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Peer reviewed

## FLAME-MODE DESTRUCTION OF HAZARDOUS WASTE COMPOUNDS

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Incineration is a promising technique for the disposal of organic hazardous wastes. However, the waste destruction characteristics of turbulent spray flames have not been characterized. In the present research two reactors are used to simulate various aspects of liquid injection incinerator flame zones. The following questions are addressed: (1) Under what conditions do flames quantitatively destroy waste compounds, and (2) how must the flame be perturbed to cause it to fail to quantitatively destroy wastes. The two reactors operated on a simulated waste stream consisting of acrylonitrile, benzene, chlorobenzene, and chloroform. A microspray reactor was used to investigate destruction processes associated with individual droplets of waste compounds. A turbulent flame reactor used a heptane-fueled waste-doped turbulent spray flame to simulate incinerator flame-zone processes.

The flames were found to be capable of quantitative waste destruction without the necessity of using common post-flame processes such as afterburners. Furthermore, the high waste destruction efficiency conditions corresponded to high combustion efficiency conditions (i.e., minimum CO and hydrocarbon emissions). Failure to achieve high destruction efficiency resulted from the perturbation of flame parameters. Failure conditions were identified with high and low theoretical air, low temperature, poor atomization quality, and flame impingement on a cold surface. Each failure condition also resulted in elevated CO and hydrocarbon emissions. Thus, the results suggest that CO and hydrocarbon measurements can be used as an indirect, continuous means of monitoring incinerator flame-zone performance.

### Introduction

Incineration is an attractive means for the disposal of organic hazardous waste. However, the factors that limit the efficiency of incinerators are poorly understood and the waste release mechanisms have yet to be identified. This fundamental understanding is necessary to systematically design and modify waste incinerators, and to estimate the impacts of variations in waste composition on the performance of existing incinerators.

The most common type of incinerator is the liquid injection incinerator.<sup>1</sup> Waste is fired through an atomizing nozzle with sufficient auxiliary fuel to ensure flame stability and satisfy minimum temperature requirements. Post-flame processes include afterburners, heat recovery units, and scrubbers. For

incomplete waste destruction to occur in such a device some waste must penetrate the flame-zone and survive post-flame thermal destruction. A large number of escape mechanisms can be hypothesized. For example, incomplete flame-zone destruction can occur if atomization quality is sufficiently poor and large droplets escape the flame unevaporated. Incomplete post-flame destruction can occur due to poor mixing or quenching within cold thermal boundary layers at the incinerator wall.

Prior research has utilized nonflame thermal decomposition to establish the relative ease with which waste compounds are destroyed in a given environment.<sup>2,3</sup> Extent of destruction is obtained by exposing mixtures of waste compounds, diluted in air, to various temperatures in a laboratory plug-flow reactor. The present study addressed the destruc-

tion of waste compounds under flame-mode conditions. The approach utilizes two reactors.<sup>4</sup> In the microspray reactor, the reaction of individual droplets of waste compounds are studied in a laminar flame environment. In the turbulent flame reactor, an auxiliary fuel doped with waste compound is injected into a swirl-stabilized turbulent spray flame. Each experiment is operated under both high waste destruction efficiency conditions and under conditions that simulate the hypothetical escape mechanisms. The destruction efficiency of each waste compound is measured under each condition. The objectives are to (1) identify regimes of high- and low-efficiency operation in practical systems, (2) establish the relative importance of each mode of inefficiency, and (3) determine the relative destruction efficiency of each compound in a representative waste stream as a function of mode of inefficiency.

## Experimental

### Microspray Reactor

The microspray reactor is a modification of a design described elsewhere.<sup>4,5</sup> As shown in Fig. 1, the reactor utilized an up-fired flat-flame stabilized on an 8.9-cm-square ceramic honeycomb. Droplets of waste mixtures were introduced into the reactor through a 1.3-cm-diameter opening in the burner center. Monodisperse droplets (38 microns) were generated by a vibrating orifice technique.<sup>6</sup> The

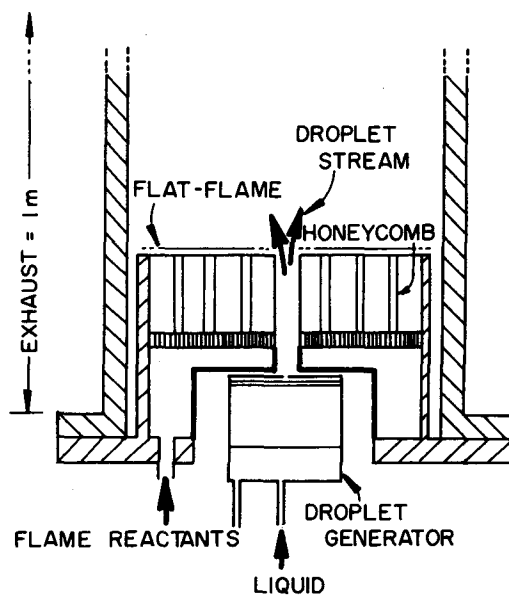


FIG. 1. The microspray reactor.

droplet stream passed through a second orifice where the droplets were dispersed by a small gas flow whose composition was adjusted such that uniform stoichiometry was maintained at all points within the reactor. The flat-flame products and droplets passed through a 10-cm-square 100-cm-long stainless steel-chimney within which the droplet reactions occurred. Products exiting the chimney were homogenized by a series of mixing baffles prior to the sampling point.

The flat-flame reactants consisted of a hydrogen/nitrogen/air mixture. Reactant stoichiometry and nitrogen dilution were used to obtain independent control of temperature and post-flame oxygen concentration at a constant cold reactant velocity (25 cm/sec). These gases constituted the thermal and compositional environment within which the individual droplet reactions occurred. Due to heat losses, the temperature of the reactor gas declined in a well-characterized manner through the chimney; examples of temperature profiles are available elsewhere.<sup>5</sup>

### Turbulent Flame Reactor

The design of the turbulent flame reactor is based on a configuration for which the aerodynamic flow field has been previously characterized.<sup>7</sup> The reactor consists of a swirling air/liquid spray burner firing into a 30.5-cm-diameter by 91.5-cm-long water-cooled cylindrical enclosure, as shown in Fig. 2. The water-cooled cylinder is made of 304 stainless steel formed into three interchangeable segments which

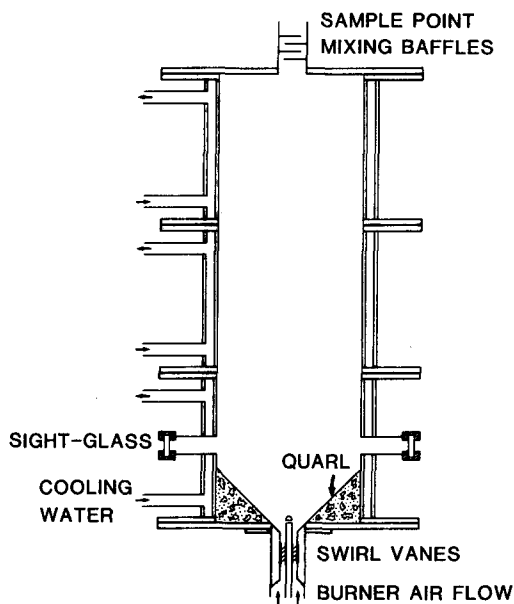


FIG. 2. The turbulent flame reactor.

are joined by flanges and gasketing. The lowest segment has four sight glass ports, one of which is used for flame ignition. The reactor top plate contains an exhaust fitting which includes the sampling ports, and a Vycor plate/mirror arrangement for obtaining an axial view of the flame.

The burner consists of a pressure-atomized hollow-cone nozzle (Delavan WDA 60° Series) located level with the bottom plate of the reactor as shown in Fig. 2. The main burner air was introduced through the annular space around the nozzle. Variable area flow constrictors were fixed into this space to vary burner air velocity independently of air flow rate. A swirl vane was placed in the gap between the constrictor and the nozzle shaft; the vane angle was set to provide a swirl number of unity.<sup>8</sup> To provide a smooth entry of air into the burner and to prevent corner recirculation, a castable refractory quarl was placed in the lower water-cooled segment. As shown in the figure, this has the form of a 45-degree cone.

#### Compound Selection

Four compounds representative of liquid organic hazardous wastes were selected for testing: acrylonitrile, benzene, chlorobenzene, and chloroform. These compounds were selected to represent the various structures and halogen levels typical of wastes. Table 1 shows the values assigned to each of the compounds by the various ease of destruction tests. The  $T_{99.99}$  value represents the temperature to which the compound must be exposed to achieve 99.99 percent destruction efficiency in 1.0 sec in the dilute-phase non-flame experiments. The values are derived from Lee et al.<sup>3</sup> except for chloroform.<sup>9</sup> The NBS ranking is based on the susceptibility of bonds to radical attack (lower ranks are more difficult to incinerate).<sup>10</sup> Heat of combustion and autoignition temperature have also been proposed as ranking procedures,<sup>10</sup> as have parameters affecting volatility such as heat of vaporization and normal boiling point.

Equimolar mixtures of the four compounds were

used in both reactors. In the microspray reactor the mixture was injected directly. In the turbulent-flame reactor the mixture was blended into *n*-heptane as a 3.0 percent-by-mass mixture.

#### Analytical

The analytical technique for measuring waste compounds in the flue gas is based on the methods of Parsons and Mitzner<sup>11</sup> and Dellinger et al.<sup>2</sup> A known volume (2.3 liters at 0.23 liter/min.) of product gas is sampled, quenched to 473 K, filtered, and passed through a 293 K cartridge trap containing 0.65 gm of Tenax-GC. At the conclusion of sampling the trap is thermally desorbed onto a 0.5-m by 3.18-mm OD Teflon column packed with Porapak-Q and analysis is performed by GC-FID. The analytical technique has been characterized through calibration to ensure that (1) compound collection by the Tenax-GC is quantitative for the sampling conditions utilized, and (2) compound desorption is complete.

Auxiliary measurements for the turbulent flame reactor included exhaust CO and hydrocarbon determinations. The CO was analyzed by NDIR. Hydrocarbons were analyzed by a flame ionization detector and are reported as equivalent mole fraction methane.

## Results and Discussion

#### Microspray Results

The microspray reactor was used to investigate waste destruction associated with single droplet reactions. The reactor was forced into incomplete waste destruction by reducing the gas flame temperature for two environments: Oxygen rich (10-mole percent free oxygen in the post-flame gas) and oxygen starved (less than 0.25 mole-percent oxygen in the post-flame gas). Under fuel-lean stoichiometry, if temperature was sufficiently high, a small flame (either envelope or detached) was visually observed

TABLE I  
Test compounds and values of proposed ease of incineration ranking procedures

Compound	Boiling point (K)	Heat of vaporization (J/g)	$T_{99.99}$ (K)	NBS ranking	Heat of combustion (J/g)	Autoignition temperature (K)
Acrylonitrile	350.8	627.	1003.	n. a.	33.2	754.
Benzene	353.2	433.	1007.	4	42.0	836.
Chlorobenzene	405.2	325.	1038.	3	27.6	911.
Chloroform	334.4	271.	925.	18	3.1	n. a.

n. a.—Not available.

to be associated with each droplet. Otherwise the vapors mix into the free stream and undergo reaction at positions remote from the droplet.

The unreacted fraction of waste at the reactor exit is presented in Fig. 3 as a function of flat-flame temperature for the oxygen-rich environment. For flat-flame temperatures in excess of 875 K, the droplets were visually observed to support individual droplet flames. Under these conditions waste destruction was complete. Below 875 K a faint chemiluminescence was observed that was associated with the vapor region in the inter-droplet space. This corresponded to partial destruction of the waste compounds by thermal decomposition or partial combustion. Two destructibility rankings are observed. Well below the ignition point, the most difficult compound to destroy is chlorobenzene followed by benzene, chloroform, and acrylonitrile. The order is rearranged, just prior to ignition, into benzene, chlorobenzene, acrylonitrile, and chloroform. The droplet ignition temperature corresponds with the approximate mean of the compound autoignition temperatures.

Data obtained for the oxygen starved droplet environments, shown in Fig. 4, indicate that the shift between zero and complete destruction occurs over a relatively narrow temperature range centered about 1050 K. Although the data for each of the compounds showed similar behavior, at 1050 K a sufficient variation between the compounds occurred to establish the following destructibility ranking: Chlorobenzene, benzene, chloroform, and acrylonitrile.

To assist in comparing the present data to the non-flame thermal decomposition data,<sup>2,3</sup> a model was developed in which the simultaneous evaporation and reaction of the waste compounds were

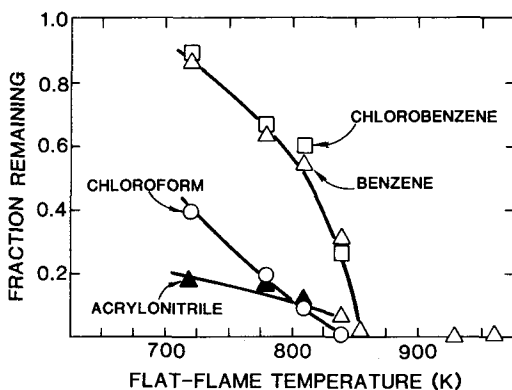


FIG. 3. Fraction of test compounds remaining in microspray exhaust when 38  $\mu\text{m}$  droplets of mixtures of compounds were injected into lean (10% post-flame oxygen)  $\text{H}_2/\text{air}$  flames as a function of flame temperature.

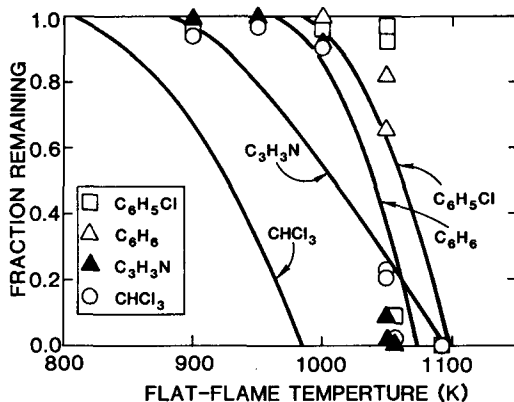


FIG. 4. Fraction of test compounds remaining in microspray exhaust when 38  $\mu\text{m}$  droplets of mixtures of compounds were injected into low oxygen ( $\sim 0.25\%$ ) post-flame gas as a function of flat-flame temperature.

calculated. The model consists of two coupled first-order differential equations. The first expresses the appearance rate of vapor within a control volume due to droplet evaporation. The second equation relates the appearance rate of vapor due to droplet evaporation with the rate of thermal destruction to yield the time-dependent vapor phase concentration of waste. Following Spalding's development<sup>12</sup> the evaporation rate of an individual droplet is given by:

$$dm/dt = -2\pi D \lambda \ln(1 + B)/C_p \quad (1)$$

where  $B$  is the transfer number. In the absence of a flamelet associated with the drop, the transfer number is given by:

$$B = C_p(T_g - T_o)/L \quad (2)$$

where:  $D$  = droplet diameter  
 $\lambda$  = vapor phase thermal conductivity  
 $C_p$  = liquid phase heat capacity  
 $T_g, T_o$  = free stream and droplet surface temperatures  
 $L$  = heat of vaporization

This analysis ignores variations in the relative vaporization rate of the various components of the droplet. This assumption is only justified because of the short droplet lifetime (*ca.* 5 msec) compared to the reactor residence time.

The chemical reaction is assumed to occur uniformly in the interdroplet space (*i.e.*, the diffusion rate of material away from the evaporating droplets is rapid compared to the reaction rate). Balancing the appearance rate due to evaporation with the

disappearance rate due to reaction yields the time rate of change of vapor-phase concentration:

$$dC/dt = -n(dm/dt) - kC \quad (3)$$

where:  $n$  = number of droplets per unit volume  
 $k$  = first order rate constant for waste destruction (an Arrhenius function of temperature).  
 $dm/dt$  = rate at which vapor is produced by a single droplet.  
 $C$  = waste compound concentration.

Rate data were obtained from Lee et al.<sup>3</sup> except for chloroform.<sup>9</sup> Equations 1 and 3 were simultaneously integrated to yield profiles of (1) unevaporated liquid versus time and (2) unreacted compound versus time. The calculated results are shown as the lines in Fig. 4. These results indicate three major points. First, the droplets are predicted to evaporate early in the reactor for droplet diameters less than 500-microns (the evaporation time of the 38-micron droplets used in the experiment was *ca.* 5-msec). Second, the predicted temperature range required for the destruction of the various compounds (850–1100 K) agrees more closely with the experimental temperature for the low oxygen condition (1050 K) than for the fuel-lean condition (700–850 K). This is not unexpected since the kinetics used in the model are based on nonflame thermal decomposition experiments. The fuel-rich conditions lacked sufficient oxygen for droplet combustion to occur. Thus, nonflame thermal decomposition also dominated the present fuel-rich data. Third, the predicted behavior exhibits an approximately 150 K variation between the compounds while the data exhibit little variation in compound behavior.

### Turbulent Flame Results

The turbulent-flame reactor was used to characterize the destruction efficiency behavior under conditions where aerodynamics are strongly coupled to the burner performance. The baseline experimental conditions were selected to provide high combustion efficiency, as defined by low CO and hydrocarbon measurements, and high compound destruction efficiency. These optimal conditions were perturbed by changing one or more of the experimental parameters to obtain non-optimal behavior, i.e., reduced compound destruction efficiency and reduced combustion efficiency.

The experimental conditions examined with the turbulent-flame reactor were as follows. The nozzles were operated at their normal flow capacity except where indicated. In the baseline test the air velocity (7.1 m/s) and flow (17.3 liters/s) were held constant as the fuel flow was varied. In the second test a cold surface was introduced into the flame to

induce quenching reactions. In the third test, the atomizers were operated "off-design" to obtain oversized droplets. In the final test, the auxiliary fuel was changed from heptane to No. 2 fuel oil. Two parameters were varied which did not substantially affect destruction efficiency: The air velocity (7.1 to 17 m/s at constant fuel flow) and the concentration of compounds in the auxiliary fuel (3.0 to 25.0 percent).

The results shown in Fig. 5 indicate the effect of stoichiometry at the baseline condition. Two regimes of behavior are clearly indicated. Between 120 and 150 percent theoretical air the flame exhibits high compound destruction efficiency and high combustion efficiency. Outside these bounds combustion and compound destruction efficiencies both degrade. At higher fuel flows mixing was not sufficient to eliminate all of the fuel-rich pockets even though the burner was operated at an overall fuel-lean stoichiometry. At very fuel-lean conditions the excess air lowered the flame temperature and likely quenched portions of the flame prior to complete consumption of reactants. The rankings under low excess air, starting with the most difficult to destroy, are chloroform, benzene, acrylonitrile, and chlorobenzene; under high excess air it was benzene, chloroform, chlorobenzene, and acrylonitrile.

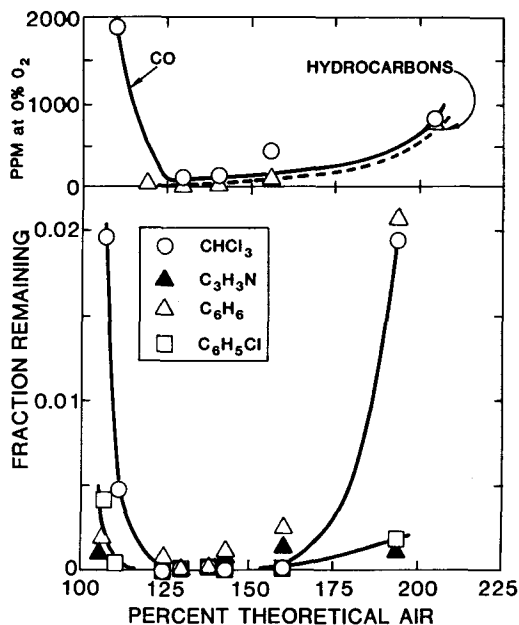


Fig. 5. Impact of theoretical air on CO, hydrocarbons, and fraction of test compound remaining in exhaust of turbulent flame reactor (constant air velocity, variable load: 24–42 kW; equal molar mixture of compounds added 3.0 percent-by-weight to heptane).

Variations in incinerator operating parameters can result in considerable changes in flame size and shape and can cause the flame to impinge on a surface. The effect of the extreme limit of this behavior, impingement on a cold surface, was studied by immersing a water-cooled coil directly into the flame zone. The data were obtained at the same conditions shown in Fig. 5, and are plotted in Fig. 6. The results indicate that the cooled coil changed a high-efficiency condition into a non-optimal condition with elevated compound release and increased CO concentrations. Compound destruction performance was sufficiently poor outside of the 130 to 160 percent theoretical air range to render the chromatograms uninterpretable due to interferences from products of incomplete combustion. The ease of destruction ranking, starting with the most difficult to destroy, was chloroform, benzene, and chlorobenzene.

The pressure atomized nozzles used in this study were designed to operate at liquid pressures in excess of 3.5 atm. At reduced pressure, the mean droplet diameter for the spray increases and the ballistic velocity of the individual droplets decreases. The baseline data of Fig. 5 were obtained using nozzles of various capacities to maintain constant atomization quality as fuel flow was changed. The effect of degraded atomizer performance was tested by reducing fuel flow (increasing theoretical air) while using a nozzle with a design pressure that corresponds to 130 percent theoretical air. Thus, as theoretical air increased, atomizer performance became progressively more degraded. Figure 7 shows

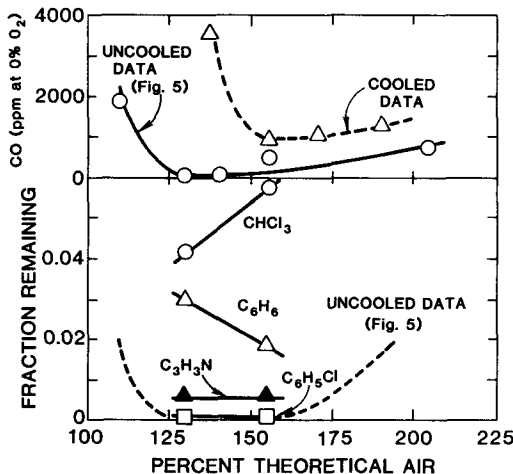


FIG. 6. Impact of cooling coil placed in flame on CO and fraction of test compound remaining in exhaust of turbulent flame reactor. Dashed line represents corresponding uncooled data from Fig. 5. (Constant air velocity, equal molar mixture of compounds added 3 percent by weight to heptane).

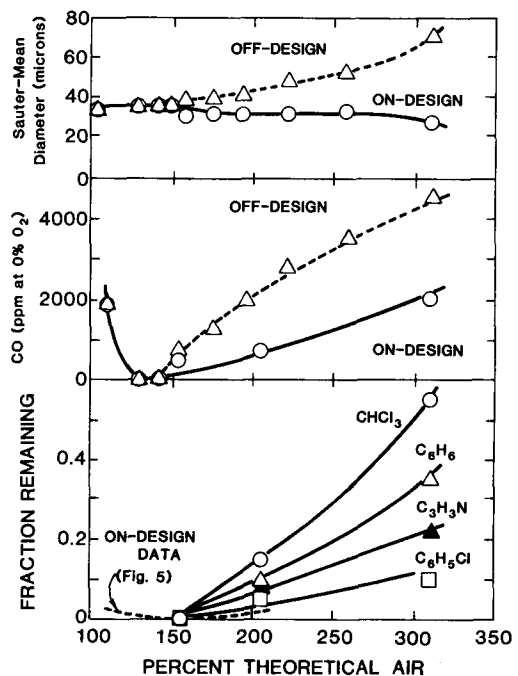


FIG. 7. Impact of atomizer performance on Sauter-Mean droplet diameter, CO, and fraction of test compound remaining in exhaust as a function of percent theoretical air (constant air velocity, variable load: 42–16 kW; equimolar mixture of compounds added 3 percent-by-weight to heptane).

the compound destruction efficiency and CO concentrations for “on-design” and “off-design” atomizer performance. Also shown is the Sauter-Mean droplet diameter for the two nozzle conditions, as measured in cold-flow by a Malvern 2600HSD laser diffraction particle size analyzer. At 130 percent theoretical air the behavior of the nozzles starts to diverge and at 320 percent theoretical air the “off-design” nozzle produces 70-micron mean droplets vs. 25-microns for the “on-design.”

The results shown in Fig. 7 indicate that compound destruction efficiency and combustion performance were substantially degraded over the corresponding “on-design” atomizer performance. The ease of destruction ranking was similar to that obtained in the quench coil experiments; chloroform was the most difficult compound to remove followed by benzene, acrylonitrile, and chlorobenzene.

In many incinerators the auxiliary fuel dominates the combustion chemistry. In the present experiment the *n*-heptane auxiliary fuel was replaced by a No. 2 fuel oil and the baseline experiment of Fig. 5 was repeated. The results, plotted in Fig. 8, are qualitatively similar to those of Fig. 5. The com-

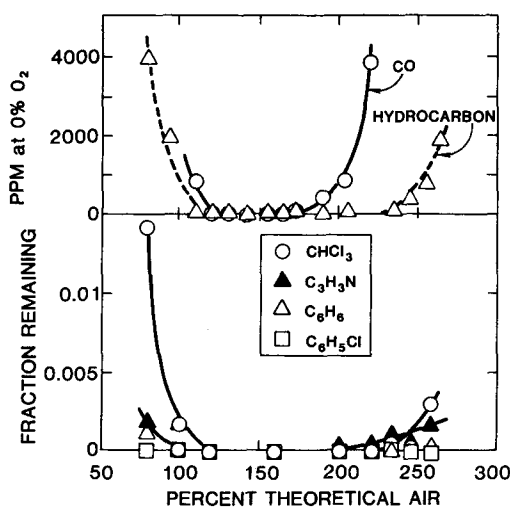


FIG. 8. Impact of theoretical air on CO, hydrocarbons, and fraction of test compounds remaining in exhaust of turbulent flame reactor for No. 2 fuel oil auxiliary fuel.

pound ranking is similar to that of Figs. 6 and 7: chloroform, acrylonitrile, benzene, and chlorobenzene. The range of theoretical air values over which optimal operation was obtained expanded from 120–150 percent theoretical air (for heptane) to 110–200 percent theoretical air when fuel oil was burned. It is also noteworthy that the variation of CO and hydrocarbon measurements with stoichiometry closely correlates with the waste emission measurements. Figure 8 shows that (1) the hydrocarbon and waste measurements are at a minimum over an identical range corresponding to 110 and 200 percent theoretical air, and (2) the CO measurements are at a minimum over a narrower range corresponding to 120 to 170 percent theoretical air.

#### Data Summary, Implications, and Conclusions

Previous research has focused on thermal waste destruction processes characteristic of the non-flame portion of incinerators. In the present research attention has been focused on the waste destruction characteristics of flames. The results show that an optimally operated turbulent flame is capable of high waste destruction efficiency independent of post-flame processes. The results also show that the flame fails to completely destroy wastes only when the operating parameters are significantly perturbed from their high efficiency values. Failure conditions were identified which were associated with high and low excess air, poor atomization, and flame impingement on a cold surface. Variation in burner air ve-

locity (7.1–17 m/s) and waste concentration (3–25%) did not induce failure.

Each of the proposed procedures for ranking waste compounds by their ease of destruction assumes some hypothetical dominant escape mechanism. The rankings arise due to the unequal susceptibility of the various waste compounds to destruction under the assumed escape mechanism. Thus, the rankings obtained from the flame reactors provide information that can potentially identify escape mechanisms. In the microspray reactor, incomplete waste destruction was observed only for conditions in which non-ignited droplets existed. Under these non-flame conditions relative destruction rankings compared well with the non-flame, plug-flow experiments.<sup>2,3</sup> The relative destruction efficiencies observed for the various turbulent flame conditions did not match any of the proposed ranking procedures. Thus, the dominant waste escape mechanism for the turbulent flame has not been defined. The nature of the mechanism that gives rise to the relative waste destruction rankings observed in the turbulent reactor is indicated as an area requiring further research at the fundamental level.

A close correlation between combustion intermediate measurements (CO and hydrocarbons) and the waste destruction efficiency is demonstrated in Figs. 5 and 8. A significant practical consequence of this correlation is the potential use of intermediate measurements as a means of monitoring incinerator performance. Continuous real-time measurement techniques for wastes in flue-gas have not proved feasible on a practical scale. This problem is avoided if continuous analyzers for CO and hydrocarbons provide the necessary monitoring information. Figure 8 shows that hydrocarbon and waste measurements are approximately linearly correlated. However, CO emissions define a narrower range of high-efficiency operation (120–170 percent theoretical air) than do waste emissions (110–200 percent theoretical air). Thus, use of CO as a performance monitor could result in overly-conservative control of the process.

#### Acknowledgments

This study was supported by the U.S. Environmental Protection Agency through the Industrial Environmental Research Laboratory—Cincinnati via contract 68-03-3113. We wish to express our appreciation to C. C. Lee, the EPA Project Officer, and the other members of the technical advisory committee who assisted in program guidance: R. M. Fristrom, A. F. Sarofim, F. W. Marble, V. S. Engleman, B. Dellinger, W. Tsang, R. A. Carnes, and E. P. Crumpler. R. K. Nihart, E. M. Poncelet, and H. D. Crum materially aided the experimental effort. This paper has not been subjected to the EPA peer and policy review and therefore does not nec-



essarily reflect the views of the Agency and no official endorsement should be inferred.

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#### COMMENTS

G. R. Lester, *Signal UOP Research, USA*. Your organization has been quoted to the effect that levels of CO below 30 ppm from incinerators is assurance that dioxins will also be absent in the flue gas. Is that based on this EPA-sponsored work, or on separate studies. In either case, wouldn't this depend on being certain that mixing is extremely good?

*Authors' Reply*. We have not published, presented or otherwise made a statement that a specific CO level ensures either high waste destruction efficiencies or avoidance of dioxins in the flue gas. Field measurements, in fact, do not support the validity of such a statement over the broad range of incinerator designs currently in use. We have performed work investigating the potential use of CO and/or total unburned hydrocarbons (THC) as an indirect, continuous, real-time means of monitoring incinerator performance. The approach is suggested by Figure 8 in which conditions that favor THC emissions also favor reduced waste destruction. Low CO measurements define a smaller "safe" theoretical air range (120-170%) than are indicated by the waste and THC (110-220%). These results suggest a monitoring and control scenario in which CO is used to tune the flame zone and indicate the approach of an unsafe condition, and THC is used as

an immediate indicator of waste emission. Note, however, that this scenario neither implies nor indicates a specific level of CO below which the emission of waste or hazardous byproducts can be precluded.

●

G. G. DeSoete, *Institute Francais du Petrole, France*. Did you try to identify the nature and the concentration of the final reaction products into which these hazardous waste compounds were transformed during incineration? Especially under reducing incineration conditions, some of these products might eventually show to be as hazardous, or even more hazardous, than the initial compounds.

*Authors' Reply*. The destruction efficiencies reported in our paper were determined by comparing the exhaust emission rate of waste with the feed rate to the reactor. Thus, the results do not take account of the fate of the waste, and a situation could exist in which waste destruction is complete but significant hazardous byproducts are formed.

The method used to determine waste emissions was to trap the organic compounds on Tenax-GC, and to thermally desorb the concentrated sample

onto a gas chromatograph equipped with a flame ionization detector (FID). This approach also enabled the detection of hydrocarbon combustion by-products at approximately the same sensitivity as the waste measurement, the peaks of which were limited in number and low in apparent concentration. The identification of the unknown product peaks and their resultant concentrations was not established during this study.

•

*J. A. Clark, Ohio State University.* In your complex flow burner what percentages of hazardous waste in the burner fuel did you test, and is there an upper limit above which complete destruction is not assured, assuming the burner is operating efficiently?

*Authors' Reply.* All of the results discussed in the paper were for an equimolar mixture of the four surrogate compounds added to the extent of 3% (weight) in the auxiliary fuel. Data were obtained but not presented for 10 and 25% surrogate loadings. These were obtained as a function of theoretical air in the form of Figure 5 of the text. For this limited range of concentrations, no systematic effect on compound destruction efficiency was noted.

We did not investigate the upper limit of surrogate concentration; however, field data have indicated that waste concentration can be arbitrarily high (in some cases 100%), and as long as a stable, well-behaved flame is established, the waste destruction can be high. Thus, the upper limit on waste concentration depends in practice on the flammability characteristics and heat content of the waste.

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*W. J. McLean, Sandia National Laboratory, USA.* My questions regard volatility effects. Many of your results seem to correlate with fractionation or lack thereof. Have you made any attempt to correlate the results for different compounds with their volatilities? Also, is it necessary to consider fractionation effects during vaporization?

*Authors' Reply.* A number of scenarios can be hypothesized in which vaporization or fractionation would affect the results. If, for example, droplets reach the cold wall of the turbulent flame reactor before complete vaporization, they may be partially stripped of their more volatile compounds. Should the waste compound emissions be dominated by this

material then the emission of low volatility compounds will be favored. In the microspray reactor early evolution of volatile compounds will provide a longer time at a higher temperature in the gas phase. If all other destruction rates are equal, the low volatility compounds will also dominate the emissions from the reactor. Another situation could occur in which high volatility compounds are stripped from the spray before the fireball and are swept around the reactor flame in the excess air.

These scenarios notwithstanding, the results in the present reactors are likely independent of vaporization. The 38-micron droplets used in the microspray reactor were estimated to require 5-msec to complete evaporation. This is small compared to the approximately 100-msec available for reaction. Thus, any variation in component vaporization rates would not be expected to significantly affect the individual compound emissions. In the turbulent flame reactor, most conditions involved droplets in the 25–35 micron range. Thus vaporization would be rapid and complete within the approximately 50-msec flame residence time. The only potential variance would be in the case of oversized droplets that are capable of surviving the flame-zone.

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*A. Macek, U. S. National Bureau of Standards, USA.* Two important parameters for destruction of compounds are the temperature and the residence time. You gave only the temperatures for one of your two combustors. Can you give us an idea of the relative values of these two parameters for the two combustors?

*Authors' Reply.* Due to non-isothermal conditions, neither reactor can be characterized by a single temperature/residence time. In the microspray reactor the time/temperature history is approximately represented by a linear decrease in gas temperature with distance from the flat-flame (see Ref. 5 in the text). The overall residence time was about 1.0 sec and the available reaction time in the high-temperature zone was approximately 100 msec.

In the turbulent flame reactor, exit temperatures varied around 750 K. We made no systematic effort to characterize the flow or thermal fields within the reactor; detailed measurements are available on the experiment upon which the present design is based (Ref. 7 in the text). The overall residence time was approximately 1.5 sec, and the mean flame residence time is estimated at 50 msec.