Design Aspects of a Low Emission, Two-Stage Incinerator

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ABSTRACT

This paper is intended to present a rational and practical design procedure for a low emission, two-stage, starved-air incinerator, based both on the theory of combustion and incineration and on the results of experimental studies.

INTRODUCTION

GENERAL BACKGROUND

The two-stage, starved-air incinerator was conceived in the mid 50's and immediately showed promise as an effective means of incineration. Compact size, low emission levels without the need of scrubbers or settling chambers, and overall simplicity are advantages inherent in the concept. Because of these advantages and because of the increasing solid waste problem, this concept has seen numerous development efforts during the past ten years. Most of this work has been aimed at one or more of the following problems: circumventing patent rights, reducing emission levels, increasing capacity, improving overall cost effectiveness, and eliminating operational problems.

One of the main obstacles in solving the preceding problems is the irregularity of the waste which must be eliminated. The more important variables are chemical composition, shape, size, heat content, and moisture content. While certain industrial operations produce fairly uniform and predictable waste products, institutions such as hospitals produce waste varying from highly flammable styrofoam cups to soggy rags and tissue.

Ecological Science Corporation has been involved with two-stage, starved-air incinerators since 1968 through its American subsidiary, Energy Dynamics, Inc., and more recently through its Mexican subsidiary, Ecologia, S.A. de C.V. In 1970 an on-going product development program was initiated.

OBJECTIVES

Our objective was the general problem of designing an incinerator to cope with virtually any type of waste without any human intervention. Of course, low emissions, high cost effectiveness, and operational reliability were additional constraints. The result is not revolutionary but is an evolution of an old design through application of the fundamental theory of fluid mechanics, thermodynamics and combustion. In the process of understanding and improving the product, numerous useful relationships were necessarily learned and developed, and these are presented along with the design procedure.

GENERAL OPERATION

The basic principle of operation of a two-stage, starved-air incinerator is as follows:

Raw waste is fed into the first stage, or primary chamber, which is a large refractory lined shell. A fraction of the waste, generally the fixed carbon, is oxidized releasing heat. This heat causes the endothermic pyrolysis of the volatile fraction of the waste, and results in a dense combustible smoke. The air flow rate into the first stage is
carefully metered and is less than the stoichiometric rate required for complete combustion of the waste—hence the term "starved-air."

The smoke passes from the first stage to the second stage where additional air and pilot fuel are added, the mixture is ignited, and the smoke is oxidized. The second stage can be thought of as a gas burner which uses smoke as the fuel. The problem in second stage design is the irregularity in both quantity and quality of the smoke produced in the first stage, as a direct consequence of the irregularity of the waste and rate of loading.

The significance of the starved-air concept is that, since only a fraction of the total air required for combustion (typically 25%) is supplied under the waste bed, the reactions in the primary chamber are mild, the air stream velocities are low, and hence very little flyash is entrained by the smoke. A well designed second stage then oxidizes all of the volatile compounds making up the smoke, and the result is a virtually pollution free effluent. If the effluent contains an unacceptable level of inert emissions (flyash), poor first stage operation is the cause because the flyash should never have left the primary chamber. If the problem is with volatile emissions then incomplete combustion due to poor second stage design is to blame.

**THE FIRST STAGE**

**DESIGN**

The design concept of the primary chamber is relatively straightforward. The shape is not critical and can be based on manufacturing considerations. Any of numerous schemes that will supply the underfire air in a uniform manner will suffice. The loading port should be located where the charge of waste will have a minimum disruptive effect on the waste bed. And finally, the refractory and insulation should be adequate both mechanically, chemically, and thermodynamically.

Our first stage is a sealed, horizontal, cylindrical steel shell lined with insulation and refractory (see Fig. 1). The chamber receives waste through a loading port, air through underfire air tubes, and discharges smoke to the second stage through an exhaust port in the ceiling. The underfire air tubes have holes sized to supply the proper amount of air at the design pressure.

Most units have a hydraulic loader with two doors: a top cover for loading the waste, and a guillotine door connecting with the main chamber. After the waste bin is loaded and the top cover is closed, the automatic loading sequence can be initiated: the guillotine door is hydraulically opened, the hydraulic ram forces the waste into the primary chamber, the ram is extracted and the guillotine door is closed. Aside from making loading easier, the main significance of the hydraulic loader is that the double doors inhibit the escape of smoke from the main chamber or the influx of air which would upset the air-flow rate into the first stage.

One end of the cylinder consists of a full diameter door. This is used for ash removal and is not normally opened during operation.

**SPECIFICATION**

For a given design, a given waste, and a given load rate, there are three quantities that must be specified: primary air supply rate, auxiliary fuel requirements, and chamber volume. Let us define an idealized, on-dimensional,
steady-state model as shown in Fig. 2, and let us specify
the significant characteristics of the waste as listed in
Table 1. Waste, having a mass loading rate of \( m_w \), is intro­
duced at the top. Primary air, having a mass flow rate
of \( m_{pa} \), is introduced at the bottom, flowing upward in
the direction opposite to the movement of the waste.
Smoke, with a mass flow rate of \( \dot{m}_s \), exits through the
opening at the top.

The primary chamber has four zones, each character­
ized by a different phenomenon: the ash bed, the char
bed, the pyrolysis zone, and the overfire zone. The porous
ash bed is an inert region composed of the inorganic, in­
combustible fraction of the waste which accumulates at
the bottom of the chamber. The char bed is the region
where the char (or fixed carbon) fraction of waste is
oxidized. The pyrolysis region is comprised of the waste
in various states of gasification; that is, the region where
the endothermic pyrolysis of the volatile fraction and the
vaporization of the moisture fraction of the waste occur.
And finally, the overfire zone comprises the remaining
volume and is the region through which the gaseous smoke
must pass before exiting.

Under continuous feed conditions, a particle of waste
gradually settles as mass is removed—first water and vola­
tiles in the pyrolysis zone, then carbon in the char bed —
until it comes to rest at the ash bed interface.

As the underfire air rises up through the primary cham­
ber, it attaches (or oxidizes) carbon in the char bed with
an increase in temperature, and picks up hydrocarbons
and water vapor in the pyrolysis zone with a decrease in
temperature, before exiting at the top as smoke.

**PRIMARY AIR SPECIFICATION**

The first criteria for the underfire air rate is that it
must be sufficient for steady state oxidation of the fixed
carbon fraction, \( X_c \).*

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*For a detailed description of char bed behavior, see ref. [4].

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### Table 1 Waste Characteristics

<table>
<thead>
<tr>
<th>A. Mass Breakdown</th>
<th></th>
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<tbody>
<tr>
<td>1. Moisture fraction</td>
<td></td>
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<tr>
<td>2. Dry fraction</td>
<td></td>
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<tr>
<td>( a. ) char fraction</td>
<td></td>
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<tr>
<td>( b. ) ash fraction</td>
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<tr>
<td>( c. ) volatile fraction</td>
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<table>
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<tr>
<th>B. Energy Breakdown</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Total heat of combustion (dry)</td>
<td>( H_Z )</td>
</tr>
<tr>
<td>2. Heat of pyrolysis</td>
<td>( H_P )</td>
</tr>
<tr>
<td>3. Heat content of char</td>
<td>( H_c )</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Other</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Surface/volume ratio of waste, char</td>
<td>( a_w, a_c )</td>
</tr>
<tr>
<td>2. Densities of waste, char, ash</td>
<td>( \rho_w, \rho_c, \rho_a )</td>
</tr>
<tr>
<td>3. Rate of pyrolysis</td>
<td>( \dot{X}_{p} )</td>
</tr>
<tr>
<td>4. Specific heat of volatiles</td>
<td>( (C_p)_{l,p} )</td>
</tr>
</tbody>
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It is useful, here, to introduce the relative carbon saturation factor which is defined for the primary chamber by

\[ f_{rcs} = \frac{\text{moles of fixed carbon}}{\text{moles of oxygen}} \cdot \]

When there is exactly enough primary air for the overall reaction

\[ C + \frac{1}{2}(O_2) \rightarrow CO \]

then \( f_{rcs} = 1 \), and the air is oxidizing the carbon at the maximum rate. This reaction represents the theoretical minimum primary air requirement and releases 4300 Btu/(1 lbm of carbon) but requires a char bed of infinite depth.

For practical purposes, more air is required, and experience has shown that when \( f_{rcs} \) is about 0.7 the char bed is of a reasonable depth. In this case some of the carbon undergoes the overall reaction

\[ C + O_2 \rightarrow CO_2 \cdot \]

This reaction releases 14,400 Btu/(1 lbm of carbon).

In terms of waste and air input to the first stage,

\[ f_{rcs} = 5.72 \left( \frac{\dot{m}_c}{\dot{m}_{pa}} \right) = 5.72 \frac{\dot{m}_w (1 - X_m) X_c}{\dot{m}_{pa}} \cdot \]

where \( \dot{m}_c, \dot{m}_{pa}\) and \( \dot{m}_w \) are the average flow rates of fixed carbon, primary air and waste, respectively. With known values of \( \dot{m}_w, X_m, \) and \( X_c \), and a design selection for \( f_{rcs} \), we can determine \( \dot{m}_{pa} \).

We can also express \( f_{rcs} \) in terms of volumetric gas fractions so that performance can be checked by a gas analysis:

\[ f_{rcs} = \frac{X_{CO} + X_{CO_2}}{X_{CO} + 2X_{CO_2} + 2X_{O_2}} \cdot \]

The second criteria for primary air specification is based on the energy required to pyrolyze the volatile fraction, \( X_p \), and to vaporize the moisture fraction, \( X_m \). The overall relationship in the primary chamber is

\[ \dot{Q}_{pc} = \dot{Q}_{loss} + \dot{Q}_a + \dot{Q}_p + \dot{Q}_{vap} \]

where

\[ \dot{Q}_{loss} \] is the heat loss through the chamber walls,

\[ \dot{Q}_a \] is the convective heat loss primary air out of the chamber,

\[ \dot{Q}_p \] is the endothermic heat of pyrolysis, and

\[ \dot{Q}_{vap} \] is the heat of vaporization of the moisture.

The last two terms also constitute convective losses of the stack. The terms on the right hand side of the equation can be determined as follows:

\[ \dot{Q}_{loss} = A (h_c + h_r)(T_{sk} - T_o) \]

where \( A \) is the external area of the primary chamber, \( T_{sk} \) is the exterior skin temperature, \( T_o \) is the ambient temperature, and the quantity \((h_c + h_r)\) is the total heat transfer coefficient which can be obtained from a basic heat transfer book.\(^2\) An estimate of the skin temperature is required here, but with a well insulated chamber, the heat loss is small and this is generally the least significant term.

\[ \dot{Q}_p = \dot{m}_w (1 - X_m) (X_p) H_p + (C_p)_p (T_s - T_o) \]

where \( T_s \) is the smoke exit temperature and, \( H_p \) is the combined latent heat and pyrolytic heat of reaction of the volatile hydrocarbons, and \((C_p)_p \) is the average specific heat of all phases of the hydrocarbons. This equation is approximate in nature because the values of \( H_p \) and \((C_p)_p \) are temperature dependent and are not readily available in the literature. \( T_s \) is a design constraint selected to be about 100°F above the temperature at which pyrolysis occurs at the desired rate.

\[ \dot{Q}_{vap} = \dot{m}_w (X_m) \left[ (C_p)_1 (212 - T_o) + H_m + C_{p_3} (T_s - 212) \right] \]

where \( H_m \) is the latent heat of steam, \((C_p)_1 \) is the specific heat of water and \((C_p)_3 \) is the specific heat of steam. The sum of the terms on the right hand side of the overall relationship gives us the required value of \( \dot{Q}_{pc} \).

We can calculate the heat release in the char bed with the relationship

\[ \dot{Q}_c = \dot{m}_w X_c (1 - X_m) \left[ f_1 (4300) + f_2 (14,400) \right] \]

where \( f_1 \) is the fraction of the char bed reacting to CO and \( f_2 \) the fraction going to CO\(_2\).

When \( \dot{Q}_c > \dot{Q}_{pc} \), the heat released in the char bed is greater than that required for the pyrolysis and vaporization in pyrolysis zone. This is typical for wastes with high char contents such as celulosic wastes with \( X_c \approx .16 \) and black rubber with \( X_c \approx .36 \). Either \( T_s \) will be higher than the design value or we can set \( \dot{Q}_c = \dot{Q}_{pc} \) in the above
equation, solve for \( f_1 \) and \( f_2 \) (remembering that \( f_1 + f_2 = 1 \), and that both must be positive) and recalculate the primary air flow rate.

When \( \dot{Q}_c < \dot{Q}_{pc} \) and all of the carbon is being completely oxidized to \( \text{CO}_2 \) (the theoretical state requiring an infinite bed depth and where \( f_{res} = .5, f_1 = 0, f_2 = 1 \)) then there is not enough heat release in the char bed for the reactions in the pyrolysis zone. This is typical for wastes with a low char content, such as polyethylene and polypropylene for which \( X_c = 0 \). In this case, in addition to the char content of the waste, some of the hydrocarbons must be oxidized in the first stage to produce the required heat so that

\[
\dot{Q}_c + \dot{Q}_{hc} = \dot{Q}_{pc}
\]

We must then determine the additional primary air to produce \( \dot{Q}_{hc} \). Here we can use the approximate relationship that, for hydrocarbons, 1 scf of air yields 100 Btu's of energy (accurate to within ±5%). Therefore the primary air rate required in addition to what is needed for the char is, in scfm,

\[
\dot{V}_{pc}' = \frac{\dot{Q}_{hc}(\text{in Btu's/hr})}{6000}
\]

AUXILIARY FUEL REQUIREMENTS

When the moisture content exceeds 25% it is often necessary to supply auxiliary fuel to the primary chamber, or, at least, have the capacity to add extra fuel. If the total heat content of the waste is less than \( Q_{vap} \), it is of course essential, and we have

\[
(\dot{Q}_{aux})_{\text{min}} = \dot{Q}_{loss} + \dot{Q}_a + \dot{Q}_{vap} + \dot{Q}_p - \dot{Q}_t
\]

where \( \dot{Q}_t \) is the total heat of combustion of the waste. For practical purposes, the auxiliary burner capacity should be at least twice this value, because poor heat transfer to the waste in the primary chamber can produce low burner efficiencies.

PRIMARY CHAMBER SIZE

For a given load rate and waste type, the theoretical required volume of the primary chamber, based on steady state, one-dimensional, homogeneous conditions can be written as

\[
V_{pc} = V_a + V_c + V_p + V_o
\]

where the \( V_i \) are volumes and the subscripts refer to the regions shown in Fig. 2.*

The partial volumes are defined as follows:

\[
V_a = \dot{m}_a X_a \Delta s / \rho_a
\]

where \( \Delta s \) is the period of operation and \( V_a \) represents the volume of ash accumulated in this time period.

\[
V_c \approx \frac{\delta \dot{m}_{gas}}{4k \rho_c e \rho_{gas}} \ln \left( \frac{f_{res}}{.05} \right)
\]

which represents the volume necessary for the steady state char reaction, and where \( \delta \) is the average pore diameter of the char bed, \( k \) is the coefficient of diffusivity, \( \rho_c \) is the surface-to-volume ratio of the char, \( e \) is the porosity of the char bed and the subscript "gas" refers to the effluent from the char bed.

\[
V_p = \frac{X_p (1 - X_m) \dot{m}_w}{\rho_{pop}}
\]

which represents the steady state volume required for the pyrolysis zone, and where \( X_p \) is the temperature dependent rate of pyrolysis[3] and \( \rho_p \) is the average density of the material in the pyrolysis zone. This equation ignores the volume required for vaporization of moisture, and would have to be modified for wet waste. \( V_o \) is the overfire region whose shape and size are based on prevention of flyash entrainment. The velocity of the gasses leaving the pyrolysis zone into the overfire region should be

\[
U < U_{crit}
\]

where \( U_{crit} \) is the terminal falling velocity of particles of the critical size and mass, the entrainment of which would cause an emissions problem.

In fact, the steady state, one-dimensional homogeneous assumption is far from valid in an actual incinerator, and the values of \( \delta, \rho_c, e, \rho_p \) and \( U_{crit} \) are almost impossible to estimate with reasonable accuracy. The above formulation for the calculation of the main chamber volume is therefore of little more than academic interest.

Hence, we must relate load rate to primary chamber volume by direct experiment. This can be done simply by loading a given waste at increasing load rates with appropriate increases in primary air until the capacity is reached. There are two possible criteria for establishing maximum capacity. The first is the inert emissions level (other problems such as high chamber pressure or incomplete combustion of the smoke are due to improper matching of

*Refer to ref. [1] for a detailed development of this argument.
the second stage). The second criteria is simply a physical overloading of the primary chamber—that is, the volume necessary for the reactions approaches the total chamber volume. The first case is more likely to be the governing criteria with highly combustible waste, the second with less combustible waste. Wastes are generally classified into five types (see Table 2), based on heat and moisture content, so that the results of testing can be generalized.

The primary chamber volume required for a given load rate of a new waste of known heat and moisture content can then be estimated and the proper size incinerator can be selected. Heat content, moisture content, and mass breakdown (proximate analysis) are available for a wide variety of wastes so that reasonable estimates can be made without actual testing. [4], [5]

SECOND STAGE

DESIGN PHILOSOPHY

The underlying concept for this design is that for normal combustible wastes (type O, I), the smoke generated in the first stage is combustible and will be the “fuel” for the second stage. Additional fuel will be used only as a pilot and as a supplement when the smoke is not rich enough to sustain combustion.

As previously mentioned, the difficulty in second stage design is that the quantity and composition of the smoke varies widely. This is due to two separate causes. One is the variation in the type of waste. The other is that the operation of the first stage is never actually steady state. Aside from the start-up and burn-down periods, there is a periodicity associated with the loading cycle. Pulses of volatiles shortly after a load is charged can reach as high as 200% of design conditions.

A further complication is that typical smoke is not a high quality fuel. For example, in our experiments with a waste composed of 90% dry corrugated cardboard and the remainder a mixture of Polystyrene, Polyethylene, Polyurethane and PVC (type O waste), the maximum observed temperature was 2450°F (corrected for thermocouple radiation) with 4.3% excess air. Other tests with card chips have yielded temperatures up to 2500°F. Both of these temperatures occur with relatively high Btu wastes and are still low in comparison to the 3600°F flame temperature obtainable from fuels such as liquefied butane. From our experience, normal type I waste will produce temperatures in the 1500°F to 2000°F range with a lower limit of combustion of about 1000°F.

Because of the relatively low heat content of the smoke, and the lower limit of combustion of about 1000°F, the acceptable range of equivalence ratios (actual air supplied/stoichiometric air) of an air-smoke mixture would be from 1.0, necessary for complete combustion, to about 2.0, the extinction limit. This is a 2:1 turndown ratio. By contrast, the turndown ratio required for an incinerator (from peak load to pilot load) is about 70:1.

Therefore, if the smoke and air streams are mixed prior to ignition, the equivalence ratio will have to be maintained between 1.0 and 2.0 throughout the operating range, either by controlling the air supply rate or by adding fuel to supplement the smoke. To reduce the problem of achieving the necessary turn-down ratio, our second stage will be based on the theory of jet flames. [7]

This principle is most easily illustrated by the example of a laminar diffusion flame, such as jet of pure butane burning in air. As the fuel stream penetrates the air, the air and fuel mix in the transverse plane via laminar molecular diffusion. In the absence of combustion, an axismetrical envelope could be plotted which would define a surface where the air and fuel are in stoichiometric ratio. If the jet is ignited such a surface still exists, and, since reactions are very rapid, this surface effectively becomes the domain in which oxidation occurs. A turbulent jet-flame works on the same principle, except that the mixing is dominated by turbulence rather than molecular diffusion.

What is significant about jet flames is that they have a tremendous turndown ratio. For a given butane jet, the upper limit can be considered flame lift-off at a gas velocity of several hundred feet per second, and the lower limit is essentially zero flow. Because of this almost infinite turndown ratio, this principle can be employed very effectively in burning the widely fluctuating flow of smoke that is generated by the primary chamber.

OBJECTIVES

The following goals were established, and achieved, for the second stage:

A. Emissions below .05 grains/scf corrected to 50% excess air.
B. Smoke free operation for all operating conditions from start-up to design load, to peak load, to burn down for all waste types from 0-3 with no adjustments required during operation.
C. Low fuel consumption.

A series of particulate emissions tests were conducted on an early model incinerator in 1971 in the United States. Type O and 1 waste, similar to department store waste, was burned and emissions levels of .04 grams/scf were routinely obtained.
The second objective of smoke-free operation for practically any type of waste resulted from a specification by the Mexican Social Security for incinerators to be used in hospitals. Extensive modifications were made to the second stage and controls in order to cope with this problem, and the resulting design is the one discussed in this text. The Mexican government is not presently enforcing any standards regarding particulate emissions levels, and as this development work was done in Mexico for the Mexican market, no particulate emissions testing has been done on the new design. This unit enjoys virtually smoke-free operation during the entire operating cycle, however, and it is the author’s opinion, based on extensive observation of the operation of both the old and new configurations, that the emission level of the new unit is lower than that of the old one.

The goal of low fuel consumption was also met, as will be discussed later.

SECOND STAGE DESIGN

The second stage is comprised of a transition section and the lower portion of the stack (see Fig. 1). The bulk of the secondary combustion actually takes place in the stack, with the flame envelope seated on the top of transition section. Smoke exiting the neck of the transition section encounters air which is entrained through the annular opening around the neck, and combustion occurs at the air-smoke interface as with a turbulent jet-flame.

To insure ignition of the smoke, a flame holder has been incorporated into the top of the transition neck which coincides with the base of the air-smoke interface. The flame holder is ringed with pilot jets through which passes an air-fuel mixture from an annular plenum. A continuous spark insures ignition of the pilot jets, and the ring of pilot jets insures ignition of the smoke.

It has been found that a more stable flame results if a small amount of air is mixed with the smoke prior to ignition. This pre-mix air is injected through peripheral holes at the entrance of the neck.

The design of the transition section was arrived at experimentally with the benefit of a working understanding of combustion theory and flame holder concepts. The diameter and minimum height of the stack are based on a momentum analysis. The criteria is that the stack must exhibit a positive pressure recovery. This is necessary for the entrainment of sufficient secondary air and the maintenance of a negative primary chamber pressure which will prevent smoke leakage.

By writing the momentum equation in the vertical direction for a segment of the stack as shown in Fig. 3 and regrouping the terms we have the following:

\[(p_2 - p_1) = \frac{(\Delta Z)(\rho_0 - \rho)}{2D_s g_o} - \frac{F_f \rho \bar{U}^2(\Delta Z)}{A_s (p_2 - p_1) U^2} \]

where \(p\) is gage pressure, \(\Delta Z\) is the segment length, \(\rho\) is density, \(F_f\) is the friction factor, \(U\) is velocity, \(D_s\) is stack diameter, \(A_s\) is the cross sectional area of the stack, \(g_o\) is the gravitational constant, subscripts 1 and 2 refer to stations, subscript \(o\) refers to ambient conditions, and a bar over a character indicates the average value for the segment. The first term in the equation is the change in pressure, the second term is due to buoyancy, the third is the frictional resistance and the fourth is the change in momentum.

The maximum flow for which \((p_2 - p_1) > 0\) occurs when the frictional and dumping losses, both of which increase approximately with the square of the load rate, equal buoyancy which is governed by

\[\text{Buoyancy} \sim 1 - \frac{1}{\text{load rate}}.\]

Therefore, peak conditions should be used for stack design.

In order to evaluate the momentum equation, the mass flow rates must first be established based on the combustion requirements, and an estimate must be made of the temperature profile as a function of vertical position \(Z\). The temperature at the base of the stack is calculated in the primary chamber analysis and the exit temperature can be estimated from the overall heat release rate and overall flow rates:

\[T_e = \left\{ \left( \dot{m}_w H_T + \dot{m}_{C_p \text{air}} T_s + \dot{m}_{C_p \text{dw}} T_s \right) \right\}^\left( \frac{\dot{m}_w}{\dot{m}_m} \frac{212C_p}{\dot{m}_p} - H_m - C_p \left( 212 - T_s \right) \right) + \dot{m}_m \frac{212C_p}{\dot{m}_p} - H_m + C_p \left( 212 - T_s \right) + \dot{m}_{C_p \text{air}} + \dot{m}_{C_p \text{dw}} \]

where subscript “\(e\)” refers to stack exit, subscript “air” refers to total air, subscript “\(dw\)” refers to dry waste and the others are the same as before. The curve for temperature can then be estimated between these points with the benefit of some operating experience (see Fig. 3). Reasonable accuracy can be obtained by using one “element” for the entire stack and average values based on these two temperatures. The available \(P\) for entrainment of secondary air can then be calculated. For a stack with entrainment at two different stations, as in Fig. 1, two “elements” should be used.

OPERATION AND CONTROLS

This design does not require control of air flow rates (the only exception is the air for the auxiliary burner...
which goes on and off with the burner). Nominal air flow rates, relative to the design stoichiometric rates, have been determined as follows:
- Total air, excluding auxiliary burner, 220%
- Premix air, 20%
- Lower entrained air, 55%
- Upper entrained air, the difference.

These rates are typical for type 1 waste and may be modified slightly if some other waste type is predominantly encountered.

Nominal fuel rates have also been determined, relative to the design heat release of the waste:
- \( \dot{Q} \) (pilot) = \( 0.026 \dot{m}_w M_T \)
- \( \dot{Q} \) (supplementary) = \( 0.10 \dot{m}_w M_f \)

The supplementary fuel fed into the premix air, is required only for low flow conditions when the maximum temperature in the second stage falls below the extinction point. The critical temperature varies with heat and moisture content of the waste but is generally about 1000°F.

Referring to Fig. 3, note that the maximum temperature shifts up and down the stack according to the level of combustibles in the smoke.

Curve #1 represents conditions 2 minutes after a load of waste is charged when pyrolysis is occurring at a peak rate. Curve #2 is 4 minutes after loading, curve #3 is 8 minutes after, and curve #4 is 12 minutes after. Curve #4 illustrates conditions after almost all of the volatiles have been pyrolyzed, and, therefore, the products in the effluent from the primary chamber are due predominantly to char bed reactions. Note that, when the rate of pyrolysis is high, the exit temperature from the primary chamber drops because of the endothermic reaction in the pyrolysis zone.

Thermocouple #2, which controls the supplementary fuel valve, is located up the stack from the intersection of curves #1 and #4 so that the supplementary fuel will not be supplied during periods of high pyrolysis when the exit temperature from the primary chamber is low. The cut-in temperature can be determined experimentally with the prevention of smoke or haze as the criteria. Since thermocouple #2 is not necessarily located at the hottest point in the stack at the instant of extinction, the cut-in temperature reading may be lower than the extinction temperature of the smoke.

Since the supplementary fuel only needs to heat up the effluent from the first stage and the premix air, a relatively small flow rate is required. Over five times as much fuel would be required if all the air to the second stage were supplied prior to the pilot. Furthermore, if future developments can reduce or eliminate the premix air, the supplementary fuel requirements can also be reduced. This is an additional advantage of the turbulent jet-flame concept.

**AUXILIARY BURNER**

The auxiliary burner is required when waste with a high moisture content and low heat content must be incinerated. In some cases it is only required to speed up reactions, in other cases it is necessary for any reaction whatsoever. A charge of low combustibility waste will cause a drop in primary chamber temperature as detected by thermocouple #1. Highly volatile wastes will also cause a drop in this temperature, however, so the auxiliary burner control must also be linked to thermocouple #2. The auxiliary burner turns on only when both thermocouple #1 and thermocouple #2 read low simultaneously. Again, the critical temperature for control are determined experimentally.
Table 2 Waste Classification

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>Description</th>
<th>Moisture Content</th>
<th>Heat Content (Btu/lbm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Dry paper, cartons, up to 10% plastics</td>
<td>10%</td>
<td>8500</td>
</tr>
<tr>
<td>1</td>
<td>Paper, cartons, up to 20% garbage, no plastic</td>
<td>25%</td>
<td>6500</td>
</tr>
<tr>
<td>3</td>
<td>An average mixture of types 1 and 3</td>
<td>50%</td>
<td>4300</td>
</tr>
<tr>
<td>4</td>
<td>Garbage: animal and vegetable wastes</td>
<td>70%</td>
<td>2500</td>
</tr>
<tr>
<td>5</td>
<td>Pathological wastes</td>
<td>85%</td>
<td>1000</td>
</tr>
</tbody>
</table>

**SUMMARY**

We have acquired an understanding of incinerator principles and combustion theory which enables us to eliminate most of the experimental work necessary to design and specify an incinerator. Once the experimental evidence has been obtained for a given incinerator, we can specify units of different sizes by applying the relationships presented herein.

We have also developed a second stage which has excellent operational versatility, negligible emissions, and low fuel consumption. The operation of the second stage is analogous to that of a turbulent jet-flame.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


