PDHonline Course C446 (5 PDH)

Fundamentals of Combustion for Environmental Applications - Part 2 of 2

Instructor: Walter R. Niessen, PE, BCEE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

Fundamentals of Combustion for Environmental Applications - Part 2 of 2

Walter R. Niessen, P.E., B.C.E.E.

COURSE CONTENT

Combustion is complicated; made so by the inherent complexity of the chemical and physical processes that must be successfully dealt with; by the survival issues arising from the physical and chemical stresses placed on the several components of the system (feeders, burners, enclosures, heat recovery, air pollution control, fans and stack); and by the high performance requirements demanded by the stringent regulatory limits in air permits and the increasingly critical cost requirements for energy efficiency. Part 1 of this course introduced the basic engineering analysis tools of combustion technology. Part 2 focuses on issues coming out of the application of combustion in real systems: the combustion processes themselves and an introduction to the design and operational features of burning systems − furnace fluid flow, heat transfer, waste feeding, enclosures, and heat recovery. Although air pollution control is an increasingly important part of equipment design, selection and cost, that topic will be left to future courses.

This course assumes that the student has satisfactorily passed the course Fundamentals of Combustion Part 1 and has a basic understanding of chemistry and mathematics. It presumes basic engineering analysis perspectives but, through text and examples guides the student an understanding of the key processes and design features of combustion systems. The course includes:

- The basic processes controlling solid, liquid and gas combustion;
- The aspects of fluid flow and heat transfer affecting furnaces and furnace   operation;
- Waste/fuel feeding (burner characteristics for solids, liquids and gases;   and
- The combustor components of enclosures (including refractories), fans and   stacks and heat recovery.

A. The Combustion Process

Combustion is a high temperature process. This obvious fact has a collerary: combustion is, substantially, limited to solids and gases. Liquids are present, through evaporation with heat absorption, at temperatures that are at or below their boiling point which is, generally, much too low for combustion reactions to proceed at meaningful rates. Once evaporated, the chemistry of the liquid engages in combustion processes but in the gas phase. Complex solids (such as wood, plastics or coal) degrade as temperature increases to yield gases and a carbonaceous char. Both of these products can then engage in combustion. These paths are illustrated below.
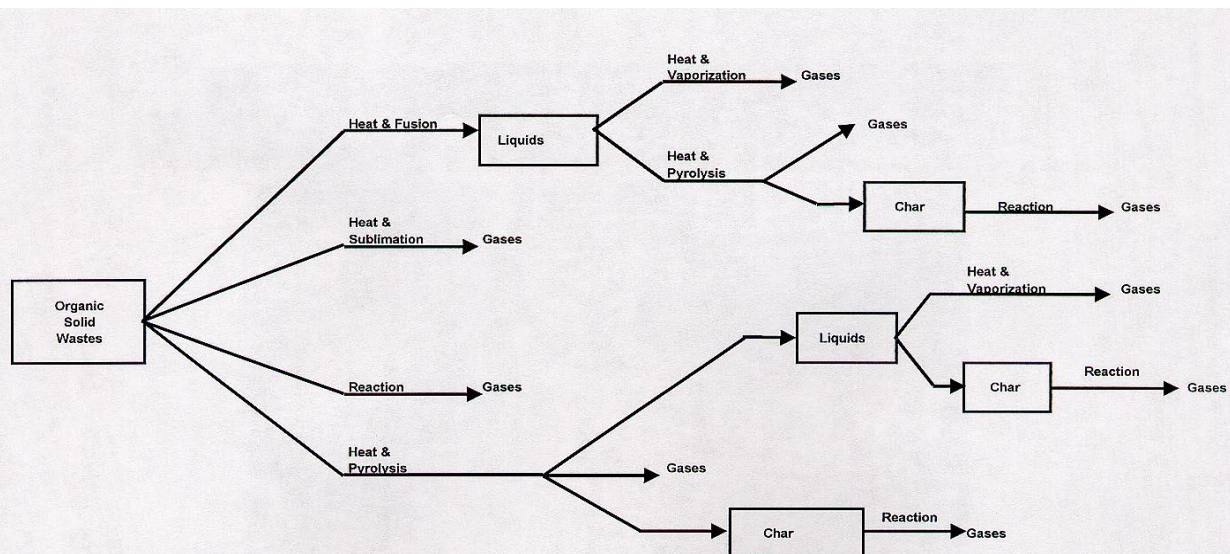
Phase Changes in the Combustion of Organic Solids

1. Combustion of Solids

Solids burn after they are dry (the presence of liquid moisture holds the temperature at or below 100 °C); when their surface temperature exceeds 300-400 °C where gasification by pyrolysis begins or above 600 °C where surface oxidation begins; and when oxygen is available. Thus, combustion systems for solids involve means to thrust the solid into a hot environment (raising surface temperature by all three heat transfer modes) and providing an air supply. Often, the process includes some kind of mechanical abuse to abrade off (insulating) ash on the surface of the fuel thus exposing fresh material to dry and ignite. Inherently, these steps involve mechanical equipment that must operate and survive at high temperatures in an environment that is potentially corrosive and definitely abrasive. Clearly, these requirements have challenged the hardware design and supply industry who have, in general, succeeded but left with an injunction to the operator to pay attention to maintenance and operation within specified environmental limits.

The development of furnaces to burn solids has led to three characteristic firing modes:

● *Suspension burning*. Solids burn while entrained in a fast-moving air stream. In some embodiments, the particles of solids are finely divided and dry as is the case for pulverized coal, rice hulls etc. Alternatively, the feed can be fed as a semi-liquid which dries, gasifies and burns in suspension as for wastewater treatment plant sludge in a fluid bed combustor. The gaseous environment is hot and, often oxygen rich. Combustion is completed while the particles are suspended in the gas flow. Much of the residue leaves the system still entrained in the flue gases.

● *Semi-suspension burning*. Coarsely subdivided solids are injected mechanically or pneumatically into the combustion space. Drying and combustion occurs partially while the solids are airborne, and is completed after the particles fall to a grate which, most commonly, draws the burning mass back toward the boiler face incorporating the feed system. This technology is used for spreader stoker-fired coal and refuse derived fuel (RDF). Residue is dumped periodically or is continuously withdrawn.

● *Mass burning*. Unprocessed or coarsely subdivided solids (e.g. with a simple shear rather than a shredder) are moved into the combustion space by mechanical means (e.g., by a hydraulic ram, manual charging or are drawn in on a grate) and are pushed, dragged or tumble through the furnace until a satisfactory degree of burnout is obtained. Residue is discharged periodically or continuously.

Studies [1] of the off-gas from beds of burning refuse in a municipal incinerator have confirmed the hypothesis that the bed off-gas composition may be characterized by the water-gas shift equilibrium. This equilibrium describes the relative concentration of reactants according to the following:

$$H_2O + CO \leftrightarrow CO_2 + H_2$$
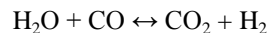
$$K_p = \frac{p_{H_2O}\, p_{CO}}{p_{CO_2}\, p_{H_2}} \tag{1}$$

The importance of this equilibrium in mass burning is the increased gasification potential given to the underfire air. If the water-gas shift equilibrium holds, over 1.5 times as much refuse can be gasified by a given quantity of air as would be predicted for stoichiometric combustion to CO_2 and H_2O. Burning/gasification rate data show rates 1.7 to 2.1 times those corresponding to stoichiometric combustion [2]. A second result coming from the water-gas shift reaction is that a definite and relatively large combustion air requirement will necessarily be placed on the overfire system: as much as 30 to 40% of that expended in gasification, thus creating a need for effective overfire air injection and mixing.

The thermal decomposition or pyrolysis of waste solids in the absence of air or under limited air supply occurs in most burning systems. Pyrolysis is a destructive distillation process effected by the application of heat in an insufficiency of air to yield gaseous, liquid (after cooling), and solid products. In comparing suspension burning and mass burning processes, both involve pyrolysis of incoming solids, but for suspension burning the physical scale of the fuel-rich zone is smaller, and the pyrolysis products will differ due to the differences in heating rate. Physical and chemical changes occur in solids undergoing pyrolysis. An important physical change in some materials (e.g. bituminous coal and some plastics) is a softening effect yielding a plastic mass; then re-solidification.

Cellulosic materials increase in porosity and swell as volatiles are evolved. As cellulose pyrolysis begins (at about 200°C), complex, partially oxidized tars are evolved. As the temperature increases, these products further decompose or crack, forming simpler, more hydrogen-rich gaseous compounds and solid carbon. The solid residue approaches graphitic carbon in chemical composition and physical structure.

Whether the overall pyrolysis process of a given solid is endothermic or exothermic depends on the ultimate temperature attained. For most materials, the process is endothermic at lower temperatures and exothermic at higher temperatures.

The rate controlling step in pyrolysis (the rate of heat transfer into the waste or the pyrolysis reaction rate) is dependent upon the temperature and the physical dimensions of the waste. The pyrolysis time for plates and spheres and the chemistry and yield of the liquid and solid by- products of pyrolysis are discussed and quantified in relevant texts [2].

A solid combustion process of interest relates to the burn-out of soot particles. The control of soot burnout can best be understood by examining the kinetics of combustion of graphitic carbon particles [3]. For spherical particles, review of the considerable research on this topic suggests the following:

$$q \; = \; \frac{p_{O_2}}{\frac{1}{K_s} + \frac{1}{K_d}} \qquad\qquad (2)$$

where: q = rate of carbon consumption (g/cm^2 sec^{-1})
p_{O2} = partial pressure of oxygen (atm)
K_s = *kinetic* rate constant for the consumption reaction
K_d = *diffusional* rate constant.

For (small) particles of diameter d (centimeters) typical of soot, the diffusional rate constant at temperature T (K) is approximately given by:

$$K_d = \frac{4.35 \text{x} 10^{-6} T^{0.75}}{d} \qquad\qquad (3)$$

The kinetic rate constant is given by:

$$K_S = 0.13 \exp\left[\left(\frac{-35,700}{R}\right)\left(\frac{1}{T} - \frac{1}{1600}\right)\right] \qquad\qquad (4)$$

where R is the Universal Gas Constant (1.986 cal/g mol K).

For a particle of initial diameter d_0 and as assumed specific gravity of 2.0, the time (t_b) in seconds to fully consume the soot particle at an oxygen partial pressure of p_{O2} atmospheres is given by:

$$t_b = \frac{1}{p_{O_2}}\left[\frac{d_0}{0.13\exp\left[\left(\frac{-35,700}{R}\right)\left(\frac{1}{T} - \frac{1}{1600}\right)\right]} + \frac{d_0^2}{5.04 \text{ x } 10^{-6} T^{0.75}}\right] \qquad\qquad (5)$$

2. Combustion of Liquids

The combustion of liquids begins with the accumulation of heat in the liquid mass from radiation from the flame or from hot refractory walls, from recirculating burned gases, or from a pilot burner. Eventually, the fuel approaches its boiling point and it begins to vaporize. The fuel vapors then diffuse from the liquid surface, mixing with oxygen in the air and increasing in temperature. At some point, the rate of oxidation reactions and associated heat release is high enough that full ignition and combustion ensues.

A review by Williams [4] suggested the following as the burning time t_b (sec) of a droplet of initial diameter d_o (cm) of a hydrocarbon oil of molecular weight M_W at a temperature T (K) in an atmosphere with an oxygen partial pressure p_{O2} (atm) as:

$$t_b = \frac{29{,}800 M_w d_o^2}{p_{O_2} T^{1.75}} \qquad (6)$$

3. Combustion of Gases

In reviewing gas-phase combustion, systems may be divided into those where fuel and stoichiometric oxidant enter the combustion environment separately and where the combustion rate is almost always mixing limited, and those where combustion is initiated in homogeneous fuel-oxidant mixtures, with the flame reactions propagating through the system in a substantially continuous (although, perhaps, smudged by turbulence) flame front. The latter case is found primarily only in premixed gas burners. The former is by far the most common.

The mechanism by which oxidant and fuel are brought together provides a second classification of flame type. When molecular diffusion predominates, the flame is known as a laminar diffusion flame. When eddy diffusion predominates, the flame is known as a turbulent diffusion flame. The Reynolds number of the stream, a measure of the ratio of momentum forces (scaling eddy mixing) to viscous forces (scaling molecular mixing), can be a useful indicator of the regimes where one or the other flow conditions exist. The Reynolds number (N_{Re}) for a fluid with the velocity u_o, the density ρ_o and the viscosity μ is given by:

$$N_{Re} = \frac{d_o u_o \rho_o}{\mu} \qquad (7)$$

If $N_{Re} < 2{,}100$ the flow is usually laminar in nature with limited or no eddy motion. Above this threshold, eddies begin to appear until, at high N_{Re}, the flow is characterized by high levels of turbulence. At or near this threshold N_{Re} value, the flow is in the transition zone where eddy flow can break out or subside.

● The Premixed (Bunsen) Laminar Flame − Visual examination of simple, premixed conical hydrocarbon-air flames indicates three regions: the pre-luminous, luminous, and post-luminous. In the pre-luminous zone, the cold feed gas undergoes preheating and some "seeding" with reactive species due to thermal and mass diffusion against the direction of convective flow. At some point the combination of temperature and mixture reactivity reaches a level where rapid heat release begins. Activated radicals (e.g., OH·, C=C, and others) appear in high concentration and account for much of the visible light released in the blue luminous zone. The conical shape of the luminous zone can be explained by assuming that the flame propagates normal to itself at a constant rate, known as the flame speed. For most hydrocarbon fuels, the flame speed falls in the range from 35 to 60 cm/sec at normal atmospheric temperatures and pressures.

The combustion reaction is seldom complete within the luminous zone. Particularly for the combustion of complex fuels, heat release from CO and H_2 oxidation extends into post-luminous zone (an afterburning region). In the post-luminous zone, the temperature falls due to radiation heat loss and to the assimilation of cool ambient fluid into the flame flow, and combustion is completed.

● The Diffusion Flame − In a diffusion flame, fuel combustion reactions must await the arrival of oxidant. Preparatory steps such as pyrolysis, evaporation, or thermal cracking, however, may proceed under the influence of radiative heat transfer from the (typically) hot surroundings, the heating due to turbulent mixing of hot burned gases into the fuel stream, and conduction from the flame regions. For most burner systems, the fuel is introduced into the combustion chamber in a jet, with or without swirl. Since combustion is mixing-limited, the flow characteristics (especially entrainment) of the jet are prime determinants of combustion rate, flame length, and flame shape. Since jet behavior is very important to diffusion flame and combustor fluid mechanics, it is discussed in detail below. One important flame quantity, the flame length, will be mentioned here for the more common case, the turbulent diffusion flame.

Based on a simplified model for jet mixing, Hottel [6] proposed and tested the following relationship defining the flame length L, corrected for the distance X^+ from the nozzle face to the break point where turbulence is initiated:

$$\frac{L - X^+}{d} = \frac{5.3}{f_s}\left\{\left[f_s + (1 - f_s)\left(\frac{M_a}{M_o}\right)\right]\frac{T_F}{\theta_m T_o}\right\}^{1/2} \qquad (8)$$

Where L =   Flame length (meters)
X^+ =   Distance from nozzle face to initiation of turbulence (meters)
d =   Nozzle diameter (meters)
f_s =   Mole fraction of nozzle gas in a stoichiometric gas-air mixture
M_a, M_o =   Molecular weight of air and nozzle gas, respectively
T_F =   Adiabatic flame temperature (K) of a stoichiometric mixture
T_o =   Nozzle gas temperature (K)
θ_m =   Moles of reactants (fuel, O_2) per mole of product (CO_2, H_2O) in a stoichiometric mixture

Estimation of X^+ is necessary if total flame length is to be determined. Generally, X^+ is small compared to ($L - X^+$) except for CO flames for which $X^+/(L - X^+)$ is as high as 0.4. On the average, X^+ is about 0.05L, is less than 0.09L in the turbulent range, and decreases with increasing nozzle Reynolds number.

This correlation is useful in that it allows anticipation of flame jet impingement problems, and allows estimates of the effect of fuel changes (changes in f_s, M_o, T_F, and θ_m) and of preheat (changes in T_o) on flame length. Its accuracy for a variety of gaseous fuels ranged within 10 to 20% of the experimental values. It should be recognized that devices which increase the rate of entrainment of oxidant will act to shorten the flame. Thus, swirl in particular, will significantly shorten flame length.

B. Fluid Flow in Furnaces

1. Basic Considerations

Furnace fluid mechanics are complex. Flows in real systems are often driven by burner or air jets and by buoyancy. They interact in swirling, recirculating eddies, all while traversing complex geometrical sections. Yet a basic under-standing of furnace flow processes gives great insight into the design of air jets, and the anticipation of burner-chamber interactions, mixing problems, and other effects which are vital elements of the combustion process.

2. Jets and Jet Penetration

The designer has within his control an effective and flexible flow control tool: jets of air or steam and/or, for gaseous, liquid, or pulverized fuels, jets of fuel or burner flames. These jetting flows introduce fuel or the sensible heat of combustion products, combustion or temperature control air or serve to inject energy to mix and/or direct the furnace gas flow.

The gasification behavior of refuse beds (creating a requirement for air injection over the bed) and the need to induce mixing of furnace gases show where jet systems can be of assistance to achieve better burnout of combustible pollutants and to control furnace temperature distributions. Jets have been utilized for many years as an integral part of furnaces, boilers, and other combustion systems. The important characteristics of jets which underlie these uses are:

> The controlled addition of mass to contribute to the oxidation process (air jets) or to serve as a thermal sink to maintain gas temperatures below levels where slagging, corrosion, or materials degradation may occur (air or steam jets).

> The controlled addition of linear and/or angular momentum to promote mixing of the jet-conveyed gas with gases in the combustion chamber or to promote mixing of gases from different parts of the combustion chamber. In the latter case, high-pressure steam jets are often used to provide high momentum fluxes with a minimum introduction of mass.

Jets are conveniently categorized, according to flow regime (laminar or turbulent, supersonic or subsonic) and geometry (round or plane). Laminar jets occur only at very low jet velocities and are of no practical interest.

Supersonic jets are of limited interest (steam jets). Plane jets, which issue from a long slot, are primarily of academic interest but we note that a row of closely spaced round jets behaves like a plane jet [2].

Other important parameters characterizing jet flow behavior include the relative densities of the jet and ambient fluids, the velocity of the ambient fluid relative to the jet velocity, and the degree to which the space into which the jet issues is confined by walls. We consider here the basic characteristics of jets issuing into an infinite atmosphere of quiescent fluid of the same density as the jet fluid.

As shown in the figure, the round, isothermal turbulent jet shows three characteristic regions. Immediately adjacent to the nozzle mouth is the mixing region. Fluid leaves the nozzle with an essentially flat velocity profile. The large velocity gradients between this "potential core" and the ambient fluid induce turbulence which causes ambient fluid to mix into the jet. The mixing results in momentum transfer between the jet and ambient fluids and progressively destroys the flat velocity profile. At a distance of about 4.5 jet nozzle diameters downstream, the influence of shear forces reaches the centerline of the jet and eliminates the potential core [3].

Regions in jet flow.
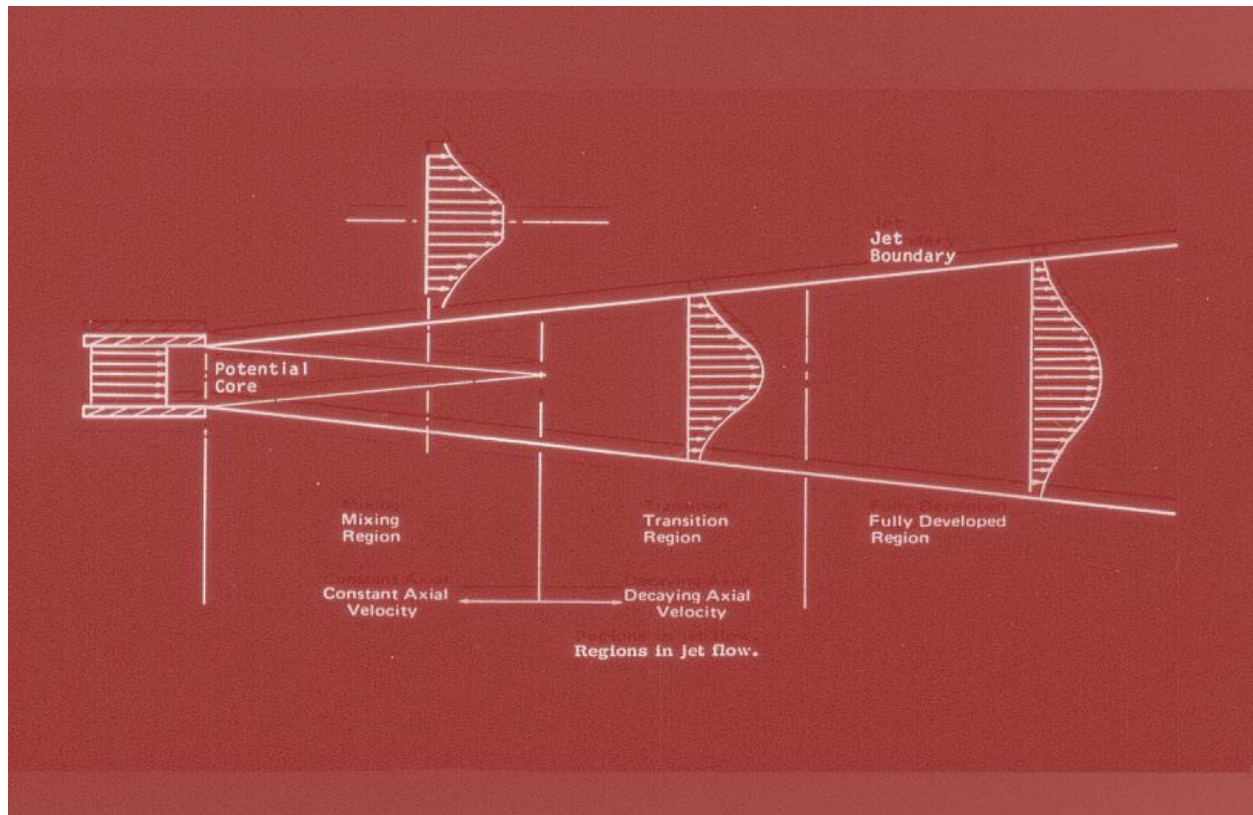
It is important to note that the "nozzle diameter" characterizing jet flow is not necessarily the physical dimension of the orifice from which the jet issues. If, for example, the jet issues from a sheet metal plenum, a flow contraction to about 60% of the open discharge area (the area of the vena contracta) characteristic of the flow past a sharp edged orifice, will define the effective nozzle diameter and the location of the effective jet discharge plane will be displaced about two-thirds of a diameter downstream of the orifice (the location of the vena contracta). If a relatively long (2-3 diameters) constant area section lies upstream of the discharge plane, the nozzle diameter may be taken as the orifice diameter. Attention should be given, therefore, to the geometry of the entire nozzle fluid delivery system in analysis of jet behavior.

In the region from 4.5 to about eight diameters downstream, the transition of the flat entrance velocity profile to a fully developed profile is completed. Beyond this transition region the velocity profile retains a more or less con-stant shape relative to the velocity of the axis of the jet and is referred to as "self-preserving." This is the fully developed region.

Important jet characteristics include:

- The centerline velocity and concentration changes with axial distance from the nozzle mouth;

- The shape of the radial velocity and concentration profiles in the fully developed region;

- The intensity of turbulence in the jet; and

- The rate of entrainment of ambient fluid into the jet.

These characteristics are all interrelated: turbulence generated by high velocity gradients induces entrainment which causes momentum and mass transfer between the jet and the ambient fluid. These characteristics are important in practice because they determine the quantitative effect of firing a jet into a combustion chamber. The axial decay of velocity establishes how far the jet penetrates into the chamber. The radial velocity distributions determine how large a volume is affected by the jet. The entrainment rates determine how effectively furnace gases are mixed along the jet path.

Correlation of data taken by many experimenters leads to the following expressions for the axial decay of centerline velocity and concentration [3].

$$\frac{\overline{u_m}}{\overline{u_o}} = 6.3 \left(\frac{\rho_o}{\rho_a}\right)^{1/2} \frac{d_o}{(x+0.6d_o)} \qquad (9)$$

$$\frac{\overline{c_m}}{\overline{c_o}} = 5.0 \left(\frac{\rho_o}{\rho_a}\right)^{1/2} \frac{d_o}{(x+0.8)} \qquad (10)$$

where $\overline{u}_m$ and $\overline{c}_m$ are the time averaged centerline velocity and concentration of jet fluid at distance x downstream from the nozzle; $\overline{u_o}$ and $\overline{c_o}$ are the comparable para-meters at the nozzle; and d_o is the nozzle diameter. ρ_o and ρ_a are the densities of the jet and ambient fluids, respectively. These equations apply only in the fully developed region (i.e., $x/d_o > 8$).

The experimentally measured radial velocity and concentration profiles in the fully developed region can be represented by either Gaussian or cosine functions. The Gaussian representations [3] are:

$$\frac{\overline{u_{x,r}}}{\overline{u_m}} = \exp\left[-96\left(\frac{r}{x}\right)^2\right] \qquad (11)$$

$$\frac{\overline{c_{x,r}}}{\overline{c_m}} = \exp\left[-57.5\left(\frac{r}{x}\right)^2\right] \qquad (12)$$

where $\overline{u}_{x,r}$ and $\overline{c}_{x,r}$ are the time averaged velocity and concentration at distance x downstream and distance r from the jet centerline.

The spread of the jet is defined in terms of the half-angle to the half-velocity point (i.e., the angle subtended by the jet centerline and the line from the centerline at the nozzle mouth to the point where the velocity is one-half of the centerline velocity. This angle is independent of distance from the nozzle mouth in the fully developed region, a consequence of the self-preserving nature of the velocity profile. The half-angle of the half-velocity point is approximately 4.85 degrees; based on concentration in the same way, the half-angle is 6.2 degrees [3].

Ricou and Spaulding [7] measured entrainment rates and determined that the mass flow rate ($\dot{m}_x$) in the jet is linearly related to x according to:

$$\frac{\dot{m}_x}{\dot{m}_o} = 0.32 \left(\frac{\rho_a}{\rho_o}\right)^{1/2} \left(\frac{x}{d_o}\right) \qquad (13)$$

This relationship holds for all values of nozzle Reynolds number greater than 2.5×10^4 and for $x/d_o > 6$. The Reynolds number (N_{Re}) for a fluid with the velocity u_o, the density ρ_o and the viscosity μ is given by:

$$N_{Re} \; = \; \frac{d_o u_o \rho_o}{\mu} \qquad\qquad (14)$$

At $x/d_o < 6$, the entrainment rate per unit jet length is lower, increasing with distance until it stabilizes at the constant value corresponding to Eq. 13. Entrainment is an inherent characteristic of jet flows: Eq.13 indicates that the magnitude of the entrained flow exceeds the nozzle flow in only a few nozzle diameters. The importance of the entrainment phenomena is felt most strongly in ducted flows (e.g., an axially mounted burner discharging into a cylindrical chamber) when an insufficiency of fluid relative to the entrainment requirement leads to significant recirculation flows.

In incinerators, the effects of crossflow of the ambient fluid and density differences between the jet and ambient fluids are important. These effects are less well documented, and their inclusion in the design criteria poses some difficult problems. These matters are dealt with below.

When the jet and ambient fluids are of different density, the buoyant forces acting on the jet can cause deflections of the jet trajectory. This effect is potentially important in incinerator applications since the air introduced by the jets will be much colder than the furnace gases and hence of higher density. From an incinerator design and operating standpoint, this could be critical: jets could "sink" from an anticipated flow trajectory passing above the bed to one causing entrainment of particulate from the bed or causing overheating of the grates with a "blowpipe" effect.

Field et al. [3] considered the behavior of the centerline of a buoyant jet and obtained Eqn. 15 for the case when a jet of density ρ_o issues at a velocity of u_o from a circular nozzle of diameter d_o. The ambient fluid is at rest of density ρ_a, α_o equals the injection angle relative to the horizontal and "g" is the acceleration of gravity (9.807 m/sec^2).

$$\left(\frac{y}{d_o}\right) \; = \; \left(\frac{x}{d_o}\right)\tan\alpha_o + \frac{0.047}{\cos(\alpha_o)}\left[\frac{gd_o}{u_o^2}\right]\frac{(\rho_a-\rho_o)}{\rho_o}\left(\frac{\rho_a}{\rho_o}\right)^{1/2}\left(\frac{x}{d_o}\right)^3 \qquad (15)$$

The need to understand the behavior of a jet issuing into a crossflow normal to the jet axis arises in the analysis of furnaces, plume dispersion from chimneys, and elsewhere. With crossflow, the interaction of the flow deflects the jet and alters the cross-sectional shape of the jet. The originally circular cross-section is distorted into a horseshoe shape by the shearing action of the external flow around the jet, and internal patterns of circulation are set up. Measurements in the external flow around the jet show a decreased pressure downstream of the jet, recirculation of the external fluid, and a process leading to the periodic shedding of vortices into the wake of the jet. These phenomena are similar to those observed in the wake of a solid cylinder exposed to crossflow. Analysis of jets in crossflow are generally correlated using the ratio of momentum flux in the external and jet flows (M) where ρ_a is the density in the ambient, ρ_o is the density in the jet fluid, u_o the velocity in the jet and u_1 the velocity of the crossflow:

$$M \; = \; \frac{\rho_a u_1^2}{\rho_o u_o^2}$$

Additional correlations on these phenomena are found in Reference 2.

3. Swirl

In waste and fuel burners and within furnaces, swirl is often used to modify flow characteristics. Because of the intense recirculation patterns in swirling flows (burning gases travel back towards the burner bringing heat energy and reactive species to promote ignition in the entering fuel-air mixture), rotation is found to shorten the flame. The recirculation and flame shortening effects may be exploited to reduce the size and cost of the enclosure or to increase the post-flame residence time.

Velocities in axially symmetrical swirling jets (the axial swirl burner) can be defined in terms of three components. Axial velocity $\bar{u}$ is the component parallel to (but not necessarily on) the jet axis; radial velocity $\bar{v}$ is the velocity towards or away from the axis; and $\bar{w}$ is the velocity tangent to a circle centered on the axis. The intensity of swirl in a jet has been characterized using the swirl number Ns which is defined as the dimensionless ratio of jet angular momentum $\dot{L}_o$ to linear momentum $\dot{G}_o$.

$$L_o^{\cdot} = 2\pi\rho_o \int_0^{r_o} (\bar{u}\bar{v})_o r^2 \, dr \qquad (16)$$

$$G_o^{\cdot} = 2\pi \int_0^{r_o} \left(P + \rho\overline{u^2}\right)_o r \, dr \qquad (17)$$

$$N_s = \frac{2L_o^{\cdot}}{G_o^{\cdot} d_o} \qquad (18)$$

where the static pressure P (gauge) in Eq. 17 allows for pressure variations over the nozzle cross-section owing to centrifugal forces. Swirl numbers of typical burners are usually in the range 0.6 to 2.5 [2].

4. Residence Time

Vague references to the "3-T's" of time, temperature and turbulence are often made as if this "secret" provides the key to the achievement of good combustion performance. Unfortunately, the effluent streams from real combustors do not have a single, unique time or temperature characterizing their history in the system. The real case is one where the flow is described best with *distribution functions of stay-time and of temperature*. The mathematical characteristics of the two distributions (e.g., the standard deviation and skewness of the distribution) differ and neither is routinely measured. Also, "turbulence" is a concept well understood in theory and readily observed in the fluid flow laboratory but difficult to quantify, measure and design for in practice. Imagine, for example, a large refractory furnace with a range of temperatures and gas velocities from undergrate flows, buoyancy driven accelerations and air jets. What is the "characteristic dimension" and which velocity do you use to calculate Reynolds number? What density should you use? What composition and associated viscosity? Thus, it is appropriate to look more closely at the critical system characteristic of residence time as an aid to design and performance troubleshooting.

Attaining a temperature high enough to stimulate vigorous reaction rates, a degree of mixing (with oxygen) complete enough to assure rapid oxidation and a stay-time long enough for substantial burn-out is vital in hazardous waste incineration. The achievement of destruction-removal efficiencies at the 99.9999 % level is required in the United States for polychlorinated biphenyl (PCB) and a few other designated compounds. Performance to the 99.99% level is mandated for all others. For the PCBs this means that only one part in one million of PCB in the feed stream can fail to meet or exceed the minimum temperature/stoichiometry/time scenario that completes the destruction reactions.
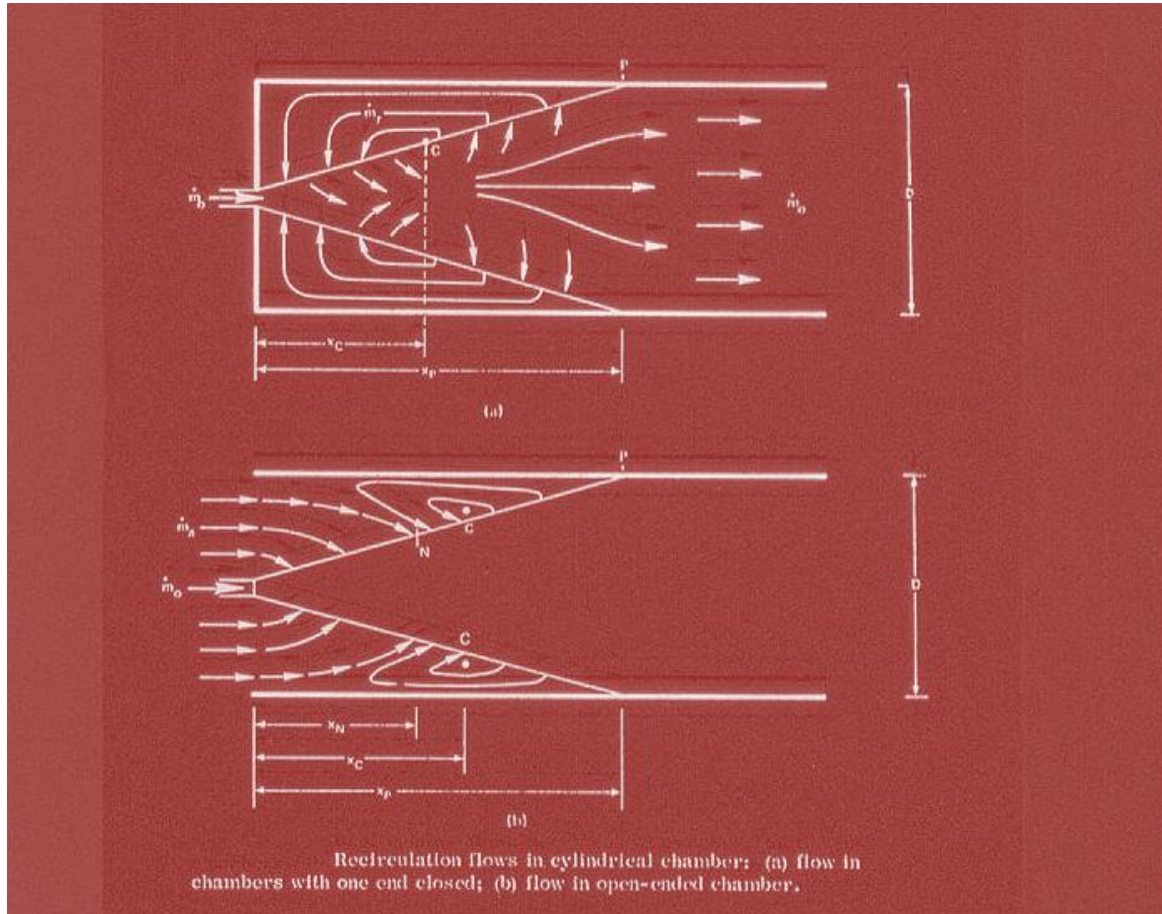
However, it is likely that most of the unoxidized, emitted material is not a residual "heel" of an overall reaction that is quenched just short of completion by the reaction-quenching effect of a wet scrubber or the like. Instead, the unreacted material is more likely to be contained in the packets of chamber gases that never made it to satisfactory combustion conditions: "failure modes" brought about by chilling at cold walls, excessive dilution and cooling by air in-leakage, weak mixing with combustion air so only the slow pyrolysis reactions were operative, etc. Thus, the problem of achieving a high destruction efficiency of is concerned not with the temperature, residence times (say, calculated from the chamber volume and average volumetric gas flow rate) and the oxygen concentration of the bulk flow, but with the "low-end tails" of the temperature, time and oxygen distribution functions: the fraction of the flow that experiences temperatures below the ignition temperature, sub-stoichiometric oxygen concentrations etc. A part of understanding this "failure" type comes by understanding the distribution functions of time, temperature and oxidant concentration that characterize the system behavior. Residence time provides a useful model for this investigation.

If one analyzes real systems, two conceptual "failure modes" are useful: dead space and short circuiting. The concept of dead space takes account of circumstances when, due to the character of the flow field, a portion of the chamber volume is not in steady flow but contains a recirculating eddy. Thus, the effective volume of the chamber is less than that calculated from the physical dimensions. Examples of such dead space include the outside corner and the downstream wall on the inside corner for a right-angle turn in a rectangular duct or the recirculating eddy in the larger duct just after a sudden expansion before the entering jet attaches at the wall.

The concept of short circuiting presumes that a portion of the flow passes through the chamber to the effluent with "infinite velocity". This type of bypassing has been observed in fluidized beds associated with large bubbles that move rapidly through the bed with little or no contact with the bed solids. In combustion analyses, this might also be a useful representation of a portion of the flow that was below the ignition temperature.

Discharging a jet of fuel and/or air down the axis of a combustor induces recirculation flow which, in extreme cases, can be the controlling influence in establishing combustor performance. Such cases include the long, cylindrical, axially fired liquid waste incinerator and most rotary kilns.

The theory of Thring and Newby [8], provides for relatively simple formulations to identify the approximately location of the point C where disentrainment begins as shown in the figure below:

Recirculation flows in cylindrical chamber: (a) flow in chambers with one end closed; (b) flow in open-ended chamber.

The Thring-Newby theory (modified by Field et al. [3]) assumes that the jet with mass flow rate m_o and density ρ_o discharging into a chamber containing gas with density ρ_a entrains as a free jet up to the point C (at $x = x_C$). Thus, the total entrainment up to this point (the net recirculation flow m_r using Eqn. 13) is given as:

$$\dot{m}_r = \left[0.32 \left(\frac{\rho_a}{\rho_o} \right)^{1/2} \frac{x_c}{d_o} \dot{m}_o \right] - \dot{m}_o \qquad (19)$$

The point C is postulated to lie midway between the point x_o where entrainment begins ($\dot{m}_x = \dot{m}_o$), according to Eq. 13 and the point P where the envelope of an unconfined jet would strike the wall:

$$x_o = \frac{d_o}{0.32} \left(\frac{\rho_o}{\rho_a} \right)^{1/2} \qquad (20)$$

Assuming a jet angle of 9.7 degrees, the jet strikes the wall at a distance x_P which, relative to the duct diameter D, is given by:

$$x_P = 2.925D \qquad (21)$$

and x_C is given by:

$$x_C = \frac{1}{2}\left[x_P + \frac{d_o}{0.32} \left(\frac{\rho_o}{\rho_a}\right)^{1/2} \right] \qquad (22)$$

A parameter ω is then defined:

$$\omega = \frac{d_o}{D}\left(\frac{\rho_o}{\rho_a}\right)^{1/2} \qquad (23)$$

hence

$$x_c = \frac{1}{2}\left(x_P + \frac{D\omega}{0.32} \right) \qquad (24a)$$

$$= D\left(1.467 + \frac{\omega}{0.64} \right) \qquad (24b)$$

$$\frac{\dot{m}_r}{\dot{m}_o} = \frac{0.47}{\omega} - 0.5 \qquad (25)$$

For the case where a secondary air flow of mass flow $\dot{m}_a$ but a negligible momentum is introduced (as in a kiln), it is assumed that the secondary air is entrained by the primary jet flow before any recirculating gas is entrained. For this situation, an equivalent nozzle diameter d'_o is calculated as:

$$d'_o = \frac{2(\dot{m}_r + \dot{m}_r)}{(\pi\rho_o m_o \overline{u_o})^{1/2}} \qquad (26)$$

Eq. (25) still holds, but now the left side is $\dot{m}_r / (\dot{m}_o + \dot{m}_r)$, and ω' is given by

$$\omega' = \left(\frac{\dot{m}_a + \dot{m}_o}{\dot{m}_o}\right) \frac{d'_o}{D} \left(\frac{\rho_o}{\rho_a}\right)^{1/2} \qquad (27)$$

The theory then gives the position N, where recirculation entrainment begins (x_N) and the position C, which is the core of the recirculation eddy (x_C) as:

$$x_N = 3.125\ \omega'\ D \qquad (28a)$$

$$x_C = 1.56(\ \omega' + 0.94\ )D \qquad (28b)$$

The distance to the point P where the jet strikes the wall (x_P) is as in Eq. (19) and

$$\frac{\dot{m}_a + \dot{m}_o}{\dot{m}_o} = \frac{0.72}{\omega'} - 1 \qquad (29)$$

Data from cold models and hot furnaces show that Eq. (25) fits the slope of the data but is consistently high in its estimation by an increment of about 0.25 in a plot of $\dot{m}_r/\dot{m}_o$ vs $1/\omega$. A similar comparison of data using Eq. (29) (plotting vs. $1/\omega'$) over-predicts the mass flow ratio by up to a factor of 1.7 (at $1/\omega' = 7$) but joins the data at $1/\omega' = 2$.

The position of points N, C, and P, in data compared by Field et al. [3] gave a reasonable fit. The fit was improved, however, by using a narrower effective jet angle (9.2^o vs. 9.7^o) in estimating x_P. It should be noted that these analytical expressions are valid only for d_o' / D less than about 0.05.

One mixing scenario of interest both academically and in some industrial systems involves the "perfectly stirred reactor." This concept was developed for laboratory measurement of the reaction rate of simple fuel materials (hydrogen, methane, etc.) in an apparatus where high pressure impinging jet streams generated a flow field so intensely mixed that the chemical reaction rate was by far the dominant and controlling process (not mass transfer). In such a device, the reaction kinetics could be studied over a range of oxidant concentrations, temperatures etc.

C. HEAT TRANSFER
It is beyond the scope of this course to deal with the complex problems of heat transfer analysis for combustors. However, several heat transfer-related considerations should be noted.

1. Conduction

The primary areas of application of conduction heat transfer analysis in the design of incineration systems are in estimating solid fuel heating rates for wastes thrust into a combustion environment (see Ref. 2) and in predicting heat losses and outside wall temperatures for the combustion chamber. Although the heat flux in combustion systems is importantly radiative (except the convective heating of boiler tubes), heat loss by conduction through refractory walls can exceed 2 to 5% of the total heat release and can result in unsafe outside wall temperatures. See the Enclosure Section below for information on refractory and their properties.

In refractory-lined systems, where worker comfort or safety require cool outside wall temperatures, an analysis of wall heat loss is appropriate. Boundary conditions for the analysis would include:

● Assume that the inside wall temperature will be maintained within a few hundred degrees of the hottest large areas or volumes in the combustion chamber. This assumption recognizes the fact that since wall conduction is relatively poor, the inside temperature will approach radiative equilibrium with such intense radiation sources.

● Allow for both convective and radiative losses from the outer wall. Rather than introducing the mathematical complexity of the fourth power of temperature dependency of radiation, use an overall "natural convection plus radiation coefficient", available from standard tests [10]. Note, however, that if outside temperatures exceed, say, $200°C$, a more careful consideration of radiation is appropriate.

For one-dimensional heat transfer by conduction in the x-direction, the heat transfer rate per unit area is given by:

$$\dot{Q}_a = -\lambda \frac{dT}{dx} \ \ \text{kcal hr}^{-1}\text{m}^{-2} \qquad (30)$$

where λ is the thermal conductivity and dT/dx is the thermal gradient. The minus sign acknowledges the fact that heat flow in the positive x-direction requires a decline in temperature with increasing x. The conversion factor for λ from the commonly tabulated values (e.g., Ref. 5) of Btu hr^{-1} ft^{-2} ($°$F/ft)$^{-1}$ to kcal hr^{-1} m^{-2} ($°$C/m)$^{-1}$ is 1.487.

For steady, one-dimensional conduction in isotropic solids, the thermal gradient will be linear and Eq. (30) becomes

$$\dot{Q}_a = -\lambda \frac{\Delta T}{\Delta x} \ \ \text{kcal hr}^{-1}\text{m}^{-2} \qquad (31)$$

where Δx is the thickness of the slab and ΔT the surface-to-surface temperature difference.

It should be noted that the thermal conductivity often varies appreciably over the temperature extremes common to combustion systems, and a suitable average must often be selected. More complex problems which relax the assumptions indicated above (isotropic materials, one-dimensionality, etc.) may often be solved by the use of special texts (e.g., Ref. 11).

EXAMPLE 1. A horizontal, cylindrical incinerator 4 m in diameter is burning liquid waste in a chamber. The chamber is constructed with 20 cm (X_R) thick insulating firebrick walls, sheathed with 6 mm (X_S) thick steel. The mean radiative temperature of the flame is $1100°C$. What is the approximate outside skin temperature?

Assume the equilibrium temperature of the inside wall (T_1) is $1000\,°C$ and that the ambient is at $25\,°C$ (T_a). The outside refractory temperature is at T_2 and the outside steel temperature at T_3. Simplify the analysis by assuming that the thermal gradients within the wall and the steel shell are linear.

$$[\dot{Q}_a]_R = \text{ conduction through refractory}$$

$$= \frac{\lambda_R}{x_R}\,(T_1 - T_2)\ \text{kcal hr}^{-1}\text{m}^{-2} \qquad (32)$$

$$[\dot{Q}_a]_S = \text{ conduction through steel (neglecting conduction of air film)}$$

$$= \frac{\lambda_S}{x_S}\,(T_2 - T_3)\ \text{kcal hr}^{-1}\text{m}^{-2} \qquad (33)$$

$$[\dot{Q}_a]_{a,c} = \text{ convection loss to the ambient air}$$

$$= h_c\,(T_3 - T_a)\ \text{kcal hr}^{-1}\text{m}^{-2} \qquad (34)$$

where

$$h_c = 2.84\,[\,\Delta T_s/D_o\,]^{0.25}\ \text{kcal hr}^{-1}\ \text{m}^{-2}\ °\text{C}^{-1} \qquad (35)$$

Note that Equation (35) is a dimensional equation, with ΔT_s being the temperature difference between the surface and the ambient in $°C$ and D_0 is the outside diameter in meters. The equation applies to horizontal cylinders or to long vertical cylinders only. For other configurations:

Vertical plates higher than 1.0 meter:

$$h_c = 4.23\,[\Delta T_s\,]^{0.25} \qquad\qquad \text{kcal hr}^{-1}\ \text{m}^{-2}\ °\text{C}^{-1} \qquad (36)$$

Horizontal plates:
    Facing upward

$$h_c = 5.93\,[\Delta T_s\,]^{0.25} \qquad\qquad \text{kcal hr}^{-1}\ \text{m}^{-2}\ °\text{C}^{-1} \qquad (37)$$

    Facing downward

$$h_c = 3.12\,[\Delta T_s\,]^{0.25} \qquad\qquad \text{kcal hr}^{-1}\ \text{m}^{-2}\ °\text{C}^{-1} \qquad (38)$$

$$[\dot{Q}_a]_{a,r} = \text{ radiation to ambient} = h_r\,(T_3 - T_a)\ \text{kcal hr}^{-1}\ \text{m}^{-2} \qquad (39)$$

where

$$h_r = \frac{4.92 \times 10^{-8}}{(T_3 - T_a)}\,(T_{3'}^4 - T_{a'}^4)\varepsilon_S\ \text{kcal hr}^{-1}\ \text{m}^{-2}\ \text{K}^{-1} \qquad (40)$$

$T_{3'}$ and $T_{a'}$ are the surface and ambient temperatures (respectively) expressed in degrees Kelvin and ε_S is the emissivity of the outer steel shell. Property values of use are:

$$\lambda_R \quad = 0.15\ \text{kcal hr}^{-1}\ \text{m}^{-2}\ (°\text{C/m}\,)^{-1}$$

$$\lambda_S \quad = \ 37\ \text{kcal hr}^{-1}\ \text{m}^{-2}\ (°\text{C/m}\,)^{-1}$$

$$\varepsilon_S \quad = 0.8\ \ \text{(Oxidized steel, rough oxide coat)}$$

Note that:

$$[\dot{Q}_a]_R = [\dot{Q}_a]_S = [\dot{Q}_a]_{a,c} + [\dot{Q}_a]_{a,r}$$

 Rather than attempting to solve a fourth order equation, assume T_3, calculate h_c and h_r, calculate T_3, and iterate to acceptable convergence:

Assume:

$T_3 = 120\,°C$ (393 K)

$$h_c = 2.84 \left(\frac{120 - 25}{4} \right)^{0.25} = 6.27 \text{ kcal hr}^{-1} \text{ m}^{-2} \, °C^{-1}$$

$$h_r = \frac{4.92 \text{ x } 10^{-8}}{(120 - 25)} (393.15^4 - 298.15^4)(0.8) = 6.62 \text{ kcal hr}^{-1} \text{ m}^{-2} \text{ K}^{-1}$$

$h_{c+r} = h_c + h_r = 12.89 \text{ kcal hr}^{-1} \text{ m}^{-2}°C^{-1}$

Eliminating T_2 between the steel-to-refractory and the refractory-to-ambient heat loss terms and using the notation.

$$C_1 = 1 + \left(\frac{\lambda_S X_R}{\lambda_R X_S} \right) = 8223$$

$$C_2 = \left(\frac{X_R}{\lambda_R} \right) h_{c+r} = 17.19$$

Then

$$T_3 = \frac{(C_1 - 1)T_1 + C_1 C_2 T_a}{(C_1 - 1 + C_1 C_2)}$$

$T_3 = 78.6\,°C$ and $T_2 = 78.7\,°C$.

Clearly, the conductive resistance of the steel is negligible in comparison to that of the firebrick and the problem could be simplified by neglecting it.

   Recomputing h_c and h_r for the new T_3 yields

$$h_c \quad = 5.43 \text{ kcal hr}^{-1} m^{-2}°C^{-1}$$

$$h_r \quad = 5.43 \text{ kcal hr}^{-1} m^{-2}°C^{-1}$$

$$h_{c+r} \quad = 10.86 \text{ kcal hr}^{-1} m^{-2}°C^{-1}$$

and $T_3 \quad = 88\,°C$ (acceptable convergence)

It is noteworthy that changing the assumed inside wall temperature by $100\,°C$ would change T_3 by less than $10\,°C$. Also, if the outside wall is as hot as $90\,°C$ ($194\,°F$), care should be exercised to prevent worker contact or consideration should be given to lagging the wall with insulation to bring the temperature within safe limits.

2. Convection

Convection from hot gases to the wall, though important in boiler design, is usually less important than radiation in combustion system analysis. A particular exception occurs when jets of heated air or flames impinge upon a surface. This can happen when sidewall overfire air jets are discharged across narrow furnaces or burner flames impinge on the opposite end of the furnace. The heat transfer rates at the point of impingement can be extremely high. Consequent damages to refractory or to boiler tubes can be excessive. For this reason, flame length or jet penetration calculations should be used to assure a reasonable margin of safety.

In general, convective heat transfer is calculated using equations of the form:

$$Q_{conv} = h_c \, A \, (T_g - T_s) \qquad (41)$$

where h_c is the convective heat transfer coefficient in units of $kcal \, hr^{-1} m^{-2} {}^{\circ}C^{-1}$, A is the area in square meters, T_g is the gas temperature and T_s is the temperature of the surface being heated. The convective coefficient is a function of the flow conditions (turbulent vs. laminar) and the eddy intensity as scaled by the Reynolds Number.

3. Radiation

In high temperature combustors, radiation is the dominant mechanism for heat transfer. The relationship defining the total radiant emissive power W_B from a black body at a temperature T is known as the Stefan-Boltzmann law:

$$WB \;\; = \sigma \, T^4 \; kcal \; m\text{-}2 \; hr^{-1} \qquad\qquad (42)$$

where
  σ   = the Stefan-Boltzmann Constant

  = 4.88 x 10-8 kcal m^{-2} hr^{-1} $^{\circ}K^{-4}$ or 0.171 x 10-8 Btu ft^{-2} hr^{-1} $^{\circ}R^{-4}$

One should note that the emissive power is spectral in nature (different at different wavelengths). For black bodies (which absorb and emit fully at all wave-lengths), this is unimportant. For solids, liquids, or gases which absorb or emit preferentially in one or more spectral regions, however, (importantly including carbon dioxide and water vapor) the spectral characteristics of both emitter and absorber must be taken into account. To simplify computation, the concept of a "grey body" has been developed. At the same temperature, the total emissive power of a grey body W is somewhat less than a black body. The ratio of emissive power of the grey to the black body at the same temperature is known as the emissivity, i.e.,

$$\frac{W}{W_B} \; = \; \varepsilon \qquad\qquad (43)$$

The emissivity of surfaces generally increases as tarnish or roughness increases (e.g., oxidized steel or refractory) and may change with temperature.

Radiation follows straight lines. Thus, the geometrical relationship between surfaces and volumes has a direct impact on the net flux. Also, surfaces will absorb and reradiate and may reflect heat, thus compounding the difficulty of analysis. Texts such as Reference 9 provide guidance to quantifying these effects.

Gases and luminous flames are radiators. Although carbon dioxide and water vapor (particularly) are essentially transparent in the visible region of the spectrum, they absorb strongly in other spectral regions and participate significantly in radiant heat transfer in furnaces. It should be noted that the overall characteristics of gas emissivity (a "grey gas") may be conveniently approximated with an exponential formulation

$$\varepsilon_{gas} = 1 - \exp(-apx) \qquad\qquad (44)$$

where "a" is a constant characteristic of the gas, "p" is the partial pressure of the gas, and "x" is the thickness of the gas layer. Thus, thick sections of gas at high concentrations will have relatively higher emissivity than the converse. As an indication of the importance of these effects, at $1100\,^{\circ}C$, a 3 meter thickness of flue gas containing 10% water vapor in air has an emissivity of 0.2, about 25% of that of a refractory wall. Similarly, flames emit a significant radiative flux due both to the radiative emission of gases and to the hot particulate matter (ash and soot) contained within it.

4. Heat Transfer Implications in Design

In many cases (e.g., burning wet refuse) there is a significant heat requirement to initiate and maintain a steady burning condition. When heat recovery is of no interest, no serious compromises are required and the shape and

operating temperature of the surfaces in radiative "touch" with the incoming waste can be readily designed such as to assure rapid and stable ignition. When heating of boiler surfaces or stock is an objective, care should be given to avoid robbing the feed zone of the heat flux required to maintain steady ignition and burning.

The designer should consider the heat fluxes within and through the furnace as they may affect wall temperatures. Often, in waste burning systems, the fly ash may react with the refractory at elevated temperatures to yield low melting eutectics. Such processes result in rapid, even catastrophic, wall degradation. Also, high wall temperatures may foster adherence of ash (slag build-up) which can cause mechanical damage to walls and, in mass burning systems, to the grates when the accumulated slag brakes off and falls. Such slag deposits can build up to the point where the flow of gases and even waste moving on grates can be impeded as, for example, by completely bridging across a 3meter-wide furnace. Also, tube corrosion reactions often take place in reduced atmospheres below fused deposits on boiler tubes (especially the superheater where the fire-side temperatures run higher).

The designer should also be aware that cold surfaces are heat sinks, draining away the radiative energy from within a furnace. Many furnaces are constructed with (from a radiative heat loss standpoint) clear "views" of cold zones from the hot primary chamber. The result is a chilling of the combustion zone with noticeable increases in soot and carbon monoxide generation.

D. Waste Feeding

1. Solid Waste Storage and Feeding

Most solid wastes have a low bulk density and, except for process wastes, include a substantial fraction of cellulose (wood, paper, cardboard). The low bulk density requires relatively large storage space and often involves re-handling of the waste (stacking) to increase storage capacity. For hazardous waste materials that present a toxicity problem to plant personnel, enclosed storage such as single-outlet bins, multiple-outlet silos and portable bins. Incinerators for solid wastes fall into two, broad categories: mass burn (where the wastes are burned without pre-processing) and refuse-derived-fuel (RDF) systems where the wastes are subjected to size reduction often followed by classification to separate "heavies" (stones, crockery, metal, very wet organic matter, massive wood etc.) from the fluffier "lights" (paper, textiles, plastics etc.). The obviously different materials handling characteristics of the material fed for these two waste incinerator categories leads to very different storage and feeding strategies (and problems).

Multiple-outlet silos are useful to store small or medium quantities since they rely on gravity to discharge the solids. Therefore, hopper slopes and outlet dimensions must be generous to ensure uninhibited flow. Single-outlet bins are common in industry. These bins use funnel-flow with a steep, pyramidal hopper sloping 60° or more from the horizontal. Portable bins ("dumpsters") are used for on-site waste accumulation at many industrial and commercial sites. In most instances a rectangular container is used; equipped with a hydraulic compactor to increase capacity, minimize pilferage and vector access and to reduce the frequency of pick-up.

In small mass burn facilities (say, up to 100 tons per day among 3 or 4 furnaces), the domestic solid wastes are often dumped on a concrete tipping floor and pushed about or stacked using a front-end loader. A schematic of the feeding concept usually used for the incinerator furnace is shown below.

For a loading operation, the cover over the feeding hopper is opened and the hopper is filled. The cover is then returned, the guillotine is raised and a hydraulic ram pushes the waste into the furnace. Then, the guillotine is closed, the ram withdrawn and, after opening the cover, the hopper is now ready for the next load. Since many of these furnaces operate with the primary chamber in a starved air mode (say, at 80% of theoretical air, fed at a fixed rate), the control signal to add waste is an <u>increase</u> in primary chamber temperature as the combustion process moves toward the stoichiometric state.
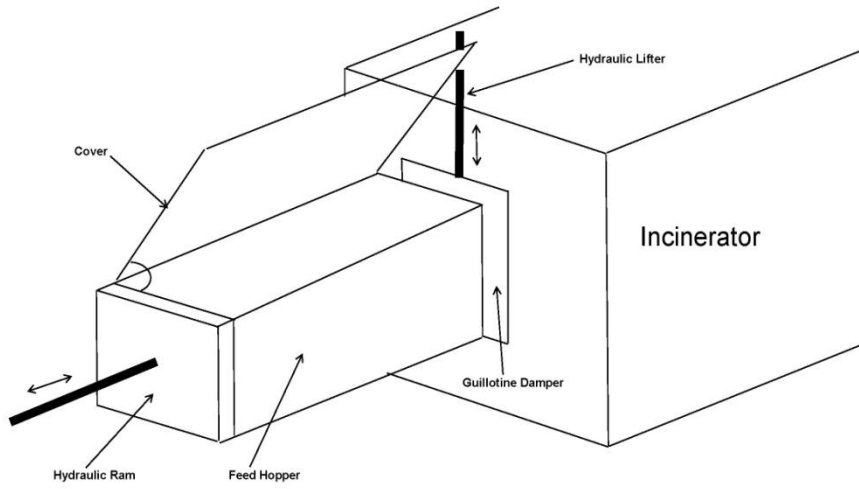
In larger plants, a concrete pit and bridge crane system is more common. Pit and crane systems are much more costly than the floor dump approach but are appropriate for the much larger quantities of waste stored (typically, 2-3 days processing quantity to supply the plant over the weekend) and for the larger waste throughput rates.
The waste is charged into a hopper using a clamshell or the more common "orange peel" grapple (shown above) over a feed chute terminating on the mechanical grates that move the waste into and through the combustion chamber. The waste plug in the chute prevents furnace gases from flowing back through the incoming

"Orange Peel" grapple as used in large plants

waste thus starting a "chute fire." The grapple is manipulated by an operator sitting in an air-conditioned booth or pulpit overseeing the pit area. Oversize or problem wastes (such as "white goods") can be seized and moved to a recovery zone in the side.

Rubber belt and steel apron or vibrating conveyors have been used to transport raw and shredded solid waste for short distances. Pneumatic systems have been used with shredded wastes for transport for over 300 meters. Frequent and severe problems with abrasion wastage of the piping and with plugging indicate that pneumatic

conveyors should be selected only when absolutely necessary. The layout should incorporate an absolute minimum of turns. Conveyors of any type for solid wastes can be counted upon to present a continuing problem with maintenance and housekeeping.

Storage and reclaim of RDF-type solid wastes is also a problem area. Frequent bridging problems in chutes or in bins, compaction on standing and other operating difficulties in confined flow situations are common. These problems result from the tendency of shredded solid waste to interlock or knit together or to catch on minute projections and then compress and bridge. Forced expulsion through flaring cross-sections (e.g., with a ram) or open storage in pits or on open floors are preferred. Bins with vertical screws (to keep the bed uncompacted) and "live bottom" design have been effective for bunkered, shredded waste.

Fires in a storage pit or fires in floor-dump operations are also problems; not only for the potential human injury and/or the loss of buildings or equipment but, also, because aggressive fire-fighting leads to tons and tons of soaking wet refuse to process.

2. Burners for Liquids and Gases

Liquid and gas burners function in devices designed for heat recovery (e.g. boilers), burn waste streams (e.g. liquid or gas incinerators) or high temperature treatment (e.g. annealing furnaces) to (1) feed the fuel/waste into the furnace, (2) to position the flames for useful heat release, (3) to incorporate means to ignite and maintain ignition, (4) to facilitate gasification of liquid and solid fuels, (5) to proportion air and fuel, and to assure safe operations. Figure 1 illustrates eight common flame types. One notes that Type 5 uses flame convection to heat adjacent refractory so it depends on re-radiation to heat the furnace load. Types 6 and 7 produce a high radiative flux component, even with natural gas.

a. Burners for Liquids

The heat release per unit volume of the combustion chamber is set by the fuel type, the mixing intensity and the tolerance of the chamber to exposure to high convective and radiative heat flux. Gas burners with intense mixing and substantial radiant heat feedback can achieve as much as 360 million kcal/hr/m^3 heat release. More conventional gas and light oil burners in refractory chambers run much lower: perhaps 900-1800 Mkcal/hr/m^3. In boilers, where reliability is critical, design heat release is usually limited to 175 – 360 Mkcal/hr/m^3.

Liquid fuels must first be vaporized before they burn. In low rate, inexpensive burners, this is accomplished by flowing the liquid onto a plate heated by radiation from the flame. Larger, industrial burners use some means to atomize the fuel, creating a cloud of small droplets which are then evaporated (at high rates) by radiation from the oil flame. In most situations it is desirable to subdivide the oil into small droplets in order to enhance vaporization rate (increasing the combustion rate per unit volume), to minimize smoking, and to ensure complete combustion. Atomization is effected by a number of means, including:
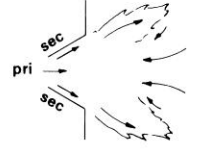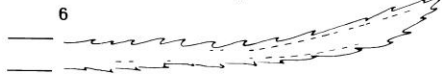
> ● Low pressure (0.03 to 0.35 atm) air atomization
>
> ● High pressure (2 atm or more) air or steam atomization
>
> ● Mechanical atomization of fluid through special orifices at   pressures from 5 to 20 atmospheres
>
> ● High speed rotating conical metal cups

Early analysis of droplet burning was based on analogies with coal combustion (the diffusion of oxidant to the droplet surface followed by heterogeneous i.e. two-phase reaction). Later work led to the presently accepted concept that combustion occurs in a homogeneous diffusion flame surrounding an evaporating droplet.

The minimum energy input requirements for atomization are determined by the viscosity of the waste at the atomization point. The kinematic viscosity ν (absolute viscosity/density) of the liquid is often used to characterize atomizer requirements. In the CGS system, the units of kinematic viscosity are cm^2/sec, or "stokes" calculated by dividing the absolute viscosity in centipoises by the density in gm/cm^3. For oils and other viscous liquids, the centistoke (0.01 stokes) gives numerical values in the 0 to 100 range. The more common unit is based upon a

determination of the kinematic viscosity by measurement of the time t (sec) of efflux of a fixed volume of fluid through a short standard capillary tube. Commercial viscometers are designed to obey the empirical relationships

Figure 1 Common Industrial Flame Types (courtesy FivesGroup Ltd.)

Type		Flame description	Swirl	Recirculation	Jet description△	Mixing rate
1†		Conventional forward flame	none, or weak in center only	little or none	axial	moderate
2†		"Headpin" flame	some	between pri and sec jets	pri jet penetrates internal reverse flow pri jet vel > sec jet vel	moderate
3†		Ball of flame	considerable, S* > 0.6	hot reverse flow into center	sec jet vel > pri jet vel	intense
4		Conical flame	high, S* > 1	cold reverse flow into center	sec jet vel >> pri jet vel	intense
5		Coanda burner flame	very high	minimal	radial or swirled flow contained by a refractory shape	fast
6		Long, luminous, lazy flame	none	none	fuel jet vel and air jet vel equally low (laminar) — bouyancy controlled	delayed, slow, diffusion
7		Long luminous "fire hose" flame	none	none	fuel□ jet vel >> air jet vel—thrust controlled	delayed
8			low	small scale internally, large scale externally	flow contained by re-fractory shape—burning inside and outside tile	fast

△ pri = primary—refers to central jet;
  sec = secondary—refers to outer jet.
† Type numbers 1, 2, and 3 were established by the International Flame Research Center of IJmuiden, Netherlands. Type 3 corresponds to Type B and 5 to C in Reference 6.b.
□ Or fuel and atomizing medium.   * See footnote (*) on page 235.

$$\nu = a_1 - \frac{a_2}{t} \quad cm^2/sec \text{ (stokes)} \qquad (45a)$$

$$t = \frac{\nu}{2a_1} + \left[\left(\frac{\nu}{2a_1}\right)^2 + a_2\right]^{1/2} \quad sec \qquad (45b)$$

For a common viscometer [5]:

<u>Viscometer</u>

	a_1	a_2
Saybolt Universal (SSU)	0.0022	1.8
Redwood No. 1	0.0026	1.72
Redwood No. 2 (Admirality)	0.027	20.00
Engler	0.00147	3.74

It is also useful to recognize that, for many liquids, a plot of absolute viscosity versus absolute temperature on log-log paper is, essentially, a straight line.

● Low Pressure Air Atomization – These burners require air at from 0.035 to 0.35 atm supplied by blowers. A heavy pitch of 85 SSU requires air at over 0.1 atm, whereas aqueous wastes can be atomized at 0.035 atm. Turn-down ranges from 3:1 to 6:1. The air used for atomization ranges between 2.8 and 7.4 m^3/liter, with less air required as the air pressure increases. These flames are comparatively short as about 40% of the stoichiometric air is intimately mixed with the fuel spray as the mixture enters the furnace.

● High Pressure Air or Steam Atomization – These burners require air or steam at pressures from 2 to 10 atm with air consumption from 0.6 to 1.6 m^3 air/liter of waste. Steam use ranges from 0.25 to 0.5 kg/liter with careful operation (a wasteful operator may use up to 1 kg/ liter). Waste heating to reduce viscosity is required only to the extent needed for pumpability. High pressure atomizing burners show poor turndown (3:1 or 4:1) and consume considerable compressor energy or steam (typically, for boilers, about 2% of the steam output). Since only a small fraction of the stoichiometric air or inert gas (when steam is used) is mixed with the emerging fuel spray, flames from these burners are relatively long. These burners are often used for incineration of liquid wastes.

● Mechanical Atomization – These burners atomize by forcing the liquid, under high pressure (5 to 20 atm), through a fixed orifice yielding a conical spray into which combustion air is drawn. In its simplest embodi-ment, the waste is fed directly to a nozzle. With such an arrangement, turndown is limited to 2.5 to 3.5:1, since, for example, a 75% reduction in pressure (atomization energy) is required to reduce the flow rate by 50%. Thus atomization effectiveness (droplet fineness) drops rapidly as the burner moves off the design flow rate.

The second type of mechanical atomizing nozzle incorporates a return flow such that a much smaller change in atomization pressure is needed to effect a change in flow rate. For these atomizers, turndown can be as great as 10:1. The viscosity of fluids atomized mechanically need not be as low as that for low pressure air atomization: 150 SSU is a typical design value. The flame from mechanical atomizing burners is usually short, bushy, and of low velocity. These mechanical atomizing burners are usually applied where large peak capacities (40-4000 liters/hr) are required and where large turndown ratios are desirable.

● Rotary Cup Atomization – These burners atomize by the action of a high speed rotating conical metal cup (typ. 5,000 rpm) from the outer edge of which the waste liquid is thrown into a stream of low pressure air entering the incinerator around the cup. Supply pressures are low (0.3 – 0.5 kilopascals) and there are relatively large openings for fuel passage thus minimizing plugging problems. These burners are ideal where the solids content of the waste is high and are generally free from plugging problems. Rotary atomizers offer a substantial turn-down capability (as much as 8:1 or greater). The flame shape from rotary cup burners is similar to that from mechanical atomizing burners, but with a somewhat increased combustion rate since a portion of the combustion air is supplied with the waste stream.

b. Burners for Gases

Industrial gas burners may be classified as premix, nozzle-mix or delayed mix burners. In premix burners, the primary air and gas are mixed upstream from the burner ports by an inspirator, an aspirator or a mechanical mixer. In an inspirator mixer, the gas emerges from a drilled nozzle ("spud") into a Venturi-shaped mixing conduit. The high gas velocity entrains and mixes with air, induced in proportion to the as flow. In an aspirator mixer, the air flows through a Venturi where the gas is introduced at the throat (the low pressure zone) and mixes with the air in the expanding section. In mechanical mixers, gas is admitted to the air inlet of a compressor, blower, or fan.

In nozzle-mix burners, the gas and combustion air do not mix until they leave the ports of the burner but the nozzle orifices are designed to enhance mixing of gas and air as they leave.

Delayed mixing burners utilize a long, slow, diffusion flame (Type 6 in Fig. 1) created by discharging a relatively slow-moving central stream of gas surrounded by a sheath of air injected at a comparable velocity or a "fire-hose" jet of gas that moves rapidly across the chamber before the low velocity surrounding air mixes, ignites and burns the fuel (Type 7 in Fig. 1). They are used when heating of the work must be uniform so that temperature gradients are minimized throughout the combustion space. Heating of the gas prior to mixing and ignition often leads to thermal cracking of the gas yielding a highly luminous, radiant yellow-orange flame.

c. Flame Safety

The objective of a flame safety system is to stop the flow of fuel if the flame is extinguished. Without such a device, the combustion chamber may fill with combustible or explosive mixtures leading to catastrophic losses. While a pilot light can achieve the goal of igniting the incoming gas/air mixture, the pilot itself may be extinguished or inadequate if atomization efficiency fails. Thus, an effective and reliable flame monitoring device is necessary coupled with means to close the fuel inlet valve.

In small systems where fast cooling is assured on flame failure, low cost thermopiles or bimetal warping devices are used that shut down the gas or oil flow on cooling. Photocells are seldom used since they can be stimulated by non-flame radiation (say, from hot refractory) and, thus, are not reliable. Smaller gas burners sometimes make use of flame rod detectors mounted at the intersection of the pilot and main flames which detect the ionization of gases in the flames. In large gas or oil burners, ultraviolet detector tubes (the "Purple Peeper" by Honeywell is the best known in this category) are almost exclusively used. The detector is insensitive to infrared radiant flux.

In all installations, the location and "view" of the flame safety device must be carefully considered to avoid being "fooled" by extraneous inputs which allow unsafe conditions to develop. Thus, if spark igniters are used, ultraviolet detectors must be shielded from the high ultraviolet emissions from the spark. Also, the flow and flame shape effects of high and low fire, rich and lean must be considered in establishing the flame safety system geometry.

E. Enclosures

The enclosure, the furnace shell itself, plays a key role in assuring adequate performance of a thermal processing system. Specifically, the enclosure and its characteristics affect the process by:

● Enclosure shape affects the radiative flux onto incoming fuel. This impact affects ignition time and flame length, the gross flow pattern in the furnace (including recirculation and bulk mixing), and the heat absorption patterns in boiler type enclosures.

● Enclosure volume determines the mean residence time, affecting burnout of CO, volatile organic compounds ("VOC"s), soot, tars, and other combustible pollutants.

● The enclosure may include heat absorbing surfaces for energy recovery; burners for auxiliary fuel to maintain temperature or for the burning of atomizable liquid wastes; air jets for overfire combustion and temperature control in units burning solid wastes or secondary and tertiary combustion air jets for liquid or gas fired units; means to feed waste and withdraw slag or solid residues; water sprays to cool the combustion gases as a precursor to temperature sensitive air pollution control devices and so forth.

1. Refractory Enclosure Systems

Refractories are non-metallic materials suitable for the construction or lining of furnaces operated at high temperatures. Stability (physical and chemical) at high temperatures is the primary material requirement, as the refractory system may be called upon, while hot, to withstand compressive and (limited) tensile stresses from the weight of the furnace or its contents, thermal shock resulting from heating or cooling cycles, mechanical wear from the movement of furnace contents (or even the furnace structures themselves due to thermal expansion or, in a kiln,

for the entire furnace), and chemical attack by heated solids, liquids, gases, or fumes. The issues involved in refractory selection and application are complex and merit exploration in texts and references (e.g. [2]).
In most incineration systems, refractory materials constitute an important part of the furnace enclosure, ducting, and/or stack. The functions of refractory materials include:

● Containment of the combustion process and flue gases in an enclosure resistant to failure from thermal stresses or degradation from high temperature abrasion, corrosion, and erosion;

● Re-radiation of heat to accelerate drying, ignition, and combustion of incoming feed;

● Protection of plant personnel from burn injury by their insulating qualities;

● Enhancement of combustion by incorporation into refractory baffles which increase turbulence in high temperature flue gas passages;

● Support of the burning mass or residues (hearth burning systems); and

● Protection of vulnerable system components in unusually severe environments (e.g., incinerator boiler superheater surfaces or sidewalls alongside grates).

To serve these many functions, a wide range of refractory materials have been developed. Art and science must be combined for proper application of refractory systems. This is particularly true for incineration systems where frequent and sometimes unanticipated changes in waste character can result in wide swings in temperature and ash (or slag) and gas composition.

Refractory materials are supplied mainly in:

● Preformed shapes, including standard sizes of brick and other shapes used to build arches or to line cylindrical chambers and flues; special and often proprietary designs; and special application shapes such as ignition tiles or checker brick;

● Plastic refractory (a mixture of aggregate, clays and bonding materials premixed with sufficient water for workability and ready to use), and dry, ramming mix (to be mixed with water before using) which can be rammed into place to form monolithic structures;

● Castable and gunning mixes which are poured or sprayed (gunned), respectively, to form large monolithic structures;

● Mortar and high temperature cements; and

● Granular materials such as dead-burned dolomite, dead-burned magnesite and ground quartzite.

The primary constituents of many refractories commonly used in incineration applications include fireclay, alumina, and silica refractory materials composed of mixtures of alumina (Al_2O_3) and silica (SiO_2) with minor constituents, including titania (TiO_2), magnesite (MgO), lime (CaO), and other oxides. In high abrasion areas or where resistance to thermal shock and/or high thermal conductivity is important, silicon carbide is also incorporated.

2. Properties of Refractory

a. Refractory Structure. At room temperature, refractory products consist of crystalline material particles bonded by glass and/or smaller crystalline mineral particles. As the temperature increases, liquid phase regions develop. The mechanical properties of the refractory at a given temperature depend on the proportion and composition of the solid minerals, glassy structure, and fluid regions.

b. Melting Behavior. Alumina-silica refractory (e.g., fireclay and high alumina brick) contain both crystal-line and glassy material. At temperatures above approximately 980 to 1095 °C, the glassy bond begins to become

progressively less rigid and, indeed, becomes a viscous liquid. As viscosity drops, the glass lubricates relative motion of the crystalline particles and, under stress, deformation can occur. At higher temperatures, the crystalline material begins to dissolve in the glass and, finally, the mass is unable to retain its original shape, deforming under its own weight.

c. Dimensional Changes. Almost all unburned (green) refractory materials exhibit permanent dimensional changes on initial heating. As firing proceeds, the rate of change of dimensions diminishes. If actual use reflects a careful choice of refractory and a specific curing cycle, little further significant dimensional change should be observed in service. As with most materials, refractories also exhibit reversible expansion and contraction when heated or cooled, respectively. Thermal expansion must be given careful consideration in design of refractory structures.

d. Abrasion and Impact. In the incineration of solids, refractories are often subject to the impact of heavy pieces of material charged into the furnace, abrasion by moving solids, or direct impingement by abrasive fly ash suspended in fast moving gas streams. Abrasion and impact resistance are often evaluated using standard rattler tests (ASTM C-7) and, more recently, by blasting the surface using silica or silicon carbide grit.

e. Spalling. Excessive thermal or mechanical stresses which are applied near to the face of a refractory brick or monolithic structure or adverse changes in the internal structure of the refractory in zones paralleling the hot face can lead to the loss of fragments (or spalls) of surface material. If the newly exposed refractory material is also over-stressed or undergoes a second cycle of internal structural change, the degradation process will continue until structural failure occurs or until heat losses through the thinned brick require shutdown. The loss of face refractory through cracking and rupture is known as spalling. Spalling is of three general types thermal, mechanical, and structural).

THERMAL SPALLING. Thermal spalling results from stresses generated within the refractory arising from the unequal extent of thermal expansion (or contraction) due to temperature gradients. Failure of the refractory is usually associated with rapid changes in temperature. Thus, thermal spalling failures can be traced to material and/or operational factors.

MECHANICAL SPALLING. Rapid drying of wet brickwork; inadequate provision for thermal expansion; or pinching of hot ends (especially in arches) can lead to stress concentration and failure. "Pinch spalling" is common on the inner surfaces of sprung arches since the hot faces expand more than the cold ends or when inadequate provision for expansion has been made in the refractory design.

STRUCTURAL SPALLING. Structural spalling refers to losses of surface material due to changes (in service) in the texture and composition of the hotter portions of the brick. These changes can be brought about through the action of heat; through reactions with slags or fluxes; or through the reactions of or with gases which permeate the brick. The changes resulting in spalling are those where zoned structures are formed which show markedly different thermal expansion characteristics, increased sensitivity to rapid temperature change, or the presence of shrinkage or expansion cracks.

f. Chemical Reactions. At the temperatures found in incinerators and many other combustion systems, chemical action can be one of the greatest factors contributing to the ultimate destruction of refractory structures. The mineral constituents of wastes (or fuels) or the gases in the furnace enclosure may penetrate the refractories; changing the size and orientation of crystals, forming new minerals or glass, altering the texture and physical or chemical properties of the brick, or dissolving (corroding) granules or bonding structures. The chemical agents which participate in these chemical reactions are known as fluxes and the corrosive melting action which ensues as fluxing.

ACIDIC AND BASIC FLUXES. In evaluating the potential for refractory reactions, the most useful general concept matches acidic slags with acidic refractories and basic slags with basic refractories. In this context, the oxides of the following elements show acidic or basic properties (defined as a consequence of the electronic structure of the elements and not the "pH" measure of acidity related to hydrogen ion concentration) as shown below.

Acidic and Basic Properties of Refractory Fluxes

Acidic Oxides	Basic Oxides
Silicon (as SiO_2)	Iron (as FeO)
Aluminum (as Al_2O_3)	Calcium (as CaO)
Titanium (as TiO_2)	Magnesium (as MgO)
Phosphorous (as P_2O5)	Potassium (as K_2O)
Iron (as Fe_2O_3)	Sodium (as Na2O)
	Chromium (as Cr_2O_3)

Since fluxing involves chemical reactions, the analyst should take care to evaluate the acid-base balance using composition expressed in mol percent instead of the commonly reported weight percent.

Refractory brick falls into acidic (fireclay, high alumina and silica brick) or basic (chrome, magnesite and forsterite brick) categories. The use of the net acidic or basic chemistry of a slag is a good but not a perfect criterion for refractory selection. Exceptions are common due to differences in operating and reaction temperatures, reaction rates, viscosities of reaction products, and the formation of protective glazes and coatings on the refractory.

CORROSION RATE. The corrosion rate of refractories depends on a number of factors, factors affecting the rate at which reactants are brought together, react, and are carried away as well as the chemistry of the reactants (the flux and the refractory) themselves.

REACTIONS WITH ALKALI METAL COMPOUNDS. The alkali metal-containing wastes (most commonly, sodium and potassium compounds) are often critical relative to fluxing reactions. Sodium compounds enter into reactions with common refractory materials. The end results of these alkali metal interactions include glazing and sealing of the exposed refractory surfaces, formation of liquid phases by eutectics or low-melting oxides that penetrate the refractory and, by the changes in expansion coefficients for the refractory-alkali mixture compared to the base refractory, leading to structural spalling losses on cooling.

REACTIONS BETWEEN REFRACTORIES. Just as "foreign materials" such as fly ash can react with refractories, so refractory bricks and/or mortars of different compositions can enter into reactions with one another.

REACTIONS WITH GASES. Furnace gases can have a major impact on refractory-slag and refractory-refractory reactions; affect the melting range and viscosity-temperature properties of slag; and can, themselves, participate in refractory attack.

The most important measure of furnace atmosphere corrosive impacts relates to its oxidizing or reducing nature. For most refractory, oxidizing atmospheres are preferred. An exception is silicon carbide which slowly oxidizes above 900 °C. Reducing atmospheres tend to enhance the corrosivity of iron bearing slag, perhaps due to the greater basicity of FeO versus the more fully oxidized forms.

Chlorine reacts with some components of various refractories (e.g., alumina) at temperatures about 950 °C to form volatile chlorides. Alumina also can react with sulfur oxides to form aluminum sulfate. The volume increase accompanying the "sulfating" reaction will weaken the brickwork. Fluorine and hydrofluoric acid are aggressive furnace gases through their unique reaction with silica and silicates to form silicon tetrafluoride (SiF4): a highly volatile gas.

$$SiO_2(s) + 6HF \rightarrow H_2SiF_6 (s) + 2H_2O\uparrow$$

$$H_2SiF_6 (s) \rightarrow SiF_4\uparrow + 2HF$$
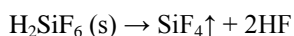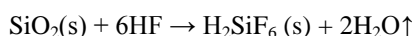
g. Thermal Conductivity. Thermal conductivity is an important refractory property. Since the function of refractory is to contain gases and solids at high temperature, the conductive loss of heat through the refractory wall represents an energy loss to energy recovery processes and/or results in high outside wall temperatures that present

an employee safety hazard. To minimize heat loss by conduction, several layers of refractory material are often used:

● High temperature castable or brick inner layer suitable to contain the highest expected gas temperature, resist abrasion and spalling, and present a surface relatively inert to slag or gas attack. These process-related needs dominate refractory selection.

● Insulating castable or brick selected primarily because of its low thermal conductivity.

● Insulating liner selected for easy application and low thermal conductivity.

The thermal conductivity of several refractory types is shown in Figs. 2, 3 and 4.

The following summarizes the features of alternative refractory systems.

Refractory Type	Advantageous Features	Problematic Features
Brick	Strength, high density	Joints, installation cost
Plastic	Joint-free, thermal and shock resistant after curing	Cracks, curing time
Castables	Low cost, fast installation, insulating qualities	Forms required, only moderate hot strength
Gun Mix	Joint-free, insulating qualities flexible, fast installation	Low heat strength, debonding tendency
Alumina (ceramic blanket)	High insulating qualities, easy to install, usable 850-1650 °C, inert, insensitive to thermal shock	No strength or abrasion resistance, needs many supports

2. Water Cooled Enclosures & Heat Recovery Systems

Containment of combustion processes in refractory lined chambers limits the peak temperatures which can be permitted (requiring increased excess air levels and, consequently, larger air pollution control and fan equipment). An alternative enclosure concept uses metal surfaces protected against overheating by water cooling. In small units or where energy recovery is economically unsound, simple water sprays on the outside of a metal furnace wall may be reasonable. Although not strictly an enclosure concept, heat removal in waste heat boilers is often used in small and medium-sized incinerators both as a means to recover useful heat and/or to cool the gases ahead of air pollution control.

In larger units, the walls are constructed of tubes welded in an air-tight membrane wall (a "waterwall") and considerably more complex strategies of energy recovery are implemented. Here, the waterwall constitutes the enclosure of the combustion system in addition to its heat recovery function. This enclosure concept is discussed below under "Heat Recovery."

F. Heat Recovery

The utility and value of recovered energy is often an economically critical benefit in waste incineration systems. Even in smaller facilities, recovered steam can offset fossil fuels for building heat or hot water. In larger facilities (e.g. municipal systems), steam at high pressures and temperatures (with superheat) is sent to turbines for electrical generation.

1. Fire-Tube Waste Heat Boilers. Fire-tube boilers are so-named because the products of combustion pass through tubes or flues that are surrounded by water. These boilers produce only saturated steam. Generally, incinerator fire-tube boilers are of the horizontal type with a long cylindrical shell set on saddles equipped with rollers to permit

movement of the boiler as it expands and contracts or suspended from hangers and supported by overhead beams. Because the outer shell of the fire-tube boiler must contain the full steam pressure, economics and practicality of fabrication limit the maximum pressure available. Boilers with steaming rates from 500 to 20,000 kg/hr at pressures from one to slightly over 15 atmospheres are available. These boilers are usually shop fabricated and are low in first cost. They find common application for smaller incinerators burning non-hazardous plant trash. They have the disadvantages of requiring a large water volume and their circulation is poor, resulting in slow response to changes in firing rate. Also, their capacity, pressure and steam temperature are limited.
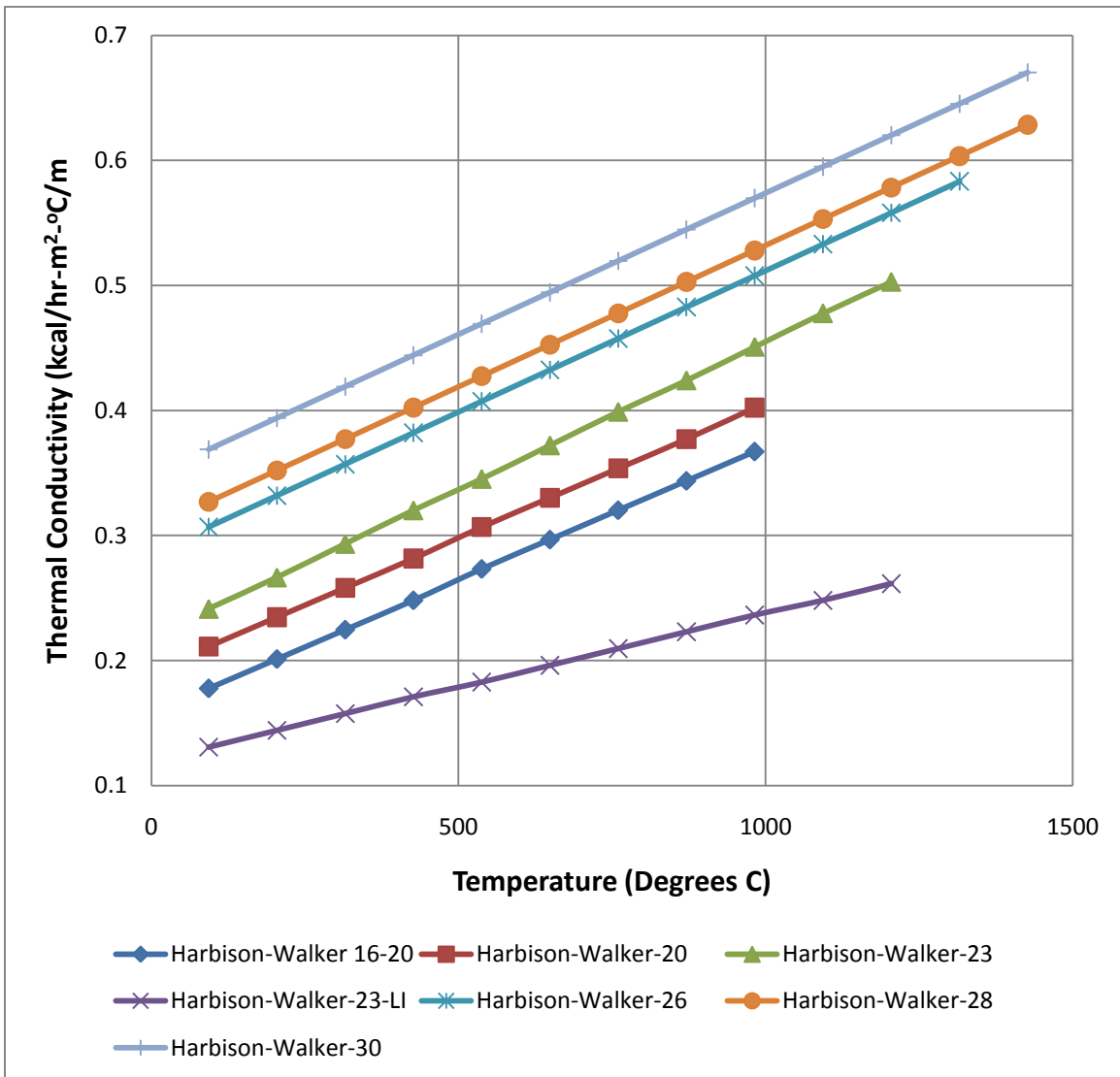

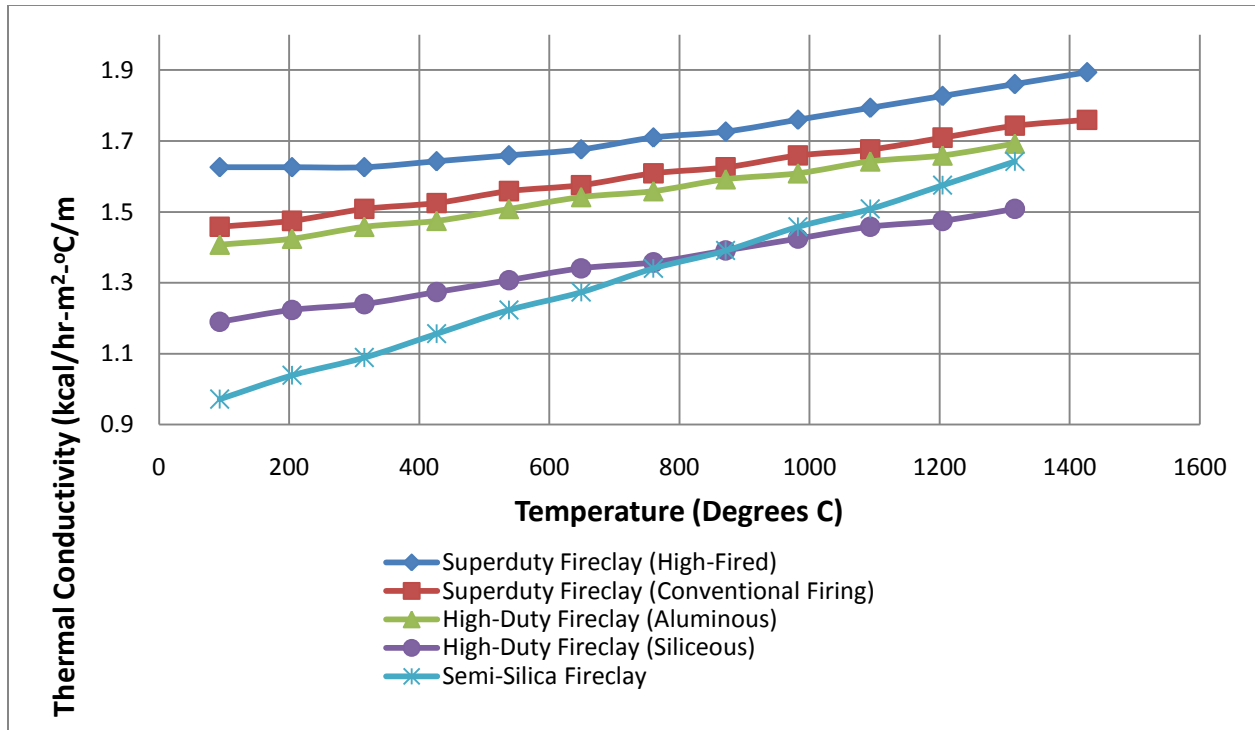**Figure 2 Thermal Conductivity of Insulating Firebrick [12]**

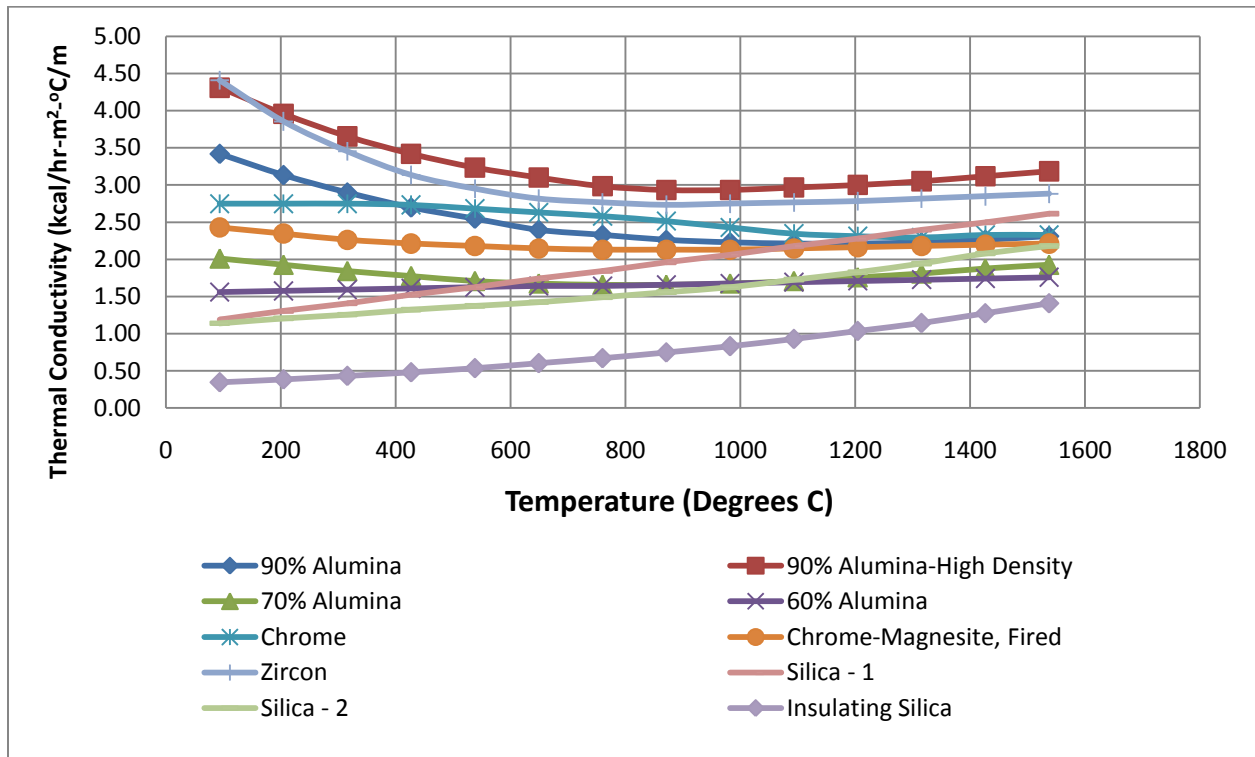**Figure 3 Thermal Conductivity of Fireclay Brick [12]**

Figure 4. Thermal Conductivity of Various Refractory Brick [12]

Common fire-tube designs used in small incineration systems include 2-pass (Fig. 2) and 3-pass (Fig. 3) embodiments. The 2-pass design is particularly adaptable where large volumes of relatively low temperature gases are available as the heat source. Pressure drop is small. The 3-pass design has maximum efficiency and minimum floor space. Flue gases pass a full three lengths of the boiler.

2. Water-Tube Waste Heat Boilers. In a water-tube boiler, the products of combustion pass around tubes containing water. The tubes are welded into one or more cylindrical drums. The uppermost drum (the "steam drum") receives the rising froth of steam and liquid water and is the point of entry of the feedwater. In order to provide high-purity water for processes, for a subsequent superheater or a turbine, the steam drum also includes steam scrubbers and separators to aid in separating the gaseous steam from liquid water. The steam drum also mixes the saturated water remaining after steam separation with the incoming feedwater, mixes any chemicals added for corrosion control, and provides a point of water accumulation to accommodate rapid changes in furnace heat release or boiler load.

If there are no other drums, the bottom of the steam drum is the point where a portion of the boiler water is drawn off as a blowdown stream to purge accumulated solids from the system. In boilers with two or more drums, the lowest drum (the "mud drum") accumulates scale and other solids and is the preferred source of the blowdown stream.

3. Water wall Boiler Enclosures.

In larger combustors, convective heat transfer surface, as in a waste heat boiler is used to withdraw heat by boiling water. In addition, however, feedwater, under pressure, is also passed into tubes in panels lining the furnace wall. These panels of wall tubes are welded together with a narrow steel strip between the individual tubes to form a continuous, gas-tight membrane or "water wall" enclosure.
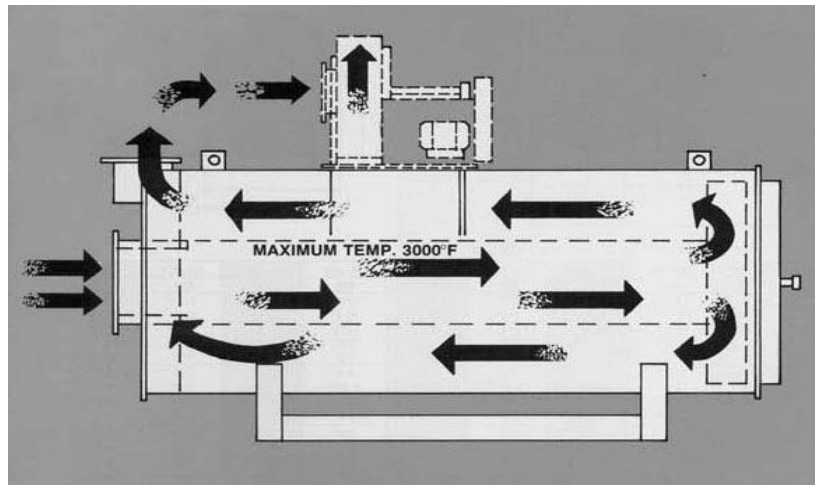

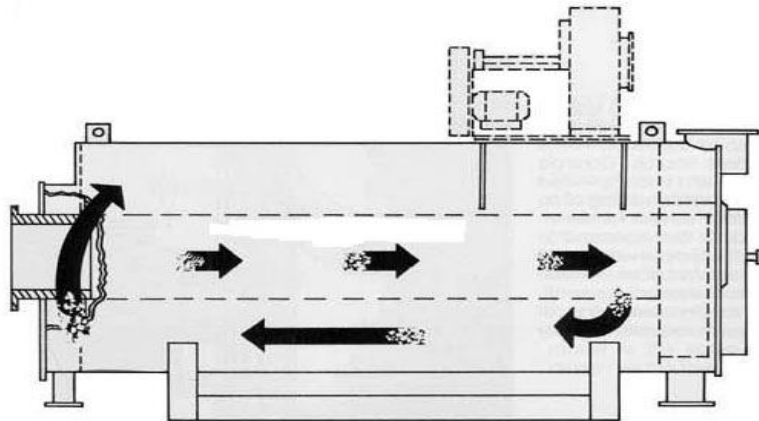**Figure 2. 2-Pass Waste Heat Boiler (Courtesy, York-Shipley Global)**

Figure 3. 3-Pass Waste Heat Boiler (Courtesy, York-Shipley Global)

At the point of introduction into the boiler, the feedwater is treated, deaerated, and, perhaps, preheated such that its temperature is at or slightly above the boiling point at the boiler's operating pressure. It is important to be sure that the outside surface temperature in the boiler exceeds the dew point of the furnace gases to avoid condensation and corrosive attack of the tube surface. In passing the water through the boiler, it is desirable to optimize the temperature difference between the water and the hot combustion gases (maximum heat transfer rate) to minimize the required amount of heat transfer area (capital cost) while still extracting the maximum amount of heat from the combustion gases. In larger boilers, this will include such components as:

   a. Radiant Boiler. The water walls and, in some cases, banks of tubes exposed to the high temperature combustion zone. Heat transfer rates are very high and radiant energy transport from the incandescent refuse bed, flame, and/or hot gases (see subsequent sections of this chapter) is the predominant means of heat transfer.

   b. Slag Screen. Banks of specialized boiler tubes at the entrance to the convection passes that are designed to accept and cope with the accumulation of slag deposits.
   c. Convection Boiler. One or more banks of tubes ("or passes") between which the hot flue gases flow where the water (from the economizer) is evaporated. Heat transfer is predominantly by convection. Flow of the water through the tubes may be due to buoyancy effects (a natural convection boiler) or pumps (a forced convection boiler) and is two-phase: containing both liquid water and steam.

   d. Steam Drum. One or more large accumulators with disengagement space and mechanical devices to separate the gaseous steam from the liquid water. The liquid is recirculated to the convection or radiant boiler sections. The product steam, in thermodynamic equilibrium with liquid water, is "saturated" at the temperature and pressure of the steam drum contents. Saturated steam may be the desired product or the steam may be further heated in the superheater.

   e. Superheater. One or more radiantly and/or convectively heated tube banks where the gaseous saturated steam is further heated to produce dry steam with a higher heat content (enthalpy) than saturated steam at the same pressure. Because the heat transfer from the tube walls to the steam is less efficient than that in tubes where boiling occurs, the tube walls run hotter and their outside (the "fireside") surface is more prone to corrosive attack. On the plus side, superheated steam can generate more power per kg of steam or, in heating applications, can travel longer distances before condensation begins to occur.

   f. Economizer. One or more banks of tubes between which the hot flue gases flow and convectively transfer heat to the feedwater. The feedwater supplied to the economizer is usually heated near or to the boiling point such that the fireside metal temperatures are safely above the dew point of the flue gases. The economizer is located in the part of the boiler where the flue gas temperature is the lowest.

g. Sootblowers. Mechanical devices used for on-line cleaning of gas side boiler ash and slag deposits. Sootblowers clean the tubes using a cleaning medium (saturated or superheated steam, compressed air or water, or metal shot) singly or in combination.

h. Auxiliary burners. In some cases, auxiliary burners are provided to assure that furnace temperatures exceed preset minimums during startup, shutdown or during upset conditions. Such burners are usually equipped for oil or gas firing and are used only when needed to adhere to regulatory minimums.

F. Fans and Stacks

1. Combustion Air Fans

Centrifugal fans with electric motor drives are commonly used to supply combustion air. Since the fans for high velocity combustion air must operate at higher tip speeds and therefore with considerable noise, the fans should be located where their noise will not be a nuisance. In general, sound absorbing devices should be considered on these and other high-speed fans.

Combustion air for suspension burning of shredded and air classified refuse or other finely divided waste material that does not use grates as the principle site of waste gasification (even when a burnout grate is provided), requires a different combustion air concept than that appropriate for a grate system. In suspension burning within a waterwall furnace or within a refractory furnace, the air that conveys the shredded refuse into the chamber may be half or all of the theoretical air required for combustion; however, it must be sufficient to convey and inject the shredded refuse into the furnace. Often, a portion of the air is supplied through registers that impart some swirl to the injected flow.

2. Induced Draft Fan
The induced draft (ID) fan may be regarded as the heart of a combustion system by effecting the necessary gas flow without which the system could not operate. The ID fan draws the flue gas from the furnace, through the heat recovery train and the air pollution control train and discharges it into the stack. The selection of the ID fan must be based on the maximum gas volumetric flow, the gas temperature and the estimated pressure drop through the furnace, boiler, air preheater and the air pollution control train.

Heat and material balances can be used to estimate the design flow and temperature data. Allowance must be made for further cooling through the air pollution control system and the possibility of pick-up of water vapor if wet scrubbers are used. The estimate of the pressure drop through the complete system requires an analysis of the flow resistance of each component coupled with data based on experience in existing plants.

3. Incinerator Stacks

Several types of stacks or chimneys are used to discharge incinerator flue gases into the ambient atmosphere. The primary engineering design issues include corrosion due to flue gas; flow pressures; thermal stresses; forces due to wind and earthquakes; and weathering conditions.

Stub stacks are usually fabricated of steel and extend a minimum distance upward from the discharge of an induced draft fan. Stacks taller than about five diameters and less than 30 m high are often referred to as "short" stacks. These are constructed either of unlined or refractory lined steel plate, or entirely of refractory and structural brick. "Tall" stacks are constructed of the same materials as the short stacks above, and are used to provide greater draft than that resulting from the shorter stack, and to obtain more effective diffusion of the flue gas effluent.

Some metal stacks are made with a double wall with an air space between the metal sheets. This double wall provides an insulating air pocket to prevent condensation on the inside of the stack and thus avoid corrosion of the metal. The draft or negative pressure within a modern incinerator is commonly provided with an induced draft fan. The need for a fan (as opposed to natural draft) is occasioned by the high pressure drop of modern air pollution control devices, the depressed stack temperatures occurring when wet scrubbers or dry scrubbers" are used, and the control advantages realized with mechanical draft systems.

Whenever stack gas temperatures are higher than the ambient, draft will be produced by the buoyancy of the hot gases. The theoretical natural draft may be estimated by:

$$P_{ND} \; = \; 0.0342 \, P_a L_S \left(\frac{1}{T_a} - \frac{1}{T_S} \right) \qquad (46)$$

where

P_{ND} = Theoretical draft (atmospheres) Note that one atmosphere equals 101,325 pascals.
P_a = Barometric (ambient) pressure (atmospheres)
L_s = Height of stack above the breeching (meters)
T_a = Ambient temperature (K)
T_s = Stack gas temperature (K)

The value used for T_s should be an average value taking into account heat losses and (for tall stacks) the temperature drop on expansion (Eqn. 47) as the atmospheric pressure (in atmospheres) declines with increasing altitude.

$$p \; = \; p_o \, (1 - 2.244 \mathrm{x} 10^{-5} H)^{5.256} \qquad (47)$$

where p is the pressure at an attitude H (meters) above sea level and p_o is the pressure at sea level. As the stack gases pass up the stack, frictional losses reduce the fraction of the theoretical draft which is available. Frictional losses may be estimated [13] from the following where stack perimeter and area are in meters and square meters respectively.

$$F_S \; = \; \frac{2.94 \text{ x } 10^{-5} \, L_S \, (\bar{u})^2 \text{ (stack perimeter)}}{T_S \, A_S} \qquad (48)$$

where F_s = Friction loss (atmospheres)
$\bar{u}$ = Mean stack gas velocity (m/sec)
A_S = Stack cross-sectional area (square meters)
L_s = Height of stack above the breeching (meters)

In addition, some of the draft is lost to the velocity head in the rising gases. This "loss," referred to as the "expansion loss" (F_e) may be estimated [13] by:

$$F_e \; = \; \frac{1.764 \text{ x } 10^{-4} \; (\bar{u})^2}{T_S} \quad \text{(atmospheres)} \qquad (5)$$

Typical natural draft stacks operate with a gas velocity of about 10 m/sec. For forced draft systems, 20 m/sec is more economical and provides a significant plume rise that adds to the dispersion characteristics of the chimney. (see Chapter 14 in Reference 2).

There are numerous accessory features that should be incorporated into the stack specification. These include access ladders and working platforms for use in inspections and maintenance and, in larger stacks, for stack sampling activity; utilities (esp. electrical services, perhaps a jib beam to lift equipment, supplies and lighting); two, down-leads (for non-metal stacks) for lighting protection; and aviation obstruction lights in accord with the requirements of the relevant aviation agency.

G. Summary

You have taken the second step down the path to understanding combustion. There is much more to learn if you wish to extend into the range of specific incineration technologies important in solving environmental problems but the tools and insights from these two courses give you a strong running start at the evaluation of combustion systems: their fundamental input and output characteristics regarding mass and energy and a peek "under the hood" at the basic processes and components comprising combustion systems. Future courses will focus on particular applications to municipal solid waste, biosolids and other waste streams and unit operations; each with its unique set of equipment and design/operating characteristics. I hope you will find these in-depth courses of interest but, in any length. I trust you enjoyed and learned a lot in this pair.

H. References

1. Dos Santos, A.M. and Collin, R., "Study of a MSW Incinerator: Overall Operation and On-Site Measurements Over the Flame," Proc. ASME National Solid Waste Processing Conf., pp 133-143, Detroit, May 17-20, 1992

2. Niessen, W., "*Combustion and Incineration Processes, Applications in Environmental Engineering* - 4th Ed.," Taylor and Francis Group, Boca Raton, FL, 2010

3. Field, M.A., Gill, D.W., Morgan, B.B., and Hawksley, P.E.W., "*Combustion of Pulverized Coal*," British Coal Utilization Research Assn., Leatherhead, Surrey, England, 1967

4. Williams, A., "The Mechanism of Combustion of Droplets and Sprays of Liquid Fuels," Oxidation Combustion Review, **3**, 1-45 (1968)

5. Perry, J.H., (ed.) "*Chemical Engineers Handbook*," 3rd Edition, McGraw-Hill, New York, 1950

6. Hottel, H.C., "Burning in Laminar and Turbulent Fuel Jets," *4th Symposium (Int'l) on Combustion*, Williams and Wilkins, Baltimore, 1953, pp 97-113

7. Ricou, F.P., and Spaulding, D.B., *J. Fluid Mech.*, **11**, pp21-32, 1961

8. Thring, M.W., and Newby, M.P., *Proc. 4th Int'l Symp. On Combustion*, Combustion Institute, Pittsburgh, PA, pp 739-796, 1953

9. Hottel, H.C. and Sarofim, A.F.,"*Radiative Transfer*," McGraw-Hill, New York 1967

10. *ASHRE Handbook*, ASHRE, New York, 1974

11. Carslaw, H.S. and Jaeger, J.C., "*Conduction of Heat in Solids*," Oxford Univ. Press, Oxford, England, 1959

12. *Modern Refractory Practice*, Harbison-Walker Refractories Company, William Feather Co., Cleveland OH, 1961

13. Sowizal, J.C., and Wilber, R., "*Chimney for Municipal Waste Combustion Projects*", Proc. 1991 International Conference on Municipal Waste Combustion, Pages 408-418, November, 1992