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Project Summary

Control of Industrial VOC Emissions by Catalytic Incineration

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This two-phase study was part of a comprehensive assessment of the performance, suitability, and costs of various technologies to control the emission of volatile organic compounds (VOCs), including the use of catalytic incineration. In Phase 1, information was assembled from the literature on the use and cost of using catalytic incineration for VOC control. Phase 2 was a testing program (involving eight industrial catalytic incinerators) designed to increase the catalytic incinerator performance data base.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in nine separate volumes (see Project Report ordering information at back).

Introduction

The emission of volatile organic compounds (VOCs) from industrial plants significantly increases ambient levels of photochemical oxidants, ozone, and smog. Control of industrial VOC emissions, therefore, can result in substantial environmental benefits. Catalytic incineration has been evaluated as an industrial VOC control technology. This study was part of a comprehensive assessment of the performance, suitability, and costs of various VOC control technologies. Objectives of the program were two-fold: (1) to provide an overview of how catalytic incineration is applied to control industrial VOC emissions and to assess the overall performance typically achieved in various applications, and (2) to gather actual performance data through an EPA-sponsored testing program on operating industrial catalytic incinerators.

These objectives were met in two phases. In Phase 1, information was assembled from the literature on the use and cost of using catalytic incineration for VOC control. This work involved: (1) a review of current and developing catalytic incineration technology, (2) an assessment of the overall performance of catalytic incinerators, (3) a review of applications where catalytic incinerators are used, (4) a comparative analysis of catalytic incineration with other competing VOC controls, (5) an examination of available methods for testing emissions from catalytic incinerators, and (6) an assessment of the need for additional performance test data.

Based on the recommendations of Volume 1 of this report (prepared following Phase 1), that additional performance test data were needed to more fully characterize catalytic incinerators, Phase 2 was initiated. Phase 2, designed to increase the catalytic incinerator performance data base by testing eight catalytic incinerators at industrial sites, included site identification and selection, test plan development, and performance data collection.

The output from Phase 2 consisted of a series of reports documenting the performance of eight catalytic incinerators at six industrial sites. Performance was measured at several process conditions at each site visited. The results of Phase 2 are presented in Volume 2 (the final report) and in Volumes 3 through 8 (test reports on the individual sites).

This Summary is divided into two parts, reflecting the work under Phases 1 and 2 (emissions control by catalytic incinera-

tion and catalytic incinerator performance, respectively).

Phase 1. Control of Industrial VOC Emissions by Catalytic Incineration

This portion of the Summary describes the technology, performance, and current usage and applications; compares catalytic incineration with other VOC control alternatives; discusses test methods; and indicates a need for additional test data.

Technology Description

The destruction of VOCs in an incinerator involves high temperature oxidation (burning) of the VOCs to carbon dioxide and water. Conventional thermal incinerators typically use a supplementary fuel (e.g., fuel oil or natural gas) to heat the VOC-containing waste gas to the required oxidation temperature, which depends on the VOCs being oxidized, mixing and residence time, and the desired destruction efficiency.

Catalytic incinerators are similar to thermal incinerators; however, a catalyst bed is incorporated into the design. The catalyst allows the oxidation reaction to proceed at a lower temperature. In some applications, catalytic incinerators can be designed with flue gas heat recovery systems so that no supplemental fuel is required for self-sustaining operation. However, most catalytic incinerators require some supplementary fuel to maintain incinerator operating temperatures during periods when the process is running at reduced capacity.

The catalyst bed usually consists of a precious metal deposited on a metal or ceramic catalyst support. Platinum and palladium alloys are the most common catalysts; however, other precious (and some nonprecious) metals are used. Common types of catalyst bed geometries are ribbons, pellets, rods, and honeycombs. Both catalyst formulation and substrate configuration are considered proprietary by catalyst manufacturers.

Although not required for operation, many catalytic incinerators incorporate some method of recovering (reclaiming) heat from the hot exhaust exiting the catalyst bed. Recuperative heat exchangers preheat the VOC-containing waste gas and/or combustion air prior to the catalyst bed; the hot exhaust gases exit the catalyst bed. Recycle heat recovery systems return a fraction of the hot exhaust gases to the VOC emitting process. Another way to recover heat is to duct the hot incinerator exhaust to a waste heat boiler to produce hot water or steam. Heat recovery systems may use combinations of these schemes and may integrate the system into the overall plant energy recovery system.

Catalytic incineration is a relatively mature VOC control technology, with about 10 vendors supplying the market. Although refinements in design are continually occurring, no major new design advances were identified.

Performance

The performance of a catalytic incinerator is affected by variables including: operating temperature, space velocity, VOC concentration and species, catalyst characteristics, the presence of poisons or masking agents, and a heat recovery system. Of these, operating temperature is a major factor affecting VOC destruction efficiency. Higher operating temperatures result in greater VOC destruction; however, supplemental fuel usage is generally increased. The optimum operating temperature provides adequate VOC destruction at minimum fuel cost. Most catalytic incinerators operate in the temperature range of 700 to 1100 °F (370 to 590 °C).

An analysis of available test data indicates that catalytic incinerators can achieve VOC destruction efficiencies greater than 95 percent and VOC outlet concentrations less than 200 ppm. Some units achieve efficiencies greater than 98 percent. A few applications with relatively high inlet concentrations have obtained efficiencies of greater than 99 percent. Typically, however, the incinerator is operated at lower temperatures to reduce supplemental fuel use while still providing adequate VOC destruction.

Current Usage and Applications

Catalytic incinerators are used in a number of VOC pollution control applications: an estimated 500 to 2000 units are in service. Current applications can be categorized in three broad process areas: solvent evaporation, organic chemical manufacturing, and miscellaneous.

Solvent evaporation comprises the most catalytic incinerator applications, including metal coating (can, coil, wire, auto/truck, furniture, small parts), paper coating (adhesive coating, rotogravure printing, flexography printing), and fabric coating. These operations generally produce waste gas streams with VOC concentrations of up to 25 percent of the lower explosive limit (LEL), the VOC concentration at which an explosion can occur after an initiating spark or flame. The two principal VOC emitters are application stations and ovens/dryers. In many processes, the oven exhaust includes solvent vapors captured during solvent application. Approximately 60 percent of the plants identified as using catalytic incinerators are solvent coating operations.

The second group of processes includes a variety of organic chemical manufacturing processes. Air oxidation processes used in petrochemical manufacture are frequently suitable for control with catalytic incinerators. To date, VOC emission streams from the production of ethylene oxide, acrylonitrile, formaldehyde, ethylene dichloride, vinyl chloride monomer, and maelic anhydride have been controlled with catalytic incinerators. Waste gas streams from organic chemical manufacturing processes vary greatly depending on the specific chemical being produced and the type of process. VOC concentrations show considerable variation, from 5 to over 100 percent LEL. The number of catalytic incinerators used in the control of organic chemical processes is considerably smaller compared to solvent evaporation processes. Of the plants identified as using catalytic incinerators, about 15 percent are organic chemical manufacturing plants.

The third group, miscellaneous processes, includes a wide variety of industrial VOC emitting processes. Catalytic incinerators are being, or have been, applied to varnish cooking, catalyst regeneration, foundry core ovens, textile manufacturing, kraft pulping, plywood veneering, filter paper processing, and gasoline vapor emission control. This third group comprises about 25 percent of the plants identified as using catalytic incinerators.

Comparison with Other VOC Control Alternatives

Catalytic incineration is one of several available VOC control technologies, including carbon adsorption, absorption, condensation, thermal incineration, and process modifications which reduce uncontrolled VOC emissions. Although each of these technologies is suitable for specific processes, only incineration and adsorption are generally applicable to a wide variety of VOC emitting processes. In most applications, catalytic incineration competes directly with thermal incineration and carbon adsorption as the most cost effective control technique. A direct comparison of these three control alternatives provides useful information concerning the relative advantages and disadvantages of each.

Concerning VOC destruction efficiency, catalytic incineration, thermal incineration, and carbon adsorption all can potentially achieve VOC removal efficiencies greater than 95 percent. Because thermal incinerators can be operated at extremely high temperatures (up to 2000°F—1090°C—with proper construction), the ultimate potential efficiency of thermal incineration is somewhat higher than either catalytic incineration and carbon adsorption. However, all of these technologies are typically designed and operated to achieve lower than ultimate VOC destruction due to cost constraints. Where extremely high VOC removal efficiencies and/or extremely low VOC outlet concentrations are required, thermal incinerators may be preferred.

Energy use variations between the three technologies are significant. Thermal incineration is the highest energy user due to the high supplemental fuel required to preheat the VOC waste gas stream to oxidation temperature. If hot water or steam is required, coincident with incinerator operation, a waste heat boiler may be used to recover much of this heat. Catalytic incinerators require significantly less fuel than thermal incinerators in most applications. Compared to a thermal incinerator achieving similar VOC destruction, a catalytic incinerator can reduce supplemental fuel by 25 to 100 percent, depending on the types and amounts of heat recovery employed. This reduction is due to the lower operating temperature required to sustain catalytic oxidation. Carbon adsorption systems are potentially the lowest energy users and, in fact, usually provide a net energy credit, because of the energy credit realized in the recovery of VOCs. The recovered VOCs may be either used as a fuel or recycled for reuse.

The ability of each technology to meet the site-specific needs of a given application differs widely for the three technologies. Carbon adsorption systems are generally the least flexible, requiring: (a) waste gas temperatures of 100°F (38°C) or less, (b) low levels of waste gas particles, and (c) reasonably consistent waste gas VOC compositions. Considerations (a) and (b) are necessary to prevent damaging or masking the carbon beds; constraint (c) ensures that the adsorbed VOCs can be separated and recycled. Use of waste gas coolers, waste gas filters, and complex VOC distillation systems can alleviate these considerations (at higher costs).

Catalytic incinerators are more tolerant of waste gas impurities; however, poisons (e.g., phosphorus, bismuth, lead, arsenic, antimony, and mercury) must be avoided. Catalyst deactivating agents (e.g., sulfur, halogens, zinc, iron, tin, and silicon) may be tolerated for short periods. Particles in the waste gas stream can be tolerated at low levels; however, erosion of the catalyst is accelerated. Sticky substances which mask the catalyst must be avoided unless the catalyst is frequently cleaned.

Since thermal incinerators have limited constraints associated with waste gas characteristics, they are ideal for applications involving the treatment of multiple streams from different processes.

Both thermal and catalytic incinerators are well suited to retrofit applications where size and space are at a premium. Catalytic incinerators, somewhat smaller and lighter than thermal incinerators, have a slight advantage in this regard.

Operation and maintenance requirements also vary considerably among the three technologies. Carbon adsorption systems are comparatively complex and generally have the highest operation and maintenance requirements. Both catalytic incineration and thermal incineration have roughly similar operation and maintenance requirements.

The cost of applying any of the three technologies varies greatly depending on the process. A cost analysis of eight VOC emission sources indicates catalytic incineration is the most economical for processes with low waste gas VOC concentrations, and that carbon adsorption is the most economical for processes with high waste gas VOC concentrations. However, many processes with high waste gas VOC concentrations are unsuitable for control with carbon adsorption due to either high waste gas temperatures or the difficulty in separation and recovery of the VOC after adsorption. In these cases, thermal and catalytic incineration are directly competitive. In the range of VOC concentrations from 15 to 25 percent LEL, costs of both incineration techniques are similar. Thermal incineration is generally the lower cost option at the upper end of this range, and catalytic incineration is generally the lower cost option at the lower end of the range.

The primary reason for the lower cost and energy requirements of catalytic incineration compared to thermal incineration is the reduced supplemental fuel use. A relatively new type of thermal incinerator, now available, reportedly uses considerably less fuel through the use of regenerative heat exchange. Depending on overall costs, this reduction in fuel use can result in thermal incineration's being cost competitive at VOC concentration levels of less than 15 percent LEL.

The costs of carbon adsorption are very sensitive to the economic value of the recovered VOC. Relatively expensive VOCs can make carbon adsorption cost effective for sources with relatively low VOC concentrations.

To summarize, catalytic incineration is well suited to VOC control problems with the following characteristics:

- — destruction efficiencies of 95 percent or higher;
- — VOC concentrations of 20 percent LEL or less;
- — high temperature waste gases;
- — mixtures of VOCs where separation/recovery would be difficult for carbon adsorption systems;
- — VOCs of relatively low economic value;
- — little or no poisons, masking agents, or particles; and
- — retrofits where small size and light weight are critical.

Test Methods

For an overall assessment of the performance of catalytic incineration in a given application, both process/incinerator characterization and emission measurements are required. Process/incinerator measurements collected include temperatures, pressures, flow rates, and fuel use. Emission measurements include VOC concentrations and gas flow rates in the inlet and outlet of the incinerator.

A variety of VOC measurement methods are available. To ensure that data are collected using standardized and accepted procedures, EPA reference methods were recommended. A combination of Method 25A and draft Method 18 provides several advantages. Method 25A, utilizing a flame ionization analyzer (FIA), could be run continuously over several days to allow the effect of process fluctuations to be assessed. A disadvantage of Method 25A is the lack of compound specific VOC concentration information (the FIA gives only a relative concentration with respect to a calibration gas). Method 18 involves gas chromatographic analysis which provides compound specific concentrations.

Need for Test Data

The information data base collected prior to the current testing program was judged deficient in several respects. Available data had been collected with varying test procedures and were lacking in documentation. Most emission data were collected with the sole objective of determining compliance with emission

standards. For this reason, other factors pertinent to catalytic incineration performance (e.g., fuel use) were neither measured nor recorded.

It was recommended at the conclusion of Phase 1 of this study that a comprehensive testing program be initiated to test in the field a variety of operating catalytic incinerators. The remainder of this Summary discusses results of the tests that were initiated as a result of this recommendation.

Phase 2. Performance of Catalytic Incinerators at Industrial Sites

This portion of the Summary describes test site selection criteria, the testing approach and methods, and test results.

Test Site Selection Criteria

The catalytic incinerator tests examined catalytic incinerator performance from two perspectives: (1) how well the technology performed when applied to industries that typically use catalytic incineration, and (2) how incinerator performance relates to a variety of process variables.

During Phase 1 of this study, 149 sites using catalytic incinerators were identified. These sites formed the basis of the site selection task. (Note: This list of plants is a random compilation of sites based on available data. As such, the relative number of plants identified in any industrial sector may be biased due to the availability of information in that sector.)

Of the 149 sites identified, 86 (58 percent) represent four industries: metal can coating, magnet wire production, organic chemical manufacturing, and printing. To test at least one incinerator in each of these four major industries using catalytic incineration, 8 to 10 plants were contacted in each category. Industry participation in the test program was strictly voluntary; several factors (economic and operational) resulted in several plants being tested in some areas and none in others. Catalytic incinerators were ultimately tested in four industries: metal can coating, coil coating, magnet wire production, and graphic arts printing.

Testing Approach and Methods

Evaluating the performance of industrial catalytic incinerators consisted of (1) developing plant-specific test plans and test methods to characterize incinerator performance, and (2) several days of comprehensive on-site testing for each incinerator. Testing focused on simultaneously monitoring inlet and outlet VOC concentrations and measuring incinerator operating conditions.

The primary test method used to measure incinerator destruction efficiency was EPA Method 25A. Draft EPA Method 18 was also used as an auxiliary method to determine destruction efficiencies and to speciate components in the gas stream. Samples of the incinerator inlet and outlet gas streams were drawn continuously from the stack through a heated probe, pump, and Teflon^{R} umbilical to a mobile laboratory for analysis.

Results of Testing

Eight catalytic incinerators were tested at six industrial sites between November 1982 and March 1983. All eight were used to control VOC emissions from solvent evaporation processes. In these processes, pigments, inks, or resins dissolved in organic solvents are applied to metal or paper surfaces. The solvents are then driven off the surfaces in drying ovens, and the oven exhaust is ducted to a catalytic incinerator for solvent destruction. Incinerators at can coating, coil coating, magnet wire, and graphic arts printing plants were tested.

Incinerator performance was characterized in terms of destruction efficiency, outlet solvent concentration, and energy usage. Inlet and outlet solvent concentrations were monitored with hydrocarbon analyzers during a nomimal 1-week test at each site. Incinerator design and operating data (e.g., operating temperature, solvent type, and catalyst volume and age) were collected on each incinerator to document the operating conditions during the test. Waste gas characteristics and design and operating parameters for each incinerator are shown in Table 1.

Performance data collected during typical plant operation are summarized in Table 2. Four of the eight incinerators showed destruction efficiencies in excess of 90 percent under typical plant and incinerator operating conditions. These incinerators were applied in can coating, coil coating, and graphic arts printing. Destruction efficiencies for each incinerator generally varied over a narrow range for different coatings or inks.

A fifth incinerator showed slightly lower efficiencies, between 88 and 94 percent. This incinerator was also applied in can coating.

The three remaining incinerators all showed comparatively low destruction efficiencies of about 80 percent. The lower efficiencies at two of these sites are attributed to the catalyst condition. One catalyst bed was fouled or deactivated by high temperature operation or material masking, and the other appears to have been deactivated by normal catalyst aging. The lower efficiency at the third site is due to a lower solvent-laden air (SLA) residence time. This incinerator, which was much older, had a SLA residence time approximately half that of the newer incinerators tested.

Two of the three incinerators that showed comparatively low destruction efficiencies were applied in the graphic arts printing industry, and the third was applied to a magnet wire coating line.

Outlet total hydrocarbon (THC) concentrations based on EPA Method 25A ranged widely for the eight incinerators, from 46 to 1590 ppmv carbon. However, measured outlet concentrations were below 350 ppmv for six of the eight incinerators.

Energy usage for most of the incinerators ranged from 78 to 268 kJ/Nm^3 (2.1 to 7.2 Btu/scf) of waste gas treated. One incinerator had an estimated energy usage of 782 kJ/Nm^3 (21 Btu/scf).

Comparison of destruction efficiencies measured according to Method 25A and Method 18 showed good agreement.

At several test sites, the incinerator operating temperature was varied to observe the effect of temperature on performance. As expected, destruction efficiency increased with increasing operating temperature. However, the relative effect of temperature on destruction efficiency varied widely for the different incinerators. Of five incinerators for which the temperature was varied, two showed a fairly small effect of temperature and three showed a comparatively large effect. The largest increase in efficiency for a temperature rise of 14°C (25°F) was 2.5 percent, from 84.0 to 86.5 percent.

Inlet concentration as measured by Method 25A was also observed to have an effect on destruction efficiency. For similar catalyst bed inlet temperatures, destruction efficiency increased with increasing inlet concentration. Inlet concentrations generally varied for different coatings and coating rates. The effect of inlet concentration was found to be greatest for incinerators operating at efficiencies below 85 percent.

Table 1. *Waste Gas Characteristics and Incinerator Design and Operating Parameters*

Plant ID (Incinerator No.)	Process	Waste Gas Flowrate[a] Nm^3/s	Waste Gas Flowrate[a] (scfm)	Waste Gas Temperature °C	Waste Gas Temperature (°F)	Major Solvents Identified[b]	Average Temperatures[c] Catalyst °C	Average Temperatures[c] Inlet/Outlet (°F)	Catalyst Bed Pressure Drop kPa	Catalyst Bed Pressure Drop ("H_2O)	Catalyst	Catalyst Age months	SLA Residence Time sec	Design Destruction Efficiency %
Plant C-1 (27)	Can coating	3.6	(7600)[d]	121	(250)	Toluene, xylenes, ethyl benzenes	363/396	(685/745)	0.60	(2.4)	Ceramic honeycomb	8	0.03	90
Plant C-1 (28)	Can coating	3.2	(6780)[d]	89	(190)	MIBK, xylenes[c] methyl ethyl benzenes	316/410	(600/770)	0.57	(2.3)	Ceramic honeycomb	23/<1[f]	0.03	90
Plant C-4	Can Coating	2.52	(5330)	164	(327)	MIBK, cellusolve, xylenes, ethylbenzene[e]	332/393	(630/740)	0.42	(1.7)	Ceramic honeycomb	11[g]	0.03	90
Plant C-2	Graphic arts printing	0.9	(2000)	127	(260)	C12 to C18 hydrocarbons	493/438	(920/820)[h]	2.5	(10)	Ceramic honeycomb	[i]	NA	90
Plant C-3 (20)	Graphic arts printing	1.26	(2660)	177	(350)	C12 to C18 hydrocarbons	372/379	(701/713)	0.25	(1.0)	Ceramic spherical pellets	16	0.04[j]	90
Plant C-3 (21)	Graphic arts printing	2.20	(4670)	178	(352)	C12 to C18 hydrocarbons	353/412	(667/774)	0.25	(1.0)	Ceramic spherical pellets	8	0.04[k]	90
Plant C-5	Magnet wire	0.28	(603)	233	(451)	Phenol, cresols	393/507	(740/945)	0.17	(0.7)	Metal ribbons	<1	0.015[k]	NA[l]
Plant C-6	Coil coating	5.33	(11300)	143	(290)	MEK, toluene[e]	285/427	(545/800)	0.42	(1.7)	Ceramic honeycomb	1	0.03	95

[a] *Total inlet gas flow to the incinerator on a wet basis*
[b] *Identified by gas chromatography and/or mass spectroscopy*
[c] *Measured for each incinerator during typical incinerator operation*
[d] *Calculated from a CO_2 mass balance around SLA fan. Flows were not measured because acceptable sampling location was not available*
[e] *Formulations varied for different coatings. MIBK = methyl isobutyl ketone, MEK = methyl ethyl ketone*
[f] *Two catalyst ages were tested*
[g] *Catalyst was cleaned 5 months prior to test*
[h] *Believed to have been deactivated by either high temperature operation or material masking. The temperature drop across the catalyst bed and a 2.5 kPa (10 in H_2O) pressure drop measured for this catalyst is evidence of the deactivation.*
[i] *The catalyst was 8 years old, but the number of operating hours logged by the incinerator (although unknown) is much less than 8 years.*
[j] *Assumes 40 percent void fraction*
[k] *Assumes 50 percent void fraction*
[l] *Unknown because incinerator was modified by plant to increase catalyst volume*

Table 2. *Summary of Performance Data for Typical Operating Conditions*[a]

Plant ID (Incinerator No.)[b]	Process	Coatings Tested	Hours of Data[c]	Method 25A Concentrations[d]		Destruction Efficiency %[e]	Average Energy Usage[f]		Heat Recovery, %
				Inlet, ppmv	Outlet, ppmv		kJ/Nm^3	(Btu/scf)	
Plant C-1 (27)	Can coating	1	27.6	4000-5810	181-275	95.4-96.4	270	(7.2)	39[g]
Plant C-1 (28)	Can coating	3	7.8	2840-7760	173-321	93.4-95.9	230	(6.1)	46[g]
Plant C-1 (28)	Can coating	7	26.0	2270-5755	46-341	96.3-98.6 (91.7-93.4)[h]	230	(6.1)	46[g]
Plant C-4	Can coating	2	13.0	5480-7560	385-687	88.7/94.0	260	(6.9)	None
Plant C-2	Graphic arts printing	1	23.0	1020	169	81.2	780	(21)	None
Plant C-3 (20)	Graphic arts printing	1	5.5	1240	241	80.1	160	(4.3)[i]	36[i]
Plant C-3 (21)	Graphic arts printing	5	7.2	1370-4030	90-165	93.4-95.9	80	(2.1)[i]	66[i]
Plant C-5	Magnet wire	1	13.8	8720	1590	80.6	240	(6.4)[i]	None
Plant C-6	Coil coating	5	27.0	6220-12,860[k]	272-305	96.5-97.5	150	(3.9)	31[g]

[a] *For steady state incinerator and coating process operating conditions.*

[b] *Tests conducted between November 1982 and March 1983.*

[c] *Collected at typical incinerator operating temperature (see Table 1).*

[d] *For the incinerator inlet/outlet gas streams. The range of values represents the range of average concentrations measured during monitoring periods for the different coatings tested. Monitoring periods generally exceeded 1 hour, ranging up to about 14 hours. Method 25A results for different monitoring periods are summarized in the Site Test Reports. ppmv = parts per million by volume carbon, quantitated against propane standards.*

[e] *For all except Plant C-1:*

$$\text{Destruction efficiency} = \frac{M_{in} - M_{out}}{M_{in}} \times 100\%, \text{ where}$$

$$M = \text{VOC mass flowrate} = \frac{V \text{ moles C}}{10^6 \text{ moles gas}} \times \frac{12g \text{ C}}{\text{mole C}} \times \frac{\text{moles gas}}{0.024 \text{ m}^3} \times \frac{Q \text{ m}^3 \text{ gas}}{\text{sec}}$$

V = VOC concentration, ppmv (in or out)

Q = gas flowrate, Nm^3/sec (in or out)

For Plant C-1:

$$\text{Destruction efficiency} = \frac{V_{in} - V_{out}}{V_{in}} \times 100\%.$$

[f] *For fuel gas required to heat waste gas to catalyst bed inlet temperature.*

[g] *By recycling incinerator outlet gas to drying oven; represents percent recovery of heat generated by natural gas and fuel combustion in the incinerator.*

[h] *Values for one of the seven coatings tested. This solvent formulation apparently had a greater percentage of MIBK and a higher average solvent molecular weight than the others.*

[i] *Based on waste gas temperature and catalyst bed inlet temperature.*

[j] *By recuperative heat exchange; represents percent recovery of heat required to raise the waste gas temperature to the catalyst bed inlet temperature.*

[k] *For gas stream from exhaust oven.*

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"Volume 1. Assessment of Catalytic Incineration and Competing Controls," (Order No. PB 84-225 762; Cost: $16.95)
"Volume 2. Final Report on Catalytic Incinerator Performance at Six Industrial Sites," (Order No. PB 84-225 770; Cost: $11.95).
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