From Pollution Control to Combined Heat and Power Technology Systems

John A. "Skip" Laitner, American Council for an Energy-Efficient Economy

ABSTRACT

Conventional pollution control technologies do just that: they control pollution to acceptable levels but provide little else in the way of economic benefits. But what if the redesign of such systems makes it possible to produce useful by-products beyond the so-called "end of pipe" controls? In the case of industrial plants required to reduce volatile organic compounds (VOC), the conventional abatement technologies include regenerative thermal oxidizers (RTOs) that have an efficiency removal rate of 98% and higher. Environment and Power Systems International, LLC (EPSI) has developed an alternative technology that uses the VOC-containing gases enriched with natural gas to generate both electricity and useful thermal heat as a by-product of pollution control. This paper describes the alternative technology and reviews the potential contribution to the nation's electricity supply. Preliminary data suggests there may be 100,000 industrial facilities that might be able to take advantage of this alternative technology. If 60% of these facilities adopt the EPSI system by 2025, the primary energy savings might exceed one quad of energy. This is equivalent to the petroleum production that might be provided by opening the Alaska National Wildlife Refuge.

Introduction

Few question the importance of reducing or eliminating air and water pollutants from our nation's industrial processes. To the extent there is any controversy it is about the need to balance benefits with costs as we try to manage the reduction of those pollutants. In the case of air pollution generally, and more specifically, the reduction of volatile organic compounds (the primary technology driver in this paper), standard engineering practice generally requires some form of pollution control technology. The good news is that this approach does very well, typically achieving emission reductions of at least 98% when the technology is appropriately designed, engineered, and operated. On the other hand, the conventional pollution control technologies do only that: they control pollution to acceptable levels but provide little else in the way of economic benefits.

But, as this paper asks, what if the redesign of such systems makes it possible to produce useful by-products beyond the so-called "end of pipe" controls? In the case of industrial plants required to reduce volatile organic compounds, the dominant abatement technologies include regenerative thermal oxidizers, which provide an efficiency removal rate of 98% and higher. Environmental and Power Systems International has developed an alternative technology that uses the VOC-containing gases enriched with natural gas to generate both electricity and useful thermal heat as a by-product of pollution control. This paper describes the alternative technology and reviews the potential contribution to the nation's electricity supply. Preliminary data suggests there may be 100,000 industrial facilities that might be able to take advantage of this alternative technology (EPRI 2006). If 60% of these facilities adopt the EPSI system by

2025, the primary energy savings might exceed one quad of energy. This is equivalent to the petroleum production that might be provided by opening the Alaska National Wildlife Refuge.[1]

Background and Technology Characterization

Ground-level or tropospheric ozone is a widespread air pollutant, a gas that forms in the atmosphere when three atoms of oxygen are combined together. It is not emitted directly into the air, but is produced by chemical reactions between oxides of nitrogen (NOx), and volatile organic compounds near ground level and in the presence of sunlight.[2] Hence, NOx and VOC are identified as precursors to the formation of ozone. Nitrogen oxides are formed when fossil fuel is burned at high temperatures. Many of the nitrogen oxides are colorless and odorless, although nitrogen dioxide can often be seen as a reddish-brown gas. NOx results from sources that burn fuel, including motor vehicles, electric generating plants, boilers, and other industrial and residential sources. These NOx emissions can drift hundreds of miles away from their point of origin, allowing one geographic location to affect an entire region.

VOCs, the specific focus of this new technology, are compounds that contain carbon that can volatilize to form an organic vapor in the air and participate in atmospheric photochemical reactions.[3] The major man-made sources of VOCs are industrial processes (46%) and automobiles (30%) (Noll 1999). VOCs are widely used as solvents in a large number of industrial processes because they evaporate into air leaving no residue.

The Clean Air Act will continue to be the pre-eminent driver of the VOC recovery and destruction market. The EPA and several states finalized many relevant and demanding regulations during the last few years, increasing the rate of growth in the pollution control markets to their highest levels (Frost and Sullivan 2003). Due to the nature of most industrial processes, one option to meet these air quality regulations is the installation of pollution control equipment. As we previously noted, the equipment is required to achieve at least a 95 to 98% VOC reduction rate from what would be released without pollution control equipment.

The largest end-users of VOC destruction and recovery equipment continue to be chemical, oil, gas, and lumber and wood industries (EPSI 2004). Specific industries that focus on VOC technologies include aerospace, semiconductor, printing, automotive, and generally all coating operations including can, wire, appliances, and furniture. In total, there are 104 industries subject to Clean Air regulatory requirements for VOCs including the subset list of 189 Hazardous Air Pollutants (HAPs).

There are a number of ways VOC emissions can be reduced to meet EPA limitations. New VOC abatement technologies including absorption, ultraviolet oxidation, and refrigeration/condensation equipment captured 17% of the total market in the year 2000 (EPSI 2004). Older, more mature technology segments growing more slowly include carbon

[1] This estimate is derived from calculations by Laitner (2007) and compared to ANWR production potential found in Koomey et al. (2003).

[2] Ozone occurs in two layers of the atmosphere. The atmospheric layer near the Earth's surface is the troposphere. Ground level or "bad" ozone is an air pollutant that damages human health, vegetation, and many common materials. It is a key ingredient of urban smog. Strong sunlight and hot weather cause ground level ozone to form in harmful concentrations in the air. The troposphere extends from ground level to about ten miles up, where it meets the second layer, the stratosphere. In the stratosphere, there is a "good" ozone layer that extends upward from about 10 to 30 miles, and this ozone protects life on earth from the sun's harmful ultraviolet rays.

[3] The following compounds are excluded from this list of volatile organic compounds: carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate.

adsorption, distillation, and air stripping equipment. Thermal oxidation captured 55+% of the total market in that year (EPSI 2004). Each method has its own benefits and limitations that may make them more desirable for certain applications. The applicability of a given technique is dependent on the physical and chemical properties of the pollutant and the characteristics of the exhaust stream.

VOC equipment companies are combining multiple technological processes to create unique solutions. Integrated pollution control systems have a strong potential for future growth. Pre-wired, pre-piped, pre-tested and certified systems reduce project costs, trading slightly higher integrated and functionally tested equipment costs for decreased field installation and start-up costs, and reduced site installation and maintenance problems.

Thermal Oxidation

Thermal oxidation, by definition, converts a hydrocarbon, in the presence of oxygen and heat, to carbon dioxide and water vapor. As we already indicated, this technology provides the greater part of the VOC control market and becomes the basis for estimating national benefits of the alternative control market based on the Gas Turbine Oxidation approach. A general equation showing this relationship is shown below (Rafson 1998):

$$c_n H_{2n} + (n + m/2) O_2 \Rightarrow n CO_2 + H_2O + Heat$$

The particular *n* and *m* subscripts of the equation are used to define the number of carbon atoms and hydrogen atoms. The amount of oxygen atoms present are converted to *n* molecules of carbon dioxide and *m* molecules of water vapor and heat, which is given off in the exothermic reactor. This last aspect, the exothermic nature of thermal oxidation, is a key to generating multiple benefits beyond mere pollution control.

There are three critical requirements to ensure combustion and destruction of the VOCs: time, temperature, and turbulence. Time refers to the retention time or residence time, which is the length of time that an organic is at the appropriate temperature to ensure proper VOC destruction. Typically, a residence time of 0.5 second is adequate to ensure at least a 95% destruction rate at the proper temperature. Temperature must be maintained in conjunction with time. As time is decreased, temperature will need to be increased and vice versa. A minimum temperature for VOC destruction is approximately 1400ºF. Turbulence implies an adequate level of mixing. By changing the configuration of the air stream, the inlet air to the destruct chamber is properly mixed to ensure complete combustion takes place. There are three different thermal oxidation processes. These include:

1. *Direct Flame Incineration:* A direct flame incinerator consists of only a combustion chamber with no heat recovery from the incinerator. Direct flame incinerators are the simplest type of thermal oxidizers. Direct flame incinerators have the advantages of minimum complexity and low cost, but, since they are typically used in applications with dangerous pollutants (explosive, corrosive, or poisonous), the overall system including the required safety equipment is typically very complex.
2. *Recuperative Thermal Oxidation:* The technique of recuperative thermal oxidation involves the recovery of energy produced by burning a support fuel to achieve VOC destruction using a primary or secondary heat exchanger to heat the incoming process air

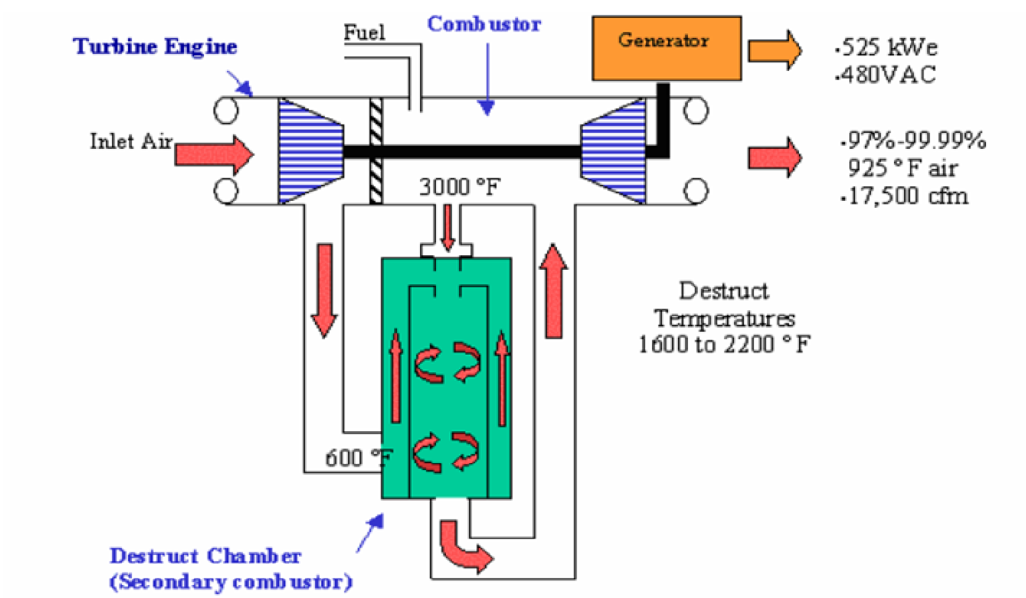
utilizing hot waste gases from the oxidizer. The exhaust gases from the oxidizer pass through a shell and tube or plate-type heat exchanger to recover the heat of combustion and increase the fuel efficiency of the VOC destruction process. Recuperative oxidizers are ideal for high VOC emission rates. A recuperative thermal oxidizer is generally able to recover 70% of the heat available from the oxidizer. Some units are designed with a secondary heat recovery unit to preheat air or water or heat transfer fluids for other plant processes such as drying ovens.

3. *Regenerative Thermal Oxidation:* Another type of thermal oxidizer is the regenerative thermal oxidizer, which appears to be the system of choice among industrial users. These systems are used when the contaminated air stream has a low concentration of VOC (< 1000 ppm) and/or large airflows. They also are used in industrial processes that require a high oxidation temperature. Regenerative oxidizers allow for better heat recovery than a recuperative oxidizer and diluted vapor streams can be incinerated at lower costs. Regenerative systems use beds of ceramic material as a heat sink. Once the ceramics are heated, the flow shifts and the post-combustion gas stream is used to heat up the second bed of ceramic material while pre-combustion air flows through the first hot bed gaining heat as it travels to the burner. Flow is shifted between the beds as they heat up and cool down. Heat transfer efficiencies of 95% can be achieved with regenerative units. The alternating sequence decreases the removal efficiency of the VOC. The overall removal efficiency can be as high as 99%, but typically is 98% (GTI 2003).

Gas Turbine Oxidizer

Another type of thermal oxidizer is a gas turbine oxidizer (GTO). As described in this paper, this technology provides the basis for generating both electricity and thermal energy as a byproduct of pollution control. The GTO consists of a turbine and a secondary combustion chamber for thermal destruction of production process or waste volatile organic compounds and hazardous air pollutants emissions including renewable hydrocarbon fuels and other organic materials within an air stream.

Figure 1. Schematic Drawing of Gas Turbine Oxidizer



As shown in Figure 1, the VOC-laden air, combined with ambient atmospheric concentrations of oxygen (20.9%) is compressed within the gas turbine engine's compressor section to approximately 132 psig or 9 atmospheres. This raises the VOC-laden air temperature to 600°F. This air enters a patented VOC destruction chamber where it is mixed with the 3000°F combustion products from the turbine combustor. The resultant air (now ~ 1850°F, but in the range of 1600–2200°F) travels in a cyclonic fashion inside the destruction chamber. This cyclonic action allows for good mixing and a residence time of approximately 0.44 seconds in which the VOCs oxidize into carbon dioxide and water. This "clean" air stream enters the turbine combustor where it is mixed with fuel and ignited, creating temperatures ~ 3,000°F. This high-energy air is routed through the turbine section of the engine where the air is quickly cooled to 925°F, creating a significant airflow that rotates the turbine shaft. This shaft is connected to a generator that produces electricity (approximately 525 kWe) (GTI 2003).

Gas turbines have several advantages to their design. Due to their high operating temperatures, large amounts of heat are available for recovery. This heat can be used for other plant processes and/or pretreatment of air into a VOC concentrator, which will allow for more VOC destruction within the turbine. The unit is also able to generate electricity, which can be used to power other plant equipment. The footprint of the system is smaller than other VOC destruction technologies. The turbine itself is durable and should last much longer than other technologies.

System Performance

Although the GTO system requires a higher cost outlay, the lower annual operating costs, together with the credits associated with heat recovery and electricity generation, indicate a highly cost-effective system. As summarized in Table 1, the generic cost characterizations suggest a simple payback on the order of 2.6 years (Laitner 2007).

Table 1. Cost and Performance Characterization

	RTO System	**EPSI GTO System**
Total Capital and Project Costs	$1,800,000	$3,200,000
Total Annual Costs	$390,000	$155,000
Fuel and electricity	$276,000	$326,675
Maintenance	$35,000	$25,000
Administration	$94,000	$90,000
Refurbishment fund	$261,000	$40,000
Total Annual Credits	$0	$295,000
Electricity generation	$0	$117,000
Heat recovery	$0	$178,000
Simple Payback Period	None	2.6 Years
Return on Investment		38%

The higher capital costs associated with the GTO system include system costs associated with the generation of electricity and thermal energy. At the same time, the system design reduces annual operating costs (especially depreciation and normal wear and tear, or what we call "refurbishment costs"). The design also anticipates slightly increased natural gas purchases but substantially reduced electricity costs. Most important are the revenues or credits earned through the generation of electricity and process heat or steam.

Assuming a 525 kW unit operating at 63% capacity factor (or 5520 hours per year), and subtracting 35% parasitic or ancillary loads needed to safely operate the system, the GTO unit will provide 1.9 million kilowatt-hours (kWh) of electricity. Priced at 6.2 cents per kWh implies an electricity credit of $117,000 annually. At the same time, the potential for waste heat recovery approaches 25 billion Btu per year for this same unit. If purchased from local utilities at $7.2 per million Btu, this implies an even bigger annual credit of $178,000. The higher capital costs, then, are clearly offset by reduced annual operating costs and a sizeable credit for both electricity and heat. So what is now possible through a technology redesign is to convert a pollution control technology into a new system that provides a new source of combined heat and power operations that pays for itself in two to three years.

Size of Opportunity

The GTO-VOC technology will compete with other abatement equipment and with CHP systems on the basis of quality, price, and service. However, there are no industry players that supply VOC destruct chambers for gas turbines. North American penetration of this market segment is zero percent and recent technological and design advances in environmental/cogeneration by EPSI have set the stage for making significant inroads against the incumbent VOC destruct only suppliers. With over $2 billion in North American annual sales, this market segment is expected to provide significant growth for EPSI over the next ten years. But to evaluate the potential for market penetration, we provide a closer look at the economics of the GTO-VOC system.

EPSI will compete in a $200 billion North American market (Frost and Sullivan 1995) for air pollution control solutions. It is estimated that there are over 100,000 VOC destruct devices with annual turnover of $13 billion. Growth in this market is being driven by the need for 104 discrete industries subject to EPA-regulated control of environmental pollution and is estimated at 7% annually. EPSI's approach is to target these existing thermal oxidizers with its GTO products. EPSI's value proposition to replace these existing thermal oxidizers is its high VOC destruct efficiency, utilization of the useful byproducts of the destruction process (electricity and heat), and its low maintenance costs. This value proposition provides the customer with an attractive return on investment on the EPSI system as shown below. An additional investment of $1.4 million in the EPSI technology will generate annual cash flow of $530,000, a return on investment of 38% and a payback of 2.6 years. This provides an excellent return compared to a technology now used only as a pollution control strategy.[4]

Perhaps just as exciting as the attractive return on investment, the GTO system can deliver a sizeable reduction in the nation's total primary energy supply. If we assume that just

[4] By way of comparison, the EPSI developers cite a configuration that provides a payback as low as 1.6 years (EPRI 2006). These are based, in part, on 2004 costs and energy prices. Special design and installation requirements together with changes in energy prices will, of course, vary these results.

60% of the existing 100,000 VOC destruct devices are converted to the GTO-VOC technology over the next 15–18 years, the primary energy savings from the avoided electricity generation and the reduced thermal energy requirements might exceed 1.25 quads. This is about the same as the anticipated annual average production from the Alaska National Wildlife Refuge[5] and about 2% of current electricity generation. Hence, we have a cost-effective technology redesign that moves pollution control into a significant energy supply opportunity.

Further Discussion

The EPSI system's ability to generate electricity, provide recoverable heat for use beyond the VOC destruction process, and its ability to operate within a large temperature band to destroy VOC more efficiently and completely differentiates it from other pollution control technologies currently available in the market. The development of the 480 VAC synchronous generator component is critical to the success of the EPSI product, as it will provide a sufficient load to the turbine independent of the local electric utility's grid status, assuring combustion temperature for VOC destruction. It will also enable the EPSI system to function as an emergency generator (utilizing the EPSI system's electric output) to power the exhaust fans that move the VOC laden air stream, avoiding the potential of VOC build-up (a potential explosion hazard) that could occur with loss of the local utility grid and the use of an RTO.

The ability to quickly achieve VOC destruction temperatures from a cold start position is another advantage over RTO technology. Based on the information supplied by the RTO manufacturer and the end-user's data, the RTO requires one to eight hours to achieve proper temperatures from a cold start position. The GTO should be able to achieve destruction temperatures within minutes.

Based on the information gathered by the end-user, the major overhaul frequency of an RTO (50 to 60 SCFM) is between seven and ten years, at a cost of approximately $250,000. This amount is almost three times higher than EPSI's estimates for the GTO. One unknown with the GTO is the impact particulate or foreign matter will have on the turbine if inlet air scrubbing and filtration is not used appropriately. When particulate begins to collect on an RTO, its performance will begin to degrade. On the other hand, depending on the type and the amount of particulate, the turbine of the GTO may become damaged, possibly inoperable if corrosives or particulates are not addressed for gas turbine protection.

After reviewing all the information, a number of advantages and disadvantages might be noted. Advantages of the EPSI GTO system over standard (tower type) RTO include:

- Shorter initial cold start-up time (5 minutes versus 1 to 8 hours)
- Recoverable heat for use by end-user (RTOs use their heat in the VOC abatement process)
- Electrical power generation
- Higher combustion temperature (which in combination with high residence time, assures more complete destruction of VOC)
- Smaller equipment footprint
- Lower major overhaul cost
- Short-term return on investment

[5] For a review of the "fully-risked" market production potential of ANWR, see Koomey et al. (2003).

The disadvantages of EPSI system when compared to standard (tower type) RTO include the following:

- Airflows greater than 6,200 scfm, which need to be treated, requiring a VOC concentrator
- Although based on the proven ASE™8 gas turbine (there are over 500 units installed in the field), this is a new product (the secondary combustor is the new component), whereas hundreds of RTOs have been installed and are in use.
- Greater local consumption of natural gas (although likely producing a significant net primary energy savings at the regional or national level).

Using the electricity the GTO can produce, it may also be possible to use the energy to purge the VOC stream ductwork (in the event of loss of the local electric grid) to minimize or eliminate the potential of VOC buildup, which would increase plant safety. One final note is that the EPSI system reviewed here is based on a 525 kW system. The implementation of the concept, using a larger turbine (for example, in the 2 to 5 MW range) would improve system economics by eliminating the need for a concentrator, obtaining a greater amount of usable electrical power and a greater amount of recoverable heat.

Conclusions

A significant part of current VOC pollution control strategies depend on the classic "end of pipe" technologies. Yes, the air pollutants are effectively destroyed but there is little further benefit associated with the VOC destructive process. As this paper asks, what if the redesign of such systems made it possible to produce useful by-products beyond the usual "control-only" designs? Based on the discussion in this paper, the evidence suggests that a new integration and technology design, such as that illustrated by EPSI system, can provide a more thorough destruction of VOC compounds due to its higher temperature variable thermal oxidation process (compared to an RTO) while simultaneously generating electricity and delivering supplemental thermal energy. This latter capability makes the GTO-VOC technology a better choice of the two pollution control devices. Perhaps more important from a climate or energy policy perspective, however, the development of waste-to-energy technologies can also reduce overall primary energy consumption within the industrial sector (Bailey and Worrell 2005). This has clear benefits with respect to overall economic competitiveness as well as climate change policies.

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