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Survey of Control Technologies for Low Concentration Organic Vapor Gas Streams

CONTROL TECHNOLOGY CENTER

Sponsored by

Information Transfer and Program Integration Division
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
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Prepared by:

Robert A. Zerbonia
James J. Spivey
Sanjay K. Agarwal
Ashok S. Damle
Charles W. Sanford
Research Triangle Institute
Research Triangle Park, NC 27709

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Project Manager

Robert J. Blaszczak
Information Transfer and Program Integration Division
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Prepared for

Control Technology Center
U.S. Envionrmental Protection Agency
Research Triangle Park, NC 27711

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PREFACE

The Control Technology Center was established by the U.S. Environmental Protection Agency's (EPA's) Office of Research and Development (ORD) to provide technical assistance to State and local air pollution agencies. Several levels of assistance can be provided when appropriate. These include the following:

- **CTC HOTLINE** provides quick access to EPA expertise, information, and assistance on matters relating to control technology (919/541-0800).
- **Engineering Assistance Projects** provide more in-depth assistance to State and local agencies when needed to address a specific pollution problem or source.
- **Technical Guidance Projects** address problems or source categories of regional or national interest by developing technical guidance documents, computer software, or presentation of workshops on control technology issues.
- **Federal Small Business Assistance Program (SBAP)** coordinates efforts among EPA centers participating in the Federal Small Business Assistance Program to assist State SBAPs.
- **RACT/BACT/LAER Clearinghouse (RBLC)** bulletin board system (BBS) provides access to more than 3,100 pollution prevention (P2) and control technology determinations addressing over 200 pollutants. Select the RBLC from the technical BBS menu on the OAQPS Technology Transfer Center (TTN) BBS (919/541-5742).
- **CTC BBS** on the OAQPS TTN provides around-the-clock access to all CTC services, including downloadable copies of many CTC products. Select CTC from the TTN BBS Technical BBS menu (919/541-5742).
- **CTC NEWS** is a quarterly newsletter published by the CTC. It contains updates on all CTC activities including the RBLC and Federal SBAP. Call or write the CTC to get on the CTC NEWS mailing list.

This document was funded by EPA's Control Technology Center and prepared by Research Triangle Institute (RTI). This document is the result of a request for technical assistance from the State and Territorial Air Pollution Program Administrators and the Association of Local Air Pollution Control Officials (STAPPA/ALAPCO) to identify control technologies that are effective on treating gas streams with low concentrations of volatile organic compounds (VOC) and/or organic hazardous air pollutants (HAP). This document presents the results of a series of studies conducted to identify commercially available control technologies applicable to low organic concentration gas streams. Technical and economic background information relevant to the control technologies is presented by technology type. Performance of the air pollution control devices is documented in the form of source test reports or permits issued by State or local air pollution control agencies. The document with the information and data presented provides the basis for evaluating the availability and efficacy of air pollution control devices in reducing organic emission in low concentration, high flow rate gas streams.

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INTRODUCTION

1.1 BACKGROUND

A commonly applied approach to control of organic vapor emissions from stationary or point sources is the application of add-on control devices. Several different air pollution control technologies can be applied to sources of organic air emissions (once they are covered, enclosed, or vented) to recover or destroy the pollutants. In general, application of a particular technology depends more on the emission (gas) stream under consideration than on the particular source type. Selection of applicable control techniques for point-source organic emission abatement is made for the most part on the basis of stream-specific characteristics and the desired control efficiency. A key stream characteristic that affects the applicability of a particular control technology is the concentration of organics in the gas stream.

This document presents the results of a series of studies conducted to identify commercially available control technologies suitable for application to low organic concentration gas streams. Initially, OAQPS's Emmision Standards Division conducted a study to survey and document the performance of control technologeis applicable to gas streams containing low concentrations (i.e., less than 100 ppm) of organic vapors[1] (see EPA-RTI contractor report, "Survey of Control Technologies for Low Concentration Gas Streams," Research Triangle Institute (RTI) September 1993). The study also evaluated technical and economic aspects of control systems specifically designed for low organic concentrations. To the extent possible, results of source tests reflecting operation of the control technologies at actual facilites were used as the primary source of documentation of performance. However, at that time, there was very little available information on field tests of technologies in use on low organic concentrations gas streams. In many cases, manufacturers claims on the effectiveness of the technologies were not supported by test data. As a result, the actual test data included in the original report were limited. In this first phase of the work, information and data were obtained from various offices within the EPA including the Office of Air Quality Planning and Standards; the Office of Research and Development, and the Office of Solid Waste; the EPA Regional Offices; several State and local air pollution control agencies; and numerous equipment manufacturers and vendors. Appendix A presents a list of the organizations contacted regarding control technologies for gases containing low organic concentrations.

As a continuation of the initial work in this area, the EPA's Control Technology Center (CTC) supported a study to identify control technologies that have been documented effective on low concentration/high volume flow streams. The work was presented as an appendix to the original report, i.e., Identification of Permitted Control Technologies for Low Concentration Gas Streams, as a continuation of EPA's work in this area and utilized the material and knowledge gained in compiling the original report, (i.e., “Survey of Control Technologies for Low Concentration Gas Streams,” RTI, September 1993). The object of the second phase of the study was is to identify permitted control devices that have been installed and demonstrated to be effective for low concentration organic vapor (OV) gas streams, particularly those with high air flow rates. Low concentration is assumed to mean 100 ppm or below, although some control devices currently controlling higher OV concentrations are included if they are feasible for lower concentration OV gas streams or are of particular interest. High flow rates are assumed to be those above 100,000 cfm, although some devices currently controlling lower flow OV gas streams are included. The demonstration of control device performance is either in the form of source test reports or permit conditions issued by State or local air pollution control agencies. In this second phase of the study, information and data were obtained primarily from two sources. First, equipment manufacturers and vendors were contacted in order to identify locations where low concentration/high flow rate devices have been installed and tested. Next, State and local air pollution control agencies were contacted to request both permit and source test information on these particular devices.

Permitted control devices are presumably associated with Federally enforceable pollutant reductions, and include devices that are installed on full-scale facilities rather than bench-scale applications. Devices installed pursuant to a consent order prior to permitting are also included.

The performance of some of these air pollution control devices has been documented through a compilation of source tests and those results are summarized under the appropriate technology. Source tests in most cases were conducted using reference or equivalent methods, and observed by a representative of an air pollution control agency. Performance results obtained by other test methods are also included in the final report, and such results are noted; however, a rigorous evaluation of each testing protocol was not made as a part of this study.

1.2 SCOPE

Although there are a number of control technologies in use for gases with high organic concentrations, not all are applicable at low concentrations. There are also other technologies which, in principle at least, can remove or destroy organic vapors from gas streams but are less cost effective at low concentrations. For the purposes of this document, technologies such as membranes and recuperative thermal oxidation systems fall into this category. For example, recuperative thermal oxidation is very useful for control of hydrocarbon gases at inlet concentrations of around 1,500 to 3,000 ppm because the heat of combustion of these gases is sufficient to sustain the high temperatures required without addition of expensive auxiliary fuel. At 100 ppm, however, large amounts of auxiliary fuel are needed and recuperative thermal oxidation, though in principle an effective control technique, generally is not economically feasible. Biofiltration, though perhaps applicable to low organic concentration gases, is also not within the scope of this study.[2] A brief description of the biofiltration process is included in Section 5.0 for background information. The technologies that were evaluated for this document include the following:

- incineration
  - catalytic
  - regenerative thermal

- adsorption
  - nonregenerable
  - modified regenerable (including adsorption/incineration)

- absorption

- other commercial technologies
  - UV/ozone catalytic oxidation
  - enhanced adsorption

- emerging technologies
  - corona destruction
  - heterogeneous photocatalysis.

The results of the studies are summarized and presented in this document by technology beginning in Section 2.0. In general, the overall performance of the control technologies was found to be poorly documented relative to EPA standards. For example, the lack of rigorous analyses (using test data) of the inlet and outlet gas compositions in all but a few cases makes a comprehensive evaluation of these technologies difficult.

The cost-effectiveness ($/ton OV removed) of these technologies was calculated using the model gas streams and general methods described by the OAQPS Control Cost Manual.[3] Though cost information for model streams was requested from vendors of all technologies, responses were few. Therefore, to compare the technologies on a common basis, capital and operating costs were calculated using published values and vendor-supplied cost factors to the extent possible on four model gas streams. These were 100 and 10 ppm benzene in air and 100 and 10 ppm tetrachloroethylene in air, all at a flow rate of 10,000 scfm. Estimates of total annualized cost for the various technologies based on the model gas streams are presented in Appendix B.

Because of the uncertainty associated with both the emission reduction and the costs, the accuracy of the cost-effectiveness values in some cases is probably no better than order of magnitude and thus conclusions should not be drawn about relative cost effectiveness when differences are small, e.g., between regenerative thermal incineration and regenerable fixed-bed adsorption for 100 ppm benzene. Overall, cost-effectiveness values range from $2,000 to about $67,000 per ton of OV removed (in 1991 dollars). These relatively high values reflect the very dilute concentrations of interest. As expected, cost-effectiveness values are much higher for lower concentrations.

1.3 CONCLUSIONS

1. The control of low concentration organic gas streams is currently one of the most dynamic segments of the air pollution control technology industry. The technologies as well as their applications are undergoing rapid change and development. Since originally compiling the information and data for this document, performance data have become more available and most recent indications are that the cost-effectiveness of some of the technologies has improved. For this reason, some of the data and information in the document may be outdated.

2. Commercially available technologies exist for control of gas streams containing less than 100 ppm OV. Destruction and removal efficiencies >99 percent have been demonstrated at a number of sites for each of the technologies discussed here. As expected, the lower the concentration the higher the cost-effectiveness of the controls.

3. Based on the number of commercial installations, adsorption-based processes are most widely applicable to low concentration gases. A recent development by several vendors is the pairing of adsorption and desorption steps that concentrate the OV with a separate step to treat the concentrated OV. These systems are specifically designed for low concentrations.

4. Concentrating adsorption systems (including but not limited to rotary carbon or zeolite absorbers from Dürr and Munters Zeol) are increasingly proposed by vendors in conjunction with incinerators (or other devices) to control low concentration, high flow OV streams. These adsorption systems are more widely demonstrated in Europe, probably because of more stringent regulations.

5. In addition to adsorption-based processes, other technologies are being used specifically for low concentration gases. These include absorption/stripping process and UV/ozone catalytic oxidation. Preliminary evaluation suggests that absorption may be competitive with the more widely used adsorption-based processes at concentrations close to 100 ppm. Insufficient cost information was available to evaluate the cost effectiveness of UV/ozone technologies.

6. Thermal or catalytic incinerator systems with regenerative heat recovery are being proposed more widely by vendors. Regenerative heat recovery is often more cost effective than recuperative heat recovery for systems with flows above 50,000 scfm.[4] A number of combinations of these regenerative systems are available, although not all are demonstrated at the concentration (and flow rate) examined in this study. Pure thermal oxidizers without heat recovery were not proposed for low concentration, high flow OV streams by any vendor contacted.

7. There is a trend for vendors to collaborate on proposal to provide “best-of-breed” combinations of devices to make up a (case-specific) control system. An example of this is a system proposed using a Dürr rotary concentrator, an Anguil recuperative incinerator, and

a Johnson Matthey catalyst. Numerous such systems are proposed and are available with a performance warranty.

8. The development of these modified or hybred systems and devices is proceeding at a rapid pace. These devices are generally installed on new sources or existing sources affected by newly implemented regulation, and so this rapid technological development appears to be largely driven by the implementation of new and existing regulations.

9. Twenty-five (25) control devices for low concentration, high flow OV gas streams are currently known to exist in the U.S. All are either permitted, being permitted, or installed under a consent order. Documentation in the form of permits and source test results was requested for all these devices. A table containing the relevant details on these devices (e.g., inlet concentration, flow-rate, industrial application, and location) is provided in Appendix C.

10. A need exists to more rigorously document the performance of field systems. Reliable and complete inlet/outlet gas composition measurements taken at conditions of practical interest are scarce. Data reported on many field tests are incomplete or inconsistent. In addition, the acquisition of performance data on these devices was hindered by the reluctance of some vendors to disclose the identity of their clients, and the limited access to state and local air pollution control agencies's files.

1.4 RECOMMENDATIONS

1. Further research on documenting the performance of control devices for low concentraiton OV streams with high flows should be conducted; this would include continued gathering of information on field tests of technology in use on low organic concentration gas streams, especially those with high flow rates. Much of the information requested was not received. Therefore, collection of additional permit information and field test data will likely require commitment of resources, e.g., it may be necessary to travel to various local, State, or regional air offices to collect the information directly. Visits to a few State and local air pollution control agencies may be the quickest and least expensive method of gathering such data if detailed and/or extensive documentation is desired.

2. Several of the technologies applicable to low concentration, high flow streams now have a better defined cost history. The capital and annual operating costs reported in the original study were, in large part, based on either EPA estimates or vendor estimates because of the limited number of these technologies in actual field applications in 1991. The number of these devices in full scale operation has dramatically increased over the past few years and many of these technologies now have several years of operating history. Updated capital and operating cost information could be obtained that would better reflect current actual costs. Additional cost effectiveness studies also could be performed to determine which technologies are most cost-effective for low OV concentrations and high gas flow rates. This may involve formally requesting vendors to develop quotes. Detailed costs were not available for the modified regenerable adsorption systems. The fact that they are being commercially used does, however, suggest that they are of comparable cost

to the conventional regenerable systems.

3. Consideration should be given to conducting field tests of some demonstrated devices to better document performance at realistic conditions and as a means of broadening the concept of availability (for use during standards setting). The modified (or hybred) adsorption systems and the alternative design, i.e., horizontal flow, regenerative thermal oxidizers appear to be good candidates for performance testing.

4. There is an increasing number of technologies being applied to control of indoor air pollution in large buildings (e.g., the ozone/catalyst system developed by Union Carbide[5,6]). The very low concentration of indoor air contaminants (typically around 1 ppm) and large flow rates in buildings make these technologies of interest for study. However, these technologies were not evaluated as a part of this study, though they may be of particular interest for concentrations near 1 ppm OV.

SECTION 2

INCINERATION

Incineration is an oxidation process which ideally converts organic compounds, whether hydrocarbon or oxygenated, to CO_2 and H_2O. If the organic is halogenated, the corresponding halogen acids will be formed as products of combustion. Incineration is widely used for the destruction of a wide variety of OV. It is best suited to applications where the gas stream has a consistent flow rate and concentration. There are two main types of incinerators: thermal and catalytic. In thermal incineration, the OV-containing stream is heated to very high temperatures to oxidize the organic compounds in the gas phase. In catalytic incineration, a catalyst promotes the oxidation reaction on its surface (i.e., solid-gas interface) at lower temperatures by providing alternative reaction pathways that have faster rates than the corresponding gas-phase reactions. A thermal incinerator burns the OV at very high temperatures, usually in the 750 to 1,000 °C range; catalytic incinerators operate between 350 and 500 °C.

To save fuel, a heat exchanger often is used to recover the valuable heat generated during incineration by preheating the inlet gas. Thermal incinerators without heat recovery are not known to be used to control high flow, low concentration OV gas streams. This is due to the high rate of fuel consumption in pure thermal systems when compared to systems using heat recovery or catalysis. Numerous companies such as the John Zink Co.[7] (now including McGill) market small thermal incinerators for the control of low concentration OV gas streams, but they are typically for low flow applications such as small air stripper outlets.

Depending upon the type of heat recovery unit, incinerators are further classified as (1) regenerative or (2) recuperative. Thermal and catalytic oxidizers are available with or without recuperative or regenerative heat recovery. Regenerative thermal incinerators consist of a flame-based combustion chamber that connects two (or three) fixed beds containing inert (e.g., ceramic) packing. Incoming gas enters one of the beds where it is preheated. The heated gas flows into the combustion chamber, burns, and the hot flue gases flow through the packed beds which capture, store, and permit recovery of the heat generated during oxidation. The packed beds store the heat energy during one cycle and then release it as the beds preheat the incoming OV-laden gas during the second cycle. Up to 95 percent of the energy in the flue gas can be recovered in this manner. The packed beds, in effect, are direct contact heat exchangers.

A recuperative thermal incinerator uses a shell and tube heat exchanger to transfer the heat generated by incineration to preheat the feed stream. Recuperative thermal incineration has a much lower thermal efficiency and as a result it is far less economical for low OV concentrations. The lack of recuperative thermal incinerators in high flow, low concentration OV streams is probably driven by the high operating costs for these systems.

Recuperative thermal incineration is not considered further in this document. The regenerative thermal incinerator is better suited for low concentration OV streams because its higher thermal efficiency makes it more economical at low OV concentrations[8]; these systems are discussed in Section 2.2.

Catalytic incinerators modify the flame-based incinerator concept by adding a catalyst to promote the oxidation reaction, allowing faster reaction and/or reduced reaction temperature. This may allow more cost-effective operation at low OV concentrations than even regenerative thermal incineration. A faster reaction requires a smaller vessel, thus reducing capital costs; and low operating temperatures generally reduce auxiliary fuel requirements, thus reducing operating costs. Catalytic incineration, however, is not as broadly applicable as thermal incineration because of its greater sensitivity to pollutant characteristics and process conditions. Design and operating considerations are therefore critical because the catalyst may be adversely affected by high temperatures, high concentrations of organics, fouling from particulate matter or polymers, and deactivation by halogens or certain metals.

2.1 CATALYTIC INCINERATION

Figure 2-1 shows the schematic of a catalytic incinerator system.[9] The OV-containing gas is first indirectly preheated by the exhaust gas. For the low concentrations of interest here, supplemental fuel is used to further preheat the gas, usually in an open flame burner, to the reaction temperature. The gas then passes over the catalyst, where the OV is oxidized. The operating temperature to achieve a particular destruction efficiency depends on the concentration and composition of the OV in the emission stream and the type of catalyst used. Commercial catalysts usually consist of noble metals or metal oxides. The type of catalyst used depends on the type of OV. For example, some noble metal catalysts may be poisoned by chlorinated OV, even at the very low concentrations of interest here. In such cases metal oxides that are more resistant to halogenated compounds must be used.

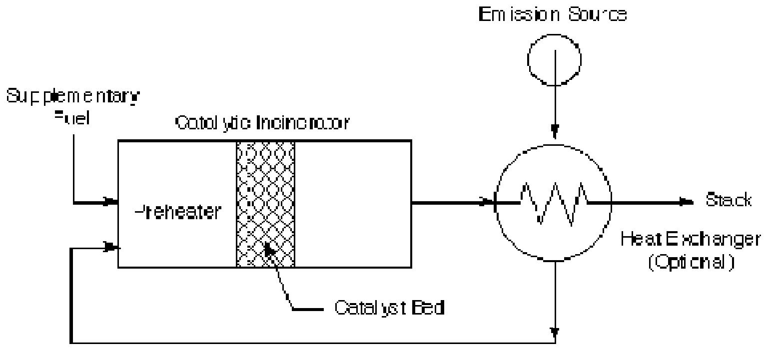


Figure 2-1. Schematic Diagram of a Catalytic Incinerator System

Several companies market catalytic incinerators for OV destruction. These companies include ARI Technologies, Wheelabrator, Hunington Energy Systems, Anguil, Monsanto Enviro-Chem, CSM, Amcec, Alzeta, and Thermo Electron. However, the only information obtained on systems used for concentrations less than 100 ppm is for units made by ARI Technologies, Inc. (Palatine, IL). This group of companies markets a full range of incinerators, including the fluidized bed Econ-Abator® catalytic oxidizer. These systems are available with recuperative heat exchangers for smaller flows, and regenerative heat exchangers for larger flows. Other vendors of catalytic incinerators were contacted, but none reported having field units operating on gases with OV concentrations less than 100 ppm. Table 2-1 shows the available information on catalytic incinerators used for OV concentrations less than 100 ppm. No ARI systems are known to be installed in the U.S. on high flow, low concentration organic vapor streams.[14] (Note: The permit for the 3M Company's facility in St. Paul (No. 23GS-93-0T-1)[15] lists an ARI, Econ-Abator fluidized bed catalytic oxidizer as in-use control equipment. The unit is listed as having a 95% design construction efficiency and an exhaust (stack) gas flow rate of 19,511 scfm (43,774 acfm at 680°F). This unit serves several emission units at the plant that are reported in the permit as Emission Point No. 2.

Table 2-1. Summary of Field Studies of Catalytic Oxidation for Control of Gases with less than 100 ppm Inlet OV Concentration

Vendor	Site	Gas flow (scfm)	Inlet concentration (ppm)	Outlet concentration (ppm)	Destruction/ removal efficiency (%)	Comments/ Reference
ARI	Mobile Unit[a]	500	3-200	NR[b]	72-98	Six gas streams tested; Palazzolo et al., 1986[10]
ARI	Wurtsmith AFB, MI[c]	1,200	1-2	0.01	98-99	Major contaminant is trichloroethylene; Hylton, 1990[11]
ARI	Wurtsmith AFB, MI[c]	1,200	2.1	.072	96.6[d]	Different feed gases from groundwater air stripper; Hylton, 1990[12]
ARI	McClellan AFB, CA	348-691	6-44[e]	.05-0.3	>99	Paint spray booth emissions; Ritts, et al., 1990[13]

[a] Pilot scale tests conducted in RTP, NC, using a mobile unit.

[b] Not reported.

[c] Unit was tested on several gases from an operating air stripper.

[d] These are results for a second test at this site using a different feed which contained benzene, toluene, and three C_1 - C_2 chlorocarbons plus one CFC.

[e] Calculated assuming an average molecular weight of 80. Feed consisted of hydrocarbon and oxygenated hydrocarbon compounds. Up to 100 ppm CO was present in the exhaust.

2.1.1 ARI's Fluid-Bed Catalytic Incinerator

ARI markets a fluid-bed catalytic incinerator for OV oxidation. This system uses a chromia-alumina catalyst suitable for oxidation of both hydrocarbons and halogenated compounds. The catalyst is in the form of small beads through which the gas passes in an upward direction. Figure 2-2 shows a schematic of the unit which, in principle, is similar to other catalytic processes as shown in Figure 2-1, the only difference being that the gas flows upward through a fluid bed of catalyst. The gradual attrition of the catalyst is claimed to avoid catalyst deactivation by continually exposing fresh catalyst surface. The purchased equipment costs of the ARI units are somewhat higher than fixed-bed units of the same size,[16] but the ARI catalyst is one of the few commercially available that is designed to oxidize chlorinated OV.

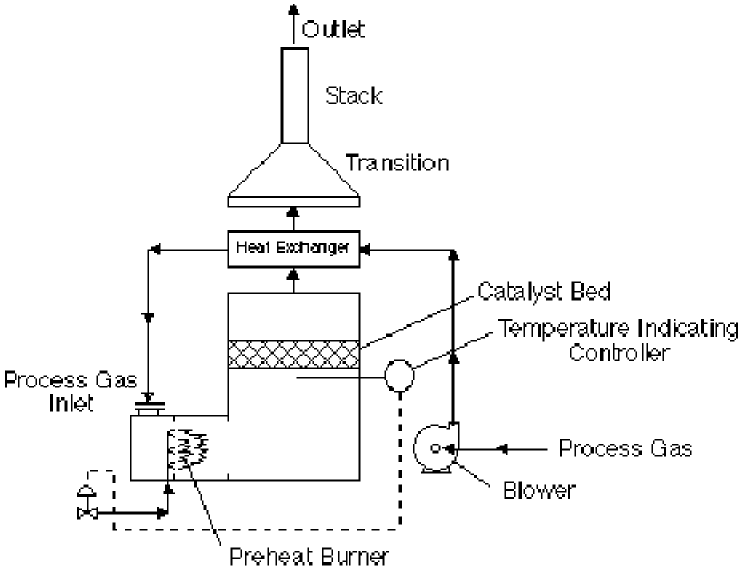


Figure 2-2. ARI Fluid-Bed Catalytic Incinerator

2.1.1.1 Pilot Plant Tests

ARI's fluidized bed has been tested for the destruction of low concentration OV streams.[17] The particular system was designed to handle 500 scfm. Various feed streams with inlet OV concentration ranging from 3 to 200 ppm were investigated to determine overall destruction efficiency. Two types of feedstreams were studied: one containing only chlorocarbons and the other containing a mixture of hydrocarbons and trichloroethylene. Table 2-2 summarizes the composition of the five streams used in this work.

Table 2-3 presents the destruction efficiencies for the different feedstreams that are less than 100 ppm as a function of space velocity and inlet temperature.

Table 2-2. Feed Stream Composition (in ppm) Tested Using ARI System

Compounds	Mixture 1	2	3	4	5
Trichloroethylene	6.3	2.7	1.8	10	50
1,2 Dichloroethylene	8.5	-	-	-	-
Vinyl chloride	-	-	7.5	-	-
1,2 Dichloroethane	-	-	-	10	50
1,1,2-Trichloroethane	-	-	-	10	50
Tetrachloroethylene	-	-	-	10	50
Benzene	-	1.5	-	-	-
Ethylbenzene	-	5.6	-	-	-
Pentane	-	11.5	-	-	-
Cyclohexane	-	14.1	-	-	-
Total concentration	14.8	35.4	9.3	40	200

Table 2-3. Destruction Efficiencies for the Different Mixtures Using ARI System

Mixture[a]	Feed concentration (ppm)	Space velocity (h^{-1})	Temperature (°F)	Destruction efficiency (%)
1	13.1	10,300	648	86
	16.7	10,100	792	93
	19.2	6,840	794	95
2	39.1	10,800	654	93
	40.8	10,500	807	98
	33.3	7,790	653	96
3	12.4	11,300	648	89
	9.92	10,500	947	98
	10.7	7,350	656	92
4	50.2	10,600	653	72
	57.1	10,200	953	96
	42.2	7,430	649	75

[a] It is assumed that slight differences in the total feed concentration between these mixtures and the compositions given in Table 2-2 simply reflect the slight differences in various gases blended to make the mixture. Results for mixture 5 are not present because the concentration is greater than 100 ppm.

In general, the trend shows increasing destruction efficiency with increasing temperature and decreasing space velocity, as would be expected. The highest destruction efficiency was observed for mixture 2, containing mostly hydrocarbons, and the lowest efficiencies were observed for mixture 4, containing mostly chlorocarbons. This reflects the generally more rapid oxidation of hydrocarbons compared to chlorocarbons. The effect of feed concentration and temperature on the destruction efficiency was also investigated in this work. Table 2-4 shows that the destruction efficiency for this technology is independent of the inlet concentration, i.e., similar destruction efficiencies are observed even when the feed concentration is varied by a factor of 4 at both temperatures studied.

In addition to the total oxidation products, some incomplete oxidation products were observed in the effluent stream. For example, oxidation of mixture 3 produced 1,1,1-

trichloroethane (0.03 ppm) and tetrachloroethylene (trace to 0.01 ppm). Similarly oxidation of mixture 4 produced 0.09 to 0.73 ppm of 1,2-dichloroethylene. Formation of such partial oxidation products is possible in all incineration processes, though such products are particularly hard to detect at the low inlet concentrations of interest here.

2.1.1.2 Wurtsmith Air Force Base

The Wurtsmith Air Force Base has been operating an ARI fluidized-bed catalytic incinerator to treat contaminated air produced from groundwater air strippers.[18] The incinerator, designed to treat 1,200 scfm, has been fully operational only since October 1989. The major contaminant present in the feed gas stream is trichloroethylene (TCE) at inlet concentrations of 1 to 2 ppm.

Table 2-5 summarizes the trichloroethylene destruction efficiency as a function of temperature. Significant destruction of TCE was obtained in the preheater, which is an open flame natural gas burner. The overall destruction efficiency (in the preheater and in the incinerator) was greater than 98 percent at all temperatures. Small quantities of some additional compounds including benzene, toluene, and 1,2-dichloroethylene were also observed after the incinerator. These may be products of incomplete combustion of TCE or could have been observed in the stack analysis (and not in the inlet analysis) because of the higher sensitivity used during this analysis.

Table 2-4. Effect of Inlet Concentration and Temperature on Destruction Efficiency for ARI System

Catalyst temperature (°F)	Space velocity (h^{-1})	Feed concentration[a] (ppm)	System destruction efficiency (%)
653	10,600	50.2	72
660	11,200	192	72
953	10,200	57.1	97
953	10,200	216	95

[a]Feed composition in all 4 tests consists only of equimolar concentrations of the 4 chlorocarbons shown in Table 2-2 for mixtures 4 and 5.

Table 2-5. Catalytic Destruction Efficiency for Trichloroethylene Conducted at Wurtsmith AFB using ARI's Fluidized-Bed Catalytic Incinerator

Temperature (°C)	Concentration (ppm)		Destruction efficiency (%)		
	Feed	Preheater	Stack	Preheater	Overall
370	1.36	1.01	0.012	25.6	98.1
425	1.05	0.04	0.011	20.0	98.9
480	2.09	0.40	0.009	80.9	99.6

Tests were conducted at this facility to investigate the catalyst activity with time-on-stream at 370 °C. The feed stream consisted mainly of TCE with small quantities of benzene, toluene, 1,2-dichloroethylene, trichlorofluoromethane, 1,1,1-trichloroethane and chloroform.

Table 2-6 summarizes the destruction efficiencies for the various OV. While the destruction efficiency for TCE was 97 percent, it was negative for benzene and trichlorofluoromethane suggesting that some of these compounds may be produced during oxidation. The total destruction efficiency was 96.6 percent. The catalyst lost some activity with time on stream. For example, the concentration of TCE in the stack increased from 0.012 ppm to 0.051 ppm in 5 months, corresponding to a decrease in TCE destruction efficiency from 99.4 to 97.5 percent.

Table 2-6. Summary of Wurtsmith AFB's Catalytic Oxidation Test Results for ARI System

Component	Feed concentration (ppm)	Effluent concentration (ppm)	Efficiency (%)
TCE	2.0100	0.0511	97.5
Benzene	0.0007	0.0170	-2172.7
Toluene	0.0647	0.0024	96.3
1,2-Dichloroethene	0.0511	0.0003	99.5
Trichlorofluoromethane	0.0008	0.0014	-77.1
1,1-Trichloroethane	0.0004	0.0000	100.0
Chloroform	0.0006	0.0001	77.8

2.1.1.3 McClellan Air Force Base

A pilot plant test of fluidized-bed catalytic incineration was conducted at the "Big Bertha" paint spray booth in Building 655 at McClellan Air Force Base, California.[19] Tests were conducted with varying inlet OV concentration, temperature, and total flow rate. Table 2-7 summarizes these results. The concentration of OV has been reported in terms of lb/h. Since the feed concentration of individual OV was not reported, the concentration cannot be presented in terms of ppm. However, assuming that the average molecular weight of the OV was 80 g/gmol, the concentrations of the individual OV shown in Table 2-7 vary from 6 to 44 ppm. The OV destruction efficiencies for all the tests were greater than 99 percent. Of all the OV present in the feed stream, only toluene was detected in the exhaust. The other compounds were completely

Table 2-7. Fluidized-Bed Catalytic OV Incineration Results of a Study Conducted at McClellan AFB using ARI's Fluidized-Bed Catalytic Incinerator

OV concentration (lb/h)		Destruction efficiency (%)	Temperature (°F)	Flow (scfm)	CO concentration in the exhaust (ppm)	Fuel usage rate (Btu/h)
In	Out					
0.13	0.0013	99	698	466	43	370,000
0.11	0.00024	>99.8	950	348	58	434,000
0.26	0.00024	>99.9	950	446	56	490,000
0.1	0.00025	>99.8	1000	402	45	525,000
0.055	0.00042	>99.2	807	691	40	548,000
0.28	0.0022	99.2	775	611	99	498,000

oxidized. In addition to CO_2, produced by complete combustion, some amount of CO was also present in the exhaust.

2.1.2 Anguil

Anguil manufactures various systems including oxidizing with regenerative heat exchangers, recuperative heat exchangers, catalysts, and concentrators. Projects are usually in the 100 to 35,000 scfm airstream flow rate range; however, the company has recently expanded its product line to include equipment in the 100,000 scfm range due to market demands.[20] Anguil has no system known to be installed currently in the U.S. on high flow, low concentration organic vapor streams.[21]

2.1.3 Monsanto Enviro-Chem

Monsanto Enviro-Chem manufactures a wide range of control devices including the DynaCycle regenerative unsteady state catalytic oxidizer (RUSCO) which has been demonstrated to provide 99 percent reduction of OV from oriented strand board manufacture. RUSCO has been used for the removal of sulfur dioxide with oxygen over vanadium, titanium, and tungsten oxides; oxidation of carbon monoxide with air over copper, chromium, and iron oxides; destruction of C_1, C_4, C_6, and C_8 alcohols; destruction of phenols, formaldehyde, hydrogen cyanide, acrylonitrile, ethyl acetate, cyclohexanone, and other compounds. It has not, however, been demonstrated in the U.S. at high flow rates.[22]

RUSCO is a technology first demonstrated in Russia. It consists of a three-layered fixed bed (see Figure 2-3). The center layer is the catalyst, and on both ends are layers of inert ceramic material functioning as heat absorbers/desorbers. When the temperature of the downstream layer reaches a certain temperature, the flow is reversed, and the inert layers switch their heat absorber/desorber function. The reaction is said to occur in a narrow zone in

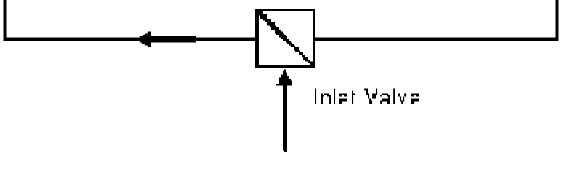


Figure 2-3 Monsanto Enviro-Chem Dynacycle Regenerative Unsteady State Catalytic Oxidizer

the catalyst layer, which suggests that the rate of reaction is very high. Oxidation is essentially complete for reversible and irreversible reactions, and efficiencies measured below 100 percent appear to be due only to the short time required for the switching valves to cycle. Unlike steady-state devices, temperatures in a RUSCO device never approach the theoretical equilibrium, and so the RUSCO device is self-optimizing.[23]

2.1.4 CSM

CSM manufactures mainly catalytic oxidizers, but has none installed in the U.S. for control of low concentration, high flow OV streams.[24]

2.1.5 Amcec

Amcec has no catalyst based control systems operating on low concentration, high flow OV streams in the U.S.[25]

2.1.6 Alzeta

Alzeta manufactures a broad line of air pollution control devices, including the Alzeta Adiabatic Radiant Burner, which is an inward firing incinerator that is reported to produce much less oxides of nitrogen compared to conventional burners (see Figure 2-4). Alzeta markets this incinerator with a zeolite concentrator wheel from Munters. However, no systems installed on low concentration, high flow OV streams in the U.S. are documented.[26] These systems are described in more detail in Section 5.4.2 of this report.

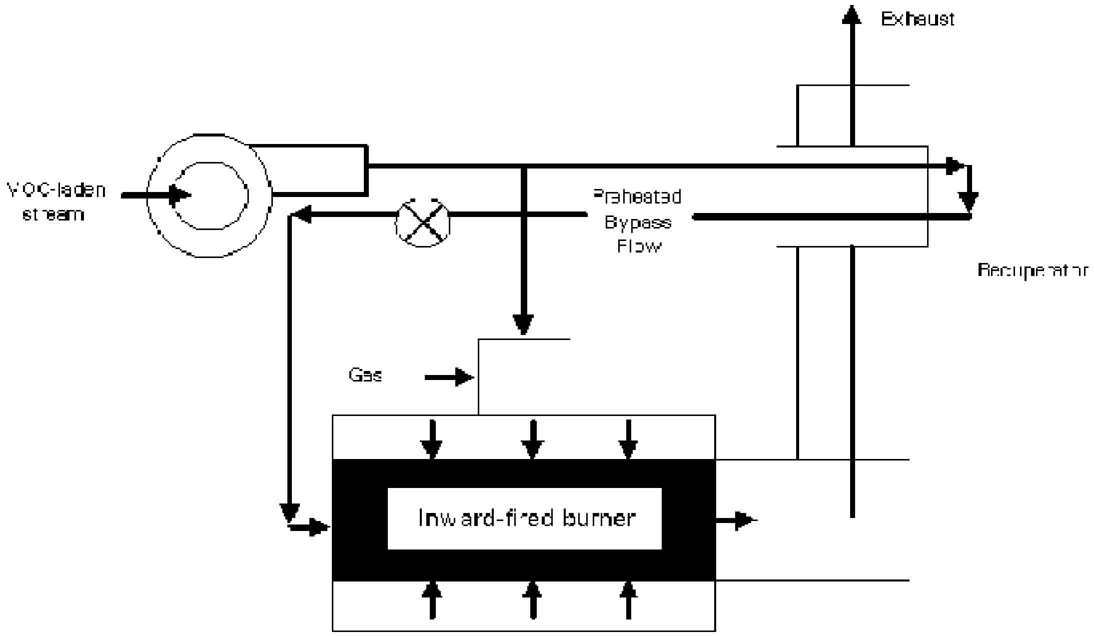


Figure 2-4 Alzeta Adiabatic Radiant Burner

2.1.7 Thermo Electron

Thermo Electron has no control systems operating on low concentration, high flow OV streams in the U.S.[27]

2.1.8 Catalytica

Catalytica has no control systems operating on low concentration, high flow OV streams in the U.S.[28]

2.1.9 Costs

Costs for catalytic oxidation units were developed using the methodology given in the OAQPS Control Cost Manual.[29] All costs presented here are calculated from factored estimates and are given in detail in Appendix B. Though several vendors were contacted about supplying costs, none responded.

Costs were developed for four cases:

- 100 ppm benzene,
- 10 ppm benzene,
- 100 ppm tetrachloroethylene, and
- 10 ppm tetrachloroethylene.

All these cases are for *continuous* streams; other stream conditions are:

- OV in clean air,
- 10,000 scfm,
- 70 percent relative humidity,
- 70 °F inlet temperature, and
- 95 percent destruction efficiency.

Assumption for the cost calculations are as follows:

- Catalyst replacement for streams containing benzene is required every 3 years and for streams containing tetrachloroethylene every 2 years,

- Operating temperature for the benzene-containing gas is 399 °C (750 °F) and for the tetrachloroethylene-containing gas is 427 °C (800 °F),

- 95 percent overall destruction or removal efficiency,[30]

- 8,000 h/yr operation,

- 10^4 h^{-1} space velocity,

- 10,000 scfm (283,000 L/min), and

- 70 percent heat recovery for the unit.

All other costs (operating and supervisory labor, maintenance costs, and indirects) are calculated as shown in the OAQPS Control Cost.[31] Total capital investment (TCI) is calculated based on purchased equipment costs (PEC) and 79 percent installation costs.[32] PECs are a function of volumetric throughput (scfm) and percent heat recovery and are given in cost curves presented in the OAQPS Control Cost Manual.[33]

The total annualized costs (TAC, $/yr) and cost-effectiveness are shown in Table 2-8. As expected, the TAC does not vary significantly with OV concentration. This is because the OV concentration is too low to affect the usage of auxiliary fuel, which is the single largest operating cost. Other costs contributing to TAC depend almost entirely on the size of the unit, measured as volumetric throughput (scfm), which is fixed for the sample case here. TAC for the chlorinated OV is slightly higher than for the hydrocarbon benzene due to the lower heat of combustion and more frequent catalyst replacement. The cost-effectiveness varies inversely with concentration, reflecting the assumption of constant removal efficiency regardless of inlet concentration (see Table 2-4).

Table 2-8. Catalytic Oxidation Costs

	Benzene concentration		Tetrachloroethylene concentration	
	100 ppm	10 ppm	100 ppm	10 ppm
Total annualized costs,[a] ($/yr)	271,900	274,400	290,700	291,500
Cost effectiveness,[a] ($/ton OV removed)	5,500	55,400	5,900	58,800

[a]All costs are in 1991 dollars rounded to nearest $100; calculations are based on 10,000 scfm flow rate. Other assumptions discussed in text.

2.2 REGENERATIVE THERMAL INCINERATION

In regenerative thermal incineration, the contaminated air enters the system through a heated (ceramic) packed bed which preheats the gas to near its final oxidation temperature. The preheated air then enters a combustion chamber where it is further heated to oxidize the OV. The hot clean (flue) gas exiting this chamber passes through a second (ceramic) packed bed cooled in an earlier cycle. This bed absorbs most of the heat; thus, cooling the gas before it is discharged to the atmosphere. A third (ceramic) packed bed may simultaneously be purged of any exhaust still contaminated with inlet OV emissions. This heat exchange cycle is repeated, alternating between the three (ceramic) beds for heating, cooling, and purging operation. Thermal energy recoveries as high as 95 percent can be achieved with a regenerative thermal incinerator. The alternation between chambers/beds typically results in somewhat lower destruction efficiencies than are achieved in a conventional recuperative thermal vapor incinerator, generally below 99%.[34] The lower destruction efficiency for regenerative thermal incinerators has been attributed in part to valve leaks within the system.

Smith Engineering Systems (Ontario, CA) and Reeco (Morris Plains, NJ) market regenerative thermal systems and are the only vendors identified here whose systems have been used on low concentration gases. Smith Engineering provided test results from two sites in California used for the destruction of low concentration OV; other source test results and permit information were obtained from State agencies. Similarly, test results from two sites for OV oxidation using Reeco system are presented although Reeco did not disclose the exact location of these sites. Industry provided field results are summarized in Table 2-9.

2.2.1 Smith Engineering Systems

Smith Engineering Company (Smith, SEC) manufactures recuperative, regenerative, and catalytic oxidizers. Figure 2-5 shows the schematic of a regenerative thermal incinerator made by Smith Engineering Systems (Ontario, CA) to destroy OV from contaminated air.[35] It consists of three ceramic packed beds that are alternately heated and cooled during the heat exchange cycle. Smith regenerative incinerators have been used at numerous sites for the destruction of low concentration OV emissions. They have seven regenerative oxidizers installed in the U.S. on high flow, low concentration organic vapor streams.[36] All are at fiber board manufacturing facilities owned by Louisiana Pacific. These devices were installed pursuant to orders of consent, and will be permitted at some time in the future.[37]

2.2.1.1 Source Test Data

Louisiana Pacific Corporation (LPC) in Hanceville, Alabama has 3 Smith regenerative thermal oxidation (RTO) systems at the facility. Two control emissions from 5 oriented strand board (OSB) Dryers and 1 unit controls emissions from a process vent. These units were tested for air emissions in June 1994 by Environmental Monitoring Laboratories, Inc. Testing was performed to determine emissions of particulate matter, volatile organic compounds (VOC), formaldehyde, nitrogen oxides, and carbon monoxide. Testing was simultaneously performed at the RTO inlets and outlets in order to determine removal efficiency. The test report summary[44] shows that overall removal/ destruction efficiency for the RTO system serving the OSB dryers was 99.3 percent. The dryers' RTO inlet VOC loading was reported as

Table 2-9. Summary of Field Studies of Regenerative Thermal Oxidation for Control of Gases with less than 100 ppm Inlet OV Concentration

Vendor	Site	Gas flow (scfm)	Inlet concentration (ppm)	Outlet concentration (ppm)	Destruction/removal efficiency (%)	Comments/ References
Smith Engineering Systems Digital Equipment	Cupertino, CA	24,332	63-80[a]	0.2-1.2[a]	99.8	Smith Engineering, 1990[38]
Smith Engineering Systems Mobil Chemical Company	Bakersfield, CA	38,000	100	1-2	98-99	Organic contaminant was isopentane; Smith Engineering, 1990[39]
Reeco	Morris Plains, NJ	4,529	69	0.9	98.7	[b]NETAC, 1991[40] Pennington, 1991[41]
Reeco	(same)	19,475	96	0.9	98.9	[d]; NETAC, 1991[42] Pennington, 1991[43]

[a] As CH_4.
[b] OV include acetone, butyl acetate, ethyl acetate, toluene, and xylene.
[c] Given by the vendor only as "in California."
[d] OV include acetic acid, isophthalic, trimellitic anhydride, and tri-methylbenzene.

Figure 2-5 Schematic of Smith Engineering Systems' Regenerative Thermal Vapor Incinerator

263.6 pounds per hour (lb/hr) and the outlet was measured at 1.25 lb/hr at the West RTO unit and 0.62 at the East unit, for a total outlet loading of 1.87 lb/hr. The Press Vent RTO had an inlet loading of 147.4 lb/hr with and outlet loading of 0.34 lb/hr. RTO outlet VOC concentrations (in ppm) were reported in the testing summary; however, inlet VOC concentrations were not contained in the summary information received from the State. Outlet concentrations are provided in Table 2-10.

The Louisana Pacific Corporation conducted air emisison tests at the LP Waferboard Plant in Two Harbors, Minnesota in February of 1989.[45] This facility is reported to utilize a regenerative thermal oxidizer (RTO) as a VOC control device. A copy of the test results summary received from the Minnesota Pollution Control Agency's Division of Air Quality[46] indicated only the emission rate results in terms of concentration and mass; the summary did not provide details on the characteristics of the gas streams controlled by the RTO (e.g., VOC concentration or gas stream flow rate).

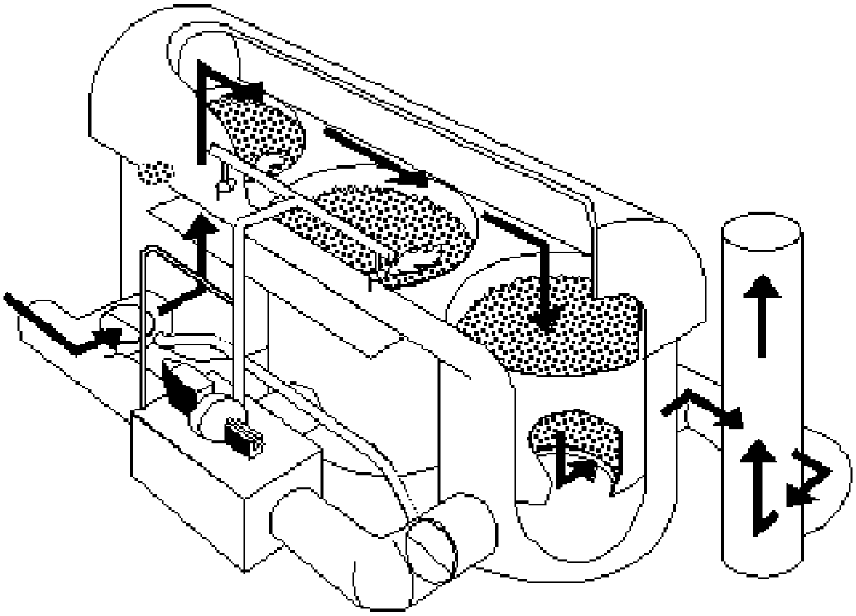


Figure 2-5. Schematic of Smith Engineering Systems' Regenerative Thermal Vapor Incinerator

Source testing of the Louisiana-Pacific Corporation's Urania, Louisiana OSB Plant MDF Dryers' South RTO and North RTO units was performed by Armstrong Environmental, Inc., in January 1994.[47,48] Inlet sampling was done simultaneously with outlet sampling in order to determine removal efficiency. A summary of the available test results is presented in Table 2-11. The VOC control efficiency for the individual RTO units was not reported in the limited information obtained from the State Air Quality Division, but the overall control efficiency was calculated using available information to be about 98.25%.

Table 2-12 shows the results for the tests of the Smith RTO system conducted at Digital

Equipment Corporation, Cupertino, CA.[49] In all four tests, the overall destruction efficiency was above 98 percent. The feed stream contained a mixture of several OV.

Table 2-10. Source Test Results for the Smith RTO at Louisiana Pacific's Hanceville, Alabama, OSB Plant[50]

DRYERS RTO	VOC as C		HCOH	
	lb/hr	ppm	lb/hr	ppm
WEST RTO	1.25	9.10	0.12	0.34
EAST RTO	0.62	5.10	0.13	0.43
RTO INLET	263.60	---	5.52	---
REMOVAL EFFICIENCY	99.3		95.4	
PRESS VENT RTO	VOC as C		HCOH	
	lb/hr	ppm	lb/hr	ppm
RTO OUTLET	0.34	1.60	0.03	0.06
RTO INLET	147.40	---	1.81	---
REMOVAL EFFICIENCY	99.8		98.3	

Table 2-11. Source Test Results for the Smith RTO at Louisiana Pacific's Urania, Louisiana, OSB Plant.[51,52]

	Outlet North RTO	Outlet South RTO	Inlet[A] Loading
VOC Emissions (lb/hr as C)	0.22	0.08	17.10
VOC Emissions (ppm as C)	5.4	0.5	176.7
HCOH Emissions (lb/hr)	0.41	3.28	6.11
HCOH Emissions (ppm)	1.19	1.23	7.84
Volumetric Flowrate (acfm)	101,615	111,751	192,381
Volumetric Flowrate (dscfm)	72,697	81,914	166,065
Stack Temperature (°F)	224	217	118

[a] Data were only available for the total inlet gas stream that is controlled by the 2 RTO systems from Smith Engineering.

Table 2-12. Smith RTO System Test Results, Digital Equipment Corporation, Cupertino

Test No.	Inlet OV (lb/h)	OV Concentration[a]		Temperature (°C)	Destruction efficiency (%)
		Inlet	Outlet		
1	4.83	80	1.3	816	98.1
2	4.22	70	0.2	816	99.8
3	3.80	63	0.9	816	98.4
4	4.28	71	0.8	816	98.8

[a] Organic carbon as CH_4

Flow = 24,332 scfm

The results of a Smith system at Mobil Chemical Company, Bakersfield, CA are shown in Table 2-13.[53] The feed stream contained 100 ppm of isopentane. Again, 98 to 99 percent destruction efficiency was achieved at 816 °C. The thermal efficiency of this system was 94.7 percent.

2.2.1.2 Permit Conditions

A review was conducted of the Air Permit issued to Louisiana Pacific Corporation (Number 702-0027-X008, issued February 8, 1994), by the Alabama Department of Environmental Management, Air Division, for the board press system with regenerative thermal oxidation at LPC's Hanceville Plant.[54] Item 21 in the permit states that the VOC emission rate shall exceed neither 4.74 lbs/hr and/or 0.087/lbs per thousand square feet of board, measured in accordance with 40 CFR Part 60, Appendix A, Method 18, 25, 25A or 25B. Item 22 states that the VOC collection (destruction) efficiency across the RTO shall be at least 95 percent. Item 23 states that the regenerative thermal oxidizer's combustion chamber operating temperature shall not fall below 1400 degrees Fahrenheit. Emission limits also are established in the permit for RTO formaldehyde, diphenylmethane diisocyanate (MDI), and phenol emissions. No limits are placed on the RTO unit with regard to inlet or outlet VOC concentration.

Table 2-13. Smith RTO System Test Results, Mobil Chemical Company, Bakersfield

OV	Isopentane
Inlet concentration, ppm	100
Outlet concentration, ppm	1-2
Destruction efficiency, %	98 - 99
Temperature, ° C	816
Flow rate, scfm	38,000

The LPC's Hanceville Plant's Permit Number 702-0027-X014, issued February 8, 1994, for the No. 1-5 Rotary Drum Wood Wafer Dryers with Two (2) Regenerative Thermal Oxidation Systems has a number of permit conditions specific to the RTO's and the organic gas streams controlled by these units.[55] Item 24 states that the VOC emission rate shall exceed neither 24.89 pounds per hour and/or 0.553 pounds per ton of dry wafers when up to three dryers are operating (oxidizer exhausts to be sampled simultaneously). Item 26 states that the VOC collection (destruction) efficiency across the multiclone and RTO shall be at least 95%. Item 27 has a requirement that neither regenerative thermal oxidyers' combustion chamber operating temperature shall fall below 1400 °F.

The information and test results obtained from the Louisiana Air Control Commission (in their submittal, dated 08/09/94) did not contain any information or data relevant to the RTO units reported to be in operation at the Louisiana-Pacific Plywood facility located in Urania, Louisiana.

2.2.2Reeco

Reeco manufactures a full range of control devices, and may be most often associated with regenerative oxidizers. Figure 2-6 shows a schematic of the regenerative thermal incinerator made by Reeco (Morris Plains, NJ). It is similar in **Figure 2-6 Schematic of Reeco's Regenerative Thermal Incinerator** principle to that made by Smith. These regenerative thermal systems have been used at various sites for destruction of low concentration OV gas streams.[56,57] They have four regenerative oxidizers installed on high flow, low concentration OV streams in the U.S.[58]

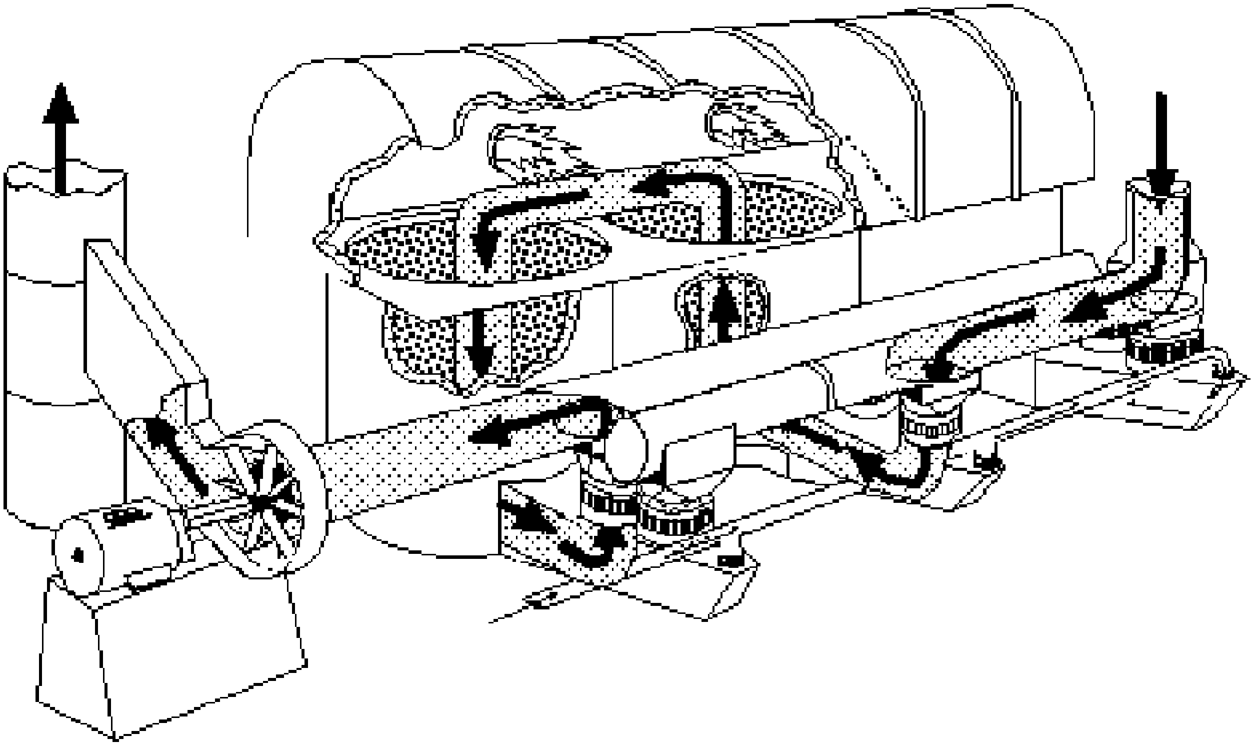


Figure 2-6. Schematic of Reeco's Regenerative Thermal Incinerator

2.2.2.2 Source Test Data

The 3M St. Paul Tape Plant in St. Paul, Minnesota, contracted Precision Environmental to test the Reeco regenerative thermal oxidizer destruction efficiency in June 1993.[59] The summary of the test results indicates that an average control device efficiency of greater than 95% was achieved for a variety of inlet VOC loading rates, ranging from a high of about 1,400 lbs/hr to a low of about 120 lbs/hr. No inlet gas stream characteristics were included in the available summary.

Table 2-14 shows the results of two additional Reeco systems operating on gas streams containing less than 100 ppm OV. These units are installed in New Jersey and California. Actual sites and customer names are considered confidential by Reeco. The gas streams to both units contained a mixture of OV. The destruction efficiency in both cases was above 95 percent. These units were said to represent typical performance of Reeco systems with chamber flushing and valve sealing features.

2.2.2.3 Permit Conditions

Air Emission Permit No. 23GS-93-OT-1, dated March 1993, for a pressure sensitive tape and label manufacturing plant operated by 3M company in St. Paul and issued by the Minnesota Pollution Control Agency's Air Quality Division, contains a description of a Reeco regenerative thermal oxidizer in Section 1.3 of the permit.[60] The Reeco unit is listed as serving Emission Point Number 1 that consists of a large number of ovens and dryers. The maximum inlet capacity of the RTO unit is listed in the permit as 5,600 lbs/hr of solvent; with a design destruction efficency of 95%. The inlet gas stream characteristics are not provided. The exhaust (stack) gas flow rate is reported as 270,000 scfm (428,000 acfm at 380°F). The permit does not specify a unique VOC emission limit for the sources served by the Reeco unit; the emission limit specified in the permit is an aggregate value that covers numerous emission points at the facility. This emission limit is formatted in terms of tons per year (i.e., 4,596 tons/yr). No limits on the gas stream characteristics are contained in this permit for the Reeco unit.

Table 2-14. Reeco Regenerative Thermal Incinerator Test Results at Sites in NJ and CA

	Unit #1 (in NJ)	**Unit #2 (in CA)**
OV	Acetone, butyl acetate, ethyl acetate, toluene, and xylene	Acetic acid, Isophthalic, Trimellitic anhydride, and trimethylbenzene
Flow	4,529 scfm	19,475 scfm
Inlet concentration	69 ppmv	96 ppmv
	4.2 lb/h	20.2 lb/h
Outlet concentration	0.9 ppmv	0.9 ppmv
	0.05 lb/h	0.22 lb/h
Destruction efficiency	98.7 %	98.9 %

The engineering evaluation submitted as part of NUMMI's application for an air permit (Application Number 3611, Plant Number 1438) from the Bay Area Air Quality Management District contained, as part of the BACT Evaluation, a discussion of recent New Source Review (NSR) Projects at other similar facilities.[61] Mentioned in the discussion was the Reeco regenerative thermal oxidizer at the General Motors plant in Arlington, TX. The report states that BACT for the first topcoat spray booth at this plant will be a Reeco RTO. The required destruction efficiency of the RTO unit is 93%; no recirculation or solvent concentrating equipment will be used. The RTO unit is reported to have a capacity of 429,000 acfm and is an existing unit installed on the previous topcoat spray booth to meet RACT requirements.

2.2.3 Other Manufacturers

Regenerative thermal oxidizers, such as those made by Dürr, Huntington, and Eisenmann, are not discussed in any detail in this document even though this technology has recently undergone considerable development. In principle, these systems, which are similar in design to the regenerative thermal oxidizer systems previous described, will oxidize low concentration gases; Somary (1993)[62] claims that the Eisenmann regenerative thermal oxidizer can be used for concentrations as low as 100 ppm, although there are apparently no such field installations.

It is also of interest to note that an alternative design for regenerative thermal oxidizers has recently become commercially available. This design involves what is termed as horizontal flow and results in a much more compact unit (see Figures 2-7 and 2-8) that is capable of handling small to moderate gas flows. The main advantage offered by the alternative design is that the unit requires less space and, as a result, is amenable to retrofit situations.

2.2.4 Costs

Costs were provided by Reeco for the model gas streams and are summarized in Table 2-15. Details are given in Appendix B. No cost data were obtained for the Smith Engineering System, Dürr, Huntington, or Eisenmann regenerative thermal oxidizing systems.

2.3 RECUPERATIVE HEAT RECOVERY

Recuperative heat recovery is offered by nearly all incinerator vendors, but is generally not cost-effective compared to regenerative systems above 50,000 scfm.[63] No currently documented control system for low concentration, high flow OV streams uses recuperative heat recovery.

2.4 FLARES

Flaring is an open combustion process in which the oxygen is supplied by the air surrounding the flame. Flares are either operated at ground level (usually with enclosed multiple burner heads) or they are elevated. Elevated flares often use steam injection to improve combustion by increasing mixing or turbulence and pulling in additional combustion air. Properly operated flares can achieve destruction efficiencies of at least 98 percent. Figure 2-9 is a schematic of the basic components of a steam-assisted elevated flare system. The U.S. EPA has developed regulations for the design and operation of flares to ensure that high destruction efficiencies are achieved (40 CFR 60.18)[64]; design requirements include specification of tip exit velocities for different types of flares and gas stream heating values (i.e., greater than 7.45 MJ/scm [200 Btu/scf]). The flare is a useful emission control device and can be used for most nonhalogenated organic streams. However, low volumetric flows and low organic concentrations are conditions that do not favor the use of flares. In the case of low organic concentration gas streams, supplemental fuel costs generally eliminate flares

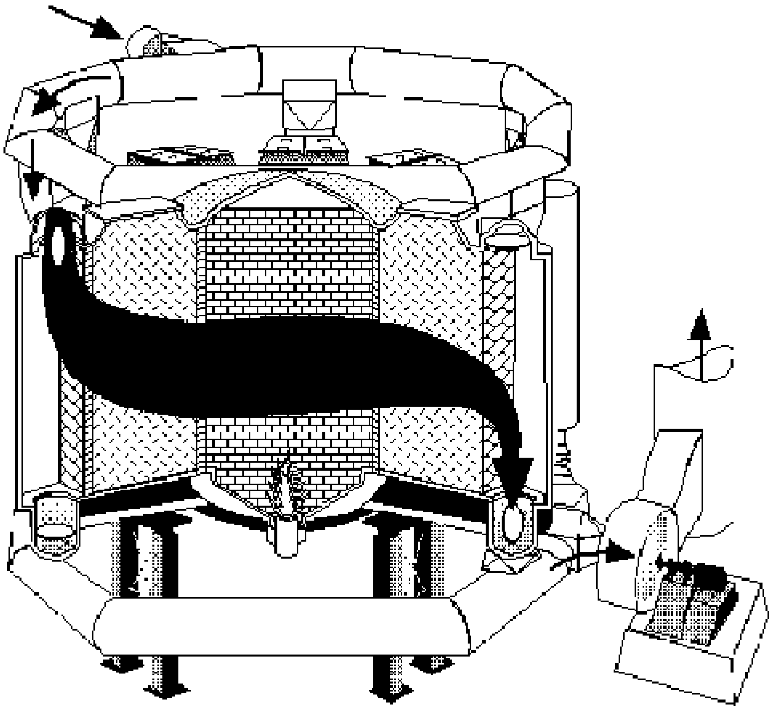


Figure 2-7 Reeco's Regenerative Thermal Incinerator—Horizontal Flow Design

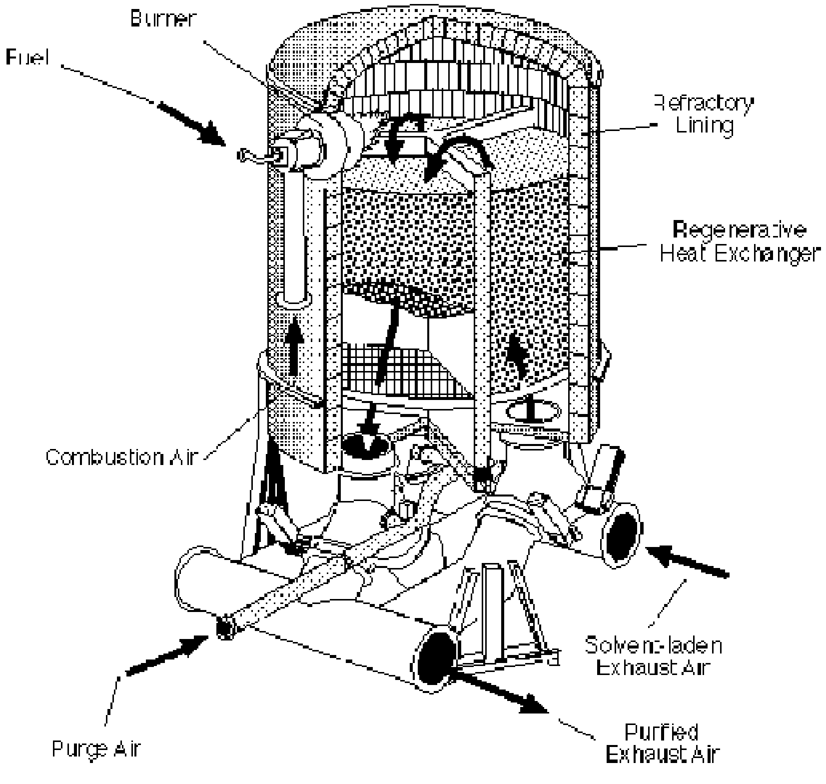


Figure 2-8 Dürr Regenerative Thermal Incinerator—Horizontal Flow Design

Table 2-15. Cost Effectiveness for Reeco Regenerative Thermal Incineration

	Benzene concentration		Tetrachloroethylene concentration	
	100 ppm	10 ppm	100 ppm	10 ppm
Total annualized costs,[a] ($/yr)	181,000	181,000	245,900	252,300
Cost effectiveness,[a] ($/ton OV removed)	3,700	38,100	5,000	50,900

[a] All costs are in 1991 dollars rounded to nearest $100; calculations are based on 10,000 scfm flow rate. Based on Pennington (1991) for Reeco system. Details are given in Appendix B.

as a viable control alternative; flares have no heat recovery capability. In addition, because flaring is an open combustion process, it is very difficult and economically impracticable to directly measure emissions from a flare. No currently documented control system for low concentration, high flow OV streams in the U.S. uses a flare.

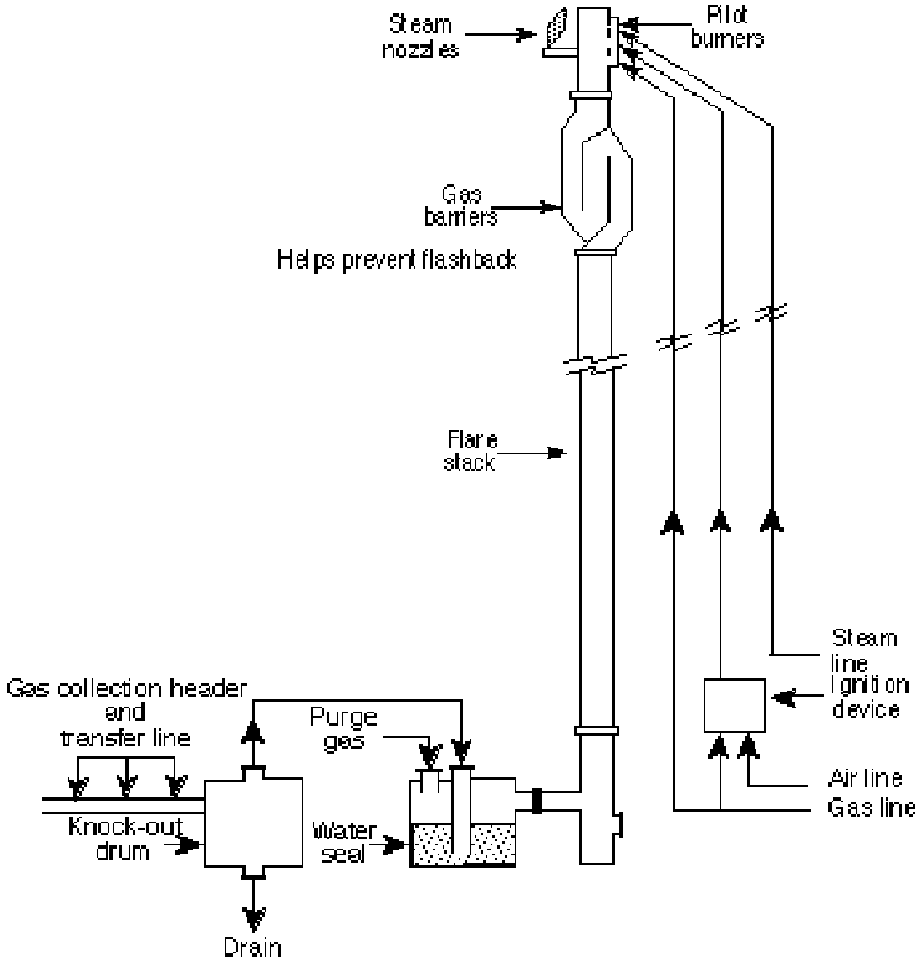


Figure 2-9 Schematic of the Basic Components of a Steam-Assisted Elevated Flare System

2.5 BOILERS AND PROCESS HEATERS

Boilers, process heaters, and other existing combustion devices can be used as control devices to limit organic emissions by incorporating the vent stream into the inlet fuel or injection through a separate burner, or by feeding the stream into the boiler or process heater, etc., as combustion air. Where applicable, use of existing combustion devices can achieve high destruction efficiencies for organic emissions at a reasonable cost.[65]

The parameters that affect the thermal efficiency of a boiler or process heater are the same parameters that affect the efficiency of these units when they function as air pollution control devices. These are combustion temperature, residence time, inlet organic concentration, compound type, and flow regime (i.e., mixing). A series of U.S. EPA-sponsored studies of organic vapor destruction efficiencies for industrial boilers and process heaters have been conducted.[66] The results of these tests showed 98 to 99 percent overall destruction efficiencies for OV; however, none of the tests involved low-concentration (i.e., less than 100 ppm) organic gas streams. No currently documented control system for low concentration, high flow OV streams in the U.S. using boilers or process heaters was identified.

SECTION 3

ADSORPTION

Adsorption is one of the most widely applied control technologies for organic vapors (OV). In the adsorption process, organics are selectively collected on the surface of a porous solid. Activated carbon is by far the adsorbent most often used for low organic gas concentrations because of its low cost and relative insensitivity to water vapor at relative humidities below about 50 percent.[67] Other common adsorption media include silica and alumina-based adsorbates. In addition, recently developed hydrophobic zeolites have been incorporated into systems which, in principle, are similar to those based on carbon. The basic principles of adsorption for separation of gas mixtures are described in a number of texts and are not discussed here.[68,69,70] Because adsorption processes simply separate the contaminant (OV) from the gas stream, adsorption processes must be used in conjunction with other unit operations to recover or destroy OV.

The carbon adsorption capacity for organics is affected by the concentration of organics in the gas stream. Carbon manufacturers generally have equilibrium data for specific compounds and their specific carbon types. For virtually any adsorbate, the adsorption capacity is enhanced by lower operating temperatures and higher organic concentrations. As the concentration of an organic constituent in the gas stream decreases, it becomes more difficult to adsorb the constituent on activated carbon. In theory, activated carbon can be tailor-made to remove pollutants at very low organic concentrations. However, a carbon adsorption system designed to achieve a 95 percent control efficiency for a given organic present at 1,000 ppm may not achieve a 95 percent control efficiency for the same constituent present at a lower concentration, e.g., 10 ppm.

Carbon adsorbers are essentially constant outlet concentration devices; prior to breakthrough, outlet concentration generally remains constant through an adsorption cycle even though the inlet concentration may vary more than an order of magnitude.[71] Inlet concentrations are typically limited by the adsorption capacity of the carbon bed or by safety problems. The maximum practical inlet concentration is usually about 10,000 ppm. Outlet concentrations around 50 ppm can be routinely achieved with state-of-the-art systems; concentrations as low as 5 to 10 ppm can be achieved with some compounds.[72] For organic concentrations above 100 ppm, carbon absorbers can achieve control efficiencies of at least 95 percent, and control levels of 97 to 99 percent have been demonstrated in many applications. Theoretically, fresh activated carbon should remove nearly all organics from an air stream containing organics at concentrations of 100 ppm and less; but performance data, which are quite limited, indicate that high removal efficiencies are not attained in a significant number of cases handling these low organic concentration.[73,74,75] The reasons for the low removal efficiencies have not been clearly established.

There are two types of adsorption systems that can be used for removal of OV from gas streams. These are nonregenerable (e.g., carbon canisters) and regenerable (e.g., fixed bed systems).

3.1 NONREGENERABLE ADSORPTION SYSTEMS

3.1.1 Principle of Operation

These systems typically consist of one or two fixed beds of adsorbent (e.g., granular carbon). The OV-containing gas flows upward through one bed. The OV is adsorbed over a period of time until breakthrough occurs. In practice, the outlet gas stream is seldom monitored to determine this breakthrough point, though regulatory compliance requirements are changing this.[76] In most cases, the bed is simply replaced on a time schedule determined by calculating the bed life from the inlet concentration and the working capacity of the carbon bed. Once breakthrough occurs, the carbon is returned for reactivation to the vendor or a central reactivation facility, at which point other emissions may be generated during the reactivation process.

In principle, nonregenerable systems are simple and find many applications in cases where the flow rate and/or OV concentration is low. Table 3-1 summarizes the performance of nonregenerable adsorption system at sites treating inlet gases containing less than 100 ppm OV. Nonregenerable adsorption systems are especially attractive if, in addition, the OV is difficult to desorb. These applications include odor control and control of indoor air. As a guideline for their use, Stenzel and Bourdeau state that nonregenerable systems are economically feasible when the carbon life is expected to exceed 3 months.[77]

An example of such a system is the Verona Well Field site, at which two 314 ft^3 carbon beds are used to control 5,350 cfm offgas from an air stripper.[78,79] The total concentration of the inlet gas to the carbon bed is shown in Table 3-2. Assuming 5 wt% working capacity of the carbon before breakthrough,[80] it can be shown that this bed will last 257 days of continuous use.

It is important to note that at concentrations approaching 100 ppm and above, the capacity of nonregenerable systems may not be sufficient to remain on line for a reasonable time. In the above example, for instance, a 100 ppm inlet concentration would require replacement every 2.6 days. No currently documented control system for low concentration, high flow OV streams in the U.S. uses nonregenerable adsorption systems.

3.2 REGENERABLE FIXED BED ADSORPTION SYSTEMS

3.2.1 Principle of Operation

A fixed-bed regenerable system consists of two or more vessels, each containing adsorbent. Figure 3-1 shows a general flow scheme.[81] One vessel is on line while a second is being regenerated, usually with low pressure

Table 3-1. Summary of Field Studies of Nonregenerable Carbon Adsorption for Gases Containing less than 100 ppm Inlet OV Concentration

Vendor	Site	Gas flow (scfm)	Inlet concentration (ppm)	Outlet concentration (ppm)	Destruction/ removal efficiency (%)	Comments/ References
NR	Verona Well Field; Battle Creek, MI	5,500	0.48	NR	[a]	Byers, 1988[82]
NR	Verona Well Field; Battle Creek, MI	NR	0.18	NR	12.8	low removal due to carbon being saturated; PEI, 1989 p. 61[83]
	Tyson's Dump	170	20.2	.017	99.97	Vancil et al., 1987[84]
Calgon[b]	NR	175	80-95[c]	15[d]	81-84	paint bake oven emissions; Schuliger, 1983[85]; Urbanic and Lovett,1974[86]
Various[e]	Tyndall AFB, FL	NR	7-93	NR	NR	Chlorinated C_2 compounds and aromatics were tested; Lubozynski et al., 1988[87]
Calgon	Verona Well Field; Battle Creek, MI	5,350	1.0[f]	ND	>99	C_2 chlorinated compounds from air stripper; Stenzel and SenGupta, 1985[88]
NR	Newark AFB, OH	2,800	4-292[g]	ND	>99[h]	emissions were Freon 113 and traces of trichloromethane; Ayer and Wolbach, 1990[89]

NR = not reported.
ND = not detected.

[a] Outlet concentration reported to be below detection limits; detection limits not given.

[b] Carbon regenerated by heated gas rather than steam.

[c] As C_6.

[d] Outlet consisted mostly of C_1 and C_2 compounds.

[e] A number of different carbons were evaluated.

[f] Calculated from measured value of contaminants in groundwater to air stripper.

[g] Concentration varied due to cleaning schedule for operations whose emissions were vented to the adsorber. The time weighted average concentration for the 27-hour test period was 126 ppm.

[h] Data reported for Carbon Adsorber 3 (Table 9, p. 27-28) for the period 0900 September 14 through 1200 September 15 during which (p. 41) breakthrough did not occur. Detection limits for spectrophotometer used to measure outlet concentration is not given. A >99% DRE is based on an assumed detection limit of 1 ppm and a time averaged inlet concentration of 126 ppm.

Table 3-2. Concentration of Inlet Gas at Verona Well Field Site

Contaminant	Concentration in gas inlet to carbon bed, ppm
cis-1,2-dichloroethylene	.55
1,1,1-trichloroethylene	.17
tetrachloroethylene	.10
trichloroethylene	.08
1,1-dichloroethane	.08
total	1.0

steam, though hot inert gas can be used. In practice, three beds are sometimes used; the third is dried while the second is being regenerated.

At the low concentrations of interest here, steam usage rates (lb steam/lb OV) are somewhat higher than for higher concentrations of OV because the adsorbed organic is more difficult to desorb. SenGupta and Schuliger give a steam usage rate of 5 to 20 pounds steam per pound OV recovered for concentrations below 100 ppm compared to 2 to 5 pounds/pound for OV concentration around 500 ppm.[90] The working capacity of the carbon is somewhat lower at low concentrations also, roughly 2 to 10 wt% at OV concentrations below a few hundred ppm compared to 5 to 15 wt% at higher concentrations.[91]

3.2.2 Applications

This type of regenerable system is limited to situations in which the OV either can be easily recovered by, for example, condensation of the steam/OV mixture produced during the regeneration cycle (or cooling of the inert gas/OV mixture) or can be disposed of at a minimal cost. In most cases this is not true, and there exists a need to destroy the OV after the regeneration cycle.[92] This need, coupled with the development of novel carbon absorbers, has led to the development of modified regenerable adsorption systems.

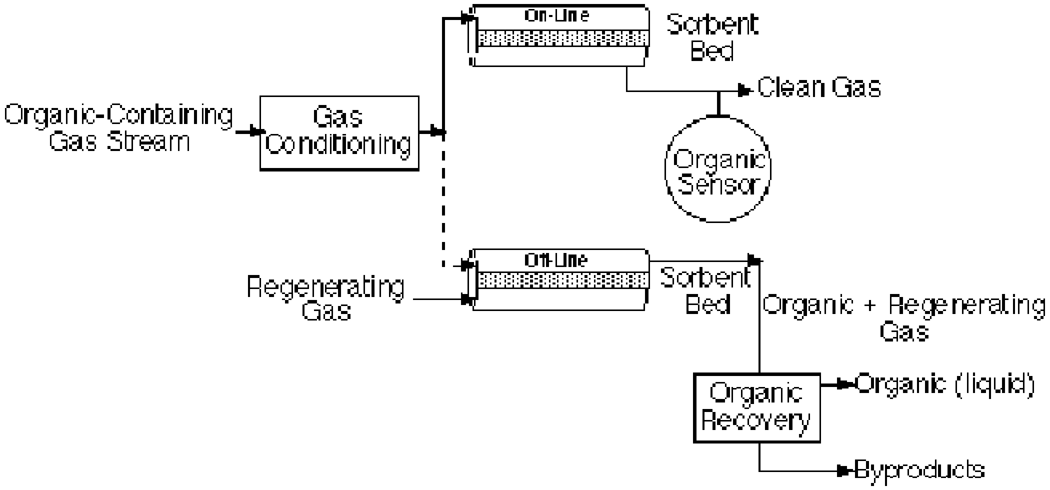


Figure 3-1 General Process Flow Diagram of an Adsorption Process for OV Recovery

3.3 MODIFIED ADSORPTION SYSTEMS

A recent development in adsorption processes is systems designed specifically for control of low concentration (i.e., less than 100 ppm) OV gas streams that are based on an adsorber followed by treatment of the concentrated OV in the regenerated gas. There are basically three treatment options:

- **Discharge**. This method simply transfers the OV from the workplace to outdoors; it is apparently used in some industrial applications, primarily for odor control or worker exposure reasons.

- **Incineration**. Either thermal or catalytic incinerators can be used to oxidize the desorbed OV, which typically has as high as 10 to 15 times the OV concentration of the inlet gas (and also a correspondingly lower flow rate).

- **Recovery**. The OV in the desorbed gas can be recovered by condensation or other techniques.

3.3.1 Principle of Operation

The most promenant example of these modified adsorption based systems is a rotary carousel system (Figure 3-2). In these systems, one sector of the carousel is being used for adsorption while another sector is being regenerated (or desorbed) with hot gas. As the carousel turns, any one position alternately adsorbs OV from the gas and is then regenerated. There are several variations of these rotarary carousel systems on the market, differing primarily in the way the desorbed OV-containing gas is treated.

3.3.2 Applications

For OV concentrations of interest here, these modified adsorption systems offer the advantage of essentially concentrating the OV from less than 100 ppm in the vent gas to the range of 500 to 2,000 ppm in the regeneration gas. Of course, the flow rate of the regeneration gas is correspondingly lowered. This higher concentration/lower flow rate regeneration gas can then be treated in a number of ways. One vendor states

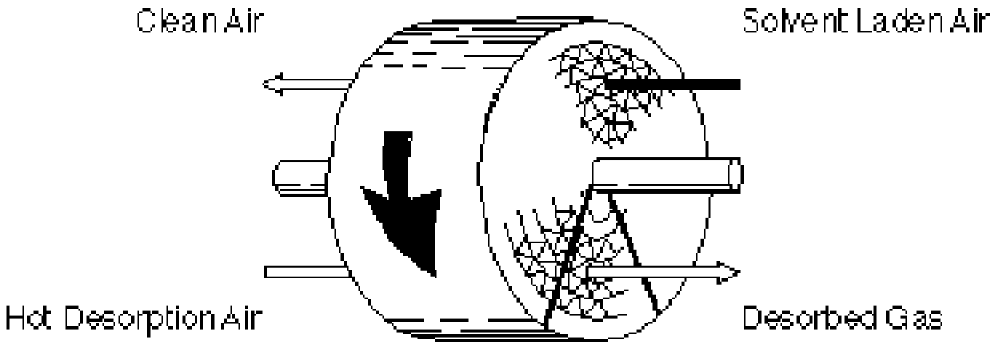


Figure 3-2 Rotary Carousel System

that their system is specifically designed for inlet concentrations in the 50 to 100 ppm range, at which neither nonregenerable nor regenerable fixed-bed adsorption systems are entirely suitable.[93]

Vendors offer several treatment options for this concentrated regeneration gas. These include thermal incineration, catalytic incineration, and a fixed-bed regenerable carbon bed system. The choice among these depends on the concentration and chemical nature of the OV. In general, thermal incineration is best for higher concentration gases consisting of many different OV constituents, above for example 1,500 ppm, and catalytic incineration is best at the lower end of the concentrated regeneration gas range, from 500 ppm up to about 1,500 ppm. A regenerable carbon bed is best used when the OV is of value and can be recovered and reused on site, which generally means single component gases.

Survey of the industry and the literature revealed 12 modified adsorption systems commercially available in 1991/1992, 5 of which use a rotary carousel adsorber with some type of downstream oxidation or recovery. These are described individually in Table 3-3.

3.3.3 Met-Pro KPR System

The KPR system (Figure 3-3) consists of a rotary carousel, made of microporous activated carbon fiber, designed to adsorb low concentration organics. These organics are then desorbed at a concentration roughly 5 to 15 times greater than that of the inlet gas. This desorbed gas, containing the concentrated contaminant, can be catalytically oxidized, or, in some applications, fed to a second regenerable carbon adsorption system where it is recovered. Catalytic oxidation is the method of choice for complex, multicomponent OV mixtures, whereas a second carbon adsorption system is best when the OV consists of only one or two compounds and has some value when recovered. When a catalytic incinerator is used, the heat from the combustion is used to indirectly heat the air used for desorption

Table 3-3. Modified Adsorption Systems

Trade Name	Vendor	Adsorbent	**Regeneration options**	**State of development**
KPR	Met-Pro Harleysville, PA	Rotary carbon carousel	Catalytic oxidation carbon adsorption	Commercially available
CADRE	Calgon Pittsburgh, PA	Fixed carbon beds	Thermal oxidation	Commercially available
Zeol Rotor Concentrators	Munters Zeol Amesburg, MA	Rotary hydrophobic zeolite	Incineration or carbon adsorption	Commercially available
EVOC	Catalytica Mountain View, CA	Noncarbon	Catalytic incineration	Developmental
Hybrid	Amcec Oak Brook, IL	Fixed carbon beds	Thermal incineration	Commercially available
Cyclosorbon	Dedert Corp. Olympia Fields, IL	Fixed beds, activated carbon or zeolite	Thermal incineration	Commercially available

Trade Name	Vendor	Adsorbent	**Regeneration options**	**State of development**
Honeydacs	Daikin Industries	Rotary carbon carousel	Catalytic incineration/ conventional recovery	Commercially available
Dürr	Dürr Industiries, Inc.,Plymouth,MI	Rotary carbon or Zeolite carousels	Thermal or Catalytic incinceration	Commercially available
Eisenmann System	Eisenmann, Inc. Crystal Lake, IL	Rotary carbon carousel	Catalytic or thermal incineration, or conventional recovery	Commercially available
Padre	Purus, Inc. San Jose, CA	Fixed bed polymer sorbent	Condensation	Commercially available
Vaporrex	Kelco Group, Inc. Rayham, MA	Fixed carbon beds	Condensation	Commercially available
EcoBac	EC&C Environmental Tempe, AZ	Fluidized carbon bed	Condensation	Commercially available

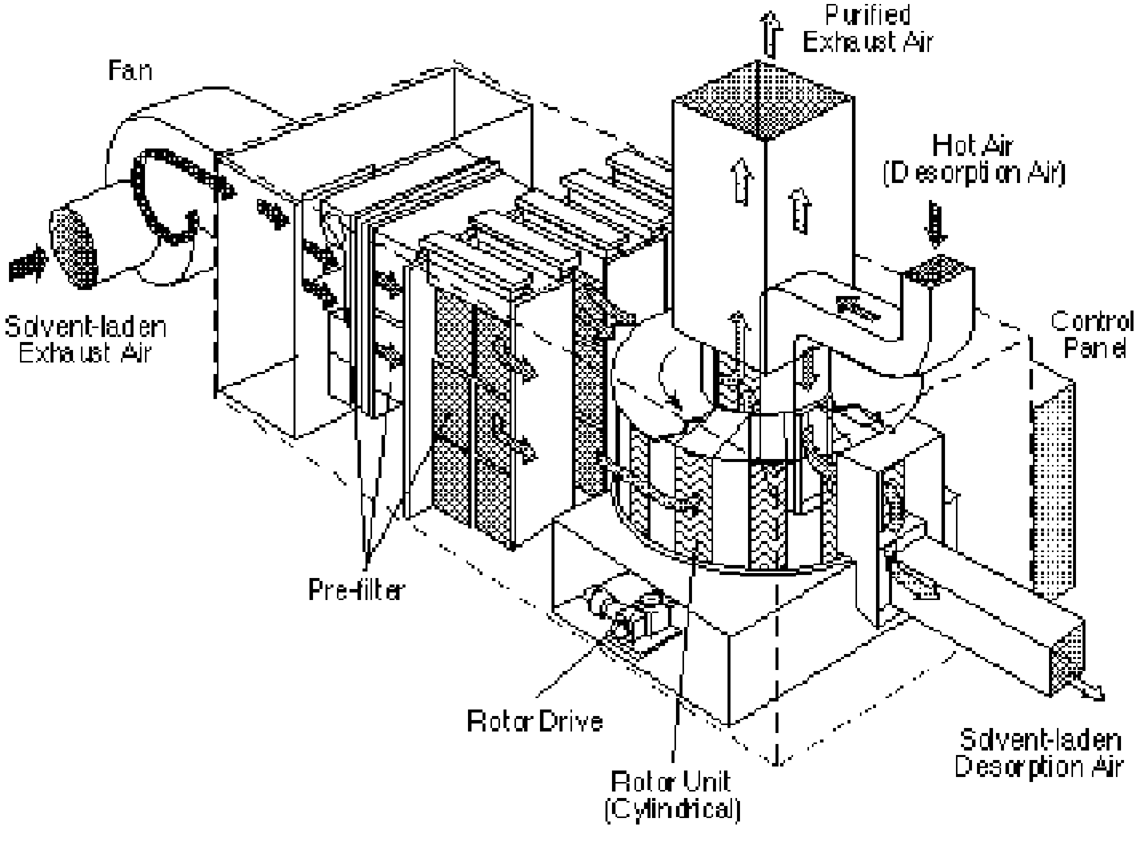


Figure 3-3 KPR System Flow Chart

of the rotary carousel. This, in turn, keeps energy costs down.

Table 3-4 shows data reported by Met-Pro for the KPR system for gases with inlet concentrations <100 ppm. The KPR system has also been used to control gases with higher inlet concentrations, but these data are not reported here. Tests 5 and 6 are the only ones for which emissions from both the rotary carousel adsorber and the catalytic incinerator are reported. If these results are general, it suggests that the mass emission rate (lb/h emitted) from the adsorber is less than that of the catalytic incinerator, though it must be kept in mind that the inlet gas concentration to the catalytic incinerator is 5 to 15 times higher than to the adsorber. Thus, even if the adsorber and incinerator have comparable removal efficiencies, higher mass emission rates from the incinerator would be expected.

Met-Pro KPR has installed several high flow, low concentration control systems worldwide. Most of the reported applications of the KPR system are for control of paint spray booth emissions. They are typically used in aerospace painting. Thirty systems are reported in use as of 1988, with sites in the United States, Europe, and Japan. One new U.S. installation is at the LTV aircraft manufacturing facility in Dallas, TX. This facility has been field tested.[94] Sizes for the KPR system range from roughly 10,000 to 100,000 scfm. In such applications, care must be taken to filter the air upstream of the rotary carousel to remove ordinary particulates and high molecular weight compounds. Both of these will quickly deactivate the carbon fiber used in the rotary carousel. Particulates are removed in two stages: one removing large particles (>5 m), and another using cloth filters to remove small particles (<5 m). High molecular weight organics (boiling point >400 °F), which will not readily desorb from carbon, are captured in a thin carbon bed upstream of the carousel that is either disposed or regenerated off-site.

Table 3-4. Field Data for MET-PRO KPR System

Test no.	Flow rate (scfm)	Adsorber Inlet concentration (ppm)	Adsorber outlet concentration (ppm)	Incinerator outlet concentration (ppm)	Overall removal efficiency (%)	Source	Reference
1.	18,400	53.08	NR	1.63	96.9[a]	Paint spray booth	Toyobo, Ltd. (Japan) Kenson, 1985[95]
2.	18,400	78.11	NR	1.43	98.2[a]	Paint spray booth	Toyobo, Ltd. (Japan) Kenson, 1985[96]
3.	11,300	59.94	NR	ND	>99.9[a]	Paint spray booth	Toyobo, Ltd. (Japan) Kenson, 1985[97]
4.	9,700	72.8	NR	ND	>99.9[a]	Paint spray booth	Toyobo, Ltd. (Japan) Kenson, 1985[98]
5.	56,100	5.8	0.3	2.6	90[b]	Aerospace plant paint booth	Kenson and Jackson, 1988[99]
6.	86,260	24	0.9	6.4	95[b]	Aerospace plant paint booth	Kenson and Jackson,1988[100]
7.	105,000[c]	24	NR[d]	NR[d]	95	Aerospace plant paint booth	Kenson, 1990[101]
8.	70,000[c]	5.8	NR	NR	90	Aerospace plant paint booth	Kenson, 1990[102]

ND= Not detected.

NR= Not reported.

[a] Based on incinerator only, this does not account for losses through the rotary carousel which would make the number somewhat lower.

[b] As reported by the author, a higher removal efficiency value is suggested by reported mass emission rates at this site.

[c] Tests 7 and 8 appear to be performance tests at the same site reported for tests 5 and 6, respectively.

[d] Inlet OV loading is reported as 23.04 lb/hr for test 7 and 3.668 lb/hr for test 8 and the combined OV emissions from both the rotary carousel and incinerator outlets total 1.197 lb/hr for test 7 and 3.623 lb/hr for test 8, giving an overall efficiency of 95% and 90%, respectively.

Overall control efficiency for the KPR system normally exceeds 90 percent, including the capture efficiency of the rotary carousel and destruction efficiency of the catalytic oxidation (or recovery) system. The individual efficiencies of the rotary carousel unit and catalytic unit are reported to be 95 to 98 percent each.

3.3.4 CADRE (Calgon, Inc.)

The CADRE process (Figure 3-4) uses two fixed beds of activated carbon (one on-line, one off-line) to adsorb dilute organics. The carbon beds function to concentrate the OV, producing upon regeneration a higher concentration, lower flow-rate gas stream that can be incinerated more economically compared to a thermal incinerator designed for the dilute inlet gas stream. Concentrating OV results in both lower capital costs (i.e., a smaller incinerator) and lower operating costs (i.e., less auxiliary fuel required for oxidation and the heat produced in the oxidation step used for regeneration of the carbon). This process was developed specifically for the control of gases with concentrations in the range of interest here. As with other adsorption based processes, particulates and high boiling compounds (>200°F) must be removed before the gas contacts the carbon beds.

The CADRE system can be applied to air-stripper offgases, surface coating operations, and a wide range of other manufacturing processes.[103] However, only seven actual installations of the CADRE system exist as of September 1991. The CADRE system is designed for 1,000 to 50,000 scfm but most installations to date have been for inlet gas concentrations above 100 ppm and for flow rates near 50,000 scfm. Results of a pilot unit test feeding a gas containing 230 to 350 ppm OV,[104] and tests results for gases below 100 ppm are shown in Table 3-5. Calgon recently has installed a new CADRE system controlling high flow, low concentration OV streams in the U.S. This system is installed on a 320,000 cfm paint booth at the Saturn Corporation in Spring Hill, TN. This system has reportedly undergone warranty testing, and is scheduled for an agency compliance test as soon as methods are approved by EPA.[105]

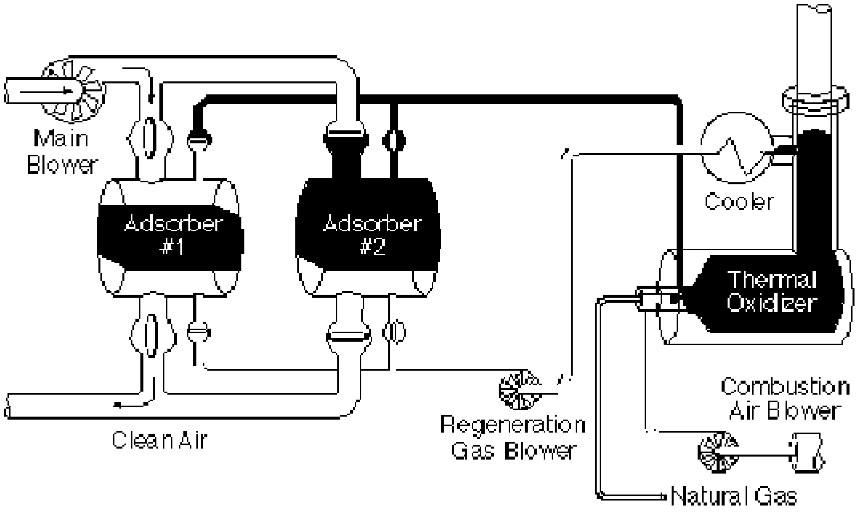


Figure 3-4 CADRE Adsorption-Regeneration Process

Table 3-5. Summary of Field Studies of CADRE Adsorption/Incineration System for Gases Containing less than 100 ppm Inlet OV Concentration

Vendor	Site	Gas flow (scfm)	Adsorber Inlet concentration (ppm)	Thermal Oxidizer Outlet concentration (ppm)	Destruction/ removal efficiency (%)	Comments/References
Calgon (CADRE)	Western Processing	2,650-3,170	31	NR	17-71	PEI, 1989[106]
Calgon (CADRE)	Purex, (Nassau County, NY)	9,000				NETAC, 1991[107]
Calgon (CADRE)	Occidental Chemical (Ashtabula, OH)	3,000	~15	NR[a]	NR[a]	CADRE system, used for periodic control of air-stripper offgases NETAC, 1991[108]
Calgon (CADRE)	Steelcase (Grand Rapids, MI)	77,000	73	NR	97	OV from furniture coating Calgon, 1991[109]
Calgon (CADRE)	Calgon pilot test	1,500	60-270	<0.1[b]	>99[c]	Chlorinated C_1,C_2 compounds , SenGupta and Schuliger, undated[110]

NR = Not reported

[a]Because of the high variability in inlet concentration, reliable data are not available.

[b]The CADRE process has two outlet gases, one from the carbon adsorber and one from the thermal oxidizer. The 0.1 ppm is the outlet from the oxidizer; the out concentration from the adsorber is not reported.

[c]This is the removal efficiency of the adsorber. The removal efficiency of the oxidizer is >99.8% based on 60 ppm inlet and a reported detection limit of 0.1 ppm.

SenGupta gives costs for a case study comparing a regenerative thermal oxidizer with 90 percent heat recovery and a CADRE system (consisting of multiple units) for a 110,000 scfm flow rate on an OV inlet concentration of 42 ppm.[111] Fuel costs for the regenerative thermal oxidizer are roughly an order of magnitude greater than for the CADRE system, making CADRE more economical, at least for this case study.

3.3.5 Catalytica

This process is similar in principle to other adsorption/incineration system such as the Met-Pro KPR process. The OV are adsorbed in a first stage, thermally desorbed, and then catalytically oxidized. Little technical detail of the technology is given by Catalytica. For example, the adsorbent is not disclosed nor is the contacting scheme (rotary carousel, fixed bed, etc.). A key to the process is said to be the “way in which the adsorbent and catalyst are heated.[112]” A technical brochure, apparently elaborating on this, states that “Heat is supplied only during the oxidation position of the cycles. . .” and “The adsorption and oxidation systems are heated directly . . .” Their process also is said to be highly automated and not to require dedicated operating labor.

Catalytica claims its process is most advantageous for gases in the 100 to 20,000 scfm flow range with concentrations between 50 and 1,000 ppm. They report what is presumed to be a lab demonstration giving 96 percent removal of 250 ppm methyl ethyl ketone in air.

Catalytica has no adsorption based control systems operating on low concentration, high flow OV streams in the U.S.[113]; therefore, the Catalytica system has not yet been field tested for the concentrations and flow rates of interest, though a working prototype was being developed under an EPA Phase II Small Business Innovative Research (SBIR) Grant at the time information was gathered for this report.

3.3.6 Munters Zeol

The Munters Zeol system (Figure 3-5) consists of a rotary adsorber, similar in principle to the Met Pro KPR unit, differing in that it rotates on a horizontal rather than vertical axis and that it is made from a hydrophobic zeolite rather than activated carbon fiber. As in the Met-Pro system, the dilute contaminant-bearing air flows through one sector of the carousel while, simultaneously, hot desorption air removes the contaminants in another sector, at a much higher concentration. As with other adsorption systems, both particulate filters and some adsorbent for removing high boiling compounds are provided. An interesting feature of the Munters system are zeolite beds located upstream of the rotary carousel. They are used to minimize rapid changes in OV concentration from the process by adsorbing them when their concentration is high and desorbing them into the inlet gas to the rotary carousel when the concentration drops. Though Munters Zeol does not manufacture either the incinerator or carbon recovery units for treating the concentrated desorbed gas, the company provides them for their customers.

Munters also makes a fixed-bed version using the same hydrophobic zeolite for applications where there are “reactive or high boiling solvents.” The high thermal stability of the zeolite allows the zeolite to be simply heated in air to high temperatures which either desorb the OV or burn it off.

Munters claims that their hydrophobic zeolite has two advantages over activated carbon. The first is a higher capacity at lower solvent concentrations (Figure 3-6). The second is a higher capacity at relative humidities above 50 percent (Figure 3-7).

Munters has provided a list showing installations using the hydrophobic zeolite system, in Europe, the USA, and Japan (Table 3-6). Inlet concentrations for these units vary from 20 to 150 ppm. No specific removal efficiencies are available for individual field installations, but meeting the European regulations would require 95 percent efficiency for an inlet concentration of 90 ppm or

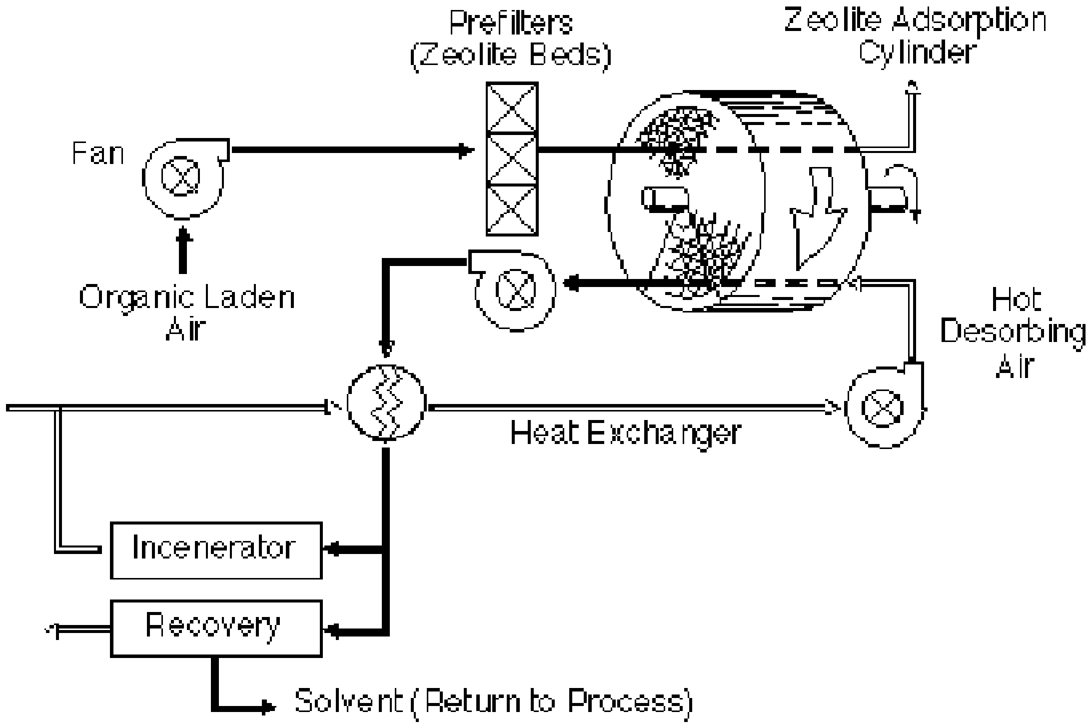
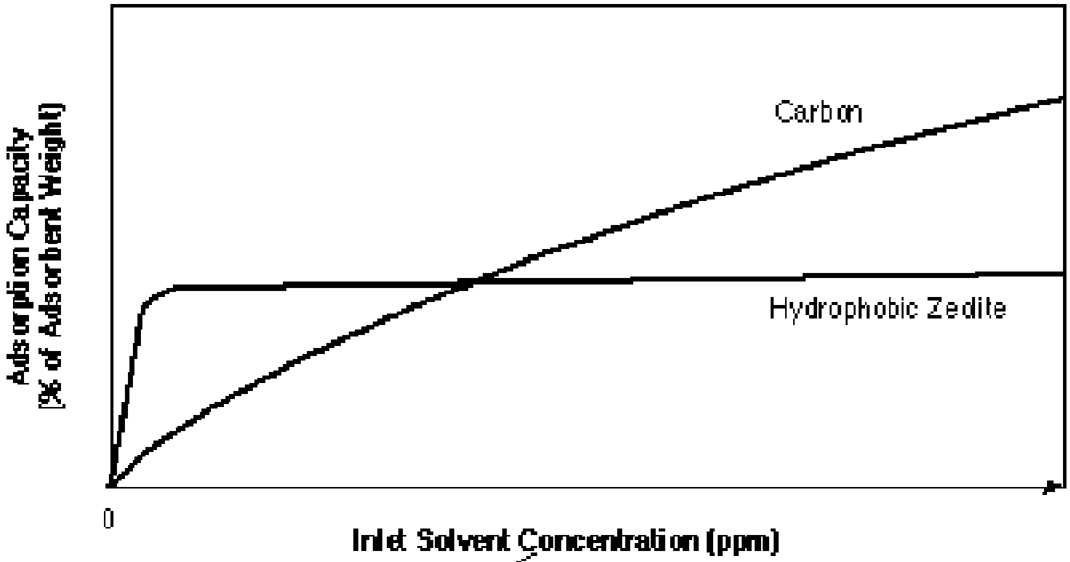
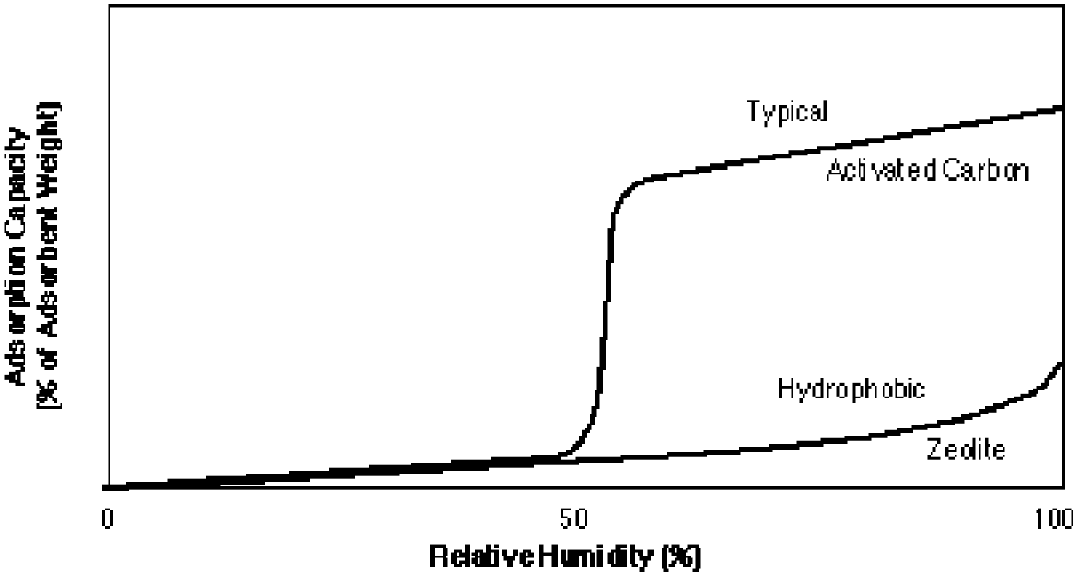


Figure 3-5 Munters Zeol System



Zedites have greater capacity than carbon at low inlet concentrations.
At high concentrations, carbon has more capacity.

Figure 3-6 Munters' Hydrophobic Zeolite Showing Inlet Solvent Concentration Versus Adsorption Capacity



Hydrophobic zeolites adsorb very little water until the relative
humidity exceeds 90%.

Figure 3-7 Munters' Hydrophobic Zeolite Showing Relative Humidity Versus Adsorption Capacity

Table 3-6. OV Abatement Systems Using Munters Hydrophobic Zeolites[a]

Company	Location	Size (cfm)	Plant type	Year of install	Type of pollutant	Industry
Installations in United States:						
GM	Linden,New Jersey	140,000	Concentrator	1993	Automotive Spray Painting	Automotive
Read Rite	Fremont, CA	30,000	Concentrator	1993	Mixed Solvents & Thermal Oxidizer	Semiconductor
Sillconix, Inc.	Milpitas, CA	10,000	Concentrator & Thermal Oxidizer	1993	Mixed Solvents	Semiconductor
Sillconix, Inc.	Milpitas, California	10,000	Concentrator & Thermal Oxidizer	1993	Mixed Solvents	Semiconductor
Digital Equipment Corporation	Shrewsbury, MA	20,000	Concentrator & Thermal Oxidizer	1993	Mixed Solvents	Semiconductor
Worthington Plastics	Mason, Ohio	64,000	Concentrator	1992	Paint Solvents	Automotive Plastic Parts
Munters	Jackson, GA	15,000	Concentrator & Catalytic Oxidizer	1992	MEK/Toluene	PVC Glueing
YDK America, Corporation Incorporated	Canton, Georgia	30,000	Concentrator & Catalytic Oxidizer	1991	Paint Solvents	Computer Plastic Parts
Installations in Europe:						
Tetra Pak	Berlin, Germany	26,000	Fixed Bed	1991	Plastic Fumes	Packaging
Becker Acronma	Marsta, Sweden	11,000	Concentrator	1991	Paint Solvents	Paint/ Resins Manufacturing
ABB Fläkt	Växjö, Sweden	59,000	Concentrator	1991	Paint Solvents	Auto Paint Pilot Plant
AIS/Citroèn	Rennes, France	18,000	Concentrator	1991	Paint Solvents	Automotive
Daimier Benz	Bremen, Germany	140,000	Concentrator	1991	Paint Solvents	Automotive
IBM	Paris, France	30,000	Concentrator & Thermal Oxidizer	1991	Acetone, NMP	Semiconductor
Hohe	Dorfprozelten, Germany	100,000	Concentrator Wet Electrostatic Precipitator	1991	Paint Solvents	Automotive Plastic Parts
Tetra Pak	Madrid, Spain	24,000	Fixed Bed	1990	Solvents	Packaging
Soab	Mölndal, Sweden	13,000	Concentrator & Thermal Oxidizer	1990	Solvents	Metal Fabrications
Volvo	Torslanda,Sweden	34,000	Concentrator	1990	Solvents	Automotive
Volvo	Umeå, Sweden	10,600	Concentrator & Catalytic Oxidizer	1990	Solvents	Automotive (Truck)
Volvo	Umeå, Sweden	75,000	Concentrator & Catalytic Oxidizer	1990	Solvents	Auto-Truck
Termoregulator	Motala, Sweden	18,000	Concentrator	1990	Solvents	Metal Fabricating
Tetra Pak	Forshaga,Sweden	27,000	Fixed Bed	1990	Solvents	Packaging
Saab	Luleå, Sweden	18,000	Concentrator & Catalytic Oxidizer	1990	Solvents	Automotive (Truck)
Daimier Benz	Bremen, Germany	24,000	Concentrator	1989	Solvents	Automotive
Nusec	Hamburg,Germany	1,200	Concentrator	1989	Petroleum Comp	Confidential
AGA	Knivsta, Sweden	11,000	Fixed Bed	1989	Solvents	Gas Cylinders
Tetra Pak	Lund, Sweden	27,000	Fixed Bed	1988	Plastic Fumes	Packaging
Dalmter Benz	Sindel Figen, Germany	1,000	Concentrator	1988	Solvents	Automotive Pilot Plant
Tetra Pak	Lund, Sweden	3,000	Fixed Bed	1987	Plastic Fumes	Packaging Pilot
Volvo	Torslanda,Sweden	3,500	Fixed Bed	1987	Solvents	Packaging Pilot
Installations in Japan:						
Toyo Can	Yokohama, Japan	7,000	Concentrator & Catalytic Incinerator	1993	Solvents	Can Coating
Hitachi Zosen	Japan	17,700	Concentrator & Catalytic Incinerator	1993	Solvents	Ship Building

[a] Inlet concentrations for these 32 installations vary from 20 to 150 ppm. Outlet concentrations were reported to meet regulations requiring less than 20 mg/Nm^3 which, for a compound of molecular weight 100 would be 4.5 ppm.

higher. European regulations, specifically the German “TA Luft,” require a specific *outlet* concentration of 20 mg/Nm^3 which, for a compound of molecular weight 100, would be 4.5 ppm. Flow rates for these installations range from 1,000 to 140,000 cfm and many applications are for control of painting emissions with typical (inlet) concentrations of 25 to 75 ppm OV; control efficiencies for these applications are reported by Munters to be generally above 95 percent.

Munters Zeol has installed one new control system in the U.S. It is a 135,000 cfm concentrator on a refinishing operation at Letterkenny Army Depot/ABB Paint in Chambersburg, PA. No source test data or permit information has been obtained for this unit.

3.3.7 Amcec

The Amcec HYBRID process uses multiple fixed beds of activated carbon to adsorb the OV (Figure 3-8). These beds are then cyclically regenerated using steam and the desorbed gas, containing a higher concentration of OV, is thermally oxidized. The heat from the oxidation step is used to produce the low pressure regeneration steam.

Amcec has no modified adsorption based control systems operating on low concentration, high flow OV streams in the U.S.[114]; though in mid-1991, they described a project involving two Amcec systems with a common oxidizer as being under construction. The size and inlet concentration were not given.

3.3.8 Dedert/Lurgi Cyclosorbon

Dedert markets a conventional dual fixed-bed carbon adsorber called Supersorbon™ .[115] The beds are regenerated with steam and the OV-steam mixture is condensed and gravity separated. A schematic is shown in Figure 3-9. As with other systems using steam regeneration, OV that reacts with steam or is miscible with water cannot be recovered in this system. However, common hydrocarbon solvents such as toluene, hexane, carbon tetrachloride, acetone, and methylene chloride can be recovered. There are plans to install this type of system on a waste wood-fired boiler at an installed cost of $300,000 for a 20,000 ft^3/min system ($15/$ft^3$/min).

In addition, Dedert/Lurgi has recently developed a modified adsorption process, the Cyclosorbon, that uses multiple cells of pelletized activated carbon or zeolite as the adsorbate. The concentrated desorption gas is then thermally incinerated. This system which is designed specifically for low organic concentration gas streams can process gas flows from 5.7 to

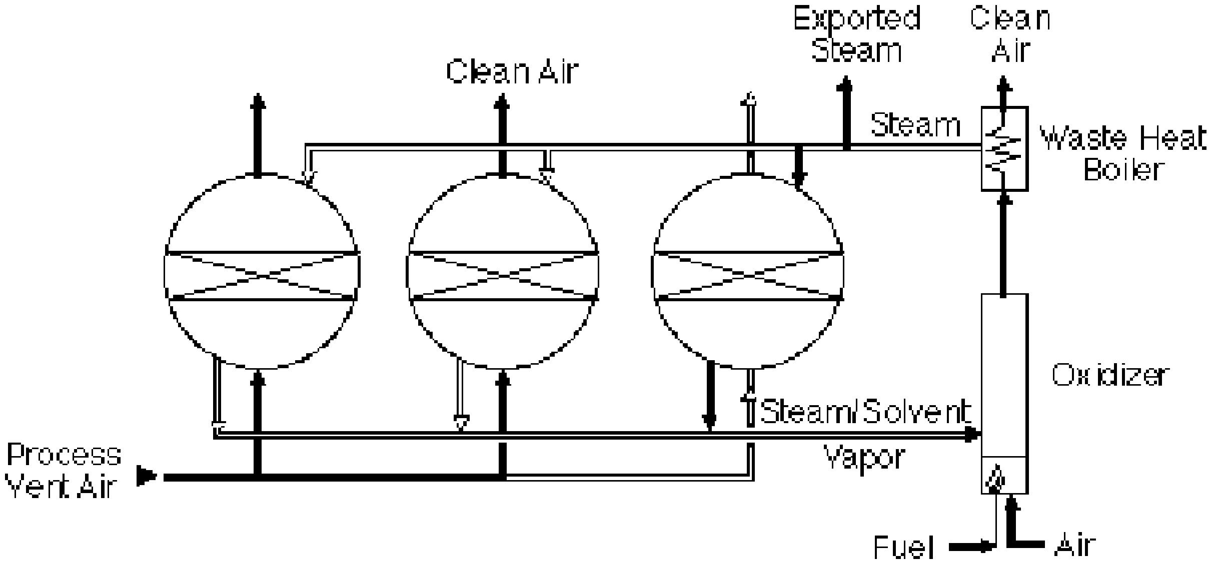


Figure 3-8 Amcec HYBRID Adsorption/Oxidizer Process

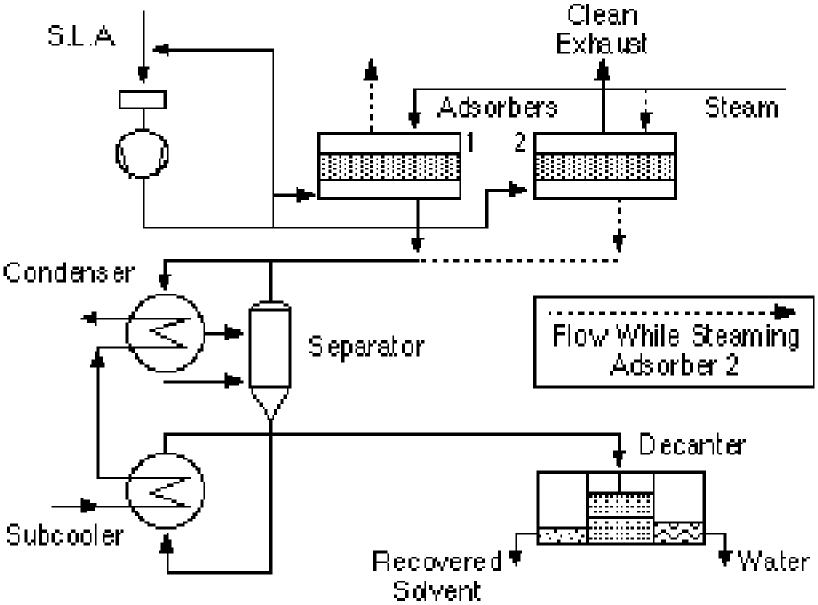


Figure 3-9 Supersorbon Solvent Recovery Plant

133.1 cms (12,000 to 282,000 scfm) by increasing the number of adsorber cells from one up to nine, as needed. The manufacturer notes that in the Cyclosorbon system (Figure 3-10) the adsorption cells are individually valved to allow operation in either adsorption or desorption mode. No performance or cost data are currently available from the manufacturer on this system; however, the manufacturer reports that the Cyclosorbon is competitively priced and offers advantages over the carousel (or rotary wheel) adsorber; for example, no rotating face seals are required, a wide selection of compatible adsorbent media are available, and the use of conventional adsorbents results in low cost replacement of adsorbent media when its useful life is finished. It is said to be applicable to OV concentrations from 50 to 500 ppm.[116] Installed capital costs range from about \$25/ft^3/min (for low flow rates) to 15/ft^3/min (for 100,000 ft^3/min or larger).[117] Dedert/Lurgi Cyclosorbon has no systems installed in the U.S. on high flow, low concentration OV streams at this time.[118]

3.3.9 HONEYDACS™ System (Daikin Industries)

This system is based on a rotary carbon wheel, similar in principle to that used in the Met-Pro KPR™ system previously described in this report. The OV-containing gas flows through one section of the wheel while hot desorption gas flows through another (see Figure 3-3). The desorbed gas is simply discharged outdoors in most odor control applications. However, Daikin Industries does provide both catalytic incineration and recovery options for the desorbed gas. They suggest that catalytic incineration be used when the OV concentration is 800 to 1,000 ppm, and that recovery be used for chlorinated OV. Table 3-7 shows the performance of the adsorption system on a hydrocarbon OV-containing gas from a paint booth with an inlet concentration of 172 ppm. Specifications are given in their product literature for various unit sizes with solvent concentrations of 100 ppm, suggesting that this system can be

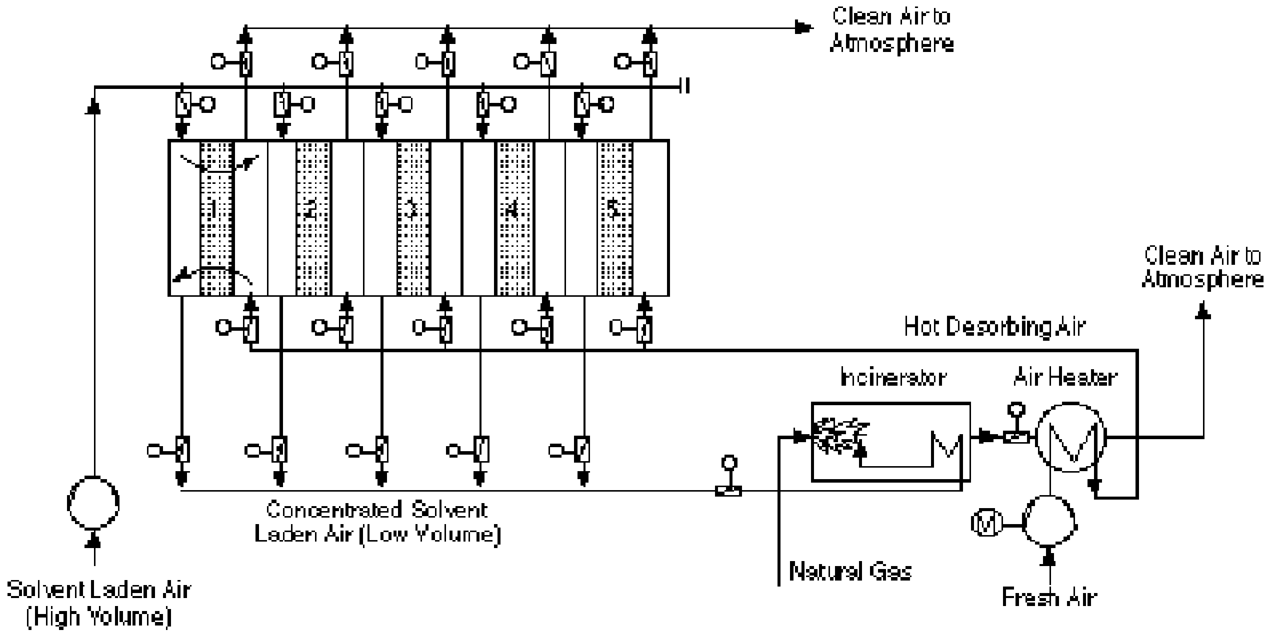


Figure 3-10 Dedert/Lurgi Cyclosorbon Modified Adsorption System

applied to the gas streams of interest here. No costs were available.

3.3.10 Dürr Industries System

Dürr manufactures various control systems including adsorption based rotary concentrators as well as incinerators with regenerative heat exchangers. Dürr also teams with other vendors such as Anguil to provide a variety of complete, integrated control systems. Crompton and Gupta describe a Dürr rotary adsorption system that can be **either** carbon or zeolite (Figure 3-11).[119] The rotary wheel is protected by a fixed carbon “guard bed” which removes high molecular weight compounds. The desorbed OV can be thermally or catalytically incinerated or recovered by condensation or a second-stage adsorber. Results are reported on a pilot unit (of unspecified size) for a ternary mixture of methanol, xylene, and methyl n-amyl ketone (MAK). Total OV inlet concentrations of these compounds were 80, 172, and 275 ppm, respectively. Results shown in Figure 3-12 correspond to removal efficiencies **in the adsorber** of about 93 percent for the three inlet concentrations for carbon. There will be some emissions from the thermal oxidizer as well. Somewhat lower removal removals (83 to 93 percent) were observed for the zeolite adsorbent. Rotary wheels containing both carbon and zeolite had higher removals than either single material (96 to 98 percent). Blocki presents test results from in-house studies of the Dürr system at OV concentrations of 70 and 85 ppm (Table 3-8).[120] Overall removals are 91 and 95 percent for two simulated solvent mixtures containing polar and nonpolar organics.

Table 3-7. Composition of Organic Solvents Versus Efficiency for the HONEYDACS™ System

Solvent	Exhaust gas concentration (ppm)	Purified gas concentration (ppm)	Deodorizing efficiency (%)
n-Hexane	2.2	0.6	72.7
Acetone	1.2	0.2	83.3
Benzene	5.4	0.4	92.6
Toluene	104.2	3.2	96.9
n-Butanol	11.4	0.3	97.4
p-Xylene	22.0	0.5	97.7
m-Xylene	18.8	0.4	97.9
o-Xylene	6.4	0.1	98.4
Total	171.6	5.7	96.7

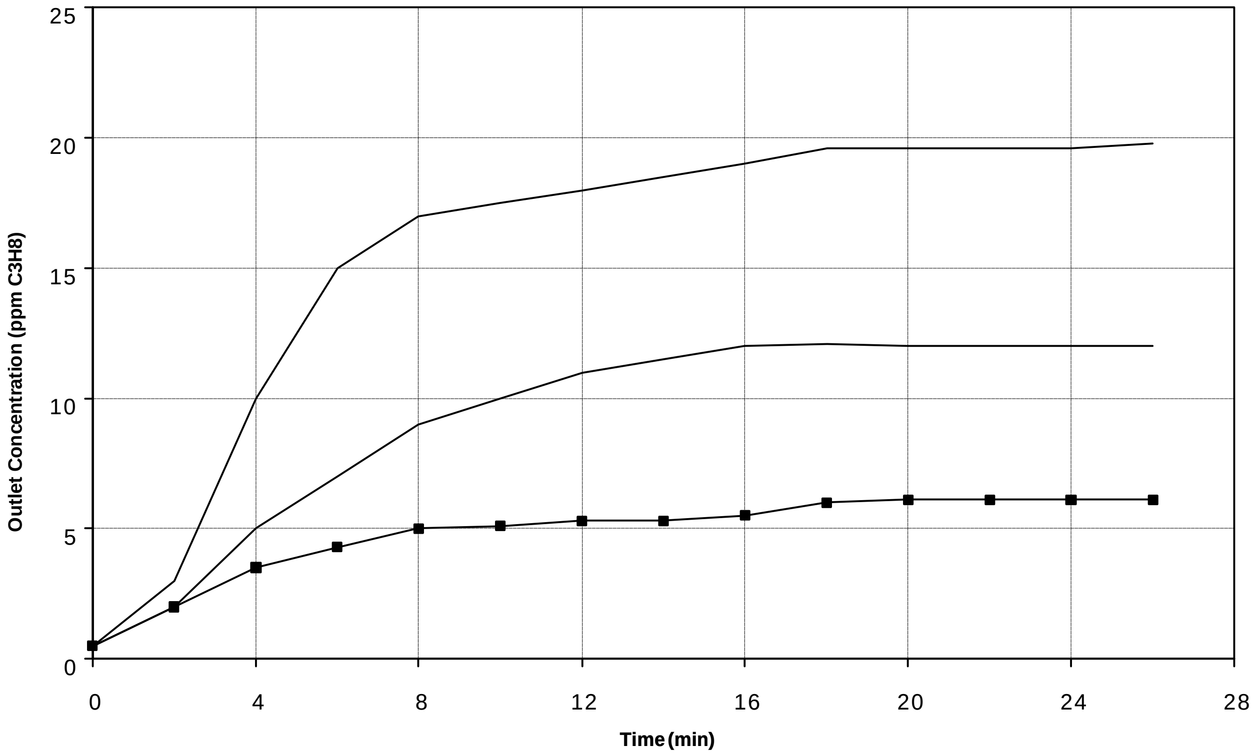


Figure 3-12. Outlet Concentration Profiles for Carbon Honeycomb Blocks for Solvent Mixture

Table 3-8. Results of Test of Dürr Industries System

Test Conditions	
Inlet gas temperature (°C)	32 °C
Inlet gas RH (%)	60
Face velocity (m/s)	1.8
Reactivation	160 ° C
Concentration ratio	10

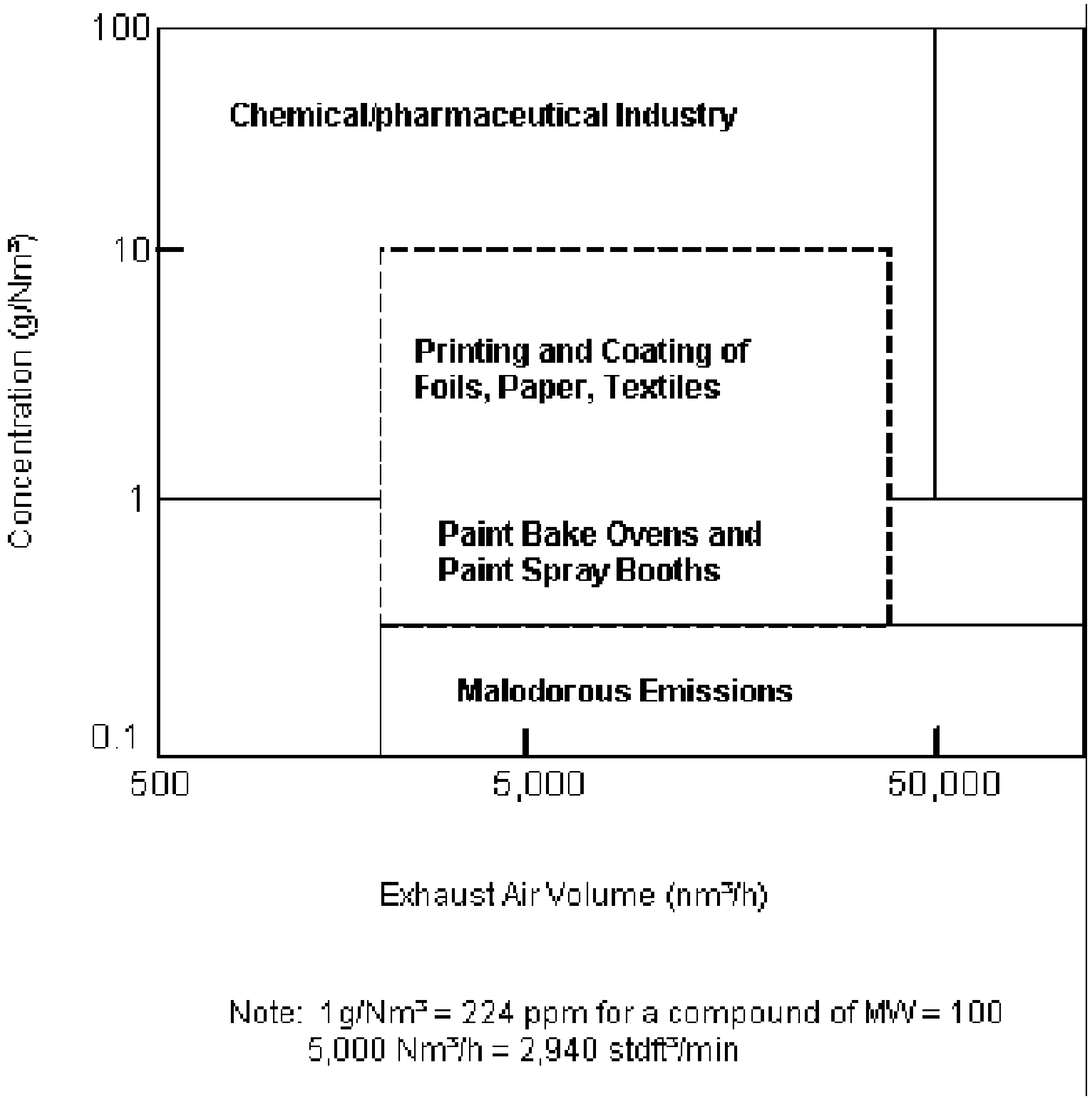
				Concentration (ppm)		
Solvent	**MW**	**vol%**	**BP (°C)**	**In**	**Out**	**Efficiency**
Solvent Compostion One						
Solvesso 100	--	20	160	14	1.72	87.7
Ethanol	46.1	21.9	78	15.3	3.37	78
MAK	114.2	16.1	150	11.3	N.D.	100
MEK	72.1	8.3	80	5.9	0.05	99.1
MIBK	100.2	7.6	118	5.3	N.D.	100
n-Butyl acetate	116.2	9.9	126	6.9	N.D.	100
Xylene	106	9.7	138	6.7	1.15	82.8
Octyl acetate	172	6.5	200	4.6	N.D.	100
wt'd avg.			127	70	6.29	91
Solvent Compostion Two						
Butyl Cellosolve Acetate	160	5.0	192	4.3	0	100
Xylene	106	80.0	138	68.0	3.3	95.2
IPA	60	8.0	66	6.8	0.8	88.0
Ethyl acetate	88	3.0	77	2.6	0	100
Butyl cellosolve	118	4.0	168	3.4	0	100
wt'd avg.			134	85.0	4.1	95.2

Figure 3-13 shows that, for the Dürr systems, catalytic and regenerative thermal oxidation and concentration (by adsorption, followed by recovery or oxidation) are applicable for the concentrations that are of interest here. This figure also characterizes OV concentration of less than 100 ppm as typically being malodorous, not necessarily hydrocarbons only. Dürr has seven control systems installed in the U.S. on high flow, low concentration organic vapor streams.[121] All use rotary zeolite or activated carbon adsorbers followed by incinerators. Six are installed on automobile painting lines, and one is installed on a semi-conductor facility.

Annual electricity and fuel costs are given (Table 3-9), but no allowance is made for low OV concentrations. The costs given, however, show the clear advantage of an adsorption concentrator. Table 3-10 presents a comparison of the Dürr system to a regenerative thermal oxidizer and a carbon-based rotary adsorption system, showing the lower utility costs of the latter two concentrators and a somewhat lower capital cost of the hydrophobic zeolite concentrator.

3.3.10.1 Permit Conditions

Review of the draft permit (dated, July 18, 1994) issued by the Air Pollution Control Bureau of the New Mexico Environment Department to the Intel Corporation does indicate that permit conditions are placed on the three Dürr VOC control systems in use at this facility.[122] Condition 1.c specifies allowable emission rates prior to control resulting from the Dürr thermal oxidizer. Condition 3.a establishes operating requirements for the units, and notes an oxidizer efficiency of 90%. Condition 3.c specifies that each thermal oxidizer unit shall achieve and maintain a VOC reduction efficiency of at lest 90% on an hourly basis for all VOC's except methanol (60%). Various other conditions are specified in Section C of the permit; these deal with requirements for the thermal oxidizer units relating to maintenance, restrictions on halogenated compounds, fuel use, firing rate, and incinerator combustion temperature. No



Note: 1 g/Nm³ = 224 ppm for a compound of MW = 100
5,000 Nm³/h = 2,940 stdft³/min

Figure 3-13 Dürr Industries Concentration Versus Flow Rate Application Chart

Table 3-9. Comparative Operating Costs for Dürr Systems

Abatement options	**Annual operating cost**		
30,000 std ft^3/min	**Gas**	**Electricity**	**Total**
Concentrator/thermal oxidizer	$18,854	$9,951	$28,805
Regenerative thermal oxidizer	66,568	77,942	144,510
Recuperative thermal oxidizer	320,309	28,169	348,478
Catalytic thermal oxidizer	172,931	28,169	201,100

1. Solvent credit for 50 lb/h input at 15,000 Btu/lb.
2. Gas cost = $3.00/1,000 ft^3
3. Electric power cost = $0.05/kWh
4. Annual operating hours = 8,000/yr.

Table 3-10. Dürr Industries Comparative Costs

Case One	Regenerative thermal oxidation	Carbon rotor concentration/ thermal oxidation	Hydrophobic zeolite concentration/ thermal oxidation	Basis
Investment cost (base=100)	100	102.8	91.7	68,000 cfm
Fuel gas	$145,300	$45,800	$45,800	$4.00/MMBtu
Electricity	$105,200	$25,800	$24,800	$0.05/kWh
Dry filters	$19,300[a]	$19,300	$19,300	1.0 g/K stdft^3 inlet
Total utility cost	$269,800	$90,900	$90,900	

Case Two	Direct regenerative thermal oxidation	Hydrophobic zeolite concentration/thermal oxidation	Basis
Complete cost	$8,200,000	$7,800,000	327,000 cfm
Fuel	$574,600	$79,200	$4.00/MMBtu
Electricity	$496,100	$134,900	$0.06/kWh
Dry filters	$0[a]	$60,200	1.5 g/K stdft^3 inlet
Total annual cost	$1,070,700	$274,300	

[a] Dry filters are not mandatory for the regenerative thermal oxidation option. Without filters a bake-out feature is typically purchased. When operated, fuel gas expense will be higher than stated above.

permit conditions relate to the gas stream characteristics, such as flow rate or VOC concentration, for the Dürr systems at the facility.

Review of the engineering evaluation included in the New United Motor Manufacturing, Inc., (NUMMI) facility in Fremont, California application for an air permit (Application Number 3611, Plant Number 1438) indicated that Dürr rotary carbon adsorption/incineration systems were proposed a BACT for control of VOC emission from paint shop spray booths.[123] The estimated capture efficiency of these systems is reported by NUMMI as 85% and the minimum destruction efficiency of the incinerator is 95%. NUMMI estimates that the cost of VOC control for the spray booth will be approximately $20,000 per ton, using a 10 year annualization.

3.3.10.2 Source Testing Data

Review of the source test report for the stack testing conducted at the Ford Motor Company's Twin Cities Assembly Plant in April 1993 indicates that the Dürr concentrator/ oxidizer system achieved an overall VOC removal efficiency of 95.8 percent.[124] The total inlet gas flow rate was calculated to average about 370,000 dscfm during the test runs. The inlet VOC concentration was well below 100 ppmv, averaging about 50.4 ppmv on the uncontrolled stream (measured as propane). The carbon wheel removal efficiency was calculated at an average of 97 percent. The incinerator outlet was measured to be 39,565 dscfm with a VOC concentration of 10 ppm, for an overall emission rate of 2.78 lb/hr from the incinerator exhaust. Interpretation of the available source test summaries was not straight forward however; a diagram of the source and control device would aide in further interpreting the test results in relation to the overall performance of the control system.

VOC destruction efficiency and emissions testing were conducted in January, February, and March, 1992, on the incinerators located at the New United Motor Manufacturing, Inc. (NUMMI) facility in Fremont, California.[125] At the NUMMI automotive production facility, fumes from the truck plant coating ovens are vented to four Dürr thermal incinerators; fumes from the truck plant spray booths are vented to three combination carbon adsorption and incineration units. The incinerators were tested by simultaneously monitoring the inlet duct of the incinerator and the outlet exhaust stack for VOC concentration using BAAQMD method St-7; tests were conducted at a variety of incinerator operating temperatures, flow rates, inlet VOC mass loadings, and VOC concentrations. This was done in order to ascertain the effect of incinerator temperature on controlled emissions. Gas stream VOC inlet concentrations varied from as low as 30 ppm to as high as 1500 ppmv. Flow rates for the incinerator test were quite low; most units showed inlet flows of less than 10,000 scfm. No flows were reported prior to the rotary concentrator. The VOC destruction efficiencies determined under the variety of operating conditions were, in nearly all cases, greater than 95%.

3.3.11 Eisenmann System

Eisenmann markets a rotary adsorption system that can be coupled with either a catalytic or thermal incinerator (for low value, multicomponent OV) or a condenser (for high value, relatively pure OV). Figure 3-14 shows the rotary system coupled to a thermal oxidizer for OV destruction and Figure 3-15 shows the rotary system coupled to a condenser for OV recovery. Table 3-11 summarizes field installations reported by Eisenmann for OV concentrations approaching 100 ppm.

3.3.12 Purus System

Purus has developed the PADRE™ system that uses a hydrophobic polymer sorbent developed by Dow. A schematic is shown in Figure 3-16. The system consists of dual fixed beds which are alternately on-line and off-line. The OV is condensed and recycled. One advantage claimed by Purus is that the Dow sorbent has high OV capacity even at high humidities. This appears to have led to a number of applications of this system for air stripping and soil venting.

One field installation in California is operating on a small (14 ft^3/min) gas flow with inlet OV concentration of 330 ppm of C_2 chlorinated solvents. Adsorption isotherms are provided by Purus for OV concentrations down to less than 10 ppm, suggesting that the sorbent is capable of removing practical levels of OV at inlet concentrations that are of interest here. No costs were available.

3.3.13 Kelco System

The VAPOREX™ system is similar in principle to the Dedert Supersorbon system. It consists of dual fixed carbon beds with steam regeneration. The OV is condensed and either recycled or disposed (Figure 3-17). Field applications of the system have been low flow rate gases

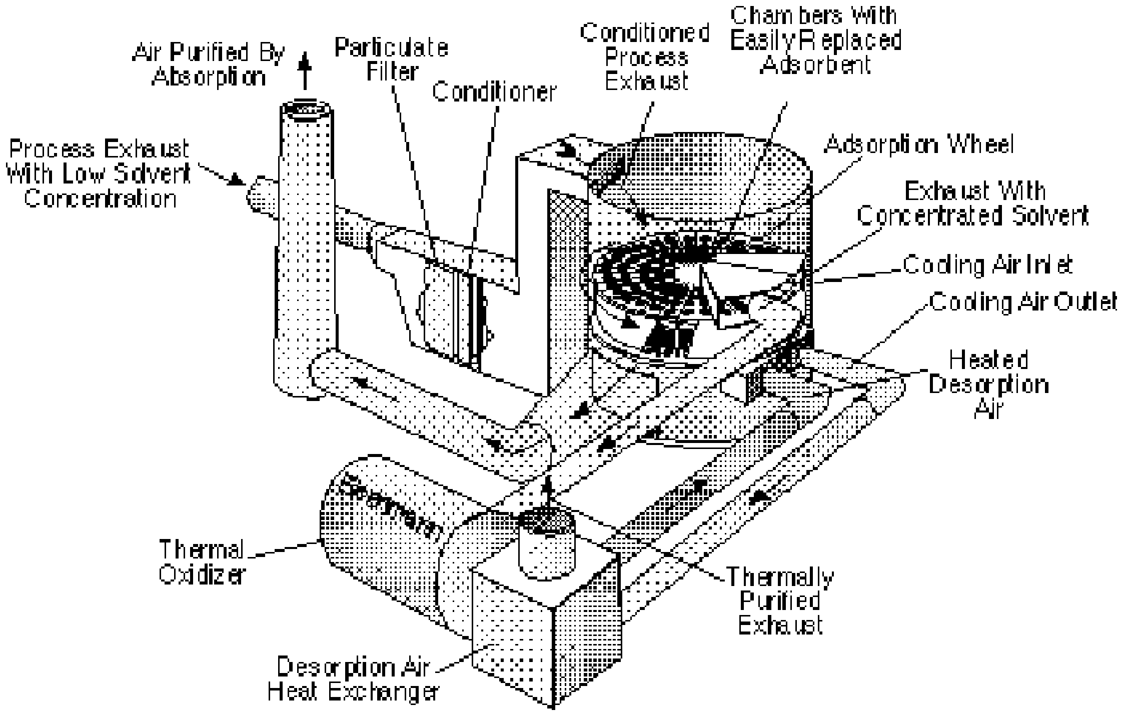


Figure 3-14. The Eisenmann Rotary Adsorber.

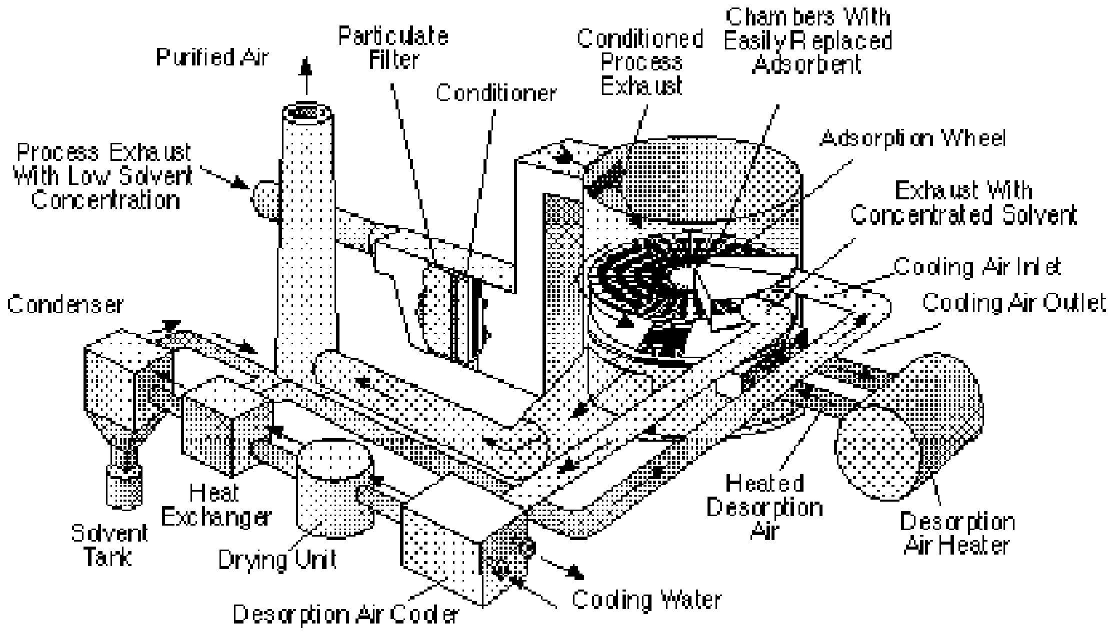


Figure 3-15 The Eisenmann Rotary Adsorber Coupled With Condensation System for Solvent Recovery

Table 3-11. Eisenmann Adsorption System Field Installations

OV source	Inlet conc. (ppm)	Inlet flow (stdft^3/min)	Desorbed OV treatment
Paint spray booth	160[a]	35,300	Condensation
Low temperature paint ovens	125-150	17,600	Thermal oxidiation
Coil coating	160	15,300	Returned to process oven

[a] OV consist of toluenes, methyl isobutyl ketone, methoxy 2 propyl acetate, ethyl glycol, and butanol.

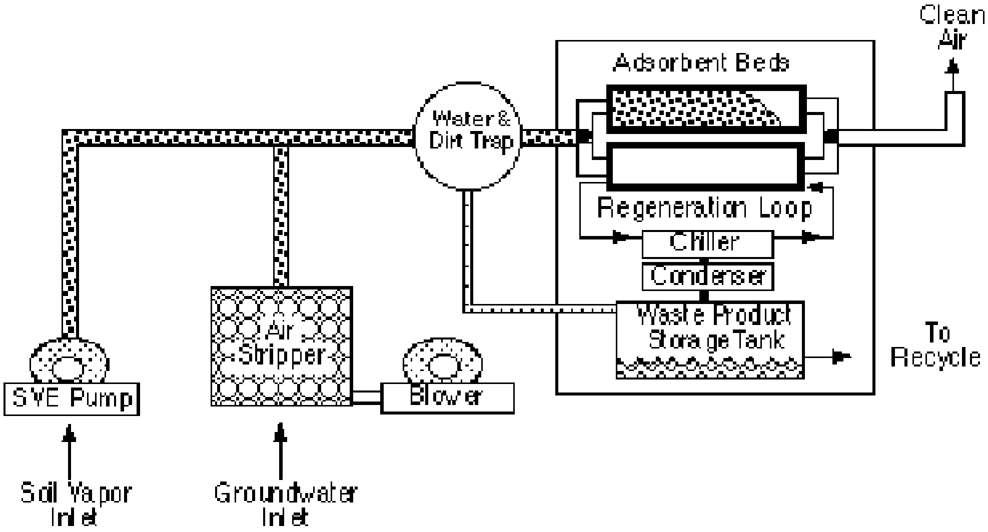


Figure 3-16 PADRE™ Schematic: Soil or Water Remediation Vapor Treatment System

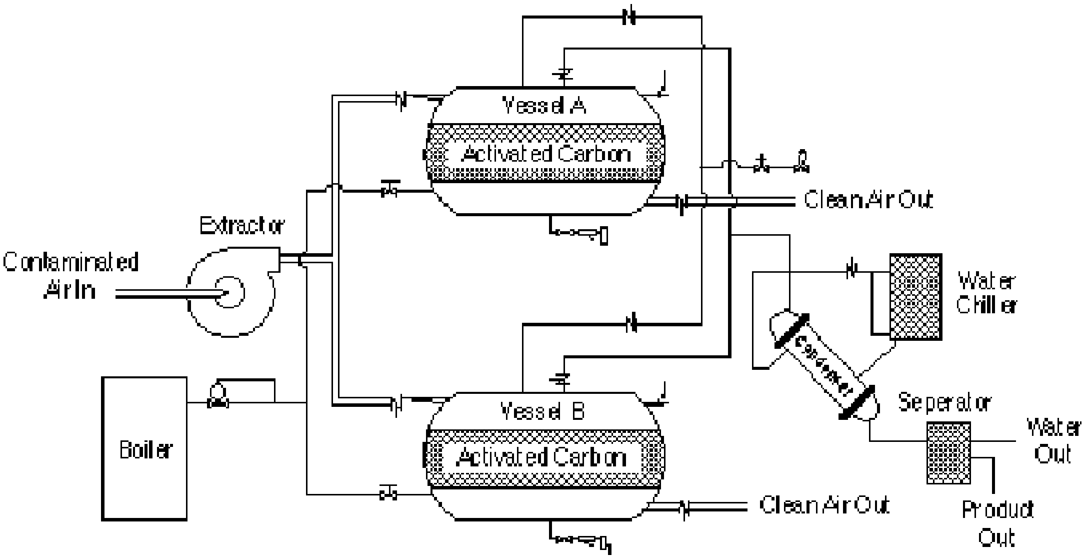


Figure 3-17 Kelco VAPOREX™ System

(<600 scfm) from air stripping or soil extraction. Inlet OV concentrations in these applications often decrease dramatically with time, sometimes from levels as high as 10^4 ppm. In principle, however, this system would be applicable to low OV concentrations. Equipment costs for a 600 ft^3/min are $35,000.[126]

3.3.14 EC&C System

EC&C developed the EcoBAC™ system, which is a fluid-bed carbon adsorption system (Figure 3-18). The principle of operation relies on the same adsorption/desorption process common to all adsorption systems. The difference is that the process is carried out continuously in one vessel as the carbon itself moves from the top (adsorption) section to the bottom (desorption or "stripping") section. The "stripping agent" in this case is an inert hot gas which removes the OV from the carbon, after which the OV is condensed and recovered. The stripping agent can be steam, hot nitrogen, or even hot ambient air in some cases.

Vendor literature states that for unspecified "low" OV concentrations and high air flows, this system is preferable to fixed-bed systems because, in fixed beds, the small working capacity of the carbon requires large bed volumes and long regeneration times. Table 3-12 gives some actual field data, showing applications with inlet OV concentrations as low as 30 ppm. This system is generally most cost effective for high flow rates; the largest reported application for this technology is 145,000 scfm. There are 1,000 installations worldwide. Table 3-13 gives a summary of applications.

3.4 COSTS FOR ADSORPTION SYSTEMS

Table 3-14 shows total annualized costs and corresponding cost effectiveness for nonregenerable and regenerable carbon-based adsorption processes. Available information was insufficient to evaluate the modified regenerable systems. These costs are calculated for 10,000 scfm gas flow, other assumptions are described in Appendix B.

Table 3-12. Field Data for EcoBAC™ System

Application	VOC makeup	Inlet (ppmv)	Outlet (ppmv)	Removal (%)
Ink production	Toluene, MEK, IPA, etc.	350	10	98.2
Semiconductor	Phenol	200	0.05	>99
Semiconductor	Phenol, solvent blend	100	0.05	>99
Semiconductor	Naphthalene, mixed solvents	100	0.05	>99
LSI	Phenol, DCB	250	10	96
Magnetic tape production	Terpenes, mixed solvents	30	0.01	>99

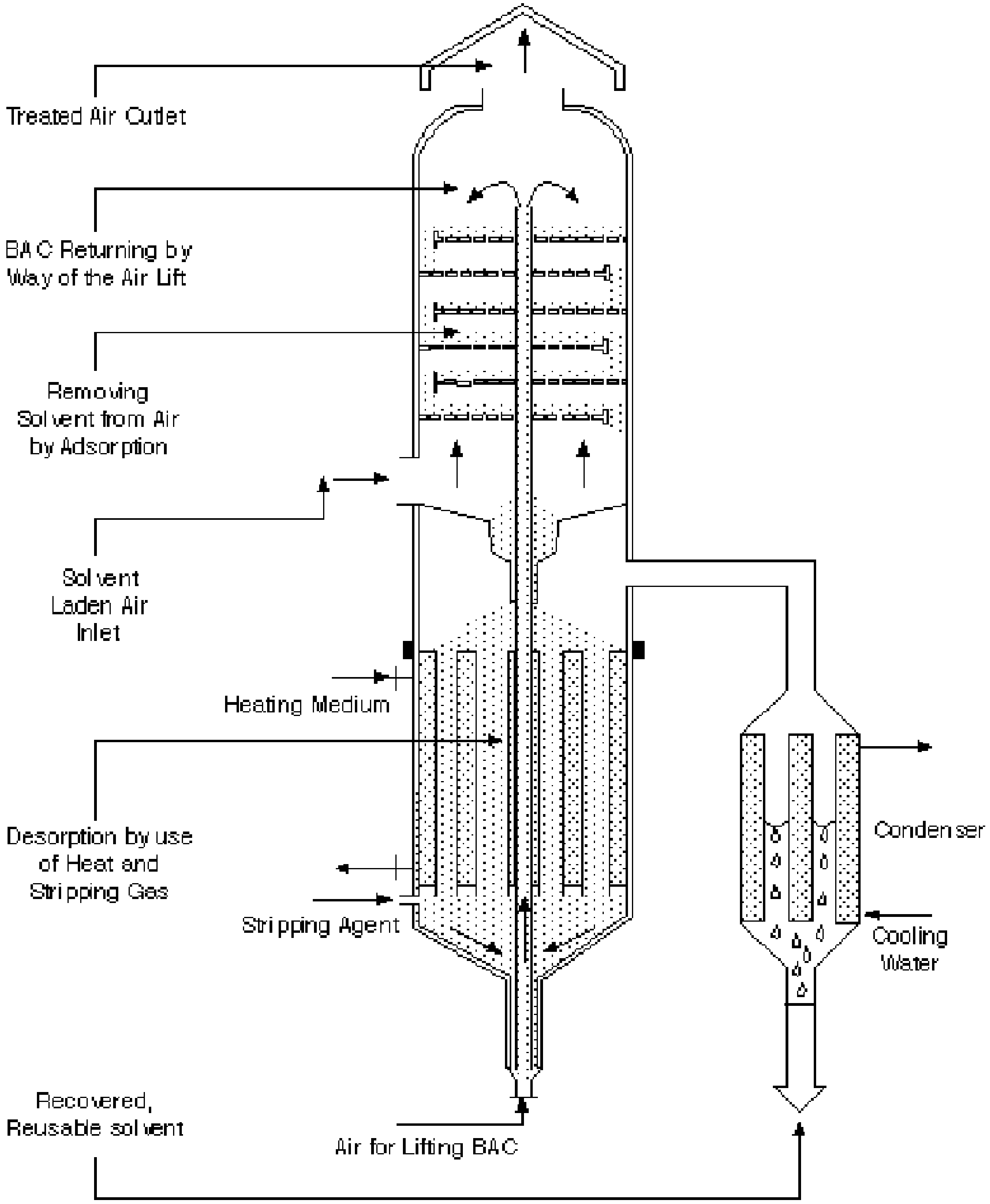

Treated Air Outlet
BAC Returning by Way of the Air Lift
Removing Solvent from Air by Adsorption
Solvent Laden Air Inlet
Heating Medium
Desorption by use of Heat and Stripping Gas
Stripping Agent
Condenser
Cooling Water
Recovered, Reusable solvent
Air for Lifting BAC

Figure 3-18 ECC EcoBAC™ System

Table 3-13. Application of the EC&C System by Industry Type and Materials Treated

Fabric washing	Perchloroethylene
Car wash	Kerosene
Auto parts degreasing	Trichloroethylene
Chemical production	Carbon tetrachloride
PVC resin manufacturing plant	Vinyl chloride
Feed processing	Odor control
Film coating	Toluene
Paint booth	Thinner
Animal lab	Odor control
Lacquering of film	Toluene, ethyl acetate, MEK
Gravure printing	Toluene, xylene
Medicine manufacturing plant	Butanol
Electronics parts cleaning	Trichloroethylene, toluene, etc.
Adhesive tape manufacturing	Toluene
Iron casting	Phenol, formaldehyde, ammonia
Film laminating	Toluene, ethyl acetate, *n*-hexane
Magnetic tape	Chlorinated hydrocarbon
Film coating	MEK, methyl cellosolve, etc.
Electronics manufacturing plant	DMF, MEK, etc.
Aluminum casting	Phenol, formaldehyde, ammonia
Wastewater aeration	Ordor control
Gravure printing	Mixed solvents
Landfill	Odor control
Ceramic condenser	ὰ-Terpineol
Atomic power plant	Styrene
Medicine manufacturing plant	Methylene chloride
Brewery	Odor control
Sand paper manufacturing	Toluene, xylene, ethyl acetate
Bakery	Odor control
Lubrication manufacturing	Mixed solvent odor control
Chemical production	Toluene, higher m.w. alcohols
Coating process	Acrylate odor
Printing ink manufacturing	Mixed solvents
Film coating	Tetrahydrofuran
Rubber coating	Toluene
Resin manufacturing	*n*-Hexane
Agricultural products	Organic acid & ammonia odor
Confectionery	Odor control
Gravure printing	*n*-Propanol, *n*-propyl acetate
Rubber vulcanizing	Odor control
Electronic parts cleaning	1,1,1-trichloroethane
Resin plant	Methylene chloride
Silk screen printing	Xylene, mixed solvents
Cellophane coating	Toluene, ethyl acetate, butyl acetate
Dye production	Perchloroethylene
LSI manufacturing plant	Phenol, mixed solvents
Electronics manufacturing plant	Trifluorotrichloroethane
LSI manufacturing plant	Acetone, methanol, etc.

Table 3-14. Cost Effectiveness of Adsorption Processes

	Benzene concentration		Tetrachloroethylene concentration	
	100 ppm	**10 ppm**	**100 ppm**	**10 ppm**
Nonregenerable Total annualized costs,[a] $/yr	1,285,000	241,000	991,000	171,900
Cost effectiveness,[a] $/ton OV removed	25,900	48,700	20,000	34,700
Regenerable fixed-bed total annualized costs	98,900	61,100	88,200	58,700
Cost Effectiveness[a] $/ton OV removed	2,000	12,300	1,800	11,900

[a] All costs are in 1991 dollars rounded to nearest $100; estimates are based on 10,000 scfm flow rate. Other assumptions discussed in text and Appendix B.

SECTION 4
ABSORPTION

Absorption is a commonly applied operation in chemical processing that is used as a raw material and/or a product recovery technique in separation and purification of gaseous streams containing high concentrations of organics (e.g., in natural gas purification and coke by-product operations). In absorption, the organics in the gas stream are dissolved in a liquid. The contact between the absorbing liquid and the vent gas is accomplished in counter current spray towers, scrubbers, or packed or plate columns. This emission control technique is much more commonly employed for inorganic vapors (e.g., hydrogen sulfide, chlorides) than for organic vapors.

The use of absorption as the primary control technique for organic vapors is subject to several limitations and problems. One problem is the availability of a suitable solvent. The OV must be soluble in the absorbing liquid and even then, for any given absorbent liquid, only OV that are soluble can be removed. Some common solvents that may be useful for volatile organics include water, mineral oils, or other nonvolatile petroleum oils. Another factor that affects the suitability of absorption for organic emissions control is the availability of vapor/liquid equilibrium data for the specific organic/solvent system in question. Such data are necessary for the design of absorber systems; however, they are not readily available for uncommon organic compounds. Another consideration in the application of absorption as a control technique is the treatment or disposal of the material removed from the absorber. In most cases, the scrubbing liquid containing the OV is regenerated in an operation known as stripping, in which the OV is desorbed from the absorbent liquid, typically at elevated temperatures and/or under vacuum; the OV is then recovered as a liquid by a condenser. In addition, the low outlet concentrations typically required in organic air pollution control applications often lead to impractically tall absorption towers, long contact times, and high liquid-gas ratios that may not be economically viable.[127] Nevertheless, for many organics, absorption can be used to achieve extremely low outlet concentrations.

Only one commercial system was identified that is directly applicable to low concentration (i.e., less than 100 ppm) organic gas streams, although the use of absorption processes at higher organic concentrations and for organic removal coupled with sulfur dioxide (SO_2) and hydrochloric acid (HCl) removal is reported.[128,129,130]

4.1 QVF GLASTECHNIK

4.1.1 Principle of Operation

QVF (Weisbaden, Germany) has developed an absorption process specifically for low concentration OV removal. The OV-containing gas is brought into contact with a liquid at ambient temperature and pressure in a countercurrent absorber into which the OV dissolves.

The contaminant-containing liquid is then regenerated by steam in a stripping column at 100 to 130°C temperatures under vacuum (around 50 mbar or 38 mmHg). The regenerated liquid is then returned to the absorber column. The process is shown in Figure 4-1.

Because the OV must be soluble in the absorbing liquid, the choice of the liquid is critical. The QVF system uses tetraethyleneglycol dimethylether. The process is limited to OV with boiling points greater than 30°C. High humidities are said not to adversely affect the process, though water vapor is absorbed and later desorbed in the stripping column.

Because the system recovers the OV (with no ultimate disposal), this process is limited to those gases containing compounds with boiling points above 30 °C and that have some value when recovered. Otherwise, subsequent disposal is needed. This system should thus be compared to regenerable carbon adsorption processes. However, carbon systems frequently are not able to recover low concentration OV at the 95 percent efficiency level in a consistent and practicable way. Thus, the QVF system may have some technical or cost advantage when both low concentrations and high removal efficiencies are required.

The systems are designed in accordance with the German “TA-Luft regulations,” which place limits on both mass flow and concentration, depending on the defined “class” of the emission:

$$\begin{array}{l}\text{Capital Cost for}\\ \text{10,000 scfm units}\end{array} = \left(\frac{10{,}000}{5{,}883}\right)^{0.6} (\$1.1 \text{ million}) = \$1.51 \text{ million}$$

Class	Mass flow	Concentration	Typical solvents
I	> 0.1 kg/h	20 mg/Nm^3	dichloromethane, acetaldehyde, dichlorobenzene
II	> 2.0 kg/h	100 mg/Nm^3	ethylbenzene, toluene, styrene
III	> 3.0 kg/h	150 mg/Nm^3	acetone, alcohols, ethers

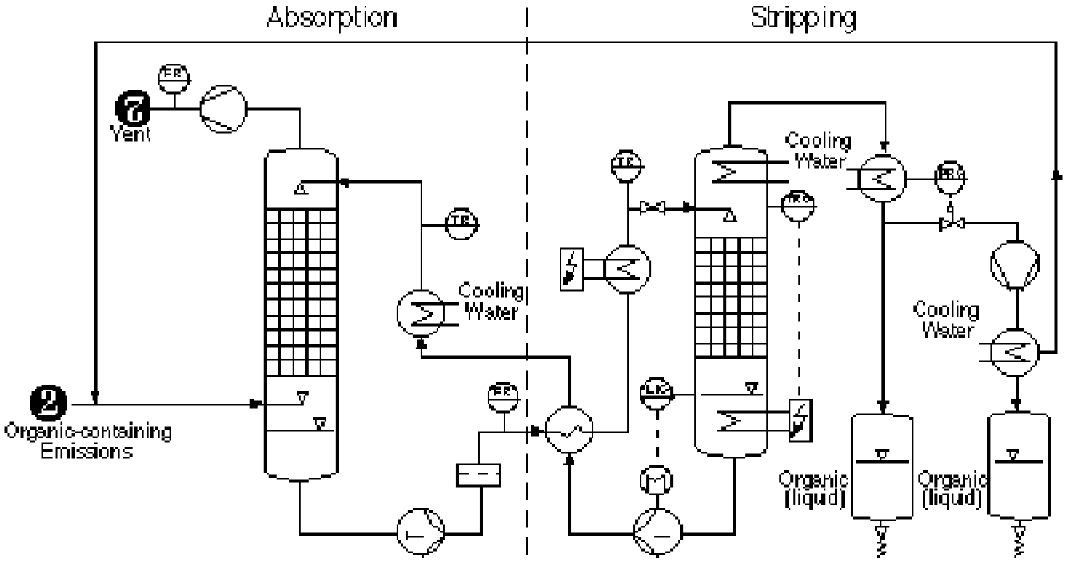


Figure 4-1 QVF Process

4.1.2 Applications

No currently documented control system for low concentration, high flow OV streams in the U.S. used QVF Glastechnik devices. One initial press release on QVF Glastechnik process[131] states that it is designed to be used in applications where suitably low exit concentrations cannot be achieved with carbon adsorption. QVF has 13 plants either installed or under construction as of mid-1991; however, no data are yet available on these sites. A mobile pilot unit (20 scfm) has been built and tested on a gas stream containing between 2 and 45 ppm methylene chloride, but no results are reported by QVF.

4.1.3 Costs

Costs for the QVF absorption process are based solely on information supplied by the vendor. Capital costs for a 10,000 m^3/h (5,883 scfm) unit are given[132] as $1.1 million. This $1.1 million is assumed to be the total capital investment, including direct and indirect installation costs. This cost is scaled up to the 10,000 scfm model gas stream flow rate using an exponential factor of 0.6, i.e.,

Utility usage rates are scaled linearly from the following values given for the 5,883 scfm unit:

	Size	
Utility	5,883 scfm	10,000 scfm
Electricity	11 kW	18.7 kW
Cooling Water	22 gpm	37.4gpm

The nature of the absorption process is that the operating costs are essentially independent of concentration in the range of interest here. This is because the energy needed for circulation and heating of the absorbent depends primarily on the volume of absorbent, which is constant for the cases considered here. The energy and cooling water are assumed to be independent of concentration and are also, for the purposes of this report, assumed to be the same for benzene and tetrachloroethylene.

Costs and cost-effectiveness values are shown in Table 4-1.

Table 4-1. Cost Effectiveness for QVF Absorption Process

	Benzene concentration		**Tetrachloroethylene concentration**	
	100 ppm	**10 ppm**	**100 ppm**	**10 ppm**
Total annualized costs,[a] $/yr	331,400	331,400	331,400	331,400
Cost effectiveness,[a] $/ton OV removed	6,700	66,900	3,300	32,800

[a] All costs are in 1991 dollars rounded to nearest $100; estimates are based on 10,000 scfm flow rate. Other assumptions discussed in text.

4.2 QUAD

4.2.1 Principle of Operation

The QUAD system for OV control is an absorption technology developed and patented by QUAD Environmental Technologies Corporation as the Chemtact system. In principle, it is simply a once-through (non-regenerable) absorption process in which the absorbing liquid is finely atomized. No liquid stripping section is provided (as in the case of the QVF process). This technology was traditionally used for odor control applications where the contaminant concentration may be only a few ppm and the mass of organics involved was not considered to be a significant air pollution problem. The QUAD system has only recently been employed for removal of toxic and nontoxic OV generated in ventilated air at wastewater facilities; in this and other types of air pollution applications, the mass of organics would be greater and their ultimate removal or destruction must be considered.[133,134]

The QUAD system consists of a concurrent gas-liquid absorption chamber. Figure 4-2 shows the schematic diagram of such an atomized mist system. The contaminated air enters from the top and the OV-free air is discharged from the bottom of the tower. The crucial component of this system is a patented liquid atomizing nozzle located at the inlet of the reaction chamber. The nozzle is designed to continuously spray liquid droplets as small as 10 m into the reaction tower. This provides a very high surface area between the gas and liquid interface. The OV molecules are absorbed from the gas phase into these fine liquid droplets. The clean air is vented to the atmosphere and the atomized mist containing the OV is coalesced and removed from the base of the reaction chamber as a liquid for further treatment. OV removal efficiency has been reported to be as high 90 to 95 percent by this method.[135,136]

The liquid absorbent solution consists of softened water mixed with sodium hypochlorite. Depending on the type and concentration of the OV, the pH of the scrubbing solution is adjusted with an alkali such as sodium hydroxide. The high pH of the solution helps in capturing acid gases. Different chemical additives can be used to enhance the OV removal efficiency.

Every QUAD Chemtact system can be custom designed to handle varying OV concentrations, type of OV, destruction efficiency, and total gas flow rates. By varying the tower diameter from 6 to 12 ft, the system can be designed to handle air flows ranging from 500 to 70,000 cfm. Depending on the desired destruction efficiency, the design gas-liquid contact times can be varied from 10 to 60 seconds by varying the tower height from 10 to 70 ft.

One advantage of this technology over the conventional countercurrent packed tower is the complete use of the scrubbing solution and therefore no liquid recycle. This decreases the consumption of chemicals and water and also reduces the electrical power requirement needed to circulate the absorbent liquid between the absorption and stripping towers in a conventional system (e.g., Figure 4-1). Furthermore, since the reaction chamber in the QUAD system is empty, it provides low pressure drop and does not plug up. However, with a once-through nonregenerable absorption process, a water treatment step is necessary for ultimate removal or destruction of the organics.

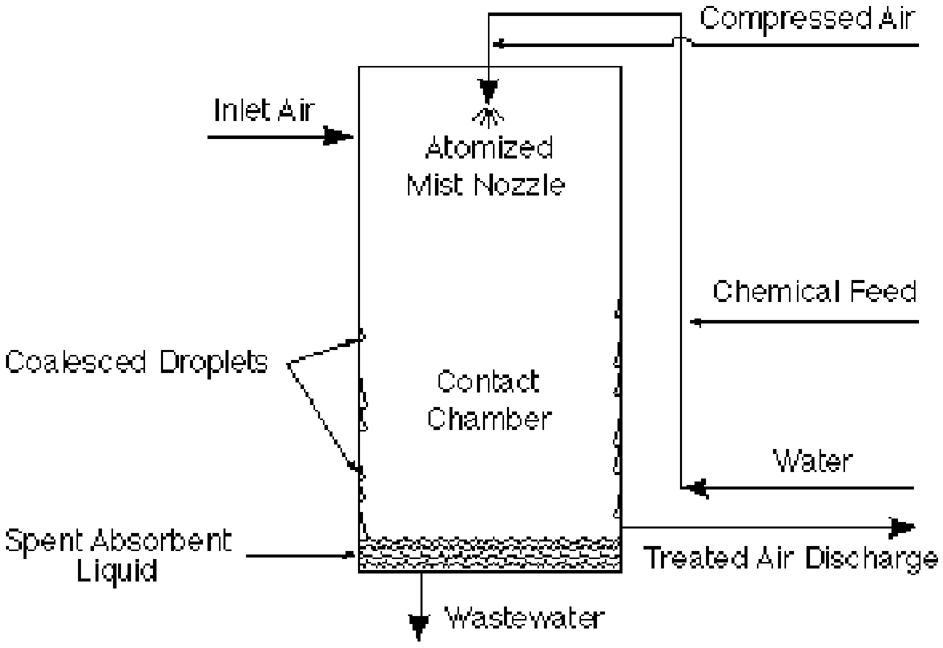


Figure 4-2 Schematic Diagram of an Atomized Mist System – QUAD System

4.2.2 Applications

This system is frequently used for odor control at wastewater treatment plants and rendering plants; the manufacturer reported that more than 30 systems were installed in 1992 and 1993 for this purpose.[137] QUAD also has installed several systems controlling low concentration OV streams in the U.S., but the flows do not exceed 75,000 cfm. Table 4-2 shows information from a few of the sites at which this technology has been applied. Tables 4-3 to 4-6 present the OV removal efficiencies from various sites using the QUAD system. In all cases, the overall removals were in the range of 60 to 98 percent, most frequently over 80 percent. In general, the removal efficiency for benzene was effectively 100 percent. However, the toluene removal efficiency was in the range of 50 to 93 percent.

4.2.3 Permit Conditions

The permit issued to Valley Proteins, Inc., by the Maryland Air Management Administration (Permit No. 02-00023, Issued October 1, 1992) lists a QUAD system, two stage fog air scrubber, Model 11-11-1, in the permit's source description.[138] The spray scrubber serves as control equipment for the Dupps Continuous Rendering Cookers. The State reported in their cover letter that there are no source test information or data available on this facility, but, the company reported that the control equipment had been stack tested in July 1992. No gas stream flow rate or concentration data were contained in the permit. The only terms and conditions in the permit were a requirement for proper maintenance and operation of the QUAD scrubbing system. No limits or restrictions are placed on the emission rate, gas stream characteristics, or overall performance of the device as a part of the operating permit.

4.2.4 Costs

Although no cost data were available at the time information was gathered for this report, the vendor believes this technology to be significantly cost competitive compared to carbon adsorption. Ullinsky et al. have compared the cost for treatment of 90,000 scfm air flow at Los Angeles - Glendale water

Table 4-2. Summary of Field Studies of QUAD System for Gases Containing less than 100 ppm Inlet OV Concentrations

Technology	Vendor	Site	Gas flow (scfm)	Concentration, ppm Inlet	Outlet	Removal efficiency (%)	Reference
Mist scrubbing	QUAD	Site 1	NR	3.61[a]	1.17	67.6	Rafson (1991)[139]
		Site 2	NR	10.75[b]	1.65	84.6	
		Site 3	NR	0.49[c]	0.083	83.2	
		Site 4	NR	1.25[d]	0.027	97.8	

NR = Not reported
[a]Mixture of benzene, toluene and an unknown. Feedstream from wastewater plant.
[b]Mixture of benzene and toluene. Feedstream from wastewater plant.
[c]Mixture of benzene, toluene and an unknown. Feedstream from compost facility.
[d]Mixture of benzene, toluene and an unknown. Feedstream from dewatering facility.

Table 4-3. Results of OV Removal from Wastewater Plant Using the QUAD System - Site 1

OV	Concentration (ppm)		Removal efficiency (%)
	Inlet	Outlet	
Benzene	0.135	ND[a]	>96.3
Toluene	2.75	0.97	64.7
Unknown 1	0.55	0.2	63.6
Four more unknowns	0.175	ND	>97.1
Total	3.61	1.17	67.6

[a] ND = less than 0.005 ppm

Table 4-4. Results of OV Removal from Wastewater Plant Using the QUAD System - Site 2

OV	Concentration (ppm)		Removal efficiency (%)
	Inlet	Outlet	
Benzene	0.05	ND[a]	>90
Toluene	10.7	1.65	84.6
Total	10.75	1.65	84.6

[a] ND = less than 0.005 ppm

Table 4-5. Results of OV Removal from a Compost Facility Using the QUAD System

OV	Concentration (ppm)		Removal efficiency (%)
	Inlet	Outlet	
Unknown	0.005	ND[a]	>37.5
Benzene	0.279	ND	>97.1
Toluene	0.206	0.083	59.7
Total	0.493	0.083	83.16

[a] ND = Less than 0.005 ppm

Table 4-6. Results of OV Removal from a Dewatering Facility Using the QUAD System

OV	Concentration (ppm)		Removal efficiency (%)
	Inlet	Outlet	
Unknown	0.863	ND[a]	>99.4
Benzene	0.005	ND	>28.6
Toluene	0.378	0.027	92.8
Total	1.248	0.027	97.84

[a] ND = Less than 0.005 ppm

reclamation plant (LAGWRP).[140] The cost comparison is shown in Table 4-7. Dunson, referring specifically to wastewater plant odor control, states that this type of technology is less expensive than others for concentrations below 100 ppm.[141] It is not clear whether the cost of subsequent treatment of the saturated absorbent liquid is included.

4.3 DAVIS PROCESS SYSTEM

A number of different contacting systems are available for this absorption based technology; all are based on countercurrent packed towers (Figure 4-3). The OV-containing gas (typically containing H_2S or mercaptans), at inlet concentrations of 60 to 100 ppm, is fed into the towers. The scrubbing solution removes the OV and the spent solution is simply returned to the wastewater plant or discharged. No recovery is attempted because of the dilute concentrations of contaminant in the scrubbing liquid.

Table 4-7. ODOR/OV Emission Control Systems Costs[a]

(FOR EXPANDED 50 mgd PLAN, 90,000 scfm AIR FLOW)

	Capital cost[b]	**Annual cost**[c]
Mist scrubber (QUAD)	$1,304,000	$251,000
Granular carbon adsorption	2,723,000	1,472,000
Mist scrubber/incineration	3,394,000	1,635,000

[a] All costs are in 1991 dollars.

[b] Includes 10 percent contingencies and 15 percent allowance for engineering, legal, and administrative.

[c] Includes amortized capital cost (20 years, 8-5/8 percent), power, labor, chemical, and material costs.

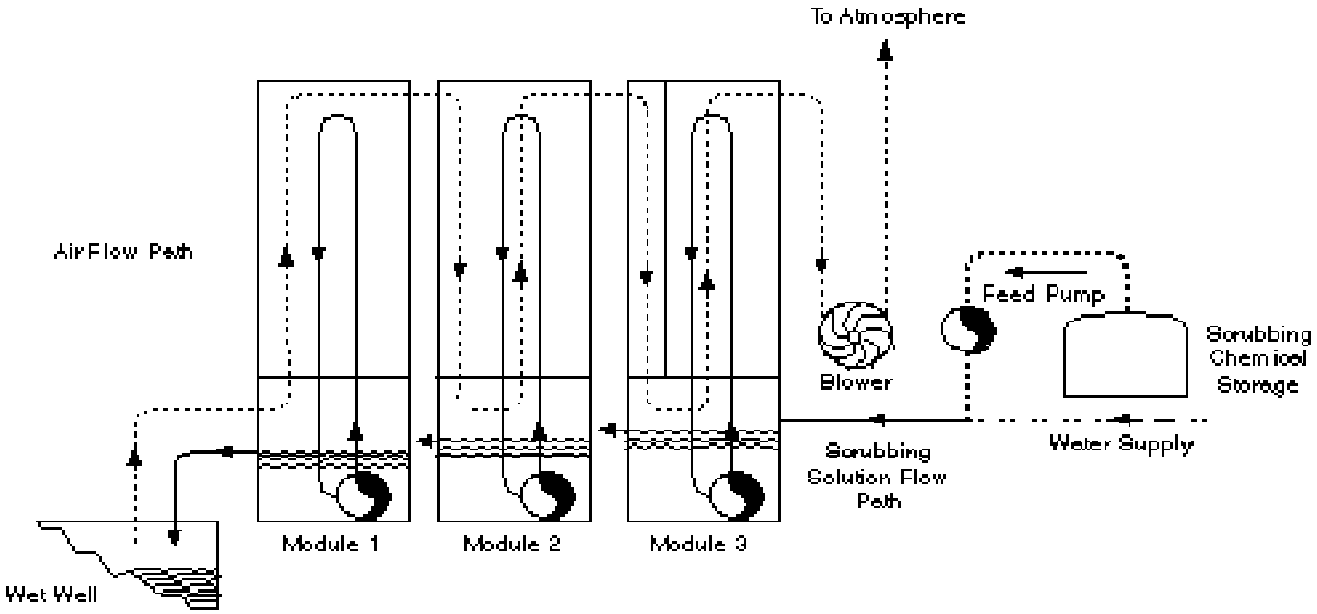


Figure 4-3 Typical Triplex™Scrubber System Operational Flow Diagram

SECTION 5
OTHER COMMERCIAL TECHNOLOGIES

In addition to the technologies described in Sections 2.0 through 4.0, there are two other commercially available processes that differ in principle from those described earlier and have been applied to low concentration gases. Table 5-1 summarizes the results reported on these processes.

5.1 ULTROX D-TOX SYSTEM

5.1.1 Principle of Operation

Ultrox International (Santa Ana, CA) has developed a catalytic oxidation system called D-TOX Process for destroying OV in humid air.[142] This system uses small amounts of ozone to oxidize the organic compounds to carbon dioxide and water. A patented oxidizing catalyst is used for this purpose. The use of ozone enables the oxidation to be conducted at a relatively low temperature, 160 to 220 °F. Any unreacted ozone in the effluent stream is converted back to oxygen using a second catalyst. An adsorption bed placed downstream of the catalytic reactor is used to capture any residuals or acids. The adsorbent is made up of a mixture of bases and is replaced about every 3 months. The catalyst life is about 2 years.

The schematic of the Ultrox system is shown in Figure 5-1.[143] [No process schematic was provided by Ultrox for the D-TOX system. It is assumed that the system shown in Figure 5-1 also represents the D-TOX process.] No exhaust gas stream is shown in Figure 5-1 by Palazzolo et al. (1986, p. 14). It is assumed that the exhaust gas to the atmosphere is located just downstream of the degasser. The OV-containing air stream is introduced upstream of the gas-phase UV-catalytic reactor shown in Figure 5-1. An air-stripping unit, which is part of the commercial Ultrox system and which is located between the ozone generator and reactor in Figure 5-1, was not used in the tests reported by Palazzolo et al. and is therefore not included in Figure 5-1. The major parts of this system are the ozone generator and a gas phase UV-catalytic

Table 5-1. Summary of Field Studies of Other Commercial Technologies for Gases Containing less than 100 ppm Inlet OV Concentrations

Technology	**Vendor**	**Site**	**Gas flow (scfm)**	**Concentration, ppm**		**Destruction efficiency (%)**	**Reference**
				Inlet	**Outlet**		
Enhanced carbon adsorption	Terr-Aqua Enviro Systems	General Dynamics Pomona Division, CA	29,523	31[a,b]	0.31	99	Jackson(1991)[144]
				52[a,b]	0.21	99.6	
UV/oxidation	Ultrox (D-Tox)	Pilot test	20	2.8-10.6	1.9-7.2[c]	19-64	Palazzolo, et al. (1986)[145]

[a] OV include acetone, butyl acetate, ethyl acetate, toluene, and xylene.
[b] Concentration converted to ppm from lb/h summing an average molecular weight of 80.
[c] Calculated from reported destruction efficiencies.

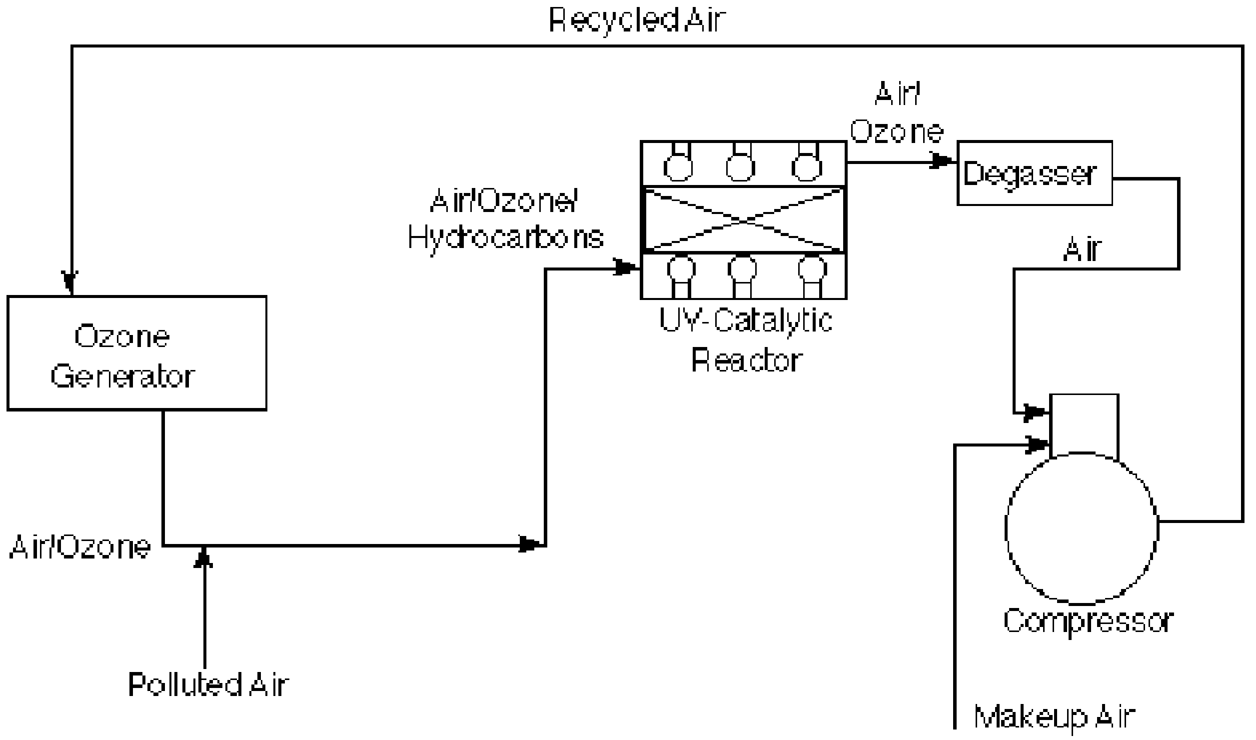


Figure 5-1 Schematic Diagram of Pilot-Scale Ultrox D-TOX UV-Catalytic Test System

reactor. The OV-laden air is mixed with small amounts of ozone and passed over the catalyst in the reactor. The reactor contains UV lamps with a specific wavelength. The heat generated in the reactor by UV lamps is removed by a precooled stream of air or nitrogen

5.1.2 Applications

To date, the D-TOX Process has been installed at three locations although none are documented for low concentration, high flow OV streams in the U.S. Performance data from these three locations and from several pilot plant studies indicate 95 to 99 percent OV destruction are achievable with feed concentration ranging from <2 ppm to 200 ppm.

In a parametric test of the Ultrox D-TOX process on a 20 scfm pilot plant,[146] the effect of inlet D-TOX OV concentration was investigated by using two feed streams: one with about 15 ppm concentration, and the other with about 3 ppm. Both streams contained trichloroethylene and 1,2-dichloroethylene. A series of experiments were conducted to study the effect of UV, ozone, space velocity and humidity on the OV destruction efficiency.

The presence of ozone in the feed stream was found to be important in achieving high destruction efficiency. Thus, destruction efficiencies of only 16 to 67 percent were achieved in the absence of ozone over a wide range of space velocities. Table 5-2 summarizes the results, in absence of ozone, for three different space velocities, two levels of humidity and two different OV concentrations. The single most important parameter affecting destruction efficiency was space velocity, i.e., the relationship between feed rate and reactor volume in a flow process is defined as the volume per unit time per unit volume of reactor (e.g., hours(h)$^{-1}$). The highest destruction efficiency (64 percent) was obtained at 200 h^{-1}.

The presence of small quantities of ozone (140 to 440 ppm) increased the destruction efficiency of trichloroethylene and 1,2-dichloroethylene to as high as 99 percent, as shown in Table 5-3. However, three products of incomplete combustion were formed in the presence of ozone. Two of these were identified as methyl formate and methyl acetate. The total concentration of these incomplete combustion products was 2 ppm (quantitated as **trichloroethylene). If the products of incomplete combustion are accounted for, the total OV destruction efficiency was only about 75 percent for tests conducted at space velocities of 800 to 3,000 h^{-1}.**

5.2 ENHANCED CARBON ADSORPTION

5.2.1 Principle of Operation

The Terr-Aqua Enviro Systems’ Air Pollution Control System combines the industrially proven technologies of wet scrubbing, carbon adsorption, and ozone reaction.[147,148] The schematic of this system is shown in Figure 5-2. The system uses various stages for the collection and elimination of the OV. Stage one is a 2-step prefilter to collect particulates from the air stream. The pre-filter is designed to collect up to 99 percent of particulates down to a nominal 1 m in size.

The organic-laden air then enters the photolytic reactor where it is exposed to ultraviolet light and mixed with activated oxygen/ozone. At this stage, partial destruction of the OV begins. The air then enters a countercurrent ozonated water scrubber, called the Aqua Reactor, where the OV from the gas phase is transferred to the liquid phase. The water is then heavily oxidized in the reactor recycle tank for an extended period of time. The OV present in the water is oxidized to CO_2 and H_2O, and, presumably, HCl if chlorine atoms are present.

After the Aqua reactor, the effluent air stream enters a coalescer to remove m level water droplets and wetted particles entrained in the air stream. The air stream then enters one of two activated carbon beds which remove any remaining OV that did not dissolve in water. These carbon beds are alternated every 24 hours. At any time, one of the beds is on-line to collect the OV while the other is sealed and fed oxidant to regenerate the carbon. During this regeneration, the OV is converted to CO_2 and H_2O.

Table 5-2. Summary of Test Results on Ultrox D-TOX System Without Ozone[a]

Experiment No.	Compound	Inlet concentration (ppmv)	Space velocity (h^{-1})	Humidity level (lb H_2O/lb dry air)	Destruction Efficiency (%)	Outlet CO concentration (ppmv)
1	dichloroethylene	5.99	3,000	Ambient	16	1.3
	trichloroethylene	3.82		(0.0133)	23	
	Total	9.92			19	
2	dichloroethylene	6.43	800	Ambient	29	3.0
	trichloroethylene	4.12		(0.0138)	36	
	Total	10.60			32	
3	dichloroethylene	5.18	800	High	30	2.3
	trichloroethylene	3.28		(0.0144)	44	
	Total	8.46			35	
4	dichloroethylene	1.91	800	High	36	0.5
	trichloroethylene	0.95		(0.0229)	25	
	Total	2.86			32	
5	dichloroethylene	1.80	200	High	67	3.0
	trichloroethylene	1.03		(0.0150)	50	
	Total	2.83			64	

[a] All tests conducted with a catalyst temperature between 80 and 96 °F.

Table 5-3. Summary of Test Results on Ultrox D-TOX System with Ozone[a]

Experiment No.	Compound (retention time)	Inlet concentration (ppmv)	Space velocity (h-1)	Outlet concentration (ppmv)	Humidity level (lb H_2O/lb dry air)	Destruction efficiency (%)	UV lights (on - off)
6	Dichloroethylene	4.66	800	ND[b]	0.0150	99+	on
	Trichloroethylene	2.88		ND		99+	
	Unknown (1.04)[c]	-------		1.2		-----	
	Unknown (1.59)	-------		0.36		-----	
	Unknown (1.90)	-------		0.43		-----	
	TOTAL 4.66	7.54		1.99		74	
7	Dichloroethylene	4.83	3,000	ND	0.0150	99+	on
	Trichloroethylene	2.99		ND		99+	
	Unknown (1.0)	------		1.0		-----	
	Unknown (0.34)	------		0.34		-----	
	Unknown (0.52)	------		0.52		-----	
	TOTAL	7.82		1.86		76	
8	Dichloroethylene	4.83	3,000	ND	0.0150	99+	off
	Trichloroethylene	2.88		ND		99+	
	Unknown (1.1)	------		1.1		-----	
	Unknown (0.32)	------		0.32		-----	
	Unknown (0.60)	------		0.60		-----	
	TOTAL	7.71		2.02		74	

[a] All tests conducted with catalyst operating temperature of 88 °F.
[b] ND = not detected at 0.03 ppmv detection limit.
[c] Unidentified compound quantitated as trichloroethylene. GC column retention time given in parentheses.

Terr-Aqua Enviro Systems has no U.S. control systems for low concentration, high flow OV streams. They did, however submit permits and test reports for a 18,000 cfm system at the Northrop Corporation B-2 Division in Pico Riviera, CA. The test was on a paint booth and

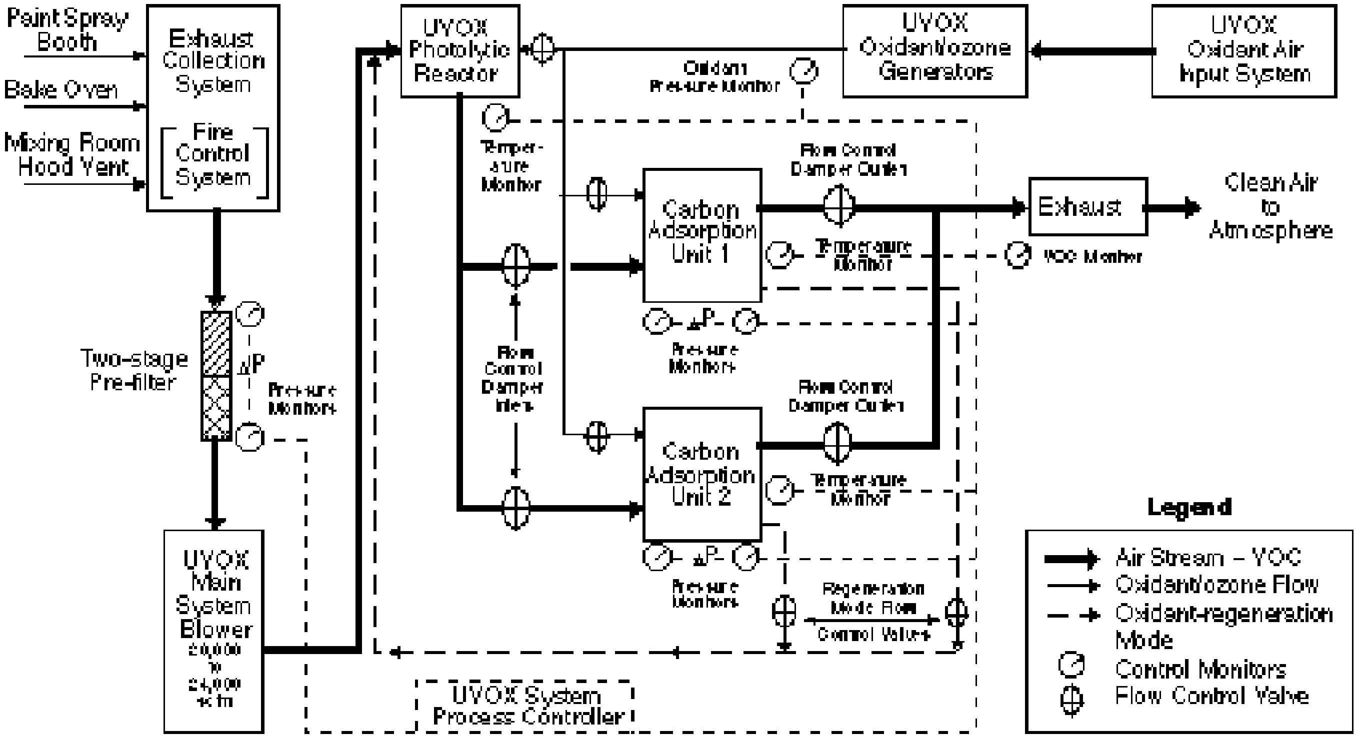


Figure 5-2 Schematic of Terr-Aqua Enviro Systems' Air Pollution Control System

indicated 99 percent removal efficiency. Test reports and permit information were also submitted for 2 additional units located at General Dynamics facilities. Summaries of the information and data for these systems are provided below.[149]

5.2.2 Source Test Results

5.2.2.1 Northrop Corporation, Pico Rivera, California

On January 25, 1990, personnel of VOC Testing, Inc. and Horizon Air Measurement Services performed emissions testing of a Terr-Aqua UV-AO Enhanced Carbon Adsorption Treatment System controlling organic emissions from an automated paint spray booth at the Northrop Corporation Plant in Pico Rivera, California.[150] The test program included the continuous monitoring of volatile organic concentrations at the inlet and exhaust of the control device during the spraying of solvent compounds in the paint spray booth, using EPA's Method 25A, and composite inlet and outlet sampling in accordance with SCAQMD Method 25.1.

The results of the continuous monitoring performed in accordance with EPA's Method 25a at the inlet and outlet (exhaust) of the control device are summarized in Table 5-4.

5.2.2.2 General Dynamics, Pomona, California

Aqua Enviro Systems, Inc. contracted York Research Consultants to perform a VOC study on their Terr Aqua Enhanced Carbon Treatment System in October, 1988.[151] The VOC control unit is located at the U.S. Naval Weapons Development Facility and is operated by General Dynamics Pamona Divison. The control system is designed to remove OV from paint spray booths and ovens at that location. The objectives of this testing program were to demonstrate a minimum recovery efficiency of 91% for the total VOC and to show a 91% or greater recovery efficiency for each of the solvents used.[152] A spray gun was used to simulate the OV emissions from a spray booth. The solvents chosen for the test were based on the actual use rate in the facility on a weekly basis. EPA's Reference Method 25A was performed to determine the total hydrocarbon concentration (THC) of the exhaust stack. One test was performed on each of the two carbon beds in the system. The average THC for carbon beds #1 and #2 was determined to be 12.35 ppmv (as propane) and 12.89 ppmv (as propane) respectively. The emission rate (controlled) for the carbon beds was calculated to be 0.252 lb/hr and 0.263 lbs/hr. The removal efficiency for the system was calculated to be 97.9% for carbon bed #1 and 98.7 for bed #2 (on a mass basis). The calculated emission rate (uncontrolled) of the solvent mixture at the control device inlet was 11.97 lbs/hr for carbon bed #1 and 20.34 lbs/hr for bed #2. Inlet gas flow rates and concentration information were included in the materials received in the test reports.[154] Table 5-5 summarizes the type of OV and their concentration used in the test by individual chemical constituent. During the testing of bed #2, the feed OV concentration was nearly doubled. The total flow rate was 29,523 cfm. The destruction efficiency for each OV was 98 to 99 percent (on a concentration basis) with the overall destruction efficiency also being above roughly 99 percent.

Table 5-4. Continuous Monitoring Results—Terr-Aqua Unit at Northrop Corporation[153]

Test Number[a]	Hydrocarbon Concentration (ppmv as propane)	Flow Rate (ACFM, Wet)	Control Efficiency	
			Inlet	Outlet
1	644	2.2	18,143	99.7
2	719	2.2	17,935	99.7
3	564	1.0	18,000	99.8
4	282	1.0	18,140	99.6
5	232	1.0	18,000	99.6
6	211	1.0	18,060	99.5

[a] During tests 1 and 4 the solvent used was xylene. During tests 2 and 5 the solvent sprayed was methyl isobutyl ketone (MIBK). During tests 3 and 6 the solvent sprayed was VM & P Naptha (60%), toluene (20%) and cellosolve/glycol ether (20%).

5.2.2.3 General Dynamics, Rancho Cucamonga, California

The Terr-Aqua system at the General Dynamics Valley Systems Division Facility was tested in September 1990 to determine hydrocarbon removal and collection efficiency.[155] Test runs were conducted simultaneously at the control system outlet and at each of the two inlet ducts, one inlet duct venting a touch-up spray booth and the second venting 3 spray booths. Testing of the coater system collection and destruction efficiency shows a collection of 98.6% and a destruction efficiency of 99.4%, for an overall efficiency of 98.0 percent. Stack gas characteristics were also reported in the test results; the average inlet gas flow for the 3 spray booths was 19,789 acfm (17,981 dscfm) and the average for the touch-up booth was 2,143 acfm (1,947 dscfm). The total non-Methane hydrocarbon concentrations were 438 ppm and 2,496 ppm, respectively for the 2 flows at the system inlet.

Table 5-5. Results of Terr-Aqua Enviro Systems' Air Pollution Control Equipment at General Dynamics, Pomona Division

OV	Concentration (ppm)		Efficiency (%)
	Inlet	Outlet	
Bed #1			
Isopropyl alcohol	9.09	0.14	98.5
Methyl ethyl ketone	9.60	0.08	99.2
Cyclohexanone	0.79	0.01	98.7
Toluene	1.29	0.01	99.2
Butyl cellosolve	2.78	0.03	98.9
m-Xylene	6.16	0.08	98.7
	29.71	0.35	98.8
Bed #2			
Isopropyl alcohol	15.47	0.03	99.8
Methyl ethyl ketone	16.33	0.06	99.6
Cyclohexanone	1.34	0.01	99.3
Toluene	2.16	0.01	99.5
Butyl cellosolve	4.72	0.02	99.6
m-Xylene	10.45	0.10	99.0
	50.47	0.23	99.5

5.2.3 Permit Conditions

5.2.3.1 Northrop Corporation, Pico Rivera, California

The permit issued by the South Coast Air Quality Management District, Permit No. D34532, A/N 175368, contains a number of permit conditions that apply directly to the Terr-

Aqua control device in use at this facility.[156] Permit Condition No. 3 states that the collection efficiency of the system shall not be less than 90% by weight of emissions generated. Condition No. 4 states that the destruction efficiency of the system shall not be less than 95% by weight of emissions it collects. Condition No. 5 limits the total quantity of VOC emissions vented to this equipment to not more than 210 lbs in any one day.

5.2.3.2 General Dynamics, Pomona, California

The permit issued by the South Coast Air Quality Management District, Permit No. D37050, A/N21442, contains a number of permit conditions that apply directly to the Terr-Aqua control device in operation at this General Dynamics facility.[157] The total amount of VOC emissions vented to the control system from the emission sources is limited to 25 lbs per day for each of 3 spray booths and 14 lbs per day for the remaining spray booth (Permit Conditions 4, 5, 6, and 7). A filtering system for prefiltering the gases and a VOC monitoring system to indicate carbon breakthrough are required by the permit (Permit Conditions 3 and 8).

5.2.3.3 General Dynamics, Rancho Cucamonga, California

The permit issued by the South Coast Air Quality Management District, Permit No. D 39603, A/N236597, contains a limit on the total amount of VOC emissions that the source and control device can discharge to the atmosphere, i.e., 1 lb per day.[158] No other restruction relevant to the control device are contained in the permit.

5.2.4 Costs

No cost data were provided by the vendor. However, the reported advantages of Terr-Aqua system include low operating and maintenance costs and no secondary waste generation.

5.3CONDENSATION

Condensation has not generally been considered applicable to gases with OV concentrations that are of interest here.[159] This is because condensation is a simple vapor-liquid equilibrium process and the temperatures needed to condense OV at levels below several thousand ppm have been impractical. As an example, the vapor pressure of methylene chloride, a common solvent, is 1 mm Hg (corresponding to a concentration of 1,316 ppm at 1 atm pressure) at -70 °C. Much lower temperatures would be needed to even begin to condense inlet concentrations of 100 ppm.

Nevertheless, condensation processes, largely based on liquid nitrogen (-196 °C), have been developed and are claimed to be applicable for low OV concentrations. Of course, these systems are best for low flow rate gases, such as working and breathing losses from tank and containers. Because there is no physical contact between the OV-containing gas and the coolant, recovered solvents are not contaminated with water, as would be the case if steam is used in adsorption-based systems (recall, however, that inert nitrogen can be used to overcome this problem). Systems based on cooling by means other than liquid nitrogen (e.g., the Brayton cooling cycle) have also been developed.

5.3.1 Liquid Nitrogen Systems

5.3.1.1 Airco Gases Systems

The Kryoclean™ system uses liquid nitrogen to cool the incoming gas in the system shown in Figure 5-3. It has been used in the pharmaceutical industry on low flow rate gases (500 to 1,000 stdft^3/min[160]). The operating cost benefit for this system depends on the pre-existence of a liquid nitrogen storage system at the site, which is true at about half the U.S. pharmaceutical plants. For a 500 stdft^3/min system, the capital cost for the heat exchanger and control system is \$650,000 to \$1.5 million. Two units have been ordered for pharmaceutical plants. Inlet OV concentrations are not known.

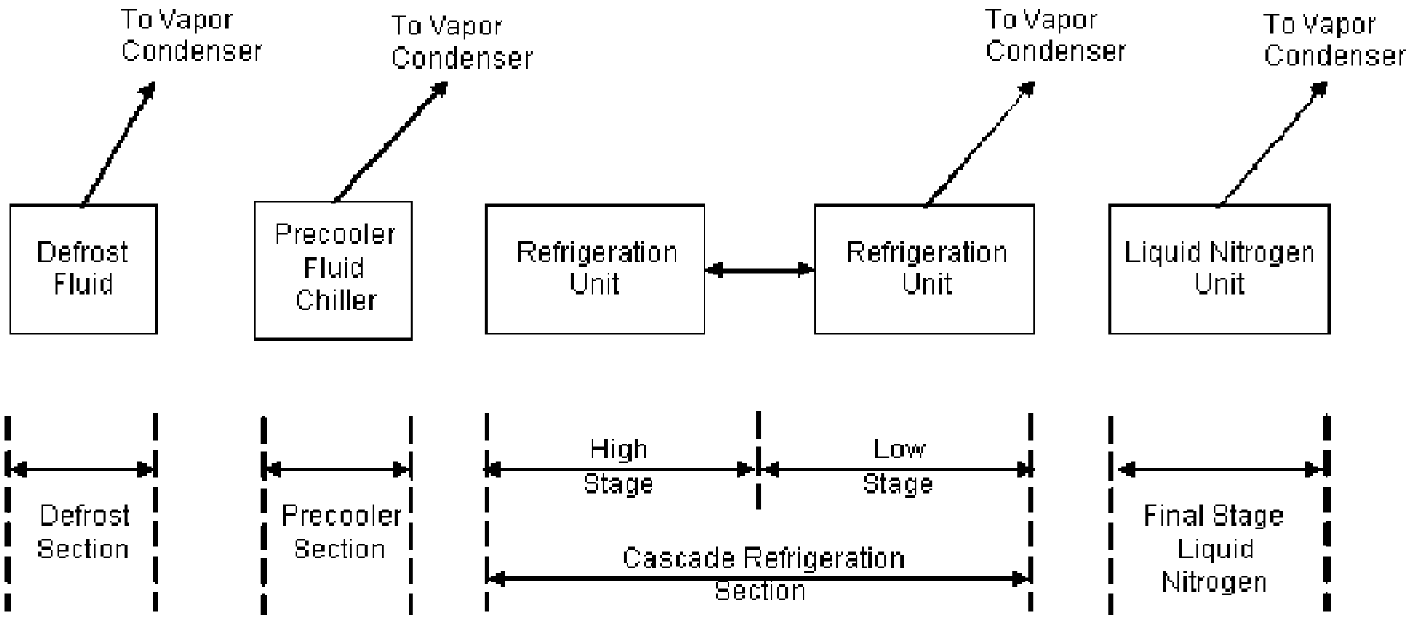


Figure 5-3 Vapor Recovery System: Refrigeration Liquid Nitrogen Sections

5.3.1.2 Edwards Engineering System

This is actually a hybrid system that couples liquid nitrogen cooling with a conventional Rankine refrigeration cycle. A mechanical refrigeration unit cools the gases to about -70 °C and then liquid nitrogen cools the gas further to -185 °C (Figure 5-4). The optimum flow rate for the process is <5,000 ft^3/min.[161] Several hundred such systems are installed in the field. Vapors include solvents, gasoline, chlorocarbons, and alcohols. Inlet OV concentrations are not reported and no costs were available.

5.3.2 NUCON System

The Braysorb™ system combines carbon adsorption with a reverse Brayton thermodynamic refrigeration cycle to cool OV-containing desorbed gases. This cooling step is simply a variant on conventional mechanical refrigeration cycles and involves the compression and expansion of a refrigerant gas.[162,163,164]

A schematic is shown in Figure 5-5. The system consists of two fixed carbon beds using nitrogen as the desorbing gas. One variation is the use of a vacuum during desorption to remove strongly adsorbed OV. Desorbed gas at 310 °F is cooled in a series of steps to -44 °C, although lower temperatures are possible.

One installation is reported treating 8,000 to 10,000 $stdft^3$/min at a 3M plant in Greenville, South Carolina. The capital cost was $1.45 million and annual operating costs (including depreciation) are $397,000 per year. Inlet OV concentrations are not reported.

5.4FLAMELESS THERMAL OXIDATION

Flameless thermal oxidation is the name given to the oxidation of gaseous contaminants or fuels by contacting them with air (and an auxiliary fuel for the low concentrations that are of interest here) in a hot inert ceramic matrix which provides the necessary heat for complete reaction to take place. There is no visible flame in these systems. Once combustion is initiated, heat is transferred by convection and radiation from the ceramic to the incoming gas mixture, raising its temperature to the ignition point. Heat released in this reaction is, in part, transferred back to the ceramic. This process results in low NO_x and CO levels compared to flame-based systems which operate at comparable temperatures. The economic feasibility of this type of system of inlet OV concentrations less than 100 ppm is somewhat questionable, though field applications approaching these concentrations are reported.

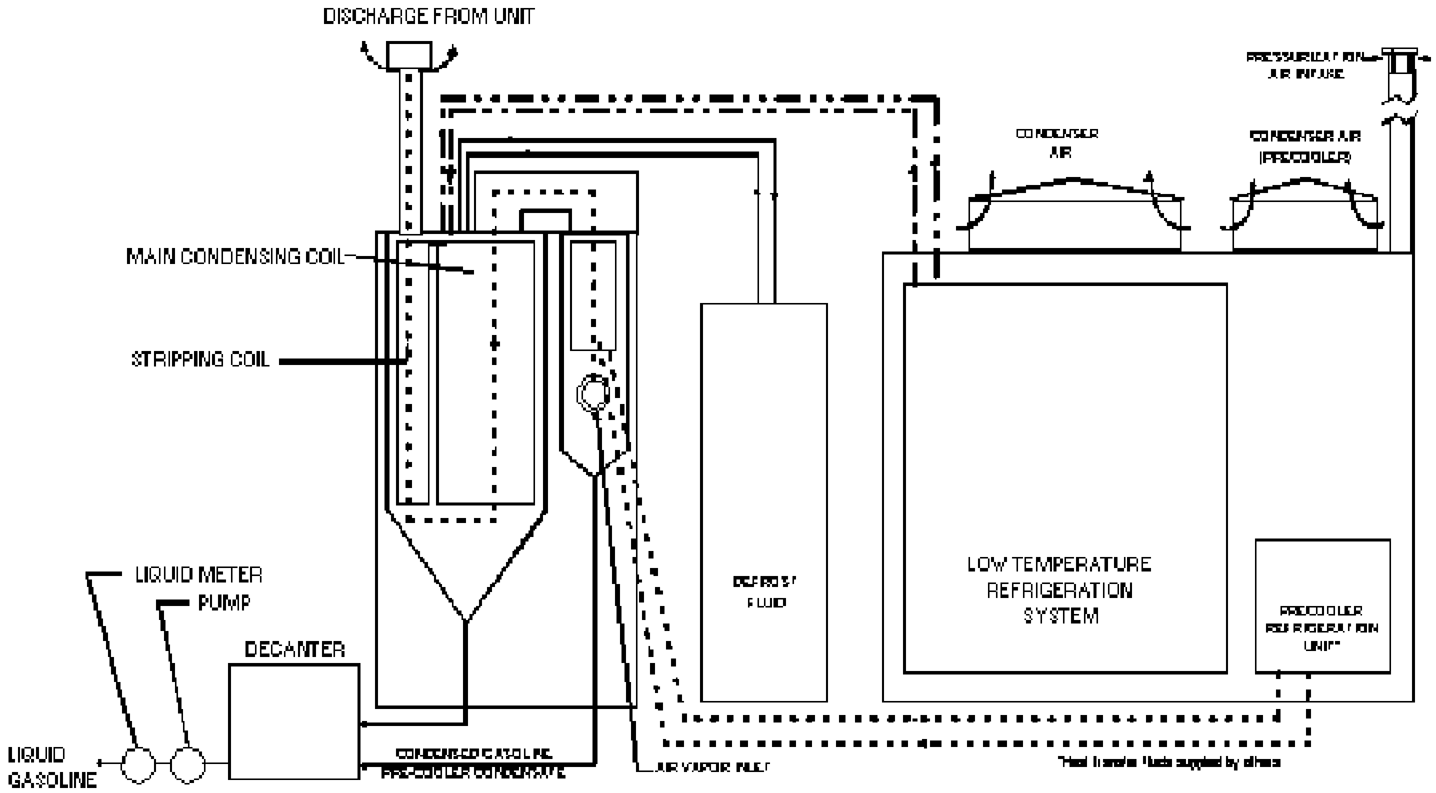


Figure 5-4 Refrigeration Vapor Recovery System: Components

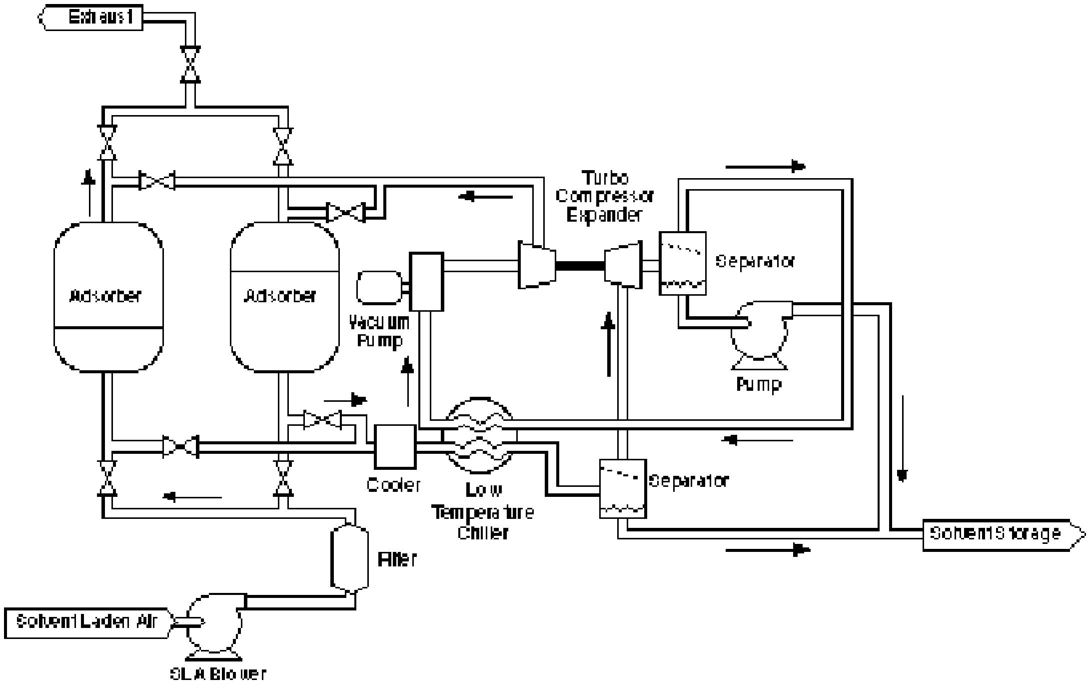


Figure 5-5 The Braysorb® Process Regeneration Flow Diagram

5.4.1 Thermatrix System

Figure 5-6 shows the Thermatrix system, which operates on the principle described above. Other contacting patterns are also available. Thermatrix reports control systems on low concentration but not high flow OV streams.[165] Test results show the use of this system on an inlet gas containing 400 ppm isopropanol, but most results appear to be for concentrations in the 10^3 to 10^5 ppm range. In principle, OV concentrations of 100 ppm could be destroyed, but would require supplemental gaseous fuels to reach a required inlet gas enthalpy of 7 to 15 Btu/stdft^3.[166] [An inlet OV concentration of 100 ppm corresponds to about 0.5 Btu/stdft^3 for C_6 to C_8 hydrocarbon solvents.]

5.4.2 Alzeta System

Alzeta manufactures a broad line of air pollution control devices, including the Alzeta Adiabatic Radiant Burner, which is an inward firing incinerator that produces much less oxides of nitrogen compared to conventional burners (see Figure 5-7). They market this incinerator with a zeolite concentrator wheel from Munters. However, no systems installed on low concentration, high flow OV streams in the U.S. are documented.[167]

In control systems using the Alzeta Adiabatic Radiant Burner, the OV-laden air is inducted to a blower and directed through a paper element filter to eliminate dust and entrained droplets. After filtration, the stream passes through a recuperator, an optional flame arrestor, and then enters a mixer where natural gas is added if necessary. The air stream is then passed through a perforated support screen coated with a porous ceramic or metallic fiber mat. The mat has been treated and bonded to permit stable operation on its surface with no flashback at inlet temperatures exceeding 800 °F. Typical oxidizer temperatures are between

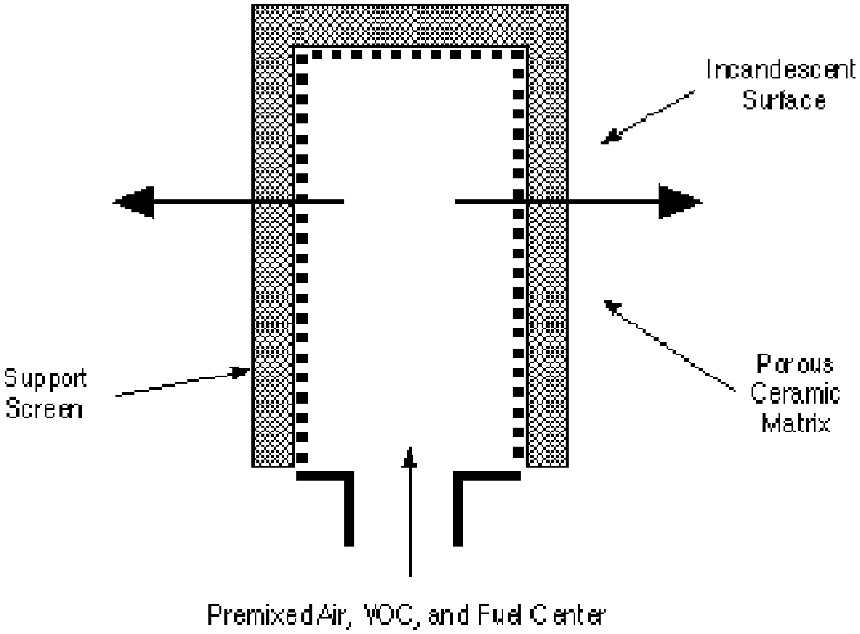


Figure 5-6 Thermatrix System’s Porous Surface Radiant Burner

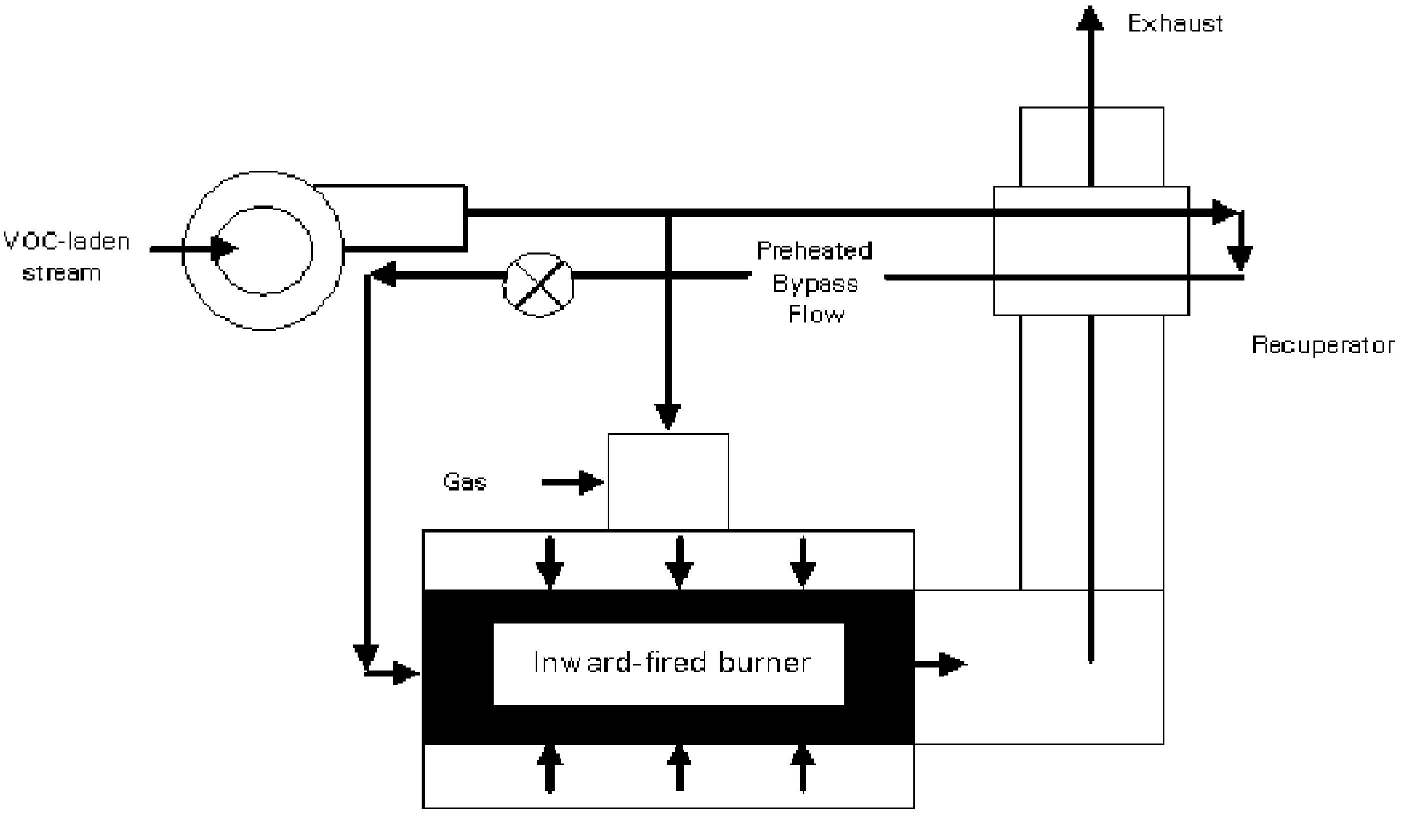


Figure 5-7 Alzeta Adiabatic Radiant Burner

1,600 to 1,800 °F. As the mixture passes through the mat, ignition and most of the combustion occur. A substantial fraction of the combustion heat dissapates to the external surface of the burner causing it to glow uniformly without a visible flame.

This burner is similar in principle to the Thermatrix system (Figure 5-6), but uses different ceramic geometry and can be inwardly and outwardly fired (air/fuel can flow inside-out or outside-in). Results are presented by Bertz and Barone for gasoline vapors with concentrations as low as 335 ppm and for chlorobenzene at 210 ppm.[168] Destruction efficiencies are >99% in both cases. Alzeta also markets their burner coupled with an upstream rotary adsorption wheel to concentrate the OV (Figure 5-8), identical in principle to those units described in Sections 3.3.9 to 3.3.11.

5.5 BIOFILTRATION

Biofiltration is a relatively recent air pollution control technology in which off-gases containing biodegradable organic compounds are vented, under controlled temperature and humidity, through a biologically active material (Figure 5-9). The microorganisms contained in the bed of compost-like material digest or biodegrade the organics to CO_2 and water. This technology has been successfully applied in Germany and The Netherlands in many full-scale applications to control odors, VOC, and air toxic emission from a wide range of industrial and public sector sources, though the process is limited to organic concentrations of approximately 1,000 ppm or less. Control efficiencies of more than 90 percent have been achieved for many common air pollutants.[169] Information on capital and operating cost for various biofilter systems installed in Europe and the USA has been reported; however, cost-effectiveness values were not calculated for biofiltration in this study. The literature reports that, due to lower operating costs (i.e., $0.60 to $1.50 per 100,000 cubic feet of off-gas), biofiltration can provide significant economic advantages over other air pollution control technologies if applied to off-gases that contain readily biodegradable pollutants in low concentrations.[170] Environmental benefits include low energy requirements and the avoidance of cross-media transfer of pollutants. No currently documented control system for low concentration, high flow OV streams in the U.S. uses biofiltration.

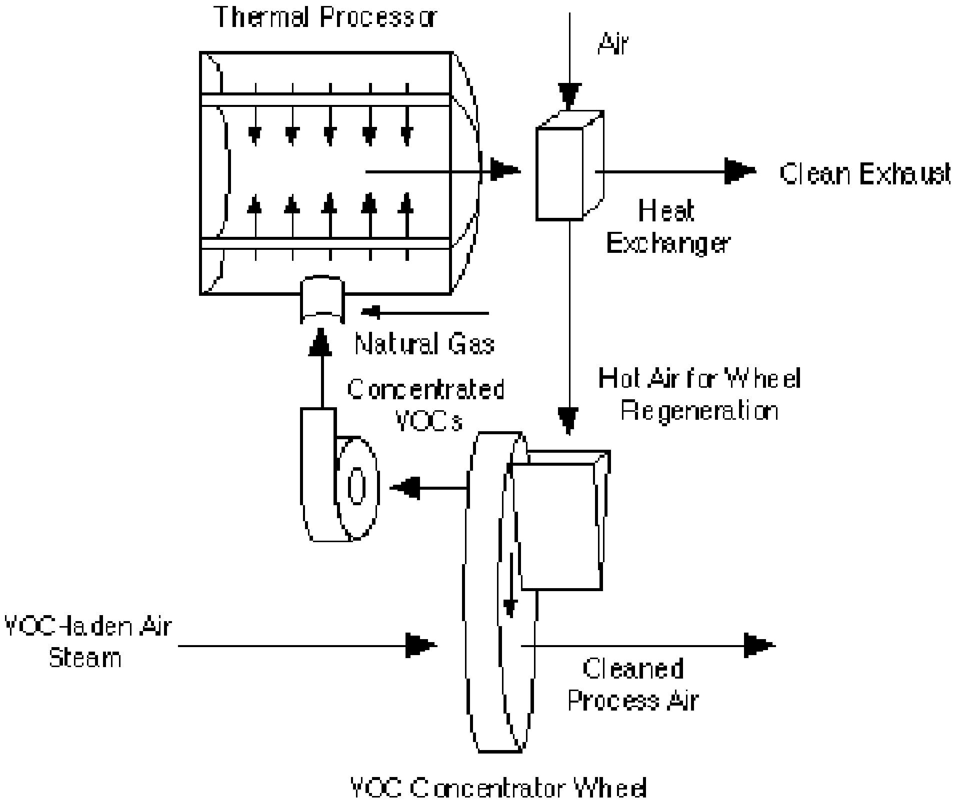


Figure 5-8 Alzeta VOC Flameless Thermal Oxidizer

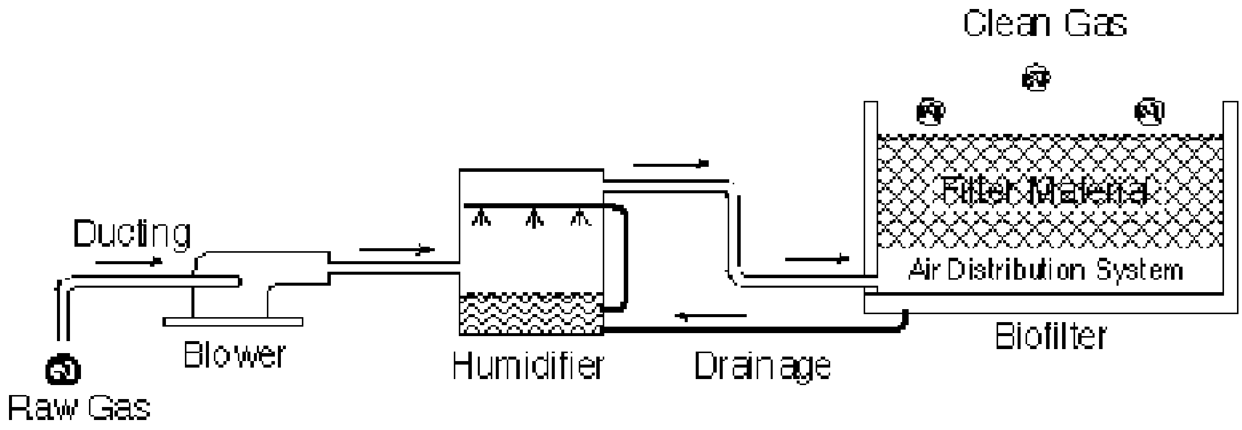


Figure 5-9 Schematic of an Open Single-Bed Biofilter System

SECTION 6
EMERGING TECHNOLOGIES

In addition to the commercially available processes described in earlier sections, there are two technologies currently under development that appear to be applicable to low concentration gases for which technical information was obtained. Neither has been applied in the field, though both offer some possible advantages over current systems.

6.1 CORONA DISCHARGE PROCESSES

Corona discharge processes use a high voltage/low current electrical discharge to destroy a wide range of molecules in an OV-containing gas stream. Although no currently documented control system for low concentration, high flow OV streams in the U.S. uses corona discharge processes, the use of these processes for low concentration OV destruction is described by Yamamoto.[171] This technology is being evaluated by RTI and EPA/AEERL for conditions of interest here. Several process and electrical configurations are possible. Although the so-called silent corona (which uses radio frequency energy) and the direct current corona have been evaluated, both have been found to require too large an energy input to be practical. Two recent developments to overcome this limitation are the dielectric packed-bed reactor and nanosecond pulse corona. The packed bed system is shown in Figure 6-1.[172] The OV-containing gas simply flows through a bed of dielectric beads (such as the perovskite $BaTiO_3$). At both the entrance and exit of the bed an electrode is connected to a high voltage AC power supply. The beads act as small capacitors and charge and discharge out of phase with the applied field. The intra-bead discharge generates electrons that react with the OV to destroy it. The nanosecond pulse corona uses a wire centered in an unfilled tube through which the OV-containing gas flows (Figure 6-2). A novel power supply discharges a capacitor through a spark gap to generate a high voltage pulse. The advantage of such a configuration is thought to be the generation of free electrons without excessive generation of ions.

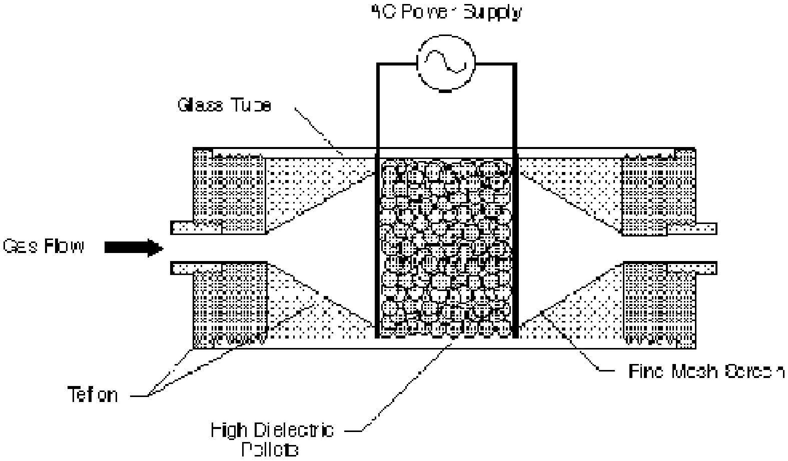


Figure 6-1 Schematic of AC Packed-Bed Corona Reactor

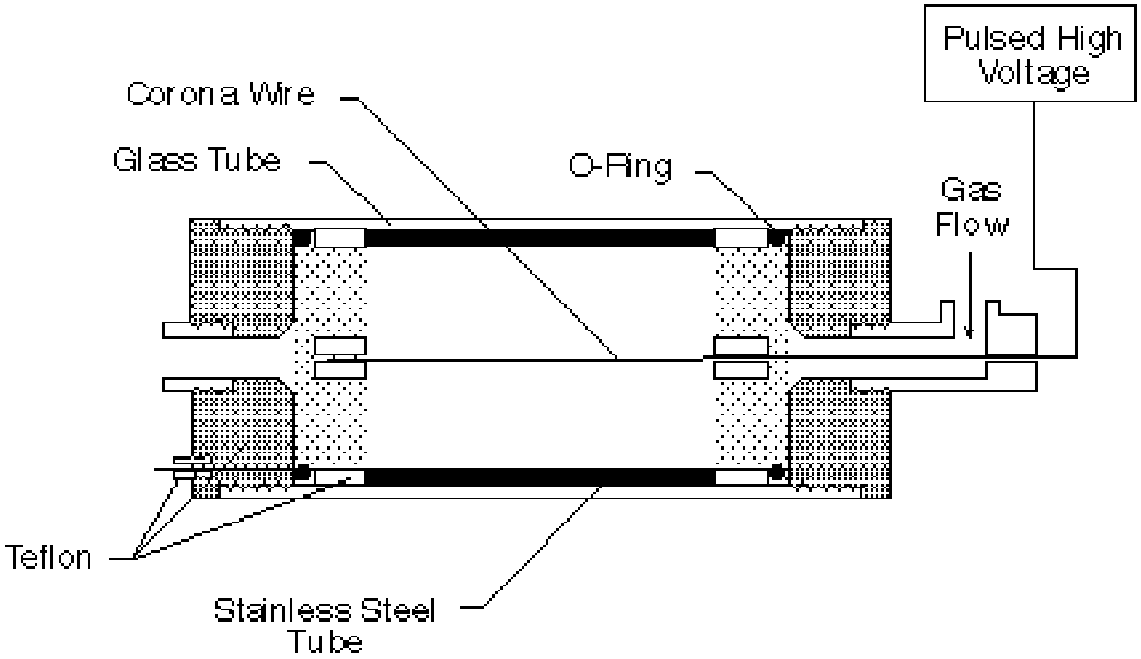


Figure 6-2 Schematic of Pulsed Corona Reactor

Results are shown in Figure 6-3 for 48 ppm toluene in air for the nanosecond pulse corona. Though high destructive efficiencies are possible, generation of ozone, NO_x, and partial reaction products is possible (about 500 ppm ozone was generated at a voltage corresponding to near 100% destruction efficiency in Figure 6-3). Figure 6-4 shows comparable results for the packed-bed corona.

Further work is focused on reducing power consumption and byproduct formation, and on scaleup to commercial application.

6.2 HETEROGENEOUS PHOTOCATALYSIS

Peral and Ollis at N.C. State University report research on the use of near-ultraviolet light to continuously activate a semiconductor (such as TiO_2).[173] The activated surface of the semiconductor then acts as a catalyst for the oxidation of OV in air. A schematic of the heterogeneous photocatalysis system is shown in Figure 6-5. This process is closely related to the Ultrox process (Section 5.1) except that ozone is not generated upstream of the catalyst bed. There may also be differences in the wavelength and/or intensity of the UV light as well as the catalyst itself, but insufficient information is available on the Ultrox process to make this determination. Results for formaldehyde oxidation with inlet concentrations between 4 and 72 ppm showed destruction efficiencies between 54 and 98 percent.[174]

This technology offers the possibility of ambient temperature operation and high oxidation activity for a wide range of organics. Possible limitations include incomplete reactions at all but dilute concentrations (perhaps even at 100 ppm), the development of a contacting pattern to allow UV illumination of the entire catalyst surface, and possibly slower rates at high humidities. No currently documented control system for low concentration, high flow OV streams in the U.S. uses heterogeneous catalysis devices.

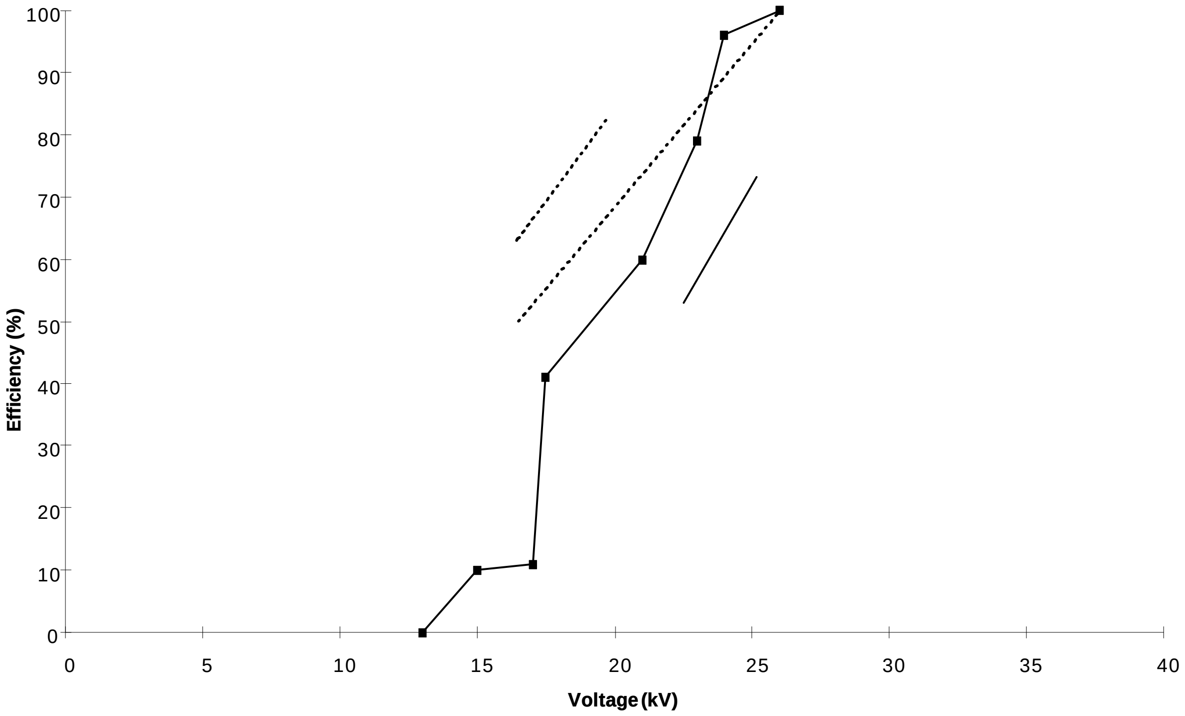


Figure 6-3 Toluene Destruction Variac 44, 40 Pf, 1 L/min (48 ppm Toluene)

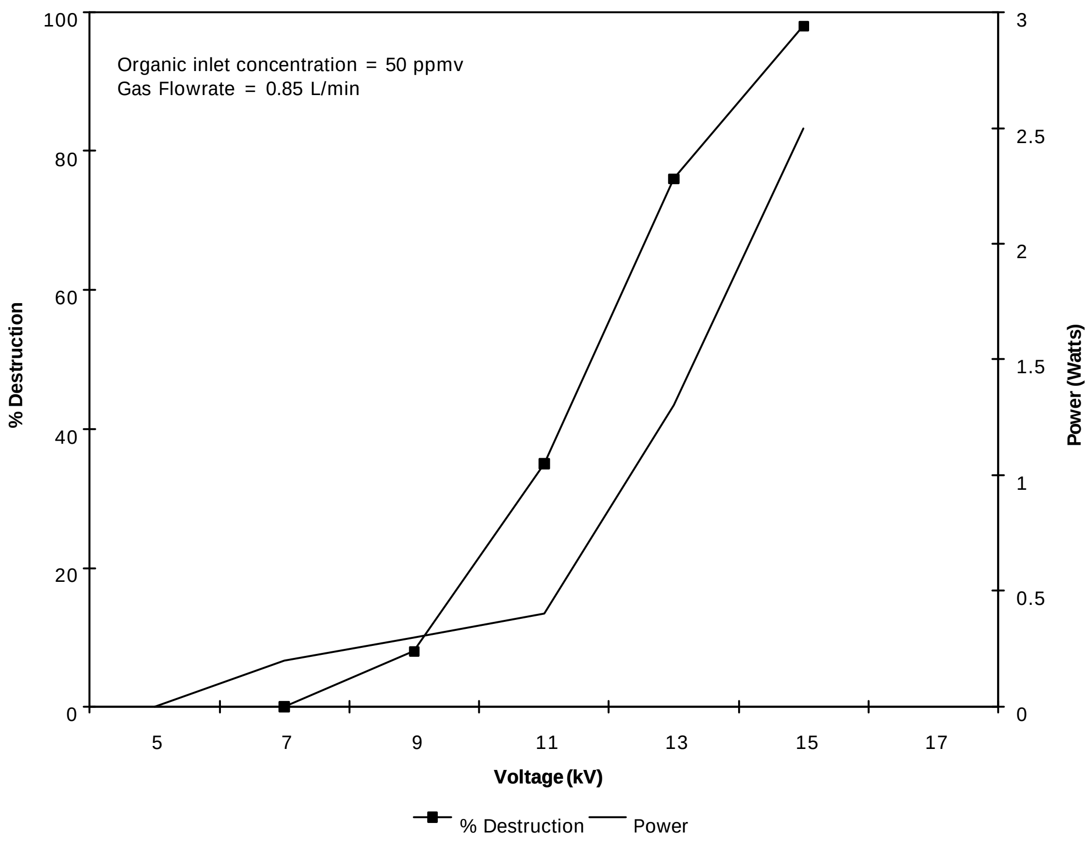


Figure 6-4 Effect of Increasing Voltage on Power Usage and Destruction Efficiency for the Packed-Bed Corona System

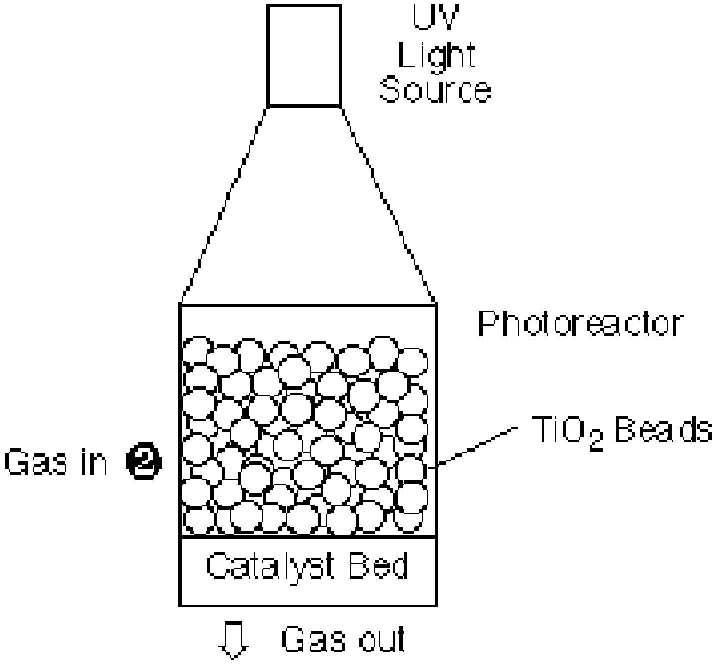


Figure 6-5 Experimental Heterogeneous Photocatalysis System Used for Experiments at NCSU

SECTION 7
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APPENDIX A

ORGANIZATIONS CONTACTED FOR CONTROL TECHNOLOGIES FOR GASES CONTAINING LESS THAN 100 ppm INLET OV CONCENTRATION

APPENDIX A. ORGANIZATIONS CONTACTED FOR CONTROL TECHNOLOGIES FOR GASES CONTAINING LESS THAN 100 ppm INLET OV CONCENTRATION

Organization	Person Contacted	Phone/FAX	Comments
Allied Signal Palatino, IL	George Lester	(708) 391-3314	Allied only makes catalysts for OV oxidation; however, they do not market complete oxidation systems for OV control.
Amcec Oak Brook, IL	Robert Saxer	(708) 954-1515 (708) 954-4077	Amcec provides both carbon adsorption systems and a hybrid system for low concentrations (20-300 ppm).
Anguil Environmental Systems, Inc. Milwaukee, WI	Gene Anguil	(414) 332-0230 (414) 332-4375	120 oxidation systems in the market. Use noble metal catalysts from Engelhard, Johnson-Matthey and Allied Signal. Some of these system are operating on less than 100 ppm OV streams.
ARI Technologies, Inc. Palatino, IL	Ed Dowd	(708) 359-7810 (708) 359-3700	ARI has several catalytic oxidation systems in the market using chromia-alumina-based catalyst. Radian has tested a low concentration OV stream using ARI's pilot plant. ARI has also developed an adsorption-catalytic oxidation system, especially suited for low concentration OV stream.
Bay Area Quality Management District San Francisco, CA	Alex Saschin	(415) 749-4713	Conducted tests using catalytic oxidation at higher OV concentrations than are of interest here. A request for information to possibly review low concentration sites has not been answered as of December 1991.
Calgon, Charlotte, NC	Carol Thomas	(704) 527-7580 (704) 523-3550	Calgon provides nonregenerable, regenerable, and CADRE modified adsorption systems. There are a number of installations, including three CADRE installations, with inlet concentrations less than 100 ppm.
New Jersey	Kim Freidman	(908) 526-4646	
Pittsburgh, PA	Alan Roy	(412) 787-6700	
Orlando, FL	Utpal SenGupta	(412) 787-6713 (407) 567-1320	
Carus Chemical Company Ottawa, IL	Nirmal Singh	(815) 224-6818 (815) 433-9075	Carus only makes catalysts for OV oxidation and does not market complete oxidation systems for OV control. Carus catalyst is used by Anguil Environmental, Demptrol, and M&W Industries.
Catalytica Mountain View, CA	Thomas Duffy	(415) 960-3000 (415) 960-0127	Catalytica is developing an adsorption/catalytic oxidation system. It is currently in the developmental stage.
CSM Environmental Systems, Inc. Brooklyn, NY	Thomas Otchby Walt Talbot	(718) 522-7000 (718) 852-1686	CSM has been working in the area of catalytic oxidation for the last 20 years, especially with low concentration OV control. They did not provide any technical/cost information.
Dedert Topsoe Olympia Fields, IL	John Ruhl	(708) 747-7000 (708) 755-8815	Subsidiary of Haldor Topsoe. Several catalytic systems in the market; however, all are operating at high OV concentration. The lowest concentration for which their system has been used is 1 g/m^3 (corresponds to about 290 ppm for benzene).
Demtrol Hartland, WI	Robert Hablewitz	(414) 367-7548 (414) 367-0831	Use Carus catalyst in their catalyst oxidation systems.
Engelhard Iselin, NJ	Kenneth Burns	(908) 205-6640 (908) 205-6146	Engelhard only makes catalysts for OV oxidation and does not market complete oxidation systems for OV control. Their catalyst is used by SCM, Anguil, McGill Environmental, and Temprite Industries.
KSE, Inc. Amherst, MA	Jim Kittrell	(413) 549-5506	KSE has developed their own oxidation catalyst. This catalyst has been tested below 100 ppm and as low as 1 ppm. Some of these data are proprietary and cannot be released. KSE constructs small systems (100 to 200 scfm) in-house, larger systems are made by other vendors using KSE technology.
McGill Environmental Systems, Inc. Tulsa, OK	Paul Kennedy	(918) 445-2431	Most of their systems are operating at high OV concentration.
M & W Industries, Inc. Rural Hall, NC	Denny Clodfelter	(919) 969-9526	Several oxidation units in the market designed for 4,000 to 30,000 scfm and operating at feed OV concentrations up to as high as 10 percent. Recently introduced a RE-GENSORB system consisting of a carbon adsorption bed in series with a thermal oxidizer. This is especially suited for low OV concentration stream.
Met-Pro Harleysville, PA	Robert Kenson	(215) 723-6751	Met-Pro provides adsorption/thermal incineration systems, most of which are used for control of paint spray booths.
MTR, Inc. San Francisco, CA	Vicki Simmons	(415) 328-2228	MTR has developed a membrane-based process for OV control. This technology is best suited for stream with OV concentration in the 0.5 to 20 percent range and is not economical when OV concentration is less than 100 ppm.

Organization	Person Contacted	Phone/FAX	Comments
Munters Zeol Amesbury, MA	Jasper Gronvaldt	(508) 388-2666 (508) 388-0292	Munters provides a rotary carousel for adsorption and several options for downstream treatment. They have numerous installations in Europe, the United States, and Japan.
Nichimen of America	F. Kuma	(212) 719-1000 (212) 536-0549	Nichimen provides a rotary hydrophobic adsorber, but has not yet responded to a request for information.
Occidental Petroleum Ashtabula, OH	Jim Taylor	(216) 992-3200	Occidental operates a CADRE system for groundwater remediation via air stripping. Inlet concentrations are less than 100 ppm.
On-Demand Environmental Systems San Jose, CA	Rick Hamilton	(408) 764-9104	Most of their systems are used for high concentration OV and in- batch operation. For such operations heat exchangers are not used to recover the heat.
Procedair Cedar Knolls, NJ		(201) 455-8821	Procedair provides an absorption/stripping process which, in principle, could be applied to low concentrations but, so far, has not.
Purex Nassau County, NY	Mark Whitney	(516) 222-0955	Purex operates a CADRE system for groundwater remediation via air stripping. Inlet concentrations are less than 100 ppm.
QUAD Environmental Technologies Corporation Northbrook, IL	Harold Rafson	(708) 564-5070 (708) 564-5606	QUAD makes an absorption-based control technology which transfers contaminants from gas phase to the liquid phase. The company does not provide any technology for treating the contaminated liquid. Several existing commercial technologies can be used for this purpose.
QVF Glastechnik Weisbaden, Germany	H. Blanke	(49) 611-2650 (49) 611-265108	QVF provides an absorption/stripping process designed to meet emission limits not possible with carbon adsorption.
Reeco Morris Plains, NJ	Rod Pennington	(201) 538-8585 (201) 538-0407	Market regenerative thermal incinerators. Some of these systems are being used for low concentration OV oxidation.
Seibu Giken Fukuoka, Japan		(92) 947-4311 (92) 947-4314	Seibu Giken provides zeolite/inorganic adsorbent processes for recovery of organic vapors. Contacts with the company have not yet been answered and it is not known if any installations treating low concentrations exist.
Smith Engineering Systems Ontario, CA	John Kirkwood Joe Steiwart	(714) 923-3331	Smith has been in existence since 1925. Several hundred oxidation units in the market; mostly thermal, some catalytic. Most of these units operate above 100 ppm OV concentration. Use noble metal catalysts by Johnson-Matthey.
TEC Systems De Pere, WI	Richard Carman	(414) 336-5715	This is a division of W.R. Grace & Company. Most of their systems are operating at 300 to 400 ppm inlet OV concentration.
U.S. Air Force Tyndall AFB, FL	Capt. Ed Marchand	(904) 283-6023 (904) 283-6499	Wurtsmith AFB is using a catalytic oxidation unit to control OV emissions from air strippers. The feed OV concentration is very low (about 1 ppm). Capt. Marchand sent an interim report of performance tests conducted on the catalytic unit at Eglin AFB on an air stripper.
Ultrox International Santa Ana, CA	Jerry Barich Jack Zeff	(714) 545-5557 (714) 557-5396	Ultrox makes a UV-catalytic oxidation system. Economically good for low concentration OV streams. Only three small commercial units in the market. Still working on commercialization/development. Little hesitant to release any information at this time because it has recently been bought by $7 billion construction engineering company.
VIC Nantucket, MA Minneapolis, MN	Nate Shaw Robert Cannon	(508) 228-3464 (508) 228-4293 (612) 781-6601 (612) 781-8559	VIC provides regenerable carbon adsorption systems, but has no installation with inlet concentrations below 100 ppm.

APPENDIX B
COST TABLES

Cost tables are presented here for the following technologies:

- catalytic incineration
- regenerative thermal incineration
- nonregenerable carbon adsorption
- regenerable fixed-bed carbon adsorption
- absorption/stripping.

Costs were developed using the methodology given in the OAQPS Control Cost Manual (Reference 2); all costs are in 1991 dollars, unless otherwise noted in the table. All costs presented here are calculated from factored estimates, with the exception of absorption/stripping. Costs were developed for four cases:

- 100 ppm benzene
- 10 ppm benzene
- 100 ppm tetrachloroethylene
- 10 ppm tetrachloroethylene.

All these cases are for *continuous* streams and

- OV in clean air
- 10,000 scfm
- 70 °F inlet temperature
- 70 percent relative humidity
- 70 percent heat recovery for the unit (where appropriate)
- 95 percent destruction efficiency[1]
- 8,000 h/yr operation.

For absorption/stripping, insufficient information was available to distinguish any difference in capital or operating costs among the four streams and therefore the total annualized costs are independent of both the type of OV and concentration.

[1] The destruction/removal efficiency of 95 percent was selected to represent the lower end of the range of control efficiencies required for the control of organic vapors by EPA regulations. In many cases, EPA requires higher control efficiencies especially in those situations where incineration is the technology serving as the basis of the standard. The incineration-based technolgies discussed in this document have demonstrated control efficiencies of 98 percent or higher and therefore are applicable when a higher performance standard (e.g., 98%) is required by regulation. Conducting the analysis at 95 percent as opposed to 98 percent also can impact the cost-effectiveness calculation because in many cases the additional organics control can be achieved at little or no cost. Cost-effectiveness values would therefore be lower at this higher control efficiency.

TABLE B-1. TOTAL ANNUALIZED COSTS FOR CATALYTIC INCINERATION FOR MODEL GAS STREAMS (100 ppm BENZENE)

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/hr	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/hr	5,090
Materials	100% maint. labor	--		5,090
Catalyst replacement	100% replacement every 2 years	650	$/ft^3	13,000
Utilities				
Natural gas		3.30	$/kft^3	135,921
Electricity		0.06	$/kWh	13,104
Total DC				177,530
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			8,394
Prop. taxes	1% TCI			4,197
Insurance	1% TCI			4,197
Capital recovery	(10%/10 years, or 16.275% of TCI)			68,303
Total IC				94,393
Total annualized cost (rounded)				271,923
Cost effectiveness ($/ton OV removed)				5,489

TABLE B-2. TOTAL ANNUALIZED COSTS FOR CATALYTIC INCINERATION FOR MODEL GAS STREAMS (10 ppm BENZENE)

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/hr	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/hr	5,090
Materials	100% maint. labor	--		5,090
Catalyst replacement	100% replacement every 2 years	650	$\$/\text{ft}^3$	13,000
Utilities				
Natural gas		3.30	$\$/\text{kft}^3$	138,374
Electricity		0.06	$/kWh	13,104
Total DC				179,983
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			8,394
Prop. taxes	1% TCI			4,197
Insurance	1% TCI			4,197
Capital recovery	(10%/10 years, or 16.275% of TCI)			68,303
Total IC				94,393
Total annualized cost (rounded)				274,376
Cost effectiveness ($/ton OV removed)				55,381

TABLE B-3. TOTAL ANNUALIZED COSTS FOR CATALYTIC INCINERATION FOR MODEL GAS STREAMS (100 ppm TETRACHLOROETHYLENE)

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/hr	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/hr	5,090
Materials	100% maint. labor	--		5,090
Catalyst replacement	100% replacement every 2 years	650	$\$/\text{ft}^3$	19,500
Utilities				
Natural gas		3.30	$\$/\text{kft}^3$	148,204
Electricity		0.06	$/kWh	13,104
Total DC				196,312
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			8,394
Prop. taxes	1% TCI			4,197
Insurance	1% TCI			4,197
Capital recovery	(10%/10 years, or 16.275% of TCI)			68,303
Total IC				94,393
Total annualized cost (rounded)				290,705
Cost effectiveness ($/ton OV removed)				5,868

TABLE B-4. TOTAL ANNUALIZED COSTS FOR CATALYTIC INCINERATION FOR MODEL GAS STREAMS (10 ppm TETRACHLOROETHYLENE)

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	\$/hr	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	\$/hr	5,090
Materials	100% maint. labor	--		5,090
Catalyst replacement	100% replacement every 2 years	650	$\$/\text{ft}^3$	19,500
Utilities				
Natural gas		3.30	$\$/\text{kft}^3$	148,960
Electricity		0.06	\$/kWh	13,104
Total DC				197,069
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			8,394
Prop. taxes	1% TCI			4,197
Insurance	1% TCI			4,197
Capital recovery	(10%/10 years, or 16.275% of TCI)			68,303
Total IC				94,393
Total annualized cost (rounded)				291,393
Cost effectiveness (\$/ton OV removed)				58,829

TABLE B-5. TOTAL ANNUALIZED COSTS FOR REGENERATIVE THERMAL INCINERATION FOR MODEL GAS STREAMS (100 ppm BENZENE)[a]

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Utilities				
Fuels[b]		6.0[c]	$/h	48,000
Electricity[d]		3.36[c]	$/h	26,880
Total DC				90,385
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI[e]			8,020
Prop. taxes	1% TCI			4,010
Insurance	1% TCI			4,010
Capital recovery	(10%/10 years, or 16.275% of TCI)			65,263
Total IC				90,606
Total annualized cost (rounded)				180,991
Cost effectiveness ($/ton OV removed)				3,653

[a] Thermal energy recovery is 95 percent for benzene.
[b] Based on $4/10^6 Btu.
[c] Fuel and electrical costs provided by vendor (Pennington, 1991) in units of $/h. Costs based on 8,000 h/yr operation.
[d] Based on $0.06/kWh.
[e] TCI given by vendor (Pennington, 1991) as $401,000.

TABLE B-6. TOTAL ANNUALIZED COSTS FOR REGENERATIVE THERMAL INCINERATION FOR MODEL GAS STREAMS (10 ppm BENZENE)[a]

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Utilities				
Fuels[b]		7.0[c]	$/h	56,000
Electricity[d]		3.36[c]	$/h	26,880
Total DC				98,385
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI[e]			8,020
Prop. taxes	1% TCI			4,010
Insurance	1% TCI			4,010
Capital recovery	(10%/10 years, or 16.275% of TCI)			65,263
Total IC				90,606
Total annualized cost (rounded)				180,991
Cost effectiveness ($/ton OV removed)				38,147

[a] Thermal energy recovery is 95 percent for benzene.
[b] Based on $\$4/10^6$ Btu.
[c] Fuel and electrical costs provided by vendor (Pennington, 1991) in units of $/h. Costs based on 8,000 h/yr operation.
[d] Based on $0.06/kWh.
[e] TCI given by vendor (Pennington, 1991) as $401,000.

TABLE B-7. TOTAL ANNUALIZED COSTS FOR REGENERATIVE THERMAL INCINERATION FOR MODEL GAS STREAMS (100 ppm TETRACHLOROETHYLENE)[a]

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Utilities				
Fuels[b]		13.0[c]	$/h	104,000
Electricity[d]		2.22[c]	$/h	17,760
Total DC				137,265
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI[e]			9,800
Prop. taxes	1% TCI			4,900
Insurance	1% TCI			4,900
Capital recovery	(10%/10 years, or 16.275% of TCI)			79,748
Total IC				108,651
Total annualized cost (rounded)				245,916
Cost effectiveness ($/ton OV removed)				4,964

[a] Thermal energy recovery is 88 percent. This is lower than for benzene in order to maintain the exhaust gas above 300 °F to minimize HCl condensation and subsequent corrosion problems.

[b] Based on $\$4/10^{6}$ Btu.

[c] Fuel and electrical costs provided by vendor (Pennington, 1991) in units of $/h. Costs based on 8,000 h/yr operation.

[d] Based on $0.06/kWh.

[e] Given by vendor (Pennington, 1991) as $490,000.

TABLE B-8. TOTAL ANNUALIZED COSTS FOR REGENERATIVE THERMAL INCINERATION FOR MODEL GAS STREAMS (10 ppm TETRACHLOROETHYLENE)[a]

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Utilities				
Fuels[b]		6.0[c]	$/h	110,400
Electricity[d]		3.36[c]	$/h	17,760
Total DC				143,665
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI[e]			9,800
Prop. taxes	1% TCI			4,900
Insurance	1% TCI			4,900
Capital recovery	(10%/10 years, or 16.275% of TCI)			79,748
Total IC				108,651
Total annualized cost (rounded)				252,316
Cost effectiveness ($/ton OV removed)				50,928

[a] Thermal energy recovery is 88 percent. This is lower than for benzene in order to maintain the exhaust gas above 300 °F to minimize HCl condensation and subsequent corrosion problems.

[b] Based on $\$4/10^6$ Btu.

[c] Fuel and electrical costs provided by vendor (Pennington, 1991) in units of $/h. Costs based on 8,000 h/yr operation.

[d] Based on $0.06/kWh.

[e] Given by vendor (Pennington, 1991) as $490,000.

TABLE B-9. TOTAL ANNUALIZED COSTS FOR NONREGENERABLE CARBON ADSORPTION FOR MODEL GAS STREAMS (100 ppm BENZENE)

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration	1.5 E6 lb/yr	0.80	$/lb	1,233,800
Electricity	13.5 kWh[a]	0.06	$/kWh	6,500
Total DC				1,255,805
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			1,952
Prop. taxes	1% TCI			976
Insurance	1% TCI			976
Capital recovery	(10%/10 years, or 16.275% of TCI)			15,884
Total IC				29,091
Total annualized cost (rounded)				1,284,896
Cost effectiveness ($/ton OV removed)				25,935

[a] Based on 7 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-10. TOTAL ANNUALIZED COSTS FOR NONREGENERABLE CARBON ADSORPTION FOR MODEL GAS STREAMS (10 ppm BENZENE)

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration	2.5 E6 lb/yr	0.80	$/lb	197,000
Electricity	5.6 kWh[a]	0.06	$/kWh	2,700
Total DC				215,205
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			1,630
Prop. taxes	1% TCI			815
Insurance	1% TCI			815
Capital recovery	(10%/10 years, or 16.275% of TCI)			13,264
Total IC				25,827
Total annualized cost (rounded)				241,031
Cost effectiveness ($/ton OV removed)				48,650

[a] Based on 2.9 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-11. TOTAL ANNUALIZED COSTS FOR NONREGENERABLE CARBON ADSORPTION FOR MODEL GAS STREAMS (100 ppm TETRACHLOROETHYLENE)

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration	1.2 E6 lb/yr	0.80	$/lb	942,000
Electricity	10.2 kWh[a]	0.06	$/kWh	5,400
Total DC				962,905
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			1,856
Prop. taxes	1% TCI			928
Insurance	1% TCI			928
Capital recovery	(10%/10 years, or 16.275% of TCI)			15,103
Total IC				28,118
Total annualized cost (rounded)				991,022
Cost effectiveness ($/ton OV removed)				20,003

[a] Based on 5.8 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-12. TOTAL ANNUALIZED COSTS FOR NONREGENERABLE CARBON ADSORPTION FOR MODEL GAS STREAMS (10 ppm TETRACHLOROETHYLENE)

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration	1.6 E6 lb/yr	0.80	$/lb	128,300
Electricity	5.2 kWh[a]	0.06	$/kWh	2,500
Total DC				146,305
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			1,612
Prop. taxes	1% TCI			806
Insurance	1% TCI			806
Capital recovery	(10%/10 years, or 16.275% of TCI)			13,118
Total IC				25,644
Total annualized cost (rounded)				171,949
Cost effectiveness ($/ton OV removed)				34,707

[a] Based on 2.7 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-13. TOTAL ANNUALIZED COSTS FOR REGENERABLE FIXED BED CARBON ADSORPTION FOR MODEL GAS STREAMS (100 ppm BENZENE)

Cost item	Suggested factor	Cost	Cost/unit	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration (Steam +cooling water)	1.5 E6 lb/yr	8.23	$/1000 lb	12,700
Carbon replacement	5 yr carbon bed life 5% loss in regen.	2	$/lb	17,600
Electricity	13.5 kWh[a]	0.06	$/kWh	6,500
Total DC				52,305
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			3,676
Prop. taxes	1% TCI			1,838
Insurance	1% TCI			1,838
Capital recovery	(10%/10 years, or 16.275% of TCI)			29,913
Total IC				46,568
Total annualized cost (rounded)				98,873
Cost effectiveness ($/ton OV removed)				1,996

[a]Based on 7.0 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-14. TOTAL ANNUALIZED COSTS FOR REGENERABLE FIXED BED CARBON ADSORPTION FOR MODEL GAS STREAMS (10 ppm BENZENE)

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration (Steam +cooling water)	1.5 E6 lb/yr	8.23	$/1000 lb	12,700
Carbon replacement	5 yr carbon bed life 5% loss in regen.	2	$/lb	17,600
Electricity	13.5 kWh[a]	0.06	$/kWh	6,500
Total DC				52,305
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			3,676
Prop. taxes	1% TCI			1,838
Insurance	1% TCI			1,838
Capital recovery	(10%/10 years, or 16.275% of TCI)			29,913
Total IC				46,568
Total annualized cost (rounded)				98,873
Cost effectiveness ($/ton OV removed)				1,996

[a] Based on 2.9 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-15. TOTAL ANNUALIZED COSTS FOR REGENERABLE FIXED BED CARBON ADSORPTION FOR MODEL GAS STREAMS (100 ppm TETRACHLOROETHYLENE)

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration (Steam +cooling water)	1.2 E6 lb/yr	8.23	$/1000 lb	9,700
Carbon replacement	5 yr carbon bed life 5% loss in regen.	2	$/lb	13,500
Electricity	10.2 kWh[a]	0.06	$/kWh	5,400
Total DC				44,105
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			3,432
Prop. taxes	1% TCI			1,716
Insurance	1% TCI			1,716
Capital recovery	(10%/10 years, or 16.275% of TCI)			27,928
Total IC				44,095
Total annualized cost (rounded)				88,199
Cost effectiveness ($/ton OV removed)				1,780

[a] Based on 5.8 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-16. TOTAL ANNUALIZED COSTS FOR REGENERABLE FIXED BED CARBON ADSORPTION FOR MODEL GAS STREAMS (10 ppm TETRACHLOROETHYLENE)

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	$/h	5,090
Materials	100% maint. labor	--		5,090
Carbon regeneration (Steam +cooling water)	1.65 E6 lb/yr	8.23	$/1000 lb	1,300
Carbon replacement	5 yr carbon bed life 5% loss in regen.	2	$/lb	1,800
Electricity	5.2 kWh[a]	0.06	$/kWh	2,500
Total DC				21,105
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI			2,792
Prop. taxes	1% TCI			1,396
Insurance	1% TCI			1,396
Capital recovery	(10%/10 years, or 16.275% of TCI)			22,720
Total IC				47,607
Total annualized cost (rounded)				58,711
Cost effectiveness ($/ton OV removed)				11,850

[a] Based on 2.7 in. H_2O pressure drop for fan. Electricity for the fan is the only cost accounted for here.

TABLE B-17. TOTAL ANNUALIZED COSTS FOR QVF ABSORPTION PROCESS FOR MODEL GAS STREAMS

Cost item	**Suggested factor**	**Cost**	**Cost/unit**	
Direct annualized costs, DC				
Op. Labor				
Operator	0.5 h/shift	12.96	\$/h	4,630
Supervisor	15% op. labor	--		695
Maintenance				
Labor	0.5 h/shift	14.26	\$/h	5,090
Materials	100% maint. labor	--		5,090
Utilities				
Cooling water		0.40	\$/1000 ft^3	960
Electricity		0.06	\$/kWh	8,826
Total DC				25,291
Indirect annualized costs, IC				
Overhead	60% of sum of op., supv., and maintenance labor and maintenance materials			9,303
Admin.	2% TCI[a]			30,200
Prop. taxes	1% TCI			15,100
Insurance	1% TCI			15,100
Capital recovery	(10%/10 years, or 16.275% of TCI)			245,753
Total IC				306,153
Total annualized cost (rounded)				331,400
Cost effectiveness ($/ton OV removed)				1,996
100 ppm benzene				6,700
10 ppm benzene				66,900
100 ppm tetrachloroethylene				3,300
10 ppm tetrachloroethylene				32,800

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[a] TCI is taken as \$1.51 million as discussed in Section 5.0.

[b] TAC is the same for all model gas streams.

APPENDIX C

SUMMARY TABLE OF CONTROL DEVICES INSTALLED ON HIGH FLOW, LOW CONCENTRATION ORGANIC VAPOR STREAMS

Appendix C. Summary Table of Control Devices Installed on High Flow, Low Concentration Organic Vapor Streams in the U.S.

User	Vendor	Device	Flow (scfm)	Inlet	Industry (ppmv)	Pollutants	City	State	Efficiency	Permit	Source Test	Permitting Contact
Louisiana-Pacific	Smith	Regenerative oxidizer	120,000	100-300	OSB	Formaldehyde MDI & VOC Mix	Hanceville	AL	99+(T) 95%(P)	yes	yes	Glen Golson (205) 271-7700
Louisiana-Pacific	Smith	Regenerative oxidizer	120,000	100-300	OSB	Formaldehyde MDI & VOC Mix	Hanceville	AL	99+(T) 95%(P)	yes	yes	Glen Golson (205) 271-7700
Louisiana-Pacific	Smith	Regenerative oxidizer	120,000	100-300	OSB	Formaldehyde MDI & VOC Mix	Hanceville	AL	99+(T) 95%(P)	yes	yes	Glen Golson (205) 271-7700
NUMMI	DURR	Concentrator & oxidizer	240,000	100	Automobile	Paint	Fremont	CA	98-99%(R)	yes	yes	Carol Lee (415) 749-4689
Commonwealth Aluminum	EC&C	Epcon EcoBAC	90,000	10	Aluminum mfg	Kerosene, Mineral, seal oil	Lewisport	KY	96%(T)	yes	yes	Jerry Goble (502) 573-3382
Louisiana-Pacific	Smith	Regenerative oxidizer	120,000	100-300	OSB	Formaldehyde & VOC	Urania	LA	ND		yes	Barbara Wiliamson (504) 765-0219
Louisiana-Pacific	Smith	Regenerative oxidizer	120,000	100-300	OSB	Formaldehyde & VOC	Urania	LA	ND		yes	Barbara Wiliamson (504) 765-0219
Louisiana-Pacific	Smith	Regenerative oxidizer	80,000	100-300	OSB	Formaldehyde & VOC	Urania	LA	ND		yes	Barbara Wiliamson (504) 765-0219
Valley Protein, Inc.	QUAD	Mist scrubber	75,000		Rendering	Odor	Baltimore	MD		yes		Laramie Daniel fax: (410) 631-3202
Ford	DURR	Concentrator & oxidizer	400,000	75	Automobile	Paint	Wixom	MI	97%(R)			Tom Julian (517) 373-7023
Louisiana-Pacific	Smith	Regenerative oxidizer	80,000	100-300	Waferboard	VOC Mix	Two Harbors	MN	ND			Stuart Arkly (612) 296-7331
3M Co.	REECO	Regenerative oxidizer	220,000		Tape coating & laminating	Solvents	St. Paul	MN	95%(T)		yes	Stuart Arkly (612) 296-7331
Ford	DURR	Concentrator & oxidizer	600,000	100	Automobile	Paint	Minneapolis	MN	97%(T)		yes	Stuart Arkly (612) 296-7331
?	REECO	Regenerative oxidizer	150,000		Printing & packaging	Solvents		NC				Laura Butler (919) 733-3340
Ford	DURR	Concentrator & oxidizer	250,000	75-80	Automobile	Paint	Edison	NJ	97%(R)			Patrick Zidran (609) 292-6704
General Motors	Munters Zeol	Concentrator	140,000		Automobile	Paint	Linden	NJ	95%(R)			Patrick Zidran (609) 292-6704
Intel	DURR	Concentrator & oxidizer	135,000	90	Semiconductor	Solvents	Rio Rancho	NM	90%+(P)	yes		Lawrence Alares (505) 827-2850
Inland Products	QUAD	Mist scrubber	70,000		Rendering	Odor		OH				Sara Gary (614) 644-2270
Glidden	REECO	Regenerative oxidizer	145,000		Paint mfg	Paint		OH				Sara Gary (614) 644-2270
Ford	DURR	Concentrator & oxidizer	350,000	60	Automobile	Paint	Avon Lake	OH	96%(R)			Sara Gary (614) 644-2270
Toyota	DURR	Concentrator & oxidizer	280,000	100	Automobile	Paint	Georgetown	OH	98%(R)			Sara Gary (614) 644-2270
Letterkenny Army Depot /ABB Paint	Munters Zeol	Concentrator	135,000		Refinishing	Paint/Solvents	Chambersburg	PA				Rob Fisher (717) 787-9256
Saturn	Calgon CADRE	Activated carbon	320,000	100	Automobile	Paint	Spring Hill	TN				Lacy Hardin (615) 532-6545
GM	REECO	Regenerative oxidizer	500,000		Automobile	Paint	Arlington	TX	93%(P)			Mike Coldiron (512) 239-1260
LTV	Met-Pro KPR	Rotary adsorber	105,000	24	Aerospace	Paint	Ft. Worth?	TX?	95%(R)			Mike Coldiron (512) 239-1260

OSB = Oriented strand board
ND = Not determined or not reported
P = Required by permit condition
T = Documented in test results
R = Reported by vendor