Note: This is a reference cited in *AP 42, Compilation of Air Pollutant Emission Factors, Volume I Stationary Point and Area Sources.* AP42 is located on the EPA web site at www.epa.gov/ttn/chief/ap42/

The file name refers to the reference number, the AP42 chapter and section. The file name "ref02_c01s02.pdf" would mean the reference is from AP42 chapter 1 section 2. The reference may be from a previous version of the section and no longer cited. The primary source should always be checked.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

DATE: JUN 11 1980

SUBJECT: Thermal Incinerator Performance for NSPS

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TO: Jack R. Farmer, Chief
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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 operation at a maximum of 1600°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°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°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°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 conditions be specified in regulations. As just noted, this set of conditions 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 Caribde 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 efficiency. 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 efficiency. Rather, increasing temperature increases efficiency by narrowing the range over which efficiencies 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 presented 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°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 time 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 recovery. In addition, 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°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°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°F and 1600°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°F and 1600°F incinerators. The major factors in the increase are the larger recuperative heat exchanger and larger combustion chamber needed for the 1600°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 procedure 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°F to 1600°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°F to 1600°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 control limit should be based on incinerator operation at 1600°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°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°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°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°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[1] - These data show the combustion efficiencies achieved on 15 organic compounds in a lab scale incinerator operating between 800 and 1500°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[2,3,4] - These data show the combustion efficiencies for full scale incinerators on air oxidation vents at three chemical plants. These three plants are the Uniton Caribde, 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[5,6,7,8] - 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[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 back-up 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 CO_2 and NDIR were used for analysis.

Table 2

Results - Union Carbide Tests*

Destruction Efficiency
Under Stated Conditions

Flow Regime**	Temperature (F)	Residence Time/Compound .75 seconds				.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

*The results of the Untion 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.

** Three flow regimes are presented, two-stage backmixing, complete backmixing 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)***	Outlet VOC (ppmv)	% VOC† Control
Union Carbide	2 to 3 sec/ 20,600	1160	6*	11900	243	96.1
		1475	3*	11900	10	99.9
Rohm & Haas	1 sec/ Tank Farm Vent, (TFV)-12,500 Oxidizer Vent, (OXV)-40,000	1425	3*	TFV 2580 OXV 11600	1330	82.6
		1510	4*	TFV 2600 OXV 12800	150	98.3
		1545	1*	TFV 2410 OXV 12200	25	99.7
Denka	.6 sec/33,000	1400	3*	950	13	98.5
Monsanto	(Unit size) - 18' Dia. X 36' (Outlet Flow) 75,000	Confidential	Unit 1-6**	Conf.	25	>99
			Unit 2-8**	Conf.	47	>99
Koppers††	.6 sec/30,000	1800	Inlet-4** Outlet-6*	850	Set 1 7	99.0
					Set 2 11	97.2
Petro-tex†††	.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

*Sampling conducted with integrated bags.
**Sampling conducted with grab sample bombs or syringes.
***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.
†VOC % destruction is by weight percent.
††The data in Set 1 and 2 for Koppers were taken during different time periods.
†††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*
Under Stated Conditions

Destruction Efficiency vs. Temperature

Temperature Range (°F)	Number of Tests	1st Quartile **	Median	3rd Quartile
1300 - 1380	32	93.0	96.4	98.0
1385 - 1420	40	94.0	96.0	98.6
1425 - 1475	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 - 2399	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

*Destruction efficiency as weight percent carbon.

** Medians 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	.08
propylene	1800**	150**	18.0	.70
ethane	10	375	.1	.50
ethylene	30	190	.3	.43
	2740	865	27.4	1.71
% VOC Destruction	68.4%		93.8	

*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 1425°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.

**Are not actual values. Actual values are confidential. Calculations with actual values give similar results.

Table 6
Results - Selected L.A. Incinerator Tests*

Test No.	Temperature (°F)	Inlet** Concentration	Outlet** 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

*Partial listing of tests where incinerator temperature was increased with no change or a decrease in VOC destruction.
**VOC as ppmv carbon; destruction efficiency as weight percent carbon.

Table 7

Cost Comparison - Incremental
Capital Cost and Fuel Savings
with Heat Recovery*

Incinerators not Requiring Supplemental Air**

Recuperative Heat Recovery (%)	Inlet Flow (SCFM)	1000		2000	
		Incr. Capital	Incr. Fuel	Incr. Capital	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		10000	
	Incr. Capital	Incr. Fuel	Incr. Capital	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 (SCFM)	700		5000	
		Incr. Capital	Incr. Fuel	Incr. Capital	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

* 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 recovery to 30% recovery. Costs are based on an incinerator operating at 1600°F and .75 seconds residence time. 70% recuperative heat recovery corresponds to an exit gas temperature of approximately 550°F.

** Costs based on Reference 10.

Table 8

Cost Comparison - Incremental
Costs of Combustion
Temperature Increase

Flow (scfm)	Capital Cost - 1400°F**	Incr. Capital to 1600°F	Percent Increase	Annualized Cost - 1400°F***	Incr. Annual to 1600°F	Percent Increase
Incinerators Requiring Supplemental Air*						
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%

*All money figures in thousands of dollars

**The capital cost column shows the total installed capital for an incinerator operating at 1400°F, .75 seconds residence time, recuperative recovery with an exit gas temperature of 510°F, and the listed flow. The next column shows the extra capital for a similar incinerator operating at 1600°F. The fourth column shows the percent increase in capital cost from 1400°F to 1600°F.

***The annualized cost column shows the total annual cost (depreciation, interest, taxes, utilities and maintenance) for 1400°F, .75 seconds, 510°F exit temperature and the listed flow. The next column shows the incremental annualized cost for a similar incinerator at 1600°F. The seventh column shows the percent increase in annualized cost from 1400°F to 1600°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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