DESIGN AND OPERATION OF A VERSATILE POLLUTION CONTROL/LIQUID WASTE THERMAL DESTRUCTION SYSTEM WITH MAXIMUM ENERGY RECOVERY

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ABSTRACT

The heat generated by the thermal destruction of fumes and combustible liquid wastes can be recovered to produce steam and power required by industrial plants. The instantaneous, hourly, weekly and seasonal variations in steam usage of industrial plants requires innovative system design to match heat recovery to instantaneous heat demand.

A facility initially burning #6 fuel oil was converted to burning only waste fuels, thus achieving nearly constant fuel cost in spite of skyrocketing fuel oil prices. The system recovers 85-90 percent of the heat in the fuel. Ash in the wastes accumulates on the furnace refractory and boiler tubes, requiring periodic cleaning.

The balance between relatively constant fume generation and highly variable steam requirements is accommodated by adjusting the fuel input while allowing thermal oxidizer furnace temperatures to vary above those needed to destroy the selected wastes. A steam accumulator is used to reduce peak steam demand on the boilers.

Systems of this type can destroy liquid wastes containing difficult chemicals such as chlorinated phenol and benzene compounds, by maintaining sufficient temperature, proper atomization and effective mixing. Research and theory cited shows that the reaction kinetics of chemical compounds can be determined experimentally under plug flow conditions, and that the temperature needed to achieve a required destruction efficiency depends primarily on the mixing effectiveness of the burner, furnace configuration and temperature, and to some extent on retention time. The destruction efficiencies achieved by actual configurations can be determined by tests of “surrogate” compounds having similar destruction temperature requirements, thus avoiding the need to handle hazardous materials.

INTRODUCTION

The desire for a clean environment and the passage of more stringent emission regulations in the 1970's forced many manufacturers of industrial laminates to install thermal oxidizers to destroy the fumes emitted by their treating ovens, consisting of phenolics and various types of solvents.

In addition to the burden of installing this equipment, the cost of fuel required to operate these oxidizers could double the annual fuel budget of these plants, threatening to force them out of business unless means were found to reduce these costs.

A laminate manufacturer in western New York State had coal-fired boilers which would require emissions controls or conversion to expensive fossil fuels, in addition to having to install a fume incinerator and buy fuel for its operation.

A study found that thermal oxidizers with sufficient capacity to destroy the fumes generated by the plant could also generate enough waste heat to supply the needs of the entire plant throughout the year, provided that the waste heat boilers were designed to recover the heat efficiently and that the heat generated could be matched with steam de-
FIG. 1. DAILY AND SEASONAL VARIATION OF STEAM DEMAND IN LAMINATE PLANT

FIG. 2. EQUIPMENT ARRANGEMENT, SHOWING PRE-COMBUSTOR, FURNACE, BOILER AND FUME PREHEATER
**FIG. 3** DOUBLE-VORTEX™ PRECOMBUSTOR AND THERMAL OXIDIZER

**FIG. 4** STEAM SCHEMATIC OF FUME AND LIQUID WASTE/STEAM AND POWER GENERATION SYSTEM WITH STEAM ACCUMULATOR AND TURBINE
A steam accumulator, 3 m in diameter by 10 m long was provided to absorb steam press peaks and maintain constant steam pressure to the plant, while the thermal oxidizer was accepting fumes at constant flow.

The output of the waste-heat boilers can be adjusted within the necessary range by varying furnace temperature from 1400-2200 F (760-1200 C), giving a turndown of over 2:1. Figure 5 shows how steam output is varied by changing furnace temperature. On weekends or when treaters are down, the fume flow can be reduced to help match the steam demand.

The boiler gas outlet temperature was selected to be about 900 F (480 C) to match process steam needs. A fume preheater was installed to recover heat, delivering roughy 400 F fumes to the oxidizer and 400 F stack temperature.

**THERMAL EFFICIENCY**

Startup test data is listed in Table 1. The temperature efficiency was 88 percent in spite of the 100 to 200 percent excess air associated with fume incineration. During 1977 when only #6 oil was burned, each gallon of oil produced over 125 pounds of 450 psig steam (89 percent thermal efficiency), as compared with about 100 pounds produced by the original boiler plant (72 percent). This remarkable efficiency is partly the consequence of burning 200 F fumes containing some combustibles.

**TABLE 1 TEST DATA OF THERMAL OXIDIZER HEAT RECOVERY UNIT**

| Number of Modules: | 3 |
| Steam generation: | 35,600 lb/hr (17.8 t/hr) |
| Fume intake: | 21,500 SCFM (44 t/hr) |
| Fume inlet temperature: | 190 F (88 C) |
| Fume preheat temperature: | 410 F (210 C) |
| Oxidizer exit temperature: | 1,860 F (1,016 C) |
| Boiler exit temperature: | 570 F (300 C) |
| Stack gas temperature: | 350 F (177 C) |
| Temperature Efficiency: | \(\frac{1860 - 570}{1860 - 410} = 89 \text{ percent}\) |

**BURNING LIQUID WASTES**

The facility was designed with as much flexibility as possible since fume and process steam demand is affected by marketing conditions, and the properties of available fuels will vary. In order to tolerate fuels containing significant amounts of ash, the boiler tubes are arranged in straight lanes for ready inspection and periodic cleaning, and with access doors for cleaning and flushing. In case future use of higher ash fuels would justify their installation, provision was made for fabric stack gas filters. Present permits restrict waste fuel ash to 1 percent ash and 0.5 percent halogen content.

The facility was originally permitted as a boiler burning #6 oil and 1500 gallons (5.7 m³) per day of waste solvents and aqueous wastes. The phenolic fumes and liquid wastes generated by the laminate plant were readily oxidized at the furnace temperatures normally maintained for steam generation, 1400 to 2000 F (760 to 1100 C), as determined by tests performed at the New York plant. After additional permits were obtained in 1978 to burn imported liquid wastes of similar types, a concerted effort was made to replace #6 oil with liquid wastes as much as possible. The ratio was gradually increased until #6 oil was totally eliminated as a fuel. The wastes are obtained mainly from waste processing firms. Complete assurance of the chemical analysis and heating value of the wastes is required before they are accepted. The approximate amounts and types of liquid wastes burned at the facility are listed in Table 2.

**TABLE 2 TYPICAL ANALYSIS OF WASTES**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aromatic Hydrocarbons</td>
<td>35 percent</td>
</tr>
<tr>
<td>Aliphatic Hydrocarbons</td>
<td>35 percent</td>
</tr>
<tr>
<td>Alcohol s</td>
<td>15 percent</td>
</tr>
<tr>
<td>Ketones</td>
<td>5 percent</td>
</tr>
<tr>
<td>Esters</td>
<td>5 percent</td>
</tr>
<tr>
<td>Polymeric Resins</td>
<td>5 percent</td>
</tr>
<tr>
<td>Btu/gal</td>
<td>100,000</td>
</tr>
</tbody>
</table>

In addition to the storage and pumping facilities provided in the original installation, new technology was developed to handle large volume of variable material, including tanker unloading, pre-filtering, testing, storage, mixing, pumping, piping and burner and burner management systems.

Using liquid wastes as alternate fuels requires continuous, proficient management of these highly variable materials, with frequent testing and constant attention to equipment and combustion. Under contract operation this burden is not placed on the personnel of the client, who must concentrate on his own business.

Operation of the facility requires careful selection of acceptable waste liquids, coordination of receipt, storage and burning with the steam generation requirements of the customer. Maintenance of the equipment is relatively high, requiring sched-
FIG. 5 VARIATION OF STEAM OUTPUT WITH THERMAL OXIDIZER FURNACE TEMPERATURE
uled shutdown for cleaning, replacement of worn parts, repair and replacement of refractory and cleaning of sediment from tanks. Personnel accustomed to conventional fuels and chemicals find that it takes time and training to adjust to burning fuels with widely varying properties, while providing reliable steam flow and pressure.

Conventional burner control hardware is not suited to burning of liquid wastes which can be expected to contain abrasive and sedimentary materials, such as paint pigment and plain old dirt. Pumps with critical clearances, conventional control valves used to meter fuel to the burners, and burner nozzles wear out rapidly, requiring frequent replacement and resulting in unreliable operation. High quality centrifugal pumps, pressure controls, and large-orifice burner guns have been found to be reliable. Steam atomization is used except for cold start.

COMPLYING WITH EPA/RCRA REGULATIONS

RCRA regulations require preparation of manifests for all shipments of liquid wastes, assuring cradle to grave supervision: this record-keeping assists in assuring all parties that the waste is as-described, and that it will be destroyed properly. EPA regulations require controls and alarms to prevent operation of the oxidizer under less-than-satisfactory conditions. The EPA/RCRA objective of 99.9 percent combustion efficiency and 99.99 percent destruction efficiency should be easily achieved due to good atomization, efficient mixing, the ample retention time and high temperatures maintained in the refractory furnace.

RELIABLE, EFFICIENT, ECONOMICAL OPERATION

The facility has been operated with better than 99 percent reliability since it was started in September 1976. In 1980 alone 953,000 gal (3607 m$^3$) of waste oil at 140,000 Btu/gal (39,000 mJ/m$^3$) and 2,030,000 gal (768 m$^3$) of solvent waste at 100,000 Btu/gal (28,000 mJ/m$^3$) were burned, while generating 260 million pounds (11,800 t) of steam. This indicates a steam generating efficiency of about 87 percent based on 1000 Btu/lb (2326 kJ/kg) of steam.

While the cost of #6 residual oil rose from under $2 to almost $6 per million Btu in the last few years, the actual cost of the waste fuels stayed under $3 per million Btu.

Since the fumes are generated at a steady rate, efficiency of combustion is best achieved by maintaining steady fuel firing rates. The steam accumulator has proven to be effective in absorbing the short steam peaks so that the boiler controls could slowly accommodate the firing rate to basic changes in loading.

These are the operating principles for a plant of this type: keep a clean stack (monitored by the opacity indicator on the stack, which sounds an alarm); produce reliable steam; assent all fumes generated by the plant at all times; then, burn as much unreliable fuel as possible, watching for flame-outs and other operating difficulties.

FACTORS AFFECTING DESTRUCTION EFFICIENCY

It is important to quantify the factors which determine the temperature required to destroy particular liquid wastes.

The time/temperature/oxygen relationship actually required by a thermal oxidizer depends upon the design of the equipment used as well as the chemicals to be destroyed. Up to a point, retention time can be decreased so the temperature and excess oxygen are increased, if preheat is used, speeding ignition, and if short-flame high-intensity burners, such as the Double-VortexTM burner shown in Fig. 4, are used. The facilities described above were designed for 0.5 sec retention at 1400 F (760 C), based on the “rule of thumb” published in the EPA Engineering Manual [1]. Use of refractory brick good for service up to 2,800 F (1,500 C) has raised the potential furnace temperature, so that much higher destruction temperatures could be maintained if required. The furnace temperature for a given gas flow controls the amount of steam generated as shown in Fig. 5.

Figure 6 is based on data published Hemsworth et al. [2], showing the effect of retention time on the destruction of some typical solvents in a laboratory incinerator. The data points fall on a straight line when the logarithm of the parts per million (ppm) remaining, or the destruction efficiency, is plotted versus residence or reaction time. The destruction of the most difficult solvent, Toluene, was 99.99 percent with 0.3 sec at 765 C, but increasing the temperature 65 degrees to 830 C reduced the necessary time to under 0.1 sec.

Figure 7 shows that increasing the furnace temperature to 1555 F (846 C) greatly reducing the reaction time. The effect of poor mixing is also
illustrated here: when the concentration has reached about 10 ppm out of an original 2,000 ppm (99.5 percent destruction), additional time did not reduce the concentration because some of the material was able to pass through the reaction zone without attaining the necessary temperature.

Figure 8 shows more recent data published by Duvall et al. [3] on the thermal decomposition (destruction) of pentachlorobiphenyl (PCB) in a capillary reactor in different gaseous atmospheres. PCB is a particularly hazardous material for the same reasons that it is hard to destroy: it is extremely stable. Thermal destruction (in pure nitrogen) is possible provided the temperatures are high enough (about 1000 C). With 2.5 percent oxygen the destruction is complete at less than 850 C, and in air at about 750 C. Fume incinerators generally have an oxygen content well above 5 percent, hence these difficult materials would be destroyed within the normal operating range of operating temperatures.

Figure 9 shows that some chlorinated materials are formed at lower temperatures and decomposed at higher temperatures. The temperature at which
DEGREES C 500 600 700 800 900 1000
T H E R M A L D E S T R U C T I O N O F P E N T A C H L O R O B I P H E N Y L

T H E R M A L D E S T R U C T I O N O F P E N T A C H L O R O B I P H E N Y L

DEGREES F 1000 1100 1200 1300 1400 1500 1600 1700 1800

FIG. 7 DECREASE IN TOLUENE CONCENTRATION
WITH TIME AND TEMPERATURE

FIG. 8 EFFECT OF OXYGEN CONCENTRATION AND
TEMPERATURE ON THERMAL DECOMPOSITION OF
CHLORINATED BIPHENYL [2]
FIG. 9 EFFECT OF TEMPERATURE ON PRODUCTION AND DESTRUCTION OF CHLORINATED BIPHENYL AND BENZENES, IN AIR [2]
hexachlorobiphenyl is largely destroyed corresponds with the temperature at which penta-, hexa- and tetrachlorobenzene reach their maximum degree of formation, before they start to fall apart again. This illustrates the necessity of maintaining temperatures well over 800 or 900°C when these materials are present.

**DETERMINATION OF REACTION CONSTANTS OF WASTES**

The reaction constants of wastes can be determined by laboratory tests in plug-flow (capillary tube) heated-wall reactors (4), by measuring the destruction as a function of temperature and residence time. Figure 10 shows the results of such a test, from which the reaction constants can be calculated. In order for these constants to be used to predict destruction in an actual thermal oxidizer, some knowledge is needed of the degree of mixing which can be achieved with the actual burner/furnace configuration.

Lee et al. [5] have presented mathematical methods for estimating the temperature required for several degrees of backmixing, using plug flow data as the basis. They suggest that a single stage of backmixing may be considered to be the worst case, and that actual equipment will produce results inbetween the extremes of plug flow and simple back flow. Curves showing these extremes are shown in Fig. 10 for vinyl chloride (Lee’s data). Also shown are the data of Duvall et al. [3] for plug flow tests of biphenyls and benzene compounds. Note that the vinyl chloride, dibenzo-p-dioxin and dibenzo furan all require about the same temperature for destruction.

It is important to note, in Fig. 10, the small affect which residence time has on destruction efficiency. A small increase in temperature (25°C) compensates for a range of 0.5-4 secs retention time in plug flow.

An incinerator with only simple backmixing would require about 100°C higher temperatures to achieve 99.99 percent destruction, and about 100°C covers the range of retention times. This demonstrates the importance of providing effective mixing within the burner and furnace chambers.
Lee et al. [5] have found that chemical and other properties of many substances can be correlated with the temperatures required for self-ignition and destruction, making it possible to construct destruction efficiency curves. They have also offered methods for estimating the destruction curves under simple back-mixing, presented in Fig. 10, which shows that vinyl chloride follows essentially the same lines as the Duvall data.

**SUMMARY**

The thermal oxidizer/heat recovery facilities described above demonstrate the value of building flexible systems which anticipate future needs for disposal of liquid wastes as alternate fuels while providing economical, reliable, fuel-efficient, safe generation of heat and power in an environmentally acceptable manner. They also show that contract operation by the designer/builder permits techniques and facilities to evolve optimally to suit changing conditions. They are an outstanding implementation of the philosophy expressed by the Resource Conservation and Recovery Act.

When designing and operating thermal oxidizers to destroy difficult liquid wastes, it is important to recognize the relative importance of temperature, oxygen, mixing efficiency and retention time. Laboratory tests show that temperature and mixing efficiency are the main factors, whereas retention time is relatively minor. The destruction temperatures of many substances, including chlorinated hydrocarbons, can be determined by laboratory tests under plug flow conditions and correlated with their chemical nature.

Due to the similar behavior of many chemicals, relatively benign substances can be tested as surrogates for rare, trace and hazardous substances, greatly simplifying testing. These principles also indicate that thermal oxidizers or incinerators with similar geometry may give similar mixing and destruction efficiencies.

**OBJECTIVES OF AN EFFICIENT LIQUID WASTE-TO-ENERGY PLANT**

1. Minimize costs of disposal and emission controls.
2. Reduce fuel costs: use wastes as alternate fuels.
3. Produce energy and power from waste heat.
4. Follow fume and steam load variations.
5. Single responsibility for design and operation.
6. Incentives for innovation and skill.

**PROBLEMS IN COMBINING THERMAL DESTRUCTION WITH HEAT RECOVERY**

1. Inflexible rate of fume generation.
2. Variably of daily, and seasonal steam demand.
3. Match of incineration heat with steam demand.
4. Dependence of cogeneration on LP steam demand.
5. Simultaneous combustion of multiple fuels.
6. Complete combustion of high-water wastes.
7. Adequate temperature and retention time.
8. Ash and halogen contents of some wastes.

**METHODS USED TO ACHIEVE EFFECTIVE CONVERSION OF ENERGY**

1. Follow load and permit maintenance with modular thermal destruction/heat recovery units.
2. Vary furnace temperature to control heat output.
3. Store heat with hot water or steam accumulators.
4. Cut costs or gain revenue by cogeneration of power.
5. Use multi-fuel combustors to burn liquid wastes.
6. Select wastes which can be burned within permissible emission levels.
7. Install flexible, dirt-resistant storage, pumping and control systems.
8. Central responsibility to accept wastes and assure reliable operation of the facility.

**REFERENCES**

Key Words
Bridgeport
Efficiency
Inorganic
New Orleans
Operation
Refuse
Refuse Derived Fuel
Rotating Drum
Screening
Separating
Testing
Trommel