primary factors in meeting emissions requirements.

6.4.1.1 Analysis of operating waste to energy facilities in the United States and Canada have shown that the lowest levels of chlorinated hydrocarbons and benzopyrenes are achieved when the CO levels are below 50 ppm (see figure 3).

6.4.1.2 The achievement of low NO_x is a function of what happens to the air as it passes through both the primary and secondary chamber. Since the kinetics of NO_x formation is a function of both temperature and the stoichiometric ratio of the gas (i.e., NO_x decomposes in sub-stoichiometric gases), systems that use the starved-air mode of operation in the primary combustor have lower levels of NO_x than do excess-air systems, even though they operate their secondary combustion chambers under essentially the same temperature, time, and S.R. conditions. Figure 4 shows the equilibrium concentration of NO_x.

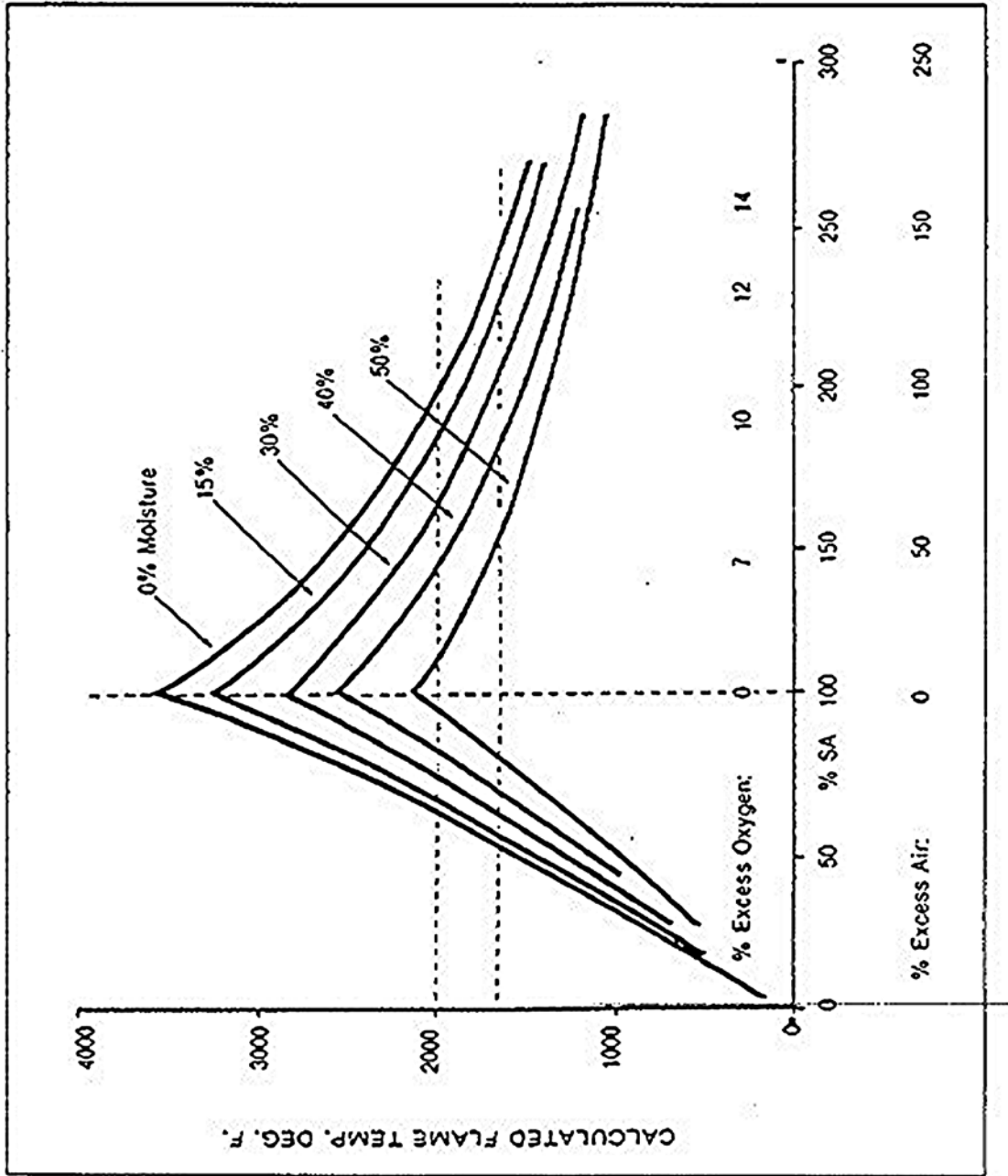


Figure 1
Theoretical temperature of the products of combustion

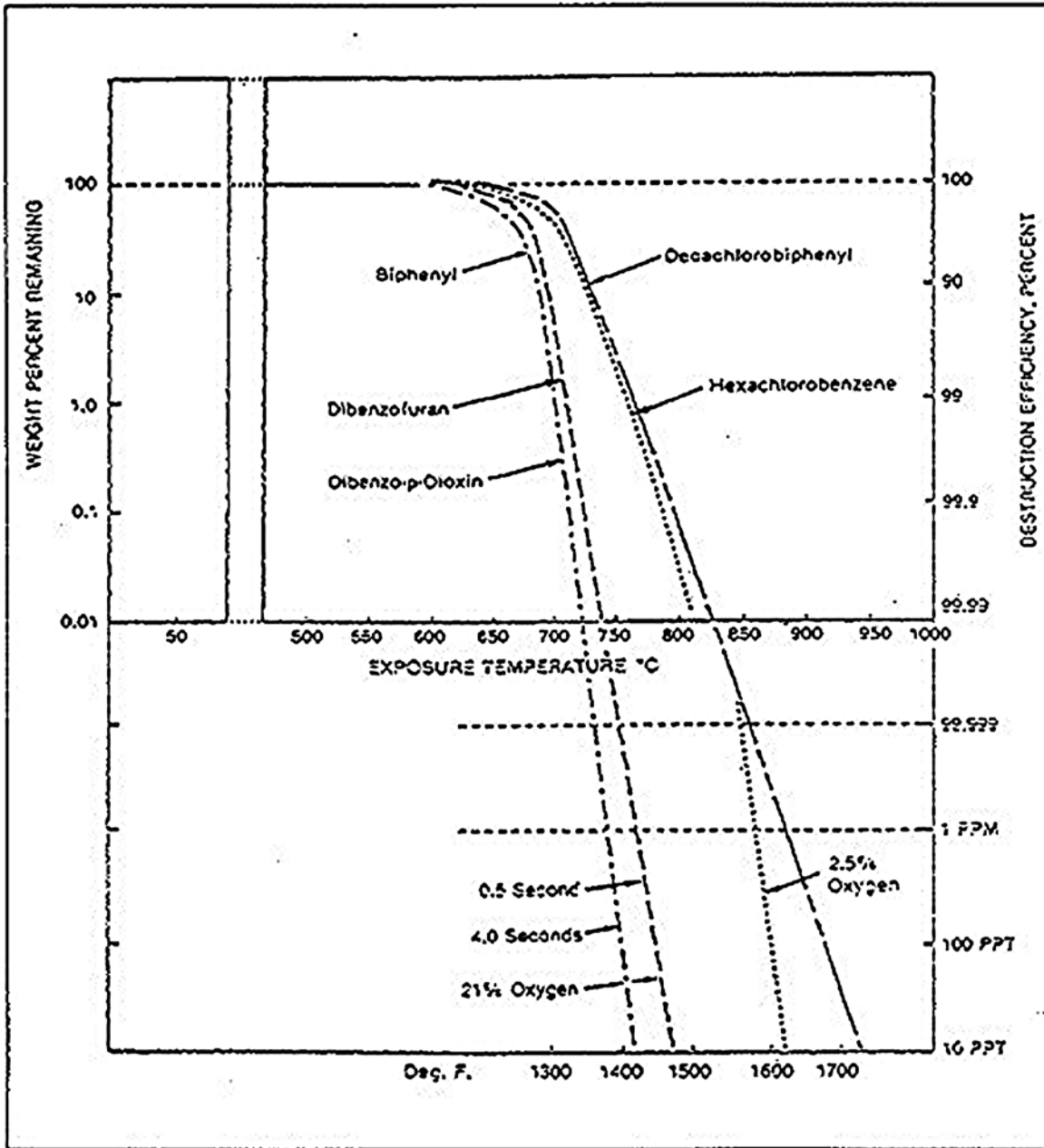


Figure 2
Relationship of destruction efficiency of biphenyls and
and chlorobenzenes with temperature

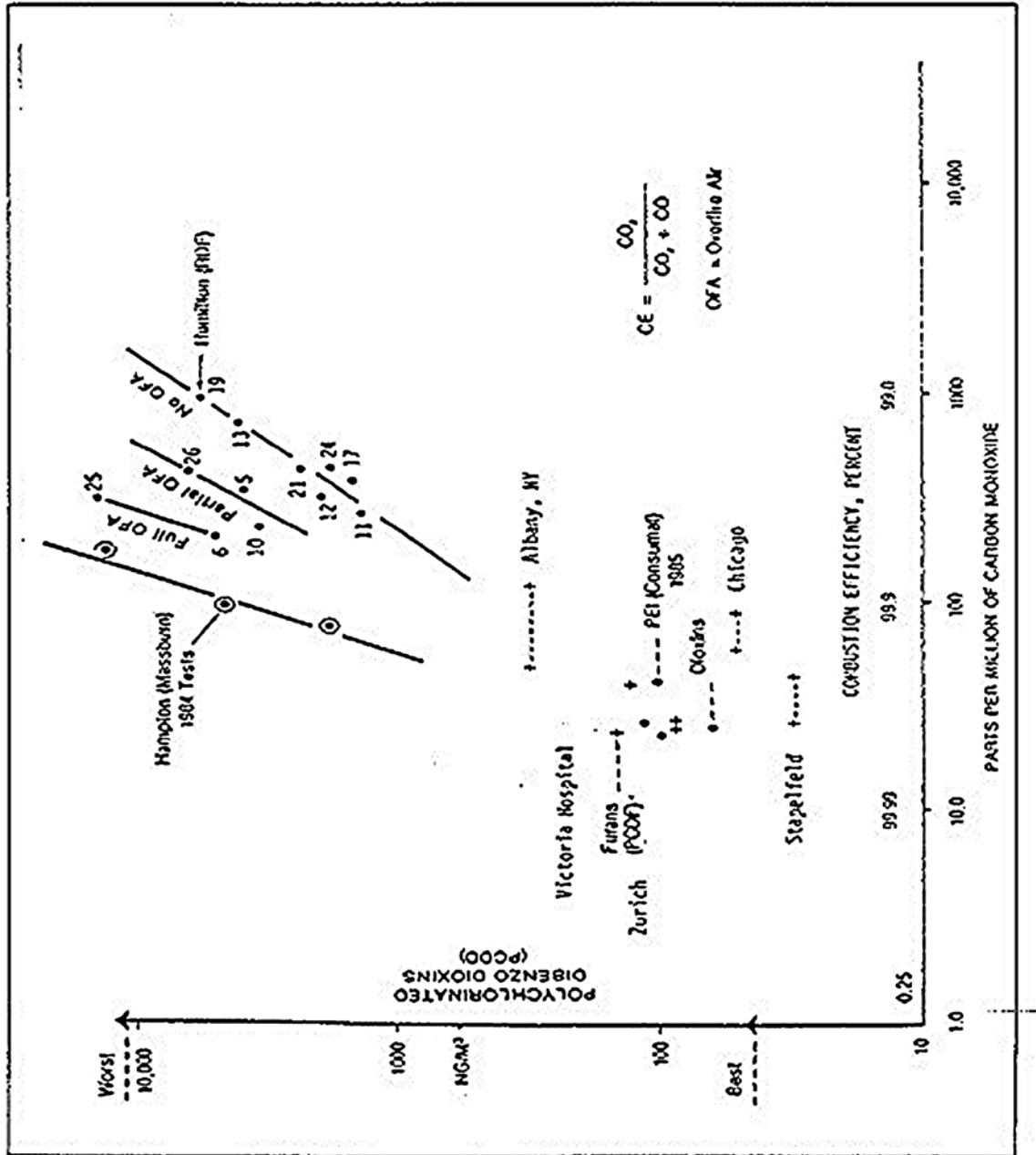


Figure 3

Logarithmic plot of PCCD versus carbon monoxide and combustion efficiency

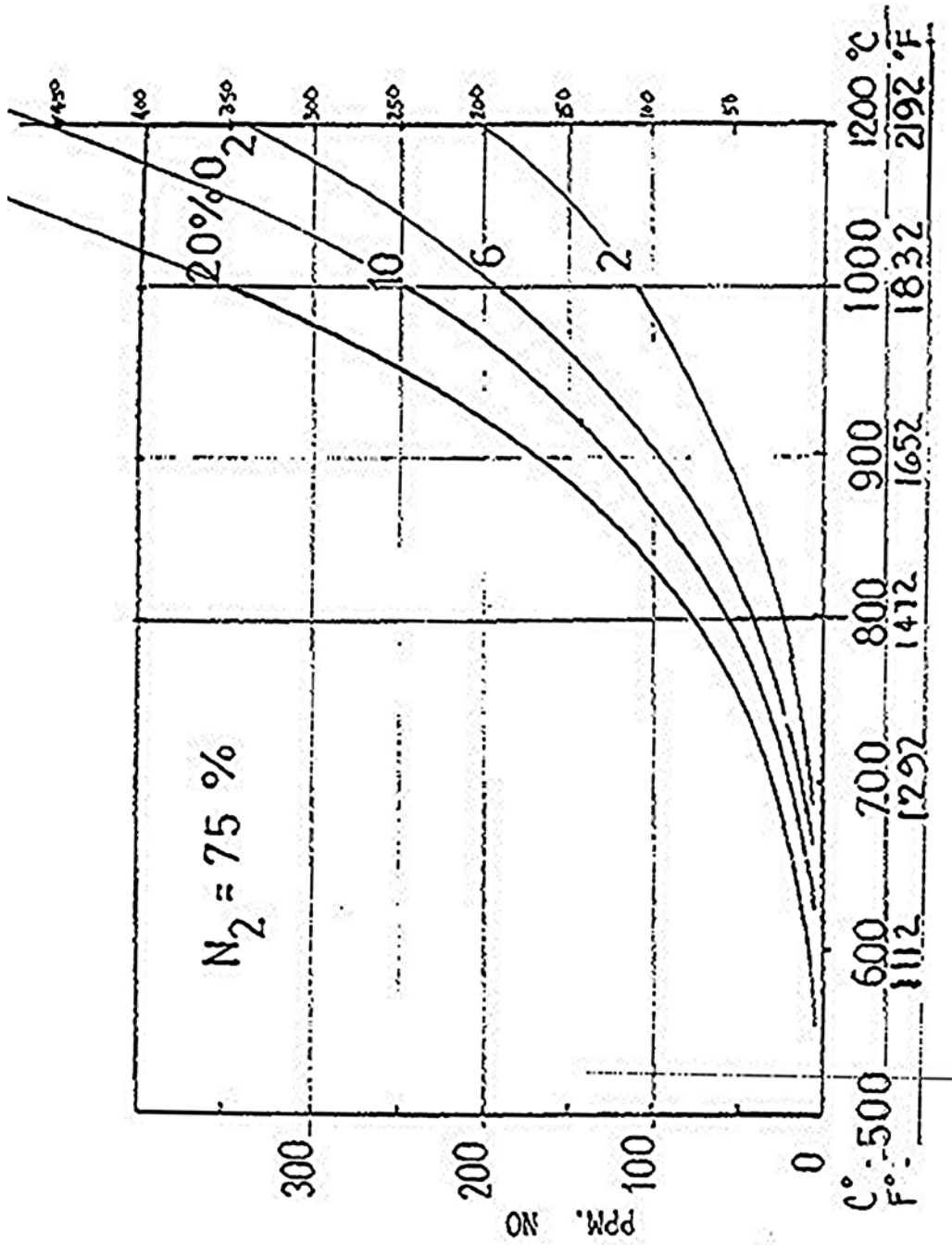


Figure 4
Equilibrium concentrations of NO_x

Table 3-1. Classification of Wastes to be Incinerated.

Classification of Wastes	Principal Components	Approximate Composition % by weight	Approximate Moisture Content %	Approximate Incombustible Solids, %	Approximate Heating Value Btu/lb	Etu of Aux. Fuel per lb of Waste to be Included in Combustion Calculations	Average Weight of Waste lb/cu. ft.*
Trash, Type 0	Highly combustible waste, paper, wood, cardboard, cartons, including up to 10% treated papers, plastic or rubber scraps, commercial and industrial sources	Trash, 100	10	5	8,500	0	8 to 10
Rubbish, Type 1	Combustible waste: paper, cartons, rags, wood scraps, combustible floor sweepings; domestic, commercial, and industrial sources	Rubbish, 60	25	10	6,500	0	8 to 10
Refuse, Type 2	Rubbish and garbage residential sources	Rubbish, 50 Garbage, 50	50	7	4,300	0	15 to 20
Garbage, Type 3	Food wastes, animal and vegetable	Garbage, 100	70	5	2,500	1,500	30 to 35
Animal solids and organic wastes, Type 4	Carcasses, organs, solid organic wastes, hospital, laboratory, animal abattoirs, animal pounds, and similar sources	Animal and human tissue, 100	85	5	1,000	3,000	45 to 55

*The weights given are general and based on materials usually expected in refuse collection. Wherever these densities are exceeded, consideration must be given to designs beyond minimum standards.

SOURCE: Incinerator Standards, Incinerator Institute of America (National Solid Wastes Management Association), Washington, D.C., Nov., 1968.

Table 1

Classification of wastes to be incinerated

Material	Sulfite Paper ^a		Average Wood		Douglas Fir		Garbage ^b	
	lb	scf	lb	scf	lb	scf	lb	scf
Carbon, C	44.34		49.56		52.30		52.78	
Hydrogen, H	6.27		6.11		6.30		6.27	
Nitrogen, N			0.07		0.10			
Oxygen, O	48.39		43.83		40.50		39.95	
Ash	1.0		0.42		0.80		1.0	
Gross Btu/lb, dry	7,590		8,517		9,050		8,820	
Constituent (based on 1 lb)	scf	lb	scf	lb	scf	lb	scf	lb
Theoretical air								
40% sat at 60°F	67.58	5.16	77.30	5.90	84.16	6.43	85.12	6.50
Flue gas with theo. air	68.05	5.18	77.84	5.93	84.75	6.46	85.72	6.53
CO ₂	13.99	1.62	15.64	1.81	16.51	1.91	16.66	1.93
N ₂	53.40	3.94	61.10	4.51	66.53	4.91	67.23	4.97
H ₂ O formed	11.78	0.56	11.48	0.54	11.84	0.56	11.88	0.56
H ₂ O (air)	0.47	0.02	0.53	0.02	0.58	0.02	0.59	0.02
Total Flue Gas/lb fuel	79.65	6.15	88.77	6.90	95.46	7.42	96.37	7.49
S.R.=1								
Flue gas with % excess air as indicated								
0 (S.R.=1)	79.65	6.16	88.77	6.91	95.47	7.43	96.38	7.50
50	113.44	8.74	127.42	9.86	137.55	10.64	139.24	10.77
100	147.23	11.32	166.07	12.81	179.63	13.86	182.00	14.04
150	181.26	13.91	204.99	15.78	222.01	17.09	224.86	17.21
200	215.28	16.51	243.91	18.75	266.38	20.12	267.72	20.58
300	283.33	21.70	321.75	24.68	349.13	26.58	353.44	27.12
constituents of sulfite paper, %								
Cellulose	C ₆ H ₁₀ O ₅	84						
Hemicellulose	C ₆ H ₁₀ O ₅	8						
Lignin	C ₆ H ₁₀ O ₅	6						
Resin	C ₆ H ₁₀ O ₅	2						
Ash	SiO ₂ & CaO	1						
^b Estimated								
^c Measured at 60° F and 14.7 psia.								

Source: Air Pollution Engineering Manual, U.S. Environmental Protection Agency, AP-40, 1973

Table 2
Combustion data for paper, wood and garbage

Waste	Btu Value/lb as Fired	Weight in lb/ft ³ , Loose	Weight in lb/ft ³	Content in Percentage Ash	by weight Percentage Moisture
Type 0 waste	8,500	10		5	10
Type 1 waste	6,500	10		10	25
Type 2 waste	4,300	20		7	50
Type 3 waste	2,500	35		5	70
Type 4 waste	1,000	55		5	85
Kerosene	18,900		50	0.5	0
Benzene	18,210		55	0.5	0
Toluene	18,440		52	0.5	0
Hydrogen	61,000		0.0053	0	0
Acetic acid	6,280		65.8	0.5	0
Methyl alcohol	10,250		49.6	0	0
Ethyl alcohol	13,325		49.3	0	0
Turpentine	17,000		53.6	0	0
Naphtha	15,000		41.6	0	0
Newspaper	7,975	7		1.5	6
Brown paper	7,250	7		1.0	6
Magazines	5,250	35		22.5	5
Corrugated paper	7,040	7		5.0	5
Plastic coated paper	7,340	7		2.6	5
Coated milk cartons	11,330	5		1.0	3.5
Citrus rinds	1,700	40		0.75	75
Shoe leather	7,240	20		21.0	7.5
Butyl sole composition	10,900	25		30.0	1
Polyethylene	20,000	40-60	60	0	0
Polyurethane, foamed	13,000	2	2	0	0
Latex	10,000	15	45	0	0
Rubber waste	9,000-11,000	62-125		20-30	
Carbon	14,093		138	0	0
Wax paraffin	18,621		54-57	0	0
1/3 wax - 2/3 paper	11,500	7-10		3	1
Tar or asphalt	17,000	60		1	0
1/3 tar - 2/3 paper	11,000	10-20		2	1
Wood sawdust, pine	9,600	10-12		3	10
Wood sawdust	7,800-8,500	10-12		3	10
Wood bark, fir	9,500	12-20		3	10
Wood bark	8,000-9,000	12-20		3	10
Corn cobs	8,000	10-15		3	5
Rags, silk or wool	8,400-8,900	10-15		2	5
Rags, linen or cotton	7,200	10-15		2	5
Animal fats	17,000	50-70			0
Cotton seed hulls	8,600	25-30		2	10
Coffee grounds	10,000	25-30		2	20
Linoleum scrap	11,000	70-100		20-30	

The chart shows the various Btu values of materials commonly encountered in incinerator designs. The values given are approximate and may vary based on their exact characteristics or moisture content.

SOURCE: Incinerator Standards, Incinerator Institute of America (National Solid Waste Management Association), November, 1968.

Table 3

Btu and other pertinent combustion values for selected materials

	1986 Gross MSW Waste Stream		Inerts/Ash		Moisture		As Discarded Heating Value	
	10 ⁶ Tons	Percent	Unit	% MSW	Unit	% MSW	Btu/lb	
1. Paper and Paperboard	64.7	41.0						
Newspaper	12.7	8.0		1.88			7,974	
Books and Magazines	4.8	3.0	1.5	0.12	6.0		5,256	
Office Paper	6.1	3.9	20.0	0.60	4.1			
Commercial Printing	3.7	2.3	7.0	0.27	5.5			
Other Nonpackaging Paper	8.5	5.4	7.0	0.16	5.5			
Corrugated Containers	19.4	12.3	1.0	0.5	4.6		7,043	
Other Paperboard	5.4	3.4	5.0	0.62	5.2			
Paper Packaging	4.2	2.7	1.0	0.03	5.6			
2. Aluminum	2.4	1.5	1.0	0.03	5.8			
Beverage Cans	1.3	0.8	100	1.50	0		0	
Other Aluminum Packages	0.4	0.3	100	0.80				
Other Aluminum Products	0.7	0.4	100	0.30				
3. Other Non Ferrous Metal	0.3	0.2	100	0.40			0	
4. Ferrous	11.0	7.0	100	0.20			0	
Beverage Containers		0.1	100	7.00			0	
Food Cans	1.8	1.1	100	0.10				
Other Steel Packaging	0.9	0.6	100	1.10				
Other Steel Products	8.2	5.2	100	1.10				
5. Glass	12.9	8.2	100	5.20			0	
Beverage Containers	5.5	3.5	100	8.2			0	
Other Glass Containers	6.3	4.0	100	3.50				
Other Glass Products	1.1	0.7	100	4.0				
6. Plastics	10.3	6.5	100	0.70				
Plastic Containers	2.9	1.8	19.0	1.00	0.2	0.013	15,000	
Other Plastic Packaging	2.8	1.8	6.0	0.34				
Other Plastic Products	4.6	2.9	19.0	0.11				
7. Yard Wastes	28.3	17.9	33.0	0.55				
8. Food Wastes	12.5	7.9	5.0	5.91	55.0	9.80	4,900	
9. Wood Products/Materials	5.8	3.7	1.6	0.40	60.0	4.74	3,700	
10. Clothes, Textiles, Rubber	5.0	3.2	14.5	0.06	20.0	0.74	7,000	
11. Tires	1.8	1.1	16.0	0.46	10.0	0.32	6,000	
12. Dirt/Inorganics/Misc.	2.8	1.8	100	0.18	10.0	0	11,300	
Total	157.7	100.0		28.65		18.05		

Table 4

Nominal composition of discards in U.S. municipal solid waste

Analyses	Portland, Oregon			Broward City, FL
	Residential	Commercial	Mixed	Mixed
Carbon	29.45%	40.17%	34.67%	40.94%
Hydrogen	6.72	6.48	6.60	5.77
Oxygen	28.44	31.33	29.86	21.64
Sulfur	1.33	2.45	1.86	0.09
Chlorine	0.19	0.31	0.25	0.41
Nitrogen	1.50	0.50	1.00	0.50
Moisture	26.34	11.24	18.98	24.58
Ash	6.09	7.53	6.79	6.07
Total	100.00%	100.00%	100.00%	100.00%
Higher Heating Value (HHV), Btu per Pound				
As Received	6,281	7,107	6,694	6,756
Dry	9,946	8,053	9,000	8,958
Moisture/ Ash Free	10,639	8,721	9,680	10,291

Table 5
Chemical analyses of some residential and commercial wastes

Component	Moisture	Volatile Matter	Fixed Carbon	Ash	As Discarded		Dry Basis	
					kJ/kg	Btu/lb	kJ/kg	Btu/lb
Newspaper	5.97	81.12	11.48	1.43	18,540	7,974	19,716	8,480
Brown Paper	5.83	83.92	9.24	1.01	16,870	7,256	17,916	7,706
Trade Magazine	4.11	66.39	7.03	22.47	12,216	5,254	12,741	5,480
Corrug. Paper Boxes	5.20	77.47	12.27	5.06	16,375	7,043	17,272	7,429
Mixed Paper	--	--	--	--	--	--	18,119	7,793
Plastic Film	--	--	--	--	--	--	32,192	13,846
Plastic, Other	--	--	--	--	--	--	21,039	9,049
Plastic Coated Paper	4.71	84.20	8.45	2.64	17,068	7,341	17,909	7,703
Waxed Milk Cartons	3.45	90.92	4.46	1.17	26,335	11,327	27,277	11,732
Paper Food Cartons	6.11	75.59	11.80	6.50	16,875	7,258	17,972	7,730
Junk Mail	4.56	73.32	9.03	13.09	14,155	6,088	14,829	6,378
Vegetable Food Wastes	78.29	17.10	3.55	1.06	4,173	1,795	19,228	8,270
Citrus Rinds and Seeds	78.70	16.55	4.01	0.74	3,969	1,707	18,635	8,015
Meat Scraps, Cooked	38.74	56.34	1.81	3.11	17,723	7,623	28,930	12,443
Fried Fats	0.00	97.64	2.36	0.00	38,283	16,466	38,283	16,466
Leather Shoe	7.46	57.12	14.26	21.16	16,840	7,243	18,195	7,826
Heel and Sole Composition	1.15	67.03	2.08	29.74	25,340	10,899	25,535	11,026
Rubber	1.2	83.98	4.94	9.88	--	--	26,342	11,330
Rags	10.0	84.34	3.46	2.20	--	--	17,791	7,652
Vacuum Cleaner Catch	5.47	55.68	8.51	30.34	14,847	6,386	15,708	6,756
Evergreen Trimmings	69.00	25.18	5.01	0.81	6,296	2,708	20,309	8,735
Balsam Spruce	74.35	20.70	4.13	0.82	5,689	2,447	22,183	9,541
Flower Garden Plants	53.94	35.64	8.08	2.34	8,596	3,697	18,563	8,027
Lawn Grass	75.24	18.64	4.50	1.62	4,785	2,058	19,325	8,312
Ripe Tree Leaves	9.97	66.92	19.29	3.82	18,563	7,984	20,620	8,869
Wood and Bark	20.0	67.89	11.31	0.80	--	--	20,025	8,613
Brush	40.0	--	--	5.0	--	--	18,368	7,900
Metallics	3.0	0.5	0.5	96.0	--	--	288	124
Glass and Ceramics	2.0	0.4	0.4	97.2	--	--	151	65
Ashes	10.0	2.68	24.12	63.2	--	--	9,700	4,172

Table 6
 Proximate analysis of waste components in household discards
 (percent by weight)

Component	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Newspaper	49.14	6.10	43.03	0.05	0.16	1.52
Brown Paper	44.90	6.08	47.84	0.00	0.11	1.07
Trade Magazine	32.91	4.95	38.55	0.07	0.09	23.43
Corrug. Paper Boxes	43.73	5.70	44.93	0.09	0.21	5.34
Mixed Paper	44.0	6.15	41.65	0.43	0.12	7.65
Plastic Film	67.21	9.72	15.82	0.46	0.07	6.72
Plastic, Other	47.70	6.04	24.06	1.93	0.55	19.72
Plastic Coated Paper	45.30	6.17	45.50	0.18	0.08	2.77
Waxed Milk Cartons	59.18	9.25	30.13	0.12	0.10	1.22
Paper Food Cartons	44.74	6.10	41.92	0.15	0.16	6.93
Junk Mail	37.87	5.41	42.74	0.17	0.09	13.72
Vegetable Food Wastes	49.06	6.62	37.55	1.68	0.20	4.89
Citrus Rinds and Seeds	47.96	5.68	41.67	1.11	0.12	3.46
Meat Scraps, Cooked	59.59	9.47	24.65	1.02	0.19	5.08
Fried Fats	73.14	11.54	14.82	0.43	0.07	0.00
Leather Shoe	42.01	5.32	22.83	5.98	1.00	22.86
Heel and Sole Composition	53.22	7.09	7.76	0.50	1.34	30.09
Rubber	77.65	10.35	--	--	2.0	10.0
Rags	55.00	6.60	31.20	4.62	0.13	2.45
Vacuum Cleaner Catch	35.69	4.73	20.08	6.26	1.15	32.09
Evergreen Trimmings	49.51	6.54	40.44	1.71	0.19	2.61
Balsam Spruce	53.30	6.66	35.17	1.49	0.20	3.18
Flower Garden Plants	46.65	6.61	40.18	1.21	0.26	5.09
Lawn Grass	46.18	5.96	36.43	4.46	0.24	6.55
Ripe Tree Leaves	52.15	6.11	30.34	6.99	0.16	4.25
Wood and Bark	50.46	5.97	42.37	0.15	0.05	1.60
Brush	42.52	5.90	41.20	2.0	0.05	8.33
Metallics	0.76	0.04	0.2	--	--	--
Glass and Ceramics	0.56	0.03	0.11	--	--	--
Ashes	0.28	0.5	0.8	--	0.5	70.2

Table 7
 Ultimate analysis of some waste components
 (dry basis, percent by weight)

Plastic Type	Moisture	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Chlorine	Ash	Btu/lb
Polyethylene Low Dens.	0.20	67.20	9.70	15.8	0.46	0.07	---	6.64	14,600
Polyethylene High Dens.	0.20	84.38	14.14	0.0	0.06	0.03	tr	1.19	20,034
Polystyrene	0.20	86.91	8.42	3.96	0.21	0.02	tr	0.45	18,096
Polyurethane	0.20	63.14	6.25	17.61	5.98	0.02	2.42	4.38	11,700
Polyvinyl Chloride	0.20	45.04	5.60	1.56	0.08	0.14	45.32	2.06	8,617
Polyethylene Terephthalate	0.20	62.50	4.14	33.10	0	0	0	0.50	9,263
Polypropylene		85.70	14.30						19,819
Natural Gas	tr	71.6	23.9	0	3.38	---	---	---	22,500
Kerosene		85.8	14.2	--	--	0.0058	---	tr	19,957
IL No. 6 Coal	12.0	63.8	3.5	--	--			16.0	11,160
No. 1 Fuel Oil		86.3	13.8	--	7.1	0.1		tr	19,810
Pine									

Table 8
 Ultimate analysis of some commonly used plastics and fuels
 (percent by weight)

	Raw MSW	RDF	RDF After Source Separation
% Original Material	100%	66-65%	43-55%
Heating Value (Btu/lb)	4,300-4,600	7,000-8,000	6,200-6,500

Table 9
Effect of processing and recycle programs

Fuels	Percent Excess Air	
Gaseous	Natural Gas	5-10
	Refinery Gas	8-15
	Blast Furnace Gas	15-25
	Coke Oven Gas	5-10
Liquid	Oil	3-15
Solid	Coal (Pulverized)	15-30
	Coke	20-40
	Wood	25-50
	Bagasse	25-45
	MSW (Excess Air)	40-50
	MSW (Starved Air)	130-150

Table 10
Excess air at furnace outlet

Material	High Heat Value, ^a Btu per lb of MAF ^b Waste	Air Needed for Complete Combustion lb per lb of MAF Waste ^c
Paper	7,900	5.9
Wood	8,400	6.3
Leaves and Grass	8,600	6.5
Rags, wool	8,900	6.7
Rags, cotton	7,200	5.4
Garbage	7,300	5.5
Rubber	12,500	9.4
Suet	16,200	12.1

^a Values are necessarily approximate, since the ultimate composition of the combustible part of the materials varies, depending upon sources. The heating value of the materials as it is received is obtained by multiplying the moisture-free and ash-free Btu value of the materials by $1 - (\% \text{ moisture} + \% \text{ ash})/100$. For example, garbage with an MAF value of 7,300 and containing 35 percent ash or other noncombustible material will have an "as-fired" heating value of 4,380 Btu per lb.

^b MAF means moisture-free and ash-free if ash refers to total noncombustible materials.

^c These values are also approximate and are based on 0.75 lb of air per 1,000 Btu for complete combustion. For various percentages of excess air, multiply these values by (100 plus percent of excess air). For example, after adjusting for moisture and ash, MAF paper requires 11.8 lb of air for complete combustion (i.e., $(5.9)(200/100) = 11.8 \text{ lb/lb}$).

SOURCE: Municipal Refuse Disposal, Institute for Solid Wastes, American Public Works Association, 1970, P. 174.

Table 11

Amounts of air needed for combustion of various kinds of waste

Major Compounds	Westchester ^a		EPA Study ^b		Swedish Study ^c		RDP ^d		Portland Cement ^e	
	Total Ash		Bottom	Fly	Bottom	Fly	Ash	Typ. I	Typ. III	
SiO ₂	40.3-46.8		0.2-4.0	0.3-5.7	49.8-60	31.6-63.6	28-47	21.3	20.4	
CaO	11.3-15.4		0.8-10	2-38	11.0-13.6	9.4-15.5	5-15	63.2	64.3	
Al ₂ O ₃	10.5-16.3		0.9-10	0.9-33.2	11.2-13.6	11.5-20.6	10-31	6.0	5.9	
Fe ₂ O ₃	8.0-19.2		0.1-19	0.1-12	5.3-7.0	2.0-5.7	2-5	2.7	3.1	
Na ₂ O	3.1-4.2		1.3-4.4	1.3-6.7	4.8-6.9	2.9-5.7	4-7	---	---	
TiO ₂	1.5-2.1		0.5-1.8	1-7.0	0.7-1.0	0.5-2.1	---	---	---	
MgO	2.4-4.2		.13-1.7	.33-3.5	2.1-3.2	2.0-4.6	4-7	2.9	2.0	
K ₂ O	1.4-3.4		.11-1.6	1.3-8.0	1.7-2.7	2.6-7.2	0.1-0.9	---	---	
P ₂ O ₅	1.0-1.4		0.7-4.1	0.7-2.1	1.4-2.9	1.2-2.5	---	---	---	
ZnO			.03-1.6	.38-19				---	---	
PbO			.01-.53	.02-2.9				---	---	
SO ₃					0.2-0.8	0.4-1.7		1.8	2.3	
Softn'g °F										
Fluid °F										
								1945-1987		
								2160-2179		

^aCundari, Incin. Ash Disposal Workshop Proceedings, Table 5 Laboratory Evaluation of expected Leachate Quality from a Resource Recovery Ashfill
^bU.S. EPA
^cHjelmer
^dCal Recovery
^eConcrete Institute

Table 12

Chemical analysis of waste-to-energy facility ashes and other material

Type of Unit	Primary Chamber Air		Secondary Chamber	Dilution Air
	Under-Fired	Over-Fired		
Modular Starved-Air	50% - 60%	nil	80 - 100%	100 - 200%
Modular Excess-Air	-60%	40 - 50%	60 - 100%	50 - 100%
Water-Wall	80 - 140%	-60%	minimal	minimal

NOTE: The percentage of stoichiometric air given above is based on a S.R. in the gases leaving the secondary chamber of 1.5-2.0.

Table 13

Comparison of Under-Fired Air and Over-Fired Air Patterns in Different Types of Combustion Systems