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SUBJECT: Thermal Incinerator Performance for NSPS

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Over the past few months, CMS has investigated incinerator efficiency, cost and fuel use. The purpose of this study has been to pick an efficiency that represents the highest control level achievable by all new incinerators, considering available technology, cost and energy use.

Conclusions

Based on our study, we conclude that 98 percent VOC reduction, or 20 ppmv by compound exit concentration, whichever is less stringent, is the highest control level achievable by all new incinerators, considering available technology cost and energy use. This level is expressed in both percent reduction and ppmv to account for the leveling off of exit concentrations as inlet concentrations drop. This level is based on incinerator operational at a maximum of 1600 degrees F and .75 second residence time. The costs and energy use of achieving this level are based on recuperative heat recovery, capable of lowering the flue gas temperature to 510 degrees F.

From our study, we also conclude that mixing is a critical factor in efficiency, a factor of equal or greater importance than other factors such as temperature. After surveying available means of improving mixing, we conclude that incinerator adjustment after start-up is the most feasible and efficient. The control levels in the previous paragraph are based on such an adjustment.

From our study, we also conclude that, with proper use of recuperative heat recovery (RHR), no significant energy penalties occur with changes in combustion temperature. The reason is that, based on the technical limits of heat recovery and present fuel costs, the optimum incinerator exit gas temperature is slightly above 500 degrees F, regardless of combustion temperature. Since incinerator fuel use depends on exit gas and not combustion temperature, RHR can essentially eliminate the fuel penalty of increasing combustion temperature.

Discussion

This section discusses our data and findings on incinerator efficiency, cost and fuel use, and presents the logic behind the choice of the above control level. This section has three parts, one on efficiency, one on cost and fuel use, and one on control levels. Tables cited in this section are at the end of the memo.

In using the conclusions and data from this discussion, the reader should be aware of several qualifications. First, this discussion picks a control level applicable to all new incinerators, even the worst cases. In reality, there will be a distribution of cases from worst to best. Thus, in many situations, incinerators will achieve greater than 98 percent, or less than 20 ppmv, control at less than 1600 degrees F and .75 seconds residence time.

Second, this discussion lists specific incinerator conditions (temperature, residence time, heat recovery) for analysis purposes only, i.e. to calculate cost, fuel and emission impacts. This memo does not recommend that these conditons be specified in regulations. As just noted, this set of conditons represents only one of many with which to achieve 98 percent reduction or 20 ppmv. Thus, the control levels in the above conclusions, not the incinerator conditions, should be the basis for regulations.

Third, this discussion focuses on thermal incineration since this control method has the widest applicability to control of ducted VOC emissions. This memo does not conclude that incineration is applicable to all situations or that, when applicable, incineration is the only feasible control method.

Fourth, this discussion covers incinerators operating with relatively constant inlets and flows and with waste gas flows greater than 500 scfm. This in general includes incinerators on solvent drying operations, polymer production plants, and air oxidation units. For incinerators with varying inlet conditions or small flows, such as those on organic liquid storage tanks, the fuel and capital cost calculations in this memo may not hold. Since these calculations are a critical basis for the above conclusions on efficiency, these efficiency conclusions are not applicable to such incinerators.

Finally, this discussion covers new incinerators applied for control of VOC for oxidant reduction purposes. Existing incinerators may not be physically capable of achieving the temperature, residence time and heat recovery conditions listed in this memo. Thus, these incinerators may not be able to reach 98 percent or 20 ppmv. On the other hand, incinerators for control of toxic or hazardous VOC need not be limited to 98 percent or 20 ppmv. As discussed below, higher efficiency incinerators are possible for all compounds with some development and design cost.

Efficiency - The available data on incinerator efficiency is described in Table 1 and summarized in Tables 2-4. The data include results from lab scale incinerator tests conducted by Union Carbide and from field tests run by EPA, Los Angeles County and chemical companies.

These data were analyzed to determine the impact of incinerator variables on efficiency. Six variables were studied, namely temperature, residence time, mixing, inlet concentration, flow regime, and type of compound, in three analyses. These analyses are described below. Mixing and flow regime are defined in Appendix A.

The first analysis was designed to remove the influence of mixing. This was desired since mixing cannot be measured and thus its impact on efficiency cannot be readily separated when studying the effect of other variables. The Union Carbide lab work was chosen for this analysis since its small size and careful design best assured consistent and proper mixing.

The results of the Union Carbide work are shown in Table 2. These results show moderate increases in efficiency with temperature, residence time and type of compound. These results also show the impact of flow regime on eficiency. This subject is discussed further in Appendix A on mixing and flow regime. Finally, the results show that a given temperature does not correspond to a given efficieny. Rather, increasing temperature increases efficiency by narrowing the range over which efficencies fall and increasing the average of the range.

The next analysis focused on mixing. To accomplish this, cases were picked where all variables except mixing were held constant or accounted for in other ways. It was then assumed any changes in efficiency would be due to changes in mixing.

The case most directly showing the effect of mixing on efficiency is represented in Table 3. The Petro-tex data show the efficiency changes due to two modifications of the incinerator after start-up. These modifications increased efficiency from 70 percent to over 99 percent, with no change in temperature. The modifications include repositioning baffles and burners, and rerouting inlet combustion air.

A case indirectly showing the effect of mixing is presented in Table 5. These data compare the efficiency of the Rohm and Haas (R&H) incinerator in combusting four specific compounds with that of the Union Carbide lab unit. The lab unit clearly outperforms the R&H unit. The data from both units are based on the same temperature, residence time and inlet stream conditions. The more complete mixing of the lab unit is judged the cause of the differing efficiencies.

Another case indirectly showing the effect of mixing is presented in Table 6. These data are a partial list of L.A. County tests where efficiency dropped or remained the same with increasing temperature. In total this result occurred in 21 of the 50 L.A. County tests in which the same incinerator was tested at different temperatures. As above, all factors except mixing remained the same or can be accounted for in other ways. Thus,

changes in the completeness of mixing are judged to be the cause of the results.

The final analysis was designed to study the effect of all variables at once. The L.A. data were chosen for this analysis since the L.A. units operated over a wide range of each of the variables of interest. In addition, the L.A. results represented the largest body of available efficiency data and thus were the most amenable to statistical analysis. The results of the analysis of the L.A. data are shown in Table 4. These results show a weak relation between efficiency and inlet concentration and no relation between efficiency and temperature.

The temperature vs. efficiency results are surprising. Kinetic theory and the lab scale results show large increases in efficiency over the 300 degree F range in Table 4, but in fact no such increase occurred in the L.A. data. Detailed analysis of this data points to poor mixing as the cause of these results. This analysis is described in Appendix A to this memo.

The conclusion from these three analysis is that mixing is the most important variable in incinerator efficiency. This is based on the large changes in efficiency in the R&H and Petro-tex results and the ability of mixing to mask the impact of temperature in the L.A. data. This is not to conclude that temperature, residence tame and other variables have no influence on efficiency. These variables do have an important, though smaller, influence.

Cost and Fuel Use - The data used to study incinerator cost and energy use are contained in the Hydroscience report on thermal incineration. Selected parts of these data are shown in Table 7 and 8. These data were used to analyze the relations between capital cost: energy use and heat reconvey. In addtion, the costs of efforts to improve mixing were also analyzed. These analyzes are discussed below.

The first analysis studied the cost trade-offs between heat recovery and energy use. The results of this analysis are shown in Table 7. This table lists the incremental capital costs and energy savings with increasing recuperative heat recovery (RHR). The 70 percent RHR case, which corresponds to a flue gas temperature slightly above 500 degrees F, represents the maximum feasible level of recovery. Beyond 70 percent RHR, problems arise with precombustion in the heat exchanger and with condensation of water in the flue gas and possible corrosion.

The results on Table 7 indicate that the maximum feasible RHR should be used. Up to this maximum, except for the 1000 scfm case, the capital cost of each increment of RHR is more than offset by the incremental energy savings. The basis for these savings is the increasing cost of energy. In older designs, based on cheaper fuel, cost savings from heat recovery were not large enough to justify maximum RHR. However, with escalating fuel costs, extra capital equipment has become cheaper than energy.

The results on table also indicate that, with the proper use of heat recovery, negligible energy penalties occur with increasing combustion

temperature. The reason is that the energy use of an incinerator depends on exit gas temperature, not combustion temperature. And as noted above, the optimum exit gas temperature is slightly above 500 degrees F, regardless of combustion temperature. Higher exit gas temperatures are not warranted since additional heat recovery produces a net savings. Lower exit gas temperatures are prevented by technical limits. Thus, with optimum RHR, increasing combustion temperatures will lead to negligible increases in energy use.

The second analysis concerned the capital cost differences between incinerators designed at 1400 degrees F and 1600 degrees F. The results of this analysis are shown in Table 8. These results show moderate increases in capital costs and small to moderate increases in annualized costs between the 1400 degrees F and 1600 degrees F incinerators. The major factors in the increase are the larger recuperative heat exchanger and larger combustion chamber needed for the 1600 degrees F degree unit.

The final analysis concerned the cost and feasibility of various methods to improve mixing. Four methods were studied: pilot plants, lab work, engineering design and adjustment after start-up.

Pilot plant work is judged too expensive. The costs involved in constructing and operating the pilot plant unit, providing a waste gas stream, and collecting and analyzing the data could well exceed the capital cost of the full scale unit. A quarter to a half million dollars could be required for such work for small incinerators, and up to a million dollars for larger units. Pilot plant work appears more appropriate as an EPA or vendor research project.

Two of the alternatives, lab work and engineering design, appear affordable but are not feasible. Lab work provides good data on kinetics, but no useable data on mixing. Engineering equations are useful in many situations, but few such equations exist for mixing. The number of trays in a distillation column can be reasonably calculated; the number of baffles in an incinerator cannot be.

The final alternative, adjusting the incinerator after start-up, does appear both affordable and feasible. Such an adjustment would involve repositioning baffles, adjusting ducts and performing similar tasks while measuring efficiency, temperature and similar variables. Such a procedure applies to incinerators the same adjustment that process equipment receives after start-up and would involve the same, moderate time, expertise, and costs. Finally, the success of such a proceoure has been demonstrated by Petro-tex.

Control Level - Based on the above findings, a series of conclusions were made which lead to the choice of 98 percent reduction, or 20 ppmv, (98/20) as the highest control level achievable for all new incinerators, considering available technology, cost and energy use. These conclusions are discussed below.

First, incinerator combustion temperature has little impact on cost and energy effectiveness ratios. This conclusion is based on the small changes

with temperature that occur in the three items, namely annualized cost, energy use and VOC control efficiency, that make up these ratios. As discussed above, these three items all increase less than 15 percent with temperature over a 1300 degrees F to 1600 degrees F range. Simple math shows that such small changes in the numerators and denominators of the cost and energy effectiveness ratios lead to almost negligible changes in the ratios. Calculations with the actual numbers confirm this. Based on a 5 percent increase in VOC control, a 12 percent increase in annualized costs and essentially no change in energy use (see Table 2 and 8 and previous discussion), a 1400 degrees F to 1600 degrees F change in temperature increases cost per pound VOC controlled only 5 to 10 percent and actually decreases energy uses per pound VOC controlled.

Second, the highest oontrol limit should be based on incinerator operation at 1600 degrees F. This conclusion is based directly on the first, i. e., that over the range of interest temperature does not adversely affect cost or energy effectiveness. Given this, higher temperatures, with higher control efficiencies, are preferred.

This conclusion on operating temperature is also based on the practical limits on metal recuperative heat exchangers. Based on the logic in the preceding paragraph, there is no upper limit to the combustion temperature which should be used. However, above 1600 degrees F, ceramic recuperative heat exchangers are required. Since these exchangers are more complex and costly, and less typical, than metal designs, the decision was made not to rely on them in considering the achievable control levels. Thus, 1600 degrees F was chosen for the incinerator operating temperature. This conclusion was further supported by the high control levels found achievable at this temperature, as discussed below.

Third, and finally, 98 percent VOC reduction, or 20 ppmv by compound, whichever is less stringent, represents the highest achievable control level for all new incinerators, considering available technology, cost and energy use. This is based on incinerator operation at 1600 degrees F, as discussed in the preceding paragraph, and on adjustment of the incinerator after start-up, as discussed in the section on cost. The dual statement of the conclusion, i .e. as percent reduction or ppmv, accounts for the observed fall-off of efficiency at lower inlet concentrations. The 98/20 numbers themselves were picked by analyzing three different control levels, 99 percent or 10 ppmv, 98 percent or 20 ppmv, and 95 percent or 30 ppmv.

The 99/10 level is judged too stringent. Two of the six non-L.A. tests and 65 percent of the L.A. tests fail this criteria. Consideration was given to the fact that many of the units tested were below 1600 and did not have good mixing. However, due to the large percent that failed, it is judged that even with higher temperatures and moderate adjustment, a large number of units would still not meet the 99/10 level.

The 98/20 ppm level is judged attainable. All of the non-L.A. and the majority of the L.A. units meet this criteria. There is concern over the large number of L.A. tests that failed, i.e. 43 percent. However, two factors outweigh this concern.

First, all the non-L.A. units meet the criteria. This is significant since, though the L.A. units represent many tests, they represent the same basic design. They all are small units designed over a decade ago to meet a rule for 90 percent reduction. They are for similar applications for the same geographic region designed in many cases by the same vendor. Thus, though many failed, they likely did so due to common factors and do not represent a wide spread inability to meet 98 percent reduction or 20 ppmv.

Second, the difference between 65 percent failing 99/10 and 43 percent failing 98/20 is larger than a direct comparison of the percentages would reveal. At 98/20, not only did fewer units fail, but those that did miss the criteria did so by a smaller margin and would require less adjustment. Dropping the criteria from 99/10 to 98/20 drops the failure rate by 20 percent, but is judged to drop the overall time and cost for adjustment by over 50 percent.

The difference between the two levels is even greater when the adjustment effort for the worst case is considered. The crucial point is how close a 99/10 level pushes actual field unit efficiencies to those of the lab unit. Lab unit results for complete backmixing range throughout the 99 range at 1600 degrees F, meaning a 99/10 level would force field units to almost match lab unit mixing. Appendix A describes the reasons the complete backmix results were used. Backing off to 98/20 increases the margin, especially for the worst cases. Given that exponential increases may occur in costs to improve mixing as field units approach lab unit efficiencies, a drop from 99/10 to 98/20 may decrease costs to improve mixing in the worst cases by an order of magnitude.

The 95/30 level was judged too lenient. The only data indicating such a low efficiency was from L.A. All other data showed 98/20. The non-L.A. data and lab data meet 98/20 and the Petro-tex experience showed that moderate adjustment can increase efficiency above 98. In addition, in the previous discussion on efficiency, the L.A. units were judged to have poor mixing. The mixing deficiencies were large enough to mask the effect of increasing temperature. Thus, it is judged that 98/20 could be reached with moderate adjustment and that a 95/30 level would represent a criteria not based on the best available units, considering cost, energy, and environmental impact.

Table 1
Description — Available Incinerator Test Data

Below are described the available incinerator test data. Four sets of such data are present. These sets are lab scale incinerator data from tests by Union Carbide and field unit data from tests conducted by EPA, chemical companies and L.A. County.

Union Carbide Test Data (see footnote 1) - These data show the combustion efficiencies achieved on 15 organic compounds in a lab scale incinerator operating between 800 and 1500 degrees F and .1 to 2 second residence time. The incinerator consisted of a 130 centimeter thin bore tube in a bench size tube furnace. Outlet analyzes were done by direct routing of the incinerator outlet to a FID and GC. All inlet gases were set at 1000 ppmv.

EPA Test Data (see footnote 2, 3, and 4) - These data show the combustion efficiencies for full scale incinerators on air oxidation vents at three chemical plants. These three plants are the Union Carbide, Taft, Louisiana, and Rohm & Haas, Deer Park, Texas, acrylic acid units and the Denka, Houston, Texas unit. The data for Union Carbide include test results based on two different incinerator temperatures and the data from Rohm & Haas, results from three temperatures. In all tests integrated bags were used for sampling and a GC/FID was used for organic analysis.

Chemical Company Test Data (see footnotes 5, 6, 7, and 8) - these data are from tests performed by chemical companies on incinerators at three air oxidation units. The companies and units are, Monsanto at their acrylonitrile unit at Alvin, Texas, Petro-tex at their oxidative butadiene unit at Houston, Texas, and Koppers at their maleic anhydride unit at Bridgeville, Pennsylvania. The Monsanto incinerator burns both liquid and gaseous wastes from the acrylonitrile unit and the Koppers incinerator is actually a boiler adapted to burn gaseous wastes. In all tests, analysis was performed by GC/FID. The sampling was performed as follows:

Monsanto — Cold water scrubbing - AN, AcN, HCN; metal sample bombs - remaining compounds
Petro-tex — Integrated bag - inlet; glass syringe - outlet
Koppers — Glass sample bombs and charcoal tubes

L.A. County Test Data (see footnote 9) - These data are from over 200 tests by L.A. County on various waste gas incinerators, most of which are on coating operations. Data from 147 tests were used, with the remaining tests being discarded since backup data were missing, the incinerators were catalytic units or similar reasons. In the L.A. data, only flow, temperature, and inlet and outlet VOC concentration are reported; data on compounds and residence time are not present. Evacuated 40 liter gas cylinders were used for sampling and oxidation to CO2 and NDIR were used for analysis.

Table 2
Results — Union Carbide Tests[a]
Destruction Efficiency Under Stated Conditions

Flow Regime[b]	Temperature (/F)	Residence Time/Compound				
		0.75 seconds				0.5 & 1.5 seconds
		Ethyl Acrylate	Ethanol	Ethylene	Vinyl Chloride	Ethylene
Two-Stage Backmixing	1300	99.9	94.6	92.6	78.6	87.2/97.6
	1400	99.9	99.6	99.3	99.0	98.6/99.8
	1500	99.9	99.9	99.9	99.9	99.9/99.9
	1600	99.9	99.9	99.9	99.9	99.9/99.9
Complete Backmixing	1300	98.9	86.8	84.4	69.9	78.2/91.5
	1400	99.7	96.8	95.6	93.1	93.7/97.8
	1500	99.9	99.0	98.7	98.4	98.0/99.0
	1600	99.9	99.7	99.6	99.6	99.4/99.8
Plug Flow	1300	99.9	99.9	99.5	90.2	97.3/99.9
	1400	99.9	99.9	99.9	99.9	99.9/99.9
	1500	99.9	99.9	99.9	99.9	99.9/99.9
	1600	99.9	99.9	99.9	99.9	99.9/99.9

[a] The results of the Union Carbide work are presented as a series of equations. These equations relate destruction efficiency to temperature, residence time and flow regime for each of 15 compounds. The efficiencies in this table were calculated from these equations.

[b] Three flow regimes are presented, two-stage backmixing, complete back mixing and plug flow. Two stage backmixing is considered a reasonable approximation
of actual field units, with complete backmixing and plug flow representing the extremes. The subject of flow regime is further discussed in Appendix A.

Table 3
Results — EPA and Company Incinerator Tests

Company	Residence Time/Inlet Flow (SCFM)	Temperature (°F)	Number of Test Runs	Inlet VOC (ppmv)[c]	Outlet VOC (ppmv)	VOC[d] Control
Union Carbide	2 to 3 sec/ 20,600	1160	6[a]	11900	243	96.1
		1475	3[a]	11900	10	99.9
Rohm & Haas	1 sec/ Tank Farm Vent, (TFV)-12,500 Oxidizer Vent, (OXV)-40,000	1425	3[a]	TFV 2580 OXV 11600	1330	82.6
		1510	4[a]	TFV 2600 OXV 12800	150	98.3
		1545	1[a]	TFV 2410 OXV 12200	25	99.7
Denka	0.6 sec/33,000	1400	3[a]	950	13	98.5
Monsanto	(Unit size) - 18' Dia. X 36' (Outlet Flow) 75,000	Confidential	Unit 1-6[b]	Conf.	25	>99
			Unit 2-8[b]	Conf.	47	>99
Koppers[e]	0.6 sec/30,000	1800	Inlet-4[a]	850	Set I 7	99.0
			Outlet-6[a]		Set 2 Il	97.2
Petro-tex[f]	0.6 sec/14,400	1400	N/A Set 1	10300	1000	70.3
			Set 2	10650	215	94.1
			Set 3	10300	10	99.6

[a] Sampling conducted with integrated bags.
[b] Sampling conducted with grab sample bombs or syringes.
[c] VOC does not include methane of ethane. This definition of VOC is different from that used in earlier memos on EPA tests, and thus results reported here may differ from results in the earlier memo.
[d] VOC % destruction is by weight percent.
[e] The data in Set 1 and 2 for Koppers were taken during different time periods.
[f] Inlet and outlet VOC for Petro-tex reported as ppmv methane. The data in set one were taken prior to adjustment of the incinerator; the data in sets two and three, after adjustment. The specific alterations made by Petro-tex are described in references 6 and 7.

Table 4
Results — L.A. Incinerator Tests
Destruction Efficiency[a] Under Stated Conditions

Destruction Efficiency vs. Temperature

Temperature Range (degrees F)	Number of Tests	1st Quartile[b]	Median	3rd Quartile
1300 - 1380	32	93.0	96.4	98.0
1385 - 1420	40	94.0	96.0	98.6
1425 - 14/5	49	91.5	95.0	97.4
1480 and greater	26	91.5	96.5	98.6

Destruction Efficiency vs. Inlet Concentration

Inlet Concentration (VOC as ppmv carbon)	Number of Tests	1st Quartile	Median	3rd Quartile
0 - 399	16	85.1	90.8	96.0
400 - 799	21	91.0	93.3	97.2
800 - 1199	14	90.0	92.5	94.7
1200 - 1599	16	86.0	92.9	97.9
1600 - 1999	9	93.0	94.5	96.0
2000 - 2339	11	91.0	95.5	97.3
2400 - 3199	12	95.9	98.4	99.3
3200 - 3999	9	97.0	97.8	99.0
4000 - 4999	13	95.5	98.4	99.2
5000 - 5999	8	94.9	97.5	98.1
6000 - 6999	8	96.0	97.5	98.4
7000 or more	10	98.2	98.7	99.5

[a] Destruction efficiency as weight percent carbon.

[b] Median and quartiles are used rather than averages and standard deviations due to the manner in which the data were distributed.

Table 5
Result Comparison — Lab Incinerator vs. Rohm & Haas Incinerator*

	Rohm & Haas Incinerator		Lab Incinerator	
Compound	Inlet (lbs/hr)	Outlet (lbs/hr)	Inlet (grams/sec)	Outlet (grams/sec)
propane	900	150	9.0	0.08
propylene	1800**	150**	18.0	0.70
ethane	10	375	0.1	0.50
ethylene	30	190	0.3	0.43
	2740	865	27.4	1.71
% VOC Destruction	68.4%		93.8%	

[a] Table shows the destruction efficiency on the four listed compounds for the Rohm & Haas (R&H) field and Union Carbide (UC) lab incinerators. The R&H results are measured; the UC results are calculated. Both sets of results are based on 1600 degree F combustion temperature and 1 second residence time. In addition, the UC results are based on complete backmixing and a four step combustion sequence consisting of propane to propylene to ethane to ethylene to CO_2 and H_2O. These last two items are worst case assumptions.

[b] Are not actual values. Actual values are confidential. Calculations with actual values give similar results.

Table 6
Results — Selected L.A. Incinerator Tests[a]

Test No.	Temperature (/F)	Inlet[b] Concentration	Outlet[b] Concentration	% VOC Destruction
1158	1300	2300	60	97.4
	1400	1600	83	94.9
1214	1400	1200	23	98.2
	1510	1200	89	92.7
1215	1400	1500	94	93.9
	1500	1500	170	89.1
1329	1300	3100	27	99.2
	1325	3700	70	98.1
	1375	3800	120	96.9
	1400	2700	7	99.7
1746	1320	7430	83	98.9
	1410	6247	88	98.6
	1500	7370	104	98.6
1842	1140	1260	83	93.5
	1285	1090	60	94.5
	1425	1420	109	93.0
2130	1300	801	34	93.9
	1375	777	66	89.4
	1495	890	63	90.7
2235	1400	11065	97	99.1
	1450	10731	254	97.6
2359	1400	871	90	85.1
	1450	871	131	72.3
2624A	1200	4110	60	98.1
	1450	3090	65	98.4
2624B	1200	1405	23	98.4
	1420	1164	18	98.8

[a] Partial listing of tests where incinerator temperature was increased with no change or a decrease in VOC destruction.

[b] VOC as ppmv carbon; destruction efficiency as weight percent carbon.

Table 7
Cost Comparison — Incremental Capital Cost and
Fuel Savings with Heat Recovery[a]

Incinerators not Requiring Supplemental Air[b]

Recuperative Heat Recovery (%)	Inlet Flow 1000 (SCM) Incr. Capital	1000 (SCM) Incr. Fuel	2000 (SCM) Incr. Capital	2000 (SCM) Incr. Fuel
30	$15,600	$11,500	$18,600	$23,000
50	$6,600	$7,500	$9,900	$15,000
70	$10,800	$7,500	$13,500	$15,000

	3000 (SCM) Incr. Capital	3000 (SCM) Incr. Fuel	10000 (SCM) Incr. Capital	10000 (SCM) Incr. Fuel
30	$22,500	$34,500	$36,000	$115,000
50	$12,000	$22,500	$29,000	$75,000
70	$18,000	$22,500	$59,000	$75,000

Incinerators Requiring Supplemental Air

Recuperative Heat Recovery (%)	Inlet Flow 700 (SCM) Incr. Capital	700 (SCM) Incr. Fuel	5000 (SCM) Incr. Capital	5000 (SCM) Incr. Fuel
30	$13,000	$27,000	$27,000	$178,000
50	$5,000	$10,000	$12,000	$84,000
70	$2,000	$9,000	$13,000	$77,000

[a] Dollar figures are the incremental annualized capital costs and incremental annual fuel cost savings for increasing the heat recovery from the previous level to the listed level. For example, the figures on the 50% line are the costs and savings of going from 30% to 50% heat recovery, and on the 30% line, of going from no heat recover to 30% recovery. Costs are based on an incinerator operating at 1600°F and 0.75 seconds residence time. 70% recuperative heat recovery corresponds to an exit gas temperature of approximately 550°F.

[b] Costs based on Reference 10.

Table 8
Cost Comparison — Incremental Costs of Combustion
Temperature Increase

Flow (scfm)	Capital Cost - 1400/F[b]	Incr. Capital to 1600/F	Percent Increase	Annualized Cost - 1400/F[c]	Incr. Annual to 1600/F	Percent Increase
Incinerators Requiring Supplemental Air[a]						
700	328	38	11%	137	11	8%
5000	593	97	17%	288	28	10%
25000	1754	438	24%	965	127	13%
50000	2970	856	28%	1741	248	14%
Incinerators not Requiring Supplemental Air						
1000	328	36	11%	139	10	7%
10000	705	135	19%	363	40	10%
25000	1310	330	25%	728	96	13%

[a] All money figures in thousands or dollars

[b] The capital cost column shows the total installed capital for an incinerator operating at 1400 degrees F, 0.75 seconds residence time, recuperative recovery with an exit gas temperature of 510 degrees F, and the listed flow. The next column shows the extra capital for a similar incinerator operating at 1600 degrees F. The fourth column shows the percent increase in capital cost from 1400 degrees F to 1600 degrees F.

[c] The annualized cost column shows the total annual cost (depreciation, interest, taxes, utilities and maintenance) for 1400 degrees F, 0.75 seconds, 510 degrees F exit temperature and the listed flow. The next column shows the incremental annualized cost for a similar incinerator at 1600 degrees F. The seventh column shows the percent increase in annualized cost from 1400 degrees F to 1600 degrees F.

Appendix A

Mixing is a key concept in incinerator efficiency. Thus, a discussion of incinerator efficiency will likely rely heavily on this concept. However, mixing is also a complex concept. Thus, discussions of efficiency can become burdened with technical explanations of mixing. To handle this difficulty, this memo only cites mixing in the main discussion and leaves detailed explanation of this concept to this appendix.

This appendix discusses mixing in three parts. The first describes the actual physical events involved in mixing and contrasts proper and improper mixing. The second discusses a related item, flow regime, and explains the importance of this idea in interpreting the lab scale data. The third analyzes the lack of a relationship between temperature and efficiency in the L.A. data and concludes that poor mixing was the cause.

Mixing

Mixing can be understood in terms of the two items required for combustion of organic compounds, high temperature and sufficient oxygen. In incineration, these are provided by combustion gases and supplemental air. The combustion gases from burning supplemental fuel provide the heat to achieve high temperatures. Supplemental air, when needed, provides oxygen to combust the supplemental fuel and VOC's.

Mixing concerns these two streams, i.e. combustion gases and supplemental air. Mixing involves the speed and completeness with which these two streams are dispersed into the waste gas. In proper mixing, these two streams are broken apart and intermingled with the waste gas on a molecular level. in addition, this process occurs within only a small fraction of the incinerator residence time.

In contrast, in improper mixing, packets of waste gas pass through the incinerator intact. The turbulence in the incinerator fails to break the waste gas into sufficiently small units for intermingling on a molecular level to occur. Poor mixing also results if this intermingling occurs too late. If the waste gas is mixed just prior to exiting the incinerator, then the actual residence time (R.T.) is much shorter than the nominal R.T., and complete combustion may not occur. Finally poor mixing results if only one of the two required streams, i .e. combustion gas or supplemental air, is properly dispersed. For example, the waste gas may be properly intermingled with combustion gases, but the supplemental air flow may be stratified. The result would be incomplete combustion.

Flow Regime

Flow regime involves the large scale gas currents in an incinerator. In a diagram of the gas flows in an incinerator, flow regime corresponds to broad arrows representing the macroscopic currents.

Certain flow regimes have been labelled. In plug flow, inlet gases remain within fixed vertical "slices" that travel directly from inlet to outlet with no backflow. in complete backmixing, the opposite occurs. inlet gases are rapidly spread throughout the incinerator and significant backflow

occurs. Other flow regimes are composites of these. In two stage backmixing, the incinerator operates like two units in series, with each undergoing complete backmixing. Clearly, actual flow patterns rarely correspond to these idealized types, but these types can serve as approximations.

Flow regime is related to both mixing and efficiency. Specifically, the flow regimes most favorable to high efficiency are the least favorable to mixing, and vice versa. Based on engineering kinetics, plug flow achieves the highest efficiencies at a given temperature. However, to achieve good mixing and still maintain plug flow, the gases in each vertical "slice" must completely mix with each other while remaining separate from the adjoining "slices." Such a phenomena is difficult to create. As the gases mix vertically they also tend to mix horizontally, resulting in a flow pattern closer to complete backmixing. Thus, providing good mixing inherently creates flow patterns less advantageous to high efficiencies.

Flow regime is important in interpreting the Union Carbide (UC) lab unit results. These results are significant since the UC unit was designed for optimum mixing and thus the UC results represent the upper limit of incinerator efficiency. This upper limit is used in evaluating the costs involved in adjusting and designing an incinerator to reach a given efficiency. The closer this given efficiency is to the upper limit, the higher the costs will be.

An understanding of flow regime is required to choose which part of the UC results represents the upper limit. As seen in Table 2, the UC results vary by flow regime. Based on the above discussion, the results under complete backmixing were chosen as the upper limit for the discussion in this memo. Though some incinerators may achieve good mixing and plug flow, the worst cases will likely require flow patterns similar to complete backmixing to achieve complete mixing. Thus, since this memo is considering efficiencies applicable to all incinerators, a conservative assumption of complete backmixing was required when considering the upper limit of efficiency.

L.A. Data

The L.A. data surprisingly showed no relation between temperature and efficiency. Various factors were analyzed to determine the cause for this result.

In a search for the cause, sampling error and the incinerator variables of residence time, inlet concentration and type of compound were ruled out. For sampling error to be the cause, the sampling would have had to consistently underestimate efficiency in high temperature tests and overestimate it in low temperature tests. With over 150 tests, this is essentially impossible. For the three incinerator variables to have been the cause, these variables would need to mask the effect of temperature. However, based on the Union Carbide work and kinetic theory, these variables only scatter the efficiencies around an average determined by temperature. In the UC cases, the effect of temperature is still seen in the increasing average efficiency.

The remaining variable is mixing. A plausible explanation of the results is possible if this variable is considered. The reason lies in two factors which allow mixing to mask the relation of temperature and efficiency. First, the completeness of mixing can drop with temperature. Thus, improper mixing can offset the effect of increasing temperature. In contrast, the other variables remain the same as temperature changes and thus offsetting cannot occur. Second, increases in temperature only increase the efficiency of the well-mixed portion of the waste gas. Since this portion contains only part of the uncombusted VOC, and likely the smaller part, the impact of increasing temperature is greatly diluted. In contrast, the other variables cannot "isolate" parts of the waste gas from the affect of temperature.

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5. November 8, 1979, Letter, Michael F. Weishaar, Monsanto, St. Louis, Missouri, to Jack R. Farmer, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711.

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10. Control Device Evaluation - Thermal Oxidation, Jim Blackburn, IT Enviroscience, Knoxville, Tennessee, December 1979.

Attachment

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

DATE: JUL 22 1980

SUBJECT: Thermal Incinerator Performance for NSPS, Addendum

FROM: David C. Mascone
Chemical Manufacturing Section

TO: Jack R. Farmer, Chief
Chemicals and Petroleum Branch

After reviewing the recent memo on incinerator performance, (Thermal Incinerator Performance for NSPS, June 11, 1980, DCM to Jack Farmer), you indicated several areas where further discussion was desired. These areas were as follows:

- continuous compliance of thermal incinerators
- the impact of compound on efficiency
- the impact of inlet concentration on cost effectivesness and efficiency

These three areas are discussed below preceeded by a summary of the conclusions.

Conclusions

In the absence of a demonstrated continuous VOC monitor for thermal incinerators, CPB is investigating alternate methods. After study of the cost and effectiveness of several such methods, the following should be considered: continuous temperature and flow monitoring and bi-annual compliance testing and inspection/maintenance. For example, in monitoring temperature and flow, a company could be required to run the incinerator between +/-50 degrees F of the temperature, and between +20 percent and -50 percent of the flow, measured during the performance test.

Detailed analysis shows that type of compound does affect incinerator efficiency. However, due to the complexity of the relationship, no attempts were made in the June 11 memo to draw fine-tuned efficiency conclusions relating different efficiencies to different compounds at different temperatures. Rather, a more conversative approach was taken in which the efficiency conclusions were based on the most difficult compounds to combust. These conclusions, based on such a worst case analysis, would then apply regardless of compound.

Detailed analysis also shows that inlet concentration affects incinerator efficiency. However, unlike type of compound, statistical study of the relationship between inlet concentration and efficiency was possible. Based on this study, the conclusions in the June 11 incinerator memo are expressed in both ppmv and percent reduction. This dual format accounts for the effect of inlet concentration.

Inlet concentration also affects cost effectiveness. One effect is that as inlet concentration drops the energy content of the waste gas drops, increasing supplemental fuel use. However, this is not the major effect. By far the largest effect of inlet concentration on cost effectiveness is to change the amount of VOC controlled. Over a typical range of inlet concentrations (i.e. 10,000 to 500 ppm) and for an incinerator with 70 percent recuperative heat recovery, increasing fuel use can increase cost effectiveness 5 to 50 percent while decreasing VOC can increase cost effectiveness 5 to 2000 percent.

Discussion

Monitoring - One CPB goal is continuous monitoring of air pollution control equipment. At present, we are limited in achieving this goal for incinerators by the lack of a demonstrated continuous VOC monitor. Given this limitation, CPB is studying alternate monitoring methods, such as measuring firebox temperature, to indicate incinerator performance.

To develop alternate monitoring methods, two goals were considered. First, these alternate methods should detect all or most cases of poor incinerator performance. Second, the methods should have reasonable costs and impose reasonable recordkeeping requirements.

To meet these goals, the variables that affected incinerator performance were analyzed. These variables are temperature, mixing, type of compound, inlet concentration, residence time, and flow regime. Of these variables, the last three were judged of little concern when considering continuous monitoring. These three variables are essentially set after incinerator construcion and adjustment and/or have only small impact on incinerator performance. The three remaining variables were then analyzed in more detail to define their impact on performance and the ability to monitor them.

Temperature was analyzed first. This analysis was based on data in the previous incinerator memo. Even with good mixing, the Union Carbide lab data and kinetic theory show that lower temperatures cause significant decreases in efficiency. In addition, the L.A. data indicate that increasing temperature can also adversely affect efficiency, apparently by changing mixing. In terms of cost, temperature monitors are inexpensive, costing less than $5000 installed with strip charts, and are easily and cheaply operated. Given the large effect of temperature on efficiency and the low cost of temperature monitors, this variable is clearly an effective parameter to monitor.

As an example, a specific requirement could be that an incinerator cannot be operated for more than three hours at an average firebox temperature above 50 degrees F over, or under 50 degrees F below, the average temperature recorded during performance testing. If an operating range greater than 100 degrees F is desired, a company could perform performance tests at more than one temperature. The three hour time period would correspond to the period required for integrated bag sampling in a typical performance test. This would make the averaging period for temperature monitoring similar to that of

the performance test. Finally, the company could be required to install, operate, and calibrate the monitor according to manufacturer's specifications. These specifications generally cover proper placement of the monitor.

The next variable studied was mixing. The most likely item to affect mixing, given a constant temperature and an already constructed incinerator, would be flow. No direct field data is available on the effect of flow on mixing efficiency. However, based on engineering judgement, increasing flow may lead to "shortcircuiting," where the increased kinetic energy of higher flow streams causes waste gas to jet through the incinerator unmixed. Decreased flow may lead to the opposite, where lower flow rates result in insufficient kinetic energy for complete mixing. As with temperature, flow monitors are inexpensive and easily operated. Given the potential impact of flow on efficiency, and the low cost of flow monitors, flow rate is also an effective parameter to monitor.

As an example, a specific requirement could be that an incinerator cannot be operated for more than three hours at an average flow less than 50 percent or greater than 120 percent of the average waste gas flow recorded during a performance test. The permissible range would be intentionally broad due to the lack of field data on the impact of flow on mixing and efficiency. The upper restriction would be tighter than the lower since increase flow not only may adversely affect mixing but decreases residence time. Any adverse effects of decreased flow may be offset by the increased residence time. The above discussion for temperature on widening the operating range, the three hour time limit, and installation, operation and calibration of the monitor would hold for this flow monitoring example.

The final variable analyzed was type of compound. For most incinerator applications, the compounds in the waste gas are set by the process to which the incinerator is attached. Thus, type of compound is of no concern. However, certain applications may have differing compounds in the waste gas. A coating operation may have at one time a solvent with an MEK base, and then switch to a solvent with a toluene base. MEK is oxidized easier than toluene, and thus an incinerator which achieves compliance on an MEK stream may be inadequate for the toluene stream.

The judgement on this item is that no general monitoring requirement on type of compound can be specified. Most cases will have the waste gas compounds set by the process. In those that do not, considerable difficulty is envisioned in defining, in a general way, when the waste gas compounds have changed enough to require additional compliance tests. For example, differentiating between solvent formulations would be difficult. The same generic name of solvent may show greater variations in composition than two different name specialized solvents. However, though a general requirement on type of compound cannot be set, specific requirements may be desired for certain standards.

Temperature and flow monitoring do not measure incinerator performance directly. Thus, concern exists over the long term stability of incinerator performance, even with temperature, flow and type of compound held constant.

Data on this issue is shown in Table 1. The top part of the table shows data from L.A. County where the same incinerator was tested in different years. The bottom part lists possible incinerator malfunctions that could affect performance, without changing temperature and flow.

Based on Table 1, incinerators, if properly designed and adjusted, are judged to have fairly stable performance over time. The L.A. units showed only small changes in efficiency over time. The efficiencies of these units changed less than two percentage points over several years, except one case. In addition, the listed malfunctions are judged to occur infrequently. This is based on several factors. First, these malfunctions involve non-moving parts subject to little wear. Also, the typical waste gases are not highly corrosive and the typical incinerator fuels, natural gas and fuel oil, have low sulfur and ash content. Finally, even though incinerators undergo wide temperature swings, incinerator components are designed to withstand these changes, given proper cooling and heating of the unit.

The above conclusion should not be overstated. Though fairly stable, all four L.A. data sets show some drop in performance over tame. And though improbable, incinerator malfunctions are not impossible. Thus, the conclusion from the data is not that no additional requirements are needed over temperature and flow monitoring. Rather, the conclusion is that the costs and recordkeeping of additional monitoring requirements must be carefully balanced against emissions potentially prevented by them.

After this balance was studied, two additional requirements were considered. These are bi-annuai performance testing and bi-annual inspection and maintenance (I & M) for incinerators. The performance testing would follow the method specified in the standard. The I & M would involve visual inspection for items such as corrosion and firebox deterioration, calibration and testing of control instrumentation, and so on. Such I & M could most likely be performed at the same time as a process turnaround.

These two additional monitoring methods would effectively detect drops in incinerator performance not detected by temperature and flow monitoring. Performance testing is the most direct means of detecting poor efficiency. The I & M will catch drops in performance by spotting equipment failures or impending failures that could lead to poor performance. The I & M has the added advantage that impending failures which could lead to incinerator shutdown would also be spotted. The two year period for compliance testing and I & M is based on the rate at which incinerator performance is likely to deteriorate. The two year period for I & M also corresponds to the typical time between process turnarounds. Thus, with a bi-annual I & M the incinerator I & M could be performed at the same time as process equipment I & M, and it would not be necessary to shut down the process just to check the incinerator. Fnally, the timing of the performance test and the I & M are not linked. They can be done together in any order or apart.

Type of Compound - One factor which affects incinerator efficiency is type of compound. The June 11 memo on incinerator efficiency excludes this

factor from its conclusions, but discusses only briefly the reasons for this exclusion. This section discusses the impact of this factor on efficiency and explains in more detail the reasons for its exclusion.

In terms of the impact of compound on efficency, the available incinerator data does show a moderate impact. The Union Carbide lab data demonstrates this most clearly. In cases where different compounds were incinerated at the same temperature, residence time, and flow regime, variations in efficiency of up to 5 percent points occurred for temperatures above 1400 degrees F. At lower temperatures, the efficiency variations increased up to 20 and 30 percentage points.

However, as a practical matter, including compound as a factor in an efficiency conclusion would be difficult. First, a precise quantitative relation between compound and efficiency could not be determined. As with mixing, no single value could be assigned to an individual compound to represent ease of combustion. Thus, analysis of the relation between efficiency and compound was limited. Second, even if a relationship could be devised, it would be complex and difficult to apply. The relationship would likely involve kinetic rate constants, autoignition temperatures, factors for molecular configuration and structural groups and similar variables.

To avoid these difficulties, an alternative approach was taken. No initial attempts were made at drawing a fine-tuned efficiency conclusion showing differing efficiencies at differing temperatures for different compounds. Rather, a conservative approach of choosing a simple set of incinerator conditions and efficiencies based on the most difficult compounds to combust was pursued. This approach proved successful.

Several factors aided in the success of this approach. First, the available test data covered a wide range of compounds. The compounds on which test data were available included C1 to C5 alkanes and olefins, aromatics such as benzene, toluene, and xylene, oxygenated compounds such as MEK and isopropanol, nitrogen containing species such as acrylonitrile and ethylamines and chlorinated compounds such as vinyl chloride. With such a range of compounds and the consideration of kinetics, it was concluded that worst case compounds had been taken into account. The second factor was the discovery that increasing combustion temperature resulted in only negligible energy penalties and moderate cost increases. Thus, choosing a higher temperature to cover the worst cases did not make incinerators unaffordable or too energy intensive.

Inlet Concentration - A second factor which affects efficiency is inlet concentration. Unlike type of compound, an allowance for this factor gas was included in the efficiency conclusions. Specifically, these conclusions included not only an efficiency of 98 percent but a minimum exit concentration of 20 ppmv by compound. Thus, as inlet concentration drops, the minimum ppmv lowers the efficiency required. For example, with a 500 ppmv inlet concentration for a waste gas containing oxygen, the 20 ppmv minimum translates to a 96 percent efficiency; with a 250 ppmv inlet a 92 percent efficiency. This section explains in more detail the reasons for this allowance for inlet concentration.

Tee test results from L.A. County form the major basis for this allowance. These results show a strong trend where lower inlet concentration results in lower efficiency. For example, for inlet concentrations less than 1600 ppmv as carbon, the median L.A. efficiency was approximately 92 percent. For inlet concentrations between 1600 and 2400, the median L.A. efficency was approximately 94 percent. For inlet concentrations above 2400, the median efficiency was approximately 97 percent.

Kinetic considerations also support the allowance for inlet concentration. The most likely Kinetic model where inlet concentration does not affect efficieny is a first order model. However, available literature indicates that combustion follows complex reaction mechanisms.[1,2] In cases, these mechanisms can be fit to a first order model. However, as a general rule, these mechanisms, which involve chain reactions, free radicals and multiple pathways, cannot be reduced to first order models.

The June 11, 1980, incinerator memo concluded that the L.A. incinerators did not all achieve proper mixing. This improper mixing may have caused or influenced the relation between efficiency and inlet concentration in the L.A. data. If this is the case, then an allowance for inlet concentration may permit lower efficiencies than are actually achievable in incinerators with proper mixing. However, the possible effect of poor mixing on the relation of efficiency and inlet concentration remains just that, possible; no conclusive statement can be made. Given this, a more conservative approach was taken and lower efficiencies for lower inlet concentrations were allowed.

Inlet concentration also impacts cost effectiveness, i.e. costs per unit weight VOC controlled. The precise impact depends on molecular weight, the size of the incinerator and the ratio of waste gas energy content to VOC. Figure 1 show these impacts.

A surprising conclusion in the analysis of inlet concentration vs. cost effectiveness is the role of supplemental fuel. The increasing cost for supplemental fuel as inlet ppm drops is not a major factor in cost effectiveness. Incinerator size and the amount of VOC being destroyed are much more important factors. An illustrative example is a 5000 SCFM incinerator burning benzene in nitrogen. The extra fuel required when dropping the inlet concentration from 5000 to 500 ppmv increases the cost effectiveness only 20 percent. The fact that only one-tenth the benzene is being destroyed for about the same cost increases the cost effectiveness 1000 percent. And decreasing the stream size to 1000 SCFM increases the cost effectiveness about 300 percent. Clearly, increasing fuel costs at lower ppmv is only a minor factor.

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[1] Rolke, R.W., et. al. Afterburner System Study, U.S. Environmental Protection Agency, Report 5-14121, Shell Development Company, 1971.

[2] Barnes, R.H., et. al Chemical Aspects of Afterburner Systems, IERL Report U.S. Environmental Protection Agency, EPA-600/7-79-096. Batelle Columbus Laboratories, April 1979.

Table 1
Long Term Incinerator Performance

Part A — Test Data[a]

Company	Test No.	Date	Inlet (ppmv carbon)	Outlet (ppmv carbon)	% VOC Destruction	Flow(SCFM)/ Temp. (F)
Day & Night Manufacturing	1754	10-30-73	443	33	92.5	3270/1300
	2442	7- 7-76	1030	91	91.4	2020/1300
	2443	8-10-78	716	94	87.3	2050/ —
Glasteel, Inc.	2286	5-12-75	6020	52	99.0	1210/1260
	2402	2-17-76	5860	71	98.9	4150/1375
National Can	1430	6-10-70	4900	31	99.4	2520/1500
	1746	3-21-74	7370	104	98.6	1990/1500
National Can	1451	6-10-70	3500	22	99.4	4620/1460
	1746	3-21-74	6247	82	98.0	4620/1460
			7370	79	98.0	4650/1525

Part B -Possible Incinerator Malfunctions[b]

Malfunction	Cause
• Firebrick Deterioration	Improper heating & cooling of incinerator during start-up & shutdown; firebox temperature too high
• Insulation Loss from Incinerator Exterior	General weathering & corrosion from rain, cold, incinerator start-up & shutdown & so on
• Corrosion of ducts, baffles & other exposed metal	Ash, acids, salts, etc. in fuel or waste gas

Table 1 (Cont'd)
Long Term Incinerator Performance

Part B -Possible Incinerator Malfunctions[b]

Malfunction	Cause
• Plugging of Burners	Ash & carbon build-up
• Breaking of Recuperative Heat Exchanger Seals	General corrosion; temperature warping from hot spots in the exchanger, improper heating & cooling during start-up & shutdown

Malfunction	Possible Effect on VOC Control
• Firebrick Deterioration	Deteriorated wall allows local heat loss resulting in cool spots in firebox, and thus potentially lower destruction efficiency in those spots
• Insulation Loss from Incinerator Exterior	Same as previous; insulation loss leads to local heat loss & cool spots in the incinerator
• Corrosion of ducts, baffles & other exposed metal	Severe corrosion of metal parts affects the gas flow patterns through and around them, potentially affecting mixing & thus efficiency

Table 1 (Cont'd)
Long Term Incinerator Performance

Part B -Possible Incinerator Malfunctions[b]

Malfunction	Possible Effect on VOC Control
• Plugging of Burners	A plugged or partially plugged burn affects the flow patterns & temperature profiles in the firebox potentially lowering destruction efficiency
• Breaking of Recuperative Heat Exchanger Seals	Inlet waste gas leaks into the out flue gas without passing through the firebox.

[a] The listed data are from incinerators which were tested in more than one year.

[b] The listed malfunctions include only those which would likely not affect temperature at a single point firebox temperature monitor or inlet/outlet flow.

Figure 1 - Notes and Explanation

Figure 1 shows the cost effectiveness of thermal incinerators by inlet concentration and waste gas flow. The cost effectiveness is in hundred dollars per 2000 pound ton; inlet concentration is ppmv by compound; and the flow rate is in SCFM. The costs in the figure assume a waste gas deficient in air, and a compound with a molecular weight of 80 and a heat of combustion of. 15,000 BTU/lb VOC. The thermal incinerator operates at 1600 degrees F and .75 seconds and achieves 70 percent recuperative heat recovery.

The figure can be used to approximate cost effectiveness for situations other than that described in the above paragraph. For compounds with different molecular weights, the x-axis scale should be increased by 80 over the molecular weight of the compound. For example, for a compound with molecular weight of 40, the x-axis scale would read 2000, 4000, and 6000. For cases where the waste gas contains sufficient oxygen for combustion, the cost effectiveness should be decreased by the following percentages:

1000	SCFM	7%
2500	SCFM	14%
5000	SCFM	21%
10000	SCFM	26%
25000	SCFM	30%

This adjustment accounts for the smaller size and lower fuel requirements of these cases. Finally, for cases where the combustion value of the stream per pound of VOC is higher, the below listed decreases approximate the costs. These adjustments assume 30,000 BTU/lb VOC.

for ppmv <500	No adjustment		
for ppmv between 500 & 3000	1000	SCFM	5%
	2500	SCFM	10%
	5000	SCFM	15%
	10000	SCFM	20%
	25000	SCFM	25%
for ppmv >3000	No adjustment		

This adjustment accounts for the lower fuel use at higher BTU/lb levels.