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# INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

D. M. Doty, et al

Fats and Proteins Research Foundation, Incorporated

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ENVIRONMENTAL PROTECTION TECHNOLOGY

# Investigation of Odor Control in the Rendering Industry


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# INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

ENVIRONMENTAL PROTECTION AGENCY

by

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Ib

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ABSTRACT

INVESTIGATION OF ODOR CONTROL
IN THE TENDERING INDUSTRY

The control of rendering plant odors was investigated, both as to equipment cost and design, and experimental performance. The design studies indicated that scrubbers are the most economical method, and a commercially available spray scrubber system was calculated to be 1/4 as costly as other methods.

The compounds mainly responsible for rendering odors were identified by gas chromatography and mass spectroscopy as well as odor panel tests, and a list of compounds was chosen for experiments. Exploratory bubbler tests were done with a list of scrubbing reagents, and the most promising were further tested in a packed scrubbing column of pilot size. Strong oxidizers, especially sodium hypochlorite, were found to be the most effective on a wide spectrum of compounds. Water is effective on soluble odorants, while alkalies are not very effective. Other agents are effective against specific compounds.

Further tests on a 2-stage scrubber system are suggested to be conducted in a rendering plant.



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# INVESTIGATION OF ODOR CONTROL IN THE RENDERING INDUSTRY

## 1. INTRODUCTION AND SUMMARY

A previous investigation sponsored by the Fats & Proteins Research Foundation, Inc. resulted in identification of some of the compounds in rendering plant odors. This information made it possible to more scientifically investigate the effectiveness of various odor control means, since for the first time the chemical and physical properties of the odor were known. Previously, only subjective evaluations could be made of the effectiveness of various odor control methods, although the dilution method allowed performance to be measured in odor units or reduction ratios.

The objective of this program was to develop an effective and economic means of odor control. Before undertaking laboratory experiments, known and potential odor control methods were compared based on limited data from the literature, and reports of performance and cost from member companies of the Fats & Proteins Research Foundation. This comparison indicated that scrubbing was probably the most economic method, especially if one or more effective scrubbing reagents could be found. Incineration was also feasible, but was more costly for most applications. The study also indicated that commercially available control equipment was not designed on a reliable basis, partly because of the lack of quantitative data on the odorous compounds in rendering odors. Rendering companies were not in a position to rationally select from among the control equipment offered by manufacturers.

Although the experimental work concentrated on scrubbers, the design analysis was extended to several types of incinerators, scrubbers and carbon beds. More novel approaches were also considered but not studied extensively. A design computer program was written for each control method (except carbon beds), and these programs can be used for preliminary estimates of the cost of each method for the particular conditions of any rendering



plant. These costs will differ depending on the size of the air stream to be treated; and its concentration, which depends on whether the source is process air or more dilute plant ventilation air. For each control method the computer program estimates the size of equipment needed based on a simplified design method; for example, the design of scrubbers is based on the idea that reagents have been found that react rapidly with the odorants, once they reach the liquid phase and that the rate of removal is controlled by mass transfer from the gas to the liquid. In the case of incinerators the rate is assumed to be governed by an overall combustion reaction, the rate constants for which are determined as a function of temperature from available plant data. Based on these concepts, the programs are able to explore or optimize the operating conditions to find the design having minimum annual cost. Cost data are supplied to each program as input data, and the basis for the cost calculations is given under the description of each program. Both investment amortization and operating costs are included in simple form.

Results of design and cost estimates for each control method are presented in tabular form for a series of air flow rates and odor reduction ratios. Most rendering plants will be able to find a case similar to theirs to obtain a preliminary idea of the control methods available to them. Individual calculations can also be done at reasonable cost.

As a result of the information presented, we can conclude that scrubbers offer the most economical control method, provided that effective reagents can be found. An incinerator may be more economic for a small, highly concentrated process air stream, since removal of the higher concentration only requires incineration at a higher temperature and/or longer contact time. The contact times and temperatures conventionally used for design of such incinerators are inadequate for odor control, however. Catalytic incineration does not appear to be economically competitive.

A novel spray scrubbing system that is commercially available is calculated to control odors at a cost 1/4 that of other available equipment. A typical unit cost is $.16 per 1000-cfm-hr of operation. Previously available spray scrubbers were not effective and the reasons for the improvement are suggested by the calculations. There have been several installations of this type of scrubber in rendering plants; a removal of 85% of odor was reported in one case. Much higher removals would be necessary in practice, and this might be achieved through more rational choice of operating conditions and selection of the best scrubbing liquids. A test of this and a conventional scrubber is proposed for the following year in a rendering plant.

Additional studies were conducted to further identify the compounds responsible for rendering odors. Improvements in gas chromatography and mass spectroscopy made possible the identification of most of the important species. At the same time, odor panel tests were done to determine which peaks are responsible for the main odors. This was done by sampling odors from six plants before and after scrubbers and incinerators. Computer regression of the odor intensity with the peaks present determined which peaks could be responsible for the odors. An effort was then made to identify these peaks by mass spectroscopy. The important peaks and their identifications are given in Table 30. They include various sulfides, disulfides (and probably mercaptans), C4 to C7 aldehydes, trimethyl amine and various C4 amines, quinoline, dimethyl pyrazine and other pyrazines, C3 to C6 acids. Other compounds that are present but are probably not so important as far as odor is concerned are C4 to C7 alcohols, ketones, hydrocarbons, as well as many common aromatic compounds. Some of these compounds contain double bonds.

A list of compounds was selected to represent the important chemical types in the rendering odors. Scrubbing experiments were then done on these pure compounds. Concentrations were measured by chromatograph, by calibrating the area under the chromatograph peak with known amounts of the pure compounds.



Two types of experiments were done. The first was an exploratory experiment, in which one or more odorant compounds was mixed with water in a gas bubbler bottle. An excess of a scrubbing agent was added, air was bubbled through the mixture and the odorant concentration in the air was compared before and after adding the reagent. This method eliminated any reaction rate effect, since the contact time was long. The most promising reagents were then tested using a packed bed scrubber. This scrubber was of standard configuration, with known mass transfer properties. Scrubbing reagents tested included types that have already been used for odor control, plus some not previously tried.

Water was found to be effective for many highly soluble odorants. Sodium carbonate was no more effective than water, and sodium hydroxide was little better. Strong oxidizing agents were the most effective. Sodium hypochlorite was effective against a spectrum of odorants. Potassium permanganate reacted slower but attacked some odorants not handled by hypochlorite. Hydrogen peroxide was almost as effective as was sodium persulfate. Sodium bisulfite was effective only against aldehydes.

It was suggested that a 2-stage scrubber might remove a wider range of odorants than 1 stage. Two oxidizing agents might be the most effective combination, although other combinations could be tried. Tests on combinations should be done with the normal odorous emissions in a rendering plant.

## 2. DESIGN AND COST OF DIRECT-FIRED INCINERATORS

A design procedure for incineration by direct flame has been completed and is presented in this section.

The design method has been programmed on a time-sharing computer.

### 2.1 Nomenclature

| | |
|---|---|
| $Y$ | Concentration of odorants, moles/liter or consistent units |
| $Y_e$ | Concentration of odorants in effluent stream, moles/liter |
| $C_E$ | Cost of electricity, $/KWH |
| $C_G$ | Cost of fuel gas, $/scf |
| $C_m$ | Cost of maintenance, $/cfm-year |
| $E_F$ | Efficiency of fan, dimensionless |
| $k$ | Reaction rate constant, $sec^{-1}$ |
| $H_V$ | Heating value, BTU/scf fuel gas |
| $T_o$ | Inlet temperature of polluted air stream, °R |
| $T_i$ | Inlet temperature of fuel-combustion air stream, °R |
| $T_e$ | Operating temperature of incinerator, °R |
| $t_R$ | Residence time in reactor, sec |
| $Q_A$ | Flow rate of polluted air stream, cfm |
| $Q_C$ | Flow rate of combustion products, cfm |
| $Q_F$ | Flow rate of fuel gas, cfm |
| $Q_G$ | Total flow rate through incinerator, cfm |
| $V$ | Volume of incinerator, $ft^3$ |
| $W$ | Weight rate of plant air flow, lb/hr. |



### 2.2 Design Equation

The reaction can be considered first order with respect to the pollutant in the plant air stream and first-order with respect to oxygen. If an excess of oxygen is present, as occurs with the incinerator shown in Figure 1, the oxygen variation will be small enough to consider it constant.

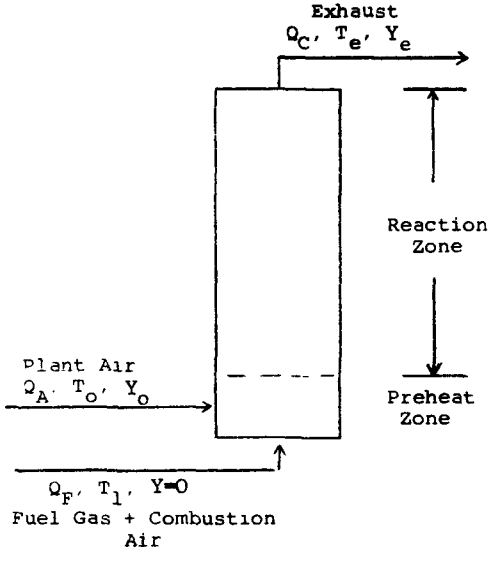


Figure 1

ODORANT INCINERATOR

For first-order kinetics and a constant volume reactor[2]

$$\ln Y_o'/Y_e = k\, t_R \quad \text{or} \quad k = \ln (Y_o'/Y_e)/t_R \ \text{sec}^{-1} \qquad (1)$$

where

$Y_o'$ is the inlet concentration of pollutant
$Y_e$ is the exit concentration of pollutant
$t_R$ is the residence time of the pollutant.

The source of combustion air is plant air. If outside air is used, the added volume significantly increases the cost of operation. The products of flame combustion are mixed with the remaining plant air to result in the calculated temperature necessary to incinerate the odor. Therefore $Y_o' = Y_o$.

The constants A and $\Delta E$ in the Arrhenius equation were not previously known for the reaction of rendering odorants in combustion products. Preliminary estimates were made from data on the incineration of phenolic and hydrocarbon compounds produced in the enameling of wire.[5] Gas analysis was done by chromatography to determine the reduction ratios.

By expressing the Arrhenius equation as

$$\ln k = \ln A - \frac{1.8\,\Delta E}{RT} \qquad (2)$$

it was solved to give

$A = 299$
$\Delta E = 7780.$

Data was provided by one rendering company on the lowering of odor units by an incinerator (Ref. F9, see appendix page 139). The use of this data indicates a reaction rate twice as fast and a slightly different temperature coefficient. This change



decreases the size of reactor required. The resulting coefficients are

$\Delta E = 9560$
$A = 1900$

These data should be checked by additional measurements on plant incinerators. They are the best values available and they were used as the basis of design calculations.

There are 2 independent variables in the incinerator design that determine the extent of oxidation of pollutants: the reactor volume and the mean gas temperature. A separate design calculation was done for each of several reactor volumes and the design having minimum cost was picked. For each chosen reactor volume there is a temperature which will give the desired reduction of odorant concentration. This temperature is determined by substituting the desired reduction ratio and the contact time corresponding to the reactor volume into the Arrhenius equation which gives the effect of temperature on the reaction rate.[2]

$$T_e = 1.8\,\Delta E/(R \ln(A/k)) \qquad (3)$$

where

k is determined by substituting the reduction ratio $Y_o/Y_e$ in Eq. (1)
$T_e$ is reactor temperature, °R
A is the Arrhenius frequency factor, 1/sec
$\Delta E$ is the energy of activation, cal/g-mole
R is the gas constant, 1.987 cal/g-mole.

2.3 Heat Input

The next problem is to determine the quantity of fuel needed to heat the plant air to the calculated reaction temperature. In the diagram of the incinerator, Figure 2 (page 13) we see that the fuel is mixed with sufficient combustion air and burned in a gas burner. The products of combustion are then mixed with plant effluent air, so that the mixture has the

CH

desired reaction temperature. A suitably designed incinerator will provide adequate mixing and the necessary retention time for reaction after mixing has been completed.

The calculation of heat requirement can be separated into 2 parts: a flame calculation and a heat balance on the mixing process. The heat balance requires us to integrate the heat capacities of 2 mixed streams: the plant air stream and the products of combustion stream.

## 2.4 Calculations of Heat Capacities

The heat capacity data[1] is expressed by an equation of the form

$$Cp = a + bT + C/T^2 \quad \frac{cal}{g\text{-mole } °C} = \frac{BTU}{lb\text{-mole } °R} \qquad (4)$$

where a, b and c are constants for each compound. Values are given in Table 1.

For a mixture, the heat capacity is the sum of the contributions of major components on a mole fraction basis.

$$Cp_{air} = .79\ Cp_{N_2} + .21\ Cp_{O_2}$$

Using this equation and the data from Table 1:

$$Cp_{air} = .79(6.66 + .00102\ T) + .21(7.16 + .001\ T - 40{,}000/T^2)$$

$$Cp_{air} = 6.78 + .00102\ T - \frac{8410}{T^2} .$$

Similarly the heat capacity of the methane combustion products is obtained from Tables 1 and 2.



$$Cp' = 7.124 + .00142\ T - \frac{17870}{T^2}$$

## 2.5 Heat Requirement

The net heat required per pound of plant air is[1]

$$H_{air} = \int_{T_o}^{T_e} Cp(air)\ dT \quad BTU/lb \qquad (5)$$

Table 1

HEAT CAPACITY COEFFICIENTS
FOR COMBUSTION PRODUCTS
Reference 1

| Component | a | b x $10^3$ | c x $10^{-5}$ |
|---|---|---|---|
| $CO_2$ | 10 55 | 2.16 | -2.04 |
| $H_2O$ | 7.17 | 2.56 | .08 |
| $N_2$ | 6.66 | 1.02 | - |
| $O_2$ | 7.16 | 1.0 | -0.4 |

Table 2

COMPOSITION OF COMBUSTION PRODUCTS
OF METHANE WITH THEORETICAL AMOUNT OF AIR
Reference 2

| Component | $ft^3/ft^3$ | Mole % |
|---|---|---|
| $CO_2$ | 1.00 | 9.5 |
| $H_2O$ | 2.00 | 19.0 |
| $N_2$ | 7.52 | 71.5 |
| | 10.52 | 100.00 |

Heating Value of Natural Gas = 1011 BTU/scf at 60°F

where

$\Delta H$ is the heat requirement, BTU/lb

Cp is the weighted average heat capacity of the major constituents of the air stream, BTU/lb-mol °R

$T_o$ and $T_e$ are inlet and outlet temperature, °R.

Integrating and using heat capacity data from the previous page

$$\Delta H_{air} = [6.78(T_e-T_o) + .000509(T_e^2-T_o^2) - 8410(T_e-T_o)/T_e-T_o]/28.8 \quad (6)$$

where

28.8 is the molecular weight of air.



## 2.6 Net Heating Value

The net heat available from one standard cubic foot of the fuel gas[1] is

$$\text{Net Heat} = H_V - \int_{T_1}^{T_e} Cp'\, dT/F_c \quad \text{BTU/scf of fuel gas} \quad (7)$$

where

$H_V$ is the gross heating value of the fuel gas with the products of combustion at 60°F

Cp' is the weighted average of the major constituents of the combustion products of the fuel gas, BTU/lb mole °R

$T_1$ and $T_e$ are inlet and exit temperatures, °R

$F_c$ = conversion factor = 379/10.52 = 36.1

10.52 = moles combustion products/mole fuel gas

379 = scfm fuel gas/lb-mole fuel gas

Integrating and using data from References 1 and 2

$$H_N = \text{Net Heat} = 1011 - [7.124(T_e-T_1) + .00071(T_e^2-T_1^2) - 17870(T_e-T_1)/T_e-T_1]/36.1 \quad \text{BTU/scfm fuel gas.} \quad (8)$$

## 2.7 Fuel Requirements

The total fuel requirement is given by

$$Q_g = \text{Fuel} = \Delta H_{air}\, W_{air}\, 1.1(1-F_H)/H_N \quad \text{scf/min} \quad (9)$$

where

$\Delta H_{air}$ is the heat requirement, BTU/lb

$W_{air}$ is the flow rate of the air stream, lb/min

$H_N$ is the net heating value, BTU/scf

1.1 is a factor to correct for an assumed 10% heat loss through the incinerator walls

$F_H$ is the fraction of sensible heat that is recovered by means of a heat exchanger.

Equations to design this exchanger have not not been included. Preliminary estimates indicated that the savings in fuel are balanced by the added investment cost.

2.8 Volume of Combustion Products

$$Q_C = 10.52\ Q_F \frac{T_e}{510} \qquad (10)$$

where

$Q_F$ is the volumetric flow rate of the fuel gas, cfm

$T_e$ is the reactor temperature, °R

The factor 10.52 is a mol ratio deduced from the stoichiometry of methane combustion from Table 8.

2.9 Equation to Compute Fraction of Air Used for Combustion

Part of the plant air is used as combustion air in the gas burner, and the rest is mixed with the combustion products. The flow scheme is shown in Figure 2.

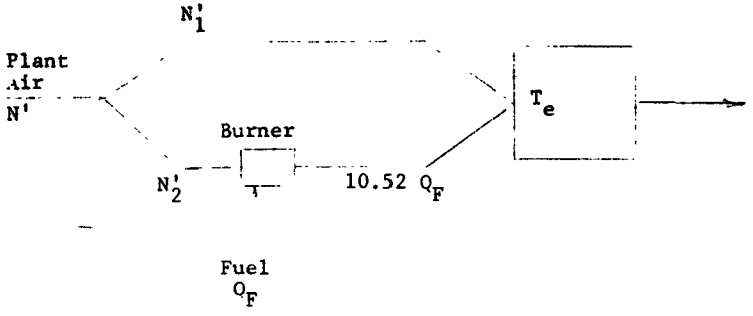


Figure 2

ODORANT INCINERATOR USING PLANT AIR FOR COMBUSTION



The material balance is on a mol basis, where N' represents the number of moles of each stream.

$$N_2' = \text{air flow} = 9.52\ Q_F \text{ (by stoichiometry of combustion)} \qquad (11)$$

$$9.52\ \text{air} = 2\ O_2 + 7.52\ N_2 + CH_4 \rightarrow 7.52\ N_2 + CO_2 + 2H_2O$$

By material balance on air

$$N' = N_1' + N_2' = N_1' + 9.52\ Q_F \qquad (12)$$

$$Q_F = \frac{N'-N_1'}{9.52}$$

By heat balance on system

$$N_1' \int_{T_1}^{T_e} Cp_1 dt + 10.52\ Q_F \int_{T_o}^{T_e} Cp_2 dt = H_V\ Q_F \qquad (13)$$

$$N_1' \int_{T_1}^{T_e} Cp_1 dt = [H_V - 10.52 \int_{T_o}^{T_e} Cp_2 dt] Q_F \qquad (14)$$

$$\frac{N_1'}{Q_F} = \frac{H_V - 10.52 \int_{T_o}^{T_e} Cp_2 dt}{\int_{T_1}^{T_e} Cp_1 dt} = R = \text{ratio} \qquad (15)$$

From Eq. 12

$$\frac{N_1'}{\frac{N'-N'_1}{9.52}} = \frac{9.52\ N_1'}{N'-N_1'} = R$$

$$N_1'(9.52 + R) = N'R$$

$$\frac{N_1'}{N'} = \frac{R}{9.52 + R}$$

$$\text{Fraction} = \frac{N_2'}{N'} = \frac{12.5\ N_{ETHT}/H_{Air}}{9.52 + 12.5\ N_{ETHT}/H_{Air}} \qquad (16)$$

2.10 Reactor Volume[2]

This volume is based on the actual flow rate and the assumed residence time.

$$\text{Volume} = \frac{(Q_A + Q_C)t_R}{60} \qquad (17)$$

where

$Q_A$ and $Q_C$ are the flow rates of the air stream and the combustion product stream, $ft^3/min$

$t_R$ is residence time, sec

The design calculations must be repeated for several residence times.

2.11 Pressure Drop

The entire gas pressure drop can be considered to be in the duct and in the entrance to the incinerator. By proper sizing of ducts, the pressure drop can be kept to one inch of water. From IITRI Report No. C8210-3:

$$P_w = 1.57 \times 10^{-4}\ \Delta P\ Q_A/E_F\ Hp \qquad (18)$$

where

$\Delta P$ is pressure drop, in. of water

$Q_A$ is plant air throughput, cfm

$E_F$ is fan efficiency, dimensionless.



2.12 Initial Cost

Having computed the reactor volume, we can now compute the equipment cost. The installed cost of an incinerator is expressed in terms of its volume. It can be estimated from a correlation of data found in IITRI Report No. C8210-3, page 25.

$$\text{Installed cost} = 7300\ V^{0.34} \qquad (19)$$

where

V is volume of the incinerator, cu ft.

This is the effective volume of the gas in the incinerator at the incineration temperature. It does not include the volume of the combustion zone.

2.13 Operating Cost

The operating cost includes fuel, fan power and maintenance costs.

2.14 Annual Fuel Gas Cost

$$\text{Cost} = \theta\ C_G\ Q_g\ 60/1000 \qquad (20)$$

where

$\theta$ is the number of hours of operation per year

$C_G$ is the cost of fuel gas, \$/MCF

$Q_g$ is the rate of fuel consumption, scfm.

2.15 Power Cost

$$\text{Cost} = .746\ \theta\ P_w C_E \qquad (21)$$

where

$\theta$ is the number of hours of operation per year

$P_w$ is the power required from the fan from Eq. 9, KW

$C_E$ is the cost of electricity, \$/KWH.

2.16 Maintenance Cost

The annual maintenance cost is[4]

$$\text{Cost} = C_m Q_G \qquad (22)$$

$$= 0.06\ Q_G$$

2.17 Total Operating Cost

$$\text{Cost} = Q_G(1.17 \times 10^{-4}\ \theta\ \Delta P\ C_E/E_F + C_m) + 0.06\ \theta\ C_G Q_F \qquad (23)$$

2.18 Economic Evaluation

The summary of costs is given in Table 3. These data are summarized from computer results for costs at various reactor temperatures and represent the optimum reactor temperature with regard to total annual cost. The fuel costs are comparable to those estimated by others, except for a 10% allowance for heat loss for the reactor. Probably, this allowance should be neglected for large systems.

2.19 References


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Table 3

INCINERATOR COST SUMMARY

| Flow, CFM | Reduction Ratio Odor Concentration | Reactor Temp., °F | Reactor Residence Time, sec | Reactor Volume, cu ft | Investment, $ | Costs Fuel* $/Year | Costs Total $/Year | $/1000 CFM-Hr |
|---|---|---|---|---|---|---|---|---|
| 1,000 | 100 | 1069 | .7 | 33 | 12,500 | 3,150 | 6,400 | 1.28 |
| | 1,000 | 1186 | .7 | 36 | 13,000 | 3,570 | 6,950 | 1.39 |
| | 100,000 | 1236 | 1.0 | 52 | 15,200 | 3,753 | 7,703 | 1.55 |
| 5,000 | 100 | 1069 | .7 | 164 | 24,500 | 15,700 | 22,540 | .90 |
| | 1,000 | 1082 | 1.0 | 237 | 28,500 | 16,000 | 23,800 | .95 |
| | 100,000 | 1111 | 1.5 | 362 | 34,000 | 16,500 | 25,700 | 1.03 |
| 25,000 | 100 | 1069 | .7 | 885 | 49,500 | 87,000 | 103,000 | .83 |
| | 1,000 | 1082 | 1.0 | 1276 | 57,600 | 88,500 | 106,500 | .85 |
| | 100,000 | 1111 | 1.5 | 1952 | 68,800 | 91,300 | 112,300 | .90 |

*Based on 5,000 hours operation per year.

## 3. CATALYTIC BED AFTERBURNER DESIGN EQUATIONS

Design equations for a catalytic afterburner are presented. A computer program was written with these equations and several examples are given.

Since a direct flame incinerator has a relatively high cost due to the high operating temperatures, use of a catalyst to reduce the incineration energy requirement offers a potential advantage. A catalyst is a material which promotes chemical reaction, although it does not enter into the reaction.

The catalyst will cause a faster rate of reaction at relatively low temperatures than can be achieved in a direct fired incinerator. It allows incineration at a lower temperature.

Catalysts are normally porous particles and are frequently used in a fixed bed contactor. The design of a catalyst bed reactor depends in part on diffusion through these pores. For certain types of catalyst in which the pore passages are short, pore diffusion can be neglected. In this case the controlling factor is mass transfer to the gross surface of the catalyst. The present results are limited to this type of catalyst.

### 3.1 Nomenclature for Catalytic Reactor Design

| | |
|---|---|
| $a$ | Specific surface area of catalysts, sq ft/cu ft |
| $A_m$ | Amortization factor, 1/yr |
| $C_{ANN}$ | Annual cost of catalytic afterburner, $/yr |
| $C_{cat}$ | Cost of catalyst, $/cu ft |
| $C_{TC}$ | Cost of catalyst bed, $ |
| $C_D$ | Cost of ducting, $/ft |
| $C_E$ | Cost of electricity, $/KWH |
| $C_{TE}$ | Cost of electricity, $/yr |
| $C_T$ | Capital cost of catalytic afterburner, $ |
| $C_F$ | Cost of fan, $/cu ft |



| | |
|---|---|
| $C_{TF}$ | Cost of fan, $ |
| $C_{Fu}$ | Cost of fuel gas, $/MCF |
| $C_{TFu}$ | Cost of fuel, $/yr |
| $C_H$ | Cost of housing for catalyst bed, $ |
| $C_I$ | Cost of insulation for catalyst housing, $/ft |
| $C_M$ | Cost of maintenance, $/cu ft |
| $C_{TM}$ | Cost of maintenance, $/yr |
| $d$ | Diameter of tube, in. |
| $E_F$ | Fan efficiency, dimensionless |
| $G_M$ | Molar flow rate, lb moles/hr-sq ft |
| Hp | Horsepower neededed for fan, Hp |
| $J_O$ | Colburn j factor, dimensionless |
| $k_g$ | Mass transfer coefficient, lb/hr-sq ft-atm |
| $N$ | Number of modules, dimensionless |
| $N_F$ | Exponent on flow in fan cost equation |
| $P$ | Total pressure, atm |
| $P_{BM}$ | Log mean pressure of non-diffusing gas, atm |
| $Q_A$ | Flow rate of odorous air stream entering preheater, cu ft/min |
| $Q_{AF}$ | Flow rate of odorous air stream leaving preheater, cu ft/min |
| $Q_C$ | Flow rate of combustion products leaving preheater, cu ft/min |
| $Q_F$ | Flow rate of fuel gas, scfm |
| $Q_T$ | Flow rate entering catalyst bed, cu ft/min |
| Re | Reynolds number, dimensionless |
| Sc | Schmidt number, dimensionless |
| $T_o$ | Inlet temperature of odorous air stream, °F |
| $T_1$ | Inlet temperature of fuel gas stream |
| $T_E$ | Outlet temperature of combined air stream |
| $Y_o$ | Mole fraction of odorant in odorous air stream |
| $Y_e$ | Mole fraction of odorant in effluent air stream |

$Y_2$ Mole fraction of odorant entering catalyst bed

$\mathcal{Z}$ Length of catalytic reactors, ft

$\Delta P$ Total pressure drop through catalytic bed, in. of $H_2O$

3.2 Design of Preheater

It is necessary to preheat the raw plant effluent gases to a temperature of approximately 800°F before they are treated by the catalytic unit. This can be done by a direct flame preheater. The flow arrangement is shown in Figure 3.

The design method and computer program for the preheater are the same as those used for the direct fired incinerator.

The volumetric flow rate into the catalytic unit is now

$$Q_T = Q_A \frac{T_1 + 460}{T_o + 460} + 10.52\, Q_F \frac{T_1 + 460}{60 + 460}$$

where 10.52 is the ratio of volume of combustion products at 60°F to the volume of fuel gas consumed, and the temperature ratios are based on the ideal gas law.

For some odorants, there will be a significant amount of reaction from the direct flame preheater. The amount of reaction will depend upon the residence time prior to entering the catalytic section of the reactor and the temperature used. This will be computed from the equations used in the design of a direct flame incinerator.

3.3 Catalytic Afterburner Design Longitudinal Flow

3.3.1 Design Equation for Honeycomb Catalyst

A material balance around a differential element for a fixed bed catalytic reactor with mass transfer controlling gives

$$-G_m dy = k_g a\, PY\, d\mathcal{Z} \qquad (24)$$



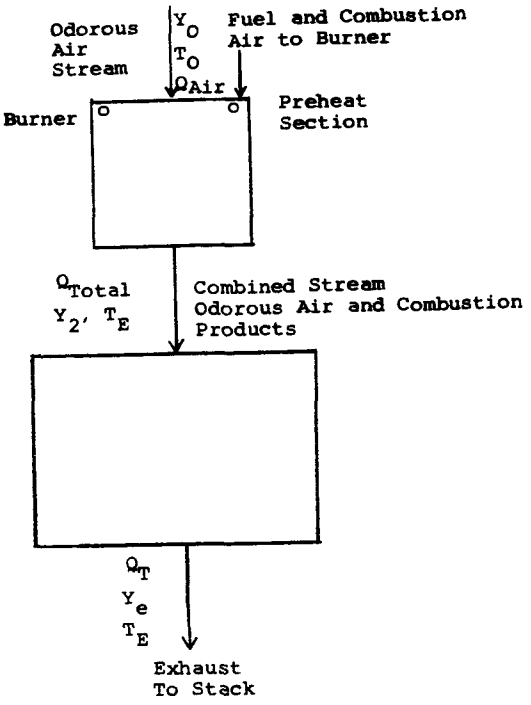


Figure 3

PREHEATER AND CATALYTIC AFTERBURNER

where

$G_m$ is the molar flow rate, lb moles per sq ft hr
$Y$ is the mole fraction of odorant
$k_g$ is the mass transfer coefficient, lb moles per sq ft hr atm
$a$ is the area for mass transfer, sq ft per cu ft or sq in/cu in
$P_T$ is the total pressure, atm
$Z$ is the length of the reactor, ft.

Integrating from ($Y = Y_o$, $Z = 0$) to ($Y = Y_e$, $Z = Z$)

$$\ln \frac{Y_2}{Y_e} = \frac{k_g a}{G_m} P_T Z \qquad (25)$$

Consider a reactor using a honeycomb type of catalyst support with flow in the longitudinal direction. The honeycomb catalyst support can be obtained in one-foot square units of short lengths. They may be stacked to any desired depth.

It is convenient to design for modules of one square foot and of suitable length. The number of modules is determined by a trial-and-error calculation to result in a reasonable pressure drop. Since the number is dependent on the total flow, an initial value is

$$N = Q_{AF}/1500$$

where $Q_{AF}$ is the flow rate of odorous air at temperature $T_E$. The flow through the honeycomb passages can be treated like flow in a pipe. In this case for $4000 < Re < 6000$; $6 < Sc < 3000$, mass transfer is correlated[1] by

$$j_0 = \frac{k_g P_{BM}}{G_M} Sc^{2/3} = .023\ (Re)^{-.17} \qquad (26)$$



where

$P_{BM}$ is the log mean pressure of the non-diffusing gas. For dilute mixtures of contaminants this is approximately the total pressure, $P_T$.
$G_M$ is the molar flow rate, lb moles per sq ft-hr
$k_g$ is the mass transfer coefficient, lb moles per sq ft - hr atm
Sc is the Schmidt number

$$Sc = \text{Viscosity } \left(\frac{lb}{ft\text{-}hr}\right) / \left[\text{density } \left(\frac{lb}{cu\ ft}\right) \text{ diffusivity } (ft^2/hr)\right]$$

Re is the Reynolds number

$$Re = \frac{\text{Diameter of tube (ft) velocity (ft/hr) density (lb/cu ft)}}{\text{Viscosity (lb/ft-hr)}}$$

Substituting $\frac{k_g P}{G_M}$ from (26) into the material balance Equation (25) becomes

$$\ln \frac{Y_2}{Y_e} = \frac{.023}{(Re)^{.17}\ (Sc)^{2/3}} Z\ a \qquad (27)$$

To evaluate this a must be known

$$a = \frac{\text{Surface Area}}{\text{Unit Volume}} = \frac{\pi d Z}{\frac{\pi}{4} d^2 Z} = 4/d \qquad (28)$$

Using this in Equation (27)

$$\ln \frac{Y_2}{Y_e} = \frac{.092\ Z}{d\ (Re)^{.17}\ (Sc)^{2/3}} \qquad (29)$$

$Z$ = length of catalytic bed, in.
$d$ = diameter of tubular catalyst honeycomb, in.

This is the final design equation for the catalyst bed.

### 3.3.2 Pressure Drop Through Honeycomb Catalyst Bed

The pressure drop through the 1/8 in. Hex-cell honeycomb ceramic bed can be computed using an equation[1]

$$\Delta P = .0585\ Z\ (Q_T/144\ N)^{1.68}$$

where

$Q_T$ is the total air flow, cfm
$\Delta P$ is the pressure drop through the bed, in. water
$Z$ is length of catalytic bed, ft

The fan horsepower required is computed from

$$Hp = Q_T\ \Delta P/6356\ E_F$$

where

$E_F$ is the efficiency of the fan.

### 3.4 Cost Calculations for a Catalytic Afterburner

#### 3.4.1 Capital Costs

Since the shape of the honeycomb catalyst is usually a square plate, the housing will be a square duct. The cost of a housing for the catalyst bed will be determined by the cost of ducting plus the cost of insulation.

$$C_H = (C_D + C_I)\ Z\ N$$

where

$C_D$ is the installed cost of ducting, $ per ft
$C_I$ is the cost of insulation, $ per ft
$Z$ is the required length, ft
$N$ is the number of catalyst units required.

The cost of the catalyst is

$$C_{TC} = N\ C_{cat}\ Z\ C_{in}$$



where

$C_{cat}$ is the cost of the catalyst, $per cu ft
$N$ is the number of 1 sq ft units required
$C_{in}$ is factor for installation cost = 1.5

A typical catalyst price is $450/cu ft of bed required.[3]

A fan and motor will be required for the operation of a catalyst bed. The cost of this fan will be

$$C_{TF} = C_F\ Q_T^{N_F} + C_{MS}\ Hp$$

where

$C_F$ and $N_F$ are constants for the type of fan chosen
$C_{MS}$ is the unit cost of the motor, $ per Hp
$Hp$ is the horsepower required
$Q_T$ is the total flow rate through the bed.

The total capital cost is the sum of the above

$$C_T = C_H + C_{TC} + C_{TF} + C_{preheater}$$

#### 3.4.2 Operating Costs for Catalytic Afterburner

The cost of electricity for the process is

$$C_{TE} = .746\ C_E\ \Theta\ Hp$$

where

$C_E$ is the unit cost of electricity
$\Theta$ is the number of hr per yr and Hp is the horsepower required for the fan.

The cost of maintenance is

$$C_{TM} = C_M\ Q_T$$

where

$C_M$ is the cost of maintenance, $ per cfm
$Q_T$ is actual flow rate through the bed, cfm.

The cost of fuel is given by

$$C_{TFu} = Q_F \, C_{Fu}$$

where

$Q_F$ is the flow rate of fuel, scfm

$C_{Fu}$ is the cost of fuel, $ per scfm.

The total annual cost is the sum of the operating costs plus the amortization

$$C_{ANN} = C_T \, A_m + C_{TF} + C_{TE} + C_{TM}$$

3.5 Design and Cost Estimate

Design and cost calculations have been carried out for a catalytic incinerator system. Results are given for three different flow rates and four different reduction ratios in Table 4. By use of a catalyst bed, the temperature necessary for incineration of odor vapors can be reduced from 1200 to about 800°F, thus reducing the fuel cost. At the same time, there is an added investment cost for the catalyst bed and additional fan cost due to pressure drop through the bed. The calculations showed that these costs are about equal to the savings in fuel costs, so that catalytic incineration offers little advantage over direct-fired incineration. Slight improvement could be obtained by finding catalysts with less pressure drop, or which operate reliably at lower temperature. However, it is clear that these improvements will be only marginal.

Only if the plant effluent gas going to the incinerator is already partly heated will a catalytic incinerator show an economic advantage, because the increment of heat necessary to reach the catalyst temperature is much less than that required to reach a direct-fired incinerator temperature. The gaseous effluent from rendering plants is not expected to exceed 120 to 140°F, and this temperature is not sufficient to affect the heat economy. If a condenser is used, as may be necessary to scrub

Table 4

CATALYTIC INCINERATION DESIGN AND COST ESTIMATES

TEMPERATURE DEGREES F

| INLET | OUTLET |
|---|---|
| 32. | 800. |

UNIT COSTS OF CAPITAL EQUIPMENT

| CATALYST | DUCTING | INSULATION | | BLOWER | |
|---|---|---|---|---|---|
| 150. | 15.00 | 10. | COEFFICIENT | 11.00 | EXPONENT .680 |

UNIT COSTS OF OPERATION

| FUEL GAS $/MCF | POWER $/KWH | MAINTENANCE $/CFM-YR | AMORTIZATION FACTOR | ANNUAL HOURS IN OPERATION |
|---|---|---|---|---|
| .500 | .015 | .080 | .250 | 5000. |

.031269841269841 .079088414991191

CALCULATED OPERATING CONDITIONS

| SPACE VEL. 1/HR | REYNOLDS NO. | SCHMIDT NO. | PRESSURE DROP IN. OF WATER | HORSEPOWER | NUMBER OF UNITS |
|---|---|---|---|---|---|
| 72013. | 589 | 2.529 | 28.12 | 105.43 | 5. |

| FLOW RATE CFM | ODORANT CONCENTRATION INLET | OUTLET | LENGTH FEET | CAPITAL COST INSTALLED | ANNUAL | ANNUAL OPERATING COST FUEL | POWER | MAINT | TOTAL OPERATING COST ANNUAL | $/1000CFM-HR |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000. | 10. | 1. | .636 | 10053. | 2513. | 2712. | 203. | 210. | 5637. | 1.13 |
| 1000. | 100. | 1. | 1.402 | 10721. | 2680. | 2712. | 447. | 210. | 6048. | 1.21 |
| 1000. | 1000. | 1. | 2.169 | 11388. | 2847. | 2712. | 691. | 210. | 6459. | 1.29 |
| 1000. | 100000. | 1. | 3.702 | 12723. | 3181. | 2712. | 1180. | 210. | 7282. | 1.46 |

CALCULATED OPERATING CONDITIONS

| SPACE VEL. 1/HR | REYNOLDS NO. | SCHMIDT NO. | PRESSURE DROP IN. OF WATER | HORSEPOWER | NUMBER OF UNITS |
|---|---|---|---|---|---|
| 72013. | 589 | 2.529 | 28.12 | 527.15 | 25. |

| FLOW RATE CFM | ODORANT CONCENTRATION INLET | OUTLET | LENGTH FEET | CAPITAL COST INSTALLED | ANNUAL | ANNUAL OPERATING COST FUEL | POWER | MAINT | TOTAL OPERATING COST ANNUAL | $/1000CFM-HR |
|---|---|---|---|---|---|---|---|---|---|---|
| 5000. | 10. | 1. | .636 | 23770. | 5943. | 13558. | 1013. | 1049. | 21562. | .86 |
| 5000. | 100. | 1. | 1.402 | 27108. | 6777. | 13558. | 2234. | 1049. | 23618. | .94 |
| 5000. | 1000. | 1. | 2.169 | 30446. | 7612. | 13558. | 3456. | 1049. | 25674. | 1.03 |
| 5000. | 100000. | 1. | 3.702 | 37123. | 9281. | 13558. | 5899. | 1049. | 29786. | 1.19 |

CALCULATED OPERATING CONDITIONS

| SPACE VEL. 1/HR | REYNOLDS NO. | SCHMIDT NO. | PRESSURE DROP IN. OF WATER | HORSEPOWER | NUMBER OF UNITS |
|---|---|---|---|---|---|
| 72013. | 589 | 2.529 | 28.12 | 527.15 | 25. |

| FLOW RATE CFM | ODORANT CONCENTRATION INLET | OUTLET | LENGTH FEET | CAPITAL COST INSTALLED | ANNUAL | ANNUAL OPERATING COST FUEL | POWER | MAINT | TOTAL OPERATING COST ANNUAL | $/1000CFM-HR |
|---|---|---|---|---|---|---|---|---|---|---|
| 25000. | 10. | 1. | .636 | 62128. | 15532. | 67789. | 5064. | 5243. | 93628. | .75 |
| 25000. | 100. | 1. | 1.402 | 78818. | 19705. | 67789. | 11172. | 5243. | 103909. | .83 |
| 25000. | 1000. | 1. | 2.169 | 95509. | 23877. | 67789. | 17279. | 5243. | 114189. | .91 |
| 25000. | 100000. | 1. | 3.702 | 128889. | 32222. | 67789. | 29494. | 5243. | 134749. | 1.08 |

out fatty particles that may interfere with the catalyst, then the temperature will be even lower. We conclude that catalytic incineration is not promising for this application.

### 3.6 References


1. Mass Transfer Operations (sec Ed.), Robert E. Treybal, McGraw Hill, 1955, pages 60-67.
2. A Study of Catalyst Support Systems for Fume-Abatement of Hydrocarbon Solvents, M. R. Miller and H. J. Wilhoyte, Journal of the Air Pollution Control Association, Vol. 17 (12).
3. Private Communication, Don Bissel, Ispen Ceramics Inc., Pecatonica, Illinois, Jan. 1972.




## 4. CARBON BED ADSORPTION

The economics of carbon bed adsorption is different from the other methods considered, and it may have a place in certain applications. The cost of the carbon and of its regeneration depend strongly on the odorant concentration to be removed, so that carbon can be considered for treatment of very dilute odors, such as ventilation air. Design computer programs have not been developed but a rough example calculation is given below.

### 4.1 Design Based on Equilibrium Capacity

The example is to treat 100,000 cfm of ventilation air containing only 10 ppm of odorant. It is assumed that a 100-fold reduction in concentration is sufficient for ventilation air, although much greater reductions are needed for process air. The amount of carbon needed is calculated from equilibrium based on the capacity of the carbon. Data is available from Calgon Corp. on the capacity of carbon for isopropyl alcohol. Odorous materials of higher molecular weight and less polarity will be more readily adsorbed, and therefore this is a safe method of design. Figure 4 is an adsorption isotherm for isopropyl alcohol on carbon at 77°F. It gives the capacity of the carbon depending on the concentration of isopropyl alcohol in the air being treated.

10 ppm corresponds to 0.0076 mm Hg vapor pressure of isopropyl alcohol. At this pressure the bed capacity is 3.8 lb/100 lb carbon. A cubic foot of carbon weighs 20 lb, so this is 0.7 lb/cu ft of bed. The total quantity of odorant removed depends on the flow rate and the concentration. 10 ppm corresponds to

$$\frac{10 \times 10^{-6}\ \text{ft}^3}{\text{ft}^3} \frac{60.1\ \text{lb}}{392\ \text{ft}^3} \frac{1000}{1000} = \frac{.0015\ \text{lb isopropanol}}{1000\ \text{ft}^3\ \text{air}} \qquad (30)$$

This uses up $\frac{.0015 \times 100}{.7} = \frac{.216\ \text{ft}^3\ \text{bed}}{\text{min}}$ for an air flow of 100,000 cfm. For a 16-hr day this requires a 208 $\text{ft}^3$ bed.

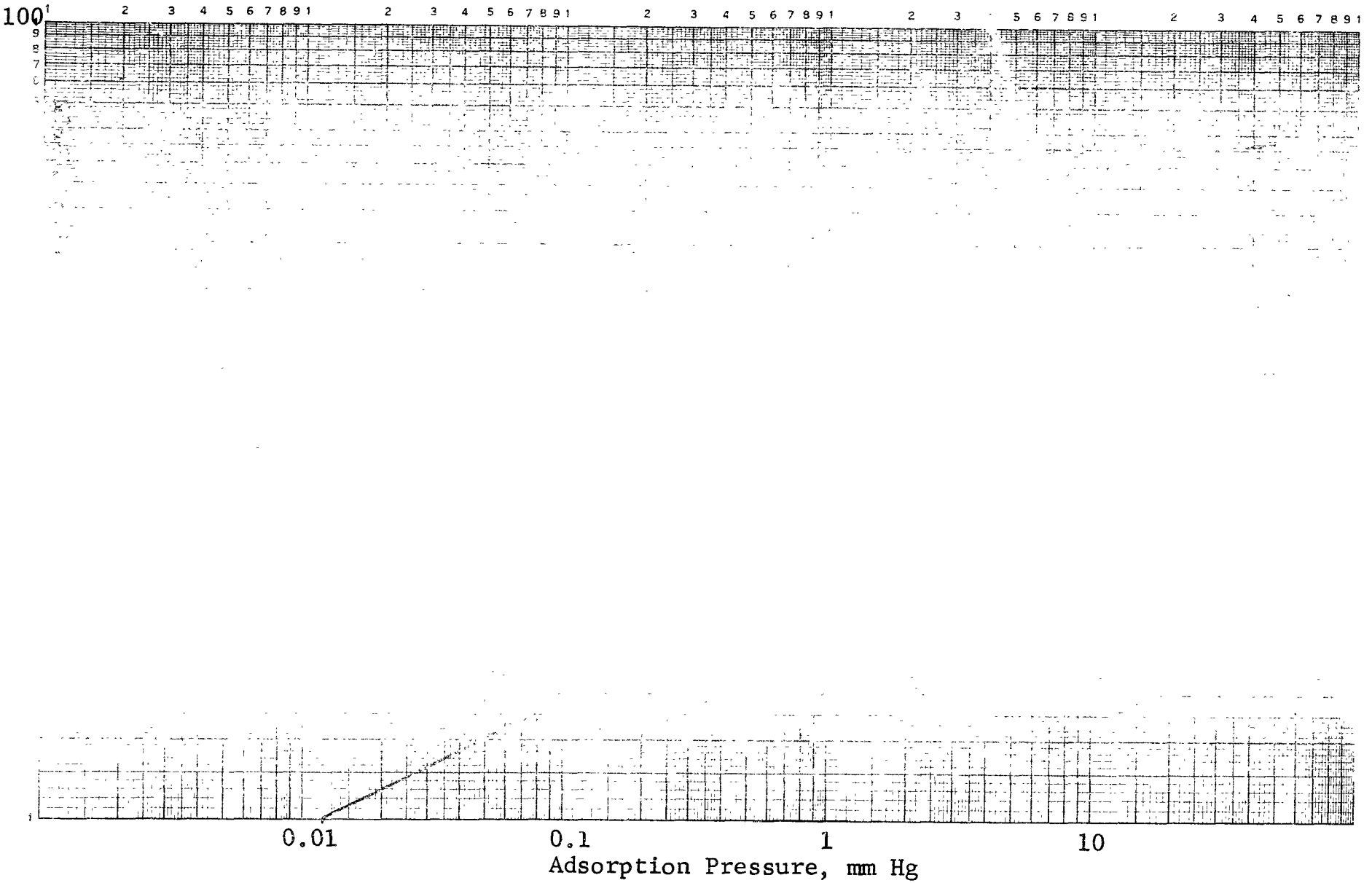


Figure 4

ESTIMATED ADSORPTION OF ISO PROPYL ALCOHOL ON BPL CARBON
Courtesy Calgon Corp.

## 4.2 Pressure Drop

The second major cost of carbon bed treatment is the cost of forcing the air through the bed. This depends on the thickness of the bed. If the bed is made too thin, mass transfer rate might limit the adsorption process. However, mass transfer data on packed beds (Ref. E-10) indicate that a bed 10 particles thick will remove several orders of magnitude of odorant concentration. Therefore, a design of bed is chosen spreading the 208 $ft^3$ over an area to give a bed thickness of 1 in. and the bed area is 2496 sq ft. The air velocity is 40 ft/min. From Figure 5 the pressure drop for a 6-16 mesh carbon bed is 4 in. water pressure. The power required is (from Report C8210-9, p. 26)

$$Hp = \frac{Q_T \Delta P}{6356\ E_F} = \frac{100{,}000 \times 4}{6356 \times .7} = 90 \text{ hp} \qquad (31)$$

## 4.3 Regeneration by Incineration

The final major cost is the cost of regeneration. The most logical way to regenerate a carbon bed is by use of hot air, since the effluent from the bed can be economically purified by a direct-fired incinerator. Part of the incinerator effluent can be mixed with fresh air and recycled to perform the regeneration. We have not worked out the details of this scheme, but previous calculations of the cost of direct-fired incineration can be used for a rough cost estimate.

The regeneration would take place at the end of the day and would require 2 hrs. If an incinerator is also used for process air treatment, then the same incinerator could be used for the regeneration air. The ability to regenerate depends on the change in adsorption isotherm for the higher gas temperature; an estimated curve is shown in Figure 4 for 400°F. Assuming a 100 to 1 concentration effect due to regenerating between 400 and 500°F, the volume of regeneration air is 1/100 the volume of air deodorized. This means that in 2 hrs a flow of 8000 cfm will regenerate the



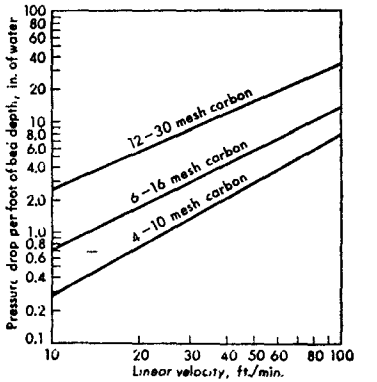


Figure 5

PRESSURE DROP THROUGH CARBON BEDS

From Yocum, J. E., and Duffee, R. A., Controlling Industrial Odors, Chem. Engr., June 15, 1970, p. 165.

bed which treated 100,000 cfm for 16 hrs. From the incinerator cost Table 3, the investment cost is about $40,000. The fuel cost is less than given in the table, because the time of operation is only 2 hrs per day. This calculation requires that the flow during regeneration be counter-current to the normal flow during use, since otherwise additional time would be required to thoroughly purge the final portion of the bed near the outlet.

4.4 Total and Annual Costs

The total and annual costs are listed in Table 5. The total cost per 1000 cfm-hr is only $.11, lower than the other methods considered. However, this is only for ventilation air. A similar calculation was done for process air, assuming 1000-fold reduction in concentration. The bed capacity and regeneration costs rise sharply.

It should be emphasized that these costs are only rough ones, and are based on data for compounds other than actual odorants. They do suggest that carbon beds can be considered for ventilation air.



Table 5

COSTS FOR CARBON BED TREATMENT OF VENTILATION AIR WITH LOW ODOR CONCENTRATION

| | Total | Annual* |
|---|---|---|
| Carbon Bed Investment | | |
| Carbon, 208 $ft^3$ | $ 3,000 | |
| Housing | 40,000 | |
| Fan | 10,000 | |
| Ducting, installation | 30,000 | |
| Total | $83,000 | $21,000 |
| Incinerator Investment | | |
| 8000 cfm | 40,000 | 10,000 |
| Operating Costs | | |
| Fan Power | | 5,000 |
| Incinerator (Fuel) | | 4,000 |
| Maintenance | | 15,000 |
| Total | | $55,000 |
| Cost per 1000 cfm-hr | | $0.11 |

*Based on 5,000 hours operation per year.

## 5. DESIGN AND COST OF COUNTER-CURRENT PACKED TOWER GAS SCRUBBING SYSTEM

A design procedure has been completed for counter-current packed scrubbing towers, and is presented in this section. A procedure for spray scrubbers is given in the next section.

This design method has been programmed on a time-sharing computer system and was used to design the experimental scrubber for use on the project. There are two versions of the program, one of which performs a series of calculations at different gas and liquid flow rates to explore the minimum cost design. The other version performs a calculation at given gas and liquid rates. Costs are expressed in terms of investment cost, as well as annual amortized and operating costs.

### 5.1 Nomenclature

| | |
|---|---|
| A | cross-sectional area of towers, $ft^2$ |
| a, $a_{AW}$ | wetted surface area of packing |
| $a_p$ | surface area of packing per unit volume of packing, $ft^2/ft^3$ |
| $C_E$ | cost of electricity, $/KWH |
| $C_F$ | friction factor |
| $C_M$ | cost of labor and maintenance, $/cfm |
| $\Delta P$, $\Delta P'$ | pressure drop, in. $H_2O$, ft of air |
| $d_s$ | equivalent diameter of a particle packing (ft) |
| $E_F$ | efficiency of fan |
| $E_p$ | efficiency of pump |
| $\varepsilon$, $\varepsilon_o$ | porosity of dry and wetted packing |
| G | gas rate, lb/hr $ft^2$ |
| $G_M$ | gas rate, lb mole/hr $ft^2$ |
| $G_T$ | gas throughput, lb/hr |
| $k_G a$ | overall gas phase mass transfer coefficient |
| L | liquid rate, lb/hr $ft^2$ |
| $L_M$ | liquid rate, lb mole/hr $ft^2$ |
| $L_T$ | liquid throughput, lb/hr |
| m | constant |



| | |
|---|---|
| n | constant |
| P | partial pressure of gas |
| $Q_G$ | gas throughput, cfm |
| $Q_L$ | liquid throughput, gpm |
| Sc | Schmidt number |
| $v_H$ | correction factor for holdup |
| X | mole fraction of liquid |
| Y | mole fraction of gas |
| $Y_E$ | exiting concentration of gas |
| $Y_i$ | gas concentration at interface |
| $Y_o$ | entering concentration of gas |
| Z | height of tower, ft |

Greek Letters

| | |
|---|---|
| $\alpha, \beta$ | constants |
| $\theta$ | operating time per year, hours |
| $\mu_G$ | viscosity of gas, lb/ft hr |
| $\rho_G$ | gas density, $lb/ft^3$ |
| $\phi_t$ | reduction in packing porosity due to holdup, fraction |

## 5.2 Design Equation

Consider the packed tower shown in Figure 6.

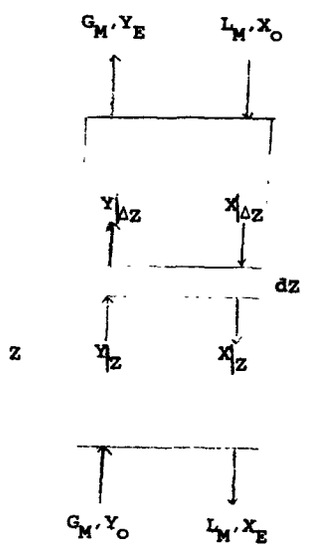


Figure 6

PACKED TOWER

If a material balance for the odorous substance is performed on an increment of volume within the tower,

$$- G_M A\, dY = L_M A\, dX = k_G a\, (P-P_i)\, A\, dZ = k_G a\, P_T\, (Y-Y_i)\, A\, dZ \qquad (32)$$



where

| | |
|---|---|
| Z | is height |
| $G_M$ and $L_M$ | are the molar gas and liquid rates per unit area |
| A | is the cross-sectional area |
| Y and X | mole fraction of pollutant in the gas phase and liquid phase |
| $k_G$ | the gas phase mass transfer coefficient, a wetted specific surface area of the packing |
| P | is partial pressure of pollutant |
| $P_i$ and $Y_i$ | are interfacial pressure and mole fraction of pollutant |
| $P_T$ | total pressure. |

Integrating equation 32

$$Z = \frac{G_M}{k_G a\, P_T} \int_{Y_E}^{Y_o} \frac{dY}{Y-Y_i} \qquad (33)$$

where

| | |
|---|---|
| $Y_o$ and $Y_E$ | are the entering and exiting mole fractions of the pollutant |

For the case of a fast reaction occurring in the liquid phase, the concentration $Y_i$ of the pollutant at the liquid surface will be approximately zero. Equation 33 then becomes

$$Z = \frac{G_M}{k_G a\, P_T} \int_{Y_E}^{Y_o} \frac{dY}{Y} = \frac{G_M}{k_G a\, P_T} \ln \frac{Y_o}{Y_E} \qquad (34)$$

## 5.3 Correlation for Mass Transfer Coefficient

For particle packings such as rings and saddles, the gas phase mass transfer coefficient has been expressed in the form of an empirical equation. (Ref. E-6, p. 165).

$$\frac{G_M}{k_G a P_T} = \frac{.837}{a}\left[\frac{d_s G}{\mu_G (1-\varepsilon_o)}\right]^{0.36} Sc^{2/3} \qquad (35)$$

where

$G$(lb/hr ft$^2$) is the mass gas flow rate per unit area
$\varepsilon_o$ the operating void space
$d_s$(ft) the diameter of a sphere of the same surface as a single packing particle
$\mu_G$(lb/ft hr) gas viscosity
Sc Schmidt number.

The wetted specific area is given by

$$a = a_{AW} V_H \qquad (36)$$

where

$$a_{AW} = m G^n L^p$$

L (lb/hr ft$^2$) is the mass liquid flow rate per unit area; m, n, p are constants as given in Table 6; H is holdup correction as given in Table 7; and $\varepsilon_o$ is given by

$$\varepsilon_o = \varepsilon - \phi_t$$

where

$\varepsilon_o$ is given in Table 8
$\phi_t$ is given in Table 7.

5.4 Correlation for Pressure Drop

The pressure drop per foot of packing is given by (Ref. E-9)

$$\Delta P = \frac{\alpha}{\rho_G} 10^{\beta \frac{L}{3600}} \left(\frac{G}{3600}\right)^2 \qquad (37)$$

## Table 6

## INTERFACIAL AREAS FOR ABSORPTION, DESORPTION, AQUEOUS LIQUIDS†

*For gases of density approximating 0.075 lb/cu ft, and below loading, $a_{AW} = mG^{n}L^{p}$. For other gases, substitute $G(0.075/\rho_G)^{0.5}$ for $G$. (Note: The original data cover $L'$ up to 4,500 lb/(hr)(sq ft). Extrapolation to $L' = 7{,}500$ has been suggested.)*

| Packing | Size, in. | Range of $L'$, lb/(hr)(sq ft) | $m$ | $n$ | $p$ |
|---|---|---|---|---|---|
| Raschig rings | 0.5 | 500–1,500 | 8,200 | $3.15(10^{-4})L' - 0.30$ | −1.04 |
| | | 1,500–4,500 | 9.32 | $0.151(10^{-1})L' + 0.148$ | −0.111 |
| | 1 | 500–1,500 | 0.274 | 0 | 0.552 |
| | | 1,500–4,500 | 463 | $0.528(10^{-4})L' - 0.0793$ | −0.47 |
| | 1.5 | 500–1,500 | 1.82 | $0.675(10^{-1})L' - 0.1013$ | 0.274 |
| | | 1,500–4,500 | 4.85 | $0.148(10^{-4})L' - 0.022$ | 0.140 |
| | 2 | 500–1,500 | 0.401 | 0 | 0.481 |
| | | 1,500–4,500 | 0.95 | 0 | 0.362 |
| Berl saddles | 0.5 | 500–1,500 | 0.0336 | 0.0529 | 0.761 |
| | | 1,500–4,500 | 2.54 | 0.0529 | 0.170 |
| | 1‡ | 500–1,500 | 15.89 | $0.686(10^{-4})L' - 0.1029$ | 0 |
| | | 1,500–4,500 | 238 | $0.420(10^{-1})L' - 0.0630$ | −0.359 |
| | 1.5‡ | 500–1,500 | 0.613 | 0.0508 | 0.455 |
| | | 1,500–4,500 | 465 | $0.325(10^{-4})L' - 0.0996$ | −0.1355 |

† Data of Shulman et al.

‡ For $G'$ 800 lb/(hr)(sq ft) only. For higher values, see Shulman, *AIChE J.*, **1**, 253 (1955), Figs. 16 and 17.

Source: (Ref. E-6)

## Table 7

### LIQUID HOLDUP IN PACKED TOWERS†

**Holdup** = $\phi_t = \phi_o + \phi_s \qquad \phi_{tW} = \phi_{oW} + \phi_{sW} \qquad \phi_t = \phi_{oW} H$

| Packing | Nominal size, in. | $d_s$, ft | $\phi_s$ | Water (ordinary temperatures) | $\mu'_L$, centipoise | H = Correction factor for other liquids. |
|---|---|---|---|---|---|---|
| Ceramic Raschig rings | 0.5<br>1<br>1.5<br>2 | 0.0582<br>0.1167<br>0.1740<br>0.238 | $\dfrac{6.85(10^{-3})\mu_L'^{0.02}\sigma'^{0.89}}{d_s^{1.21}\rho_L'^{0.37}}$ | $\phi_{tW} = \dfrac{2.25(10^{-5})L'^{\beta}}{d_s^2}$<br>$\phi_{sW} = \dfrac{0.00104}{d_s^{1.21}}$<br>$\beta = 0.965d_s^{0.376}$ | <12<br>>12 | $\dfrac{0.897L'^{0.57}\mu_L'^{0.13}}{\rho_L'^{0.84}(0.1183L'^{0.430} - 1)}\left(\dfrac{\sigma'}{73}\right)^{0.925-0.262\log L'}$<br>$\dfrac{0.575L'^{0.57}\mu_L'^{0.31}}{\rho_L'^{0.84}(0.1183L'^{0.430} - 1)}\left(\dfrac{\sigma'}{73}\right)^{0.925-0.262\log L'}$ |
| Carbon Raschig rings | 1<br>1.5<br>2 | 0.0427<br>0.178<br>0.235 | $\dfrac{6.36(10^{-3})\mu_L'^{0.02}\sigma'^{0.23}}{d_s^{1.21}\rho_L'^{0.37}}$ | $\phi_{tW} = \dfrac{7.90(10^{-5})L'^{\beta}}{d_s^2}$<br>$\phi_{sW} = \dfrac{0.00250}{d_s^{1.21}}$<br>$\beta = 0.706d_s^{0.376}$ | <12<br>>12 | $\dfrac{0.375L'^{0.57}\mu_L'^{0.13}}{\rho_L'^{0.84}(0.174L'^{0.315} - 1)}\left(\dfrac{\sigma'}{73}\right)^{0.925-0.262\log L'}$<br>$\dfrac{0.239L'^{0.57}\mu_L'^{0.31}}{\rho_L'^{0.84}(0.174L'^{0.315} - 1)}\left(\dfrac{\sigma'}{73}\right)^{0.925-0.262\log L'}$ |
| Ceramic Berl saddles | 0.5<br>1<br>1.5 | 0.0532<br>0.1050<br>0.155 | $\dfrac{1.641(10^{-4})\mu_L'^{0.04}\sigma'^{0.55}}{d_s^{1.56}\rho_L'^{0.37}}$ | $\phi_{tW} = \dfrac{2.50(10^{-5})L'^{\beta}}{d_s^2}$<br>$\phi_{sW} = \dfrac{0.00032}{d_s^{1.56}}$<br>$\beta = 0.965d_s^{0.376}$ | <20<br>>20 | $\dfrac{1.291L'^{0.57}\mu_L'^{0.13}}{\rho_L'^{0.84}(0.212L'^{0.413} - 1)}\left(\dfrac{\sigma'}{73}\right)^{1.033-0.262\log L'}$<br>$\dfrac{0.752L'^{0.57}\mu_L'^{0.31}}{\rho_L'^{0.84}(0.212L'^{0.413} - 1)}\left(\dfrac{\sigma'}{73}\right)^{1.033-0.262\log L'}$ |

† Data of Shulman et al.

**Source:** (Ref. E-6)

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## Table 8

## CHARACTERISTICS OF RANDOM PACKINGS†

| Packing | Nominal size, in. | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ¼ | ⅜ | ½ | ⅝ | ¾ | 1 | 1¼ | 1½ | 2 | 3 | 3½ |
| Raschig rings: | | | | | | | | | | | |
| Ceramic:‡ | | | | | | | | | | | |
| $C_f$ | 1,000 | 750 | 640 | 380 | 255 | 160 | 125 | 95 | 65 | 37 | |
| $\epsilon$ | 0.73 | 0 68 | 0.63 | 0.68 | 0.73 | 0.73 | 0.74 | 0.71 | 0.74 | 0.78 | |
| $a_p$ | 240 | 155 | 111 | 100 | 80 | 58 | 45 | 38 | 28 | 19 | |
| Metal: | | | | | | | | | | | |
| 1/32-in. wall: | | | | | | | | | | | |
| $C_f$ | 700 | | 300 | 258 | 185 | 115 | | | | | |
| $\epsilon$ | 0.69 | | 0.84 | | 0.88 | 0.92 | | | | | |
| $a_p$ | 236 | | 128 | | 83.5 | 62.7 | | | | | |
| 1/16-in. wall: | | | | | | | | | | | |
| $C_f$ | | | 340 | 290 | 230 | 145 | 110 | 82 | 57 | 37 | |
| $\epsilon$ | | | 0 73 | | 0.78 | 0 85 | 0.87 | 0.90 | 0.92 | 0.95 | |
| $a_p$ | | | 118 | | 71.8 | 56.7 | 49.3 | 41.2 | 31.4 | 20.6 | |
| Pall rings: | | | | | | | | | | | |
| Plastic: | | | | | | | | | | | |
| $C_f$ | | | | 97 | | 52 | | 32 | 25 | | 16 |
| $\epsilon$ | | | | 0 88 | | 0 90 | | 0.905 | 0.91 | | |
| $a_p$ | | | | 110 | | 63.0 | | 39 | 31 | | 23.4 |
| Metal: | | | | | | | | | | | |
| $C_f$ | | | | 71 | | 48 | | 28 | 20 | | |
| $\epsilon$ | | | | 0 902 | | 0 938 | | 0.953 | 0 964 | | |
| $a_p$ | | | | 131.2 | | 66.3 | | 48.1 | 36.6 | | |
| Intalox saddles, ceramic | | | | | | | | | | | |
| $C_f$ | 600 | | 265 | | 130 | 98 | | 52 | 40 | | |
| $\epsilon$ | 0.75 | | 0.78 | | 0.77 | 0 775 | | 0.81 | 0.79 | | |
| $a_p$ | 300 | | 190 | | 102 | 78 | | 59.5 | 36 | | |
| Berl saddles, ceramic: | | | | | | | | | | | |
| $C_f$ | 900 | | 380 | | 170 | 110 | | 65 | 45 | | |
| $\epsilon$ | 0.60 | | 0 63 | | 0.66 | 0.69 | | 0.75 | 0.72 | | |
| $a_p$ | 274 | | 142 | | 82 | 76 | | 44 | 32 | | |
| Tellerettes,§ ¾ to 2 in., plastic: | | | | | | | | | | | |
| High density: | | | | | | | | | | | |
| $C_f$ = 57 | | | | | | | | | | | |
| $\epsilon$ = 0.87 | | | | | | | | | | | |
| Low density: | | | | | | | | | | | |
| $C_f$ = 65 | | | | | | | | | | | |
| $\epsilon$ = 0.83 | | | | | | | | | | | |

† Table from the United States Stoneware Company. Data are for wet dumped packing in 16- and 30-in. ID towers.

‡ Nominal size and wall thickness, in inches, for ceramic Raschig rings are, respectively, ¼, 1/32; ⅜, 1/16; ½ to ¾, 3/32; 1, 1/8; 1¼ and 1½, 3/16; 2, ¼; 3, ⅜.

§ Teller and Ford: *Ind. Eng. Chem.*, **50**, 1201 (1958).

Source: (Ref. E-6)

where

$\Delta P$ (in $H_2O$) is the pressure drop

$\rho_G$ ($lb/ft^2$) is gas density

$\alpha$ and $\beta$ are constants as given in Table 9.

5.5 Costs

5.5.1 Capital Costs

The capital costs are the installed costs of the tower, fans, pumps, electrical devices, motors, and packing.

5.5.1.1 Tower

The installed cost of the tower per foot of height is given in Figure 7 as a function of diameter for several materials. Table 10 was derived from Figure 7.

5.5.1.2 Fans

The installed cost of the fans is \$.10/cfm or

$$\text{cost} = .10\ Q_G$$

where

$Q_G$ is the gas throughput in cfm.

5.5.1.3 Pumps

The installed cost of the pumps is \$1.50/GPM or

$$\text{cost} = 1.50\ Q_L$$

where

$Q_L$ is the liquid throughput in gpm.

5.5.1.4 Electrical Devices and Motors

The installed cost of electrical devices is \$30 HP and that of the motors \$15 HP, where HP is the required horsepower.

5.5.1.5 Packing

The costs of various packings as a function of height and diameter are given in Figures 8, 9 and 10.





Table 9

PRESSURE-DROP EQUATION FOR PARTICLE PACKING

| TYPE OF PACKING | MAT'L | | NOMINAL PACKING SIZE (INCHES) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1/4 | 3/8 | 1/2 | 5/8 | 3/4 | 1 | 1 1/4 | 1 3/8 | 1 1/2 | 2 | 3 |
| INTALOX SADDLES | CERAMIC | α | | | 1.04 | | 0.52 | 0.52 | | | 0.13 | 0.14 | |
| | | β | | | 0.37 | | 0.25 | 0.16 | | | 0.15 | 0.10 | |
| RASCHIG RINGS | CERAMIC | α | | | 1.96 | 1.31 | 0.82 | 0.53 | | | 0.31 | 0.23 | 0.18 |
| | | β | | | 0.56 | 0.39 | 0.38 | 0.22 | | | 0.21 | 0.17 | 0.15 |
| BERL SADDLES | CERAMIC | α | | | 1.16 | | 0.56 | 0.53 | | | 0.21 | 0.16 | |
| | | β | | | 0.47 | | 0.25 | 0.18 | | | 0.16 | 0.12 | |
| PALL RINGS | PLASTIC | α | | | | | 0.22 | | | 0.14 | | 0.10 | |
| | | β | | | | | 0.14 | | | 0.13 | | 0.12 | |
| PALL RINGS | METAL | α | | | | 0.43 | | 0.15 | | | 0.08 | 0.06 | |
| | | β | | | | 0.17 | | 0.15 | | | 0.16 | 0.12 | |
| RASCHIG RINGS 1/32 WALL | METAL | α | | | | 1.20 | | | | | | | |
| | | β | | | | 0.28 | | | | | | | |
| RASCHIG RINGS 1/16 WALL | METAL | α | | | 1.59 | 1.01 | 0.80 | 0.53 | | | 0.29 | 0.23 | |
| | | β | | | 0.29 | 0.39 | 0.30 | 0.19 | | | 0.20 | 0.14 | |

EQUATION

$$\Delta p = \alpha \times 10^{\beta L}\left(\frac{G^2}{\rho_G}\right) \text{ (LIMITED TO REGION BELOW FLOODING)}$$

$\Delta p$ = PRESSURE DROP - INCHES OF $H_2O$/FT. OF PACKING

G = GAS MASS VELOCITY - LBS./SEC. $FT^2$

L = LIQUID MASS VELOCITY - LBS./SEC. $FT^2$

$\rho_G$ = GAS DENSITY - LBS./$FT^3$

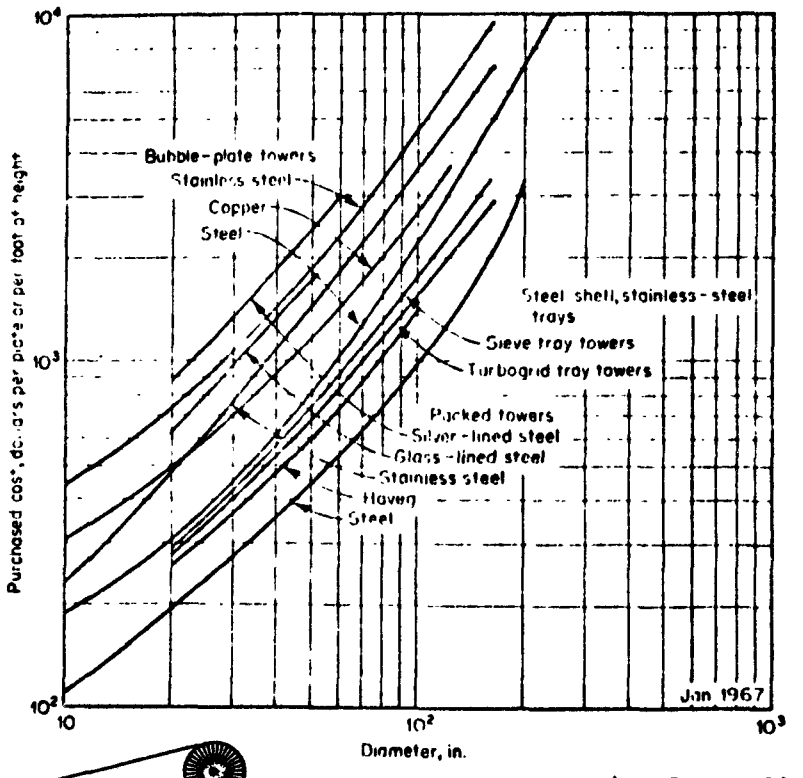
$\alpha$ AND $\beta$ = CONSTANTS

Table 10

SCRUBBER TOWER COST PARAMETERS

Cost = a $D^b$

| Material | Coefficient a | Exponent b |
|---|---|---|
| Stainless Steel | 9 | 1.2 |
| Steel | .133 | 1.92 |
| Haveg | .016 | 2.48 |




(Ref. F-8)

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Figure 7

COST OF TOWERS INCLUDING INSTALLATION AND AUXILIARIES

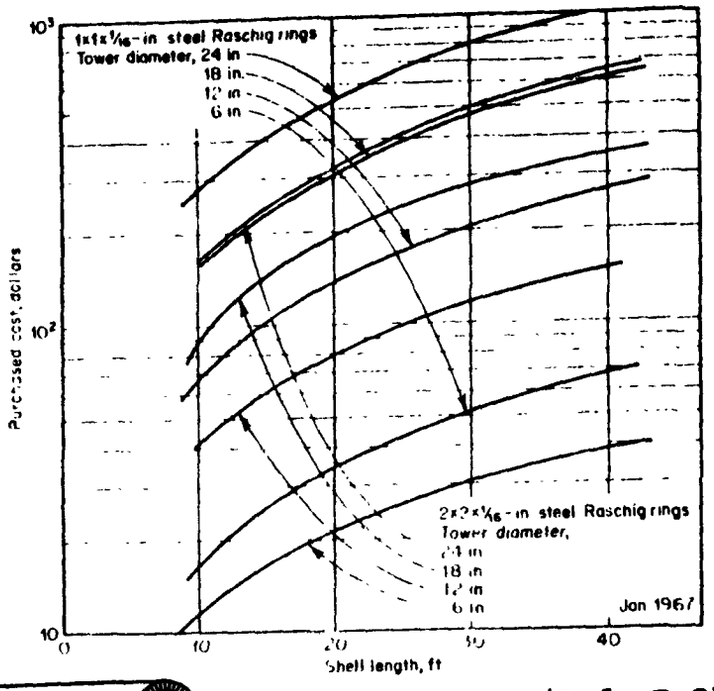


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Figure 8

COST OF STEEL RASCHIG-RING TOWER PACKINGS

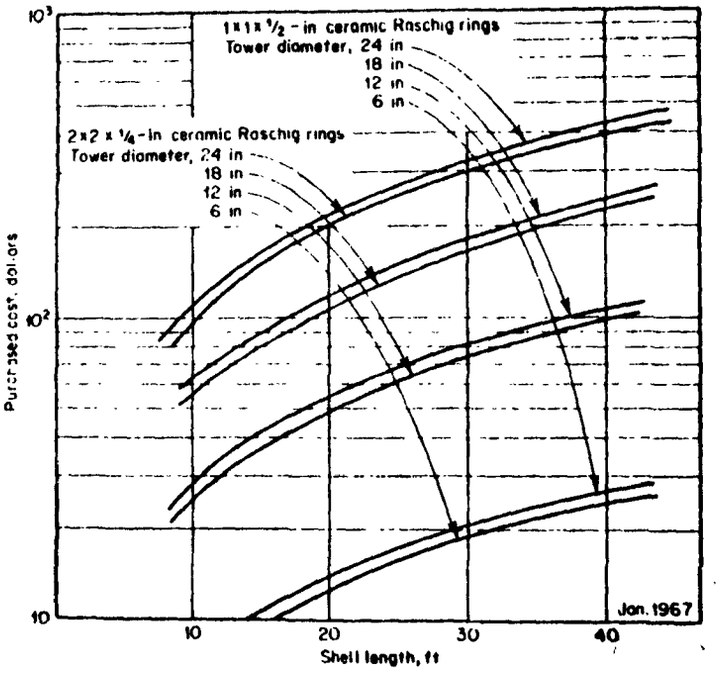


Figure 9

COST OF CERAMIC RASCHIG-RING TOWER PACKINGS

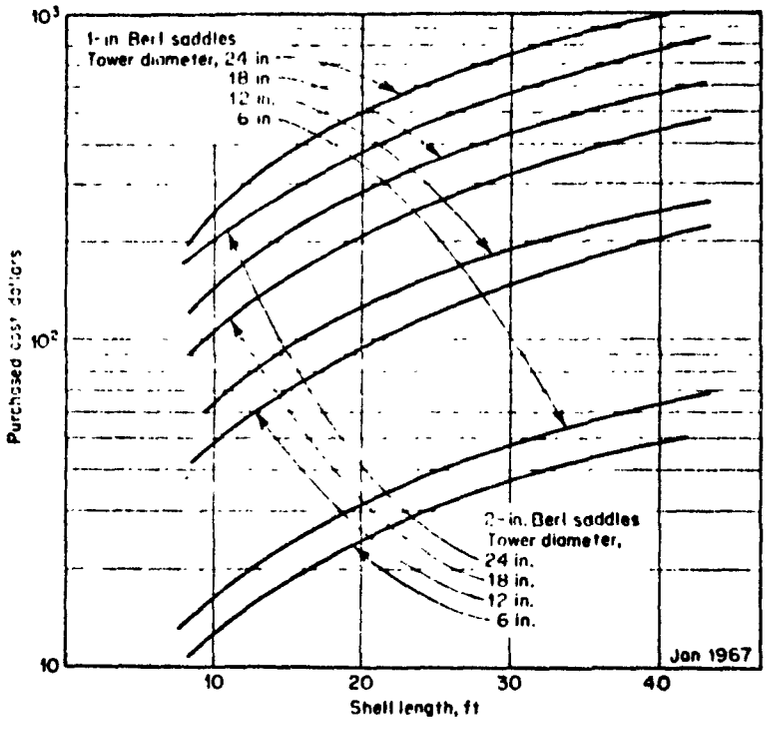


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Figure 10

COST OF BERL-SADDLE TOWER PACKINGS

5.5.2 Operating Costs

5.5.2.1 Pumping Power

The power required for pumping the liquid phase to the top of the tower is

$$\text{Power} = L_T \, A/E_p \qquad \text{(ft lb/hr)}$$

$$= \frac{8.33 \; Z \; Q_L}{3.3\text{x}10^{4} \; E_p} \qquad \text{(HP)}$$

where

$L_T$ is the liquid throughput in lb/hr
$E_p$ is efficiency of the pump.

5.5.2.2 Fan Power

The power required to draw the gas through the tower is

$$\text{Power} = G_T \, P'/E_F \qquad \text{(ft lb/hr)}$$

$$= 1.57\text{x}10^{-4} \; \Delta P \; Q_G/E_F \qquad \text{(HP)}$$

where

$G_T$ is the gas throughput in lb/hr
$\Delta P'$ pressure drop in feet of air
$E_F$ efficiency of fan
$\Delta P$ pressure drop in inches of water.

An additional pressure loss of 1 in. $H_2O$ should also be included for pressure drop through fittings.

5.5.2.3 Power Cost

The annual cost of power is

$$\text{cost} = .746 \; \theta \; P_W \; C_E$$

where

$\theta$ is the number of hours of operation per year
$C_E$ is the cost of electricity \$/KWHR
$P_W$ is the total power for pumping and fans.



5.5.2.4 Maintenance Cost

The annual maintenance cost is

$$\text{cost} = C_M \, Q_G$$

where

$C_M$ = .02, .04, .06, \$/cfm for low, medium and high costs, respectively.

5.5.2.5 Total Operating Cost

The total annual operating cost is

$$\text{cost} = Q_G[1.57\text{x}10^{-4} \; \theta \; \Delta P \; C_E/E_F + C_M] + 1.88\text{x}10^{-4} \; Q_L \; Z/E_p$$

5.6 Computer Program

A computer program has been written in the Rush time-sharing system. The program is based on the design equations given above. The cost data has been entered in the form of equations. To use the program the user specifies the air flow capacity, the fraction odor removal, and the unit cost of items, such as electricity. The program performs a series of design calculations to find a liquid flow rate and column diameter for the lowest cost. It then prints out dimensions of the tower, flow rates, and costs.

5.7 Scrubber Design and Cost Estimate

A series of packed scrubber designs were calculated, using the method described above. These calculations are based on the assumption that two scrubbing liquids can be found that will between them remove all important odors. The design is also based on a conventional type of packed tower using 1-1/2 in. saddles. Other scrubber configurations may prove to be more economical.

Preliminary calculations showed that smaller packing is less economical. Plastic Tellerette packing material may be more economic and calculations could be done with this packing.

It was found economical to use the maximum gas rate that the column can handle without flooding and the maximum liquid recirculation rate for which experimental correlations are available. Under these conditions the cost of scrubbing is less than that of incineration, except when the inlet odor concentration is as high as 1000 ppm. In this case the chemicals cost raises the cost of scrubbing above that of incineration; because the incinerator can reduce a higher odor concentration simply by operating at a higher temperature. Results are summarized in Table 11.

Table 11

SCRUBBER COST SUMMARY
(Pentanal in Air) (1-1/2 in. Intalox Saddles)
Two Scrubbers in Series

| Flow, CFM | Reduction Ratio Odor Concentration | Flow Rates, lb/hr sq ft Liquid | Gas | Packing Depth, ft | Tower Diameter, ft | Pressure Drop, in Water | Costs Investment, $ | Chemicals* $/Year | Total** $/Year | $/1000 CFM hr |
|---|---|---|---|---|---|---|---|---|---|---|
| 1,000 | 100 | 569 | 7500 | 5.2 | 3.2 | .46 | 8,200 | 7 | 2,370 | .49 |
| | 1,000 | 570 | 7500 | 7.8 | 3.2 | .69 | 12,180 | 72 | 3,450 | .69 |
| | 100,000 | 570 | 7500 | 12.9 | 3.2 | 1.15 | 20,120 | 7,200 | 12,600 | 2.50 |
| 5,000 | 100 | 570 | 7500 | 5.1 | 7.1 | .49 | 22,600 | 35 | 7,200 | .29 |
| | 1,000 | 570 | 7500 | 7.7 | 7.1 | .74 | 33,600 | 350 | 10,400 | .41 |
| | 100,000 | 571 | 7500 | 12.8 | 7.1 | 1.23 | 55,600 | 35,000 | 50,000 | 2.00 |
| 25,000 | 100 | 571 | 7500 | 5.1 | 15.8 | .49 | 67,400 | 175 | 24,800 | .19 |
| | 1,000 | 571 | 7500 | 7.7 | 15.8 | .74 | 99,800 | 1,750 | 35,200 | .28 |
| | 100,000 | 571 | 7500 | 12.8 | 15.8 | 1.23 | 164,680 | 175,000 | 225,000 | 1.80 |

*Chemical cost based on effluent concentration .01 ppm by volume. Typical chemical cost based on reaction with NaOH at 20 cents/lb.

**Based on 5,000 hours operation per year.

## 6. DESIGN AND COST OF HORIZONTAL SPRAY SCRUBBER

### 6.1 Introduction

A new type of spray scrubber has been designed by Air Conditioning Corporation, Greensboro, North Carolina. This scrubber has been installed in a number of rendering plants and found to give satisfactory odor reduction. A drawing of one unit is shown in Figure 11. This scrubber consists of a long duct into which the plant air flows. A bank of spray nozzles is mounted near the entrance of the duct, and the scrubbing liquid is atmozed by pumping the liquid under pressure through the nozzles. At the end of the scrubber is an effective mist eliminator. Two or more units can be connected in series to make use of several scrubbing liquids. It is possible to calculate the performance by using penetration theory to calculate the mass transfer to the drops in the scrubber.

The success of this scrubber depends on the use of low air velocities such that the droplets remain in the scrubber for several seconds. Previously designed spray scrubbers either have insufficient droplet area/unit volume, or insufficient contact time. Although the nozzles point upstream, the stopping distance of droplets is such that they soon acquire the air velocity, and drift down the scrubber to the exit. Therefore the droplet contact time is only slightly longer than the air contact time in the scrubber.

Nozzles are used which give a relatively coarse spray, with a mean size of about 400 μm. The size depends slightly on water pressure and significantly on size of nozzle expressed as flowrate in Figure 12. Of course there is a distribution of droplet sizes as shown by Figure 13, but some preliminary calculations showed that the mean size can represent the behavior of the spray within 10% of the integrated average.

According to the methods of calculation used, each droplet acts independently of the others. Actually the droplets can

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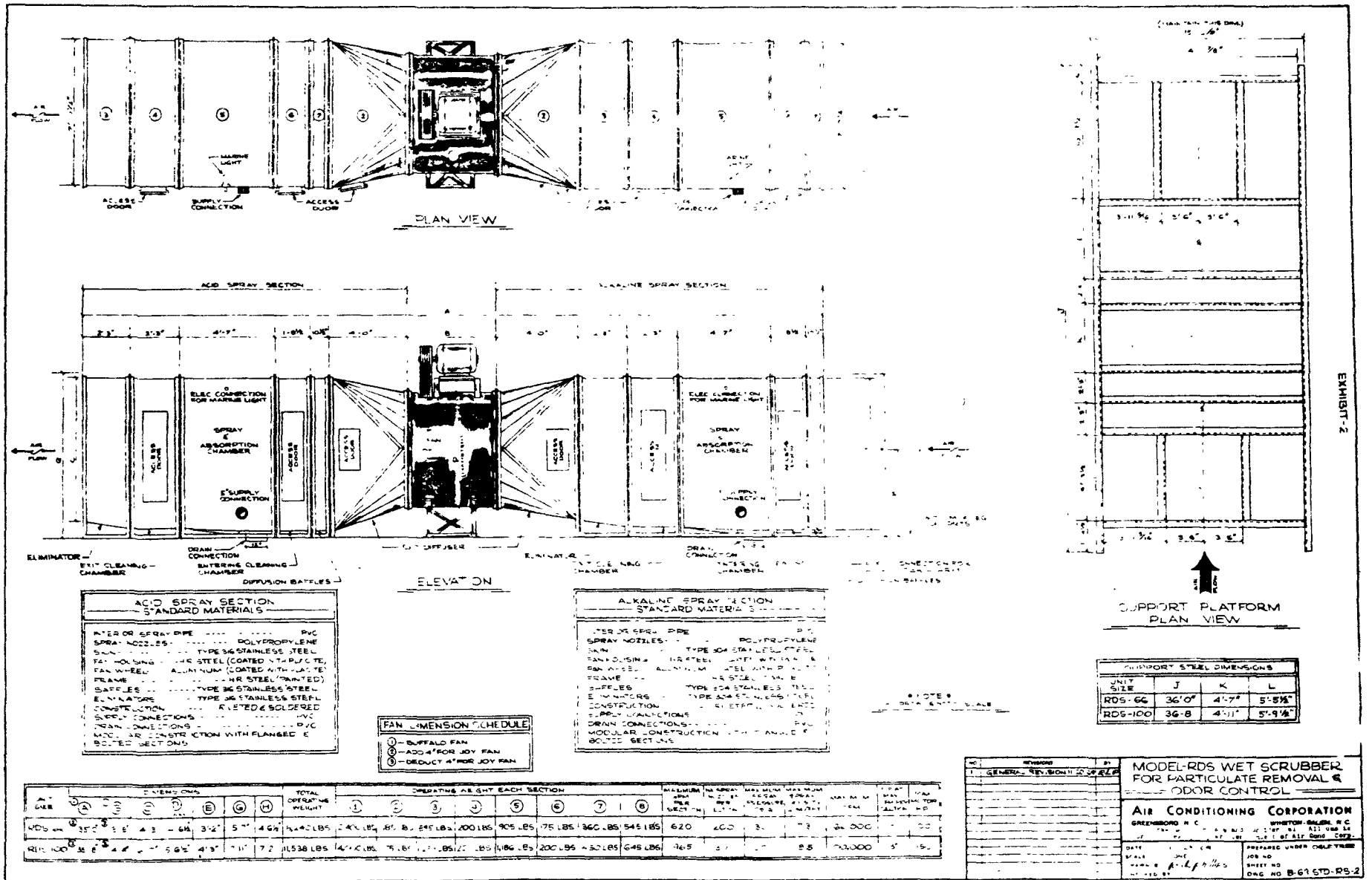
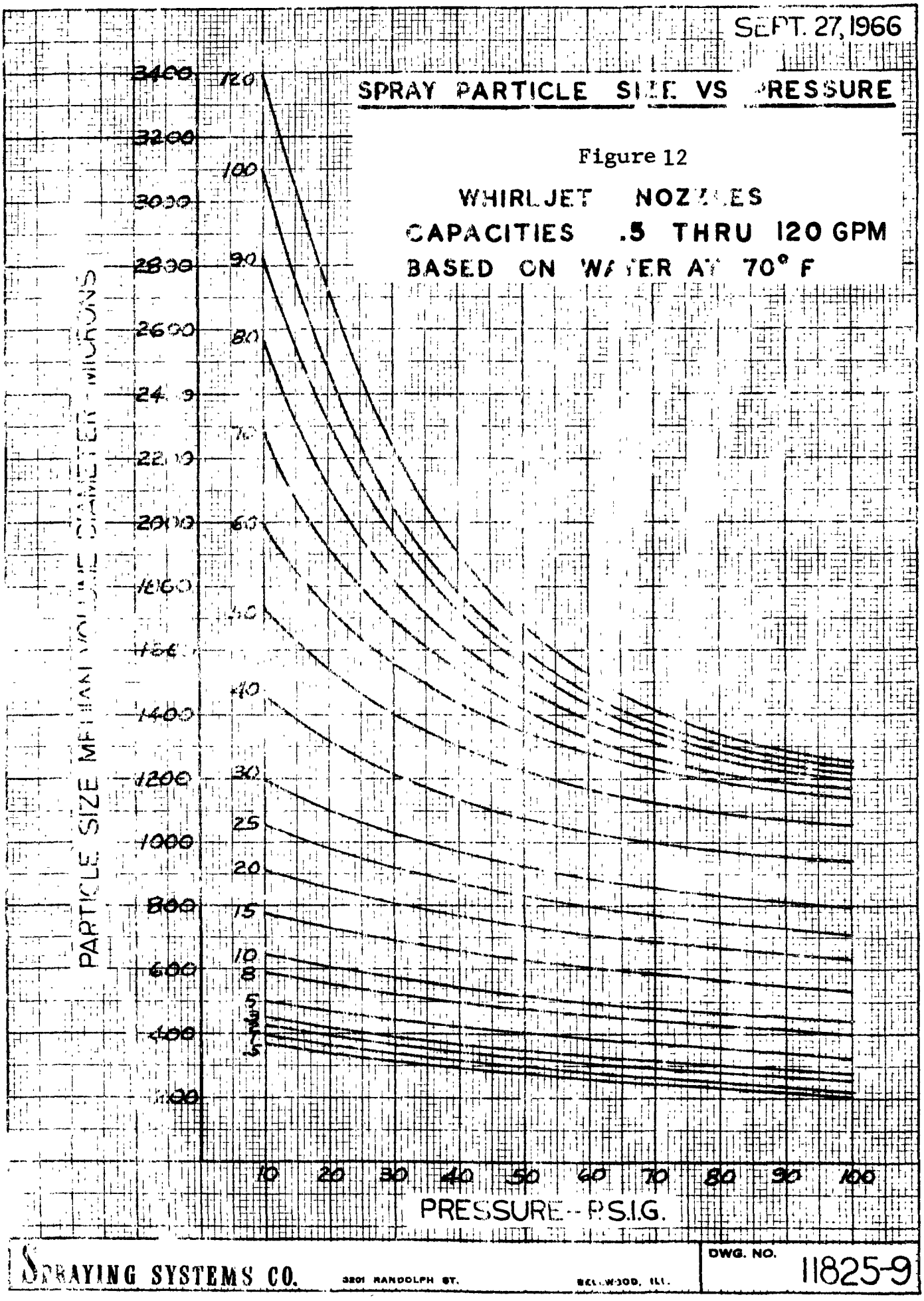
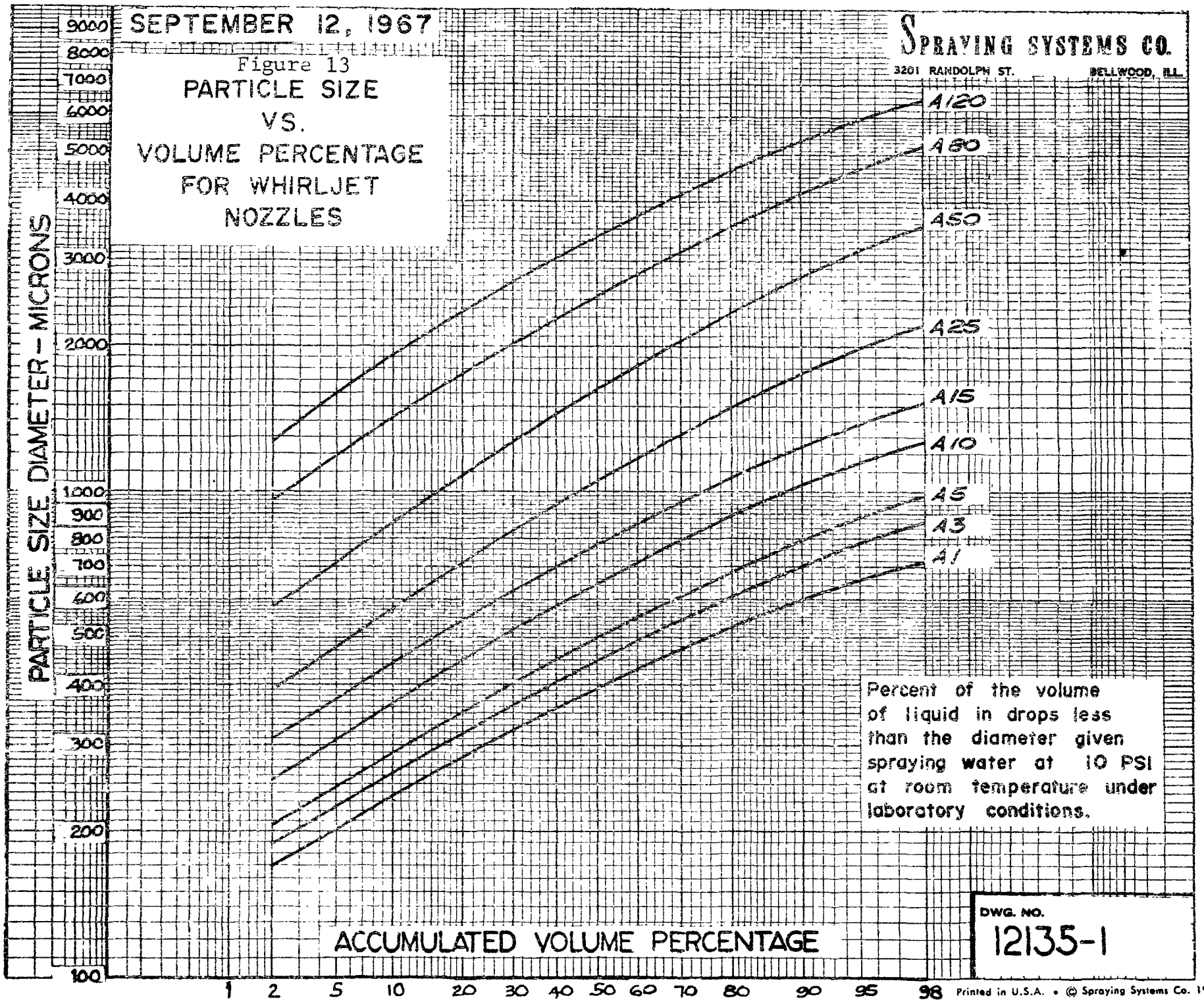



Figure 11
WET SCRUBBER


SEPT. 27, 1966
SPRAY PARTICLE SIZE VS PRESSURE
Figure 12
WHIRLJET NOZZLES
CAPACITIES .5 THRU 120 GPM
BASED ON WATER AT 70° F
PARTICLE SIZE MEDIAN VOLUME DIAMETER - MICRONS
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
120
100
90
80
70
60
50
40
30
25
20
15
10
8
5 GPM
10 20 30 40 50 60 70 80 90 100
PRESSURE - P.S.I.G.
SPRAYING SYSTEMS CO.
3201 RANDOLPH ST.
BELLWOOD, ILL.
DWG. NO.
11825-9

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collide and coalesce. This effect is computed to see if it is significant, but is not compensated for. In addition the droplets can settle and collect on the floor of the scrubber. The terminal settling velocity of 400 μm droplets in air is 3 ft/sec. This velocity cannot be directly applied to the turbulent flow conditions of the scrubber, but it suggests that the performance will be reduced if the contact time is more than a few seconds.

## 6.2 Nomenclature for Spray Scrubber

| | |
|---|---|
| $T$ | Absolute temperature, °R |
| $a$ | Area available for mass transfer, surface area of drops, $ft^2/ft^3$ |
| $\theta_c$ | Contact time of drops in scrubber, hr |
| Diff | Diffusivity of odorant vapor in air, $ft^2/hr$ |
| $N_0$ | Drop concentration at scrubber nozzles, number/$ft^3$ |
| $N_1$ | Drop concentration at scrubber outlet, number/ft |
| $d_p$ | Drop diameter, mean, μm (micrometers) |
| $d_{drop}$ | Drop diameter, μm |
| $\sigma$ | Drop diameter, ft |
| $L_{noz}$ | Flow of liquid per nozzle, gal/min |
| $V_g$ | Gas velocity in scrubber, ft/hr |
| $Z$ | Height of scrubber, ft |
| $Y_o$ | Inlet concentration, mol fraction or partial pressure of odorant |
| $X_L$ | Length of a scrubber stage, ft. |
| $L$ | Liquid flow rate, $ft^3/hr$ |
| $L_{noz}$ | Liquid flow per nozzle, gal/min |
| $X_x$ | Log of odor reduction ratio |
| $k_g$ | Mass transfer coefficient, lb-mol/hr-$ft^2$-atm |
| $u$ | Mean drop/velocity relative to gas, turbulent velocity, ft/sec |
| $G_M$ | Molar gas flow rate, lb-mol/hr-$ft^2$ |
| $v$ | Molar gas volume, 359 cu ft |
| $n_1$ | Number of collisions per drop per sec |

$N_{oza}$ Number of nozzles per sq ft of scrubber cross section

$N_{noz}$ Number of nozzles per stage

$Y_e$ Outlet concentration of odorant

T Temperature of gas stream, °R

CFM Total air flow, cu ft/min

Gpm Total liquid flow, gal/min

$P_T$ Total pressure, atm

$\epsilon$ Volume fraction of space filled with drops.

## 6.3 Design Equations

### 6.3.1 Spray Droplet Area

To compute a = spray area, $ft^2$ droplets/$ft^3$ of air

drop diameter = $d_p$, μm (about 400 μm)

$$\text{drop volume} = \frac{\pi}{6}\left(\frac{d_p}{25400 \times 12}\right)^3 ft^3 \tag{38}$$

$$\text{drop area} = \pi\left(\frac{d_p}{25400 \times 12}\right)^3 ft^2 \tag{39}$$

$$\frac{\text{drop area}}{\text{drop volume}} = \frac{6 \times 25400 \times 12}{d_p\ (\mu m)}\ 1/ft \tag{40}$$

### 6.3.2 Volume of Spray

Liquid flow

$$L = L_{noz}\ \frac{gpm}{nozzle} \times N_{noz}\ nozzles$$

$$\times\ \frac{ft^3}{\rho_L\ lb} \times \frac{7.481\ lb}{gal} \times 60\ \frac{min}{hr} \tag{41}$$

$$= ft^3\ liquid/hr$$

Spray volume/cu ft air

$$= L \frac{ft^3}{hr} \quad 60 \frac{1}{CFM} \quad \frac{hr}{ft^3}$$

$$= L_{noz} N_{noz} \frac{7.481}{\rho_L} \quad \frac{1}{CFM} = \frac{ft^3 \text{ spray}}{ft^3 \text{ air}} \tag{42}$$

$a$ = spray area/$ft^3$ air

$$a = L_{noz} N_{noz} \frac{7.481}{\rho_L} \quad \frac{1}{CFM} \quad \frac{6 \times 25400 \times 12}{d_p} \quad \frac{ft^2 \text{ spray}}{ft^3 \text{ air}} \tag{43}$$

This is independent of the length of scrubber if droplets move with the air.

6.3.3 Mass Transfer Equation

The equation for mass transfer is the same as that for a packed scrubbing tower. Only the method of calculating the mass transfer coefficient is different. This equation is given in Section 5.2.

$$\ln \frac{Y_o}{Y_e} = \frac{X_L \, k_g \, a \, P_T}{G_M} = X_x \tag{44}$$

6.3.4 Penetration Theory

The mass transfer coefficient is predicted from penetration theory based on the transient diffusion of odorant through the gas layer adjacent to each drop. The result is (Ref. 1)



$$k_g = \frac{2}{RT} \sqrt{\frac{Diff}{\pi \theta_c}} \quad \frac{lb\text{-}mol}{hr\text{-}ft^2\text{-}atm} \tag{45}$$

The contact time $\theta_c$ of droplets in air depends on the length of scrubber $X_L$ and the gas (and droplet) velocity.

$$\theta_c = \frac{X_L}{V_{gas}} \quad \frac{ft}{ft/hr} = \frac{X_L \text{ cross-sectional area}}{60 \text{ CFM}}$$

$$= \frac{X_L \, W \, Z}{60 \text{ CFM}} \quad ft^3 \quad \frac{hr}{ft^3} \tag{46}$$

6.3.5 Scrubber Design

The required performance of the scrubber is expressed by the quantity $X_x$. This can be related to scrubber dimensions by substituting 45 and 46 into 44. The ideal gas law is also used.

$$\frac{P_T}{RT} = \frac{1}{v} = \frac{1}{359 \text{ ft}^3} \tag{47}$$

$$G_M \quad \frac{lb \text{ mol}}{hr\text{-}ft^2} \times \frac{359 \text{ ft}^3}{lb \text{ mol}} \times \frac{T}{460} = \frac{ft^3 \text{ liquid}}{hr\text{-}ft^2}$$

$$= \frac{60 \text{ CFM}}{W \, Z} \tag{48}$$

$$X_x = \frac{X_L\ k_g\ a\ P_T}{G_m}$$

$$= X_L\ 2\ a \sqrt{\frac{\text{Diff CFM}}{\pi\ X_L\ W\ Z}}\ \frac{1}{359}\ \frac{W\ Z}{60\ \text{CFM}}\ \frac{359\ T}{460}$$

$$= \frac{2\ T\ a}{460} \sqrt{\frac{\text{Diff}\ X_L\ W\ Z}{60\ \pi\ \text{CFM}}} \qquad (49)$$

This is the basic design equation.

We could now design the scrubber length $X_L$ for a given width and height Z to achieve the desired reduction ratio. When this is done, impossible lengths result. Instead, we fix the length $X_L$ = 29 ft, as is done by Air Conditioning Corporation, and vary the height Z. In doing so, we allow the number of nozzles per unit cross-sectional area $N_{oza}$ to remain constant; the total number increases with height Z. The liquid flow per nozzle $L_{noz}$ is also fixed, so changing the height changes the liquid flow and increases the droplet area. It also decreases the air velocity and increases the contact time. As a result the capacity depends on $Z^{3/2}$. These substitutions are not detailed here, but they are included in the design computer program.

The flow rate per nozzle $L_{noz}$ is another variable that affects the design, and hence the scrubbing cost. The program provides for reading in 4 values of $L_{noz}$; it computes the scrubber design and cost for each, and chooses the most economic one. Other variables, such as spray nozzle pressure affect droplet size and power. These can be explored by trial calculations with the program.

6.4 Cost Equations

Costs of each component of equipment and operating costs are similar to those used for the packed tower scrubber, except the



coefficients are different. These equations are included in the computer program.

6.5 Droplet Collision Rate

The drop collision rate can be estimated from the kinetic gas theory, for example by Loeb.[4] The only difficulty is in estimating the mean turbulent velocity of the drops with respect to the gas. It is this component of velocity which causes them to collide.

From kinetic gas theory the collision rate

$n_1$ = no. of collisions per sec per drop

$$= \frac{2\ \pi u\ N\ \sigma^2}{\epsilon} \qquad (50)$$

The fraction reduced per unit time is

$$\frac{dN}{N} = \frac{1}{2}\ n_1\ d\theta = \frac{\pi\ u\ N\ \sigma^2}{\epsilon} \qquad (51)$$

This integrates to

$$\frac{1}{N_1} = \frac{1}{N_0} = \frac{\pi\ u\ \sigma^2\ \theta_c}{2\ \epsilon} \qquad (52)$$

Assume that $u = \frac{1}{2}\ V_g$

$$u\ \theta_c = \frac{1}{2}\ X_L$$

$$\frac{1}{N_1} = \frac{1}{N_0} + \frac{\pi\ \sigma^2\ X_L}{4\ \epsilon} \qquad (53)$$

The fraction of space occupied by drops is

$$\varepsilon = \frac{L}{CFM} = \frac{G_{pm}\ 7.481}{\rho_L\ CFM} \qquad (54)$$

The initial number of droplets per cu ft $N_0$ is

$$N_0 = \frac{\frac{L}{\frac{\pi}{6}\ CFM}}{\left(\frac{D_{drop}}{25400 \times 12}\right)^3} \qquad (55)$$

The number left at the end of the scrubber is

$$N_1 = \frac{1}{\frac{1}{N_0} + \frac{\pi X_L}{2\varepsilon}\left(\frac{D_{drop}}{25400 \times 12}\right)^2} \qquad (56)$$

Both $N_0$ and $N_1$ are listed by the computer program. In most cases the decrease is a small fraction of $N_0$, but it could be large if a high liquid flow rate is chosen.

6.6 Design and Cost Estimates

Tables 12A to 12H present results of calculations with the design computer program. All of these examples are for 2-stage units The cost of this method of scrubbing appears to be about 1/4 that by other methods when expressed in $/1000 cfm-hr. The effect of flow capacity on unit cost is very small as shown in the first four tables. These tables correspond to cost data kindly provided by Air Conditioning Corporation, and they check these values within 15%. The cost decreases somewhat with lower reduction ratios, as shown in Tables 12E, 12F, and 12G, and the method even competes with carbon adsorption for treating ventilation air. Table 12H is computed for an amortization factor of 0.1 corresponding to 15 year life at 7% interest.



Table 12A

DESIGN AND COST OF SPRAY SCRUBBING

| NØZZLES/SQ FT | LENGTH | UNITS/SERIES | DDRØP UM | NØZZLE PSI |
|---|---|---|---|---|
| 4.0 | 29.0 | 2.0 | 400.0 | 15.0 |

GPM/NØZZLE: 1.000 2.200 5.000 10.000

COEFFICIENTS AND EXPØNENTS FØR CØST CØRRELATIØNS

| | SCRUBBER | | FAN | | PUMP | | NØZZLES |
|---|---|---|---|---|---|---|---|
| | 176.000 | .800 | .290 | .800 | 11.500 | .600 | 5.000 |

UNIT CØSTS FØR SCRUBBER SYSTEM

| PØWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NØZZLES $ EA | AMØRTIZATIØN FACTØR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLØW RATE CFM | CØNCENTRATIØN INLET | ØUTLET | HENRY | SCHMIDT NØ | TEMPERATURE DEGREES F | HRS/YR |
|---|---|---|---|---|---|---|
| 25000. | 1000.000 | 1.000 | 0. | 0. | 70. | 5500 |

INTERMEDIATE VALUES DURING ØPTIMIZATIØN

| ANNUAL CØST | CAPITAL | TIM-SEC | HEIGHT | GPM/NØZ | FT2/FT3 | NØ | N1 |
|---|---|---|---|---|---|---|---|
| 21858.9 | 50438.0 | 6.2 | 11.1 | 1.0 | 7.8 | 1367028 | 1150861 |
| 31946. | | | | | | | |
| 20486.2 | 37340.9 | 3.7 | 6.6 | 2.2 | 10.1 | 1777898 | 1349237 |
| 27954. | | | | | | | |
| 20918.9 | 28629.5 | 2.1 | 3.8 | 5.0 | 13.3 | 2337459 | 1508854 |
| 26645. | | | | | | | |
| 22569.7 | 23846.0 | 1.3 | 2.4 | 10.0 | 16.7 | 2944946 | 1573407 |
| 20918.9 | 28629.5 | 2.1 | 3.8 | 5.0 | 13.3 | 2337459 | 1508854 |
| 26645. | | | | | | | |

ØPERATING CØNDITIØNS ØF TØWER-CALCULATED
THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TØTAL FLØW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 3.8 | 25000.0 | 607.3 |

| NØZZLES | BANKS | DDRØP UM | UNITS/SERIES |
|---|---|---|---|
| 121. | 1. | 400. | 2. |

| PRESSURE DRØP | FAN HØRSEPØWER | PUMP HØRSEPØWER |
|---|---|---|
| 3.000 | 16.821 | 198.754 |

CAPITAL CØSTS FØR SCRUBBER SYSTEM

| SHELL | NØZZLES | FAN | PUMP | EXTERNALS | TØTAL |
|---|---|---|---|---|---|
| 14541. | 1215. | 1025. | 1076. | 10773. | 28630. |

ANNUAL CØST FØR SCRUBBER SYSTEM

| AMØRTIZATIØN | PØWER | MAINTENANCE | CHEMICALS | TØTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 7157. | 12061. | 1000. | 700. | 20919. | .17 |

Table 12B

EFFECT OF AIR FLOW

UNIT CØSTS FØR SCRUBBER SYSTEM

| PØWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NØZZLES $ EA | AMØRTIZATIØN FACTØR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLØW RATE CFM | CØNCENTRATIØN INLET | CØNCENTRATIØN ØUTLET | HENRY | SCHMIDT NØ | TEMPERATURE DEGREES F |
|---|---|---|---|---|---|
| 38000. | 1000.000 | 1.000 | 0. | 0. | 70. |

INTERMEDIATE VALUES DURING ØPTIMIZATIØN

| ANNUAL CØST | CAPITAL | TIM-SEC | HEIGHT | GPM/NØZ | FT2/FT3 | NØ | N1 |
|---|---|---|---|---|---|---|---|
| 32227.4 | 72169.5 | 6.2 | 16.9 | 1.0 | 7.8 | 1367056 | 1150877 |
| 46661. | | | | | | | |
| 30463.5 | 53668.5 | 3.7 | 10.0 | 2.2 | 10.1 | 1777935 | 1349251 |
| 41197. | | | | | | | |
| 31332.4 | 41364.4 | 2.1 | 5.8 | 5.0 | 13.3 | 2337508 | 1508863 |
| 39605. | | | | | | | |
| 33954.4 | 34604.5 | 1.3 | 3.6 | 10.0 | 16.7 | 2945008 | 1573410 |
| 31332.4 | 41364.4 | 2.1 | 5.8 | 5.0 | 13.3 | 2337508 | 1508863 |
| 39605. | | | | | | | |

ØPERATING CØNDITIØNS ØF TØWER-CALCULATED

THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TØTAL FLØW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 5.8 | 38000.0 | 923.1 |

| NØZZLES | BANKS | DDRØP UM | UNITS/SERIES |
|---|---|---|---|
| 185. | 1. | 400. | 2. |

| PRESSURE DRØP | FAN HØRSEPØWER | PUMP HØRSEPØWER |
|---|---|---|
| 3.000 | 25.569 | 303.427 |

CAPITAL CØSTS FØR SCRUBBER SYSTEM

| SHELL | NØZZLES | FAN | PUMP | EXTERNALS | TØTAL |
|---|---|---|---|---|---|
| 20328. | 1846. | 1433. | 1383. | 16374. | 41364. |

ANNUAL CØST FØR SCRUBBER SYSTEM

| AMØRTIZATIØN | PØWER | MAINTENANCE | CHEMICALS | TØTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 10341. | 18407. | 1520. | 1064. | 31332. | .16 |



Table 12C

EFFECT OF AIR FLOW

UNIT CØSTS FØR SCRUBBER SYSTEM

| PØWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NØZZLES $ EA | AMØRTIZATIØN FACTØR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLØW RATE CFM | CØNCENTRATIØN INLET | CØNCENTRATIØN ØUTLET | HENRY | SCHMIDT NØ | TEMPERATURE DEGREES F |
|---|---|---|---|---|---|
| 66000. | 1000.000 | 1.000 | 0. | 0. | 70. |

INTERMEDIATE VALUES DURING ØPTIMIZATIØN

| ANNUAL CØST | CAPITAL | TIM-SEC | HEIGHT | GPM/NØZ | FT2/FT3 | NØ | N1 |
|---|---|---|---|---|---|---|---|
| 54116.9 | 116035.8 | 6.2 | 29.3 | 1.0 | 7.8 | 1367094 | 1150899 |
| 77324. | | | | | | | |
| 51677.2 | 86832.3 | 3.7 | 17.3 | 2.2 | 10.1 | 1777984 | 1349271 |
| 69044. | | | | | | | |
| 53588.8 | 67417.2 | 2.1 | 10.0 | 5.0 | 13.3 | 2337573 | 1508875 |
| 67072. | | | | | | | |
| 58353.5 | 56746.0 | 1.3 | 6.3 | 10.0 | 16.7 | 2945089 | 1573413 |
| 53588.8 | 67417.2 | 2.1 | 10.0 | 5.0 | 13.3 | 2337573 | 1508875 |
| 67072. | | | | | | | |

ØPERATING CØNDITIØNS ØF TØWER-CALCULATED

THE MATERIAL ØF CØNSTRUCTIØN IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TØTAL FLØW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 10.0 | 66000.0 | 1603.3 |

| NØZZLES | BANKS | DDRØP UM | UNITS/SERIES |
|---|---|---|---|
| 321. | 1. | 400. | 2. |

| PRESSURE DRØP | FAN HØRSEPØWER | PUMP HØRSEPØWER |
|---|---|---|
| 3.000 | 44.409 | 531.935 |

CAPITAL CØSTS FØR SCRUBBER SYSTEM

| SHELL | NØZZLES | FAN | PUMP | EXTERNALS | TØTAL |
|---|---|---|---|---|---|
| 31616. | 3207. | 2229. | 1926. | 28439. | 67417. |

ANNUAL CØST FØR SCRUBBER SYSTEM

| AMØRTIZATIØN | PØWER | MAINTENANCE | CHEMICALS | TØTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 16854. | 32246. | 2640. | 1848. | 53589. | .16 |

Table 12D

EFFECT OF AIR FLOW

UNIT COSTS FOR SCRUBBER SYSTEM

| POWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NOZZLES $ EA | AMORTIZATION FACTOR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLOW RATE CFM | CONCENTRATION INLET | OUTLET | HENRY | SCHMIDT NO | TEMPERATURE DEGREES F |
|---|---|---|---|---|---|
| 100000. | 1000.000 | 1.000 | 0. | 0. | 70. |

INTERMEDIATE VALUES DURING OPTIMIZATION

| ANNUAL COST | CAPITAL | TIM-SEC | HEIGHT | GPM/NOZ | FT2/FT3 | NO | N1 |
|---|---|---|---|---|---|---|---|
| 80460.3 | 166207.8 | 6.2 | 44.4 | 1.0 | 7.8 | 1367123 | 1150915 |
| 77323.4 | 124998.1 | 3.7 | 26.2 | 2.2 | 10.1 | 1778021 | 1349285 |
| 102323. | | | | | | | |
| 80568.3 | 97612.0 | 2.1 | 15.2 | 5.0 | 13.3 | 2337621 | 1508885 |
| 100091. | | | | | | | |
| 87961.9 | 82557.3 | 1.3 | 9.6 | 10.0 | 16.7 | 2945150 | 1573415 |
| 80568.3 | 97612.0 | 2.1 | 15.2 | 5.0 | 13.3 | 2337621 | 1508885 |
| 100091. | | | | | | | |

OPERATING CONDITIONS OF TOWER-CALCULATED
THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TOTAL FLOW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 15.2 | 100000.0 | 2429.3 |

| NOZZLES | BANKS | DDROP UM | UNITS/SERIES |
|---|---|---|---|
| 486. | 1. | 400. | 2. |

| PRESSURE DROP | FAN HORSEPOWER | PUMP HORSEPOWER |
|---|---|---|
| 3.000 | 67.286 | 815.024 |

CAPITAL COSTS FOR SCRUBBER SYSTEM

| SHELL | NOZZLES | FAN | PUMP | EXTERNALS | TOTAL |
|---|---|---|---|---|---|
| 44083. | 4859. | 3108. | 2472. | 43090. | 97612. |

ANNUAL COST FOR SCRUBBER SYSTEM

| AMORTIZATION | POWER | MAINTENANCE | CHEMICALS | TOTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 24403. | 49365. | 4000. | 2800. | 80568. | .16 |



Table 12E

EFFECT OF AIR FLOW

UNIT COSTS FOR SCRUBBER SYSTEM

| POWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NOZZLES $ EA | AMORTIZATION FACTOR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLOW RATE CFM | CONCENTRATION INLET | OUTLET | HENRY | SCHMIDT NO | TEMPERATURE DEGREES F |
|---|---|---|---|---|---|
| 150000. | 1000.000 | 1.000 | 0. | 0. | 70. |

INTERMEDIATE VALUES DURING OPTIMIZATION

| ANNUAL COST | CAPITAL | TIM-SEC | HEIGHT | GPM/NOZ | FT2/FT3 | NO | N1 |
|---|---|---|---|---|---|---|---|
| 119371.7 | 236396.5 | 6.2 | 66.6 | 1.0 | 7.8 | 1367150 | 1150931 |
| 115250.8 | 178684.4 | 3.7 | 39.4 | 2.2 | 10.1 | 1778057 | 1349299 |
| 120453.2 | 140350.3 | 2.1 | 22.8 | 5.0 | 13.3 | 2337669 | 1508894 |
| 148523. | | | | | | | |
| 131690.9 | 119277.2 | 1.3 | 14.3 | 10.0 | 16.7 | 2945210 | 1573417 |
| 120453.2 | 140350.3 | 2.1 | 22.8 | 5.0 | 13.3 | 2337669 | 1508894 |
| 148523. | | | | | | | |

OPERATING CONDITIONS OF TOWER-CALCULATED
THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TOTAL FLOW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 22.8 | 150000.0 | 3644.0 |

| NOZZLES | BANKS | DDROP UM | UNITS/SERIES |
|---|---|---|---|
| 729. | 1. | 400. | 2. |

| PRESSURE DROP | FAN HORSEPOWER | PUMP HORSEPOWER |
|---|---|---|
| 3.000 | 100.929 | 1242.514 |

CAPITAL COSTS FOR SCRUBBER SYSTEM

| SHELL | NOZZLES | FAN | PUMP | EXTERNALS | TOTAL |
|---|---|---|---|---|---|
| 60975. | 7288. | 4299. | 3153. | 64635. | 140350. |

ANNUAL COST FOR SCRUBBER SYSTEM

| AMORTIZATION | POWER | MAINTENANCE | CHEMICALS | TOTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 35088. | 75166. | 6000. | 4200. | 120453. | .16 |

Table 12F

EFFECT OF ODOR REDUCTION RATIO

UNIT COSTS FOR SCRUBBER SYSTEM

| POWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NOZZLES $ EA | AMORTIZATION FACTOR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLOW RATE CFM | CONCENTRATION INLET | CONCENTRATION OUTLET | HENRY | SCHMIDT NO | TEMPERATURE DEGREES F |
|---|---|---|---|---|---|
| 150000. | 100.000 | 1.000 | 0. | 0. | 70. |

INTERMEDIATE VALUES DURING OPTIMIZATION

| ANNUAL COST | CAPITAL | TIM-SEC | HEIGHT | GPM/NOZ | FT2/FT3 | NO | N1 |
|---|---|---|---|---|---|---|---|
| 99471.4 | 203028.4 | 4.7 | 50.8 | 1.0 | 5.9 | 1043317 | 940428 |
| 96051.0 | 156926.5 | 2.8 | 30.0 | 2.2 | 7.7 | 1356893 | 1145003 |
| 99867.0 | 126293.9 | 1.6 | 17.4 | 5.0 | 10.1 | 1783951 | 1351608 |
| 125126. | | | | | | | |
| 108378.3 | 109454.3 | 1.0 | 10.9 | 10.0 | 12.8 | 2247585 | 1490695 |
| 99867.0 | 126293.9 | 1.6 | 17.4 | 5.0 | 10.1 | 1783951 | 1351608 |
| 125126. | | | | | | | |

OPERATING CONDITIONS OF TOWER-CALCULATED

THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TOTAL FLOW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 17.4 | 150000.0 | 2780.9 |

| NOZZLES | BANKS | DDROP UM | UNITS/SERIES |
|---|---|---|---|
| 556. | 1. | 400. | 2. |

| PRESSURE DROP | FAN HORSEPOWER | PUMP HORSEPOWER |
|---|---|---|
| 3.000 | 100.929 | 937.383 |

CAPITAL COSTS FOR SCRUBBER SYSTEM

| SHELL | NOZZLES | FAN | PUMP | EXTERNALS | TOTAL |
|---|---|---|---|---|---|
| 49117. | 5562. | 4299. | 2681. | 64635. | 126294. |

ANNUAL COST FOR SCRUBBER SYSTEM

| AMORTIZATION | POWER | MAINTENANCE | CHEMICALS | TOTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 31573. | 58094. | 6000. | 4200. | 99867. | .13 |



Table 12G

EFFECT OF ODOR REDUCTION RATIO

UNIT COSTS FOR SCRUBBER SYSTEM

| POWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NOZZLES $ EA | AMORTIZATION FACTOR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .250 |

| FLOW RATE CFM | CONCENTRATION INLET | CONCENTRATION OUTLET | HENRY | SCHMIDT NO | TEMPERATURE DEGREES F |
|---|---|---|---|---|---|
| 150000. | 10.000 | 1.000 | 0. | 0. | 70. |

INTERMEDIATE VALUES DURING OPTIMIZATION

| ANNUAL COST | CAPITAL | TIM-SEC | HEIGHT | GPM/NOZ | FT2/FT3 | NO | N1 |
|---|---|---|---|---|---|---|---|
| 75955.0 | 160723.6 | 3.0 | 32.0 | 1.0 | 3.7 | 657233 | 629886 |
| 73384.0 | 129297.6 | 1.8 | 18.9 | 2.2 | 4.9 | 854769 | 796RV |
| 99244. | | | | | | | |
| 75532.5 | 108406.6 | 1.0 | 10.9 | 5.0 | 6.4 | 1123793 | 997211 |
| 97214. | | | | | | | |
| 80769.2 | 96923.6 | .6 | 6.9 | 10.0 | 8.0 | 1415857 | 1178419 |
| 75532.5 | 108406.6 | 1.0 | 10.9 | 5.0 | 6.4 | 1123793 | 997211 |
| 97214. | | | | | | | |

OPERATING CONDITIONS OF TOWER-CALCULATED

THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TOTAL FLOW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 10.9 | 150000.0 | 1751.8 |

| NOZZLES | BANKS | DDROP UM | UNITS/SERIES |
|---|---|---|---|
| 350. | 1. | 400. | 2. |

| PRESSURE DROP | FAN HORSEPOWER | PUMP HORSEPOWER |
|---|---|---|
| 3.000 | 100.929 | 582.375 |

CAPITAL COSTS FOR SCRUBBER SYSTEM

| SHELL | NOZZLES | FAN | PUMP | EXTERNALS | TOTAL |
|---|---|---|---|---|---|
| 33937. | 3504. | 4299. | 2032. | 64635. | 108407. |

ANNUAL COST FOR SCRUBBER SYSTEM

| AMORTIZATION | POWER | MAINTENANCE | CHEMICALS | TOTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 27102. | 38231. | 6000. | 4200. | 75532. | .10 |

Table 12H

EFFECT OF AMORTIZATION PERIOD AND OPERATING HOURS

UNIT COSTS FOR SCRUBBER SYSTEM

| POWER $/KWH | MAINTENANCE $/CFM | CHEMICALS $/CFM-YR | NOZZLES $ EA | AMORTIZATION FACTOR |
|---|---|---|---|---|
| .015 | .005 | .014 | 5.000 | .100 |

| FLOW RATE CFM | CONCENTRATION INLET | CONCENTRATION OUTLET | HENRY | SCHMIDT NO | TEMPERATURE DEGREES F | HRS/YR |
|---|---|---|---|---|---|---|
| 66000. | 1000.000 | 1.000 | 0. | 0. | 70. | 3700 |

INTERMEDIATE VALUES DURING OPTIMIZATION

| ANNUAL COST | CAPITAL | TIM-SEC | HEIGHT | GPM/NOZ | FT2/FT3 | NO | NI |
|---|---|---|---|---|---|---|---|
| 32587.5 | 116035.8 | 6.2 | 29.3 | 1.0 | 7.8 | 1367094 | 1150899 |
| 55795. | | | | | | | |
| 33556.1 | 86832.3 | 3.7 | 17.3 | 2.2 | 10.1 | 1777984 | 1349271 |
| 50923. | | | | | | | |
| 37026.9 | 67417.2 | 2.1 | 10.0 | 5.0 | 13.3 | 2337573 | 1508875 |
| 50510. | | | | | | | |
| 41905.8 | 56746.0 | 1.3 | 6.3 | 10.0 | 16.7 | 2945089 | 1573413 |
| 37026.9 | 67417.2 | 2.1 | 10.0 | 5.0 | 13.3 | 2337573 | 1508875 |
| 50510. | | | | | | | |

OPERATING CONDITIONS OF TOWER-CALCULATED
THE MATERIAL OF CONSTRUCTION IS STAINLESS STEEL

| SCRUBBER LENGTH FEET | SCRUBBER HEIGHT FEET | TOTAL FLOW RATES GAS(CFM) | LIQUID(GPM) |
|---|---|---|---|
| 29.0 | 10.0 | 66000.0 | 1603.3 |

| NOZZLES | BANKS | DROP UM | UNITS/SERIES |
|---|---|---|---|
| 321. | 1. | 400. | 2. |

| PRESSURE DROP | FAN HORSEPOWER | PUMP HORSEPOWER |
|---|---|---|
| 3.000 | 44.409 | 530.935 |

CAPITAL COSTS FOR SCRUBBER SYSTEM

| SHELL | NOZZLES | FAN | PUMP | EXTERNALS | TOTAL |
|---|---|---|---|---|---|
| 31616. | 3207. | 2229. | 1926. | 28439. | 67417. |

ANNUAL COST FOR SCRUBBER SYSTEM

| AMORTIZATION | POWER | MAINTENANCE | CHEMICALS | TOTAL | $/1000CFM-HR |
|---|---|---|---|---|---|
| 6742. | 25797. | 2640. | 1848. | 37027. | .14 |



Tests of a two-stage unit have been reported by a member company of NRA, and an odor reduction of 85% was reported using soda ash and sodium bisulfite. The results cannot be directly compared because the flow rates are not known.

## 6.7 References


1. Mass Transfer Operations (Second Edition), Robert E. Treybal, McGraw-Hill, 1955, p. 51 ff.
2. Perry's Chemical Engineers Handbook (Fourth Edition), Perry, Chilton, Kirkpatrick, McGraw-Hill, 1963.
3. Private Communication, Harold A. Ogletree, Air Conditioning Corporation, June, 1972.
4. Loeb, L. B., The Kinetic Theory of Gases, Second Edition, McGraw-Hill, N.Y., 1934, p. 36, 39, 95.

## 7. EXPERIMENTAL SCRUBBING INVESTIGATIONS

A preliminary economic analysis of various odor removal methods, based on literature data and reports of member companies, indicated that scrubbing with reactive liquids was the most promising method. This method was therefore chosen for experimental study.

The performance and cost of a scrubbing system depends partly on the design of the system, and partly on finding one or more chemical reagents that can effectively react with the important odor constituents present. These problems can be separately studied. Two types of scrubbing reaction experiments were conducted and, in addition, design studies were done to find the most effective and economic scrubbing system.

The two types of scrubbing reaction studies were an exploratory bubbler experiment method and a packed column scrubber method. One focuses attention on the capacity of the reagent to consume odorant, and the other measures the rate of reaction with relatively fresh reagent. Both criteria are important for selecting reagents.

A list of odorants used in bubbler or scrubber experiments is given in Table 13.

A list of scrubbing liquids was also selected and is shown in Table 14. This list includes a number of liquids previously suggested by others, some that are in actual use and a number that we have thought of. We have included several that are used as oxidizing or reducing agents in paper pulp bleaching or other industrial purification operations.





Table 13

LIST OF ODORANTS FOR SCRUBBING TESTS

| | MW | Density, g/cc | MP, °C | BP, °C |
|---|---|---|---|---|
| Sulfides | | | | |
| n-Propyl sulfide (dipropyl sulfide) | 118.2 | .839 | | 142-3 |
| Dimethyl disulfide (methyl sulfide) | 94.19 | 1.057 | | 116-8 |
| Propylene sulfide | | | | |
| Amines | | | | |
| Trimethylamine | 59.11 | gas | -117. | 2.9 |
| Tert-butylamine | 73.14 | .698 | -67. | 45.2 |
| n-Butylamine | 73.14 | .739 | -50. | 77.8 |
| Dimethyl pyrazine | 108.14 | .990 | 15 | 155. |
| Quinoline | 129.15 | 1.095 | -15.6 | 237. |
| Acids | | | | |
| Butyric | 88.1 | .949 | -47. | 155. |
| Aldehydes | | | | |
| n-Pentanal (n-valeric aldehyde) | 86.13 | .819 | -92. | 103.4 |
| Alcohol | | | | |
| n-Pentanol (n-amyl alcohol) | 88.15 | .818 | -78.9 | 138.1 |
| Ketone | | | | |
| Butandione (diacetyl) | 86.19 | .981 | -4. | 87-8 |
| Unsaturated Alkane | | | | |
| Heptadiene 2,5 (simulant for dimethyl pentadiene) | 96.17 | .733 | | 107. |

Table 14

LIST OF SCRUBBING SOLUTIONS SCREENED

| |
|---|
| Sodium hydroxide |
| Sodium carbonate |
| Sodium bisulfite |
| Sodium hypochlorite (representing free chlorine) |
| Hydrogen peroxide |
| Potassium permanganate |
| Potassium persulfate |
| Hydrochloric acid |
| Nitric acid |
| Ozone solution |
| Copper sulfate |
| Ferric chloride |
| Barium chloride |
| Aluminum chloride |



## 8. EXPLORATORY BUBBLER SCRUBBING REACTIONS

### 8.1 Experimental Method

In the bubbler exploratory method a mixture of several odorants is dissolved in 200 ml of water in a glass bubbler equipped with a fritted glass disperser. Air is drawn through the bubbler at a rate of about 50 ml/min for 1 min. This air is drawn through the sampling loop by means of an aspirator. After 1 min the air sample in the loop is transferred to the chromatograph. The process is repeated several times to establish the effluent odorant concentrations with no reagent present. Then the bubbler is opened and a 50 ml quantity of scrubbing liquid is added. Sampling is repeated several times. The ratio of effluent concentration before and after adding scrubbing liquid is a measure of the reactivity of the liquid for each odorant. The mass transfer behavior of the bubbler is effectively cancelled out by this procedure, and only the reactivity is measured.

The quantity of each odorant added to the bubbler depends on the solubility of the odorant in water. A quantity is added which gives a sufficient vapor pressure to obtain a reasonable peak size with the chromatograph. Thus, amyl alcohol is relatively soluble and requires 20 mg, while propyl sulfide is relatively insoluble and requires only a few μg. In fact, the quantity of propyl sulfide used is so small that an appreciable fraction of it is vaporized by the air stream and its effluent concentration decreases with time even when there is no reaction. In the presence of this gradual decrease, only large reductions by reaction can be definitely identified.

At the other extreme is butyric acid, which is miscible with water in all proportions. One gram of butyric acid in 250 ml water has so low a vapor pressure that it cannot be measured by chromatograph. Although the bubbler experiment cannot be done with butyric acid, this result shows that water alone is an effective scrubbing liquid and no other is needed.

In order to inject small quantities of odorants with a microsyringe, stock solutions were made up in an inert water-soluble liquid. The solvents used and concentrations are listed in Table 15.

8.2 Experimental Results

The experimental results with several odorants are presented in Tables 16-18. The first experiment shows the decreases in effluent concentration obtained with water for 4 successive samples. The numerical values represent area under the chromatogram in square inches. Previous calibrations indicated that these areas are approximately 3 times the concentration in ppm by volume.

In the second experiment, 4 samples of the effluent were taken to assure steady conditions, and then 2 more samples were taken after nitric acid was added. In the right column of the table, the reductions are expressed as a percent of initial effluent concentration. This method is followed for each of the other tests.

The method was slightly different in Table 18. Here the odorants were added to 100 ml water, and the first 2 concentrations measured in air drawn through the sample. Then the reagent was added in another 100 ml water, and the remaining concentrations were measured. Comparison of the results with those for water still gives a measure of the reduction ratio. The procedure is apparently less accurate, although it was necessary for use with ozone water.

Since several amines were found in the rendering plant odors without definitely establishing their identity, experiments were tried with various representative butyl amines as well as trimethylamine. The formulas of these amines are shown in Figure 14.



Table 15

AMOUNTS OF ODORANTS ADDED TO BUBBLER

| | Stock Solution | Added to Bubbler | Solvent |
|---|---|---|---|
| Series #1 | | | |
| 1. Amyl alcohol | 16 mg/ml | 20 ml | Water |
| 2. Dipropyl sulfide | 60 mg/ml | 0.1 ml | Ethyl ether |
| 3. Valeraldehyde | 4 mg/ml | 1.0 ml | Ethylene glycol |
| Series #2 | | | |
| 4. Trimethylamine | Varies | 1-2 ml | Water |
| 5. Heptadiene | 60 mg/ml | Added to amyl alcohol | |
| 6. Amyl alcohol | 2 ml of solution #5 is diluted to 100 ml in water | | |
| 7. Butanedione | 50 mg/ml | 5 ml | Ethylene glycol |

Table 16

EXPLORATORY EXPERIMENTS
REACTIONS OF ODORANTS WITH SCRUBBING LIQUIDS

| Odorant | Concentrations in Effluent Air from Bubbler - Arbitrary Units (3 x ppm) | | | | | | Reduction by Reagent |
|---|---|---|---|---|---|---|---|
| | Water | | | | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 110 | 97 | 92 | 95 | | | Nearly constant effluent |
| Propyl sulfide | 1248 | 596 | 506 | 394 | | | Gradually vaporizes |
| Amyl alcohol | 55 | 53 | 50 | 55 | | | Nearly constant effluent |
| | Water | | | | Nitric Acid Added (5%) | | |
| Test: | 1 | 2 | 3 | 4 | 5 | 6 | |
| Valeraldehyde | 22 | 7 | 9 | 15 | 6 | 7 | Decreased within expt. error |
| Propyl sulfide | 7875 | 1948 | - | 778 | 61 | 49 | 90% |
| Amyl alcohol | 153 | 73 | 100 | 123 | 61 | 59 | 40% |
| | Water | | | | Hydrochloric Acid Added (5%) | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 15 | 9 | 14 | 10 | 13 | | None |
| Propyl sulfide | 9288 | 784 | 434 | 70 | 41 | | 50-90% |
| Amyl alcohol | 119 | 110 | 116 | 68 | 77 | | 30% |
| | Water | | Sodium Hydroxide Added (5%) | | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 14 | 10 | 11 | 7 | | | Slight |
| Propyl sulfide | 814 | 116 | 119* | 14 | | | 90% |
| Amyl alcohol | 152 | 123 | 805 | 848 | | | Increased |
| | Water | | | Sodium Carbonate Added (5%) | | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 75 | 62 | 78 | 62 | 77 | | None |
| Propyl sulfide | 1875 | 1320 | 713 | 378 | 263 | | Uncertain |
| Amyl alcohol | 523 | 657 | 811 | 663 | 770 | | None |
| | Water | | | Hypochlorite (1%) | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 35 | 23 | 23 | 2 | | | 90% |
| Propyl sulfide | 558 | 271 | 85 | 0 | | | 99+ |
| Amyl alcohol | 104 | 102 | 168 | 210 | | | None |
| 15 min. peak) | | | | small | | | |
| 17 min. peak) | | | | small | | | |
| | Water | | Hypochlorite Added (1%) | | | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 33 | 28 | 22* | 2 | 1 | | 90% |
| Propyl sulfide | 435 | 201 | tr | 0 | 0 | | 99+ |
| Amyl alcohol | 211 | 177 | 242 | 107 | 152 | | None |
| 15 min. | | | | | small | | |
| 17 min. | | | | | small | | |
| | Water | | Hypochlorite Added (.5%) | | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 32 | 41 | 23 | 9 | | | 75% |
| Propyl sulfide | 1540 | 1038 | tr | 0 | | | 99+ |
| Amyl alcohol | 200 | 229 | 149 | 141 | | | 25%? |
| 17 min. | | | | small | | | |
| | Water | | Potassium Permanganate (.6%) | | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 32 | 29 | tr | tr | | | 99+ |
| Propyl sulfide | 1510 | 995 | 0 | tr | | | 99+ |
| Amyl alcohol | 147 | 181 | 102 | 229 | | | None |
| 1.8 min. | | | tr | 31 | | | |
| 16 min. | | | | tr | | | |
| 18 min. | | | | tr | | | |

Reproduced from best available copy.

## Table 16 (cont.)

| Odorant | Concentrations in Effluent Air from Bubbler - Arbitrary Units (3 x ppm) | | | | | | Reduction by Reagent |
|---|---|---|---|---|---|---|---|
| | Water | | | Potassium Permanganate (.6%) + NaOH (1%) | | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 65 | 43 | 38 | 2 | tr | | 98% |
| Propyl sulfide | 1970 | 893 | 348 | tr | 0 | | 99+ |
| Amyl alcohol | 758 | 563 | 635 | 927 | 882 | | Increased |
| | Water | | | Hydrogen Peroxide Added (5%) | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 61 | 65 | tr | 6 | | | 90% |
| Propyl sulfide | 690 | 366 | 11 | 1 | | | 99+ |
| Amyl alcohol | 433 | 507 | 400 | 407 | | | None |
| | Water | | | Ozone Water (~1%) | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 68 | 61 | 64 | 69 | | | None |
| Propyl sulfide | 1361 | 495 | 1596 | 636 | | | None |
| Amyl alcohol | 449 | 454 | 407 | 409 | | | None |
| | Water | | | Sodium Persulfate Added (satd) | | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 62 | 69 | 70 | 59 | 51 | | 20% |
| Propyl sulfide | 1839 | 1513 | 981 | 317 | tr | | ~99% |
| Amyl alcohol | - | 567 | 601 | 525 | 501 | | None |
| | Water | | | Sodium Bisulfite Added (5%) | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 90 | 111 | 0 | 0 | | | 99.5% |
| Propyl sulfide | 2510 | 1238 | 506 | 219 | | | None |
| Amyl alcohol | 758 | 775 | 666 | 612 | | | None |
| | Water | | | | Ferric Chloride Added (5%) | | |
| Test: | 1 | 2 | 3 | 4 | 5 | 6 | |
| Valeraldehyde | 89 | 51 | 89 | 73 | 86 | 80 | None |
| Propyl sulfide | 2616 | 1221 | 1256 | 765 | 402 | 236 | None |
| Amyl alcohol | 743 | 463 | 825 | 902 | 893 | 910 | None |
| | Water | | | Copper Sulfate (5%) | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 70 | 82 | 24 | 25 | | | 70% |
| Propyl sulfide | 2277 | 1138 | 197 | 150 | | | 80% |
| Amyl alcohol | 735 | 802 | 242 | 230 | | | 70% |
| | Water | | | Copper Sulfate (5%) pH3 | | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 41 | 44 | 41 | 31 | 28 | | 20% |
| Propyl sulfide | 1269 | 712 | 396 | 188 | 101 | | Uncertain |
| Amyl alcohol | 281 | 318 | 310 | 244 | 199 | | Uncertain |
| | Water | | | Barium Chloride Added (5%) | | | |
| Test: | 1 | 2 | 3 | 4 | | | |
| Valeraldehyde | 42 | 39 | 41 | 37 | | | None |
| Propyl sulfide | 1475 | 906 | 489 | 251 | | | None |
| Amyl alcohol | 249 | 323 | 307 | 307 | | | None |
| | Water | | | Aluminum Chloride Added (5%) | | | |
| Test: | 1 | 2 | 3 | 4 | 5 | | |
| Valeraldehyde | 90 | 71 | 70 | 68 | 81 | | None |
| Propyl sulfide | 904 | 850 | 372 | 169 | 61 | | None |
| Amyl alcohol | 515 | 499 | 515 | 910 | 610 | | None |

*In some cases the vapor space may not have been purged of effluent when first sample was chromatographed.

Table 17

BUBBLER EXPERIMENTS
Chromatograph Areas (Proportional to Concentration)

| | (1) | | (2) | | (3) | | (4) | | Percent Removal By Reagent |
|---|---|---|---|---|---|---|---|---|---|
| 21/6/72-2 | Water Blank Run for $O_3$ Experiments (Odorants in 200 ml Water) | | | | | | | | |
| Heptadiene | 7683 | | 6957 | | | | | | |
| Propylene Sulfide | 2898 | | 2159 | | | | | | |
| Dimethyldisulfide | 1532 | | 1599 | | | | | | |
| Amyl Alcohol | 57 | | 82 | | | | | | |
| 21/6/72-5 | Water Blank (Duplicate of Above) | | | | | | | | |
| Heptadiene | 7735 | | 2625 | | 332 | | 105 | | |
| Propylene Sulfide | 2601 | | 2160 | | 1865 | | 1627 | | |
| Dimethyldisulfide | 1661 | | 1417 | | 958 | | 790 | | |
| Amyl Alcohol | 80 | | 77 | | 77 | | 76 | | |
| 21/6/72-3 | Ozone in Distilled Water | | | | | | | | |
| Heptadiene | 5930 | | 1377 | | 249 | | 74 | | |
| Propylene Sulfide | 1933 | | 1758 | | 1421 | | 1205 | | |
| Dimethyldisulfide | 1430 | | 923 | | 742 | | 629 | | |
| Amyl Alcohol | 55 | | 58 | | 56 | | 58 | | |
| 21/6/72-4 | Ozone in Distilled Water | | | | | | | | |
| Heptadiene | 6797 | | 4818 | | 249 | | 104 | | None |
| Propylene Sulfide | 1915 | | 1755 | | 1705 | | 1425 | | None |
| Dimethylsulfide | 1123 | | 1256 | | 835 | | 718 | | None |
| Amyl Alcohol | 47 | | 48 | | 73 | | 71 | | None |
| 23/6/72-1 | Ozone - pH ~1 (1 ml Conc. HCl/200 ml Water) | | | | | | | | None |
| Heptadiene | 5900 | | 2275 | | 501 | | | | None |
| Propylene Sulfide | 1500 | | 1912 | | 1647 | | | | None |
| Dimethyldisulfide | 916 | | 1022 | | 803 | | | | None |
| Amyl Alcohol | 12 | | 62 | | 42 | | | | None |
| 23/6/72-3 | Ozone - pH ~1 (1 ml Conc. HCl/200 ml Water) | | | | | | | | None |
| Heptadiene | 7915 | | 4957 | | 827 | | | | |
| Propylene Sulfide | 2383 | | 1911 | | 1718 | | | | |
| Dimethyldisulfide | 1487 | | 1470 | | 964 | | | | |
| Amyl Alcohol | 53 | | 56 | | 60 | | | | |
| 23/6/72-2 | Ozone - pH ~12 (10 g $NaHCO_3$ + 1 g $Na_2CO_3$/200 ml Water) | | | | | | | | None |
| Heptadiene | 7335 | | 4600 | | 652 | | | | |
| Propylene Sulfide | 2439 | | 2403 | | 2091 | | | | |
| Dimethyldisulfide | 1563 | | 1543 | | 952 | | | | |
| Amyl Alcohol | 81 | | 80 | | 83 | | | | |
| New PK @ 2.4 min | - | | 134 | | 962 | | | | |

Table 18

BUBBLER EXPERIMENTS

Chromatographic Areas (Proportional to Concentration)

| | (1) | | (2) | | (3) | | (4) | | (5) | | Percent Removal By Reagent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 26/6/72-1 | Odorants in 100 ml Water, Further Diluted with 100 ml Water After Run 2 | | | | | | | | | | |
| Heptadiene | 6248 | | 1925 | | 133 | | 43 | | | | |
| Propylene Sulfide | 2856 | | 1776 | | 854 | | 626 | | | | |
| Dimethyldisulfide | 1652 | | 1115 | | 458 | | 364 | | | | |
| Amyl Alcohol | 108 | | 100 | | 46 | | 44 | | | | |
| 26/6/72-2 | Odorants in 100 ml Water, Further Diluted with 100 ml Water After Run 2 | | | | | | | | | | |
| Heptadiene | 6066 | | 1480 | | 92 | | 43 | | | | |
| Propylene Sulfide | 2684 | | 2258 | | 930 | | 686 | | | | |
| Dimethyldisulfide | 1395 | | 1380 | | 501 | | 390 | | | | |
| Amyl Alcohol | 94 | | - | | 84 | | 76 | | | | |
| 27/6/72-1 | HCl ~5% | | | | | | | | | | |
| Heptadiene | 6768 | | 2702 | | 297 | | 73 | | | | 0 |
| Propylene Sulfide | 3085 | | 2169 | | 1274 | | 1043 | | | | 0 |
| Dimethyldisulfide | 2000 | | 1287 | | 632 | | 567 | | | | 0 |
| Amyl Alcohol | 102 | | 48 | | 73 | | 74 | | | | 0 |
| 27/6/72-2 | NaOH ~5% | | | | | | | | | | |
| Heptadiene | 6561 | | 4252 | | 722 | | 105 | | | | 0 |
| Propylene Sulfide | 3105 | | 2259 | | 2036 | | 1026 | | | | 0 |
| Dimethyldisulfide | 1562 | | 1899 | | 1216 | | 630 | | | | 0 |
| Amyl Alcohol | 130 | | 127 | | 201 | | 184 | | | | 0 |
| 27/6/72-3 | NaOCl ~2.5% | | | | | | | | | | |
| Heptadiene | 5867 | | 5454 | | 1052 | | 79 | | 16 | | Uncertain |
| Propylene Sulfide | 3530 | | 2230 | | Trace | | Trace | | 0.2 | | >99.9 |
| Dimethyldisulfide | 1474 | | 1747 | | 0.4 | | Trace | | Trace | | >99.9 |
| Amyl Alcohol | 267 | | 174 | | 135 | | - | | 145 | | 0 |
| 28/6/72-3 | NaOCl ~2.5% (Duplicate of Above) | | | | | | | | | | |
| Heptadiene | 6424 | | 4326 | | 820 | | 156 | | | | 0 |
| Propylene Sulfide | 2720 | | 2686 | | Trace | | Trace | | | | >99.9 |
| Dimethyldisulfide | 1644 | | 1809 | | Trace | | Trace | | | | >99.9 |
| Amyl Alcohol | 122 | | 141 | | 141 | | 157 | | | | 0 |
| 28/6/72-1 | $H_2O_2$ ~5% | | | | | | | | | | |
| Heptadiene | 7684 | | 5204 | | 1719 | | 614 | | 344 | | 0 |
| Propylene Sulfide | 3227 | | 2617 | | 470 | | 6 | | Trace | | >99.9 |
| Dimethyldisulfide | 2067 | | 1791 | | 739 | | 182 | | 82 | | 60. |
| Amyl Alcohol | 103 | | 117 | | 66 | | 36 | | 57 | | Uncertain |
| 28/6/72-2 | $K MnO_4$ ~1/2 Sat @ 22°C | | | | | | | | | | |
| Heptadiene | 6103 | | 4554 | | 134 | | 8 | | | | 80. |
| Propylene Sulfide | 2565 | | 2659 | | Trace | | 1 | | | | >99.5 |
| Dimethyldisulfide | 1258 | | 1653 | | Trace | | Trace | | | | >99.9 |
| Amyl Alcohol | 79 | | 127 | | 77 | | 60 | | | | 0 |

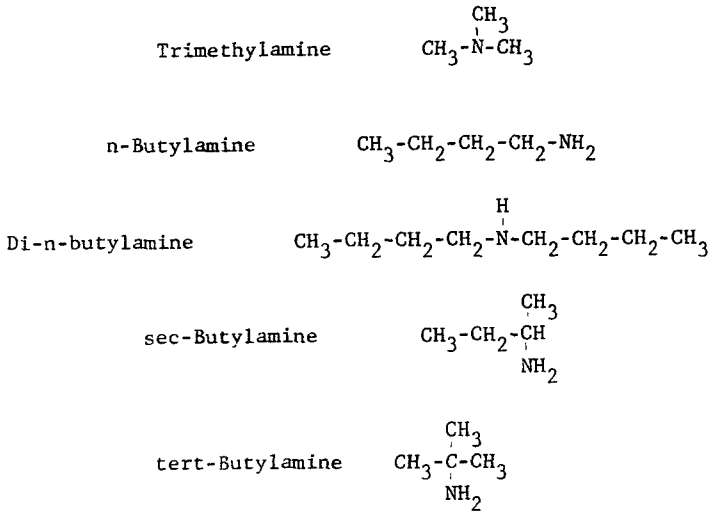


Figure 14

AMINES

Dibutylamine decomposes in water and gives five peaks of lower molecular weight. One of these is n-butylamine. A large amount of dibutylamine remains unreacted.

Tertiary butylamine is the most stable. It decomposes slowly, giving 2 smaller peaks at higher retention times. n-Butylamine decomposes rapidly, being reduced to 1/10 in 15 min. One very broad product peak is produced at higher retention time. Sec-butylamine and isobutylamine also react rapidly to give several peaks. Consequently, tert- and di-butylamines were chosen for further bubbler tests.



Results of all of the bubbler experiments are summarized in Table 19. Water is the first and simplest reagent. Butyric acid and amyl alcohol are so soluble that water is an effective scrubbing liquid for them. Various amines appear to react extensively in water, so it may effectively scrub them too. Dimethyl pyrazine reacts in water and could not be detected after the bubbler. Quinoline appeared to react in the bubbler, or the sample loop or the chromatograph, giving a very broad peak, but the result is uncertain.

Acids such as hydrochloric, nitric, and probably sulfuric react with amines, and have a slight effect on dipropyl sulfide and amyl alcohol. Acids cannot be considered as effective scrubbing liquids. Likewise alkalis are poor scrubbing liquids. Although sodium carbonate is used industrially for odor scrubbing, its action may be attributed almost entirely to the water rather than to the alkali. Sodium hydroxide will be converted to carbonate by absorbing $CO_2$ from the air scrubbed.

The most effective reagents are the strong oxidizers: sodium hypochlorite, hydrogen peroxide, potassium permanganate and sodium persulfate. All of these remove sulfides, although hydrogen peroxide is less effective on dimethyl disulfide. Permanganate is more effective on pentanal than the other oxidants, and is the only oxidant to react with heptadiene-2,5. Permanganate is more effective in neutral than in alkaline solution.

Sodium hypochlorite is the cheapest of these oxidants and it should therefore be the first choice. Chlorine water might also be considered; hypochlorite is a solution of chlorine in alkali. Chlorine was tried, but it oxidized the chromatograph column and prevented analysis of odorants. With special precautions it could be tried in a scrubber test. Hypochlorite has the advantage that the chlorine is not lost in the effluent gas.

Various metal salts were also tried; copper sulfate was the only one that offered any promise.

A hypochlorite solution can be made by releasing chlorine gas into the scrubber while a sodium hydroxide solution is being circulated. The oxidizing power of the solution can be maintained by bleeding chlorine gas into the scrubber continuously. Chlorine in bulk is very inexpensive. If the chlorine is not added continuously, the hypochlorite will soon decompose, and it will not be effective. Only occasionally will it be necessary to make up a fresh solution, if this method of replenishment is followed. The chlorine can also be produced on the site by electrolysis of salt solution; equipment for this process is commercially available.

Table 19

SUMMARY OF BUBBLER EXPERIMENT RESULTS-PERCENT REMOVAL BY REAGENT

| Odorant | Reagent | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Hydrochloric Acid 5% | Nitric Acid 5% | Sodium Hydroxide 5% | Sodium Carbonate 5% | Sodium Hypochlorite 2.5% | Sodium Hypochlorite 1% | Sodium Hypochlorite .5% | Potassium Permanganate .6% Neutral | Potassium Permanganate +1% NaOH | Hydrogen Peroxide 5% | Ozone Water ~1% | Ozone Water pH 1 | Ozone Water pH 12 | Sodium Persulfate Satd. | Sodium Bisulfite 5% | Ferric Chloride 5% | Copper Sulfate 5% | Copper Sulfate 5% pH 3 | Barium Chloride 5% | Aluminum Chloride 5% |
| Di-n-propyl sulfide | Vaporizes* | 50-90 | 90 | 90 | Uncertain | | "99+ | >'99 | >"'99 | >99 | >99 | None | | | ~99 | None | None | 80 | Uncertain | None | None |
| Dimethyl disulfide | Vaporizes* | None | | None | | >99.9 | | | >99.9 | | 60 | None | None | None | | | | | | | |
| Propylene sulfide | Vaporizes* | None | | None | | ≥99.9 | | | >99.5 | | >99.9 | None | None | None | | | | | | | |
| n-Pentanal (n-valeric aldehyde) | * | None | Slight | Slight | None | | 90 | 75 | 99+ | 98 | 90 | None | | | 20 | 99.5 | None | 70 | 20 | None | None |
| n-Pentanol (n-amyl alcohol) | Soluble* | 30 | 40 | Increased | None | | None | Uncer-tain | None | Increased | None | None | None | None | None | None | None | 70 | Uncertain | None | None |
| Butanedione | | | | | | | | | | | | | | | | | | | | | |
| Heptadiene 2,5 | Vaporizes* | None | | None | | None | | | 80 | | None | None | None | None | | | | | | | |
| Butyric acid | >99.9 | | | | | | | | | | | | | | | | | | | | |
| Dimethyl pyrazine | >90 | | | | | | | | | | | | | | | | | | | | |
| n-Butylamine | * | | | | | | | | | | | | | | | | | | | | |
| tert-butylamine | * | >99 | | | | | >95 | | | | >99 | | | | | | | | | | |
| Di-n-butylamine | * | >95 | | | | | 95 | | | | 90 | | | | | | | | | | |
| Quinoline | Uncertain | | | | | | | | | | | | | | | | | | | | |
| Isobutylamine | Reacts | | | | | | | | | | | | | | | | | | | | |
| sec-Butylamine | Reacts | | | | | | | | | | | | | | | | | | | | |

*Used as standard for comparison.

' = Product peak appeared.

## 9. SCRUBBING EXPERIMENTS

### 9.1 Experimental Gas Scrubbing System

An experimental gas scrubbing system was designed and constructed. The system provides data on the performance of a variety of scrubbing liquids with representative odorants found in rendering effluents. It also provides data on the relative rates of mass transfer and chemical reaction with the scrubbing liquids. This information can be used for design of scrubbing systems for plant applications.

We have chosen a conventional packing for the scrubber column (1/2-in. Intalox saddles) because there is extensive data on the mass transfer coefficients for this packing and we wish to compare our results to other published data for which chemical reaction rate is not a limitation.

The column was designed using this data and the gas scrubbing computer program described in Section 5. With the height of packing used and the chosen flow rates, the column should be capable of reducing any given odorant concentration 90% if the reagent reacts very fast with the odorant, so that only mass transfer from the gas to the liquid controls the scrubbing. Removals of more than 90% are suspect, since the column should not be capable of greater performance unless the flow rates are altered.

The data obtained from this experimental system will be useful for designing other types of scrubbers even though 1-1/2-in. Intalox saddles may not be the most economical packing.

The experimental scrubbing system is shown in Figure 15. It consists of two similar packed columns, the first of which humidifies the air supply to simulate typical rendering plant effluent conditions. Odorants are metered into the air stream after humidification. Odor generators consist either of a lecture bottle of the gaseous odorants or saturators. A saturator is a bottle containing glass beads wet with a

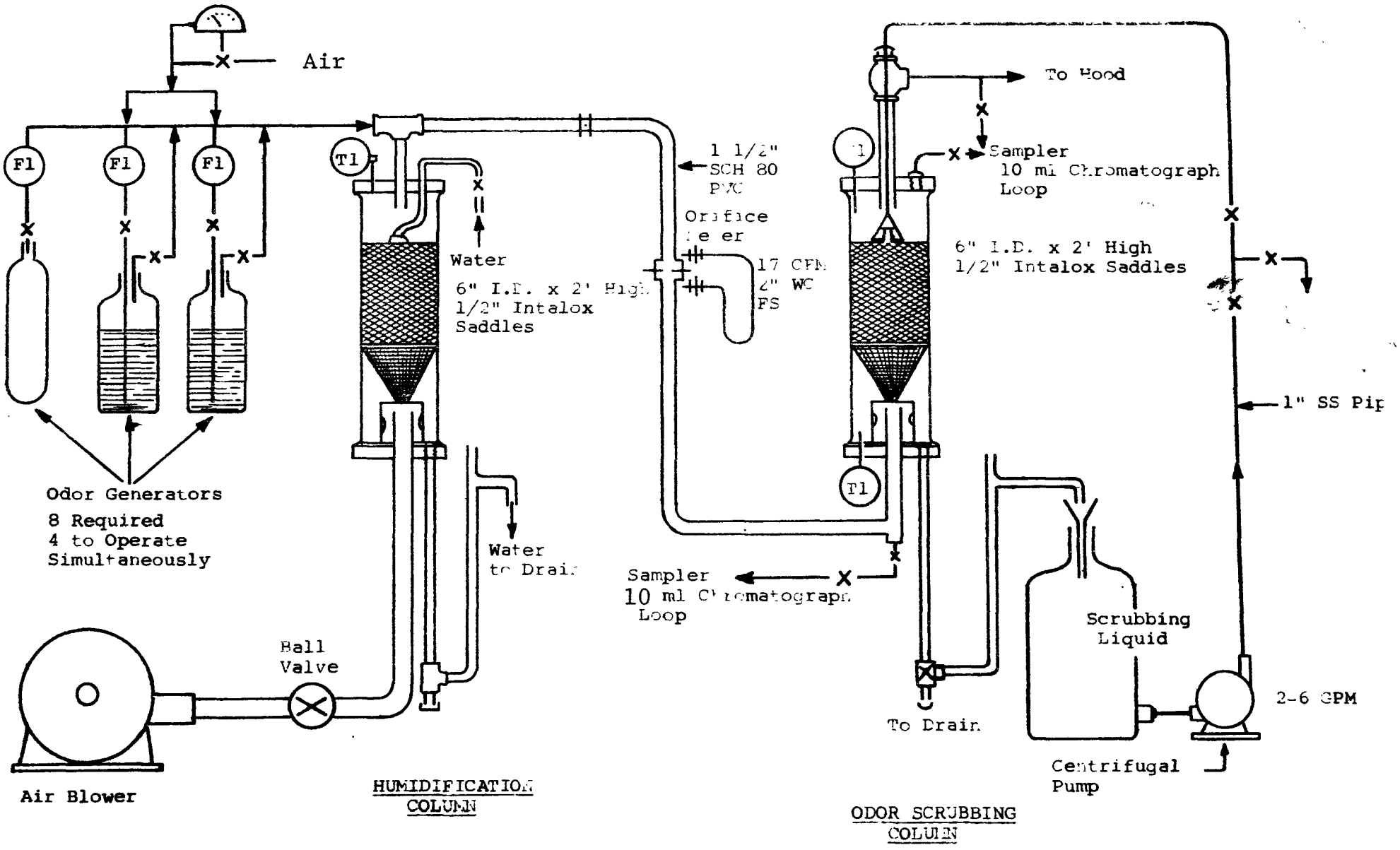


Fig. 15 LABORATORY ODOR SCRUBBING SYSTEM

liquid odorant. Air is metered through this wet packing at a rate to supply the desired concentration after it is diluted with the main air stream. Toward the end of the project it was found that ordinary gas washing bottles with a fritted glass disperser worked better than the bottles with glass beads.

The main air flow is supplied by a blower with excess capacity, both as to volume and pressure. The flow is throttled by a ball valve and metered by a standard orifice. The pressure drop across the orifice is measured by an inclined manometer.

The columns consist of 6-in. I.D. Pyrex glass pipe. The packing is supported by a cone-shaped screen resting on a stainless cap. The scrubbing liquid is sprayed onto the top of the packing. A 2-ft packing depth is designed to reduce the odorant concentrations by a factor of 10 at the flow rates chosen. The scrubbing liquid is made up in a 5-gal polyethylene bottle and pumped by a polypropylene centrifugal pump to the top of the packing. Exhaustion tests were not made, since information on reagent eventual capacity was obtained from the bubbler tests. Only in the case of potassium permanganate was there any evidence of exhaustion of the reagent during a 1-hr test.

The main air line is constructed of polyvinyl chloride pipe, while the scrubbing liquid line is constructed of stainless steel pipe and polyethylene tubing. Saturator bottles are glass and supply tubing is of stainless steel.

Eight odorant generators are fabricated but rotameters and connections are supplied for use of 6 simultaneously. It is thought best not to mix acidic and aminic odorants in the same run, since these will react in the gas phase if concentrations are high enough. Some other combinations of odorants were also found to react and had to be run separately. The concentrations used in the tests are similar to those encountered in strong rendering plant effluents.



A chromatograph is incorporated in the system in a manner which permits the sampling of the odorant stream at either the inlet or the outlet of the scrubber column. A sample of known volume may be withdrawn from the odorant stream by means of aspiration and isolated in a gas sampling loop, from which it is swept directly into the chromatograph with an adequate volume of carrier gas. A Perkin-Elmer Model 881 dual column gas chromatograph with differential flame ionization detector is currently being used. The columns are 1/8-in. x 10-ft Teflon-lined aluminum packed with 100/120 mesh SP-1000. Helium is used as carrier gas at a flow rate of 60 cc/min. Inlet and detector temperatures are approximately 200°C and the sample loop is maintained at 100°C. Initial column temperature is 60°C and is programmed to 180°C at various rates depending on the particular mixture of odorants being monitored.

### 9.2 Results of Scrubbing Experiments

Several series of scrubbing experiments were done, using a different combination of several odorants in each series. For each experiment several samples were taken from the bottom of the scrubbing column to assure steady conditions. Then water was sprayed onto the column and a sample was taken from the top of the column. Another sample was taken from the bottom to check for steady conditions. The scrubbing reagent to be tested was then added to the water and samples were taken again at the top and the bottom of the column.

The ratio of chromatograph areas at top and bottom of the column gives the reduction ratio of concentration due to the scrubber. The data for water were of interest to assure reproducibility of results and also because water is a potential scrubbing liquid.

The sensitivity of the chromatograph was calibrated from time to time by injecting known quantities of odorants from a microsyringe into the chromatograph. The concentrations in Table 20 to 28 are expressed as µg/ml, based on the chromatograph

Table 20

SCRUBBING OF VALERALDEHYDE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, µg/ml: Chromatograph: At Bottom of Scrubber | Concentration, µg/ml: Chromatograph: At Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| | | | .48 | | |
| NaOH 5% | .6 | 16 | | .48 | 0 |
| | | 16 | .57 | | |
| | | | .57 | | |
| NaOH 5% | .7 | 16 | | .50 | 10 |
| NaOH 5% | .7 | 16 | | .45 | 15 |
| | | 16.4 | .0057 | | |
| | | | .0097 | | |
| | | | .0107 | | |
| Water | .6 | | | .0054 | 50 |
| | | | .0113 | | |
| NaOCl 1% | .6 | | | .0092 | 10 |
| | | | (Background .0017) | | |
| (19/5/72) | | | | | |
| | | | .0102 | | |
| | | | .0102 | | |
| Water | .6 | 16.5 | | .0065 | 50 |
| | | | .0120 | | |
| Sodium Bisulfite | .6 | | | trace | >90 |
| | | | .129 | | |
| (23/5/72) | | | | | |
| | | 16.5 | .0051 | | |
| | | | .0036 | | |
| Water | .6 | | | .0043 | 0 |
| | | | .0044 | | |
| $H_2O_2$ 3% | .6 | | | 0 | >90 |
| $H_2O_2$ 3% | .6 | | | .0005 | >90 |
| | | | .0057 | | |
| | | | .0042 | | |
| | | | .0053 | | |



Table 20 (cont.)

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, µg/ml: Chromatograph: At Bottom of Scrubber | Concentration, µg/ml: Chromatograph: at Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| (25/5/72) | | | | | |
| | | 16.4 | .0143 | | |
| Water | .6 | | | .010 | 30 |
| | | | .0113 | | |
| $KMnO_4$ 3% | | | | .0071 | 40 |
| $KMnO_4$ 3% | | | | .0063 | |
| $KMnO_4$ 3% | | | | .0057 | |
| | | | .0088 | | |
| (31/5/72) | | | | | |
| | | 16.5 | .008 | | |
| | | | .0156 | | |
| | | | .013 | | |
| | | | .016 | | |
| | | | .012 | | |
| | | | .014 | | |
| Water | .6 | | | .0087 | 40 |
| | | | .013 | | |
| $KMnO_4$ | .6 | | | .0068 | 50 |
| $KMnO_4$ | .6 | | | .0092 | 30 |
| | | | .015 | | |
| | | 16.5 | .012 | | |
| | | | .023 | | |
| | | | .021 | | |
| Water | .6 | | | .0135 | 30 |
| | | | .020 | | |
| HCl 5% | .6 | | | .026 | 0 |
| | | | .018 | | |
| (2/6/72) | | | | | |
| | | 16.2 | .018 | | |
| | | | .018 | | |
| Water | .6 | | | .011 | 40 |
| NaOH 5% | .6 | | | .013 | 30 |
| | | | .018 | | |

Table 21

SCRUBBING OF DIPROPYL SULFIDE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Air Flow, CFM | Concentration, µg/ml Chromatograph: At Bottom of Scrubber | At Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| | | 16 | .16 | | |
| NaOH 5% | .6 | | | .17 | 0 |
| | | | .16 | | |
| | | | .18 | | |
| NaOH 5% | .7 | | .18 | .18 | 0 |
| NaOH 5% | .7 | | | .20 | |
| | | 16.3 | .029 | | |
| | | | .028 | | |
| | | | .031 | | |
| Water | .6 | | | .028 | 5 |
| | | | .031 | | |
| NaOCl 1% | .6 | | | 0 | >90 |
| (19/5/72) | | | | | |
| | | 16.4 | .028 | | |
| | | | .030 | | |
| Water | .6 | | | .033 | 0 |
| | | | .037 | | |
| Sodium Bisulfite | .6 | | | .034 | 0 |
| | | | .037 | | |
| (23/5/72) | | | | | |
| | | 16.5 | .023 | | |
| | | | .018 | | |
| Water | .6 | | | .021 | 0 |
| | | | .021 | | |
| $H_2O_2$ 3% | .6 | | | .020 | 0 |
| | | | | .019 | |
| | | | .024 | | |
| | | | .018 | | |
| (25/5/72) | | | | | |
| | | 16.4 | .042 | | |
| Water | .6 | | | .040 | 0 |
| | | | .039 | | |



Table 21 (cont.)

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Air Flow, CFM | Concentration, µg/ml Chromatograph: At Bottom of Scrubber | At Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| $KMnO_4$ 3% | | | | .028 | 25 |
| $KMnO_4$ 3% | | | | .030 | |
| $KMnO_4$ 3% | | | | .032 | |
| | | | .037 | | |
| (31/5/72) | | | | | |
| | | 16.5 | .053 | | |
| | | | .056 | | |
| | | | .054 | | |
| | | | .042 | | |
| | | | .055 | | |
| Water | .6 | | | .054 | 0 |
| | | | .048 | | |
| $KMnO_4$ | .6 | | | .040 | 10 |
| $KMnO_4$ | .6 | | | .042 | |
| | | | .050 | | |
| (1/6/72) | | | | | |
| | | 16.5 | .049 | | |
| | | | .045 | | |
| | | | .066 | | |
| Water | .6 | | | .056 | 10 |
| | | | .054 | | |
| HCl 5% | .6 | | | .053* | 0 |
| | | | .054 | | |
| (2/6/72) | | | | | |
| | | 16.2 | .069 | | |
| | | | .070 | | |
| Water | .6 | | | .065 | 10 |
| NaOH 5% | .6 | | | .067 | 0 |
| | | | .065 | | |

*Strong odor of mercaptan and $H_2S$ in scrubbing liquid.

Table 22

SCRUBBING OF AMYL ALCOHOL

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, µg/ml: Chromatograph: At Bottom of Scrubber | Concentration, µg/ml: Chromatograph: At Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| | | 5.2 | .43 | | |
| NaOH 5% | .6 | 5.2 | | .45 | 0 |
| | | 5.2 | .47 | | |
| | | 5.2 | .42 | | |
| NaOH 5% | .7 | 5.2 | | .47 | 0 |
| NaOH 5% | .7 | 5.2 | | .43 | |
| | | 15.6 | .40 | | |
| | | | .48 | | |
| NaOH 5% | .7 | 15.4 | | .08 | 80 |
| After 30 min | .7 | 15.5 | | .20 | 50 |
| After 1 hr | .7 | 15.5 | .40 | .28 | 30 |
| | | 16.4 | .23 | | |
| | | | .25 | | |
| | | | .25 | | |
| | | | (Background .007) | | |
| Water | .6 | | | .017 | 90 |
| | | | .26 | | |
| NaOCl 1% | .6 | | | .051 | 80 |
| (19/5/72) | | | | | |
| | | 15.3 | .23 | | |
| | | | .26 | | |
| Water | .6 | | | .010 | 60 |
| | | | .30 | | |
| Sodium Bisulfite | .6 | | | .067 | 75 |
| | | | .31 | | |
| (23/5/72) | | | | | |
| | | 16.5 | .16 | | |
| | | | .14 | | |
| Water | .6 | | | .038 | 75 |
| | | | .18 | | |



Table 22 (cont.)

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, µg/ml: Chromatograph: At Bottom of Scrubber | Concentration, µg/ml: Chromatograph: At Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| $H_2O_2$ 3% | .6 | | | .032 | 75 |
| $H_2O_2$ 3% | .6 | | | .064 | |
| | | | .21 | | |
| | | | .16 | | |
| | | | .19 | | |
| (25/5/72) | | | | | |
| | | 16.4 | .27 | | |
| Water | .6 | | | .031 | 85 |
| | | | .26 | | |
| $KMnO_4$ 3% | .6 | | | .051 | 75 |
| $KMnO_4$ 3% | .6 | | | .058 | |
| $KMnO_4$ 3% | .6 | | | .16 | 40 |
| | | | .28 | | |
| (31/5/72) | | | | | |
| | | 16.5 | .31 | | |
| | | | .25 | | |
| | | | .31 | | |
| Water | .6 | | | .016 | 50 |
| | | | .30 | | |
| $KMnO_4$ 3% | .6 | | | .039 | 85 |
| $KMnO_4$ 3% | .6 | | | .12 | 60 |
| | | | .34 | | |
| (1/6/72) | | | | | |
| | | 16.5 | .31 | | |
| | | | .32 | | |
| | | | .39 | | |
| Water | .6 | | | .041 | 85 |
| | | | .36 | | |
| HCl 5% | .6 | | | .073 | 80 |
| | | | .36 | | |
| (2/6/72) | | | | | |
| | | 16.2 | .32 | | |
| | | | .35 | | |
| Water | .6 | | | .035 | 90 |
| NaOH 5% | .6 | | | .10 | 70 |
| | | | .40 | | |

Table 24

SCRUBBING OF BUTANEDIONE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, ug/ml Chromatograph: At Bottom of Scrubber | Concentration, ug/ml Chromatograph: At Top of Scrubber |
|---|---|---|---|---|
| | | 16 | .11 | |
| | | 16 | .14 | |
| NaOH 5% | .6 | 16 | | trace |
| NaOH 5% | .6 | 16 | | trace |
| NaOH 5% | .6 | 16 | | trace |
| | | 16 | .13 | |

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Table 23

SCRUBBING OF BUTYRIC ACID

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, ug/ml Chromatograph: At Bottom of Scrubber | Concentration, ug/ml Chromatograph: At Top of Scrubber |
|---|---|---|---|---|
| | | 15 | 1.5 | |
| NaOH 5% | .6 | 15 | | trace |
| NaOH 5% | .6 | 15 | | 0 |
| | | 15 | 1.1 | |
| NaOH 5% | .7 | 15 | | trace |
| NaOH 5% | .7 | 15 | | trace |
| | | 22 | .67 | |
| | | 22 | .59 | |

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Table 25

SCRUBBING OF TRIMETHYLAMINE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Air Flow, CFM | Concentration, μg/ml Chromatograph: At Bottom of Scrubber | At Top of Scrubber | Ratio |
|---|---|---|---|---|---|
| | | 15 | .75 | | |
| | | 15 | .83 | | |
| NaOH 5% | .6 | 15 | | Off scale | |
| NaOH 5% 30 min | .6 | 15 | | .98 | 0 |
| NaOH 5% 1 hr | | 15 | | 1.40 | 0 |
| | | 15 | .90 | | |
| | | 15 | .14 | | |
| | | | .20 | | |
| | | | .14 | | |
| | | | .14 | | |
| | | | .10 | | |
| | | | .060 | | |
| Water | .6 | 15 | | .0018 | 97 |
| $KMnO_4$ | .6 | 15 | | .00006 | >90 |
| $KMnO_4$ | .6 | | | 0 | |
| | | | .14 | | |
| | | 15 | .24 | | |
| | | | .52 | | |
| | | | .21 | | |
| | | | .19 | | |
| | | | .23 | | |
| | | | .28 | | |
| Water | .6 | | | .00046 | >90 |
| NaOCl 2.5% | .6 | | | .0028 | >90 |
| | | | .18 | | |
| (31/5/72) | | | | | |
| | | 16.5 | .23 | | |
| | | | .28 | | |
| Water | .6 | | | .0003 | >90 |
| | | | .29 | | |
| $KMnO_4$ | .6 | | | tr? | >90 |
| $KMnO_4$ | .6 | | | tr? | >90 |
| | | | .29 | | |



Table 25 (cont.)

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Air Flow, CFM | Concentration, μg/ml Chromatograph: At Bottom of Scrubber | At top of Scrubber | Ratio |
|---|---|---|---|---|---|
| (1/6/72) | | | | | |
| | | 16.5 | .12 | | |
| | | | .28 | | |
| | | | .38 | | |
| Water | .6 | | | .03? | 90 |
| | | | .38 | | |
| HCl 5% | .6 | | | .0015 | >90 |
| | | | .40 | | |
| (2/6/72) | | | | | |
| | | 16.2 | .28 | | |
| | | | .33 | | |
| Water | .6 | | | .0006 | >90 |
| NaOH 5% | .6 | | | .37 | 0 |
| | | | .35 | | |

Table 26

SCRUBBING OF DIMETHYL DISULFIDE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, µg/ml: Chromatograph: At Bottom of Scrubber | Concentration, µg/ml: Chromatograph: At Top of Scrubber |
|---|---|---|---|---|
| | | 15 | .40 | |
| | | | .28 | |
| Water | .6 | 15 | | .22 |
| $KMnO_4$ | .6 | 15 | | .12 |
| $KMnO_4$ | .6 | 15 | | .08 |
| | | | .08 | |
| | | 15 | 1.5 | |
| | | | 1.4 | |
| Water | .6 | | | 1.2 |
| NaOCl 2.5% | .6 | | | .64 |
| | | | .17 | |



Table 27

SCRUBBING OF HEPTADIENE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, µg/ml: Chromatograph: At Bottom of Scrubber | Concentration, µg/ml: Chromatograph: At Top of Scrubber |
|---|---|---|---|---|
| | | 15 | .104 | |
| | | | .92 | |
| | | | .65 | |
| | | | .55 | |
| Water | .6 | 15 | | .295 |
| $KMnO_4$ | .6 | 15 | | .143 |
| $KMnO_4$ | .6 | 15 | | .111 |
| | | | .168 | |
| | | | .604 | |
| | | | .111 | |
| | | | .0814 | |
| | | | .117 | |
| | | | .115 | |
| Water | .6 | 15 | | .119 |
| Water | .6 | 15 | | .129 |
| | | | .118 | |
| | | | .121 | |
| $H_2O_2$ | .6 | 15 | | .127 |
| $H_2O_2$ | .6 | 15 | | .137 |
| | | | .129 | |
| | | | .29 | |
| | | | .29 | |
| | | | .28 | |
| | | | .25 | |
| Water | | | | No reduction |
| NaOCl 2.5% | .6 | | | .21 |
| | | 15 | .27 | |

Table 28

SCRUBBING OF TERT-BUTYLAMINE

| Material | Scrubbing Conditions: Liquid Flow, gal/min | Scrubbing Conditions: Air Flow, CFM | Concentration, μg/ml: Chromatograph: At Bottom of Scrubber | Concentration, μg/ml: Chromatograph: At Top of Scrubber |
|---|---|---|---|---|
| | | 15 | 43.29 | |
| | | | 61.89 | |
| | | | 77.39 | |
| | | | 70.50 | |
| | | | 82.19 | |
| Water | .6 | | | Broad |
| Water | .6 | | | .007 |
| | | | 54.36 | |
| | | | 51.08 | |
| $H_2O_2$ 5% | .6 | | | .47 |
| $H_2O_2$ | .6 | | | .28 |
| | | 15 | 13.44 | |



peak areas and these calibrations. For Tables 23 and 24 the calibrations were not determined by injection, but were determined by calculating the vapor pressure from the saturator and dividing by the air dilution ratio. This method of calibration is less accurate. In any case it is the reduction ratio that is of most interest.

Results of the scrubber experiments are summarized in Table 29. Sodium hypochlorite, NaOCl, appears to be the most effective reagent on a broad spectrum of odorants. Permanganate, which appears slightly better in bubbler tests, behaved less well on some odorants, perhaps because of a slower reaction rate. Decomposition of permanganate was apparent, a brown stain of manganese dioxide product being formed on the column packing. Sodium bisulfite is specific to aldehydes, as was expected. Sodium hydroxide and acids are not much better than water, although they might be worth trying in tests to determine the life of the scrubbing solutions.

On the basis of these results the main reagent should be sodium hypochlorite. If two scrubbing stages are needed, the first could be water, followed by hypochlorite, provided that the spent water can be disposed of without causing an odor problem. Or, the first liquid could be hypochlorite, followed by either permanganate, hydrogen peroxide, a second stage of hypochlorite, or an acid. An acid is effective on amines and it increases the solubility of alcohols.

The bubbler test results (in Table 19, page 87) gave higher odor removals than the corresponding scrubber tests in Table 29. This was expected since the scrubber is limited by mass transfer as well as by chemical reaction rate. The fraction removed by a scrubbing tower is determined by its height and it is possible to design a scrubbing tower to achieve higher reduction rates.

Table 29

SCRUBBER REMOVAL, %

| | Valeraldehyde | Dipropyl Sulfide | Amyl Alcohol | Trimethyl-amine | Butyric Acid | Butanedione | Tert-Butyl amine | Heptadiene | Dimethyl Disulfide |
|---|---|---|---|---|---|---|---|---|---|
| Water | 30 | 0 | 80-90 | 80-90 | | | >90 | 0 | 10 |
| NaOCl, 1% | 10 | >90 | 80 | >90 | | | | 20 | 50 |
| $H_2O_2$, 3% | >90 | 0 | 75 | | | | >90 | 0 | slight |
| Potassium Permanganate, 3% | 30 | 10-25 | 40-80 | >90 | | | | 25 | 20-75 |
| Sodium Bisulfite, 5% | >90 | 10 | 75 | | | | | | |
| HCl, 5% | 0 | 0 | 80 | >90 | | | | | |
| Sodium Hydroxide, 5% | 10-30 | 0 | 0-60 | 0 | >90 | >90 | >90 | | |

## 10. IDENTIFICATION OF ODORANTS

### 10.1 Kovats Indices of Odorants

Since the first project on the identification of odorants was completed, a new type of chromatographic column has become available, the SP-1000 column. Samples from a rendering plant were obtained to make a few additional measurements in the hope of identifying amines and sulfides which were not specifically identified in the first project. Vapor samples were passed through a 10-ft SP-1000 column and major peaks were introduced into the mass spectrometer. The process was repeated using a Pennwalt 223 column, which is suited to separations of amines. A number of compounds were tentatively identified but the identification could not be checked because the Kovats indices were not determined. Since then, Kovats indices have been determined for a few pure compounds on another project and the results are given in Table 30. It appears that the Kovats indices are not greatly different from those determined on a Carbowax 20M column. Published Kovats indices for the Carbowax column are given in Table 31. By comparison of these data it may be seen that the identifications appear reasonable.

### 10.2 Second Mass Spectrometer Identification Series

The new results are presented in Tables 32 and 33. Since several hydrocarbons were identified by mass spectrometer, these can be used to fix the Kovats index at several points in the tables.

### 10.3 Identification of Odorous Peaks

On another project, samples were taken from a variety of rendering plants using specially developed chromatographic adsorber samplers. Some of these were measured for odor level by a trained panel, while others were analyzed by gas chromatograph. Then a computer regression analysis was done to determine which peaks could be correlated with the odor intensity from different



Table 30

KOVATS INDICES FOR SOME SULFIDES, AMINES AND ACIDS ON SP-1000 AND CARBOWAX 20 COLUMNS

| Compound | Kovats Index 20% Carbowax 20M | Kovats Index 10% SP-1000 |
|---|---|---|
| Methyl mercaptan | 658 | |
| Ethyl mercaptan | 750 | 705 |
| Propyl mercaptan | 842 | |
| Diethyl sulfide | 890 | 925 |
| Butyl mercaptan | 942 | 975 |
| Thiophene | 1034 | |
| Pentyl mercaptan | 1042 | 1048 |
| Dipropyl sulfide | 1051 | 1083 |
| Dimethyl disulfide | 1110 | |
| Diallyl sulfide | 1142 | |
| Dibutyl sulfide | 1258 | |
| Diethyl disulfide | 1275 | |
| Heptyl mercaptan | 1280 | 1285 |
| Dihexyl sulfide | 1695 | |
| Butyl amine | Not effective | 947 |
| Propyl amine | Not effective | 857 |
| Allyl amine | | 882 |
| Isobutyl amine | | 1112 |
| Hexyl amine | | 1597 |
| Propionic acid | | 1502 |
| Butyric acid | | 1567 |
| Valeric acid | | 1690 |
| Heptanoic acid | | 1950 |
| Propanal | | 700 |
| Pentanal | | 1010 |
| Hexanal | | 1100 |
| Heptanal | | 1205 |
| Ethanol | | 920 |
| Propanol | | 1015 |
| Isopropanol | | 950 |
| Butanol | | 1155 |
| Pentanol | | 1230 |
| Acetone | | 770 |
| 2,3 Butanedione | | 1015 |
| Mesityl oxide | | 1115 |
| 3-Heptanone | | 1195 |
| 3-Methyl tetrahydrofuran | | 870 |
| Toluene | | 1130 |
| m-Dichlorobenzene | | 1460 |

# KOVATS INDICES OF CLASSES OF COMPOUNDS ON CARBOWAX 20M COLUMN

| | $V_g$ | | $I_x$ | |
|---|---|---|---|---|
| | 120° | 160° | 120° | 160° |
| METHANOL | 14.2 | 5.5 | 862 | 842 |
| ETHANOL | 16.9 | 6.2 | 893 | 869 |
| PROPANOL | 31.0 | 10.5 | 1000 | 986 |
| ISOPROPANOL | 16.0 | 6.0 | 883 | 862 |
| BUTANOL | 56.0 | 17.5 | 1111 | 1101 |
| ISOBUTANOL | 41.5 | 13.6 | 1055 | 1045 |
| S-BUTANOL | 28.6 | 10.0 | 986 | 975 |
| T-BUTANOL | 13.8 | 5.2 | 857 | 830 |
| CYCLOPROPYL CARBINOL | 91.3 | 27.3 | 1203 | 1201 |
| PENTANOL | 100 | 28.9 | 1223 | 1215 |
| ISOPENTANOL | 79.9 | 24.0 | 1178 | 1173 |
| 2-PENTANOL | 48.7 | 15.4 | 1085 | 1073 |
| 3-PENTANOL | 45.8 | 15.2 | 1073 | 1070 |
| 2-METHYL-1-BUTANOL | 79.5 | 23.9 | 1177 | 1172 |
| 2-METHYL-2-BUTANOL | 26.9 | 9.5 | 975 | 965 |
| 3-METHYL-2-BUTANOL | 42.0 | 13.8 | 1057 | 1048 |
| 2,2-DIMETHYL-1-PROPANOL | 45.7 | 14.9 | 1073 | 1065 |
| HEXANOL | 177 | 45.9 | 1331 | 1321 |
| 2-HEXANOL | 84.3 | 25.1 | 1188 | 1182 |
| 3-HEXANOL | 75.7 | 22.7 | 1168 | 1160 |
| 2-METHYL-1-PENTANOL | 136 | 36.5 | 1281 | 1268 |
| 3-METHYL-1-PENTANOL | 157 | 41.4 | 1309 | 1297 |
| 4-METHYL-1-PENTANOL | 147 | 38.8 | 1295 | 1282 |
| 2-METHYL-2-PENTANOL | 44.0 | 14.3 | 1066 | 1056 |
| 3-METHYL-2-PENTANOL | 74.0 | 22.7 | 1164 | 1160 |
| 4-METHYL-2-PENTANOL | 62.7 | 19.4 | 1133 | 1124 |
| 2-METHYL-3-PENTANOL | 60.7 | 19.1 | 1126 | 1121 |
| 3-METHYL-3-PENTANOL | 48.6 | 15.9 | 1085 | 1080 |
| 2-ETHYL-1-BUTANOL | 138 | 38.1 | 1283 | 1278 |
| 2,2-DIMETHYL-1-BUTANOL | 97.2 | 28.7 | 1216 | 1213 |
| 2,3-DIMETHYL-2-BUTANOL | 42.5 | 14.4 | 1059 | 1058 |
| 3,3-DIMETHYL-2-BUTANOL | 51.2 | 16.9 | 1094 | 1093 |
| HEPTANOL | 304 | 74.1 | 1435 | 1430 |
| 2-HEPTANOL | | 38.3 | | 1279 |
| 3-HEPTANOL | 127 | 34.6 | 1267 | 1256 |
| 4-HEPTANOL | 121 | 32.9 | 1258 | 1244 |
| 2,2-DIMETHYL-1-PENTANOL | 156 | 41.4 | 1307 | 1297 |
| 2,4-DIMETHYL-3-PENTANOL | 74.4 | 22.9 | 1165 | 1162 |
| 3-ETHYL-3-PENTANOL | 85.4 | 25.2 | 1191 | 1183 |
| OCTANOL | 534 | 112 | 1545 | 1526 |
| 2-OCTANOL | 252 | 62.9 | 1399 | 1393 |
| 2-ETHYL-1-HEXANOL | 379 | 84.4 | 1478 | 1460 |
| 2-ETHYL-4-METHYL-1-PENTANOL | 274 | 67.8 | 1415 | 1410 |
| NONANOL | 906 | 181 | 1648 | 1638 |
| CYCLOPENTANOL | 140 | 38.9 | 1287 | 1283 |
| CYCLOHEXANOL | 238 | 64.1 | 1388 | 1397 |
| 2-METHYLCYCLOHEXANOL | 255 | 68.7 | 1402 | 1413 |
| 2-PROPEN-1-OL | 46.0 | 14.6 | 1074 | 1061 |
| 2-PROPYN-1-OL | 155 | 39.8 | 1306 | 1288 |
| 2-BUTEN-1-OL | 84.4 | 25.0 | 1189 | 1182 |
| 3-BUTEN-1-OL | 66.1 | 20.5 | 1143 | 1137 |
| 3-BUTEN-2-OL | 37.3 | 12.3 | 1035 | 1022 |
| 2-METHYL-2-PROPEN-1-OL | 76.9 | 23.0 | 1171 | 1163 |
| 3-PENTEN-1-OL | 117 | 33.8 | 1252 | 1251 |
| 1-PENTEN-3-OL | 60.9 | 18.6 | 1127 | 1116 |
| 1-PENTEN-4-OL | 55.2 | 17.6 | 1109 | 1103 |
| 2-METHYL-3-BUTEN-2-OL | 30.7 | 10.3 | 998 | 982 |
| 2-METHYL-3-BUTYN-2-OL | 68.4 | 19.2 | 1149 | 1122 |
| 3-METHYL-1-PENTYN-3-OL | 110 | 30.0 | 1241 | 1223 |
| 2-ETHYL-2-HEXEN-1-OL | | 108 | | 1518 |
| ETHYLENE GLYCOL | | 147 | | 1588 |
| 1,2-PROPANEDIOL | | 121 | | 1544 |
| 1,3-PROPANEDIOL | | 270 | | 1731 |
| 2,2-BUTANEDIOL | | 177 | | 1633 |
| 1,3-BUTANEDIOL | | 228 | | 1692 |
| 1,4-BUTANEDIOL | | 469 | | 1861 |
| D,L-2,3-BUTANEDIOL | | 100 | | 1500 |
| MESO-2,3-BUTANEDIOL | | 112 | | 1526 |
| 2-METHYL-1,2-PROPANEDIOL | | 94.1 | | 1485 |
| 2,4-PENTANEDIOL | | 742 | | 1970 |
| 2,4-PENTANEDIOL | | 181 | | 1637 |
| 2,2-DIMETHYL-1,3-PROPANEDIOL | | 291 | | 1749 |
| 1,3-HEXANEDIOL | | 143 | | 1582 |
| 1,6-HEXANEDIOL | | 1154 | | 2051 |
| 2-METHYL-1,3-PENTANEDIOL | | 384 | | 1814 |
| 2-METHYL-2,4-PENTANEDIOL | | 143 | | 1583 |
| 3-METHYL-2,4-PENTANEDIOL | | 254 | | 1717 |
| 3-METHYL-1,5-PENTANEDIOL | | 966 | | 2022 |
| 2,3-DIMETHYL-2,3-BUTANEDIOL | | 81.3 | | 1452 |
| 2,4-HEPTANEDIOL | | 358 | | 1797 |
| 1,2-OCTANEDIOL | | 987 | | 2025 |
| 2-BUTEN-1,4-DIOL | | 774 | | 1983 |
| DIETHYLENE GLYCOL | | 595 | | 1917 |
| FORMALDEHYDE | 3.2 | 1.9 | 601 | 630 |
| ACETALDEHYDE | 5.2 | 2.6 | 686 | 690 |
| PROPIONALDEHYDE | 9.3 | 4.2 | 788 | 784 |

| | $V_g$ | | $I_x$ | |
|---|---|---|---|---|
| | 120° | 160° | 120° | 160 |
| BUTYRALDEHYDE | 15.9 | 6.6 | 882 | 882 |
| ISOBUTYRALDEHYDE | 11.6 | 5.3 | 827 | 832 |
| VALERALDEHYDE | 28.4 | 11.2 | 984 | 1002 |
| ISOVALERALDEHYDE | 20.4 | 8.4 | 926 | 937 |
| 2-METHYLBUTYRALDEHYDE | 20.3 | 8.4 | 925 | 936 |
| 2,2-DIMETHYLPROPIONALDEHYDE | 11.2 | 5.0 | 821 | 822 |
| HEXANAL | 49.3 | 18.0 | 1087 | 1108 |
| HEPTANAL | 83.9 | 28.0 | 1188 | 1207 |
| 2-ETHYLHEXANAL | 88.1 | 29.1 | 1197 | 1216 |
| ACROLEIN | 13.0 | 5.7 | 846 | 849 |
| METHACROLEIN | 16.0 | 7.0 | 884 | 896 |
| CROTONALDEHYDE | 40.0 | 14.8 | 1048 | 1064 |
| 2-ETHYL-2-BUTENAL | 74.4 | 25.8 | 1165 | 1189 |
| 2-ETHYL-2-HEXENAL | 158 | 49.1 | 1309 | 1338 |
| 2,4-HEXADIENAL | 254 | 72.8 | 1401 | 1426 |
| ACETONE | 10.9 | 4.9 | 815 | 819 |
| 2-BUTANONE | 18.0 | 7.4 | 904 | 908 |
| 2-PENTANONE | 28.2 | 10.7 | 982 | 992 |
| 3-PENTANONE | 28.0 | 10.5 | 982 | 987 |
| 3-METHYL-2-BUTANONE | 22.0 | 8.8 | 939 | 947 |
| 2-HEXANONE | 49.3 | 17.3 | 1087 | 1099 |
| 3-HEXANONE | 42.2 | 15.0 | 1058 | 1067 |
| 3-METHYL-2-PENTANONE | 35.7 | 14.2 | 1026 | 1054 |
| 4-METHYL-2-PENTANONE | 33.0 | 12.7 | 1012 | 1030 |
| 3,3-DIMETHYL-2-BUTANONE | 25.1 | 10.3 | 962 | 982 |
| 2-HEPTANONE | 84.1 | 26.1 | 1188 | 1192 |
| 3-HEPTANONE | 72.3 | 24.1 | 1159 | 1174 |
| 4-HEPTANONE | 63.0 | 21.8 | 1134 | 1151 |
| 4,4-DIMETHYL-2-PENTANONE | 36.0 | 14.1 | 1028 | 1052 |
| 2,4-DIMETHYL-3-PENTANONE | 32.9 | 12.7 | 1011 | 1029 |
| 2-OCTANONE | 146 | 42.7 | 1295 | 1304 |
| 2-NONANONE | 240 | 70.7 | 1390 | 1420 |
| 5-NONANONE | 185 | 54.6 | 1340 | 1360 |
| CYCLOPENTANONE | 92.8 | 32.0 | 1207 | 1238 |
| CYCLOHEXANONE | 166 | 54.7 | 1319 | 1361 |
| 3-BUTEN-2-ONE | 23.1 | 9.3 | 948 | 959 |
| 5-HEXEN-2-ONE | 62.3 | 21.4 | 1131 | 1147 |
| 3-METHYL-3-BUTEN-2-ONE | 30.6 | 11.9 | 997 | 1014 |
| 4-METHYL-3-PENTEN-2-ONE | 66.2 | 23.0 | 1143 | 1164 |
| 2,3-BUTANEDIONE | 24.6 | 9.4 | 959 | 963 |
| 2,3-PENTANEDIONE | 38.9 | 13.7 | 1042 | 1046 |
| 2,4-PENTANEDIONE | 103 | 36.4 | 1228 | 1268 |
| METHYL FORMATE | 7.3 | 3.2 | 745 | 734 |
| ETHYL FORMATE | 11.0 | 4.8 | 817 | 810 |
| PROPYL FORMATE | 19.5 | 7.8 | 918 | 919 |
| ISOPROPYL FORMATE | 13.1 | 5.4 | 848 | 837 |
| BUTYL FORMATE | 33.5 | 12.2 | 1014 | 1021 |
| ISOBUTYL FORMATE | 25.3 | 9.6 | 964 | 967 |
| S-BUTYL FORMATE | 23.1 | 9.1 | 948 | 956 |
| PENTYL FORMATE | 58.3 | | 1119 | |
| 2-PENTYL FORMATE | 37.6 | 14.1 | 1036 | 1053 |
| 3-PENTYL FORMATE | 39.7 | 14.2 | 1046 | 1054 |
| HEXYL FORMATE | 102 | 31.3 | 1226 | 1233 |
| ALLYL FORMATE | 24.9 | 9.6 | 961 | 966 |
| ETHYLENE DIFORMATE | 399 | | 1488 | |
| 1,3-BUTYLENE DIFORMATE | 630 | 150 | 1576 | 1594 |
| METHYL ACETATE | 11.4 | 4.8 | 824 | 813 |
| ETHYL ACETATE | 15.6 | 6.3 | 879 | 871 |
| PROPYL ACETATE | 25.7 | 9.7 | 967 | 969 |
| ISOPROPYL ACETATE | 16.5 | 6.6 | 889 | 882 |
| BUTYL ACETATE | 44.1 | 15.0 | 1066 | 1067 |
| ISOBUTYL ACETATE | 31.9 | 11.5 | 1005 | 1007 |
| S-BUTYL ACETATE | 27.7 | 10.3 | 980 | 982 |
| T-BUTYL ACETATE | 17.4 | 6.8 | 898 | 888 |
| PENTYL ACETATE | 79.3 | 24.8 | 1177 | 1180 |
| ISOPENTYL ACETATE | 61.1 | 19.6 | 1128 | 1128 |
| 2-PENTYL ACETATE | 44.5 | 15.3 | 1068 | 1071 |
| 3-PENTYL ACETATE | 44.1 | 14.9 | 1066 | 1066 |
| 2-METHYL-2-BUTYL ACETATE | 32.4 | 12.0 | 1008 | 1017 |
| HEXYL ACETATE | 136 | 40.5 | 1281 | 1292 |
| 4-METHYL-2-PENTYL ACETATE | 53.1 | 17.6 | 1101 | 1102 |
| 2-ETHYL-1-BUTYL ACETATE | 100 | 29.8 | 1223 | 1222 |
| HEPTYL ACETATE | 232 | 60.8 | 1383 | 1385 |
| 2-ETHYL-1-HEXYL ACETATE | 247 | 66.4 | 1396 | 1405 |
| CYCLOHEXYL ACETATE | 211 | 64.2 | 1365 | 1397 |
| VINYL ACETATE | 16.0 | 6.5 | 883 | 878 |
| ALLYL ACETATE | 33.6 | 12.0 | 1015 | 1016 |
| ISOPROPENYL ACETATE | 27.0 | 10.0 | 976 | 977 |
| 1-ACETOXY-2-PROPYNE | 91.0 | 26.1 | 1203 | 1192 |
| METHYLENE DIACETATE | 357 | 69.3 | 1466 | 1415 |
| ETHYLIDENE DIACETATE | 210 | 55.6 | 1364 | 1364 |
| ETHYLENE DIACETATE | 506 | 120 | 1534 | 1542 |
| METHYL PROPIONATE | 17.6 | 7.0 | 900 | 896 |
| ETHYL PROPIONATE | 23.4 | 9.0 | 950 | 952 |
| PROPYL PROPIONATE | 38.0 | 13.1 | 1038 | 1036 |
| ISOPROPYL PROPIONATE | 23.9 | 9.0 | 954 | 953 |

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# Table 31 (cont.)

| | $V_g$ | | $I_x$ | |
|---|---|---|---|---|
| | 120° | 160° | 120° | 160 |
| BUTYL PROPIONATE | 66.7 | 21.5 | 1144 | 1148 |
| ISOBUTYL PROPIONATE | 48.1 | 15.8 | 1083 | 1079 |
| PENTYL PROPIONATE | 114 | 35.5 | 1246 | 1262 |
| ISOPENTYL PROPIONATE | 88.8 | 29.1 | 1158 | 1216 |
| 2-PENTYL PROPIONATE | 65.5 | 19.0 | 1141 | 1120 |
| 2-ETHYL-1-HEXYL PROPIONATE | 345 | 80.7 | 1460 | 1450 |
| ALLYL PROPIONATE | 50.3 | 16.6 | 1091 | 1090 |
| METHYL BUTYRATE | 27.8 | 10.4 | 981 | 986 |
| ETHYL BUTYRATE | 36.6 | 12.8 | 1031 | 1032 |
| PROPYL BUTYRATE | 61.5 | 19.6 | 1129 | 1127 |
| ISOPROPYL BUTYRATE | 36.9 | 12.6 | 1033 | 1028 |
| BUTYL BUTYRATE | 103 | 30.7 | 1228 | 1229 |
| ISOBUTYL BUTYRATE | 74.9 | 23.8 | 1166 | 1171 |
| PENTYL BUTYRATE | 171 | 47.0 | 1325 | 1326 |
| ISOPENTYL BUTYRATE | 134 | 38.4 | 1277 | 1280 |
| 2-PENTYL BUTYRATE | 101 | 29.4 | 1224 | 1219 |
| VINYL BUTYRATE | 35.5 | 12.8 | 1026 | 1031 |
| METHYL ISOBUTYRATE | 19.6 | 7.8 | 919 | 920 |
| BUTYL ISOBUTYRATE | 70.0 | 22.3 | 1153 | 1156 |
| ISOBUTYL ISOBUTYRATE | 50.4 | 16.7 | 1091 | 1092 |
| METHYL ACRYLATE | 21.1 | 8.4 | 932 | 938 |
| ETHYL ACRYLATE | 28.4 | 10.8 | 984 | 994 |
| PROPYL ACRYLATE | 46.5 | 16.2 | 1076 | 1085 |
| BUTYL ACRYLATE | 80.5 | 25.7 | 1180 | 1189 |
| ISOBUTYL ACRYLATE | | 18.0 | | 1107 |
| 2-ETHYL-1-HEXYL ACRYLATE | | 97.5 | | 1494 |
| ALLYL ACRYLATE | 60.5 | 20.4 | 1126 | 1136 |
| METHYL METHACRYLATE | 31.2 | 11.5 | 1001 | 1008 |
| METHYLAL | 7.1 | 3.3 | 740 | 735 |
| ETHYL METHYL FORMAL | 10.2 | 4.6 | 804 | 803 |
| ISOPROPYL METHYL FORMAL | 12.2 | 5.3 | 836 | 836 |
| DIETHYL FORMAL | 13.8 | 5.9 | 857 | 857 |
| PROPYL ETHYL FORMAL | 22.5 | 8.8 | 943 | 948 |
| ISOPROPYL ETHYL FORMAL | 16.5 | 6.6 | 888 | 884 |
| S-BUTYL ETHYL FORMAL | 28.4 | 10.8 | 984 | 992 |
| DIPROPYL FORMAL | 35.6 | 12.8 | 1026 | 1031 |
| S-BUTYL PROPYL FORMAL | 45.0 | 15.8 | 1070 | 1078 |
| DIISOPROPYL FORMAL | 19.5 | 7.5 | 918 | 913 |
| DIBUTYL FORMAL | 95.3 | 30.6 | 1212 | 1228 |
| DIISOBUTYL FORMAL | 53.2 | 17.3 | 1102 | 1099 |
| DI S-BUTYL FORMAL | 61.5 | 19.0 | 1129 | 1120 |
| ETHYLENE GLYCOL FORMAL | 26.1 | 10.4 | 969 | 984 |
| 1,2-PROPYLENE GLYCOL FORMAL | 26.5 | 10.6 | 972 | 989 |
| 1,3-PROPYLENE GLYCOL FORMAL | 52.1 | 19.2 | 1098 | 1123 |
| 1,3-BUTYLENE GLYCOL FORMAL | 53.6 | 19.7 | 1103 | 1128 |
| 2,3-BUTYLENE GLYCOL FORMAL | 34.5 | 13.1 | 1020 | 1037 |
| 1,4-BUTYLENE GLYCOL FORMAL | 64.0 | 24.3 | 1137 | 1176 |
| NEOPENTYL GLYCOL FORMAL | 57.9 | 20.8 | 1118 | 1140 |
| 6-METHYL-2,4,7-TRIOXAOCTANE | 74.4 | 24.3 | 1165 | 1176 |
| DIMETHYL ACETAL | 10.0 | 4.5 | 800 | 800 |
| DIETHYL ACETAL | 16.0 | 6.5 | 884 | 879 |
| DIPROPYL ACETAL | 37.5 | 12.8 | 1035 | 1032 |
| DIISOBUTYL ACETAL | 46.2 | 15.4 | 1075 | 1072 |
| ETHYLENE GLYCOL ACETAL | 24.5 | 9.6 | 958 | 966 |
| 1,3-BUTYLENE GLYCOL ACETAL | 43.3 | 15.4 | 1063 | 1072 |
| DIMETHYL PROPYLAL | 15.7 | 6.6 | 880 | 884 |
| DIETHYL PROPYLAL | 23.2 | 8.8 | 948 | 947 |
| DIMETHYL BUTYRAL | 25.5 | 9.8 | 965 | 972 |
| 1,3-BUTYLENE GLYCOL BUTYRAL | 102 | 31.1 | 1226 | 1232 |
| DIMETHYL ISOBUTYRAL | 18.7 | 7.6 | 910 | 916 |
| ACROLEIN DIETHYL ACETAL | 29.7 | 11.0 | 992 | 997 |
| DIBUTYL CROTANAL | 346 | 76.9 | 1460 | 1439 |
| 4,4-DIMETHOXY-2-BUTANONE | 243 | 64.6 | 1392 | 1399 |
| 2,2-DIMETHOXYPROPANE | 11.9 | 5.3 | 831 | 834 |
| 2,2-DIETHOXYPROPANE | 16.1 | 6.4 | 884 | 875 |
| 2,2-DIALLYLOXYPROPANE | 71.9 | 22.9 | 1158 | 1163 |
| 2-ET-2-ME-1,3-DIOXOLANE | 41.8 | 15.1 | 1056 | 1068 |
| METHYL ETHER | 1.7 | 1.1 | 493 | 524 |
| PROPYL METHYL ETHER | 4.1 | 2.0 | 644 | 644 |
| BUTYL METHYL ETHER | 7.3 | 3.6 | 746 | 755 |
| ISOBUTYL METHYL ETHER | 5.2 | 2.5 | 685 | 683 |
| T-BUTYL METHYL ETHER | 5.1 | 2.6 | 684 | 688 |
| ETHYL ETHER | 3.5 | 1.7 | 620 | 610 |
| BUTYL ETHYL ETHER | 9.6 | 4.3 | 794 | 788 |
| T-BUTYL ETHYL ETHER | 5.6 | 2.6 | 699 | 688 |
| ALLYL ETHYL ETHER | 8.4 | 3.8 | 771 | 767 |
| PROPYL ETHER | 8.5 | 3.8 | 773 | 766 |
| ISOPROPYL PROPYL ETHER | 6.0 | 2.9 | 712 | 714 |
| ISOPROPYL ETHER | 4.3 | 2.1 | 652 | 649 |
| T-BUTYL ISOPROPYL ETHER | 6.3 | 3.0 | 720 | 717 |
| BUTYL ETHER | 25.6 | 9.7 | 966 | 969 |
| PENTYL ETHER | 74.4 | 23.2 | 1165 | 1165 |
| ISOPENTYL ETHER | 43.4 | 15.0 | 1063 | 1067 |
| HEXYL ETHER | 227 | 55.4 | 1379 | 1363 |
| 2-ETHYL-1-BUTYL ETHER | 101 | 28.6 | 1224 | 1212 |
| ETHYL VINYL ETHER | 4.9 | 2.3 | 677 | 668 |
| BUTYL VINYL ETHER | 13.9 | 6.0 | 858 | 862 |
| ISOBUTYL VINYL ETHER | 10.0 | 4.3 | 800 | 799 |
| 2-ETHYL-1-HEXYL VINYL ETHER | 80.3 | 23.2 | 1179 | 1165 |
| ET GLYCOL DIMETHYL ETHER | 19.5 | 7.8 | 918 | 900 |
| ET GLYCOL DIBUTYL ETHER | 204 | 51.8 | 1359 | 1348 |
| ETHYLENE OXIDE | 5.6 | 2.9 | 700 | 712 |
| PROPYLENE OXIDE | 8.1 | 4.2 | 763 | 787 |
| 1,3-PROPYLENE OXIDE | 12.9 | 5.7 | 845 | 852 |
| 1,2-BUTYLENE OXIDE | 13.2 | 5.9 | 849 | 855 |
| 1,3-BUTYLENE OXIDE | 12.7 | 5.8 | 843 | 850 |
| TRANS-2,3-BUTYLENE OXIDE | 9.3 | 4.2 | 787 | 785 |
| CIS-2,3-BUTYLENE OXIDE | 12.0 | 5.3 | 833 | 835 |
| TETRAHYDROFURAN | 16.0 | 7.0 | 883 | 899 |
| 2-ME-1,2-PROPYLENE OXIDE | 8.4 | 3.9 | 771 | 769 |
| 2-METHYLTETRAHYDROFURAN | 16.4 | 7.2 | 888 | 901 |
| FURAN | 9.5 | 4.2 | 791 | 786 |
| 2-METHYLFURAN | 14.8 | 6.3 | 869 | 873 |
| 2,5-DIMETHYLTETRAHYDROFURAN | 15.2 | 6.5 | 874 | 881 |
| 4,5-DIHYDRO-2-METHYLFURAN | 19.7 | 8.3 | 919 | 934 |
| 3,4-DIHYDROPYRAN | 25.1 | 10.3 | 963 | 983 |
| TETRAHYDROPYRAN | 23.0 | 9.6 | 947 | 967 |
| ETHANE | .3 | .2 | 200 | 200 |
| BUTANE | 1.0 | .6 | 400 | 400 |
| HEXANE | 3.2 | 1.6 | 600 | 600 |
| 2,3-DIMETHYLBUTANE | 2.7 | 1.6 | 574 | 598 |
| OCTANE | 9.9 | 4.5 | 800 | 800 |
| DECANE | 31.0 | 11.1 | 1000 | 1000 |
| DODECANE | 89.4 | 27.0 | 1200 | 1200 |
| TETRADECANE | 253 | 64.9 | 1400 | 1400 |
| HEXADECANE | 710 | 154 | 1600 | 1600 |
| OCTADECANE | 1960 | 362 | 1800 | 1800 |
| CYCLOHEXANE | 7.8 | 3.8 | 756 | 765 |
| 1-PENTENE | 2.3 | | 545 | |
| BENZENE | 24.9 | 10.2 | 961 | 979 |
| TOLUENE | 42.8 | 15.9 | 1061 | 1079 |
| O-XYLENE | 96.0 | 30.1 | 1213 | 1224 |
| M-XYLENE | 77.6 | 25.3 | 1173 | 1184 |
| P-XYLENE | 75.0 | 24.8 | 1166 | 1180 |
| ETHYLBENZENE | 69.6 | 24.3 | 1152 | 1176 |
| O-DIETHYLBENZENE | 204 | 57.5 | 1359 | 1372 |
| M-DIETHYLBENZENE | 177 | 49.8 | 1331 | 1339 |
| P-DIETHYLBENZENE | 187 | 52.9 | 1341 | 1353 |
| METHYLENE CHLORIDE | 19.0 | 7.6 | 914 | 915 |
| ETHYLENE CHLORIDE | 42.8 | 15.6 | 1061 | 1075 |
| ALLYL CHLORIDE | 11.0 | | 818 | |
| CARBON TETRACHLORIDE | 17.1 | 7.4 | 895 | 910 |
| CHLOROFORM | 32.0 | 11.6 | 1006 | 1010 |
| 2-CHLOROETHANOL | 198 | 56.2 | 1353 | 1367 |
| 3-HYDROXY-2-BUTANONE | 140 | 40.7 | 1286 | 1293 |
| 4-HYDROXY-2-BUTANONE | 470 | 114 | 1520 | 1530 |
| 1-HYDROXY-2-ME-3-BUTANONE | 641 | 146 | 1580 | 1587 |
| 2-HYDROXY-2-ME-3-BUTANONE | 106 | 32.8 | 1233 | 1244 |
| 4-HYDROXY-4-ME-2-PENTANONE | 202 | 57.0 | 1357 | 1370 |
| 3-METHOXYBUTANAL | 72.7 | 23.6 | 1160 | 1169 |
| 4-ACETOXYTETRAHYDROPYRAN | 466 | 111 | 1518 | 1524 |
| 2-METHOXYETHANOL | 72.1 | 23.6 | 1159 | 1169 |
| 2-ETHOXYETHANOL | 91.0 | 29.2 | 1203 | 1217 |
| 2-BUTOXYETHANOL | 243 | 62.9 | 1392 | 1393 |
| 2-ALLYLOXYETHANOL | 226 | 59.3 | 1378 | 1379 |
| 2-METHOXY-1-PROPANOL | 84.2 | 25.6 | 1188 | 1187 |
| 2-ETHOXY-1-PROPANOL | 95.6 | 28.8 | 1213 | 1214 |
| 3-ETHOXY-1-PROPANOL | 204 | 53.1 | 1358 | 1354 |
| 1-METHOXY-2-PROPANOL | 57.2 | 19.0 | 1115 | 1120 |
| 1-PROPOXY-2-PROPANOL | 104 | 31.5 | 1229 | 1234 |
| 3-METHOXY-1-BUTANOL | 200 | 53.2 | 1355 | 1354 |
| 1-ETHOXY-3-PENTANOL | 233 | 61.3 | 1384 | 1387 |
| 4-METHOXY-4-ME-2-PENTANOL | 159 | 47.9 | 1310 | 1330 |
| 2-METHOXYETHYL VINYL ETHER | 36.8 | 12.8 | 1032 | 1031 |
| BIS(2-ETHOXYETHYL) ETHER | 256 | 63.0 | 1402 | 1393 |
| 3-METHOXY-1-BUTYL ACETATE | 182 | 49.6 | 1337 | 1338 |
| 2-METHOXYETHYL ACETATE | 107 | 30.7 | 1235 | 1229 |
| 2-ETHOXYETHYL ACETATE | 135 | 37.4 | 1280 | 1274 |
| ACETONYL ACETATE | 314 | 75.3 | 1442 | 1434 |
| 3-METHOXY-1-BUTYL ACRYLATE | 183 | 49.6 | 1338 | 1338 |
| 1,1,3-TRIMETHOXYBUTANE | 98.2 | 29.8 | 1218 | 1222 |
| METHOXYMETHYLAL | 34.1 | 12.7 | 1018 | 1029 |
| DIMETHOXYMETHYLAL | 142 | 42.3 | 1298 | 1302 |
| TRIMETHOXYMETHYLAL | 561 | 134 | 1554 | 1568 |
| 1,4-DIOXANE | 45.7 | 17.0 | 1073 | 1094 |
| TRIOXANE | 74.7 | 25.5 | 1166 | 1186 |
| 1,3,5-TRIOXEPANE | 114 | 37.0 | 1247 | 1271 |
| PARALDEHYDE | 45.6 | 15.0 | 1073 | 1067 |
| WATER | 29.4 | 9.6 | 990 | 967 |

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# Table 31 (cont.)

| | $V_g$ | | $I_x$ | | | $V_g$ | | $I_x$ | |
|---|---|---|---|---|---|---|---|---|---|
| | 120° | 160° | 120° | 160° | | 120° | 160° | 120° | 160 |
| ETHANE | .3 | .2 | 200 | 200 | S-BUTYL FORMATE | 23.1 | 9.1 | 946 | 954 |
| BUTANE | 1.0 | .6 | 400 | 400 | 3-BUTEN-2-ONE | 23.[illegible] | 9.3 | 945 | 95[illegible] |
| METHYL ETHER | 1.7 | 1.1 | 493 | 524 | 2,3-BUTANEDIONE | 24.6 | 9.4 | 955 | 961 |
| 1-PENTENE | 2.3 | | 545 | | 2-METHYL-2-BUTANOL | 26.5 | 9.[illegible] | 975 | 96[illegible] |
| 2,3-DIMETHYLBUTANE | 2.7 | 1.6 | 574 | 598 | ETHYLENE GLYCOL ACETAL | 24.5 | 9.6 | 958 | 965 |
| HEXANE | 3.2 | 1.6 | 600 | 600 | ALLYL FORMATE | 24.9 | 9.6 | 961 | 964 |
| ETHYL ETHER | 3.5 | 1.7 | 620 | 610 | TETRAHYDROPYRAN | 23.[illegible] | 9.6 | 947 | 96[illegible] |
| FORMALDEHYDE | 3.2 | 1.9 | 601 | 610 | WATER | 29.4 | 9.6 | 990 | 96[illegible] |
| PROPYL METHYL ETHER | 4.1 | 2.0 | 644 | 644 | ISOBUTYL FORMATE | 25.3 | 9.6 | 964 | 96[illegible] |
| ISOPROPYL ETHER | 4.3 | 2.1 | 652 | 649 | BUTYL ETHER | 25.6 | 9.7 | 966 | 96[illegible] |
| ETHYL VINYL ETHER | 4.9 | 2.3 | 677 | 668 | PROPYL ACETATE | 25.7 | 9.7 | 967 | 96[illegible] |
| ISOBUTYL METHYL ETHER | 5.2 | 2.5 | 685 | 683 | DIMETHYL BUTYRAL | 25.5 | 9.8 | 965 | 972 |
| T-BUTYL METHYL ETHER | 5.1 | 2.6 | 684 | 688 | S-BUTANOL | 28.6 | 10.0 | 986 | 975 |
| T-BUTYL ETHYL ETHER | 5.6 | 2.6 | 699 | 688 | ISOPROPENYL ACETATE | 27.[illegible] | 10.0 | 976 | 977 |
| ACETALDEHYDE | 5.2 | 2.6 | 666 | 690 | BENZENE | 24.9 | 10.2 | 961 | 979 |
| ETHYLENE OXIDE | 5.6 | 2.9 | 700 | 712 | 3,4-DIHYDROPYRAN | 25.1 | 10.[illegible] | 963 | 992 |
| ISOPROPYL PROPYL ETHER | 6.0 | 2.9 | 712 | 714 | 2-METHYL-3-BUTEN-2-OL | 30.7 | 10.3 | 998 | 982 |
| T-BUTYL ISOPROPYL ETHER | 6.3 | 3.0 | 720 | 717 | 3,3-DIMETHYL-2-BUTANONE | 25.1 | 10.3 | 967 | 982 |
| METHYL FORMATE | 7.3 | 3.2 | 745 | 734 | S-BUTYL ACETATE | 27.7 | 10.3 | 980 | 982 |
| METHYLAL | 7.1 | 3.3 | 740 | 735 | ETHYLENE GLYCOL FORMAL | 26.1 | 10.4 | 969 | 984 |
| BUTYL METHYL ETHER | 7.3 | 3.6 | 746 | 755 | PROPANOL | 31.0 | 10.5 | 1000 | 986 |
| CYCLOHEXANE | 7.8 | 3.8 | 756 | 765 | METHYL BUTYRATE | 27.8 | 10.4 | 981 | 986 |
| PROPYL ETHER | 8.5 | 3.8 | 773 | 766 | 3-PENTANONE | 28.0 | 10.5 | 982 | 987 |
| ALLYL ETHYL ETHER | 8.4 | 3.8 | 771 | 767 | 1,2-PROPYLENE GLYCOL FORMAL | 26.5 | 10.6 | 972 | 989 |
| 2-ME-1,2-PROPYLENE OXIDE | 8.4 | 3.9 | 771 | 769 | S-BUTYL ETHYL FORMAL | 28.4 | 10.8 | 984 | 992 |
| PROPYLENE OXIDE | 8.1 | 4.2 | 763 | 783 | 2-PENTANONE | 28.2 | 10.7 | 983 | 992 |
| PROPIONALDEHYDE | 9.3 | 4.2 | 788 | 784 | ETHYL ACRYLATE | 28.4 | 10.8 | 984 | 994 |
| TRANS-2,3-BUTYLENE OXIDE | 9.3 | 4.2 | 787 | 785 | ACROLEIN DIETHYL ACETAL | 29.7 | 11.0 | 992 | 997 |
| FURAN | 9.5 | 4.2 | 791 | 786 | DECANE | 31.9 | 11.1 | 1000 | 1000 |
| BUTYL ETHYL ETHER | 9.6 | 4.[illegible] | 794 | 788 | VALERALDEHYDE | 28.4 | 11.2 | 984 | 1002 |
| ISOBUTYL VINYL ETHER | 10.0 | 4.3 | 800 | 788 | ISOBUTYL ACETATE | 31.9 | 11.5 | 1005 | 1007 |
| DIMETHYL ACETAL | 10.0 | 4.5 | 800 | 800 | METHYL METHACRYLATE | 31.2 | 11.[illegible] | 1001 | 1004 |
| OCTANE | 9.9 | 4.5 | 800 | 800 | CHLOROFORM | 32.0 | 11.6 | 1006 | 1010 |
| ETHYL METHYL FORMAL | 10.[illegible] | 4.6 | 804 | 803 | 3-METHYL-3-BUTEN-2-ONE | 30.6 | 11.[illegible] | 997 | 1014 |
| ETHYL FORMATE | 11.0 | 4.6 | 817 | 810 | ALLYL ACETATE | 33.6 | 12.0 | 1015 | 1016 |
| METHYL ACETATE | 11.4 | 4.6 | 824 | 813 | 2-METHYL-2-BUTYL ACETATE | 32.4 | 12.0 | 1008 | 1017 |
| ALLYL CHLORIDE | 11.0 | | 818 | | BUTYL FORMATE | 33.5 | 12.[illegible] | 1014 | 1021 |
| ACETONE | 10.9 | 4.9 | 815 | 819 | 3-BUTEN-2-OL | 37.3 | 12.[illegible] | 1035 | 1022 |
| 2,2-DIMETHYLPROPIONALDEHYDE | 11.2 | 5.0 | 821 | 822 | ISOPROPYL BUTYRATE | 36.9 | 12.6 | 1033 | 10.[illegible] |
| T-BUTANOL | 13.8 | 5.2 | 857 | 840 | METHOXYMETHYLAL | 34.1 | 12.7 | 1 18 | 1024 |
| ISOBUTYRALDEHYDE | 11.6 | 5.3 | 827 | 832 | 2,4-DIMETHYL-3-PENTANONE | 32.9 | 12.7 | 1011 | 1029 |
| 2,2-DIMETHOXYPROPANE | 11.9 | 5.3 | 831 | 834 | 4-METHYL-2-PENTANONE | 33.0 | 12.7 | 1012 | 1030 |
| CIS-2,3-BUTYLENE OXIDE | 12.0 | 5.3 | 833 | 835 | DIPROPYL FORMAL | 35.6 | 12.8 | 1026 | 1031 |
| ISOPROPYL METHYL FORMAL | 12.2 | 5.3 | 836 | 836 | 2-METHOXYETHYL VINYL ETHER | 36.8 | 12.8 | 1032 | 1031 |
| ISOPROPYL FORMATE | 13.1 | 5.4 | 848 | 837 | VINYL BUTYRATE | 35.5 | 12.8 | 1026 | 1031 |
| METHANOL | 14.2 | 5.5 | 862 | 842 | DIPROPYL ACETAL | 37.5 | 12.8 | 1035 | 1032 |
| ACROLEIN | 13.0 | 5.7 | 846 | 849 | ETHYL BUTYRATE | 36.6 | 12.8 | 1031 | 1032 |
| 1,3-PROPYLENE OXIDE | 12.9 | 5.7 | 845 | 852 | PROPYL PROPIONATE | 38.0 | 13.1 | 1038 | 1036 |
| 1,3-BUTYLENE OXIDE | 12.7 | 5.8 | 843 | 852 | 2,3-BUTYLENE GLYCOL FORMAL | 34.5 | 13.1 | 1020 | 1037 |
| 1,2-BUTYLENE OXIDE | 13.2 | 5.9 | 849 | 856 | ISOBUTANOL | 41.5 | 13.6 | 1055 | 1045 |
| DIETHYL FORMAL | 13.8 | 5.9 | 857 | 857 | 2,3-PENTANEDIONE | 38.9 | 13.7 | 1042 | 1044 |
| BUTYL VINYL ETHER | 13.9 | 6.0 | 858 | 862 | 3-METHYL-2-BUTANOL | 42.0 | 13.8 | 1057 | 1048 |
| ISOPROPANOL | 16.0 | 6.0 | 883 | 862 | 4,4-DIMETHYL-2-PENTANONE | 36.0 | 14.1 | 1028 | 1052 |
| ETHANOL | 16.9 | 6.2 | 893 | 869 | 2-PENTYL FORMATE | 37.6 | 14.[illegible] | 1038 | 1053 |
| ETHYL ACETATE | 15.6 | 6.3 | 879 | 871 | 3-METHYL-2-PENTANONE | 39.[illegible] | 14.[illegible] | 1026 | 1054 |
| 2-METHYLFURAN | 14.8 | 6.3 | 869 | 873 | 3-PENTYL FORMATE | 39.7 | 14.[illegible] | 1046 | 1054 |
| 2,2-DIETHOXYPROPANE | 16.1 | 6.4 | 884 | 875 | 2-METHYL-2-PENTANOL | 44.0 | 14.3 | 1066 | 1056 |
| VINYL ACETATE | 16.0 | 6.5 | 883 | 878 | 2,3-DIMETHYL-2-BUTANOL | 42.5 | 14.4 | 1059 | 1055 |
| DIETHYL ACETAL | 16.0 | 6.5 | 884 | 879 | 2-PROPEN-1-OL | 46.0 | 14.6 | 1074 | 1061 |
| 2,5-DIMETHYLTETRAHYDROFURAN | 15.2 | 6.5 | 874 | 881 | CROTONALDEHYDE | 40.0 | 14.8 | 1048 | 1064 |
| BUTYRALDEHYDE | 15.9 | 6.6 | 882 | 882 | 2,2-DIMETHYL-1-PROPANOL | 45.7 | 14.9 | 1073 | 1065 |
| ISOPROPYL ACETATE | 16.5 | 6.6 | 889 | 882 | 3-PENTYL ACETATE | 44.1 | 14.9 | 1066 | 1066 |
| ISOPROPYL ETHYL FORMAL | 16.5 | 6.6 | 888 | 884 | ISOPENTYL ETHER | 43.4 | 15.0 | 1063 | 1067 |
| DIMETHYL PROPYLAL | 15.7 | 6.6 | 880 | 884 | PARALDEHYDE | 45.6 | 15.0 | 1073 | 1067 |
| T-BUTYL ACETATE | 17.4 | 6.8 | 898 | 885 | 3-HEXANONE | 42.2 | 15.0 | 1058 | 1067 |
| METHACROLEIN | 16.0 | 7.0 | 884 | 896 | BUTYL ACETATE | 44.1 | 15.0 | 1066 | 1067 |
| METHYL PROPIONATE | 17.6 | 7.0 | 900 | 896 | 2-ET-2-ME-1,3-DIOXOLANE | 41.8 | 15.1 | 1056 | 1068 |
| TETRAHYDROFURAN | 16.0 | 7.0 | 883 | 898 | 3-PENTANOL | 45.8 | 15.2 | 1073 | 1070 |
| 2-METHYLTETRAHYDROFURAN | 16.4 | 7.2 | 888 | 901 | 2-PENTYL ACETATE | 44.5 | 15.3 | 1068 | 1071 |
| 2-BUTANONE | 18.0 | 7.4 | 904 | 908 | DIISOBUTYL ACETAL | 46.2 | 15.4 | 1075 | 1072 |
| CARBON TETRACHLORIDE | 17.1 | 7.4 | 895 | 910 | 1,3-BUTYLENE GLYCOL ACETAL | 43.3 | 15.4 | 1063 | 1072 |
| DIISOPROPYL FORMAL | 19.5 | 7.5 | 918 | 913 | 2-PENTANOL | 48.7 | 15.4 | 1085 | 1073 |
| METHYLENE CHLORIDE | 19.0 | 7.6 | 914 | 915 | ETHYLENE CHLORIDE | 47.8 | 15.6 | 1081 | 1075 |
| DIMETHYL ISOBUTYRAL | 18.7 | 7.6 | 910 | 916 | S-BUTYL PROPYL FORMAL | 45.0 | 15.8 | 1070 | 1076 |
| PROPYL FORMATE | 19.5 | 7.8 | 918 | 919 | TOLUENE | 42.8 | 15.9 | 1061 | 1079 |
| ET GLYCOL DIMETHYL ETHER | 19.5 | 7.8 | 918 | 920 | ISOBUTYL PROPIONATE | 48.1 | 15.8 | 1083 | 1079 |
| METHYL ISOBUTYRATE | 19.6 | 7.8 | 919 | 920 | 3-METHYL-3-PENTANOL | 48.6 | 15.9 | 1085 | 1080 |
| 4,5-DIHYDRO-2-METHYLFURAN | 19.7 | 8.3 | 919 | 934 | PROPYL ACRYLATE | 46.5 | 16.2 | 1076 | 1081 |
| 2-METHYLBUTYRALDEHYDE | 20.3 | 8.4 | 925 | 936 | ALLYL PROPIONATE | 50.3 | 16.6 | 1091 | 1090 |
| ISOVALERALDEHYDE | 20.4 | 8.4 | 926 | 937 | ISOBUTYL ISOBUTYRATE | 50.4 | 16.7 | 1091 | 1092 |
| METHYL ACRYLATE | 21.1 | 8.4 | 932 | 938 | 3,3-DIMETHYL-2-BUTANOL | 51.2 | 16.9 | 1094 | 1093 |
| DIETHYL PROPYLAL | 23.2 | 8.8 | 948 | 947 | 1,4-DIOXANE | 45.7 | 17.0 | 1073 | 1094 |
| 3-METHYL-2-BUTANONE | 22.0 | 8.8 | 939 | 947 | DIISOBUTYL FORMAL | 53.2 | 17.4 | 1102 | 1099 |
| PROPYL ETHYL FORMAL | 22.5 | 8.8 | 943 | 948 | 2-HEXANONE | 49.3 | 17.3 | 1087 | 1099 |
| ETHYL PROPIONATE | 23.4 | 9.0 | 950 | 952 | BUTANOL | 56.0 | 17.5 | 1111 | 1101 |
| ISOPROPYL PROPIONATE | 23.9 | 9.0 | 954 | 953 | 4-METHYL-2-PENTYL ACETATE | 53.1 | 17.6 | 1101 | 1102 |

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# Table 31 (cont.)

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| | $V_g$ | | $I_x$ | |
|---|---|---|---|---|
| | 120° | 160° | 120° | 160° |
| 1-PENTEN-4-OL | 55.2 | 17.6 | 1109 | 1103 |
| ISOBUTYL ACRYLATE | | 18.0 | | 1107 |
| HEXANAL | 49.3 | 18.0 | 1087 | 1108 |
| 1-PENTEN-3-OL | 60.9 | 18.6 | 1127 | 1116 |
| DI S-BUTYL FORMAL | 61.5 | 19.0 | 1129 | 1120 |
| 1-METHOXY-2-PROPANOL | 57.2 | 19.0 | 1115 | 1120 |
| PENTYL FORMATE | 58.3 | | 1119 | |
| 2-PENTYL PROPIONATE | 65.5 | 19.0 | 1141 | 1120 |
| 2-METHYL-3-PENTANOL | 60.7 | 19.1 | 1126 | 1121 |
| 2-METHYL-3-BUTYN-2-OL | 68.4 | 19.2 | 1149 | 1122 |
| 1,3-PROPYLENE GLYCOL FORMAL | 52.1 | 19.2 | 1098 | 1123 |
| 4-METHYL-2-PENTANOL | 62.7 | 19.4 | 1133 | 1124 |
| PROPYL BUTYRATE | 61.5 | 19.6 | 1129 | 1127 |
| 1,3-BUTYLENE GLYCOL FORMAL | 53.6 | 19.7 | 1103 | 1128 |
| ISOPENTYL ACETATE | 61.1 | 19.6 | 1128 | 1128 |
| ALLYL ACRYLATE | 60.5 | 20.4 | 1126 | 1136 |
| 3-BUTEN-1-OL | 66.1 | 20.5 | 1143 | 1137 |
| NEOPENTYL GLYCOL FORMAL | 57.9 | 20.8 | 1118 | 1140 |
| 5-HEXEN-2-ONE | 62.3 | 21.4 | 1131 | 1147 |
| BUTYL PROPIONATE | 66.7 | 21.5 | 1144 | 1148 |
| 4-HEPTANONE | 63.0 | 21.8 | 1134 | 1151 |
| BUTYL ISOBUTYRATE | 70.0 | 22.3 | 1153 | 1156 |
| 3-HEXANOL | 75.7 | 22.7 | 1168 | 1160 |
| 3-METHYL-2-PENTANOL | 74.0 | 22.7 | 1164 | 1160 |
| 2,4-DIMETHYL-3-PENTANOL | 74.4 | 22.9 | 1165 | 1162 |
| 2,2-DIALLYLOXYPROPANE | 71.9 | 22.9 | 1158 | 1163 |
| 2-METHYL-2-PROPEN-1-OL | 76.9 | 23.0 | 1171 | 1163 |
| 4-METHYL-3-PENTEN-2-ONE | 66.2 | 23.0 | 1143 | 1164 |
| PENTYL ETHER | 74.4 | 23.2 | 1165 | 1165 |
| 2-ETHYL-1-HEXYL VINYL ETHER | 80.3 | 23.2 | 1179 | 1165 |
| 3-METHOXYBUTANAL | 72.7 | 23.6 | 1160 | 1169 |
| 2-METHOXYETHANOL | 72.1 | 23.6 | 1159 | 1169 |
| ISOBUTYL BUTYRATE | 74.9 | 23.8 | 1166 | 1171 |
| 2-METHYL-1-BUTANOL | 79.5 | 23.9 | 1177 | 1172 |
| ISOPENTANOL | 79.9 | 24.0 | 1178 | 1173 |
| 3-HEPTANONE | 72.2 | 24.1 | 1159 | 1174 |
| 1,4-BUTYLENE GLYCOL FORMAL | 64.0 | 24.3 | 1137 | 1176 |
| 6-METHYL-2,4,7-TRIOXAOCTANE | 74.4 | 24.3 | 1165 | 1176 |
| ETHYLBENZENE | 69.6 | 24.3 | 1152 | 1176 |
| P-XYLENE | 75.0 | 24.5 | 1166 | 1180 |
| PENTYL ACETATE | 79.3 | 24.8 | 1177 | 1180 |
| 2-HEXANOL | 84.3 | 25.1 | 1186 | 1182 |
| 2-BUTEN-1-OL | 84.4 | 25.0 | 1189 | 1182 |
| 3-ETHYL-3-PENTANOL | 85.4 | 25.2 | 1191 | 1183 |
| M-XYLENE | 77.6 | 25.3 | 1173 | 1184 |
| TRIOXANE | 74.7 | 25.5 | 1166 | 1186 |
| 2-METHOXY-1-PROPANOL | 84.2 | 25.6 | 1188 | 1187 |
| 2-ETHYL-2-BUTENAL | 74.4 | 25.8 | 1165 | 1189 |
| BUTYL ACRYLATE | 80.5 | 25.7 | 1180 | 1189 |
| 2-HEPTANONE | 84.1 | 26.1 | 1188 | 1192 |
| 1-ACETOXY-2-PROPYNE | 91.0 | 26.1 | 1203 | 1192 |
| DODECANE | 89.4 | 27.0 | 1200 | 1200 |
| CYCLOPROPYL CARBINOL | 91.3 | 27.3 | 1203 | 1201 |
| HEPTANAL | 83.9 | 28.0 | 1188 | 1207 |
| 2-ETHYL-1-BUTYL ETHER | 101 | 28.6 | 1224 | 1212 |
| 2,2-DIMETHYL-1-BUTANOL | 97.2 | 28.7 | 1216 | 1213 |
| 2-ETHOXY-1-PROPANOL | 96.6 | 28.8 | 1213 | 1214 |
| PENTANOL | 100 | 28.9 | 1223 | 1215 |
| 2-ETHYLHEXANAL | 88.1 | 29.1 | 1197 | 1216 |
| ISOPENTYL PROPIONATE | 88.8 | 29.1 | 1198 | 1216 |
| 2-ETHOXYETHANOL | 91.0 | 29.2 | 1203 | 1217 |
| 2-PENTYL BUTYRATE | 10 | 29.4 | 1224 | 1219 |
| 1,1,3-TRIMETHOXYBUTANE | 98.2 | 29.8 | 1218 | 1222 |
| 2-ETHYL-1-BUTYL ACETATE | 100 | 29.8 | 1223 | 1222 |
| 3-METHYL-1-PENTYN-3-OL | 110 | 30.0 | 1241 | 1223 |
| O-XYLENE | 96.0 | 30.1 | 1213 | 1224 |
| DIBUTYL FORMAL | 95.3 | 30.6 | 1212 | 1228 |
| 2-METHOXYETHYL ACETATE | 107 | 30.7 | 1235 | 1229 |
| BUTYL BUTYRATE | 103 | 30.7 | 1228 | 1229 |
| 1,3-BUTYLENE GLYCOL BUTYRAL | 107 | 31.1 | 1226 | 1232 |
| HEXYL FORMATE | 102 | 31.3 | 1226 | 1233 |
| 1-PROPOXY-2-PROPANOL | 104 | 31.5 | 1229 | 1234 |
| CYCLOPENTANONE | 92.8 | 32.0 | 1207 | 1238 |
| 4-HYDROXY-2-ME-3-BUTANONE | 106 | 32.8 | 1233 | 1244 |
| 4-HEPTANOL | 121 | 32.9 | 1258 | 1244 |
| 3-PENTEN-1-OL | 117 | 33.8 | 1252 | 1251 |
| 3-HEPTANOL | 127 | 34.6 | 1267 | 1256 |
| PENTYL PROPIONATE | 114 | 35.5 | 1248 | 1262 |
| 2-METHYL-1-PENTANOL | 136 | 36.1 | 1281 | 1268 |
| 2,4-PENTANEDIONE | 103 | 36.4 | 1228 | 1268 |
| 1,1,3-TRIETHOXYPROPANE | 114 | 37.0 | 1247 | 1271 |
| 2-ETHOXYETHYL ACETATE | 135 | 37.4 | 1.80 | 1274 |
| 2-ETHYL-1-BUTANOL | 138 | 38.1 | 1283 | 1278 |
| 2-HEPTANOL | | 38.3 | | 1279 |
| ISOPENTYL BUTYRATE | 134 | 38.4 | 1277 | 1280 |
| 4-METHYL-1-PENTANOL | 147 | 38.8 | 1295 | 1282 |

| | $V_g$ | | $I_x$ | |
|---|---|---|---|---|
| | 120° | 160° | 120° | 160° |
| CYCLOPENTANOL | 140 | 38.9 | 1287 | 1283 |
| 2-PROPYN-1-OL | 155 | 39.8 | 1306 | 1284 |
| HEXYL ACETATE | 136 | 40.5 | 1281 | 1292 |
| 3-HYDROXY-2-BUTANONE | 140 | 40.7 | 1286 | 1293 |
| 3-METHYL-1-PENTANOL | 157 | 41.4 | 1309 | 1297 |
| 2,2-DIMETHYL-1-PENTANOL | 156 | 41.4 | 1307 | 1297 |
| DIMETHOXYMETHYLAL | 142 | 42.3 | 1288 | 1302 |
| 2-OCTANONE | 146 | 42.7 | 1295 | 1304 |
| HEXANOL | 177 | 45.9 | 1341 | 1321 |
| PENTYL BUTYRATE | 171 | 47.0 | 1325 | 1326 |
| 4-METHOXY-4-ME-2-PENTANOL | 159 | 47.9 | 1310 | 1330 |
| 2-ETHYL-2-HEXENAL | 158 | 49.1 | 1309 | 1336 |
| 3-METHOXY-1-BUTYL ACETATE | 182 | 49.6 | 1337 | 1338 |
| 3-METHOXY-1-BUTYL ACRYLATE | 183 | 49.6 | 1338 | 1338 |
| M-DIETHYLBENZENE | 177 | 49.8 | 1331 | 1339 |
| ET GLYCOL DIBUTYL ETHER | 204 | 51.8 | 1359 | 1348 |
| P-DIETHYLBENZENE | 187 | 52.9 | 1341 | 1353 |
| 3-ETHOXY-1-PROPANOL | 204 | 53.1 | 1358 | 1354 |
| 3-METHOXY-1-BUTANOL | 200 | 53.2 | 1355 | 1354 |
| 5-NONANONE | 185 | 54.6 | 1340 | 1360 |
| CYCLOHEXANONE | 166 | 54.7 | 1319 | 1361 |
| HEXYL ETHER | 227 | 55.4 | 1379 | 1363 |
| ETHYLIDENE DIACETATE | 210 | 55.6 | 1364 | 1364 |
| 2-CHLOROETHANOL | 198 | 56.2 | 1353 | 1367 |
| 4-HYDROXY-4-ME-2-PENTANONE | 202 | 57.0 | 1357 | 1370 |
| O-DIETHYLBENZENE | 204 | 57.5 | 1359 | 1372 |
| 2-ALLYLOXYETHANOL | 226 | 59.3 | 1376 | 1379 |
| HEPTYL ACETATE | 232 | 60.8 | 1383 | 1385 |
| 1-ETHOXY-3-PENTANOL | 233 | 61.3 | 1384 | 1387 |
| 2-BUTOXYETHANOL | 243 | 62.9 | 1392 | 1393 |
| BIS(2*ETHOXYETHYL) ETHER | 256 | 63.0 | 1402 | 1393 |
| 2-OCTANOL | 252 | 62.9 | 1399 | 1393 |
| CYCLOHEXANOL | 238 | 64.1 | 1388 | 1397 |
| CYCLOHEXYL ACETATE | 211 | 64.2 | 1365 | 1397 |
| 4,4-DIMETHOXY-2-BUTANONE | 243 | 64.6 | 1392 | 1398 |
| TETRADECANE | 253 | 64.9 | 1400 | 1400 |
| 2-ETHYL-1-HEXYL ACETATE | 247 | 66.4 | 1396 | 1405 |
| 2-ETHYL-4-METHYL-1-PENTANOL | 274 | 67.6 | 1415 | 1410 |
| 2-METHYLCYCLOHEXANOL | 255 | 68.7 | 1402 | 1413 |
| METHYLENE DIACETATE | 357 | 69.3 | 1466 | 1415 |
| 2-NONANONE | 240 | 70.7 | 1390 | 1420 |
| 2,4-HEXADIENAL | 254 | 72.8 | 1401 | 1426 |
| HEPTANOL | 304 | 74.1 | 1435 | 1430 |
| ACETONYL ACETATE | 314 | 75.4 | 1442 | 1434 |
| DIBUTYL CROTANAL | 346 | 76.9 | 1460 | 1439 |
| 2-ETHYL-1-HEXYL PROPIONATE | 345 | 80.7 | 1460 | 1450 |
| 2,3-DIMETHYL-2,3-BUTANEDIOL | | 81.3 | | 1452 |
| 2-ETHYL-1-HEXANOL | 379 | 84.4 | 1478 | 1460 |
| 2-METHYL-1,2-PROPANEDIOL | | 94.1 | | 1485 |
| ETHYLENE DIFORMATE | 399 | | 1488 | |
| 2-ETHYL-1-HEXYL ACRYLATE | | 97.5 | | 1494 |
| D,L-2,3-BUTANEDIOL | | 100 | | 1500 |
| 2-ETHYL-2-HEXEN-1-OL | | 108 | | 1518 |
| 4-ACETOXYTETRAHYDROPYRAN | 466 | 111 | 1518 | 1524 |
| OCTANOL | 534 | 112 | 1545 | 1526 |
| MESO-2,3-BUTANEDIOL | | 112 | | 1526 |
| 4-HYDROXY-2-BUTANONE | 470 | 114 | 1520 | 1530 |
| ETHYLENE DIACETATE | 506 | 120 | 1534 | 1542 |
| 1,2-PROPANEDIOL | | 121 | | 1544 |
| TRIMETHOXYMETHYLAL | 561 | 134 | 1554 | 1560 |
| 1,3-HEXANEDIOL | | 143 | | 1582 |
| 2-METHYL-2,4-PENTANEDIOL | | 143 | | 1583 |
| 1-HYDROXY-2-ME-3-BUTANONE | 641 | 146 | 1580 | 1587 |
| ETHYLENE GLYCOL | | 147 | | 1588 |
| 1,3-BUTYLENE DIFORMATE | 630 | 150 | 1576 | 1594 |
| HEXADECANE | 710 | 154 | 1600 | 1600 |
| 1,2-BUTANEDIOL | | 177 | | 1633 |
| 2,4-PENTANEDIOL | | 181 | | 1637 |
| NONANOL | 906 | 181 | 1648 | 1638 |
| 1,3-BUTANEDIOL | | 228 | | 1692 |
| 3-METHYL-2,4-PENTANEDIOL | | 254 | | 1717 |
| 1,3-PROPANEDIOL | | 270 | | 1731 |
| 2,2-DI ME-1,3-PROPANEDIOL | | 291 | | 1749 |
| 2,4-HEPTANEDIOL | | 358 | | 1797 |
| OCTADECANE | 1960 | 362 | 1800 | 1800 |
| 2-METHYL-1,3-PENTANEDIOL | | 384 | | 1814 |
| 1,4-BUTANEDIOL | | 469 | | 1861 |
| DIETHYLENE GLYCOL | | 495 | | 1917 |
| 1,5-PENTANEDIOL | | 742 | | 1970 |
| 2-BUTEN-1,4-DIOL | | 774 | | 1983 |
| 3-METHYL-1,5-PENTANEDIOL | | 966 | | 2022 |
| 1,2-OCTANEDIOL | | 987 | | 2025 |
| 1,6-HEXANEDIOL | | 1154 | | 2051 |

Table 32

MAJOR ODOROUS CONSTITUENTS OF VAPOR SAMPLES FROM PRESSED CRACKLINGS [1]

| Consecutive Peak Number [2] | Type of Column Used | |
|---|---|---|
| | SP-1000 [3] | Pennwalt 223 [3] |
| 1 | Ammonia, trimethylamine, acetone (possible), n-pentene (butanal also possible), saturated $C_6$ hydrocarbon or pentanal, saturated $C_7$ hydrocarbon | Ethane (Kovats 200) |
| 2 | Heptene (?), $C_8$ hydrocarbon (?) | Ammonia, ethylene |
| 3 | Methanol (?), methyl ethyl ketone, saturated $C_9$ hydrocarbon | Propene |
| 4 | Ethanol, benzene, unsaturated $C_7$ hydrocarbon, dimethylpentadiene (1-heptyne also possible), (5-methyl-2-hexyne also possible) | Isobutene |
| 5 | 1-Propanol (acetic acid possible), toluene | Trimethylamine |
| 6 | 2-Methyl-1,3-pentadiene (?), ethylvinyl ether (?) | n-Pentane (500) |
| 7 | Xylenes, tricyclene | Acetone |
| 8 | A $C_7$ hydrocarbon (diene,-yne or cycloalkene), a $C_8$ hydrocarbon or $C_7$ ketone (eg. 2-heptanone) | n-Hexane (600) |
| 9 | A $C_{10}$ alkyne or diene or substituted cyclohexene | 2-Methyl propanal |



Table 31 (cont.)

Note: $V_g$ = retention volume of carrier gas.

$I_x$ = Kovats index.

Data are for constant temperature runs at 120 or 160°C. For temperature-programmed runs the Kovats indices will be slightly different.

Table 33

MAJOR ODOROUS CONSTITUENTS OF VAPOR SAMPLES FROM COOKER LIQUID[1]

| Consecutive Peak Number[2] | Type of Column Used | |
|---|---|---|
| | SP-1000[3] | Pennwalt 223 |
| 1 | Ethanol | Trimethylamine |
| 2 | Propanol, 2-ethylbutonic acid (?), toluene | An alcohol |
| 3 | Methyl butanol | An amine |
| 4 | Butenal (?) | Carbon dioxide, an amine |
| 5 | Butanol | Nitrogen containing compound |
| 6 | 1-Pentene | An amine |
| 7 | Hexanol | Spectrum too complex |
| 8 | Xylene | Spectrum too complex |
| 9 | Furfuryl alcohol (?) | Spectrum too complex |
| 10 | Possibly phenol, too weak to be sure | Spectrum too complex |
| 11 | p-Cresol or benzyl alcohol | Spectrum too complex |

[1]Identified by GC-MS techniques; [2]Given in order of elution from the respective column;

[3]The question mark designates a non-positive identification.



Table 32 (cont.)

| Consecutive Peak Number[2] | Type of Column Used | |
|---|---|---|
| | SP-1000[3] | Pennwalt 223[3] |
| 10 | 1,3,7 Octatriene-5-yne (but could also be styrene on cyclooctatetraene | Tetrahydropyran, 2-Methyl furan (947) |
| 11 | Butyne-ol (?), $C_4$ substituted benzene | 3-Methyl-hexane (possibly n-heptane) (700) |
| 12 | Dimethyl pyrazine | n-Pentanal |
| 13 | 1-Hexanol | Trichloroethylene |
| 14 | Dimethyl ethylpyrazine (methoxy benzaldehyde somewhat possible) | Saturated $C_8$ hydrocarbon (probably (800) 2,4-dimethylhexane or 3-methyl-heptane or n-octane, unsaturated $C_7$ hydrocarbon or a $C_6$ aldehyde. |
| 15 | Hexyne-ol ? | Dimethyl disulfide (1110) |
| 16 | Hexadiene (?), benzaldehyde | Toluene |
| 17 | An alcohol ($C_7$ or $C_8$ possible) | 2-Methyl furan (?) |
| 18 | Methyl naphthalene | Spectrum too complex |
| 19 | Dimethyl naphthalene, biphenyl | Spectrum too complex |
| 20 | Acenaphthene | Spectrum too complex |

[1]Identified by GC-MS techniques; [2]Given in order of elution from the respective column;

[3]The question mark designates a non-positive identification.

plants. The odorous peaks were also described, and this information is summarized in the first few columns of Table 34. An asterisk indicates the most significant odorous peaks, while a plus sign indicates other significant odorous peaks.

10.4 Third Mass Spectrometer Identification Series

An additional series of mass spectrograph-chromatograph experiments was done on two samples obtained from a local rendering plant. Both the air from the press and the air after the cooker condenser were sampled. The objective was to identify the compounds responsible for the major odorous peaks previously established by panel tests. This work was done using a 10-ft SP-1000 column. Improved experimental techniques resulted in identification of additional odorants. The results are summarized in Table 30.

These mass spectrograph identifications were far more successful than any previously done and most of the odorous peaks appear to be identified. The following sulfides were found to be important: methyl sulfide, methyl disulfide, and propylene sulfide. The following nitrogen compounds were found to be important: trimethylamine, butylamine, quinoline, dimethyl, methylethyl, and trimethyl pyrazines. Other peaks with amine-like odors were not identified. A number of $C_4$ to $C_7$ aldehydes, ketones, and alcohols were also found, but specific compounds could not be definitely identified due to interference of hydrocarbons present. Acids were not identified, although several odorous peaks occur at Kovats indices where acids are expected. The acids may have been present in too low concentrations for the mass spectrometer. Several acids were tentatively identified in the first project. Butyric acid was included as one of the odorants being studied.

Table 34

IDENTIFICATION OF MAJOR ODOR COMPONENTS IN RENDERING ODORS

| Important Odorous Peaks | | | | | Mass Spectrometer Identification | | Other Possibility | |
|---|---|---|---|---|---|---|---|---|
| Odor Note | Time, sec | Odor Panel Regression | Peak No. | Kovats Index | Kovats Index | Compound | Kovats | Compound |
| Sulfide | 30 | | 52 | | 830 | Dimethyl sulfide | | |
| Grassy | 237 | | 16 | 1062 | 1010 | Pentanal | | |
| Sulfur | 236 | * | 18 | 1073 | 1035-1105 | Dimethyl disulfide | | |
| Sulfur | 173 | + | 20 | 1028 | 970 | (A sulfur compound) | | |
| Cabbage | 880 | * | 14 | 1325 | 1370 | (Dipropylene sulfide) | | |
| Sour | 52 | | 50 | 804 | 800<br>880 | Trimethylamine<br>$C_4$ Aldehyde | | |
| Yeast | 53 | | 44 | 804 | 800 | Vinyl butyl ether | | |
| Amine | 107 | | 26 | 933 | | | | |
| Amine | 107 | | 28 | 1028 | 980 | (An amine) | 950 | (Butylamine) |
| Amine | 248 | + | 36 | 1070 | 1015 | (Butanedione) | | |
| Amine | 303 | | 30 | 1115 | | | 1112 | (Isobutylamine) |
| Amine | 374 | | 32 | 1161 | | | | |
| Amine | 447 | | 34 | 1187 | | | | |
| Oil | 131 | | 38 | 984 | 945-1000 | Benzene | | |
| Refinery | 538 | | 24 | 1227 | 1210 | $C_3$ Benzene | | |
| Burnt | 1233 | + | 40 | 1440 | 1390<br>1470<br>1510 | (Dimethyl pyrazine)<br>(Trimethyl pyrazine)<br>(Dimethyl-ethyl-pyrazine) | | |
| Rendering | 1335 | + | 22 | 1488 | 1410 | (Nonadienal) | 1570 | (Butyric acid) |
| Burnt | 1687 | * | 42 | 1618 | 1700<br>1660 | Quinoline<br>(A sulfur compound) | | |
| Bitter | 655 | + | 46 | 1251 | | | 1205 | (Heptanol) |
| Unpleasant | 474 | | 56 | 1201 | 1150 | (A sulfur compound) | | |
| Unpleasant | 1860 | * | 54 | 1634 | 1620 | Me-indole or -indene | (1650) | (Isovaleric acid) |
| Cheesy | 2002 | + | 48 | 1686 | | | 1690 | (Valeric acid) |
| Unpleasant | 2582 | + | 58 | 1812 | | | (1810) | (Hexanoic acid) |
| Popcorn | 810 | | 60 | 1306 | 1260 | Difurfuryl ether | | |

NOTE: Tentative identifications are in parentheses. Estimated Kovats indices are in parentheses.

* indicates most significant odorous peaks + indicates other significant odorous peaks

APPENDIX A

REFERENCES



A. Rendering Industry

A-1 Air Pollution Aspects of the Inedible Rendering Industry, Walsh, Robert T., J. of the Air Pollution Control Assoc., Feb. 1967, 17(2), 94-7.

Informative Report No. 7 on the inedible rendering industry is one of a series of survey reports prepared by APCA's T1-2 Committee on air pollution problems and control methods encountered in the chemical industry today.

A-2 Air Pollution Engineering Manual, APCD of Los Angeles County, US Public Health Service Publication No. 999-AP-40, 1967.

Contains a description of the rendering process and of the standard odor control methods, as well as design rules-of-thumb.

A-3 Odor Sources and Odor Control Systems in the Rendering Industry, Faith, W. L., Report to Fats & Proteins Research Foundation, Inc., 1967.

Discusses sources of odors in rendering plants, odor prevention methods, and odor control methods.

B. Novel Methods

B-1 Efficiency of a Chemical System for Removing an Offensive Odor from a Bonemeal Fertilizer Plant, Muranaka, Hiromu; Hashimoto, Hiroshi; Araki, Kazuo; Ioku, Tsuneo; Yamamoto, Akira; Tatsumi, Teruo; Tsuchida, Tadafumi; Konishi, Kazuya; Ikeda, Hiroshi (Hokensyo, Osaka, Japan). Kagaku To Kogyo (Osaka) 1970, 44(6), 314-17 (Japan).

The source of the odor from the plant was an autoclave for steaming animal bones and the pans for concentration of the glue solution. Compared with other systems, such as washing with water and adsorption by resin or activated C, a contact reaction by alkali (NaOH, $Ca(OH)_2$, etc.) and by acid (sulfuric, oxalic) was suitable.

B-2 Odor Abatement in the Rendering and Allied Industries, Teller, A. J., J. of the Air Pollution Control Assoc., April 1963, 13(4), 148-9, 166.

B-3 Prevention of Offensive Odor from Fish Processing Plants. II. Effect of Enzymes and Nitrohumic Acid Treatments on Reduction of the Odor from Squid Waste, Motohiro, Terushige; Terachi, Hitoshi (Fac. Fish., Hokkaido Univ., Hakodate, Japan). Hokkaido Daigaku Suisan Gakubu Kenkyu Iho 1969, 20(2), 134-41 (Japan).

A study was made to reduce the offensive odor from squid waste: proteinase activity is highest at 30-50° to decompose nitrogenous compounds in the waste leading to odor evolution. The odor can be absorbed in diatomaceous earth. Cellulase and amylase can also digest the waste, but their activities are lower than that of proteinase. Nitrohumic acid can control ammoniacal odor of the putrid smell at 0.5-2.0% level, but is unable to control the acid smell evolved from decayed waste. Application of nitrohumic acid to a waste containing high oil would be an improper way to prevent malodor.

C. General Discussions

C-1 Catalytic Afterburning of Industrial Gases, Betz, E. C. and Feist, H. J. (KAVAT Co., Gondsroth, Ger.), Technik (Berlin) 20(6), 395-401 (1965) (Ger).

A survey is given of the chemistry and technology of the treatment of gases containing hydrocarbons and N oxides mixtures. Translation available.

C-2 Controlling Industrial Odors, Yocom, John E., Chem. Eng., June 15, 1970, 160-8.

Industrial odors can be handled as chemical engineering problems; the key is to reduce the concentration of odorants at the receptor, i.e., the nose.

C-3 Incineration of Process Wastes, Frankel, Joseph I., Chem. Eng. 73(18), 91-6 (1966) (Eng.).

The disposal of industrial wastes by incineration is discussed. Equipment designed for solid, liquid, and gaseous wastes is described.



C-4 Industrial Odor Control., Turk, Amos (City Coll., City Univ. of New York, New York, N.Y.), Chem. Eng. (New York), 1969, 77(9), 199-206 (Eng.).

In this survey, the accepted methods of odor control are reexamined with emphasis on the inaccuracies and uncertainties which occur in practice. The discussion includes: the validity of outdoor dilution calculations; the measurement of odors by the dilution-to-threshold technique; the role of particulate matter; odor threshold variability; air oxidation; activated C adsorption; counteraction; and masking.

C-5 Industrial Odor Control and Its Problems, Turk, Amos, Chem. Eng., Nov. 3, 1969, 70-8.

In this discussion, therefore, I shall reexamine some of the accepted methods of odor control, with special emphasis on what can go wrong either in the methods themselves or in our assumption about how much control is necessary.

C-6 Methods of Air Deodorization, Summer, W., Elsevier, 1963.

General discussion of odor control methods.

C-7 A New Job for the Perfume Industry: Industrial Odor Removal, Sherwood, P. W., Parfum., Cosmet., Savons 5, 390-3 (1962).

The principal methods used in the elimination of industrial odors, including catalytic combustion, absorption and adsorption, and the use of masking agents and deodorizers, are described.

C-8 Odor Control at a 2,4-D Production Plant, Henshaw, T. B., J. of the Air Pollution Control Assoc., Nov. 1965, 15(11), 516-8.

Chlorinated phenolic hydrocarbons are used as intermediate chemicals in the manufacture of 2,4-D (2,4-Dichlorophenoxy-acetic Acid) and related herbicides. These chemicals have an unusual odor with an extremely low threshold level of detection and consequently the manufacture and handling of these compounds poses a difficult odor control problem. Chipman Chemical Company at its Portland, Oregon, plant has developed a system of fume collection and caustic soda solution scrubbing capable of removing phenolic compounds in the plant exhaust air to an acceptable level from an odor release standpoint. This article describes the development, present status, and projected future improvements of this odor control system.

C-9 Off-Gas Deodorizing, Palczynski, Ryszard; Glowiak, Bohdan (Politech. Wroclaw, Wroclaw, Polant), Gaz. Woda Tech. Sanit., 1968, 42(5), 157-60 (Pol.).

A survey is given of deodorization of off gases in industry. No new material.

C-10 Prevention of Pollutant Odors Caused by Organic Compounds, Franzky, Ulrich (Landes Nordrhein-Westfalen, Essen, Ger.), Staub, Reinhaltung Luft 1968, 28(3), 113-9 (Ger).

A detailed discussion is given of the different methods used for controlling odors from industrial processes, particuarly the chemical industry. The methods include thermal and catalytic combustion, ozonolysis, scrubbing in packed columns, and adsorption on activated carbons in continuous systems.

C-11 The Technology of Gas Cleaning: State of the Art., Hall, H. J., Trans. N.Y. Academy of Sciences, 147-64.

This paper reviews technology which is available and proven for controlling particulate emissions from stationary sources. In view of the importance of and legislative pressure for reducing sulfur oxide emissions, the state of the art of controlling this source of pollution is discussed in reasonable detail.

C-12 Use of Packed Beds for Separation of Entrained Particles and Fumes from an Air Stream, Eckert, John S., J. of the Air Pollution Control Assoc., Feb. 1966, 16(2), 95-8.

This paper deals with packed beds in discussion of separation of entrained particles and fumes from an air stream. Packed beds develop between the gas and liquid a maximum of contact in order to get maximum mass transfer from a gas to a liquid phase, and they are considered to be one of the better methods of scrubbing contaminants from a gas stream.



## D. Design Data

D-1 Absorption of Chlorine in Water, Vivian, J. E.; Whitney, R. P.; Chem. Eng. Prog. 1947, 43(12), 691, 693.

Results of a study of the absorption of chlorine in water to produce bleach for pulp-mill operations are presented.

Chlorine absorption, because of low solubility, is expected to be a case of liquid film controlling. This is confirmed by the findings that the coefficient varies as the 0.6 power of the liquor rate and the 6th power of the absolute temperature, and is independent of the gas rate. These coefficients are lower than those predicted by the Sherwood and Holloway correlation, and an explanation of this lack of agreement, based on the relative rates of hydrolysis and of diffusion, is offered.

A pseudocoefficient, using an unhydrolyzed chlorine driving force, is proposed, and its relation to predicted values is discussed.

D-2 Catalytic Afterburning of Industrial Waste Gases--Its Basis and Technical Application, Gerhard Vollheim (Degussa Branch Office, Hanau, Ger.), Dechema Monograph, 52(895-911), 203-17 (1964) (Ger.).

By using suitable catalysts, such as Pt metals on metallic, ceramic, or oxide supports, base-metal oxides on oxide supports, the afterburning of organic waste gases from industrial processes can be carried out at 250°. The advantages and disadvantages of the various types of catalysts can be assessed from molecular-kinetic considerations. Practical examples are cited in which the process has already proved itself.

D-3 Concentration and Recovery of Atmospheric Odor Pollutants Using Activated Carbon, Brooman, David L.; Edgerley, E. Jr.; J. of the Air Pollution Control Assoc., Jan. 1966, 16(1), 25-9.

Activated carbon filters were used to concentrate atmospheric mixtures of acrolein, methyl sulfide, and n-propyl mercaptan. Removal efficiency and carbon capacity for each of the odor compounds were investigated using two different carbons, Cliffchar (4-10 mesh) and Barnebey-Cheney (C-4). A closed system was devised to establish a known atmospheric odor concentration for each filter run. Solvent extraction techniques were employed to

desorb and recover the odor compounds from the carbon filters. All quantitative analyses were conducted with gas liquid chromatography utilizing the hydrogen flame ionization detector. The removal studies conducted indicate that the efficiency of removal of a carbon filter is essentially 100% up to the point of filter breakthrough. This breakthrough point is governed by the filter's capacity for a particular compound. This study indicated that the filter capacity is dependent both on the type of carbon employed and the particular odor compound adsorbed. Solvent recovery of the odor compounds from the carbons varied from 0 to 4.5% for the mercaptan up to 96 to 98% for acrolein. Percent recovery was found to vary for a given odor compound with different carbons and for a given carbon with different odor pollutants.

D-4 The Design and Performance of a Bootstrapping Direct Flame Afterburner, Ridgway, S. L.; Lair, J. C.; J. of the Air Pollution Control Assoc., July 1962, 12(7), 340-7.

D-5 Efficient Design of Afterburners for Incineration of Many Industrial Fumes, Crouse, Lowell F.; Waid, Donald E.; Air Eng., 9(8), Aug. 1967, 20-3, 29.

Combustion methods to remove organic or C-containing substances from gaseous effluent streams are reviewed. The two general combustion methods involve catalytic oxidation and direct flame incineration in an afterburner. Designs of industrial direct flame incineration equipment are discussed. Quantitative data are given comparing the performance of a single-burner tunnel-type burner and the Combustifume Burner. For example, to obtain an outlet stream containing 30 ppm hydrocarbons an average temperature of 1450°F is required in a tunnel-type single burner while in the Combustifume line burner, a temperature of 1130°F is required.

D-6 Energy and Efficiency Characteristics of the Ejector Venturi Scrubber, Harris, L. D., J. of the Air Pollution Control Assoc., July 1965, 15(7), 302-5.

The scrubbing and pumping actions in the Ejector Venturi Scrubber are two separate phenomenon occurring simultaneously. Each phenomenon requires energy and has efficiency of operation and collection efficiency. These energy and efficiency relationships are discussed and illustrated in the form of numerous graphs. The scrubbing energy requirements and how they vary with particle sizes down to one micron are also discussed and presented in the form of numerous graphs.



D-7 An Evaluation of Catalytic and Direct Fired Afterburners for Coffee and Chicory Roasting Odors, Sullivan, J. L.; Kafka, F. L.; Ferrari, L. M.; J. of the Air Pollution Control Assoc., Dec. 1965, 15(12), 583-6.

Though the aroma of roasting coffee can be pleasant in small amounts, large scale plants tend to cause public complaints. As a means of control thermal afterburners operating at 1200°F and higher have been commonly employed. Australian coffee consumption in the past has been relatively small but in recent years it has been increasing markedly. As a result, odor complaints have been increasing and one plant, large by Australian standards, caused a public outcry of no small order. High cost of fuel rendered thermal afterburning unattractive and, consequently, the firm in question decided upon catalytic combustion as an alternative. Subsequently, the unit was installed and before and after tests were made for various components. At an operating temperature of about 700°F the results showed comparable fume reductions to thermal afterburning and the findings were confirmed by the cessation of complaints by the public.

D-8 Fume Control in Wire Enameling by Direct-Flame Incineration, Benforado, David M.; Waitkus, Joseph; J. Of the Air Pollution Control Assoc., Jan. 1968, 18(1), 24-6.

The results of source tests to demonstrate the applicability of direct-flame incineration for the control of the effluent from a wire-enameling bake oven are presented. The tests were conducted with a portable direct-flame incinerator under actual plant conditions. The efficiency of direct-flame incineration was established at incineration temperatures of 1000°F, 1200, and 1400°F. Evaluation of incineration efficiency was performed by both analysis and quantitative odor measurement using an odor panel.

D-9 Fume Incineration with Combustion Air at Elevated Temperature, Meyers, F. D.; Waitkus, Joseph; J. of the Air Pollution Control Assoc., July 1966, 16(7), 378-82.

The description of a unique system for the decomposition of objectionable fumes, applied for air pollution control to a fiber glass curing oven. The investigations preceding the development of the system are covered, followed by a description of the principal components of the system combining recuperative and regenerative heat exchange to produce a combustion air temperature appreciably above ambient.

D-10 Gas Absorption in Beds of Rings and Saddles, Leva, Max, A.I.Ch.E. Journal, 1(2), 224, 225, 1955.

New data are presented for the system carbon dioxide-sodium hydroxide. The effect of $CO_3^=$ buildup upon $K_Ga$ values was investigated first and the data were then used to construct a curve by means of which all data were corrected to an arbitrarily chosen reference state of 25% $CO_3$ concentration. $K_Ga$ values increased with increasing liquid rate but were not dependent on gas rate if the packings were operated below loading. For some packings examined in the loading range, however, $K_Ga$ values increased with increasing gas rate.

$K_Ga$ values examined in relation to specific surface area were found to be very irregular in connection with rings. The surface-area utilization pattern of the saddles was considerably more uniform. The ring and saddle data for the carbon dioxide-sodium hydroxide system were in good qualitative agreement with the ammonia absorption data of Fellinger and the water-water vapor data of Mehta and Parekh.

D-11 Odor Control in Poultry By-products Rendering, A Case History, Industrial Standards Committee, National Renderers Assoc. Odor Control Manual, 1971.

Describes installation of a Peabody scrubber (impingement baffle plate) in a rendering plant. It seemed to control the odor.

D-12 Some Data and Observations on Combustion of Gaseous Effluents from Baked Lithograph Coatings, Wallach, Abraham, J. of the Air Pollution Control Assoc., Mar. 1962, 12(3), 109-10.

D-13 A Study of Catalyst Support Systems for Fume-Abatement of Hydrocarbon Solvents, Miller, M. R.; Wilhoyte, H. J.; J. of the Air Pollution Control Assoc., Dec. 1967, 17(12), 791-5.

In a stainless steel pilot plant system, operating with combined thermal incineration and catalytic oxidation, studies have been made of the influence of catalyst-support geometry on abatement efficiency. Catalyst supports tested were ceramic spherical pellets, metal foils, and ceramic honeycomb structures, all with precious metal catalyst. Data obtained cover a range of space velocities from 30,000 to 175,000 scf/hr-cu ft bed and a range of catalytic reactor temperatures from 150 to 450°C. Results show that optimum fume-abatement performance is obtained by combining incineration and catalytic oxidation and that catalyst support geometry has a significant effect on performance.



## E. Design Methods

E-1 Absorption, Distillation and Cooling Towers, Norman, W. S., Wiley, 1962.

E-2 Absorption Towers, Morris, G. A. and Jackson, J., Butterworths, 1953.

E-3 Chem. Engrs. Handbook, 4th Ed., Perry, J. H., (Ed.), McGraw-Hill.

E-4 Distillation, Van Winkle, Mathew, McGraw-Hill, 1967.

E-5 Mass Transfer and Absorbers, Hobler, T., Pergamon Press, 1966.

E-6 Mass Transfer Operations, Treybal, R. E., McGraw-Hill, 1967.

E-7 Mass Transfer Process Calculations, Sawistowski, H. and Smith, W., Interscience Publ., 1963.

E-8 Tower Packings and Packed Tower Design, Leva, Max, U.S. Stoneware Co., 1953, Akron, Ohio.

E-9 U.S. Stoneware Co., "Packed Tower Design Manual," Akron, Ohio.

E-10 Mass Transfer in Heterogeneous Catalysis, Satterfield, C. N., M.I.T. Press, 1970.

## F. Cost Data

F-1 Air Pollution Manual Part II, Control Equipment, American Hygiene Association, Detroit, Michigan 48227, 1968.

Contains costs of control equipment.

F-2 Control techniques for Particulate Air Pollutants, US Public Health Service Publication AP-51, 1969.

Describes sources in various industries and gas cleaning devices. Gives extensive data on costs of equipment.

F-3 The Development of a Condenser for Odor Control from Dry Rendering Plants, Strauss, W., J. of the Air Pollution Control Assoc., Oct. 1964, 14(10), 424-6.

A new surface condenser and carbon adsorber has been developed which provides an economical solution to the problem of odors from dry rendering plants.

F-4 Fume Control in Rubber Processing by Direct-Flame Incineration, Sandomirsky, Alex G.; Benforado, David M.; Grames, Lloyd D.; Pauletta, Carl E.; J of the Air Pollution Control Assoc., Dec. 1966, 16(12), 673-6.

The application of direct-flame incineration to successfully eliminate a smoke-oil-mist and odor problem in the manufacture of rubber-base rug underlay, is presented. The investigation of various air pollution control processes leading to the development and adoption of the direct-flame incineration system, is covered. The rug-underlay curing process incorporating the direct-flame incineration system with primary heat recovery is described. Results and discussion of a source test to determine the effectiveness of direct-flame incineration in this application are included.

F-5 Fume Incineration, Brewer, Gerald, L., Chem. Eng. Oct. 14, 1968, 160-5.

Direct flame, thermal or catalytic incineration may be the most economical way to remove odor-causing gases and vapors from chemical processes. Success in coming up with the most effective and lowest cost system rests in thorough consideration of design parameters.

F-6 Odor Control by Catalytic and High-Temperature Oxidation, Hein, Glen M. (Battelle Mem. Inst., Columbus, Ohio), Ann. N.Y. Acad. Sci. 116(2), 656-62 (1964.

Direct-flame and catalytic combustion, the odor-laden effluent, together with sufficient air for combustion, is fed into a gas- or oil-fired combustion chamber where proper conditions of temperature, time, and turbulence are provided. The direct-flame afterburner method is ideally suited for the control of residual odors from small and medium size refuse incinerators that are operated intermittently. With such incinerators, the exhaust gases are already hot, and auxiliary fuel is fired to maintain temperatures required for destruction of odor in the afterburner, which is an integral part of the refuse incinerator. Combustion with air on catalyst surfaces reaches completion at much lower temperatures than those required for conventional flame burning. At lower temperatures combustion is flameless. The oxidation catalysts used in odor control applications are Pt alloys or a combination of Pt and $Al_2O_3$.



F-7 Odor Control in Rendering by Wet Scrubbing - A Case History, Anderson Leonard W., Carolina By-Products Co., National Renderers Assoc. Odor Control Manual, 1971.

Cost data on a specific wet scrubber installation.

F-8 Plant Design and Economics for Chemical Engineers, Peters, M. S. and Timmerhaus, K. P., McGraw-Hill, 1968.

F-9 Study of Costs of Non-condensable Fume Incinerators for Rendering Plant Effluents, Heilman, Bill, National By-Products, Inc., Des Moines, Iowa, 1970, National Renderers Assoc. Odor Control Manual, 1971.

Contains calculated cost comparisons for fume incinerators with and without heat exchangers.

F-10 Tellerette Manual, Ceilcoate Co., 140 Sheldon Road, Berea, Ohio 44017.

## G. Experimental Apparatus

G-1 Chemical Reactions on a Rotating Disk., Litt, M. and Serad, G., (Univ. of Pennsylvania, Philadelphia), Chem. Eng. Sci. 19(11), 867-84 (1964) (Eng.).

A model for a 2-component, rapid chemical reaction for the case of laminar flow on a rotating disk was developed. Data were obtained for dissolution of benzoic acid (I), cinnamic acid (II), and $\beta$-naphthol (III) in $H_2O$; of reaction of I with aqueous NaOH; and for dissolution of napthalene in air. The data agree with theory except for II and III. The rotating disk system is recommended for fundamental investigations of combined transport and reaction.

G-2 Kinetics of Liquid-Film Process in Gas Absorption. Part I: Models of the Absorption Process, Danckwerts, P. V.; Kennedy, A. M.; Trans. Instn. Chem. Engrs., 1954, 32, Supplement, 49-2.

Three models of the processes involved in the absorption of gas into agitated liquids are compared. These are: steady-state diffusion through a stagnant film; transient absorption into surfaces which are systematically replaced by fresh liquid; and transient absorption into surfaces which are randomly replaced. It is shown that the three models lead to closely similar predictions about the effect of physico-chemical variables (solubility, diffusivity, reaction rate, etc.) on the rate of absorption.

Hence if one of the models is correct the effects of changes in these variables will not distinguish between them, but on the other hand the formulae derived for any of the models can be used for prediction.

G-3 Kinetics of Liquid-Film Processes in Gas Absorption. Part II. Measurements of Transient Absorption Rates, Danckwerts, P. V.; Kennedy, A. M.; Trans. Instn. Chem. Engrs., 1954, 32, Supplement, 53-9.

Values of the physico-chemical quantities discussed in Part I are often not available, and are difficult or impossible to measure. The second and third models considered do not require explicit knowledge of these quantities, but only measurements of transient rates of absorption for short times of contact between gas and liquid. Such transient rates have been measured in an apparatus incorporating a rotating drum. Carbon dioxide was absorbed into water, solutions of salts, buffer solutions and sodium hydroxide solution. Times of exposure were less than 0.25 sec. Comparison with rates of absorption in a packed column suggests that none of the three models gives an adequate descritpion of the absorption process.

There is prima facie evidence of a substantial surface resistance to the absorption of carbon dioxide in water.

G-4 Liquid Phase Mass Transfer Rates and Effective Interfacial Area in Packed Absorption Columns, Fumitake Yoshida; Tetsushi Koyanagi; Ind. and Eng. Chem., Mar. 1958, 50(3), 365-7, 368.

The present work was intended to obtain a more general correlation for liquid phase mass transfer rates in packed columns. Studies were made on the absorption of pure carbon dioxide into water and methanol in a column packed with spheres, Raschig rings, and Berl saddles as well as in a bead column containing spheres connected in a vertical row. Reasonable correlations among the height of a transfer unit, the Reynolds number, and physical properties of the liquid phase were obtained. The effective interfacial area in the packed column and its variation with liquid rates were determined for both water and methanol.



G-5 Mass and Heat Transfer from an Enclosed Rotating Disk With and Without Source Flow, Kreith, Frank, Doughman, E., and Kozlowski, H. (Univ. of Colorado, Boulder), J. Heat Transfer 85, 153-63 (1963).

The heat-transfer characteristics of a partly enclosed rotating disk were investigated experimentally by means of a mass-transfer analog. Mass-transfer rates to air from naphthalene-coated disks 4 and 8 in. in diameter were measured at 0-10,000 r.p.m., and the effect of the spacing between the rotating disk and its housing was studied with and without source flow. From the experimental results a dimensionless correlation equation suitable for predicting average heat- and mass-transfer coefficients for rotating disks with source flow in turbulent flow at rotational Re up to $4 \times 10^5$ was deduced. The flow pattern was studied with a hot wire, a smoke visualization technique, and the china clay method.

## H. Odor Analysis

H-1 Analysis of Odorous Gases Generated from Fish-Solubles and Fish Meals, Kuroda, Daisuke (Osaka-Shiritsu Kogyo Shikensho, Osaka, Japan). Kagaku To Kogyo (Osaka) 1969, 43(7), 367-70 (Japan).

To obtain the fundamental information to remove odorous gases generated from fish products, a 10-g sample was placed in a 500-ml flask and heated to 250° in increments of 5°/min. After trapping the high boiling decomposition products, the gaseous component was introduced into a gas chromatograph, with a 2-m column packed with dioctyl phthalate and analyzed at 120° column temperature with 50 ml/min H. Identification of peaks was done by comparison of retention times with standard substances and chemical identification of radicals by using a reaction tube packed with sodium nitroprusside, $Pb(OAc)_2$, or isatin, connected to the gas exit of the gas chromatograph. As standard substances, the compounds and these retention time (sec.) are given as follows: $NH_3$ (Ia), 47.8; $Me_2NH$, 67.5; $Me_3N$ (II), 75.0; $EtNH_2$, 76.0; iso-$PrNH_2$ (IIIa), 108.0; n-$PrNH_2$ (IIIb), 127.5; $Et_2NH$ (IV), 142.5; iso-$BuNH_2$ (Va), 165.0; n-$BuNH_2$ (Vb), 187.5; $Et_3N$ (VI), 225.0; n-pentylamine, 247.7; n-$Pr_2NH$

(VII), 262.5; $H_2S$ (Ib), 48.0, MeSH (VIII), 56.0; EtSH (IX), 95.0, iso-PrSH, 106.0; n-PrSH, 165.0; sec-BuSH, 179.0; n-BuSH, 290.0. From practical samples, only 9 peaks were separated as retention time of 48, 60, 75, 90, 114, 143, 180, 216, and 258. So these 9 peaks were identified as Ia + Ib, VIII, II, IX, IIIa or IIIb, IV, Va or Vb, VI, and VII, respectively. Relation between the peak heights and heating times or temperatures were also shown. In the case of fish-solutions, the order of peak area of these components was II > III > V > IV, but with fish-meal, it was II > IV > III > V.

H-2 Identification of Chemical Constituents in Rendering Industry Odor Emissions, IITRI Project C8172, Fats & Proteins Research Foundation, Inc.

Analytical studies conducted on rendering odor samples were based on both vapor samples gathered at the plant sites and on synthetic laboratory vapor samples prepared from solid plant samples. Odorous components were identified by a combination of gas chromatographic-olfactronic techniques coupled with mass spectrographic analysis. More than 30 components were identified and showed the presence of such classes of organic species as alkanes, aldehydes, ketones, aromatics, acidic and miscellaneous compounds. Analysis by gas chromatography-sulfur detection methods showed the presence of sulfur components in all samples studied. Threshold data on the components identified by mass spectrographic analysis are also reported.

# APPENDIX B

# ODOR CONTROL COST COMPARISONS

## Comparative Costs for Catalytic and Flame Afterburner

| Case No. | Operating Condition: Extent of Waste Heat Recovered | Operating Condition: Calorific Value of Odor Source Gas | Item of Cost | Unit Costs, $/hr. per 1,000 cfm.: Catalytic Method | Unit Costs, $/hr. per 1,000 cfm.: Direct-Flame Method | Cost Ratio Flame/Cat. |
|---|---|---|---|---|---|---|
| 1 | None | Nil | Fixed charges | $0.15 | $0.10 | |
| | | | Burner fuel | 0.51 | 1.06 | |
| | | | Maintenance | 0.09 | 0.06 | |
| | | | Labor | 0.03 | 0.03 | |
| | | | TOTAL | $0.78 | $1.25 | 1.60 |
| 2 | None | 1/4 LFL | Fixed charges | $0.15 | $0.10 | |
| | | | Burner fuel | 0.03 | 0.58 | |
| | | | Maintenance | 0.09 | 0.06 | |
| | | | Labor | 0.03 | 0.03 | |
| | | | TOTAL | $0.30 | $0.77 | 2.45 |
| 3 | 1/2 of Input | Nil | Fixed charges | $0.19 | $0.17 | |
| | | | Burner fuel | 0.27 | 0.58 | |
| | | | Maintenance | 0.11 | 0.10 | |
| | | | Labor | 0.03 | 0.03 | |
| | | | TOTAL | $0.60 | $0.88 | 1.33 |
| 4 | 1/2 of Input | 1/4 LFL | Fixed charges | $0.19 | $0.17 | |
| | | | Burner fuel | (−0.20) | 0.10 | |
| | | | Maintenance | 0.11 | 0.10 | |
| | | | Labor | 0.03 | 0.03 | |
| | | | TOTAL | $0.13 | $0.40 | 3.10 |

(Ref. C-2)

The cost for the catalytic method is less than that of the direct flame method.

**Comparative Costs of Direct-Flame Afterburners on Rendering-Plant Emissions With and Without Heat Recovery**

| System | Incineration Without Heat Recovery | Incineration with a Single-Pass-Primary and a Single-Pass-Secondary Heat Exchanger | Incineration with a Double-Pass-Primary and a Single-Pass-Secondary Heat Exchanger |
|---|---|---|---|
| Initial cost, $ | 16,750 | 42,300 | 58,800 |
| Approximate erection, $ | 3,800 | 4,600 | 5,400 |
| Hourly operating cost, $/hr | 4.33 | 2.58 | 1.84 |
| Annual operating cost, $/yr., = fuel cost minus makeup-air savings | 25,900 | 13,510 | 9,630 |
| Annual fuel savings for makeup air, $/yr | None | 1,960 | 1,370 |
| Total system cost, $ | 20,550 | 46,900 | 64,200 |
| Annual cost, including initial cost plus operating cost, based on 15-yr. life, $ | 27,270 | 16,630 | 13,910 |
| Operating cost $/hr./1,000 cfm | .64 | .38 | .27 |

Notes:
Fuel cost 50¢/$10^6$ Btu.
Annual operating hours, 6,000.
Erection of incinerator only.

(Ref. C-2)

Heat recovery can cut the cost in half.

## INCINERATOR WITH AND WITHOUT HEAT RECLAIM
Source: (Ref. F-9)

Mfg. - Air Preheater Co., Wellsville, New York
Detention - Min. 0.3 Sec. @ 1200°F
Temp. Range - Operating 1200-1400°F

Base - 50¢/MCF Natural Gas Cost @ 1000 BTU/cu.ft.
1.5¢/KW Electrical Cost

Unit 5-2 (*Fuel Rate Based on 2,000 SCFM, 1200°F Inc. in Air Temp. 100°F)
Vol = 2000 (.3/60) = 10 $ft^3$

| Heat Exchanger | % | None | 35% Eff. | 47% Eff. | 59% Eff. |
|---|---|---|---|---|---|
| Flow Rate | SCFM | 2,000 | 2,000 | 2,000 | 2,000 |
| Equip. Cost | $ | 13,050 | 20,100 | 23,700 | 33,350 |
| Est. Installed Cost | $ | 17,050 | 26,900 | 31,900 | 44,550 |
| Fuel $10^6$ BTU/Hr. | * | 2.25 | 1.46 | 1.19 | .92 |
| Power | KW | 3.0 | 3.5 | 3.75 | 6.5 |
| Weight | # | 7,600 | 13,000 | 15,600 | 21,720 |
| Cost of Gas & Elct/Hr. | $ | 1.18 | .78 | .66 | .56 |
| Cost/1000 SCFM | | 59¢ | 40¢ | 33¢ | 28¢ |

Unit 5-5 (*Fuel Rate Based on 5,000 SCFM, 1200°F Inc. in Air Temp. 100°F)
Vol = 25 $ft^3$

| Heat Exchanger | % | None | 35% Eff. | 47% Eff. | 59% Eff. |
|---|---|---|---|---|---|
| Flow Rate | SCFM | 5,000 | 5,000 | 5,000 | 5,000 |
| Equip. Cost | $ | 15,550 | 24,230 | 29,400 | 41,800 |
| Est. Installed Cost | $ | 20,550 | 32,230 | 39,400 | 55,800 |
| Fuel $10^6$ BTU/Hr. | * | 6.20 | 4.04 | 3.28 | 2.54 |
| Power | KW | 13.0 | 17.0 | 23.0 | 34.0 |
| Weight | # | 9,400 | 15,300 | 19,000 | 26,420 |
| Cost of Gas & Elect/Hr. | $ | 3.30 | 2.28 | 1.99 | 1.78 |
| Cost/1000 SCFM | | 66¢ | 46¢ | 40¢ | 36¢ |

Unit 5-9 (*Fuel Rate Based on 10,000 SCFM, 1200°F Inc. in Air Temp. 100°F)
Vol = 50 $ft^3$

| Heat Exchanger | % | None | 39% Eff. | 48% Eff. | 64% Eff. |
|---|---|---|---|---|---|
| Flow Rate | SCFM | 10,000 | 10,000 | 10,000 | 10,000 |
| Equip. Cost | $ | 20,600 | 32,600 | 38,080 | 54,600 |
| Est. Installed Cost | $ | 26,600 | 42,600 | 50,080 | 71,600 |
| Fuel $10^6$ BTU/Hr. | * | 12.4 | 7.55 | 6.45 | 4.45 |
| Power | KW | 14.0 | 27.0 | 24.0 | 36.0 |
| Weight | # | 13,800 | 22,500 | 26,700 | 37,430 |
| Cost of Gas & Elect/Hr. | $ | 6.41 | 4.19 | 3.59 | 2.75 |
| Cost/1000 SCFM | | 64¢ | 42¢ | 36¢ | 28¢ |

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Unit 3-14 (*Fuel Rate Based on 15,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

$V = 75\ ft^3$

| Heat Exchanger | % | None | 39% Eff. | 48% Eff. | 64% Eff. |
|---|---|---|---|---|---|
| Flow Rate | SCFM | 15,000 | 15,000 | 15,000 | 15,000 |
| Equip. Cost | $ | 24,750 | 36,780 | 43,980 | 62,000 |
| Est. Installed Cost | $ | 31,750 | 47,780 | 57,980 | 82,000 |
| Fuel $10^6$ BTU/Hr. | * | 18.6 | 11.3 | 9.65 | 6.7 |
| Power | KW | 23.0 | 62.0 | 58.0 | 80.0 |
| Weight | # | 15,300 | 25,300 | 30,600 | 42,730 |
| Cost of Gas & Elect/Hr. | $ | 8.65 | 6.58 | 5.70 | 4.55 |
| Cost/1000 SCFM | | 64¢ | 44¢ | 38¢ | 30¢ |

Unit 3-10 (*Fuel Rate Based on over 20,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

$V = 100\ ft^3$

| Heat Exchanger | % | None | 39% Eff. | 48% Eff. | 64% Eff. |
|---|---|---|---|---|---|
| Flow Rate | SCFM | 20,000 | 20,000 | 20,000 | 20,000 |
| Equip. Cost | $ | 28,000 | 43,530 | 52,530 | 74,850 |
| Est. Installed Cost | $ | 36,000 | 56,530 | 68,530 | 97,850 |
| Fuel $10^6$ BTU/Hr. | * | 24.8 | 15.1 | 12.8 | 8.9 |
| Power | KW | 35 | 82 | 76 | 109 |
| Weight | # | 17,300 | 29,400 | 35,400 | 50,130 |
| Cost of Gas & Elect/Hr. | $ | 12.93 | 8.78 | 7.54 | 6.09 |
| Cost/1000 SCFM | | 65¢ | 44¢ | 38¢ | 31¢ |

Unit 3-28 (*Fuel Rate Based on 30,000 SCFM, 1200°F Inc. in Air Temp. 100°F)

$V = 150\ ft^3$

| Heat Exchanger | % | None | 39% Eff. | 48% Eff. | 64% Eff. |
|---|---|---|---|---|---|
| Flow Rate | SCFM | 30,000 | 30,000 | 30,000 | 30,000 |
| Equip. Cost | $ | 34,350 | 55,880 | 66,830 | 93,100 |
| Est. Installed Cost | $ | 43,350 | 71,880 | 86,330 | 121,100 |
| Fuel $10^6$ BTU/Hr. | * | 37.3 | 22.7 | 19.4 | 13.4 |
| Power | KW | 50.0 | 123 | 113 | 152 |
| Weight | # | 19,900 | 34,600 | 42,200 | 60,230 |
| Cost of Gas & Elect/Hr. | $ | 19.40 | 13.20 | 11.40 | 8.98 |
| Cost/1000 SCFM | | 65¢ | 44¢ | 38¢ | 30¢ |

Reproduced from best available copy.

Heat recovery can halve the cost.

## INCINERATOR PERFORMANCE DATA

## vs

## CONTRACT SPECIFICATIONS (TEST #4)

## 30 JULY 1970

| | Result Test #4 | Expected Based on Input of Test #4 |
|---|---|---|
| Flow SCFM | 28,900 | 28,900 |
| #/hr | 130,000 | 130,000 |
| Temperature in (°F) | 120 | 120 |
| Air Temperature Out Cor-Pak (°F) | 822 | 806 |
| Incineration Chamber Temperature (°F) | 1,203 | 1,203 |
| Stack Temperature (°F) | 550 | 555 |
| System ΔP ("W.G.) | 10.4 | 13.4 |
| Heater Exchanger Effectiveness | 64.8 | 63.3 |
| Fuel Rate #/hr | 600 | 642 |
| Odor Units/SCF | <150 | <150 |

## ODOR EVALUATION RESULTS

## AT

## INCINERATION CHAMBER TEMPERATURES OF

## APPROXIMATELY 1000, 1100, 1200, & 1400°F

.3 sec Contact Time

| Incineration Chamber Temperature (°F) | Test No. | Odor Concentration Odor Units/SCF | |
|---|---|---|---|
| | | Duct Inlet | At Stack Outlet |
| 1007 | 2 | 1000 | 270 |
| | | 1500 | 290 |
| 1100 (Nominal) | 5 | 3000 | 395 |
| | | 2500 | 1000 |
| 1203 | 4 | 3600 | 105 |
| | | 4200 | 90 |
| 1400 (nominal) | 7 | 3000 | 43 |
| | | 3000 | <10 |

Conclusion: At 1400°F reduction ratio is 70 to 300; and at 1100°F is 2.5 to 10.

## OPERATING COST COMPARISON

### Scrubber vs. Incinerator
### (Spray Tower)

| | Scrubber | Incinerator |
|---|---|---|
| Initial Cost - Installed | $40,000 | $65,000 |
| Capacity | 60,000 cfm | 25,000 cfm |
| Annual Operating Hours | 3100 hrs. | 2500 hrs. |
| Running H.P. | 70 H.P. | 30 H.P. |
| Estimated Actual Life | 15 yrs. | 8 yrs. |
| Annual Operating Cost | | |
| 1. Chemicals - Soda Ash 500 lb/wk @ 3.35¢ x 26 wks | $ 435.00 | - - |
| 2. Water 200 gal/wk @ 60¢/1000 gal. x 26 wks | 130.00 | - - |
| 3. Fuel $5.50/hr x 2500 hrs. | - | $13,800.00 |
| 4. Power H.P. x .7457 x $.009/KWH x Running Hrs. | 1,450.00 | 500.00 |
| 5. Maintenance (estimated) | 200.00 | 500.00 |
| 6. Labor (operational) | 500.00 | - |
| 7. Amortization of Investment | 2,670.00 | 8,120.00 |
| Total Annual Operating Costs | $ 5,385.00 | $22,920.00 |
| Operating Cost/Hr | $1.74 | $9.16 |
| Operating Cost/Hr/1000 cfm | $ .03 | $ .37 |

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(Ref. F-7)

The total annual cost of the incinerator is over 4 times that of the scrubber.

Comparison of Crossflow vs. Countercurrent

Energy Cost in Gas and Liquid Phase

Annual and First Cost of Installing Fan and Recycle Pump

With Motors

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| | Crossflow | Countercurrent |
|---|---|---|
| Energy Cost | | |
| Fan - Gas Phase | $ 2,170 | $ 4,380 |
| Pump - Liquid Phase | 595 | 4,680 |
| Total Annual Energy Cost | $ 2,765 | $ 9,060 |
| Fan HP | 41.5 | 84.0 |
| Pump HP | 11.5 | 90.8 |
| Total HP req'd. | 53.0 | 174.8 |
| First Cost Fans @ 10¢/CFM | $ 9,500 | $ 9,500 |
| First Cost Pump @ $1.50/GPM | 1,160 | 6,750 |
| First Cost Motors @ $15.00/BHP | 795 | 2,600 |
| Electrical Installation Cost for: switches, motor starters, power wiring, control wiring, etc. @ $30/BHP | 1,590 | 5,250 |
| Total First Cost | $13,045 | $24,100 |

(Ref. F-10)

Cross-flow tower gives the smaller total cost.

**Comparison of scrubber operating costs**

| Scrubber type | Liquid rate (g.p.m.) | Liquid pressure (p.s.i.g.) | Pump h.p. | Scrubber pressure drop (in. water) | Total pressure drop (in. water) | Fan h.p. | Total h.p. | Annual power cost |
|---|---|---|---|---|---|---|---|---|
| **Cross flow** | | | | | | | | |
| Tellerette packing | 50 | 5 | 0.3 | 0.5 | 1.5 | 4.3 | 4.6 | $ 370 |
| Berl saddle packing | 60 | 5 | 0.4 | 1.2 | 2.2 | 6.3 | 6.7 | 540 |
| Raschig ring packing | 60 | 5 | 0.4 | 3.8 | 4.8 | 13.8 | 14.2 | 1140 |
| **Counter-current** | | | | | | | | |
| Tellerette packing | 120 | 5 | 0.7 | 0.75 | 1.75 | 5.0 | 5.7 | 460 |
| Berl saddle packing | 140 | 5 | 0.8 | 2.2 | 3.2 | 9.1 | 10.0 | 810 |
| Raschig ring packing | 140 | 5 | 0.8 | 6.7 | 7.7 | 22.0 | 22.8 | 1840 |
| **Wet cyclone** | 80 | 60 | 5.6 | 3.5 | 4.5 | 12.8 | 18.4 | 1490 |
| **Spray tower** | 100 | 80 | 9.6 | 2.0 | 3.0 | 8.6 | 18.2 | 1470 |
| **Jet** | 600 | 60 | 42.0 | | 1.0 | none | 42.0 | 3380 |
| **Venturi** | 80 | 20 | 1.9 | 15.0 | 16.0 | 46.0 | 47.9 | 3860 |

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(Ref. F-10)

Packed cross-flow tower gives the smallest power cost of the wet scrubbers.