INTRODUCTION

It seems that the safe and economical disposal of industrial wastes has become a contradiction in terms. Disposal methods that were technically and economically feasible less than five years ago are no longer acceptable. Industrial pollution control presents complex problems different from other sectors of the economy. Large chemical processing plants may have hundreds of waste streams with each requiring individual treatment to meet air or water pollution control standards.

A comprehensive waste management program must include consideration of the pollution control laws, corporate image, social responsibilities and economics. Although a conventional return on investment analysis may not be applicable, the responsible environmental engineer must determine the most cost effective means of waste treatment.

Historically, the simplest and most economical means of solid and liquid waste disposal was placement in a landfill. An outside firm was contracted to remove the waste in dumpsters, drums or tankers from the site, effectively ending the plant's responsibility. This simply remedy is no longer legally or practically available. Many landfills are inadequate and new regulations may prohibit them from receiving chemical wastes. The results have been either escalating costs or simply the unavailability of landfills.

There are many alternatives that must be evaluated. One approach is the redesign of the process to eliminate or minimize waste generation. An example is the increased use of high solids or water based paints to eliminate solvent (VOC) emissions from drying ovens. Another alternative is to sell or exchange wastes with other industries. The waste product from one process can be the raw material for another. Industrial waste exchanges serve as clearing houses for this procedure. Economics will usually favor eliminating, selling or exchanging wastes, and these options should be the first steps considered in any waste disposal program.

Waste incineration is gaining wider acceptance as a final and ultimate industrial waste disposal method. As other disposal methods increase in cost, incineration has become a more attractive economical alternative.
The last few years have seen the growth of central waste disposal facilities which utilize waste incineration as one means of treatment. These incinerators for industrial, solids, sludges and liquids are large, complex process plants. Since they must handle a broad spectrum of wastes from literally hundreds of sources, the incineration system must be designed to safely handle the most hazardous and toxic waste materials. The profitability of these facilities is based on economies of scale and the initial investment is substantial. Although the disposal costs vary with the waste composition, the prices reflect the high equipment costs to insure the profitability of the plant.

The economics for disposal of relatively small amounts of highly toxic or extremely difficult to incinerate wastes favor these facilities. However, many wastes can be incinerated on site at a lower cost and, with heat recovery, can actually produce a return on investment.

The intent of this paper is to provide an overview of the opportunities for the in-plant incineration of liquid and gaseous wastes with and without heat recovery.

INCINERATION OVERVIEW

Waste materials are usually classified by their physical state – gas, liquid, or solid. Some wastes are mixtures, but they can usually be separated, segregated and disposed of as either a gas, liquid or solid. When evaluating the prospects for waste incineration, there are several assessments which must be made irrespective of the physical state.

ENVIRONMENTAL REGULATIONS

A thorough knowledge of Federal and state environmental regulations is of prime importance. This is particularly true for the disposal of hazardous wastes where the requirements are frequently changing.

The most significant regulation is the Federal Resource Conservation and Recovery Act of 1976 (RCRA) which deals with the identification, generation, transportation, and disposal of hazardous wastes. Most states have either adopted identical or even more stringent regulations. The term "cradle to grave" means just that. The generator of a hazardous waste is ultimately responsible for its disposal.

Regulations affecting the incineration of hazardous wastes are covered by RCRA (Code of Federal Regulations, Title 40, Part 264, Paragraph 340). Other regulations applicable to non-hazardous liquid or fume incinerators are the Clean Air Act and specific emission requirements for individual processes.

The regulations governing hazardous waste incineration specify both process and monitoring requirements. The four specific process requirements are:
1. The incinerator must achieve a destruction and removal efficiency (DRE) of 99.99 percent for each principal organic hazardous constituent (POHC) designated in the operating permit.

2. If the hydrogen chloride, \((\text{HCl})\) emissions exceed 4 pounds per hour, 99 percent of the HCl must be controlled before release to the atmosphere.

3. The particulate emissions must be less than 0.08 grains per dry standard cubic foot when corrected for the oxygen concentration.

4. The operating conditions must be continuously monitored in compliance with the requirements specified in the operating permit.

In order to obtain a permit it must either be demonstrated that essentially the same waste has been burned in substantially the same type of incinerator or a test burn will be required. In either case the waste must be clearly defined, the operating conditions of the incinerator continuously monitored and the emission levels carefully determined. Only after it has been proven that the incinerator is in compliance will a final operating permit be issued.

The control and regulation of hazardous wastes is becoming more stringent. As an example, new regulations promulgated in January, 1985 redefine solid waste and regulate the burning of hazardous wastes in boilers and furnaces. In the past it was possible to burn hazardous wastes in an incinerator but not be regulated under RCRA by adding a waste heat boiler to the discharge. This is no longer possible since a boiler is now defined so that, "the unit's combustion chamber and primary energy recovery section(s) must be of integral design... A unit in which the combustion chamber and the primary energy recovery section(s) are joined only by ducts or connections carrying flue gas in not integrally designed." As a result, many "boilers" now burning hazardous wastes will be reclassified as hazardous waste incinerators.

Currently, hazardous wastes being burned in boilers (as now defined) must be registered with EPA. New rules are forthcoming regulating their operation and emission levels.

**COMBUSTION CHARACTERISTICS**

The waste composition is critical when considering incineration. Does the waste contain combustible components; i.e., are the primary contaminants organic compounds? Organic compounds composed of carbon, hydrogen and oxygen, will be oxidized to produce innocuous products of combustion - carbon dioxide, water vapor and nitrogen. The presence of inorganic compounds, particularly metallics, salts, sulfur, and chlorine create special problems which substantially increase the incineration costs.

The heating value of the waste is another important property. Combustible wastes are defined as those which support their own combustion without the use of any auxiliary fuels. A non-combustible waste has a lower heating value and
must have an auxiliary source of heat, usually purchased fuel, to sustain combustion. Thus, in this context, the difference between combustible and non-combustible waste is based upon the heating value and whether or not auxiliary fuel is required to maintain combustion. This is a major determinant of the economics of incineration and heat recovery.

There are estimates to help determine the combustible nature of a waste. A liquid waste can be combustible if it has a minimum heating value of 50,000 BTU/gallon or about 6,000 BUT/lb. By this definition, No. 2 oil which has a heating value of 140,000 BTU/gallon, can be mixed with two parts of water and still support combustion without any auxiliary fuel. A waste gas stream is potentially combustible with a heating value of about 100 BTU/ft³. Thus, natural gas, with a heating value of 1,000 BTU/ft³, can be diluted by 10 to 1 with nitrogen and still support combustion.

Two important points must be emphasized. First, these are just generalizations. The actual chemical composition of the waste, the products of combustion, the excess air requirements, the temperature, the atomizing fluid, the type of burner, and several other factors must be considered to determine the actual combustion characteristics.

The second point concerns the important, and often misunderstood, difference between a combustible and an explosive gas. As previously defined, a combustible gas will sustain combustion without any supplementary heat. Natural gas or even a 90/10 mixture of nitrogen and natural gas is a combustible gas. In order for the gas mixture to sustain combustion and propagate a flame, however, it must first be mixed with oxygen (usually from air) and then ignited.

An explosive gas mixture is one which will propagate a flame and sustain combustion simply with the addition of an ignition source. The oxygen is already present in the mixture. All volatile oxygen compounds from an explosive mixture with air. The lower explosive limit (LEL) is the organic concentration above which, when mixed with air, an explosive mixture is formed. The upper explosive limit (UEL) is the organic concentration below which an explosive mixture is formed when mixed with air. The area between the LEL and the UEL is the explosive range. For example, the LEL for methane (the main component of natural gas) is 5.3 percent while the UEL is 13.9 percent. Thus, any mixture of methane and air between 5.3 percent and 13.9 percent methane is explosive. Waste gases should never be handled in this range. In most cases they can be safely diluted. Many safety regulations require that the waste gases be diluted by 25 percent of the LEL. Combustible gases can be safely handled and disposed of in an incinerator.

**INCINERATOR EMISSION CONTROLS**

The products of combustion exhausting from the incinerator are a major factor affecting the technical and economical feasibility of incineration and heat recovery. Incineration of low BTU waste streams, even with a relatively high
fuel consumption, can be feasible if the heat can be recovered in a useful form. The flue gas from wastes composed of organics containing carbon, hydrogen and oxygen presents very few heat recovery or air pollution problems.

There are several waste components which can create severe problems downstream of the incinerator. The worst and most common of these are sulfur, chlorine and inorganic ash which form sulfur dioxide, hydrogen chloride and particulates when incinerated. These compounds can be a source of air pollution and cause corrosion or plugging problems in the heat recovery equipment.

The presence of these compounds does not necessarily eliminate the possibility for incineration. The equipment, however, must be designed to prevent or minimize corrosion or fouling. In addition, the flue gas may require further treatment to prevent an air pollution problem. This may require a packed tower, venturi scrubber or baghouse collector downstream of the incinerator and heat recovery system. This additional equipment may make small scale incineration and heat recovery systems economically unfeasible. Central disposal facilities can be viable alternatives to on site incineration systems for small quantities of these types of wastes.

WASTE SURVEY

The first step in any waste management plan is to make a complete survey of all sources. A waste survey should include the source, flow, composition and duty cycle of each waste stream. As much information as possible must be gathered to determine the best means of disposal.

In some cases a simple analysis may not be enough. Particularly with hazardous wastes, a laboratory analysis will be required along with a detailed survey of the instantaneous flow cycle. Without question an inadequate knowledge of the waste streams being handled is the single biggest cause for the failure of an incineration system.

LIQUID WASTE INCINERATION

The purpose of this section is to identify the various types of liquid wastes and the liquid waste incinicators used to dispose of them. Most of these incinicators would be classified as hazardous waste incinicators. Rather than a detailed review of the regulations, however, the various incineration techniques will be discussed in detail.

CLASSIFICATIONS

In order to categorize the incinicators, two different "types" of liquids will be considered.
Liquids

This category includes the majority of liquid wastes. A liquid waste is a stream which does not contain a significant amount of suspended solids and which is easily pumped and atomized. Many of these wastes are extremely viscous or solids at ambient temperatures, but when heated they become liquid.

Included as liquids are waste solvent and waste water streams. The solvent streams are combustible wastes, while the waste water streams are non-combustible or aqueous wastes. Also included in this categorization are liquid byproducts from chemical reactions.

Sludges and Slurries

A broad definition for these wastes include all of those non-solid and non-gaseous streams which do not fall into the liquid classification. These wastes contain a great deal of suspended solids and cannot be pumped nor easily sprayed into an incinerator. They are usually handled by conveyors or progressing cavity pumps rather than typical gear or centrifugal pumps. Some examples are sludges from water treatment facilities and slurries from process reactions. The incineration equipment required to dispose of sludges and slurries is different and generally more expensive than that required for liquids.

CONTROL METHODS FOR LIQUID WASTES

There are several different alternatives that are used to dispose of liquid wastes. The methods are more varied than with gaseous wastes because there are more variations of liquid wastes and they can be stored and then treated on a batch basis.

On Site Treatment

Many liquid wastes are either chemically or biologically treated to eliminate the contaminants and then discharged from the plant. In a chemical treatment facility, the liquid waste is generally reacted with another chemical to produce an inert stream. The most common form of chemical treatment is the neutralization of either acid or basic wastes to form an inert salt and water.

In a biological system, organic matter is removed from the waste water by means of oxidation and cell synthesis. Waste water streams which contain a small amount of organic matter, and have a high chemical oxygen demand (COD) or high biological oxygen demand (BOD) are treated in this manner. The biological treatment process is essentially an accelerated form of natural water purification. This procedure is limited to those streams which have low concentrations of organics in the water.
Off Site Disposal

Liquid wastes which are small in volume, highly corrosive or hazardous in nature, are prime candidates for off site disposal. The cost to treat or incinerate these wastes in the plant can be excessive. Removal of the liquid waste from the plant must be contracted with a disposal company.

This type of disposal must be evaluated from both an economic and legal basis. The costs for off site disposal are very high; sometimes far in excess of on site disposal. There are also legal ramifications which must be considered. The RCRA regulations make the waste generator responsible for the ultimate disposal of any hazardous waste material. The generator must be certain that the contractor hauling the waste from the plant is disposing of it in a manner which complies with all regulations. This means that if the waste is being landfilled or incinerated, it must be into a facility that has been permitted for hazardous waste materials. If the waste is disposed of improperly, the waste generator is responsible. Waste disposal companies should be thoroughly investigated before contracting with them. This is one area where very low costs should be highly suspect.

Incineration

Incineration not only offers an ultimate means of waste disposal, but it can also provide an energy source for the plant. Incineration, however, is not a panacea for all liquid wastes.

If a waste material contains a high concentration of inorganic compounds, the incinerator will produce solid particulates in the flue gas which must be removed prior to exhaust to the atmosphere. This is not a technical problem, but the costs can be extremely high. The incinerator must also be designed to accommodate the presence of solids and prevent their buildup within the incineration chamber. Heat recovery equipment, when handling a flue gas which contains a great deal of solid particulates must be designed to minimize the potential for fouling or plugging.

Another limitation of liquid waste incineration is the potentially high operating costs. Non-combustible or aqueous liquids must be incinerated at a minimum temperature of 1800°F. Wastes which contain a small amount of organics in water require about 4,000 BTU/lb of fuel to raise the aqueous waste to the minimum operating temperature of 1800°F. This results in a high operating cost if heat recovery is not incorporated as part of the system.

There are three primary industrial liquid waste incineration methods which will be considered.

A. Fluidized Bed Incineration

A fluidized bed incinerator can handle sludges and slurries and also many solid and liquid wastes. In fact, the main advantage to this equipment is its ability to handle almost all types of industrial wastes. The waste is
fed into the bed, fluidized with air, and oxidized at temperatures of about 1800°F. The products of combustion from the fluidized bed are then available for heat recovery and further cleanup.

Two drawbacks to the fluidized bed incinerator are the high initial equipment cost and the unproven technology. The initial cost for a fluidized bed incinerator is among the highest for any type of industrial incineration equipment. While the concept is encouraging, the technology for burning chemical wastes is still developing, and there is still a great deal of field experience to be gained. One problem has been plugging of the bed due to varying melting points. There are variations of this technique which depend upon greater bed fluidization and appear promising for solving this problem.

Since the fluidized bed can handle almost any type of waste material, it is ideal for a central disposal facility which can take advantage of the economies of scale. The fluidized bed incinerator for use in all but the largest chemical plants is generally not economical.

B. Rotary Kiln Incinerator

The rotary kiln incinerator falls into the same category as the fluidized bed incinerator. This unit will also handle most physical states of waste materials. The waste is conveyed into the kiln and is oxidized as it flows from one end to the other. In some instances, existing cement kilns have been used to burn liquid waste materials. The advantage of burning a chlorinated hydrocarbon waste in a cement kiln is that the hydrogen chloride will be neutralized as it passes through the kiln and the exhaust gases may not require any chemical treatment.

The rotary kiln is a moving piece of equipment, and both the initial and maintenance costs are high. This unit is also best used in a central disposal facility because of its versatility in handling many different types of waste and because of the available economics of scale.

C. Liquid Injection Incinerators

These incinerators depend upon pumping, atomizing and spraying the waste into the incineration chamber. As a result, these types of incinerators are limited to liquid wastes. Depending upon the physical characteristics of the liquid, the waste is atomized by either mechanical, fluid or sonic mechanisms. The degree of atomization is critical to the process. The smaller the liquid droplet, the more rapidly it will vaporize and oxidize.

Streams containing very small amounts of solids with a low viscosity are generally mechanically atomized at pressures of at least 100 psig. Wastes containing higher solid concentrations or higher viscosities are fluid atomized with either steam or air.

The liquid injection incinerators are divided into two distinct types depending upon the waste heating value.
Direct Flame Incineration

In this type of incinerator, the liquid waste is combustible or almost combustible. The waste material is incinerated, or oxidized, directly in the burner flame. As a result, the incineration temperature will be in the range of 2200°F to over 3000°F. There is little or no requirement for supplemental fuel, and, therefore, the operating costs are minimal. Depending upon the inorganic content, this type of incinerator is ideal for heat recovery. In many instances, the combustion equipment on an existing boiler can be modified to incinerate a combustible liquid waste, although there are new (January, 1985) regulations which must now be considered. The most common type of wastes disposed of this procedure are waste solvents.

Thermal Incineration

This type of incinerator is used for liquid wastes which will not support their own combustion, and fuel is required to reach the final incineration temperature. Depending upon the specific compounds in the liquid waste, this temperature can range from 1800°F to 2400°F. Because of the large quantities of supplemental fuel required, heat recovery is almost a necessity to economically justify the thermal incineration technique. Unfortunately, heat recovery is not as efficient as with a direct flame incinerator because of the large quantities of water in the flue gas. Most of the fuel is used to vaporize the water, and the heat is not recovered in most conventional heat recovery equipment.

While the "three T's" of incineration - time, temperature and turbulence - are well known, their practical application is most important in this type of incinerator. Time and temperature are easily measured and sometimes assumed to be the only important criteria for a well designed incinerator. However, it is probably easier to design an incinerator to operate at 3000°F with 2 seconds retention time and incomplete combustion than one at 1800°F with 0.6 seconds retention time in compliance with regulations.

If the liquid waste is not finely atomized, the time required for vaporization will be excessive. While atomization is critical, nothing can be oxidized without oxygen. The mixing of turbulence of the waste with combustion air is the key to any good incinerator design. Incinerators which mix secondary air with the finely atomized liquid waste as it is sprayed into the chamber achieve good mixing and substantially reduce the time and temperature requirements.

WASTE LIQUID INCINERATION WITH HEAT RECOVERY

Strictly speaking, all liquid incineration systems are candidates for heat recovery. The main limitation for heat recovery is the economic feasibility. The economics are affected by the flue gas composition, flow and temperature and the need for the recovered heat.
It is technically possible to recover heat from flue gas streams containing sulfur dioxide, hydrogen chloride, and other toxic substances. It may not, however, be economically feasible because of the corrosive nature of these gases. The heat recovery equipment and control techniques must be sophisticated to prevent equipment corrosion and deterioration. Inorganic particulates in the flue gas stream may cause the heat transfer equipment to become fouled or plugged with the solid particles. These problems can be resolved, but the additional cost may prohibit heat recovery.

Flue gases which contain carbon dioxide, water vapor, nitrogen, and oxygen are ideal for heat recovery. The efficiency will be highest and the equipment cost the lowest. Streams which contain sulfur dioxide or hydrogen chloride can also be used for heat recovery. The heat recovery efficiency is lower since the flue gas outlet temperature from the heat exchanger must be higher to prevent corrosion problems. A gas cleaning device adds to the cost but is necessary to prevent an air pollution problem.

There are several different ways in which heat can be recovered from incinerators. These will be reviewed from both a process and an equipment standpoint.

PROCESS CONSIDERATIONS

Three basic processes for heat recovery are considered.

A. Preheating the Waste

The main fuel consumption for incinerating a noncombustible, aqueous waste is for vaporizing the water. The fuel required to raise one pound of water from ambient to 1800°F is about 4000 BTU/lb. Only about 10 percent of that is the sensible heat required to raise the water to its boiling point of 212°F. Therefore, there is no real economic advantage to preheat the aqueous waste.

Preheating a liquid waste is also a problem because of the contaminants in the liquid waste. In most cases, fouling of heat transfer equipment is considerable due to the organic compounds in the liquid stream. Vaporizing the liquid waste, which would provide significant fuel savings, usually creates insurmountable fouling and plugging problems due to the contaminants.

For these reasons, it is very unusual to utilize this form of heat recovery on a liquid waste incinerator.

B. Generating Steam, Hot Water, or Hot Air

In this process the flue gas from the incinerator is used to generate a process fluid which can be used in other areas of the plant. This is the most common and generally the most feasible means for recovering heat from the liquid waste incinerator.
Since the tube bundle in a hot water or stream boiler can withstand much higher temperatures than in an air heater, it is usually more feasible to utilize a boiler for the primary heat recovery. At very high temperatures, usually above 1800°F, a Scotch Marine-type boiler is ideal. The flue gas is cooled in the large radiant fire tube before it contacts the tubesheet and the main tube bundle. Due to the high costs, water tube boilers are only used for high pressure steam or for very large systems.

In some systems, hot air is produced from the liquid waste flue gas. These units generally require exotic materials of construction and great care has to be taken to protect the heat exchanger from the high flue gas temperature.

C. Preheating Combustion Air

This process is similar to preheating the waste since it acts to reduce the fuel consumption. This technique is only applicable where the waste is non-combustible and auxiliary fuel is used. The fuel consumption in the incinerator can be reduced by 5 to 25 percent depending upon the combustion air preheat temperature. Since this method reduces fuel consumption, there is no point in preheating the combustion air in a combustible waste incinerator.

There are some practical limitations on the combustion air preheat temperature. The typical liquid incinerator, operating at 1800°F, imposes a practical limitation on preheating the combustion air to about 1000°F. Most industrial burners can operate with preheated combustion air up to a temperature of about 200°F. Above 200°F, the burner must be modified for preheated air up to about 800°F. Above 800°F, the carbon steel construction must be changed to stainless steel or otherwise modified at high costs. Therefore, practically, the maximum combustion air preheat temperature is in the range of about 600°F to 800°F depending upon the actual burner being used. In this range, the fuel savings are about 10 to 15 percent.

One concern when using preheated combustion air is the fuel/air ratio control system. The control system must provide the proper fuel/air ratio when the air temperature changes from ambient to 800°F. The volumetric flow rate increases by a factor of almost 2-1/2 to 1, while the mass flow must remain constant. As a result, the control system becomes more complicated and expensive. Preheated combustion air will also increase the pressure drop across the burner for the same heat output. This increases the combustion air blower horsepower and negates some of the energy savings.

Because of the high temperatures associated with liquid waste incineration, the combustion air preheater is often located downstream of the primary heat recovery device. Many liquid waste incineration heat recovery systems use a waste heat boiler followed by a combustion air
preheater. This allows the flue gas to be cooled to a temperature where standard stainless steel or carbon steel construction can be utilized to preheat the combustion air. The fuel savings for preheating the combustion air would be the same as described previously.

HEAT RECOVERY EQUIPMENT

Primary heat recovery equipment for liquid waste incineration systems is limited. Higher exhaust temperatures make standard shell and tube and plate type heat exchangers impractical.

A. Metallic or Tubular Heat Exchangers

These types of heat exchangers are not normally used directly downstream of the liquid waste incinerator because of temperature limitations. They are used, however, after the flue gas has been cooled in a primary heat recovery device. The plate heat exchanger is particularly effective for secondary heat recovery because of its relatively low cost, low pressure drop and the lower flue gas temperatures do not cause expansion problems.

B. Waste Heat Boilers

This is the most common form of heat recovery from a liquid waste incinerator. Boilers used for heat recovery can either produce steam or hot water depending upon the plant requirements. When using a waste heat boiler or heat recovery, care must be taken, as with any boiler installation, to adhere to the required codes and to design the boiler to minimize corrosion. An operating engineer may be necessary to operate the boiler where one is not normally required for the incinerator.

The fire tube boiler is most commonly used for production of steam at less than 200 psig pressure due to its lower cost. In waste gas incineration systems a single pass straight tube bundle is utilized in most instances. At the higher flue gas temperatures of 1800°F and up from a liquid waste incinerator, the boilers are usually a two- or three-pass Scotch Marine or a water tube.

The Scotch Marine boiler is particularly effective for the higher temperatures. The large furnace tube acts as a radiant section and cools the flue gas before it contacts the tubesheet in the second pass. While the water tube boiler is substantially more expensive, there are instances where it is also feasible for heat recovery. The economics become favorable at high capacities and steam pressures. This is particularly beneficial in a cogeneration facility used to generate electricity and process steam.

It is also important to realize that steam or hot water generation can be used for primary heat recovery with hot air production as secondary heat recovery. This will be reviewed in the economics section.
LIQUID WASTE INCINERATION - ECONOMICS

The high flue gas temperature is the limiting factor for heat recovery from a liquid waste incinerator. As a result, the primary form of heat recovery is a waste heat boiler used for generation of saturated steam or hot water. To illustrate the economics of heat recovery from a liquid incinerator, two different cases will be examined. First is a combustible liquid waste and second is a non-combustible aqueous waste.

DIRECT FLAME

A combustible liquid waste in a direct flame incinerator will usually have an exhaust temperature greater than 2200°F. In this example, the waste stream will be ten gallons per hour of waste solvents assumed to be toluene with a heat release of approximately 1.4 MM BTU per hour. The hauling cost is assumed to be one dollar per gallon or about $50. per 55 gallon drum.

The first alternative for this combustible liquid waste is an incineration system without any heat recovery. Because the waste is combustible, there are no operating costs other than a small amount of electricity for the combustion air blower. Assuming 6,000 hours per year of operation, this works out to a savings of approximately $60,000, annually in hauling costs.

The incinerator will cost approximately $25,000, making the simple equipment payback approximately five months.

As has been previously discussed, the best and generally the most economical form of heat recovery from this type of incinerator is steam generation. A steam generation system for the 10 GPH example will produce approximately 1,000 pounds per hour of steam at 150 psig. This will lower the flue gas exhaust temperature to approximately 450°F. The value of the steam on an annual basis is about $37,500. The additional cost for the boiler system is about $40,000, making the simple equipment payback for the boiler about one year. This steam can now be used, of course, in the main steam system of the plant.

Another heat recovery alternative is to generate hot water. Considering a closed loop system where the hot water is used for space heat, we have the capability of generating about 50 gallons per minute of water at 200°F. This water can be used in a space heat system to produce approximately 20,000 SCFM of hot air at 100°F. The addition of the space heaters, will increase the payback beyond one year and will be dependent on how many heaters are used. It is reasonable to assume that the overall equipment payback will still be less than a year and a half.
THERMAL INCINERATOR

While these are the primary ways of recovering heat from a combustible liquid stream, there are other methods which would be utilized on an aqueous non-combustible waste. For this example, we will assume that the aqueous waste consists of 100 gallons per hour of contaminated water. It is necessary to dispose of this in a thermal incinerator at a temperature of 1800°F. The basic incinerator, without any heat recovery, would require approximately 3.3 MM BTU per hour of fuel consumption. The operating cost for 6000 hours would be about $100,000 annually and the initial equipment price would be about $50,000.

The next step is to add a waste heat boiler to the incinerator discharge. In this particular example, the boiler would be capable of producing about 2400 lbs. per hour of saturated steam at 150 psig. The value of the steam is about $90,000 per year, while the additional cost for the waste heat boiler would be about $75,000. This works out to a simple payback for the boiler of approximately ten months.

In addition, an air preheater can be added to the boiler exhaust to preheat combustion air for the burner. The combustion air could be heated to a temperature of about 320°F. This would save approximately ten percent of the fuel consumption, or about 0.33 MM BTU per hour. The fuel savings would amount to about $10,000 per year while the air heater would cost about $10,000. The waste heat boiler and air heater, operating in series, would virtually negate the incinerator operating costs.

GASEOUS WASTE INCINERATION

Waste gases are generated in many manufacturing and finishing processes. Typical sources are furnaces, ovens, dryers, coaters, spray booths, paint booths or, in general, any process which combines organics with heat.

There are many similarities between gaseous and liquid disposal techniques. Two major differences are that gaseous wastes cannot be stored and hauled away on a contract basis, and the combustion kinetics are more direct. The liquid is injected into an incineration chamber and must be vaporized to a gas before it can be oxidized. Practically, this means that the liquid waste incinerator must be designed to operate at a higher temperature to allow the reaction to proceed rapidly. Waste gases can be incinerated at a lower temperature because time is not required to undergo the phase change.

The requirements for waste gas incineration with and without heat recovery will be examined in greater detail.

CLASSIFICATIONS

Most waste gases are divided into four different categories.
Solvents

This group includes those gas streams which contain volatile organic solvents (VOC) from dryers, ovens, kilns, paint booths or similar equipment. The fume stream can consist of air, with solvent concentrations of about one percent by volume, or inert gases, such as nitrogen from purging tanks or reactors, contaminated with organics. Waste fume streams at 25 percent of the LEL or less can usually be used as combustion air for the supplemental fuel. This is important for fuel savings.

Particulates

Waste fumes in this category contain solid particles fluidized in the gas stream. These solid particles can be combustible such as smoke from a furnace or carbonaceous material from a pyrolysis reactor. The solids can also be metallic oxides, combustion generated particles from a solid waste incinerator or other inorganics which have become fluidized in an exhaust system.

Toxic Fumes

These are waste gases which contain halogenated hydrocarbons, carbon monoxide or other gaseous compounds which can produce injury upon contact, inhalation or accumulation in or on the body of a living organism.

Odorous Pollutants

These fumes contain compounds in very low concentrations which create an odor or nuisance problem without necessarily being toxic. Chemicals containing either sulfur or nitrogen are the most common pollutants in this category.

AIR POLLUTION CONTROL METHODS

There are various alternatives for pollution control from the basic types of waste gases. The two main control methods are capturing and collecting, and incineration.

Capturing and Collecting

These techniques for pollution control include adsorption, condensation, absorption, and mechanical separation.

A. Adsorption

In an adsorption system a solid material selectively adsorbs specific gases or liquids onto its surface. Typical gas adsorption systems are used to separate mixtures of gases, remove moisture, odors or toxic gases from air and to recover organic vapors for reuse.
The most common application in air pollution control is the activated carbon bed used to remove volatile organic compounds (VOC) from an effluent gas stream. The VOC is usually condensed and collected in liquid form for reuse, sale or disposal by incineration. This method is effective for both the solvent and odorous streams.

B. Condensation

Another method for capturing VOC is to condense the gaseous solvent with a refrigerant. This process is usually only feasible for low flows since the economics are prohibitive. In many cases it is difficult to reduce the VOC level to that required by regulation.

C. Absorption

While adsorption is the collection of organic compounds on the surface of a solid material, absorption is the transfer of a gas into a liquid stream. The absorbed material is dissolved in the liquid or, in some cases, there is a chemical reaction with the substances in the liquid. The equipment generally used for absorption is packed, plate or spray towers.

The absorption process is commonly found downstream of the incineration equipment used for toxic fumes. It is used to absorb and neutralize such compounds as sulfur dioxide and hydrogen chloride which are formed in the combustion process. In some cases odorous fumes can be controlled directly with absorption techniques.

D. Mechanical Separation

This technique is used to remove solid particulates from a gas stream. The equipment usually used for this process are electrostatic precipitators, fabric filters (baghouses), and centrifugal separators.

Incineration

The most common and convenient means of eliminating many gaseous emissions is by incineration. Incineration is an effective technique for eliminating pollution caused by solvent, toxic or odorous streams, but it is not effective for inorganic solid particles in a gas stream.

The primary drawback to most waste gas incineration applications is the fuel consumption. Since most waste gases containing organics are primarily air or inert gases, large amounts of fuel are required to raise the waste gases to the required incineration temperature. For this reason, heat recovery must be used in conjunction with fume incineration to provide both a technically and economically feasible system.
A. Direct Flame Incineration

Similar to liquid incinerators, this technique is best for waste gases which are combustible or almost combustible. The waste gases are incinerated directly in the flame of the burner. Typical waste gases which are incinerated in this manner would be hydrogen cyanide from a chemical reactor, carbon monoxide off gas, and hydrogen sulfide gas from sulfur processing or sulfuric acid plants.

Since the gases are incinerated directly in the burner, combustion takes place at relatively high temperatures above 2200°F. For all practical purposes, the waste gas acts as the fuel in the burner and supplemental fuel is either not required or is only used in small quantities.

B. Thermal Incineration

This is the most common form of waste gas incineration and is used where the waste stream consists of low concentrations of organics in a large amount of air or inert gas. If the direct flame technique were used, a huge amount of fuel would be required to sustain combustion. This is because most industrial burners require temperature of at least 2200°F to maintain stable operation.

In a system utilizing thermal incineration, the waste gases are mixed with the hot products of combustion from the burner and then raised to the final incineration temperature. Depending upon the specific contaminants, this temperature can range from 900°F to 1800°F, but, in any case, it will be lower, and therefore require less fuel, than direct flame incineration. In most cases, the solvents are mixed with air and secondary air is not required as with the liquid incinerators. In fact, if the fume contains a minimum of 16 percent O₂, it can be used as combustion air for the supplemental fuel. This means outside combustion air is not necessary and effectively reduces the fuel requirements by about 40 percent.

Because fuel must be added to the incinerator to raise the waste gases to the required incineration temperature, this type of system is the best candidate for heat recovery.

C. Catalytic Incineration

A catalyst is a substance which initiates a chemical reaction without becoming part of the reaction. In incineration systems, a catalyst causes the oxidation of the organics to occur at a lower temperature. This is a thermal incineration process with operation at a lower temperature. The waste gases are preheated by a burner to a temperature of about 600°F prior to entering the catalytic bed. The oxidation reactions occur in the bed causing a 200°F to 400°F temperature rise. Reduced fuel consumption is the main advantage of catalytic incineration.
There are some important limitations for catalytic incineration. The most severe problems are catalyst "poisoning" or "fouling." A catalyst is poisoned (becomes inactive) in the presence of metals such as mercury, zinc, and lead. A catalyst is fouled in the presence of inorganic dusts, alumina and silica, iron oxides, silicones, halogens, and sulfur. The types of fumes, then, that can be disposed of in catalytic incinerators are limited. Maintenance costs are substantially higher due to catalyst replacement. As the catalyst becomes fouled it loses its activity and the fuel consumption is increased.

**Waste Gas Incineration with Heat Recovery**

Since the majority of gaseous wastes are primarily air and the fuel requirements to raise them to incineration temperature are high, heat recovery is essential. There are also some options for reducing fuel consumption which are not available with liquid waste incineration.

**Process Considerations**

Three primary methods are used to recover heat from an incineration system. These include preheating the waste, generating steam, hot water or hot air, and preheating the combustion air.

**A. Preheating the Waste**

Unlike liquid incinerators this is the most common form of heat recovery from fume incinerators. The waste gas stream is preheated by the flue gas from the incinerator in a gas to gas heat exchanger. This procedure is used in a thermal incinerator to reduce fuel consumption. This differs from a system where the recovered heat is used external to the incineration system. In a direct flame incinerator, where the waste gases are combustible or almost combustible, there are no savings to be gained by preheating the waste gas stream prior to incineration.

In a typical application for thermal incineration, the waste gas stream ranges in temperature from ambient to 4000°F and the incineration temperature is 1400°F. The 1400°F flue gas is used to raise the temperature of the incoming waste gas stream from 600°F to 1200°F before it flows into the incinerator.

Operating limitations are imposed by the economic reality of equipment sizing. If the preheat temperature is too low, the fuel savings will not be high enough to justify the expenditure. However, if the preheat temperature is too high, the capital expenditure will be too high to justify the savings from reduced fuel consumption.
B. Generating Steam, Hot Water, or Hot Air

This process uses the hot flue gas to generate a process fluid which can be utilized in other parts of the plant. These fluids can be steam, thermal liquids, hot water, or hot air. The heat can be used in any plant process or for space heat purposes.

There are some limitations on the feasible steam pressure. Since the incoming gases are only 1400°F, as opposed to over 3000°F in a conventional packaged boiler, it is generally not economical to generate high pressure steam. The temperature limitations for hot water and hot air must also be evaluated from an economic standpoint.

C. Preheating Combustion Air

The economics and methods used for this form of heat recovery are similar to those for liquid waste incineration. Since the incineration temperature is usually lower, the air preheater can be the primary heat recovery device. In most cases, however, it is used for secondary heat recovery in the same manner as an economizer on a boiler.

HEAT RECOVERY EQUIPMENT

The main equipment used for heat recovery includes a metallic or tubular heat exchanger, a regenerative type heat exchanger, and a boiler.

A. Metallic or Tubular Type Heat Exchanger

This is the most common type of heat exchanger found on waste fume incineration equipment. It is used to preheat the waste or to preheat combustion air. Typical designs include shell and tube, U-tube and plate heat exchangers. Each has its advantages and disadvantages depending upon the equipment size and the operating temperatures.

The shell and tube heat exchanger is the choice for most applications. The flue gas can flow through the tubes or over the tubes depending upon the specific application. In most instances, the two streams flow countercurrent to maximize the overall heat transfer coefficient. The heat exchanger can be constructed of any material that is suitable for the temperature and corrosion characteristics of the flue gas. When the waste gases are preheated to a temperature of less than 600°F, the heat exchanger can be constructed of carbon steel, although most applications require stainless steel construction. The tubesheet can also be protected with a refractory lining when exposed to the hot flue gases.

A problem with the shell and tube heat exchanger is due to expansion of the tube bundle. One solution is to install an expansion joint on the heat exchanger shell or on the tube bundle. Because of the high temperatures, the expansion joint is generally constructed of stainless steel and on large systems the costs are substantial. Another method used
is a packed expansion joint. This joint allows the tube bundle to slide independently of the shell, but may allow some leakage between the flue gas and the incoming waste gas. If the waste gas leaks into the flue gas exhaust, there may be an air pollution problem because the organic compounds have not had a change to be oxidized in the incinerator.

The U-tube heat exchanger is particularly beneficial in higher temperature applications. The flue gases are generally on the shell side of the heat exchanger with the waste gases passing through the tubes. This flow pattern does not require a refractory lined tubesheet to prevent high temperature deterioration. Another advantage of the U-tube bundle is that the expansion is taken up within the tube bundle itself. This eliminates the need for an external expansion joint. The pressure drop and initial cost of the U-tube heat exchanger are generally higher than the shell and tube heat exchanger.

Another type of heat exchanger in use is the plate heat exchanger. The plate heat exchanger takes a much lower pressure drop for an equivalent amount of heat transfer. The plates are constructed of any material consistent with the operating temperatures. One problem is that expansion can cause deformation of the plates and restrict the flow openings through the bundle. Plate heat exchangers are generally used on low temperature and low pressure applications.

B. Regenerative Type Heat Exchangers

The two heat exchangers covered in this category are a refractory type and a rotary type. Either one can be used to preheat the load or to generate hot air for other sources.

The refractory regenerative type of heat exchanger consists of multiple compartments each of which contains a bed of refractory shapes. The hot flue gas from the incinerator flows through half of the compartments and heats the refractory shapes. After the shapes have been heated, the flue gas is diverted into the other compartments. The incoming waste gases then flow through the preheated compartments, pick up heat from the refractory shapes and then pass into the combustion chamber. Thus, at any moment, half of the chambers are being heated with exhaust gases while half are being cooled by the incoming waste gases.

This type of heat exchanger is particularly effective for waste gas streams which are corrosive or create fouling problems. The refractory is basically inert to corrosion and is difficult to foul. The main problem encountered is the difficulty of valving the hot, corrosive streams from one chamber to another. The high cost of this unit along with the high efficiencies make the economic very impressive on large systems but not for smaller units.
Another type of regenerative heat exchanger is the rotary unit. The hot flue gases pass through one-half of a wheel which contains a honeycomb type of metallic heat transfer surface. The wheel is rotating so that as the hot gases flow through one-half of the wheel, the incoming waste gases pass through the other half. One-half of the wheel is continually being heated, while the other half is being cooled with the waste gases. While the efficiency is high, there can be a problem of leakage from the incoming waste gases to the outgoing flue gases. The honeycomb in the wheel is also an area for potential fouling or plugging. This type of heat exchanger is usually limited to "clean" flue gases.

C. Boilers

Waste heat boilers are used to produce either hot water or saturated steam for use in the plant. Fire tube boilers, which are less expensive than water tube units, are usually used for this application at steam pressures less than 200 psig. The fire tube can be a single or multiple pass device. The multiple pass unit is more compact where space is at a premium. In typical applications where the incoming flue gas temperature is at 1400°F or less, the usual choice is a single pass fire tube boiler. For applications where the temperature exceeds 1800°F, a Scotch Marine boiler would be used where the hot flue gases are cooled down in the large fire tube by radiant transfer before they enter the tube bundle. The use of a waste heat boiler has no effect on the fuel consumption.

Several different process uses for heat generated by a fume incineration system have now been reviewed. In many cases, the most economical installation utilizes several of these techniques. This will be examined in more detail in the economics of heat recovery section.

WASTE GAS INCINERATION - ECONOMICS

The economics of heat recovery from a waste gas incinerator depend upon several factors. There is no standard answer as to whether any particular system should incorporate heat recovery. A specific evaluation must be made which will vary from one situation to another.

WASTE AND ENERGY SURVEY

The first step in any evaluation is to make a complete survey of all waste sources. As discussed previously, the flow, composition, and duty cycle of all emission sources are important. Intermittent purges from batch reactors may not be heat recovery candidates because of their short duration.

Following the waste survey, each waste stream should be analyzed for the best possible method of control. The first concern should be to determine if the stream can be recycled, re-used, sold or reduced in volume by process modification. Many coaters or ovens are exhausting solvents at very low concentrations. Often, the air flow can be reduced without affecting the process. The equipment savings can be substantial.
An equipment evaluation should include both initial and operating costs along with projected maintenance costs and equipment service life. The prime criteria is that the final exhaust to the atmosphere meets all environmental regulations. For example, a solvent recovery system that recovers only 90 percent of the solvents, may still require treatment of the effluent to comply with environmental regulations. If an incinerator must then be added to the system, perhaps the solvent recovery unit should have been eliminated in the first place. Another example might be using an incinerator to destroy a small amount of solvents in an airstream that contains a large amount of inorganic particles. A mechanical collector would be required following the incinerator. If the solid particulates had first been removed, the low organic concentration may not have required an incineration system at all.

The next step should be to make an energy survey of the plant. It must be determined in what form the energy is required and at what rates. The duty cycle is critical since, unlike liquids, the gases cannot be stored. There is no economy to producing steam for a water chiller during the middle of the night when air conditioning is not required.

HEAT RECOVERY EXAMPLES

In order to evaluate the economics of a fume incinerator with or without heat recovery, a typical problem will be reviewed.

The fume to be considered has a flow rate of 10,000 SCFM from a continuous drying operation. The stream is air at 200°F containing toluene at 20 percent of the LEL. The problem is to determine the initial equipment costs and operating cost for a base incinerator, and also for an incinerator with a variety of heat recovery devices.

Toluene has an LEL of 1.2 percent by volume. At 20 percent of the LEL the toluene has a flow rate of 24 SCFM and a heat release, when oxidized, of 6.5 MM BTU per hour. For this example, we will assume a fuel cost of $5. per MM BTU, plant operation of 6,000 hours per year (24 hours per day, 250 days per year) and a steam value of $6.25 per thousand pounds (based on 80 percent efficiency for a packaged boiler).

The first consideration is for an incinerator without any heat recovery. In this case the waste fume contains enough air so that it can be used as combustion air for the supplemental fuel in the burner. The toluene in the waste stream can be effectively oxidized at an incineration temperature of 1400°F with a retention time of 0.6 seconds. The fuel consumption to raise the waste fume stream from 200°F to 1400°F will be approximately 9.6 MM BTU per hour. The initial cost for the equipment is only about $50,000, but the annual fuel costs are about $288,000. This is not the total operating cost, but the electricity and any other utilities are insignificant when compared to the fuel costs.
This is the base case and different means of heat recovery can now be considered. One option is to simply add a waste heat boiler downstream of the incinerator. This does not reduce the fuel consumption, but will produce steam for use in the plant. The 1400°F flue gas will produce approximately 10,900 pounds per hour of saturated steam at 150 psig with an exhaust gas outlet temperature of about 450°F. This works out to an annual steam production of $408,750. The operating cost for the incinerator is about $288,000, producing a positive return of $120,750. The estimated additional cost for adding a waste heat boiler is about $100,000 for a total expenditure of $150,000. Therefore, the equipment payback is about ten months.

Another procedure is to preheat the waste stream. In this system a heat exchanger is added downstream of the incinerator which will preheat the waste gases from 200°F to 800°F. The 800°F stream is now injected into the incinerator where supplemental fuel must be used to raise it to a temperature of 1400°F. The 1400°F flue gas is then used in the heat exchanger as the heat source for the incoming fume. The final exhaust from the system is at a temperature of about 850°F. The fuel consumption drops to about 1.5 MM BTU per hour for annual fuel savings of $243,000 per year. Based on the additional cost for the heat exchanger of $100,000, this works out to about a five-month equipment payback. It also reduces the annual operating cost of the incinerator from $288,000 per year to a more manageable $45,000 per year.

After reducing the fuel consumption with the heat recuperator, additional heat recovery can be considered. One method is to heat up an air stream for use in other plant equipment. In this example we have assumed a need for 400°F air which could be used in dryers, ovens, furances, or any other device that needs hot air. It could also be blended with ambient air and used in the plant hot air system for space heating. The amount of air that could be produced is approximately 15,000 SCFM at 400°F. This will mean adding an additional heat exchanger which will reduce the final flue gas exhaust temperature to about 350°F. The additional heat exchanger would cost approximately $75,000 and recover approximately 5.6 MM BTU per hour. This amounts to annual fuel savings of $168,000. Comparing this to the additional capital cost of $75,000, the payback is approximately six months.

In most plants the production of 15,000 SCFM of air at 400°F is not practical. A more practical system might be to provide hot air for the continuous dryer and then to produce hot air for space heating. The first heat exchanger, sized for 10,000 SCFM of air at 300°F for the continuous dryer, would reduce the flue gas temperature from 850°F to 600°F. The flue gas, now at 600°F, then enters a second heat exchanger where ambient air is heated to 1250°F for use in the plant heating system. This will lower the flue gas temperature to about 350°F and produce about 38,000 SCFM of hot air at 1250°F. The total savings, based on the total heat recovery in the two air streams of about 5.3 MM BTU per hour, is about $159,000 per year. The additional capital cost for the two year exchangers would be about $125,000, resulting in a payback of about ten months. The total cost for the entire system is now approximately $275,000.
Another practical scheme is to produce hot water which can then be piped to any part of the plant that needs either hot water or hot air. In many cases, the incinerator is located in one central location, and it can be very expensive to duct hot air to the entire plant. It is much less expensive to put in a hot water loop and either use the water directly or in unit space heaters. In this example, after hot air production for the dryer, the 600°F flue gas is used in a hot water heater to produce approximately 135 GPM of hot water at 200°F. This assumes a closed loop system so the water flows back into the hot water heater at about 160°F. The 135 GPM of hot water is used as boiler feed water or in space heaters. The total annual savings of about $159,000 would be the same as in the previous example. The water heater, however, is more efficient than the air heater, so the total capital expenditure would drop to approximately $100,000. In addition, installation costs are substantially lower. This would make the total equipment payback about eight months.

Another potential source of energy which must be considered is the generation of electricity. In this type of system it is first necessary to generate steam for a turbine generator set and then produce the electricity. In many plants where the requirements for hot air or steam are very small, there is always a requirement for electricity. Even if all of the electricity generated cannot be utilized by the plant, it can be sold back to the utility. The equipment required could include a turbine generator set, condenser, and cooling tower. The potential for electrical production from the 10,900 pounds per hour of steam is about 600 kw. Assuming a value of $.05 per kw, this works out to about $180,000 per year of electrical generation. An approximate cost for the equipment, including the switchgear is about $500,000. Comparing this additional cost of $500,000 to the $180,000 per year of savings, it works out to a payback of approximately three years for electrical generation. The steam from the turbine generator can still be used for process purposes in a cogeneration facility.

These examples show several different ways of recovering heat from an incinerator that is handling a waste fume stream that contains a small amount of solvent in a large volume of air. The waste fume is used as combustion air for the burner. In some cases, the waste fume may contain a small percentage of organics, but for one reason or another the fume cannot be used as combustion air in the burner. In those cases, the fuel consumption would be higher and preheating combustion air for the burner might be feasible. The overall economics would be similar to those that have been discussed.

Another case is for those waste fume streams which are combustible and can be disposed of in a direct flame incinerator. The type of incinerator and the types of heat recovery systems are very similar to those for a liquid waste incinerator which have been previously reviewed.
SUMMARY

The number of systems that can be used for incineration and heat recovery are numerous. This paper has reviewed just some of the many available processes. Steam or hot water generation can be used to produce air conditioning, space heat, process heat, boiler feed water or just about any type of energy used in the plant. Economics are the key. Most of the systems that have been illustrated show equipment paybacks of less than one year. If installation of equipment and normal maintenance costs are included, the payback period is generally less than two years and, in many cases, less than a year and a half. As the costs for fuel, steam, and waste hauling increase, the economics will continue to improve. The primary advantage to the on site incineration of liquid waste might be from the piece of mind that exists knowing the waste has been treated in a socially responsible manner in compliance with all regulations.

There are several points which should be emphasized.

1. The most important part of any successful incineration system is the initial waste survey. Incinerators that operate at 50 percent or 150 percent of design load are either not economical or will not meet pollution regulations. Choose a system that provides flexibility in handling different compositions. Waste compositions and flows change with varying processes and raw materials. No one puts in a process to control the quality of the waste.

2. An energy survey is critical to the economics of the system. An oversized system produces energy which is not required, while an undersized one will waste valuable heat in the flue gas. In either case, money is going up in flames.

3. The legal ramifications may be the most important reason to use on site liquid waste disposal. Each plant is in control of its waste disposal and does not have to rely on the capability of outside contractors. Incineration is an ultimate and final disposal technique. Contamination from the waste can't come back to haunt you several years in the future.