AIR POLLUTION CONTROL TECHNOLOGY SEMINAR

Prepared For

U.S. ENVIRONMENTAL PROTECTION AGENCY
ECONOMIC ANALYSIS DIVISION
Washington, DC

THE AWARE CORPORATION consultants in environmental management
P.O.Box 40284, Nashville, TN 37204 (615) 794-0110

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Presented by:

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AIR POLLUTION CONTROL TECHNOLOGY

SEMINAR SCHEDULE

June 25, 1981

I. Types and Sources of Air Contaminants

II. Meteorological Aspects of Air Pollution Control

A. Ambient Sampling/Field Survey Design

B. Stack/Source Sampling

III. Particulate Control

A. Gravity and Centrifugal Separators

B. Electrostatic Precipitation/Baghouses

C. Fugitive Controls

D. An Example of a "Bubble"

E. Scrubbers

F. Filtration

IV. SO_x

A. Flue Gas Desulfurization

B. Emerging Technologies Like Fluidized Bed and Limestone

V. NO_x

A. Combustion Modification

B. Thermal De-NO_x

C. Selective Catalytic Reduction

D. Low NO_x Burners

VI. Hydrocarbons

A. Storage Tanks

B. Floating Roofs

C. Vapor Recovery

VII. Mobile Source/CO

A. Catalytic Converter

B. Lead in fuel

C. Non-Point Source Projections

VIII. Emission Control/Environmental Analysis

A. Toxics

B. Hazardous Wastes

C. Prediction (General Concepts)

I. TYPES AND SOURCES OF AIR CONTAMINANTS

(ORAL PRESENTATION)

II. METEOROLOGICAL ASPECTS OF AIR POLLUTION CONTROL

AIR QUALITY CONSIDERATIONS

Prepared by

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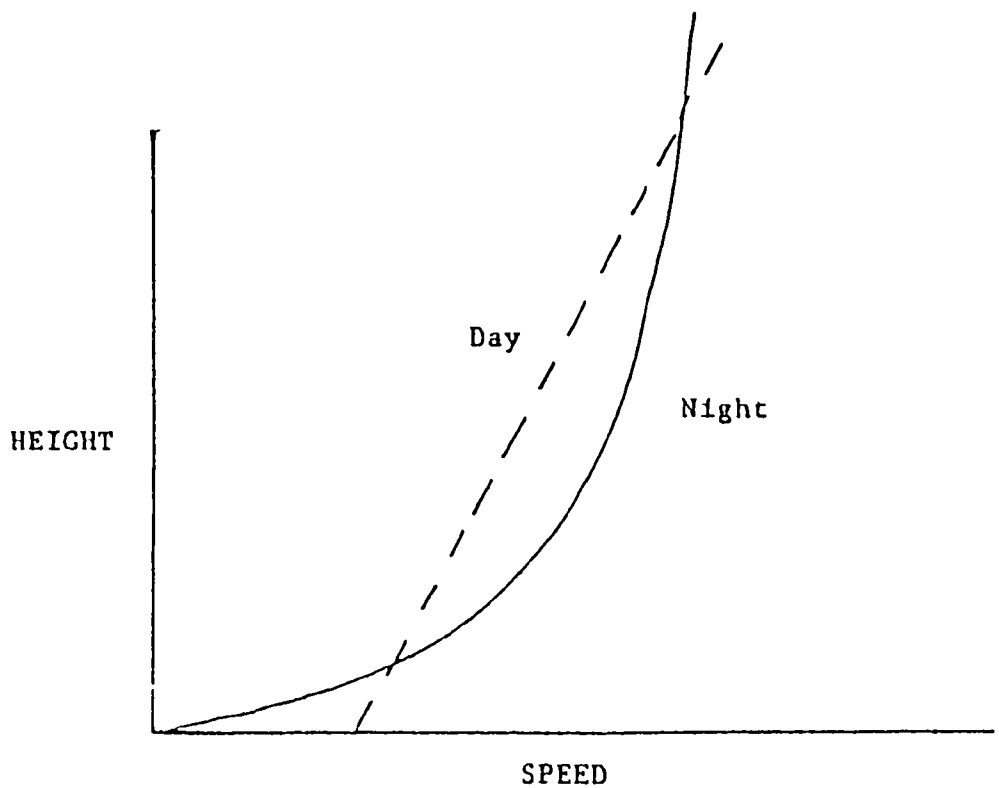
Prepared for

National Hazardous Materials Training Course
Vanderbilt University
Nashville, Tennessee
September 25-29, 1978


Day
Night
HEIGHT
SPEED

Vertical Temperature Structure of the Atmosphere

1. Dry adiabatic lapse rate (DALR)

a. Equation of state

$$Pv = RT \quad \text{or} \quad \frac{P}{\rho} = RT \text{ (Ideal Gas)}$$

b. Hydrostatic Equation

$$\frac{dP}{dz} = -g\rho$$

$$\frac{dP}{dz} = -\frac{gP}{RT}$$

$$\frac{dP}{P} = -\left(\frac{g}{RT}\right) dz$$

$$P_o = P\left(z_o\right) \quad z_o = \text{surface} = 0$$

$$\left.\begin{aligned} \frac{\ln P}{P_o} &= -\frac{g}{RT_m} z \\ P &= P_o e^{\frac{-gz}{RT_m}} \end{aligned}\right\} \quad \text{where } T = T \quad \text{(a mean temperature)}$$

$$P = P_o \exp\left[-\frac{g}{R}\int_o^z \frac{dz}{T}\right]$$

can integrate if T known as a function of z

c. Adiabatic Expansion

$$(\gamma)\frac{dT}{T} - (\gamma - 1)\frac{dP}{P} = o \qquad \text{(From 1st Law)}$$

$$\gamma \ln\left(\frac{T}{To}\right) - (\gamma - 1) \ln\left(\frac{P}{Po}\right) = o \qquad \left(\gamma = \frac{C_p}{C_v} = 1.41 \text{ for dry air}\right)$$

$$\frac{T}{To} = \left(\frac{P}{Po}\right)^{\left(\gamma - \frac{1}{\gamma}\right)}$$

d. Dry Adiabatic Lapse Rate = γ

$$\frac{dT'}{dz} = \left(\frac{\gamma - 1}{\gamma}\right) \left(\frac{T'}{P}\right) \frac{dP}{dz}$$

(T' refers to volume of air displaced)

$$\frac{dT'}{dz} = \left(\frac{\gamma - 1}{\gamma}\right) \frac{T'}{T} \left(-\frac{g}{R}\right)$$

$$\text{DALR} \equiv \gamma \equiv \frac{dT}{dz} = -\left(\frac{g}{R}\right) \left(\frac{\gamma - 1}{\gamma}\right) \qquad T' = T$$

$$T(z) = T(o) - \frac{g}{R} \left(\frac{\gamma - 1}{\gamma}\right) z$$

For Air

$$\gamma = -5.4 \frac{°F}{1000 \text{ ft}} \quad \text{or} \quad -.98 \frac{°C}{100 \text{ m}}$$

2. Vertical Temperature Structure

a. Definitions - assume a parcel of air rising or falling will follow adiabatic lapse rate from point of departure. Therefore:

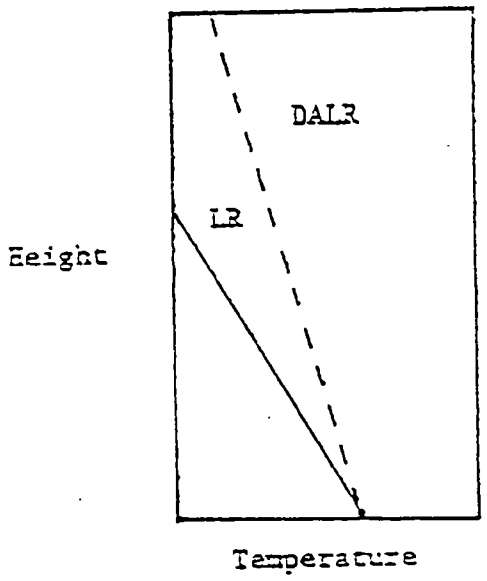
Superadiabatic - Temperature decreases faster with height than adiabatic rate - rising air parcel, cooling at adiabatic rate remains warmer and less dense than surrounding air - buoyancy forces tend to accelerate it upward - unstable equilibrium - buoyancy forces tend to produce acceleration

Subadiabatic - Temperature decreases slower with height than adiabatic rate - rising air parcel becomes cooler and sinks to its starting point - stable - buoyancy forces tend to restore parcel to original position

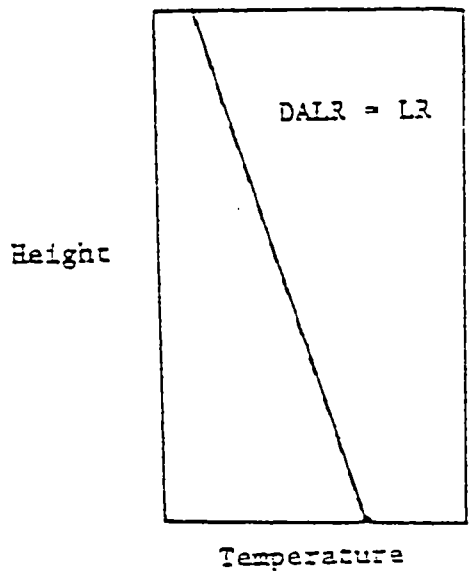
Adiabatic - Neither stable nor unstable - neutral

b. Stability conditions

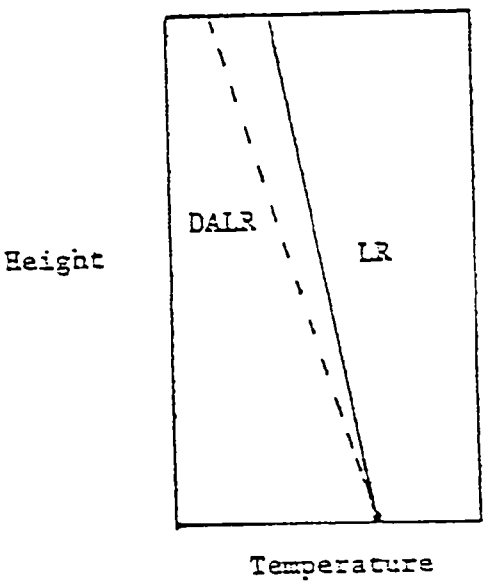
DALR = dry adiabatic lapse rate
LR = actual lapse rate



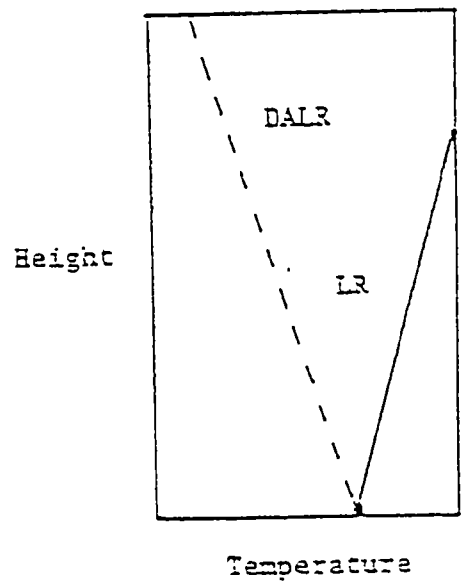
Superadiabatic
Unstable



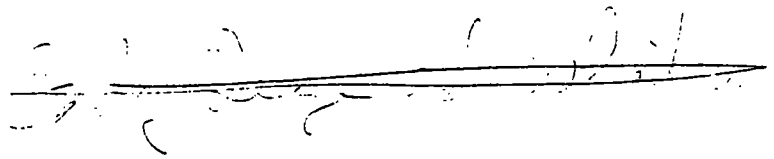
Adiabatic
Neutral



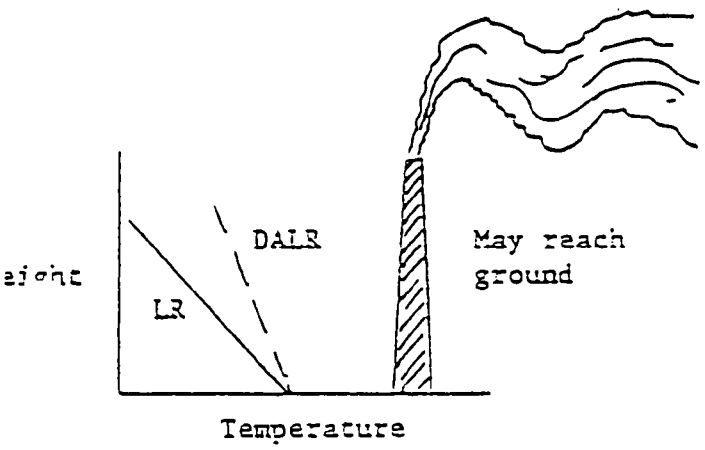
Subadiabatic
Stable



Inversion
Stable



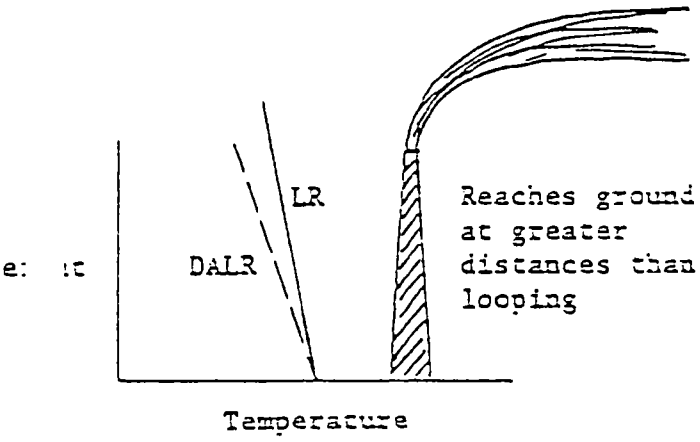
2. Characteristic Forms of Smoke Plumes



a. Looping - Unstable

Successive sections of plume traveling with different inclinations

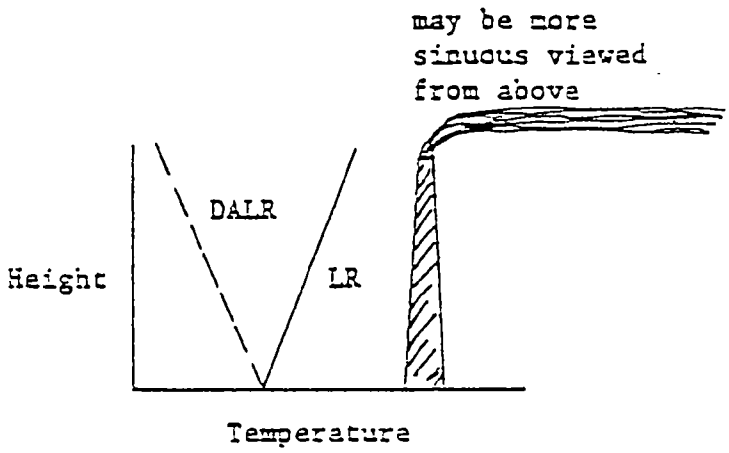
Light wind, sunshine warms ground surface, temperature lapse high degree of turbulence especially convective or large scale mechanical turbulence caused by obstructions.



b. Coning - slightly unstable or Neutral

Successive sections follow trajectories which are not widely different

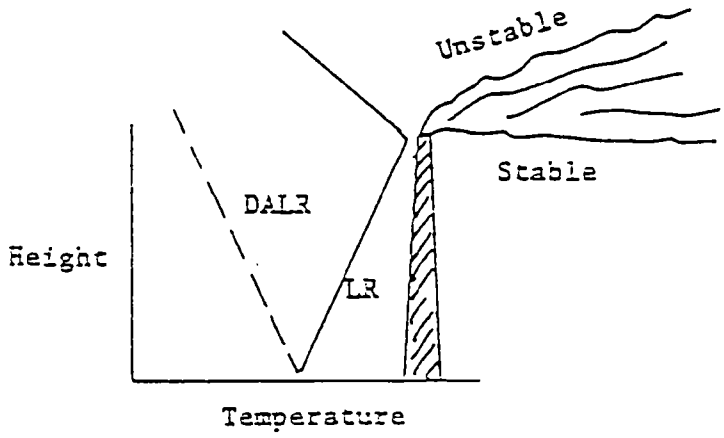
Open country, moderate wind speed, cloudy sky - or clear sky with strong winds. Diffusion equations best



c. Fanning - Stable

Cross wind spread - meanders, may be almost no vertical spread

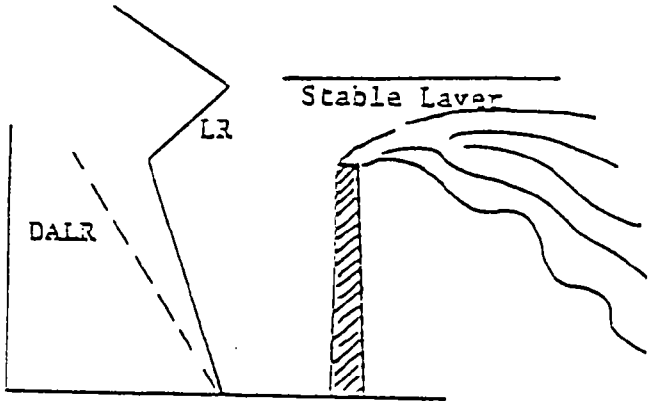
Vertical component suppressed more than horizontal, night time, clear sky, cooling of air near ground, light wind, mechanical turbulence suppressed



d. Lofting - Transition Unstable to Stable

Late afternoon and early evening

Replaced by fanning as inversion deepens

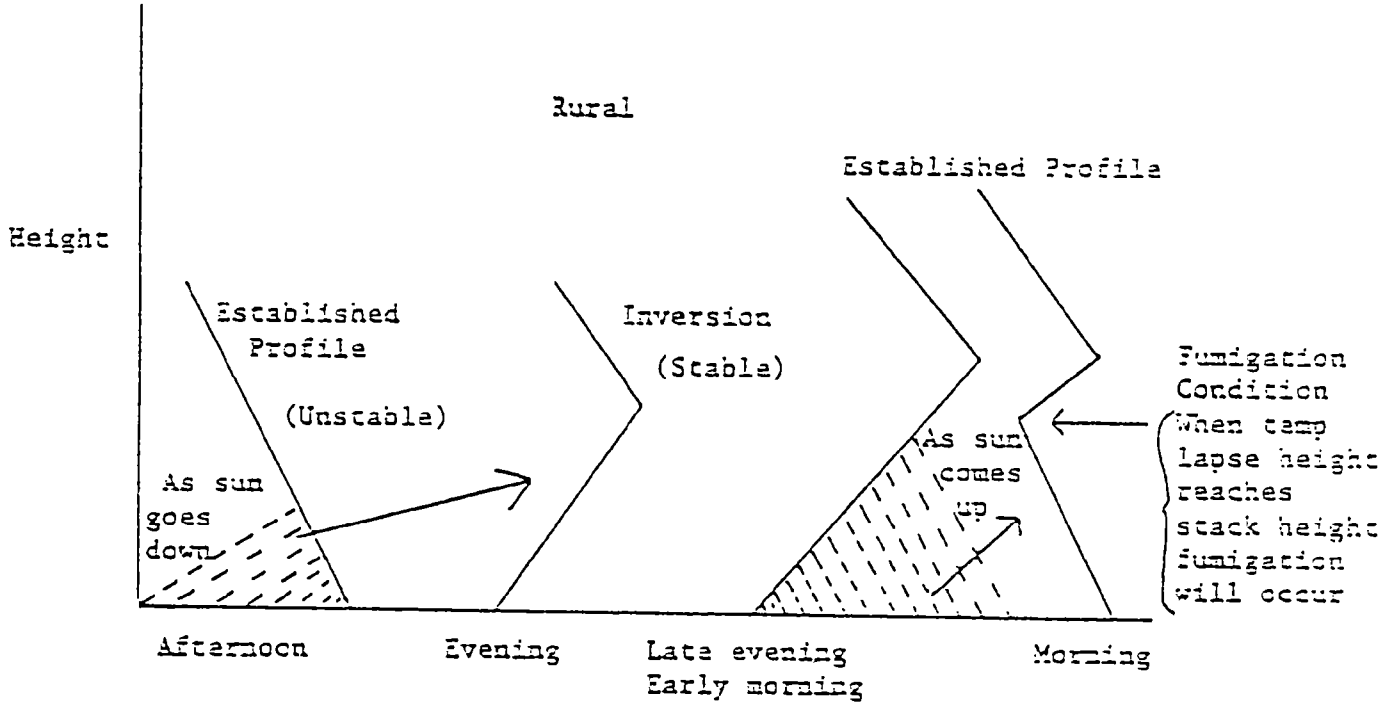


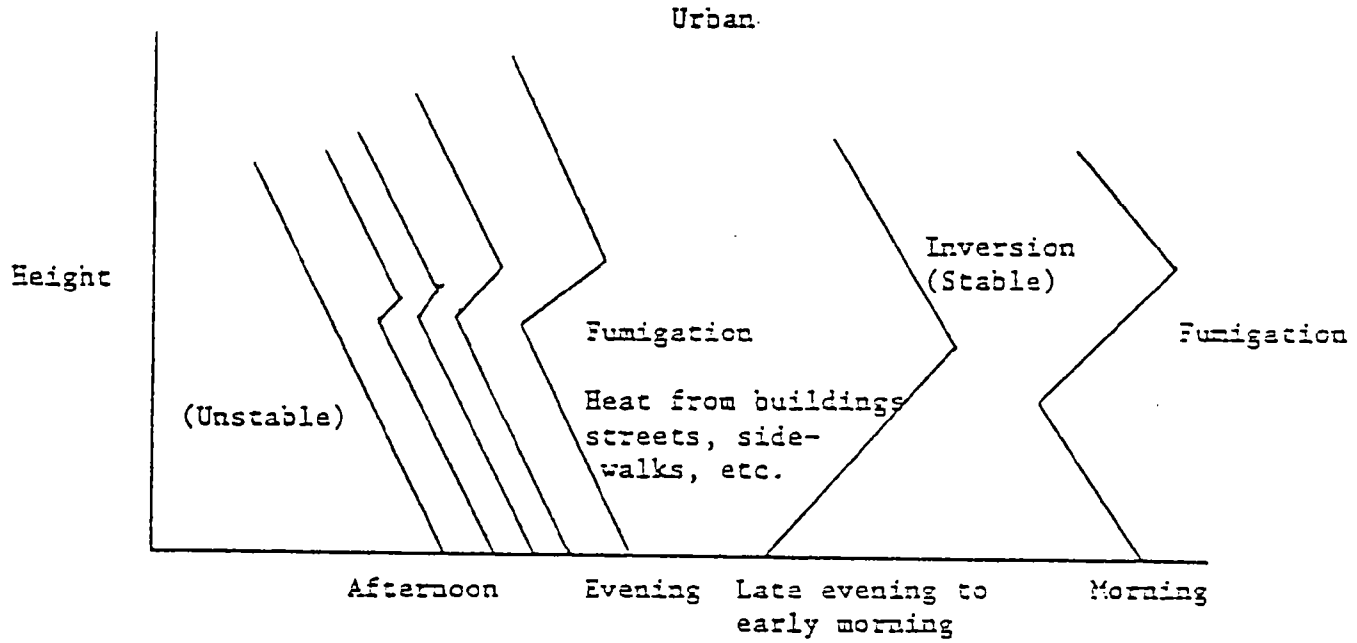
E. Fumigation - Transition Stable to Unstable

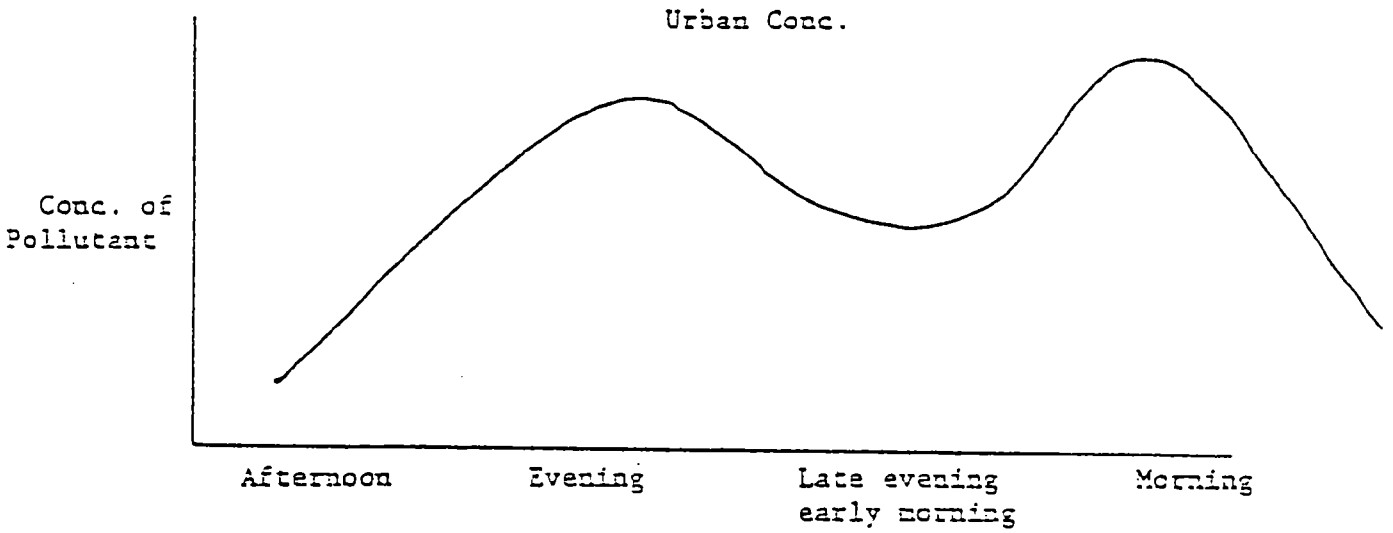
Morning following a stable night

Clear skys, light winds, summer, high concentrations more rapidly come to ground, good mixing below inversion layer

3. Diurnal Variation of Stability




Urban
Height
(Unstable)
Fumigation
Heat from buildings streets, side-walks, etc.
Inversion (Stable)
Fumigation
Afternoon
Evening
Late evening to early morning
Morning


Urban Conc.
Conc. of Pollutant
Afternoon
Evening
Late evening early morning
Morning

CHAPTER 2

Extracted From

"WORKBOOK OF ATMOSPHERIC DISPERSION ESTIMATES"

By D. Bruce Turner

ESTIMATES OF ATMOSPHERIC DISPERSION

This chapter outlines the basic procedures to be used in making dispersion estimates as suggested by Pasquill (1961) and modified by Gifford (1961).

COORDINATE SYSTEM

In the system considered here the origin is at ground level at or beneath the point of emission, with the x-axis extending horizontally in the direction of the mean wind. The y-axis is in the horizontal plane perpendicular to the x-axis, and the z-axis extends vertically. The plume travels along or parallel to the x-axis. Figure 3-1 illustrates the coordinate system.

DIFFUSION EQUATIONS

The concentration, χ, of gas or aerosols (particles less than about 20 microns diameter) at x,y,z from a continuous source with an effective emission height, H, is given by equation 3.1. The notation used to depict this concentration is χ (x,y,z;H). H is the height of the plume centerline when it becomes essentially level, and is the sum of the physical stack height, h, and the plume rise, ΔH. The following assumptions are made: the plume spread has a Gaussian distribution (see Appendix 2) in both the horizontal and vertical planes, with standard deviations of plume concentration distribution in the horizontal and vertical of σ_y and σ_z, respectively; the mean wind speed affecting the plume is u; the uniform emission rate of pollutants is Q; and total reflection of the plume takes place at the earth's surface, i.e., there is no deposition or reaction at the surface (see problem 9).

$$\chi(x,y,z;H) = \frac{Q}{2\pi\,\sigma_y\,\sigma_z\,u}\,\exp^{*}\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \qquad (3.1)$$

*Note: $\exp -a/b = e^{-a/b}$ where e is the base of natural logarithms and is approximately equal to 2.7183.

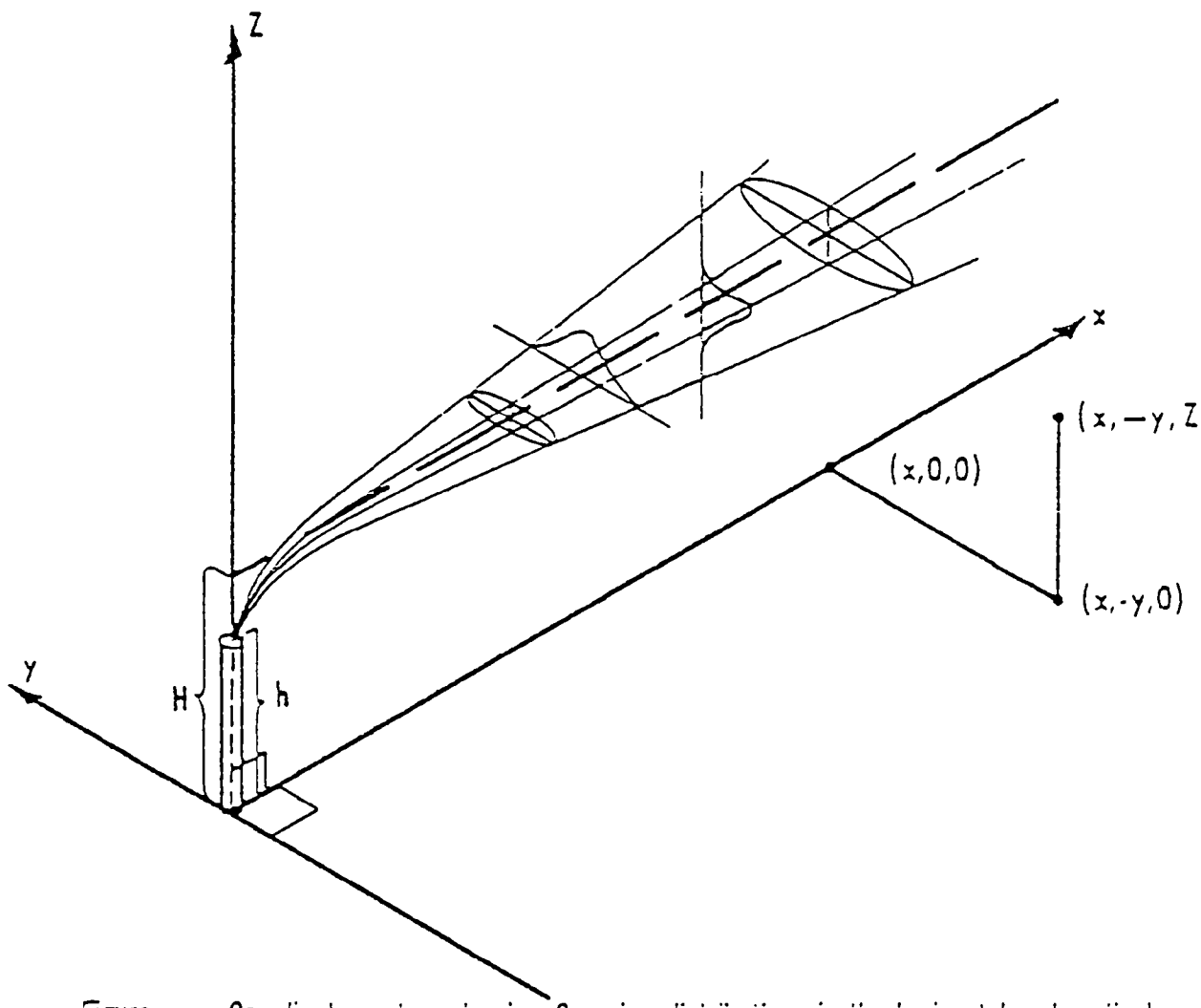


Figure Coordinate system showing Gaussian distributions in the horizontal and vertical.

Any consistent set of units may be used. The most common is:

χ (g m^{-3}) or, for radioactivity (curies m^{-3})
Q (g sec^{-1}) or (curies sec^{-1})
u (m sec^{-1})
σ_y, σ_z, H, x, y, and z (m)

This equation is the same as equation (8.35) p. 293 of Sutton (1953) when σ's are substituted for Sutton's parameters through equations like (8.27) p. 286. For evaluations of the exponentials found in Eq. (3.1) and those that follow, see Appendix 3. χ is a mean over the same time interval as the time interval for which the σ's and u are representative. The values of both σ_y and σ_z are evaluated in terms of the downwind distance, x.

Eq. (3.1) is valid where diffusion in the direction of the plume travel can be neglected, that is, no diffusion in the x direction.

This may be assumed if the release is continuous or if the duration of release is equal to or greater than the travel time (x/u) from the source to the location of interest.

For concentrations calculated at ground level, i.e., z = 0, (see problem 3) the equation simplifies to:

$$\chi(x,y,0;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (3.2)$$

Where the concentration is to be calculated along the centerline of the plume (y = 0), (see problem 2) further simplification results:

$$\chi(x,0,0;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (3.3)$$

For a ground-level source with no effective plume rise (H = 0), (see problem 1):

$$\chi(x,0,0;0) = \frac{Q}{\pi \sigma_y \sigma_z u} \quad (3.4)$$

EFFECTS OF STABILITY

The values of σ_y and σ_z vary with the turbulent structure of the atmosphere, height above the surface, surface roughness, sampling time over which the concentration is to be estimated, wind speed, and distance from the source. For the parameter values given here, the sampling time is assumed to be about 10 minutes, the height to be the lowest several hundred meters of the atmosphere, and the surface to be relatively open country. The turbulent structure of the atmosphere and wind speed are considered in the stability classes presented, and the effect of distance from the source is considered in the graphs determining the parameter values. Values for σ_y and σ_z are estimated from the stability of the atmosphere, which is in turn estimated from the wind speed at a height of about 10 meters and, during the day, the incoming solar radiation or, during the night, the cloud cover (Pasquill, 1961). Stability categories (in six classes) are given in Table 3-1. Class A is the most unstable, class F the most stable class considered here. Night refers to the period from 1 hour before sunset to 1 hour after sunrise. Note that the neutral class, D, can be assumed for overcast conditions during day or night, regardless of wind speed.

Table 3-1 KEY TO STABILITY CATEGORIES

Surface Wind Speed (at 10 m), m sec^{-1}	Day: Incoming Solar Radiation			Night: Thinly Overcast or ≥4/8 Low Cloud	Night: ≤3/8 Cloud
	Strong	Moderate	Slight		
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables (List, 1951) can be used in determining the solar altitude. Cloudiness will decrease incoming solar radiation and should be considered along with solar altitude in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (⅝ to ⅞ cloud cover) middle clouds and to slight with broken low clouds. An objective system of classifying stability from hourly meteorological observations based on the above method has been suggested (Turner, 1961).

These methods will give representative indications of stability over open country or rural areas, but are less reliable for urban areas. This difference is due primarily to the influence of the city's larger surface roughness and heat island effects upon the stability regime over urban areas. The greatest difference occurs on calm clear nights; on such nights conditions over rural areas are very stable, but over urban areas they are slightly unstable or near neutral to a height several times the average building height, with a stable layer above (Duckworth and Sandberg, 1954; DeMarrais, 1961).

Some preliminary results of a dispersion experiment in St. Louis (Pooler, 1965) showed that the dispersion over the city during the daytime behaved somewhat like types B and C; for one night experiment σ_y varied with distance between types D and E.

ESTIMATION OF VERTICAL AND HORIZONTAL DISPERSION

Having determined the stability class from Table 3-1, one can evaluate the estimates of σ_y and σ_z as a function of downwind distance from the source, x, using Figures 3-2 and 3-3. These values of σ_y and σ_z are representative for a sampling time of about 10 minutes. For estimation of concentrations for longer time periods see Chapter 5. Figures 3-2 and 3-3 apply strictly only to open level country and probably underestimate the plume dispersion potential from low-level sources in built-up areas. Although the vertical spread may be less than the values for class F with very light winds on a clear night, quantitative estimates of concentrations are nearly impossible for this condition. With very light winds on a clear night for ground-level sources free of topographic influences, frequent shifts in wind direction usually occur which serve to spread the plume horizontally. For elevated sources under these extremely stable situations, significant concentrations usually do not reach ground level until the stability changes.

A stable layer existing above an unstable layer will have the effect of restricting the vertical diffusion. The dispersion computation can be modified for this situation by considering the height of the base of the stable layer, L. At a height 2.15 σ_z above the plume centerline the concentration is one-tenth the plume centerline concentration at the same distance. When one-tenth the plume centerline concentration extends to the stable layer, at height L, it is reasonable to assume that the distribution starts being affected by the "lid." The following method is suggested to take care of this situation. Allow σ_z to increase with distance to a value of L/2.15 or 0.47 L. At this distance x_L, the plume is assumed to have a Gaussian distribution in the vertical. Assume that by the time the plume travels twice this far, 2 x_L, the plume has become uniformly distributed between the earth's surface and the height L, i.e., concentration does not vary with height (see Figure 3-4). For the distances greater than 2 x_L, the concentration for any height between the ground and L can be calculated from:

$$\chi(x,y,z;H) = \frac{Q}{\sqrt{2\pi}\,\sigma_y L u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (3.5)$$

from any z from 0 to L
for $x > 2x_L$; x_L is where $\sigma_z = 0.47$ L

(see problem 6). Note that Eq. (3.5) assumes normal or Gaussian distribution of the plume *only* in the horizontal plane. The same result can be obtained from the following equation where σ_{zL} is an effective dispersion parameter because $\sqrt{2\pi}$ L = 2.5066 L and 0.8 πL = 2.51 L.

$$\chi(x,y,z;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_{zL}\,u}\left[\exp -\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (3.6)$$

for any z from 0 to L
for $x > 2x_L$; x_L is where $\sigma_z = 0.47$ L
The value of $\sigma_{zL} = 0.8$ L

EVALUATION OF WIND SPEED

For the wind speed, u, a mean through the vertical extent of the plume should be used. This would be from the height H — 2 σ_z through H + 2 σ_z. Of course, if 2 σ_z is greater than H then the wind can be averaged from the ground to H + 2 σ_z. However, the "surface wind" value may be all that is available. The surface wind is most applicable to surface or low-level emissions, especially under stable conditions.

PLOTS OF CONCENTRATIONS AGAINST DISTANCE

To gain maximum insight into a diffusion problem it is often desirable to plot centerline concentrations against distance downwind. A convenient procedure is to determine the ground-level centerline concentrations for a number of downwind distances and plot these values on log-log graph paper. By connecting the points, one may estimate concentrations for intermediate downwind distances (see problem 6).

ACCURACY OF ESTIMATES

Because of a multitude of scientific and technical limitations the diffusion computation method presented in this manual may provide *best estimates* but not infallible predictions. In the unstable and stable cases, severalfold errors in estimate of σ_z can occur for the longer travel distances. In some cases the σ_z may be expected to be correct within a factor of 2, however. These are: (1) all stabilities for distance of travel out to a few hundred meters; (2) neutral to moderately unstable conditions for distances out to a few kilometers; and (3) unstable conditions in the lower 1000 meters of the atmosphere with a marked inversion above for distances out to 10 km or more. Uncertainties in the estimates of σ_y are in general less than those of σ_z. The ground-level centerline concentrations for these

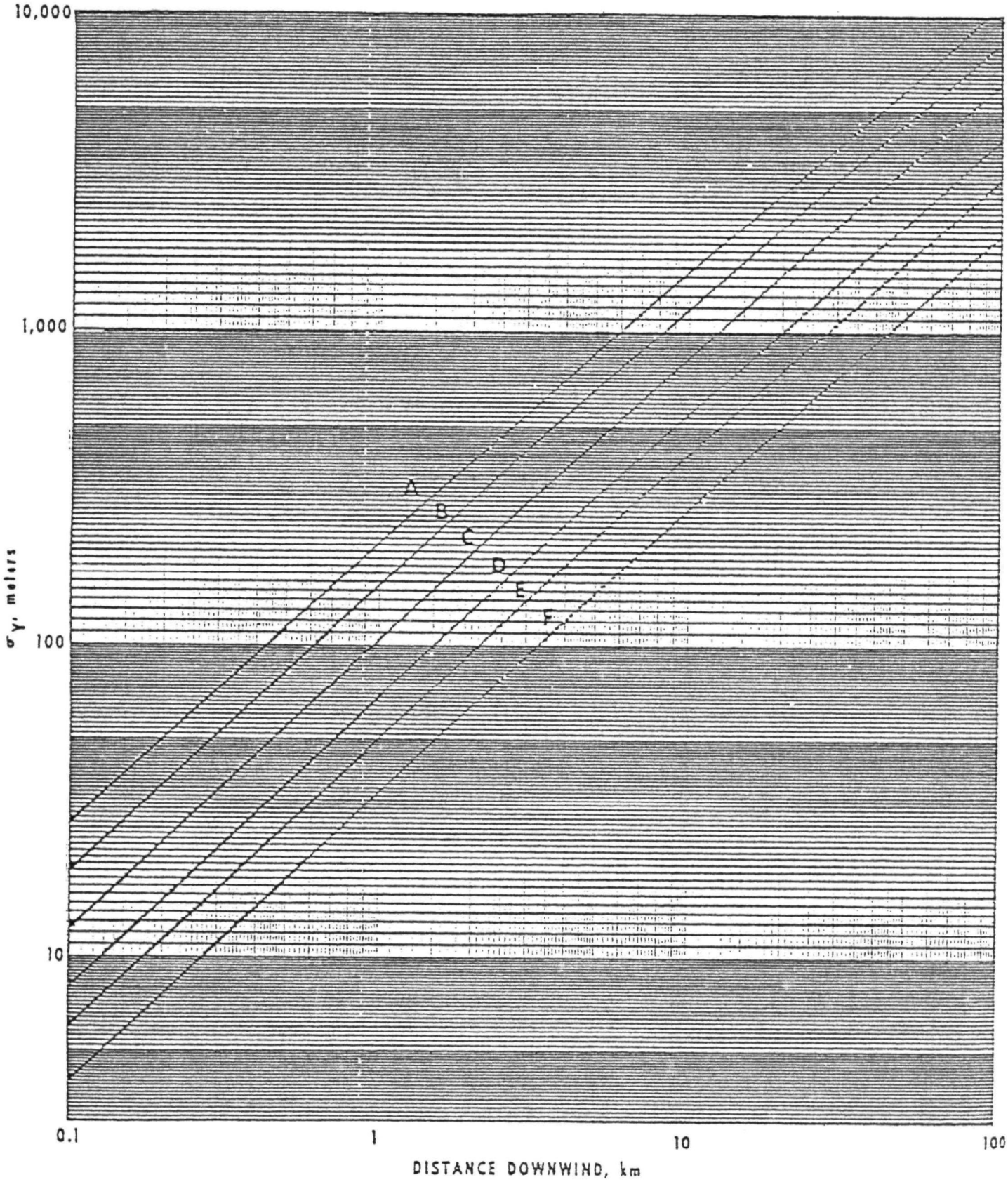


Figure Horizontal dispersion coefficient as a function of downwind distance from the source.

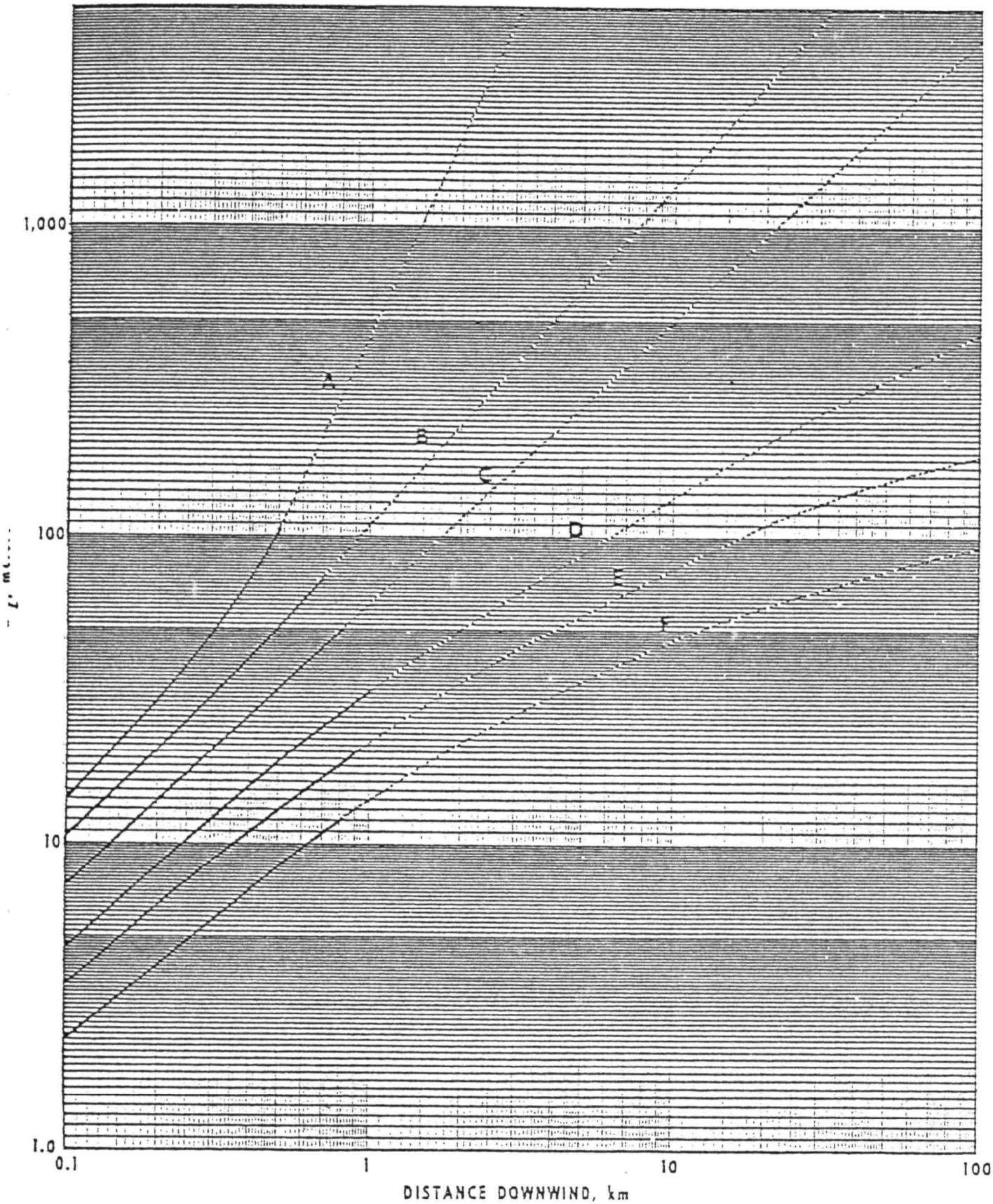


Figure Vertical dispersion coefficient as a function of downwind distance from the source.

Estimates

339-401 O - 68 - 2

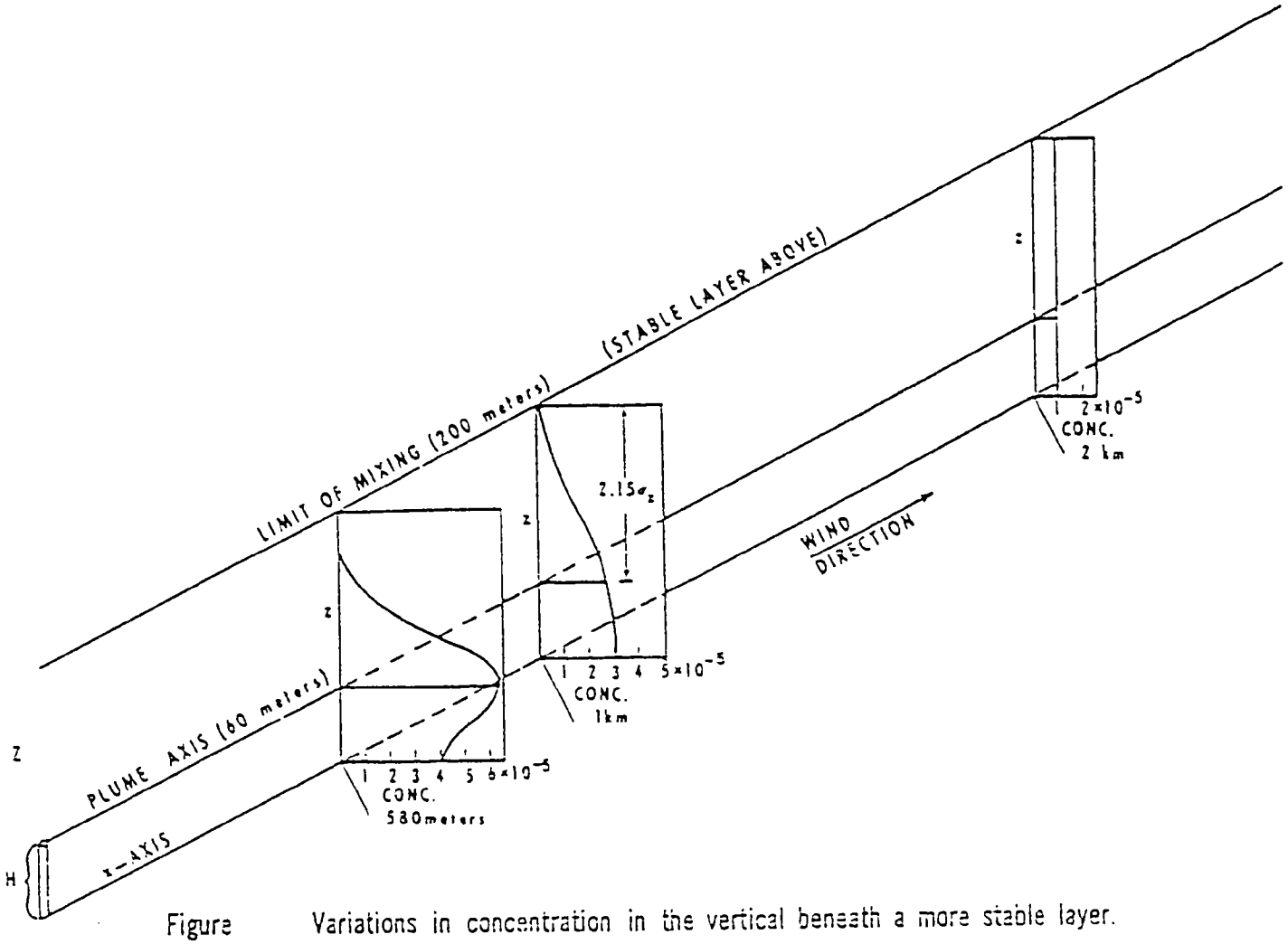


Figure Variations in concentration in the vertical beneath a more stable layer.

three cases (where σ_z can be expected to be within a factor of 2) should be correct within a factor of 3, including errors in σ_y and u. The relative confidence in the σ's (in decreasing order) is indicated by the heavy lines and dashed lines in Figures 3-2 and 3-3.

Estimates of H, the effective height of the plume, may be in error because of uncertainties in the estimation of ΔH, the plume rise. Also, for problems that require estimates of concentration at a specific point, the difficulty of determining the mean wind over a given time interval and consequently the location of the x-axis can cause considerable uncertainty.

GRAPHS FOR ESTIMATES OF DIFFUSION

To avoid repetitious computations, Figure 3-5 (A through F) gives relative ground-level concentrations times wind speed (χ u/Q) against downwind distances for various effective heights of emission and limits to the vertical mixing for each stability class (1 figure for each stability). Computations were made from Eq. (3.3), (3.4), and (3.5). Estimates of actual concentrations may be determined by multiplying ordinate values by Q/u.

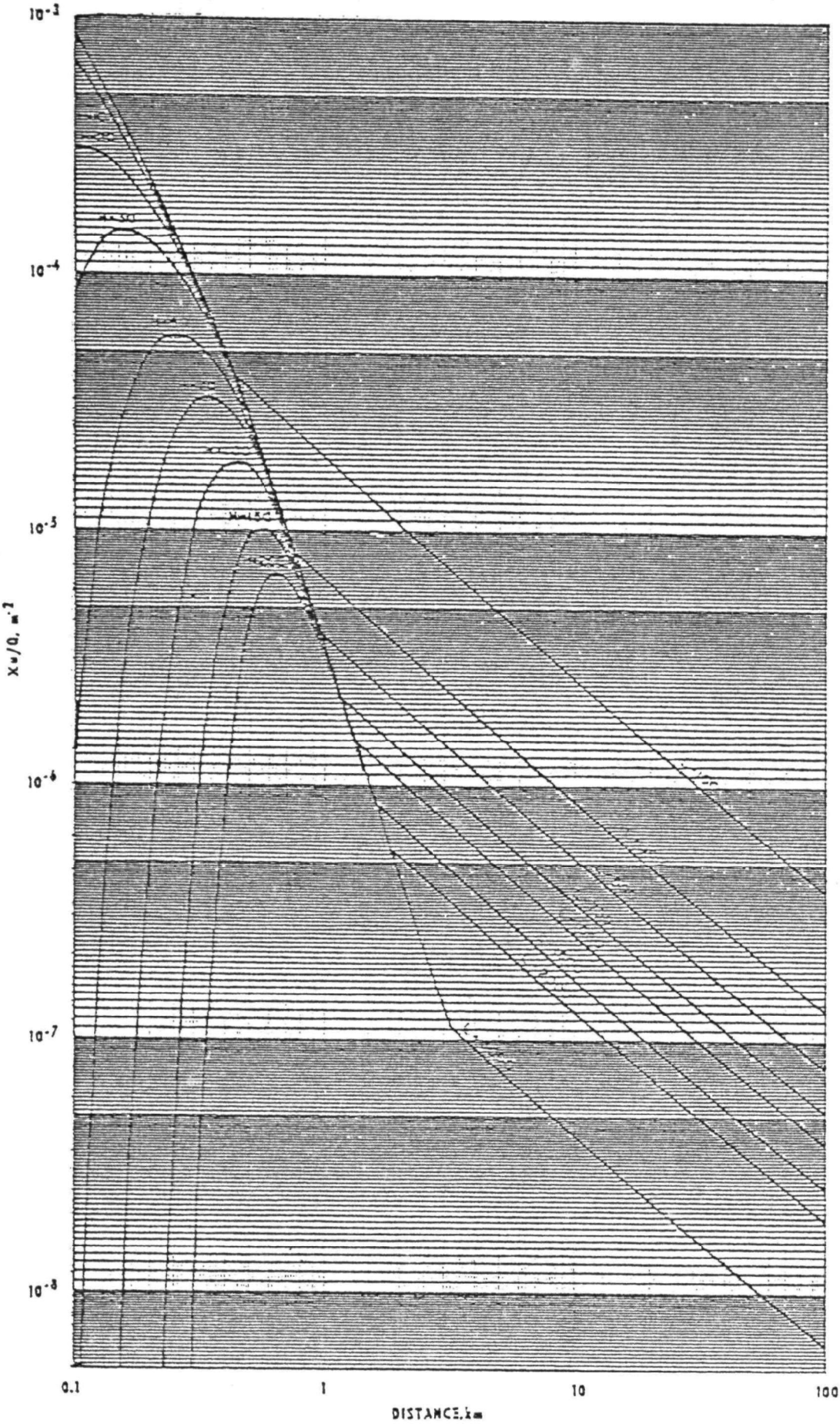
PLOTTING GROUND-LEVEL CONCENTRATION ISOPLETHS

Often one wishes to determine the locations where concentrations equal or exceed a given magnitude. First, the axial position of the plume must be determined by the mean wind direction. For plotting isopleths of ground-level concentrations the relationship between ground-level centerline concentrations and ground-level off-axis concentrations can be used:

$$\frac{\chi\,(x,y,0;H)}{\chi\,(x,0,0;H)} = \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad (3.7$$

The y coordinate of a particular isopleth from the x-axis can be determined at each downwind distance, x. Suppose that one wishes to know the off-axis distance to the 10^{-5} g m^{-3} isopleth at an of 600 m, under stability type B, where the ground level centerline concentration at this distance is 2.9×10^{-3} g m^{-3}.

$$\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] = \frac{\chi\,(x,y,0;H)}{\chi\,(x,0,0;H)} = \frac{10^{-5}}{2.9 \times 10^{-3}} = 0.345$$



ure xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), A stability.

timates

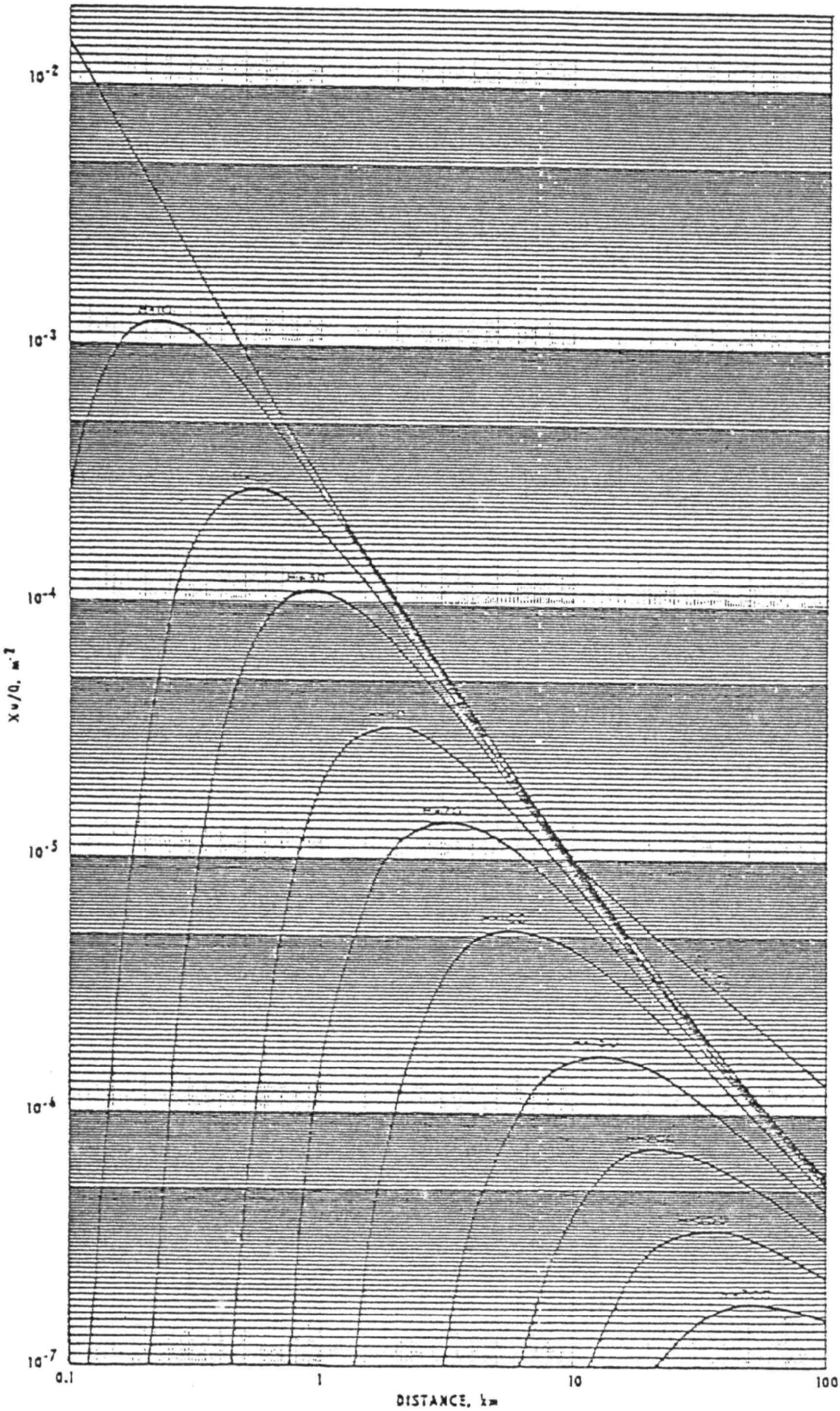


Figure xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), E stability.

Estimates

From Table A-1 (Appendix 3) when exp

$$\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] = 0.345,\ y/\sigma_y = 1.46$$

From Figure 3-2, for stability B and x = 600 m, σ_y = 92. Therefore y = (1.46) (92) = 134 meters. This is the distance of the 10^{-3} isopleth from the x-axis at a downwind distance of 600 meters.

This can also be determined from:

$$y = \left\{2 \ln^{*}\left[\frac{\chi\,(x,0,0;H)}{\chi\,(x,y,0;H)}\right]\right\}^{1/2} \sigma_y \qquad (3.8)$$

The position corresponding to the downwind distance and off-axis distance can then be plotted. After a number of points have been plotted, the concentration isopleth may be drawn (see problems 8 and 26). Figures 3-6 and 3-7 give ground-level isopleths of $\chi u/Q$ for various stabilities for sources at H = 0 and H = 100 meters. For example, to locate the 10^{-3} g m^{-3} isopleth resulting from a ground-level source of 20 g sec^{-1} under B stability conditions with wind speed 2 m sec^{-1}, one must first determine the corresponding value of $\chi u/Q$ since this is the quantity graphed in Figure 3-6. $\chi u/Q = 10^{-3} \times 2/20 = 10^{-4}$. Therefore the $\chi u/Q$ isopleth in Figure 3-6B having a value of 10^{-4} m^{-2} corresponds to a χ isopleth with a value of 10^{-3} g m^{-3}.

AREAS WITHIN ISOPLETHS

Figure 3-8 gives areas within isopleths of ground-level concentration in terms of χ u/Q for a ground-level source for various stability categories (Gifford, 1962; Hilsmeier and Gifford, 1962). For the example just given, the area of the 10^{-3} g m^{-3} isopleth (10^{-4} m^{-2} χ u/Q isopleth) is about 5 x 10^{4} $meter^{2}$.

CALCULATION OF MAXIMUM GROUND-LEVEL CONCENTRATIONS

Figure 3-9 gives the distance to the point of maximum concentration, x_{max}, and the relative maximum concentration, χ u/Q_{max}, as a function of effective height of emission and stability class (Martin, 1965). This figure was prepared from graphs of concentration versus distance, as in Figure 3-5. The maximum concentration can be determined by finding χ u/Q as a function of effective emission height and stability and multiplying by Q/u. In using Figure 3-9, the user must keep in mind that the dispersion at higher levels may differ considerably from that determined by the σ_y's and σ_z's used here. As noted, however, since σ_y generally decreases with height and u increases with height, the product u σ_y σ_z will not change appreciably. The greater the effective height, the more likely it is that the stability may not be the same from the ground to this height. With the longer travel distances such as the points of maximum concentrations for stable conditions (Types E or F), the stability may change before the plume travels the entire distance.

REVIEW OF ASSUMPTIONS

The preceding has been based on these assumptions, which should be clearly understood:

(i) Continuous emission from the source or emission times equal to or greater than travel times to the downwind position under consideration, so that diffusion in the direction of transport may be neglected.

(ii) The material diffused is a stable gas or aerosol (less than 20 microns diameter) which remains suspended in the air over long periods of time.

(iii) The equation of continuity:

$$Q = \int_{0}^{+\infty}\int_{-\infty}^{+\infty} \chi\, u\, dy\, dz \qquad (3.9)$$

is fulfilled, i.e., none of the material emitted is removed from the plume as it moves downwind and there is complete reflection at the ground.

(iv) The mean wind direction specifies the x-axis, and a mean wind speed representative of the diffusing layer is chosen.

(v) Except where specifically mentioned, the plume constituents are distributed normally in both the cross-wind and vertical directions.

(vi) The σ's given in Figures 3-2 and 3-3 represent time periods of about 10 minutes.

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Gifford, F. A., 1961: Use of routine meteorological observations for estimating atmospheric dispersion. Nuclear Safety, 2, 4, 47-51.

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*"ln" denotes natural logarithms, i.e., to the base e.

— EFFECTIVE HEIGHT OF EMISSION

GENERAL CONSIDERATIONS

In most problems one must estimate the effective stack height, H, at which the plume becomes essentially level. Rarely will this height correspond to the physical height of the stack, h. If the plume is caught in the turbulent wake of the stack or of buildings in the vicinity of the stack, the effluent will be mixed rapidly downward toward the ground (aerodynamic downwash). If the plume is emitted free of these turbulent zones, a number of emission factors and meteorological factors influence the rise of the plume. The emission factors are: velocity of the effluent at the top of the stack, v_s; temperature of the effluent at the top of the stack, T_s; and diameter of the stack opening, d. The meteorological factors influencing plume rise are wind speed, u; temperature of the air, T_a; shear of the wind speed with height, du/dz; and atmospheric stability. No theory on plume rise takes into account all of these variables; even if such a theory were available, measurements of all of the parameters would seldom be available. Most of the equations that have been formulated for computing the effective height of emission are semi-empirical. For a recent review of equations for effective height of emission see Moses, Strom, and Carson (1964).

Moses and Strom (1961), having compared actual and calculated plume heights by means of six plume rise equations, report "There is no one formula which is outstanding in all respects." The formulas of Davidson-Bryant (1949), Holland (1953), Bosanquet-Carey-Halton (1950), and Bosanquet (1957) all give generally satisfactory results in the test situations. The experiments conducted by Moses and Strom involved plume rise from a stack of less than 0.5 meter diameter, stack gas exit velocities less than 15 m sec^{-1}, and effluent temperature not more than 35°C higher than that of the ambient air.

The equation of Holland was developed with experimental data from larger sources than those of Moses and Strom (stack diameters from 1.7 to 4.3 meters and stack temperatures from 82 to 204°C); Holland's equation is used in the solution of the problems given in this workbook. This equation frequently underestimates the effective height of emission; therefore its use often provides a slight "safety" factor.

Holland's equation is:

$$\Delta H = \frac{v_s d}{u} \left(1.5 + 2.68 \times 10^{-3} p \frac{T_s - T_a}{T_s} d\right) \quad (4.1)$$

where:

ΔH — the rise of the plume above the stack, m

v_s — stack gas exit velocity, m sec^{-1}

d — the inside stack diameter, m

u — wind speed, m sec^{-1}

p — atmospheric pressure, mb

T_s — stack gas temperature, °K

T_a — air temperature, °K

and 2.68×10^{-3} is a constant having units of mb^{-1} m^{-1}.

Holland (1953) suggests that a value between 1.1 and 1.2 times the ΔH from the equation should be used for unstable conditions; a value between 0.8 and 0.9 times the ΔH from the equation should be used for stable conditions.

Since the plume rise from a stack occurs over some distance downwind, Eq. (4.1) should not be applied within the first few hundred meters of the stack.

Extracted From

"GUIDELINE ON AIR QUALITY MODELS"

U. S. Environmental Protection Agency

Research: Triangle Park, NC

CLASSES OF MODELS

Air quality models discussed in this guideline can be categorized into four generic classes: Gaussian, numerical, statistical or empirical, and physical. Within some of these classes a large number of individual "computational algorithms" exists, each with its own specific applications. While each of these algorithms may have the same generic basis, e.g., Gaussian, it is accpeted practice to refer to them individually as models. For example, the Climatological Dispersion Model, the Air Quality Display Model and the Texas Climatological Model are commonly referred to as individual models. In fact, they are all variations of a basic Gaussian model. In many cases the only real differences between models is the degree of detail considered in the inupt or output data.

Gaussian models are generally state-of-the-art techniques for estimating the impact of nonreactive pollutants. Numerical models are more developmental in nature than are Gaussian models and are not as widely applied. However, they are more appropriate than Gaussian models for multi-source applications which involve reactive pollutants. Statistical or empirical techniques are frequently employed in situations where incomplete scientific understanding of the physical and chemical processes make the use of a Gaussian or numerical model impractical. Various specific models of these three generic types are recommended in this guideline.

Physical models, the fourth generic type, are used in wind tunnel or other fluid modeling facilities. Such models may be very useful in evaluating the air quality impact of a source or group of sources

in a geographic area limited to a few square kilometers. Where physical modeling is available and applicable (e.g., stable pollutants, a narrow range of meteorological conditions and a few sources) it is recommended. However, physical modeling is frequently not a viable option due to limitations associated with (1) the need to simulate a wide range of atmospheric and source conditions, (2) availability of physical modeling facilities, and (3) requirements for technical expertise. Thus, due to these limitations, physical modeling is not discussed further in this guideline.

In addition to the four classes of models, this guideline identifies two hierarchies of models. The first hierarchy consists of general estimation techniques that provide conservative estimates of the air quality impact of a specific source, or source category. The purpose of such techniques is to eliminate from further consideration those sources that will not cause or contribute to ambient concentrations in excess of NAAQS or allowable concentration increments. Conversely these techniques can be used to identify those control strategies that have the potential to meet NAAQS and allowable increments. The second hierarchy of models are those analytical techniques which provide more detailed treatment of physical and chemical atmospheric processes, require more detailed and precise input data, and provide more specialized concentration estimates. As a result they provide a more refined and, at least theoretically, a more accurate estimate of source impact and the effectiveness of control strategies.

In some cases, the first hierarchy of models may be equated with screening techniques to determine if a second or more refined

analysis is required. However, while the use of screening techniques followed by more refined analysis is desirable, there are situations where the screening techniques are practically and technically the only models available. Thus, at times a more refined analysis is not possible and the screening techniques are the only viable option for estimating source impact and evaluating control strategies.

RECOMMENDED MODELS

To meet the need for consistency identified in Section 2, selected point source and multi-source models applicable to specific pollutants and averaging times are recommended in this subsection. It is further recommended that the set of plume rise equations given by Briggs be used to calculate the effective stack height that is input to these models.

Ideally, air quality models that are recommended should meet prescribed standards of performance for particular applications and should be subjected to specific validation procedures. However, there are no generally accepted standards of performance and validation procedures. The models recommended in this guideline are simply those which are (1) representative of the state-of-the-art for atmospheric simulation models and (2) those most readily available to air pollution control agencies.

Point Source Models for Sulfur Dioxide and Particulate Matter (All Averaging Times)

Gaussian models are considered to be state-of-the-art for sulfur dioxide (SO_2) and particulate matter (PM). They are the best choice

for most point source evaluations. For all point sources two hierarchies of models are recommended for use. The first hierarchy is composed of models which can provide a preliminary estimate of concentrations. It is recommended that such a screening process be applied to all major sources. If it is found from the screening process that the source will cause a concentration that is more than one-half of the NAAQS or other allowable air quality increment, then that source should be subjected to a more refined analysis.

For flat terrain situations that have no significant meteorological complexities, there are several standard publications and computerized models that can be used for screening. Screening should also be applied in situations where more complex conditions exist, e.g., inversion-breakup fumigation, lake/sea breezes, aerodynamic downwash, long-range transport (greater than 50 kilometers), and complex terrain. Volume 10 of the Guidelines for Air Quality Maintenance Planning and Analysis, "Reviewing New Stationary Sources," has summarized techniques applicable to both flat terrain and more complex situations. The techniques are presented in a useful format for the purpose of screening and are recommended for use.

In those cases where a more refined analysis is required and there are no significant meteorological terrain complexities, the Single Source (CRSTER) Model is recommended for use. However, if the screening process indicates that the meteorological or terrain complexities cause serious uncertainties, then a model that is more detailed or more suitable than the Single Source (CRSTER) Model should

be applied. No refined, widely available models which are applicable to complex situations are identified here. It is recommended that each complex situation be treated on a case-by-case basis with the assistance of expert advice.

If the data bases required to apply the Single Source (CRSTER) Model are unavailable, or if more refined models applicable to a complex situation do not exist, then it may be necessary to base estimates of source impact and the evaluation of control strategies on only the preliminary estimates. In such cases, every effort should be made to acquire or improve the necessary data bases and to develop more refined analytical techniques.

Models specified here and in the following subsection are also applicable to stationary sources of lead pollutants, provided the pollutants can be assumed to behave as a gas.

Multi-Source Models for Sulfur Dioxide and Particulate Matter (Annual Average)

Due to the complexity of most multi-source situations and the wide acceptability of several models, a screening process is not generally conducted. If a preliminary assessment of the adequacy of a control strategy is desired, the Rollback Model amy be used. However, in most cases such a screening does not constitute an adequate control strategy demonstration.

The Climatological Dispersion Model (CDM), the Air Quality Display Model (AQDM), and the Texas Climatological Model (TCM) are recommended for evaluating multi-source complexes. More detailed or suitable models may be used, especially in regions with

major meteorological or topographic complexities. If the meteorological or topographic complexities of the region are such that the use of any available air quality model is precluded, the model used for strategy evaluation may be limited to a Rollback model.

Multi-Source Models for Sulfur Dioxide and Particulate Matter (Short-Term Averages)

As noted in the previous subsection, a Rollback Method may be used for the preliminary assessment of a control strategy. The Real-Time Air-Quality-Simulation Model (RAM) is recommended for evaluating the impact of multi-source complexes on air quality averaged over short-term periods. The Texas Episodic Model (TEM) may be used if the data bases required to apply RAM are unavailable. Also, if the resources required to operate RAM or TEM are not available, the CDM, AQDM or TCM may be used to estimate short-term concentrations of SO_2 and particulate matter. These latter models should be used with procedures, such as that discussed by Larsen, to convert 3-hour and 24-hour average concentrations from annual average concentration estimates. Such statistical techniques are valid only in urban, multi-source areas and should not be used in situations dominated by single point sources.

A more detailed or more suitable model may be used, especially in a region which has major meteorological or topographic complexities. If the meteorological or topographic complexities of the Region are such that the use of any available air quality model is precluded, the model used for control strategy evaluation may be limited to a Rollback Model.

Point, Line and Multi-Source Models for Carbon Monoxide

The recommendations for point source screening procedures and models are also applicable to evaluate point sources of carbon monoxide (CO). The models, procedures and requirements described in Volume 9 of the Guidelines for Air Quality Maintenance Planning and Analysis, "Guidelines for Review of the Impact of Indirect Sources on Ambient Air Quality," are recommended for screening all mobile sources of CO which fulfill the definition of an indirect source. The indirect source guideline is based on the use of HIWAY and other simple dispersion techniques. It is acceptable to apply these latter techniques, e.g. HIWAY, independently of the indirect source guideline if it is found that the guideline does not adequately consider a wide enough set of circumstances. The indirect source guideline and associated techniques are also applicable as a screening technique for large numbers of mobile sources. For example, the HIWAY and Hanna-Gifford models may be used jointly to screen a large urban area.

Specific refined modeling techniques are not recommended here. Situations that require more refined techniques should be considered on a case-by-case basis with the use of expert consultation. If a suitable model is available and the data and technical competence required for this model are available, it may be used.

There are many situations where an individual indirect source or a group of sources is well defined so that the indirect source guideline is adequate to assess source impact and to evaluate control strategies. However, if a region-wide analysis is necessary and there

is no available or appropriate model, the model used for strategy evaluation in multi-source complexes (mobile and stationary) may be limited to a Rollback Model.

Point and Multi-Source Models for Nitrogen Dioxide

The recommendations for point source screening procedures and models are also applicable to evaluate point sources of nitrogen oxides (NO_x) under limited circumstances. The circumstances require an assumption that all NO_x is emitted in the form of NO_2 and that NO_2 is a non-reactive pollutant.

For sources located where atmospheric photochemical reactions are significant, a Rollback Model may be used as a preliminary assessment to evaluate the control strategies for multiple sources (mobile and stationary) of NO_x. Another acceptable screening procedure for multiple sources is to make an assumption similar to that required for point sources and then to use a model for non-reactive pollutants, such as CDM.

Specific refined modeling techniques are not recommended here. Situations that require more refined techniques should be considered on a case-by-case basis with the use of expert consultation. If a suitable model is available and the data and technical competence required for this model are available, it may be used to estimate average concentrations of NO_2. However, if a region-wide analysis is necessary and there is no available or appropriate model, the model used for strategy evaluation in multi-source complexes (mobile and stationary sources) may be limited to a Rollback Model.

Multi-Source Models for Photochemical Oxidants

To estimate maximum oxidant concentrations and to evaluate control strategies, it is recommended that the ozone isopleth technique be used in all initial assessments. Other techniques (e.g., statistical relationships) that are applicable at specific sites may be used provided that prior approval is obtained from the appropriate EPA Regional Administrator. The Rollback Model may only be used as a means for demonstrating that attainment of the standard will require at least all reasonably available control technology. Appendix J is no longer considered an acceptable technique and should not be used in demonstrating the effectiveness of control stragegy revisions.

In order to obtain a more refined estimate and to calculate the temporal and spatial distributions of oxidants, it is essential that a numerical model be used. Numerical models have the ability to mathematically simulate the transport, diffusion and chemical reaction processes that occur in the atmosphere. Specific refined modeling techniques are not recommended here; however, situations that require more refined techniques should be considered on a case-by-case basis with the use of expert consultation. If a suitable model is available and the data and technical competence required for the model are available, it may be used.

In many cases, the more refined techniques may not be practical for routine application or may have data requirements that cannot be met. In such cases the first assessment with the ozone isopleth technique may be considered adequate for control strategy evaluation until such time

as the more refined estimates are available. Generally all acceptable techniques which are applicable to oxidants are still undergoing testing and evaluation and have not been widely applied. Consequently, these techniques must be used judiciously.

STACKS—*How High?*

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So many excellent papers have been presented on the role of stacks for the abatement and control of air pollution emissions, that a significant new contribution is problematical. However, because of the important role of stacks in air pollution control, a review of TVA experience in the performance of stacks for dispersal and dilution of power plant wastes may be of special interest.

Principles for guidance in the design of stacks for the modern power plants were aptly implied by R. S. Scorer[1] when he concluded a short paper titled "Plumes from Tall Chimneys" with the following: "The gaseous products of combustion are only harmful when they are at the ground. The objective should be, therefore, to get them as high into the air as possible by means of a very few tall wide chimneys and a certain amount of buoyancy." The extremely large single generating units now being built with capacities up to 1000 mw offer a promising opportunity to apply these principles.

Tall stacks cannot remove all vestiges of air pollution. However, in many instances they can limit pollution at ground level so that no harmful or damaging effects are produced. Frequently the minimal pollution from power plants is considerably less than that which would result from individual home coal or oil heating plants, which are replaced by space heating when low cost electric power becomes available.

Basic Stack Height Criteria

Air pollution control considerations are the principal determinant for stack heights in modern power plants. While fly ash may be effectively removed from flue gas by mechanical collectors and electrostatic precipitators, no practical means other than stacks have been found acceptable for disposition of the large quantity of sulfur dioxide formed in coal combustion. Numerous factors, many of which are not common for any two plants, influence the choice of stack height.

A basic minimum requirement is provision of sufficient stack height to prevent downwash during periods of high wind velocity. With stacks less than twice the height of the main powerhouse structure, experience has demonstrated that, during high velocity wind, fumes may be caught in the turbulent vortex sheath and brought to ground level in relatively high concentrations very near the plant and sometimes reenter the building air supply. Extensive wind tunnel tests and field experience have demonstrated that downwash does not pose a problem where the stack height is at least $2^1/_2$ times the height of the powerhouse or other nearby structures and appropriate efflux velocities are provided. Thus with a 100-ft-high powerhouse, a 250-ft stack should provide adequate limitation of downwash. In commenting on the value of this simple criterion, R. S. Scorer[2] writes: "The well known $2^1/_2$ times rule concerning chimney heights is commendable because it is comprehensible as a working rule, it has no precise theoretical justification, and if experience proved to be inadequate it could be changed by Act of Parliament."

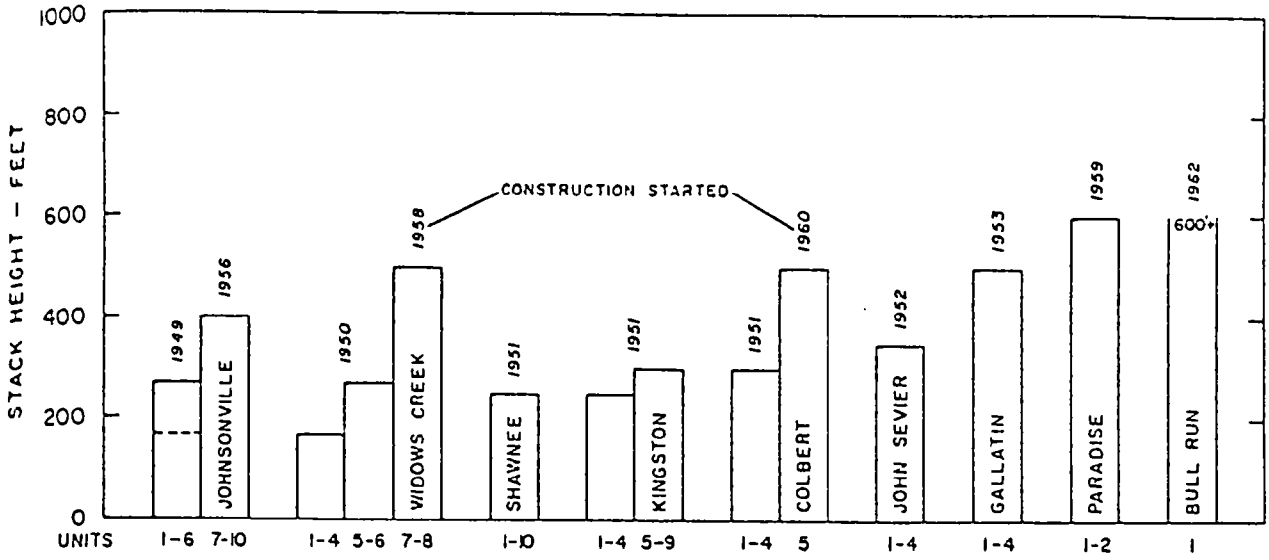
For the large modern plants which may emit 800–1200 tons of sulfur dioxide per day, higher stacks than specified by the $2^1/_2$ times rule are usually required to limit ground concentrations of sulfur dioxide resulting from normal atmospheric diffusion of the smoke plume. Environmental and operational factors requiring consideration include the number, size, and separation of units or stacks; the heat and sulfur dioxide emission rates; population density and urban development; topography and terrain; general regional meteorology and macrometeorology of the immediate area; and land use such as forest types and agricultural practices.

Stack Height Estimation

Empirical Extrapolation from Data on Existing Plants

TVA's choice of stack heights has been based largely on (*1*) a consideration of environmental, design, and operational factors for each site, (*2*) an accurate definition of dispersion from each of its previous and usually somewhat smaller plants, and (*3*) extrapolation of these data to a larger new plant with selection of a stack height which will effectively limit the magnitude and frequency of maximum concentrations. A combination of complete data on plant operations, data from well-equipped meteorological stations at each steam plant, and sulfur dioxide data from 17 autometers operated an aggregate of 111 autometer-years at selected sites 0.5 to 20 miles from six steam plants with from one to 10 generating units, has provided voluminous background information on plume dispersion from TVA steam plants. This information, along with other data from extensive plume height observations, mobile ground level sampling with a Titrilog in an automobile, and extensive dispersion measurements in a helicopter, has provided the basis for empirical procedures used in establishing stack heights for new or proposed steam plants. Basically, this procedure consists of normalizing data from all plants for the principal meteorological dispersion patterns with establishment of a data envelope or trend which is extended to encompass projected conditions at a new plant.

Figure 1 illustrates the increases in stack heights which have been provided for new and usually larger plants. The 170-ft stacks initially provided for the first large steam plant, at Johnsonville, Tennessee, in 1952, proved inadequate



			MEGA-WATTS
JOHNSONVILLE	UNITS	1-6	750
"	"	7-10	600
WIDOWS CREEK	"	1-6	750
"	"	7-8	1000
SHAWNEE	"	1-10	1500
KINGSTON	"	1-4	600
"	"	5-9	1000

			MEGA-WATTS
COLBERT	UNITS	1-4	800
"	"	5	500
JOHN SEVIER	"	1-4	800
GALLATIN	"	1-2	500
"	"	3-4	550
PARADISE	"	1-2	1300
BULL RUN	"	1	900

Fig. 1. Stack heights, TVA steam plants.

However, the possibility of this inadequacy was recognized in the design stage, and steel was sized for support of a 100-ft extension. This extension added in 1955 relieved objectionable downwash and recirculation conditions. Experience at the Gallatin Steam Plant offers a good example of application of empirical extrapolations in establishing stack height for a new plant. On the basis of data from existing plants, two 500-ft stacks, one serving two 250-mw units and one serving two 275-mw units, were built. Data indicated that with stacks of this height, ground level concentrations of SO_2 (30-min avg) in the direction of most frequent plume travel would equal or exceed 0.5 ppm only two times per year, a frequency of 0.01%. In 2¼ yr of operating experience since this generating station reached design capacity, the frequency of 0.4, 0.5, and 0.6, 30-min avg concentrations as measured by three autometers sited in this direction has been 0.032, 0.016, and 0.007%. All concentrations at the 0.5 and 0.6 levels occurred within a 3-hr period on one day when the wind speed was zero and a stagnant high-pressure system was centered over the general area. A similar check will soon be afforded the 600-ft stacks provided at the larger 1400 mw Paradise plant.

Mathematical Diffusion Analyses

This empirical approach is attractive in establishing power plant stack heights in the relatively restricted TVA area where a mass of meteorological and air pollution data has been compiled at a series of power plants. However, mathematical analyses of dispersion offer a preferable approach to general industrial plants. We believe that recent advances in the measurement and definition of vertical and horizontal dispersion rates in all ranges of atmospheric stability present the basic information necessary for confident estimate of stack height for any problem from general dispersion equations, provided a realistic estimate of plume rise is available. Data and procedures for such mathematical analyses have been effectively compiled and presented by Gifford,[3] Cramer,[4] Pasquill,[5] and others.

It is of interest to note the close agreement in estimates of stack height by several methods of analysis for a power plant with assumed SO_2 emission rate of approximately 800 tons per day. These are summarized in Table I.

Relative Effectiveness of Stacks in Principal Dispersion Models

The common objective in establishing stack heights is limitation of maximum ground concentrations during all meteorological conditions to a level and a fre-

Table I

Method	For Level Terrain Estimated Stack Height Feet Above Ground Level
1. Empirical extrapolation based on normalized data from existing TVA plants	700
2. Generalized diffusion equation for maximum ground level concentrations, i.e. $X = \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{H^2}{\sigma_z^2}\right)\right]$ and using dispersion coefficients presented by Gifford[3]	663
3. Generalized diffusion equation for maximum ground level concentration $X = \frac{Q}{\pi C_y C_z x^{k_u}}\exp\left[-\frac{1}{2}\left(\frac{y^2}{C_y^2 x^{2k_y}}\right)\right]$ and using diffusion coefficients based on full-scale dispersion studies[6] of smoke plumes from TVA steam plants	699

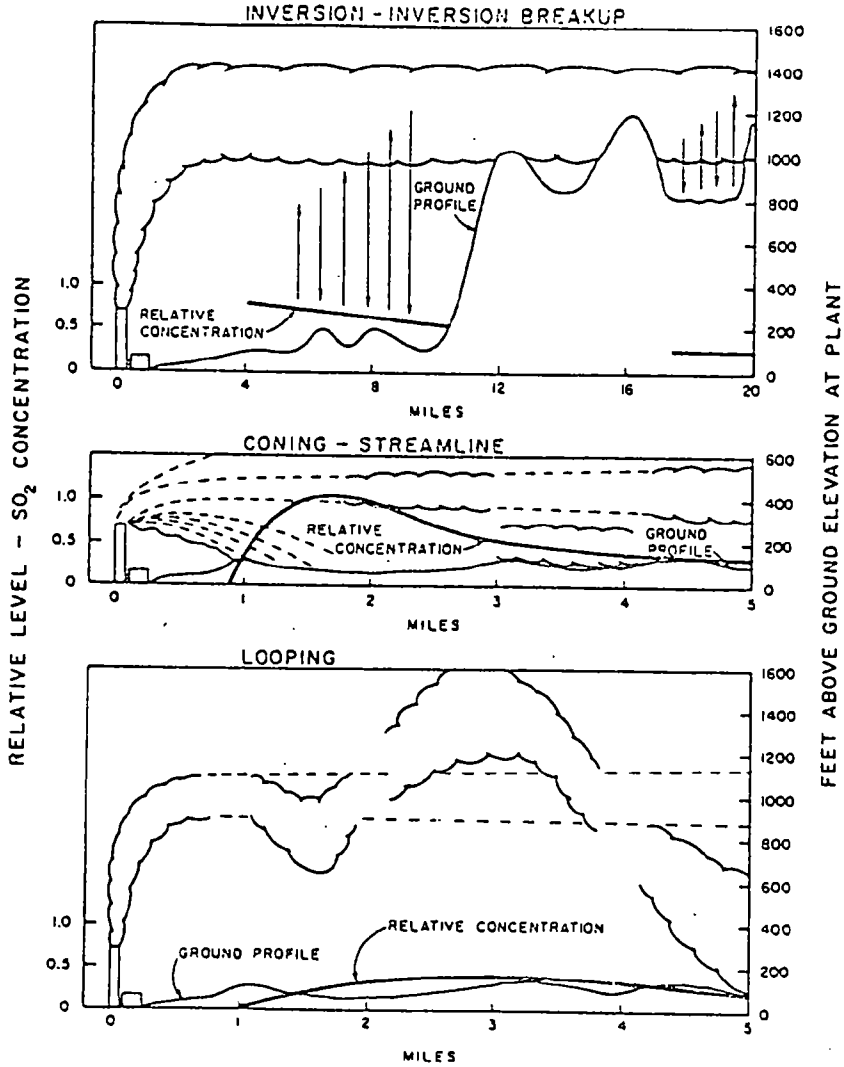


Fig. 2. Plume dispersion models.

quency which will not adversely affect the environment. In considering this objective it is pertinent to examine relative pollution levels which are expected during the meteorological conditions of principal interest; also to consider the relation of peak and time average concentrations. Such data for one large steam plant for the coning, looping, and inversion plume reported in an earlier paper[7] are illustrated in Fig. 2. Here it is of interest to note the limited variation in the magnitude of maximum 30-min avg concentrations found to have the following relative values: coning or streamline plume typical of neutral stability, 1.0; looping plume present with strong thermal instability, 0.4; and inversion breakup, 0.6. Peak concentrations as measured by the autometer which has an averaging period of 2–3 min were two to three times the value of 30-min avg concentrations. As indicated by data graphically illustrated in Fig. 2, the provision of adequate dilution for control of pollution during high velocity wind neutral conditions should generally satisfy requirements during other meteorological conditions.

Neutral Condition—Coning Plume

While stack height requirements have been primarily based on control during the high wind neutral condition, effectiveness during other dispersion models should be appraised. For a neutral condition the extent of ground fumigation is largely a function of effective stack height (actual height plus rise of the heated plume) and wind speed for the critical condition. Because of the rapid plume ventilation afforded by relatively high velocity wind, the buoyancy due to heat emission is quickly dissipated and has less opportunity to reduce ground fumigations. This obviously accounts for the relatively high fumigation levels associated with this condition. However, it is of interest to examine the buoyancy effect during inversion and looping conditions, especially for the extremely large generating units being built for current plants.

Inversion Conditions—Fanning Plume

While the condition where temperature increases with elevation, described as inversion, is of profound importance in the appraisal of air pollution dispersion, our experience suggests that it may have been unduly maligned, especially with respect to power plants. Although inversion has been described as the scapegoat in general urban air pollution for years, the equally important role of low velocity wind is now receiving recognition. Also, review of the literature suggests that a lack of discrimination may exist between ground-based radiation inversions and elevated subsidence-type inversions. With the exception of infrequent passage of warm high-pressure systems, subsidence-type inversions, which chronically accentuate air pollution problems in southern California, are considered to be a relatively minor factor with respect to air pollution from steam power plants in the Tennessee Valley.

Surface radiation inversions do, of course, affect the dispersion of steam plant plumes. However, with a few exceptions, we have considered this as a beneficial effect. Due to large heat emission, steam plant plumes generally rise and stratify 800–1200 ft above ground level where they are diluted and innocuously conveyed great distances by winds aloft. With the heating of the ground and establishment of convection, breakup and attendant fumigation occur in midmorning. However, breakup fumigations have been low level and transient except in one area where the plume traverses a plateau approximately 1000 ft above the plant elevation.

Beneficial Effect of Heat Emission

Inversion Conditions

The increase in generator size from about 100 mw to 1000 mw within the last 10 yrs, with attendant increase in heat emission, may present a practical opportunity for effective reduction of inversion fumigations. Instead of serving as ceiling which holds pollution near ground level, use may be made of inversion as a shield or isolation medium to prevent pollution from reaching ground level. The proposed Bull Run Steam Plant near Oak Ridge, Tennessee, may be used to illustrate such possibilities. Initially a single 900-mw unit will be constructed at this location. Subsequently one or more units, possibly of even larger capacity, may be added. To provide assurance of adequate dispersal from the ultimate plant, the initial unit will be served by a high stack designed to prevent significant fumigation during neutral conditions when critical wind speeds exist. The height of stack to be provided is now under study.

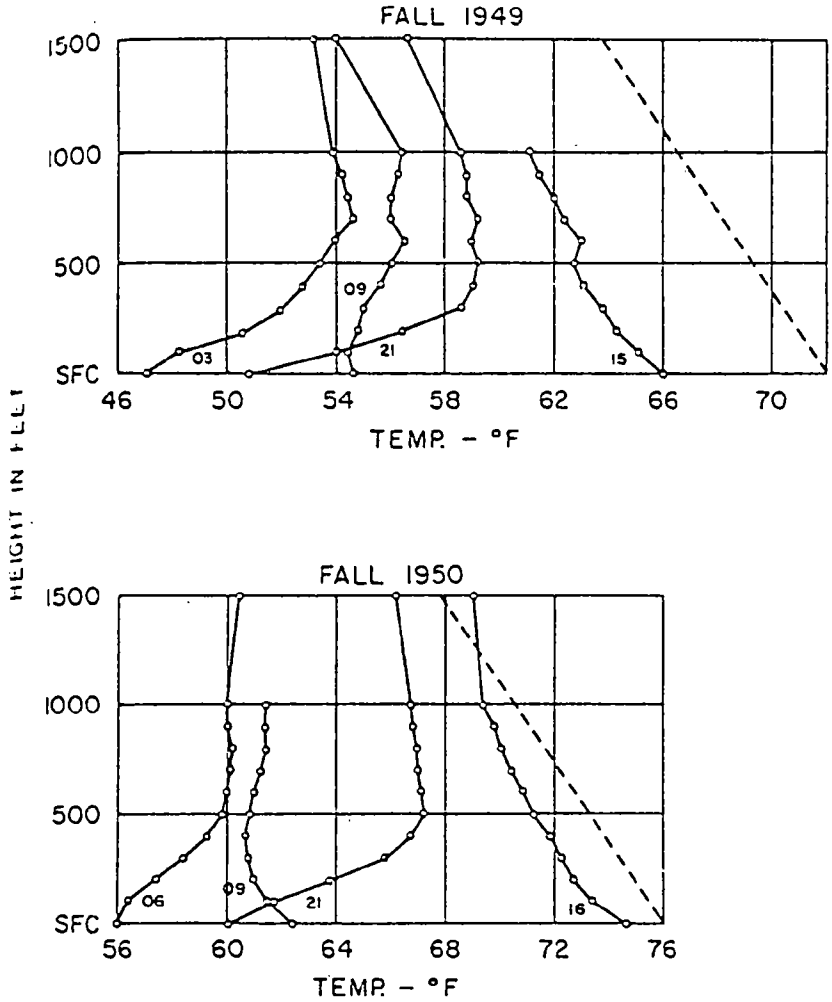


Fig. 3. Vertical temperature profiles—Oak Ridge, Tennessee.

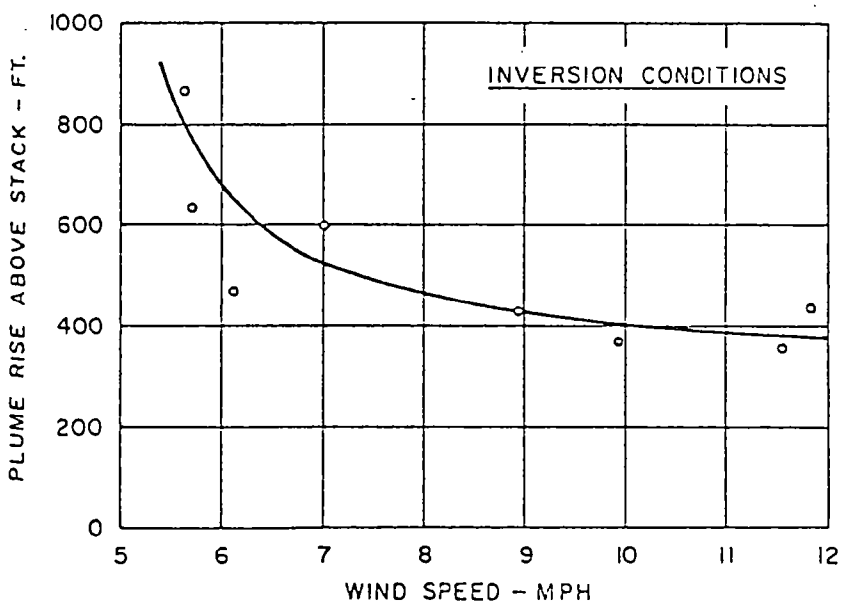


Fig. 4. Plume rise, Colbert Steam Plant.

Fortunately the temperature profile in this area up to elevation 1500 ft has been well defined by the Meteorology Section attached to AEC at Oak Ridge. Figure 3 illustrates average seasonal temperature profiles taken at 0300, 0900, 1500, and 2100 in the fall of 1949–50.[3] Extensive data reveal that temperature inversions rarely extended above 500 ft at 0300 and 2100. In the 500- to 1000-ft zone the temperature gradient varied from isothermal to some less than adiabatic. Above 1000 ft, the gradient approximated the reference adiabatic slope in 1949 and was essentially isothermal in 1950. These data on variation of temperature with elevation along with information on a plume rise during full-scale dispersion studies at the Colbert Steam Plant provide a frame in which the benefit of plume rise due to heat emission may be examined.

Figure 4 illustrates the range of plume rise observed during inversion conditions on eight sample days at the Colbert plant with three 200-mw units in operation, each with a 300-ft stack. With a 6-mph wind speed at the plume centerline, the rise was approximately 600 ft. A comparable rise above a much higher Bull Run stack should carry the plume to an elevation where temperature gradient is near adiabatic. Actually the rise from the Bull Run stack should be appreciably greater because (*1*) buoyant force is not dissipated in penetrating the intense inversion below 500 ft, and (*2*) heat emission from the single 900-mw unit is approximately four times that from a single 200-mw unit at the Colbert plant.

Actual temperature profiles and plume elevations for two of the days on Fig. 4 illustrate the penetration of a surface inversion by a steam plant plume, Fig. 5. Plume measurements and temperature profiles were taken from a specially instrumented helicopter. On September 24, the top of the plume was stratified at about 800 ft and did not penetrate the inverted temperature region. On October 8, the more intense surface inversion was penetrated and the top of the plume stratified at about elevation 1600 where the lapse rate was slightly less than adiabatic. It seems reasonably certain that a five-fold increase of the unit heat rate, as estimated for 200- and 1000-mw units and a stack height of, say, 500–700 ft, would have carried the plume well above the inversion and isothermal strata into a relatively unstable near adiabatic area where upward dispersion would be enhanced and downward diffusion blocked. As a matter of interest, a 500-ft stack has been provided recently for a new 500-mw unit at this plant.

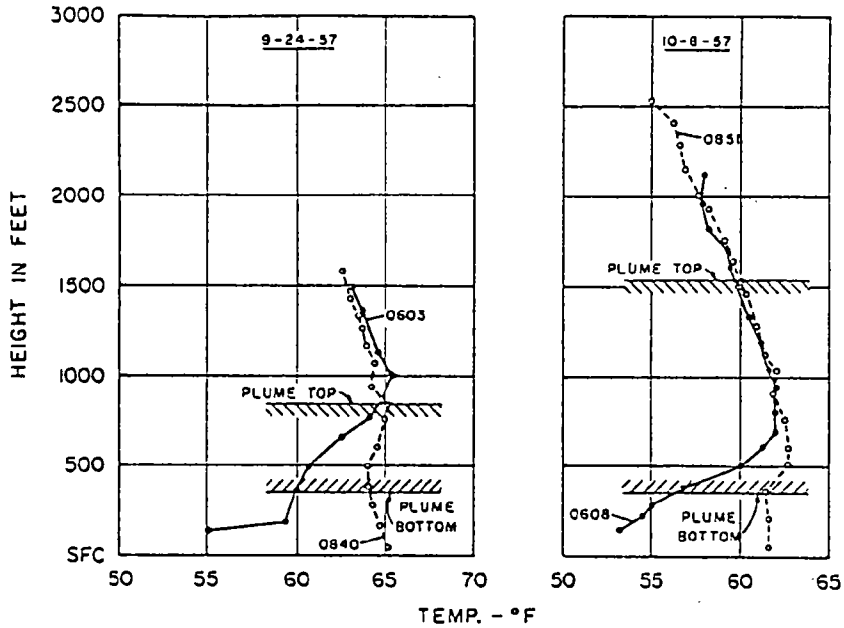


Fig. 5. Vertical temperature profile and plume elevation, Colbert Steam Plant.

Unstable Conditions—"Looping" Plume

According to the data from one of our large steam plants, illustrated in Fig. 2, 30-min avg ground concentrations during unstable low wind conditions when a looping plume exists are lower than those in either neutral or inversion breakup fumigations. These data were taken at a plant with 250- and 300-ft stacks. In the analysis of similar data from another plant with two 500-ft stacks, a point of special interest is that no significant difference exists in maximum 30-min avg concentrations for neutral and looping conditions. This suggests that as stack heights are increased the dilution effected in neutral high velocity wind conditions was no greater than that associated with thermals in looping conditions.

The above description of fumigations as looping according to Church[9] is not considered fully appropriate to plume patterns from large steam plants. Due to the large heat emission, the plume is rarely brought to ground level by small thermals. Fumigations described as looping are associated with large thermals, loops of several miles, and are not particularly transient. The magnitude of observed circulation induced by thermals acting on relatively small power plant plumes suggests that even greater dilution may be provided by the larger plants now under construction or being planned.

When thermal convection is present, the heat emission from a large power plant or similar energy source may initiate thermals and, in fact, establish a semi-independent local atmospheric circulation. In this circumstance the plume may rise several thousand feet and often produces cumulus clouds. During the release of neutral constant volume tetroons at the Colbert Steam Plant, ascent in thermals up to 5000 ft was observed.

While a heat source equivalent to 50 mw over a 500-meter-square area has been described as adequate for the initiation of thermals, the equivalent of 200 mw of heat may be released from a single 1000-mw generating unit. Obviously this four-fold greater energy source should produce stronger and larger thermals—and result in further reduction of pollution at ground level during unstable conditions.

Mathematical Formulation of Plume Rise

Implications of Common Formulae

Numerous formulae for calculation of plume rise have been presented which attempt to take into account the effects of heat load, wind velocity, atmospheric stability, and other variables. Variable temperature gradients, such as illustrated in Fig. 5, suggest that such formulae are at best approximations. Holland[8] has presented one of the more popular formulae for plume rise in average conditions which is attractive because of its simplicity. In this formula, $h = (1.5\ vd + 3 \times 10^{-4}\ Q_H)/u_1$, the plume rise is inversely proportional to the wind speed and, in part, proportional to the heat emission rate. In England, Lucas, Moore, and Spurr[10] have conducted careful and extensive studies leading to the following expression for plume rise: $h = K_1 Q^{1/4}{}_H/u$, where K was found to have values ranging from 3900 to 6200 for different power stations. These studies in England suggest that the plume rise is much more dependent on wind speed than on heat content.

It is of interest to note the relative values of plume rise given by these formulae for, say, 100- and 1000-mw units. The formulae developed at the Earley Station in England suggest that the plume rise from a 1000-mw unit is about 1.78 times that for a 100-mw unit. According to the Holland formula, an eight-fold increase in plume rise would occur.

An intriguing prospect of these plume-rise formulae is their relation to the maximum ground level concentrations. For example, Fig. 6 illustrates the relative maximum ground concentrations estimated for 100- to 1000-mw units with actual stack heights of 300, 500, and 800 ft. In the lower portion of this figure, initial observed plume rises at 100- to 200-mw plants are increased for larger units according to the Holland formula. In the upper part of the figure, plume rise is increased in proportion to the 0.25 power of the heat emission. For comparison a value of unity is given to the maximum ground concentration which occurs with a 1000-mw unit, a 300-ft stack, and plume rise proportional to the 0.25 power of heat emission.

Concentrations based on the Holland formula where plume rise approaches a linear relation to heat emission show very little change with unit size and, in fact, show a decrease above 500 mw with a 300-ft stack. This is obviously unrealistic and probably reflects the limitations of source data from small power plants. Concentrations based on plume rise proportional to the 0.25 power of heat emission approach a straight line relation and suggest appreciable increase in ground concentration with increase in unit size. These data suggest that plume rise due to heat emission may be less than generally estimated.

Estimate from TVA Data

Data compiled from meteorological stations and networks of autometers at five TVA steam plants may be used for indirect approximation of the effect of heat emission on plume rise. Extensive data have confirmed that an increase in station size as based on the number of generating units does not result in a linear or proportional increase in maximum ground concentrations of SO_2. These data, illustrated in Fig. 7, indicate that an increase in number of units from one to ten has resulted in a 5.3, say 5.0, rather than a ten-fold increase in ground concentration. This nonlinearity is attributed to (1) line source effect due to an average separation of about 80 ft between stacks and (2) increase in plume rise due to greater heat emission. This relation is essentially unchanged for wind direction

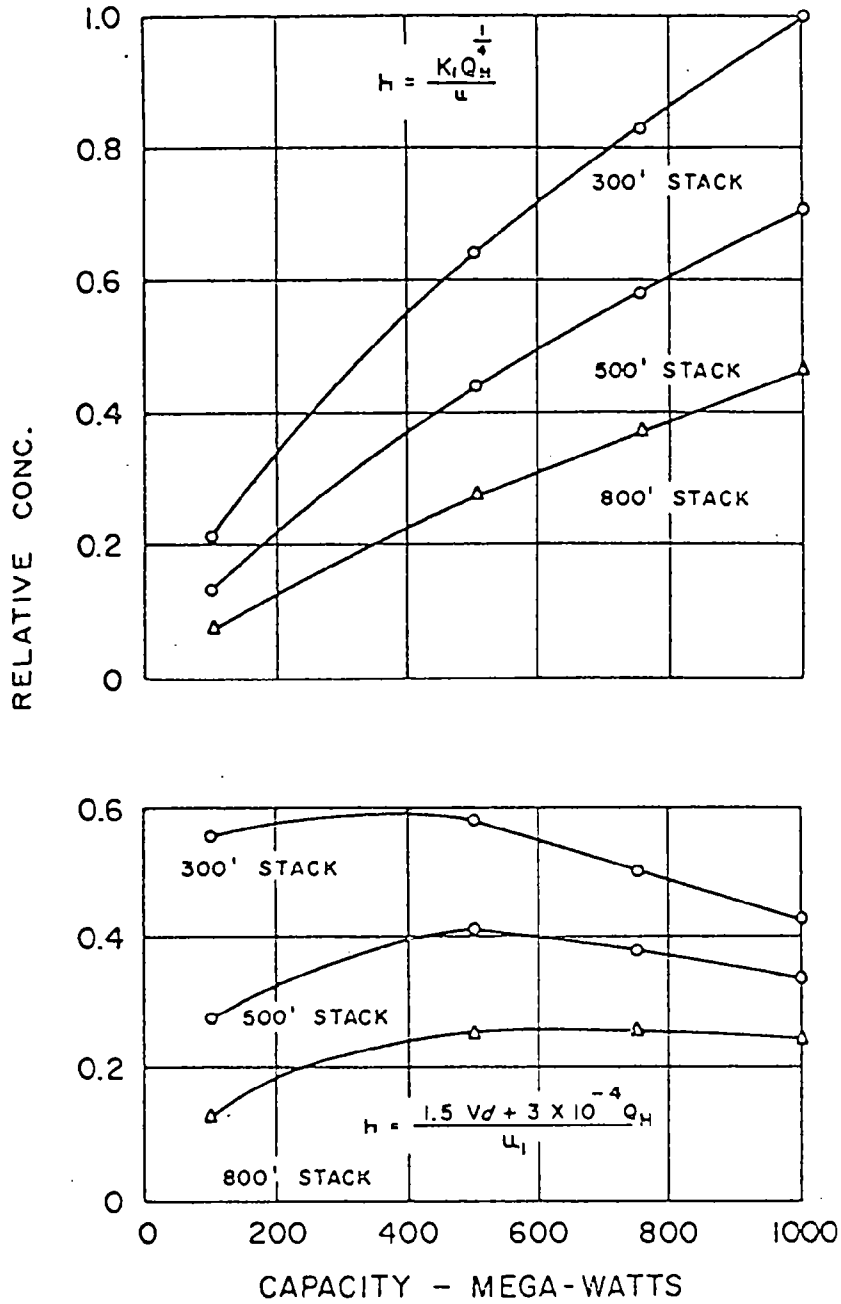


Fig. 6. Effect of plume rise on ground concentrations.

normal to or in line with the stacks, suggesting that the larger buoyant effect for in line winds approximately compensates for line source effect with wind normal to the line of stacks. As a first approximation, the assumption may be made that the nonlinearity results solely from greater buoyancy and thus higher effective stack height. Accepting the premise that the maximum ground concentration is inversely proportional to the effective stack height, the plume rise attributed to heat emission may be calculated for, say, a one and a 10-unit plant, according to the relation $C = M/H^2$

One-Unit Plant	*Ten-Unit Plant*
$1 = \frac{1}{H_1^2}$	$5 = \frac{10}{H_{10}^2}$
$H_1 = 1$	$H_{10} = 1.41$

where C equals the relative maximum ground concentration, and H equals the effective stack height (actual stack height plus plume rise).

The typical plant from which these data were derived has an actual stack height of about 250 ft. and plume rise in a 15-mph wind representative of maximum recorded fumigation conditions has been established by observation at about 150 ft. Thus, H_1 (effective stack height) is 250 + 150 or 400 ft. For a ten-unit plant and a five-fold increase in ground concentration, $H_{10} = (1.41)(H_1) = 564$ ft; and the plume rise is 564 − 250 = 314 ft. This represents about a 2.1-fold increase in plume rise from a one- to ten-unit plant. Expressed as an exponential, the increase in plume rise is proportional to the heat emission, calories per second, raised to 0.30 power. Since a part of the observed nonlinearity in concentration increase must be due to separation of the stacks, this analysis suggests that a plume rise proportional to the 0.25 power of heat emission observed in the British power stations may very closely fit our experience at generating stations with one to ten units of 125- to 250-mw capacity.

Where the increase in heat emission is due to larger units rather than more units, it is reasonable to expect that a greater plume rise will result and an exponential some greater than 0.25 may be applicable. While the studies of plume rise at British and TVA power stations demonstrate that increases in heat emission have much less than a linear relation to plume rise, the rise due to buoyancy is an important element which needs better definition for proper recognition in design studies.

Efflux Velocity

A trend for the use of increasingly greater flue gas exit velocity is evident in the design of steam plants over recent years. In some circumstances, such as legal restriction of stack heights for airways control, there may be no alternative to the use of higher exit velocities for obtaining necessary plume dilution. In other instances existing structures may be incapable of supporting higher stacks.

For large steam plants where stacks greater than 2½ times the height of powerhouse are provided for dilution of the plume, the advantage and the effectiveness of relatively high efflux velocities are considered questionable. As a test of higher exit velocities for increasing effective stack height, a nozzle was installed atop the stack of a 150-mw TVA unit increasing the velocity from 45 to 90 fps. Observations and comparison with adjacent units without nozzles revealed no appreciable increase in plume rise during inversion or high velocity wind conditions. While some benefit was detectable with medium velocity winds, 5–8 mph, dispersion during this meteorological model is generally of less concern than others.

For heat to make its greatest contribution to plume rise, dynamic mixing of the plume with ambient air should be delayed as long as possible. Thus increasingly higher efflux velocities which accelerate the mixing of a hot plume with relatively cool ambient air may actually reduce the rise of a heated plume. A velocity of 50 to 60 fps has been conventionally accepted as adequate to prevent significant downwash in the lee of the stack. Also, for velocities in this order the available draft in the stacks is approximately equivalent to the draft loss in the stacks. Higher velocities, say 90 to 120

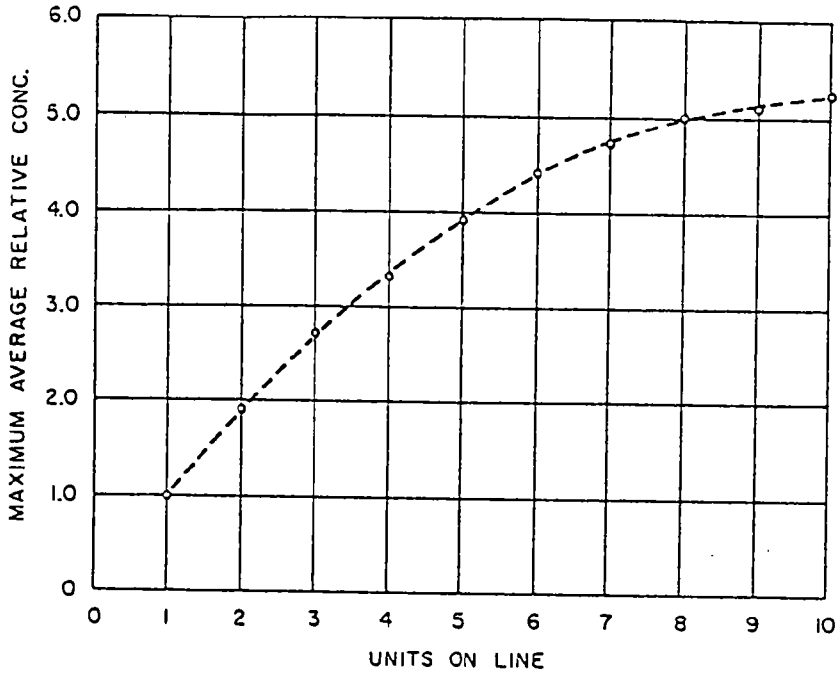


Fig. 7. Maximum average relative ground concentration at 0.01% frequency at a large power plant.

fps, will normally increase the fan, and motor size and costs, and chimney maintenance costs, and may inhibit plume rise due to buoyancy.

Nomenclature

Symbol	Meaning	Units
X	Concentration	ppm
Q	Source output	cu ft SO_2 $\times 10^6$
σ_y	Horizontal diffusion coefficients	ft
σ_z	Vertical diffusion coefficients	ft
u	Wind speed	fps
H	Plume height above ground level	ft
K_y	Stability parameter	—
K_z	Stability parameter	—
K	$K_y + K_z$	—
x	Horizontal distance from source	ft
h	Plume rise above stack top	ft
v	Stack gas exit velocity	mph
d	Stack diameter	ft
Q_H	Heat emission rate	cal/sec
u_1	Wind speed	mph
K_1	Constant based on station parameters	—
Q_M	Heat emission rate	mw
M	SO_2 emission	tons/day

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MONITORING PROGRAM

(*Continued from p. 197*)

Table II—Yearly Averages of Airborne Radioactivity Since 1953

(*Beta Emitters, Picocuries per Cubic Meter*)

1953	0.2	1958	5.2
1954	0.6	1959	4.0
1955	1.1	1960	0.2
1956	2.0	1961	3.6
1957	4.3		

levels since 1953 based upon the [illegible] weekly sample collection.

As was stated in the introduction to this paper, the interpretation of the radiation levels as they influence the general health of the people of Cincinnati is the responsibility of the Health Department. Monthly reports released to the press by the Bureau of Air Pollution Control, which carry the high radioactive fallout levels, are accompanied by statements from the Health Department. This procedure worked out well in Cincinnati as the press was interested in the high fallout levels but there was no public hysteria developed because of the high ratio of increase (nearly 1000 times) from periods of low normal background to the high levels of fallout experienced briefly following the Soviet testing program.

Summary

In a number of communities throughout the country, the Air Pollution Control Officer has inherited the radiological protection assignment. This appears to be a logical mission for an air pollution control agency since one of its peace time missions is the assessment of contamination of the atmosphere. Radiological fallout is atmospheric contamination in its truest sense. As public concern over fallout either from weapons testing or from an emergency situation grows, demand for more and more information concerning radiological fallout and its effect upon the community will arise. In the future more and more APC agencies thus will be asked to take on the radiation monitoring and civil defense RADEF assignment.

V. P. GEOPCEVIC RESIGNS

On January 15, 1963, the officers and members of the Incinerator Institute of America accepted with regret, for reasons of health, the resignation of V. P. Geopcevic who has served as Secretary-Treasurer since 1950.

The Executive Committee of the Incinerator Institute of America at the same time announced the appointment of Organization Service Corporation as management for the affairs of the Institute, with Donald V. Reed, President of OSC, acting in the capacity of Secretary-Treasurer of the Incinerator Institute of America.

III. PARTICULATE CONTROL

REMOVAL OF PARTICULATE MATTER FROM GASEOUS WASTES

GRAVITY, INERTIAL, SONIC, AND THERMAL COLLECTORS

1.00 GRAVITY SETTLING CHAMBERS

Probably the oldest device for the removal of particles from gases is the gravity settling chamber.[3a, 13, 14, 17, 23] The device, in principle, is simply an enlargement in the duct carrying the gas where the gas slows down and remains for a sufficient length of time to let the particles settle out. Because of its simplicity, the chamber has a small pressure drop, resulting mainly from the entrance and exit losses.

The lateral gas velocity distribution must be uniform and eddy currents must be minimized to achieve the maximum collection efficiency. To produce such a uniform gas distribution, gradual inlet transitions (diffusers), guide vanes, and distribution screens or perforated plates are used.[3] Eddy currents can be reduced by means of curtains, rods, or screens suspended in the gas stream. Maintaining the gas velocity below 10 fps also helps to reduce eddy currents and reduces the possibility of re-entrainment of the particles which have settled out.

Since gravity is the only force acting to settle out the particles, the simple gravity settling chamber becomes impractically large for particles finer than approximately 40 microns. If horizontal, equally spaced shelves are installed in the chamber, the collection efficiency is increased markedly because the dust does not have to settle so far. This arrangement is known as the Howard dust chamber[9] and can be used for particles as fine as 10 microns. The Howard dust chamber suffers from two disadvantages: elevated temperatures tend to warp the shelves, and the close shelf spacing makes cleaning difficult, thus limiting the practical inlet dust load to 1 grain per cubic foot, or less.

Except for some applications to natural draft exhausts from furnaces and kilns, gravity settling chambers are seldom used. There is no such apparatus currently on the market;[23] therefore, if one is to be used, it must be specially designed for the particular application.

The theory of gravity settling is relatively simple. It is based on the idea that if a particle is to be completely removed in the chamber, it must be capable of settling the distance H, the height of the chamber, in the time that it takes the gas to flow through the chamber. The usual assumptions made in the theory are: that the velocity profile is constant over a lateral cross-section, that there are no eddy currents to disturb the particle as it settles, and that the particles are not re-entrained after settling out.

Based on these assumptions (and Fig. 1), the time required for a particle to settle out is

$$t = \frac{H}{u_0} = \frac{LBH}{q} \qquad (1)$$

Where:

B = breadth of chamber.
H = height of chamber.
L = length of chamber.
q = volumetric flow rate of the gas at the actual temperature and pressure.
t = settling time.
u_0 = terminal settling velocity of the particle.

Solving for the particle terminal settling velocity,

$$u_0 = \frac{q}{LB} \qquad (2)$$

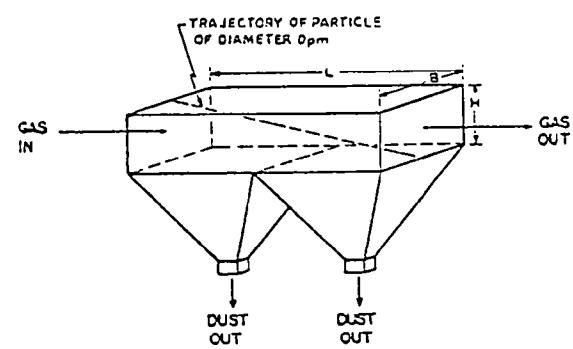


FIG. 1—Gravity Collecting Chamber.

[3] Figures refer to REFERENCES on p. 12.

SOURCE: Removal of Particulate Matter From Gaseous Wastes--Gravity, Inertial, Sonic, and Thermal Collectors, Engineering Report Prepared for American Petroleum Institute, New York, NY (1961).

The particles which are most difficult to settle out are the finer ones, and they normally obey Stokes' law of settling; therefore,

$$u_o = \frac{q}{LB} = \frac{D_{pm}^2(\rho_p - \rho)g}{18\mu} \qquad (3)$$

Where:

D_{pm} = diameter of the smallest size particle that is completely settled out.
ρ_p = particle density.
ρ = fluid density.
g = local gravitational constant.
μ = absolute viscosity.

Solving for D_{pm},

$$D_{pm} = \sqrt{\frac{18\mu q}{LB(\rho_p - \rho)g}} \qquad (4)$$

The collection efficiency, η, for particles of size D_{pm} will be 100 per cent. For particles finer than D_{pm}, the collection efficiency will be proportional to the terminal velocity u_o; therefore, by application of Stokes' law,

$$\eta = \frac{D_p^2}{D_{pm}^2} \qquad (5)$$

The collection efficiency of a Howard dust chamber is greater than that of a simple chamber because of the reduced settling distance. If N is the number of equally spaced shelves (including the bottom surface) installed in the chamber, then

$$t = \frac{H}{u_o N} = \frac{LBH}{q} \qquad (6)$$

Solving for u_o,

$$u_o = \frac{q}{NLB} \qquad (7)$$

Again, by applying Stokes' law and solving for D_{pm}, it is found that

$$D_{pm} = \sqrt{\frac{18\mu q}{NLB(\rho_p - \rho)g}} \qquad (8)$$

Thus, for example, by making N equal to 16, the minimum particle size, D_{pm}, is reduced by a factor of 4.

2.00 INERTIAL COLLECTORS

2.10 Introduction

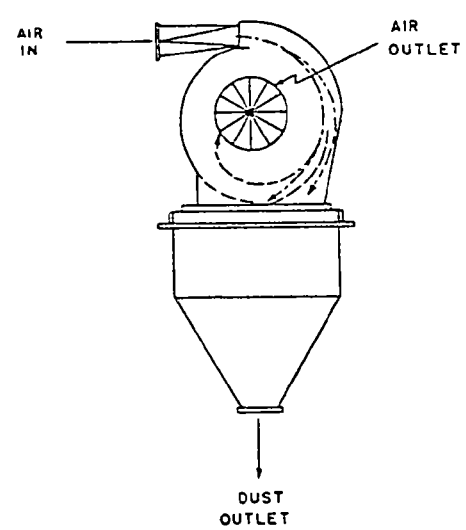
As a class, inertial collectors depend on the fact that it is easier to change the direction of motion of fluid streams than of particles being carried by that stream. Thus, if the fluid must change its direction to avoid an obstacle, the particles will tend to strike the obstacle, adhere to it, and as a result be separated from the fluid stream. The most important inertial collector is the cyclone dust collector, which has been discussed in great detail in an earlier publication of the American Petroleum Institute by A. C. Stern, et al.[29] Because of this, cyclone collectors will not be discussed in this report.

2.20 Skimmers

A skimmer is an elementary inertial collector. It consists of a chamber in which the gas is forced to reverse its path (see Fig. 2). The result is that the dust particles tend to be thrown out of the gas stream. In the skimmer shown in Fig. 2, part of the gas is drawn off with the dust particles to help carry them into the dust hopper. From the dust hopper this gas is vented to the outlet of the skimmer.

From Fig. 2 it can be seen that skimmers operate somewhat like cyclone separators except that the gas stays in the device for a much shorter time; also, they are relatively large in diameter compared with high-efficiency cyclones. Accordingly, they cannot be expected to act effectively in removing fine particles from gases. They are effective for relatively coarse dusts and are used principally for:

1. Reduction of dust loading to more efficient collectors.
2. Primary collectors for relatively coarse dusts when air pollution is not a problem.



Courtesy of American Air Filter Company.

FIG. 2—Skimmer.

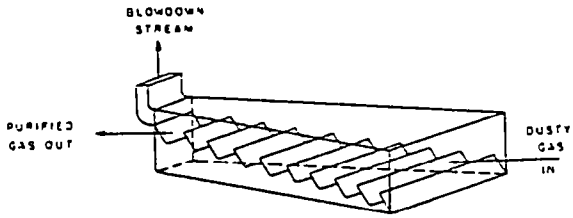


FIG. 3—Rectangular Louver Dust Collector.

From the theory of cyclone separators, one would expect skimmers to have high efficiencies for particles coarser than 50 microns. For particles finer than 50 microns, the collection efficiency falls off rapidly.

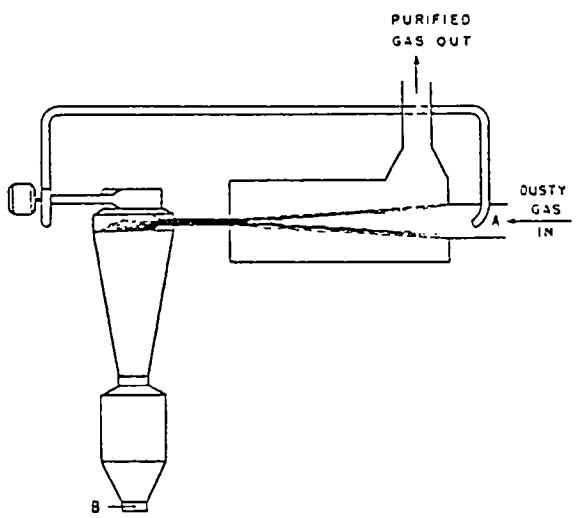
2.30 Louver-Type Dust Separators

The louver-type dust separator is a relatively recent development. There are two basic designs for this collector. One consists of a truncated cone which is approximately five times as long as its maximum diameter. The minimum diameter is about a fifth of the maximum diameter. The conical surface is made up of a large number of louvers. The louvered cones are commercially available in sizes ranging from 9 in. to 25 in. at the maximum diameter. The other design consists of a "venetian blind" structure enclosed in a box (see Fig. 3).

The principle of operation of the cone is illustrated in Fig. 4. The dusty gas enters at point A, flowing down the cone at a substantially constant velocity. Approximately 5 per cent of the gas, the blowdown, issues from point B. The remainder of the gas passes through the louvers. In order to do so, the gas must change its direction abruptly. The inertia of the dust particles prevents them from following the gas so that the dust particles tend to stay inside the cone and finally issue from the cone with the blowdown gas. Thus the louver-type dust separator acts as a concentrator rather than as a collector. The blowdown stream must be treated further by a secondary collector to complete the separation of the dust from the gas stream. A small, high-efficiency cyclone collector is normally used as the secondary collector. The cleaned blowdown gas from the cyclone is then recirculated to the louver separator to recover residual dust not removed in the cyclone collector. Some dust collects on the louvers. This is removed by rapping the cones every 8 hr or so.

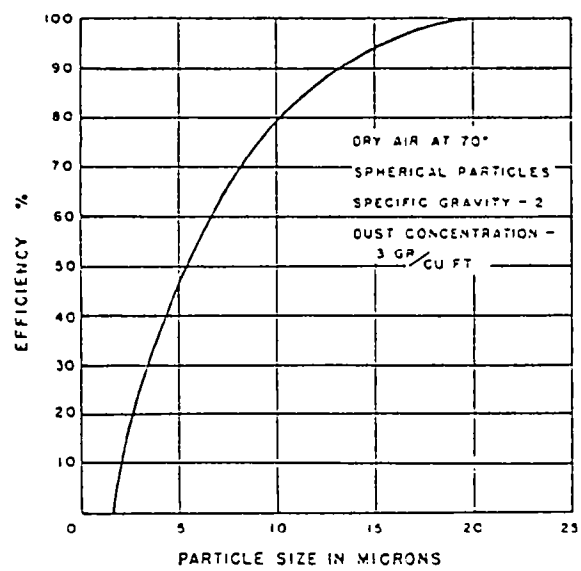
A small amount of dust collection efficiency data has been published[1] for the conical, louver-type separator combined with a cyclone secondary collector. These data are shown in Fig. 5. The data indicate that louver-type separators have efficiencies comparable to medium- to high-efficiency cyclones.

It has been reported that the collection efficiency is a function of the Stokes' law settling velocity of a particle rather than the particle diameter alone. Thus, to correct Fig. 5 to the conditions of a different gas viscosity, density,



Courtesy of Research-Cottrell, Inc.

FIG. 4—Operating Principle of Louver Dust Collector.



Courtesy of Research-Cottrell, Inc.

FIG. 5—Louver Dust Collector Efficiency Data.

and particle density, it is necessary to multiply the particle sizes shown on the figure by the ratio

$$\sqrt{\frac{\mu'}{\mu}\,\frac{\rho_p-\rho}{\rho_p'-\rho'}}$$

where the unprimed quantities are based on the conditions given in the figure and the primed quantities are based on the new set of conditions to which the figure is being corrected.

Uzhov [27] has reported some performance data for Russian designs of a rectangular louver collector. His data indicate that the Russian design is of much lower efficiency than the conical collector.

Contradictory results have been reported on the effect of the inlet gas velocity to the collector. Smith and Goglia [23] found approximately a 1-per-cent decrease in collection efficiency with a threefold increase in inlet velocity. Zverev,[29] on the other hand, found a 30-per-cent increase in collection efficiency for a threefold increase in inlet velocity.

Smith and Goglia [23] and Zverev [29] were in agreement that the ratio of the blowdown velocity to the inlet velocity had a marked effect on the collection efficiency. If the ratio is reduced below one, the efficiency drops off very rapidly. If the ratio is increased above one, the efficiency increases slowly. The moderate increase can be accounted for largely by the fact that more of the gas is leaving as blowdown.

Both the foregoing sources claim that an important mechanism involved in the separation of the dust from the gas is that the particles strike the louver and then rebound back into the dusty gas stream. Smith and Goglia observed these particle trajectories by shining a strong light at right angles to the viewing angle, causing the particle trajectories to appear as bright streaks of light. Furthermore, they noted that the louver surface became brightly polished as a result of the particle impacts.

Despite the fact mentioned previously that the particle impacts polish the louvers, it is claimed that the cone-type louver collectors are resistant to erosion. One user reports that no erosion of the cone was observed after a year and a half in fly ash recovery service. In addition, only moderate amounts of erosion of the cyclone and the fan which returns the gas from the cyclone to the cone were observed. No other maintenance problems were experienced with the unit.

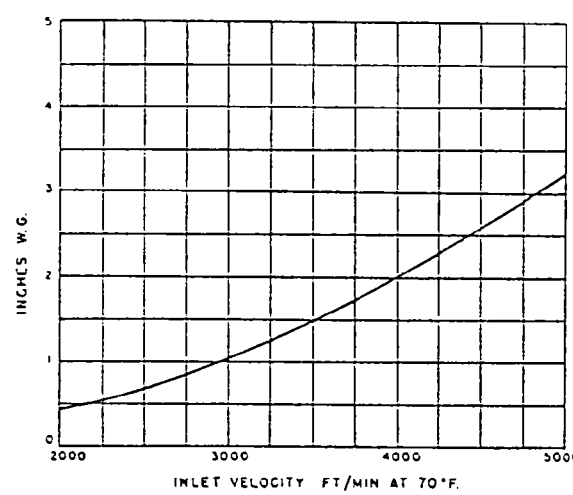
Pressure-drop data for the conical, louver-type separator have been reported [1] and are shown in Fig. 6.

No serious attempt at a theoretical analysis of the performance of these collectors has been reported. One of the difficulties involved is that it would be necessary to compute the gas flow lines first in order to determine their effect on the motion of the particles, the fine particles being particularly sensitive to the motion of the gas. The gas flow lines are quite difficult to compute because of the complicated flow boundary and because of the turbulent eddies generated at the downstream edge of each of the louvers. Thus, performance characteristics of louver separators must be measured experimentally.

In summary, the louver-type separator has a collection efficiency comparable to medium- to high-efficiency cyclones at pressure drops somewhat lower than those reported for cyclones. They act only as dust concentrators and must be used in conjunction with a secondary collector such as a small, high-efficiency cyclone.

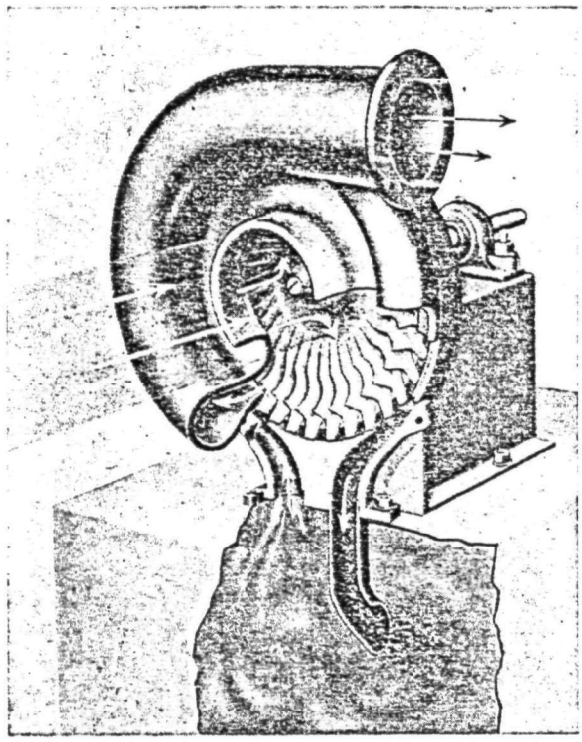
2.40 Centrifugal Impeller Collectors

There are a few collectors which combine the functions of a dust remover and of a fan. An example of such a collector is shown in Fig. 7. Dusty air is drawn into the collector at a high velocity and flows radially outward between specially designed impeller blades to the outlet scroll. As the gas passes through the collector it turns through an arc of a little less than



Courtesy of Research-Cottrell, Inc.

FIG. 6—Louver Dust Collector Pressure Drop.



Courtesy of American Air Filter Company.

FIG. 7—Centrifugal Impeller Collector.

180 deg. As a result, the particles tend to be thrown against the impeller wheel and move outward by centrifugal force to the outer edge of the impeller wheel. At this location the particles are projected through the narrow opening between the impeller and the scroll into the surrounding dust chamber. The tips of the impeller extend into this chamber, setting up a secondary air circulation which carries the particles into the airtight dust hopper located below the collector. The secondary air is slowed down in the hopper, letting the dust particles fall out, and then is drawn back into the return-air port to be recirculated through the dust chamber.

Dalla Valle [3] has said that since these units must be designed both for dust collection and air blowing one cannot expect quite as high a blower efficiency from them as from a straight air blower; but these units are compact, pressure losses are smaller because fewer ducts are required, they have been found to perform satisfactorily in capacities up to 20,000 cfm, and they are widely used.

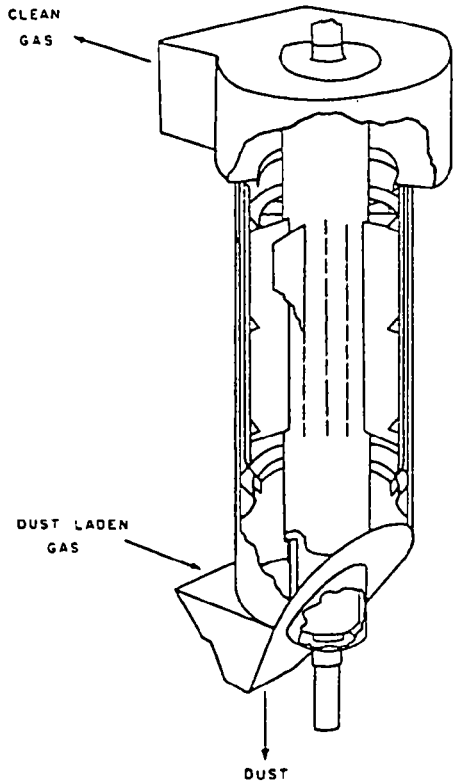
The collection efficiency of such units is comparable to that of medium-efficiency cyclone dust collectors. For particles smaller than approximately 10 microns the efficiency falls off rapidly. Dalla Valle states that there is theoretically no reason why smaller particles should not be collectible with high efficiency, but practically it appears to be impossible.

2.50 Mechanical Gas Centrifuges

A second type of motor-operated inertial collector is the mechanical gas centrifuge. The first design of this type was reported by Verhoturov [23] in 1935. He proposed using a large rotating drum with short, radial vanes mounted parallel to the axis of the drum. This drum rotated inside a stationary perforated shell. The dusty gas flowed up between the drum and the shell, and as a result of the rotary motion the dust was centrifuged out of the gas and thrown through the perforations into catch pockets mounted outside the shell. The proposed unit was very large. The rotating drum was approximately 11 ft in diameter by approximately 25 ft in height. The drum rotated at 290 rpm inside a stationary shell approximately 13 ft in diameter. The unit was to have a capacity of 40,000 cfm of gas and would require a 50-hp-drive motor. In its entirety the unit would have weighed approximately 70 tons. In short, it would be a massive machine when compared with a modern multiple-cyclone installation of the same capacity which would weigh approximately 6 to 7 tons and require approximately 35 hp to overcome the gas pressure drop.

More recently, another mechanical gas centrifuge has been reported [13] and is shown in Fig. 8. This centrifuge is relatively small compared with Verhoturov's. This is so, in part, because it is designed for a capacity of only 1,000 cfm. For higher capacities the appropriate number of these centrifuges is operated in parallel. Suggested systems handling up to 250,000 cfm have been reported.[13]

This centrifuge differs significantly from Verhoturov's in the following ways. First, because the rotating drum operates at much higher speeds, 1,500 to 2,500 rpm, the collection efficiency will be much higher. Second, it is not designed to operate continuously. During the dedusting operation all the dust removed from the gas stream remains in the centrifuge because there is no means for disposing of the dust while the centrifuge is operating. The centrifuge is then shut down after some suitable period of operation and rapped to make



Courtesy of The Fly Ash Arrester Corporation.

FIG. 8—Modern Centrifuge.

the collected dust fall into a hopper located below the centrifuge. The maximum time of operation per cycle depends upon how rapidly dust accumulates in the centrifuge and the maximum amount of dust that can be allowed to accumulate before dust disposal is required.

Such batch operation has an important advantage from the maintenance viewpoint. Once the particle strikes the inner walls of the centrifuge, the particle comes to rest. Thus there is no scrubbing effect of the particle against the metal of the equipment and therefore no erosion. As partial, experimental proof of this a sample of dust was passed repeatedly through the centrifuge [15] and no degradation of the particles was observed, which indicates that the particle-metal contacts are gentle. Furthermore, in a full-scale experimental model of the unit it was observed after several months of operation with an erosive dust that the mill scale of the carbon steel sheets from which the unit had been constructed had not been worn away.

A second advantage of batch operation is that since the units are dampered off while they are being rapped down there is no opportunity for re-entrainment of the dust during rapping.

The obvious disadvantage of batch operation is that even though the units are capable of cleaning on the order of 1,000 cfm of gas while operating, their real capacity is less than this because they are shut down part of the time for cleaning.

The draft loss is quite low ($\frac{1}{2}$ in. to $1\frac{1}{2}$ in. of water) compared with the 2 in. to 4 in. of water loss that is normal for cyclone collectors. Operating tests have shown that the collection efficiency decreases with increasing grain loading. The collection efficiency decreased from 99.7 per cent at 10 grains of dust per cubic foot of gas to 99 per cent at 60 grains of dust per cubic foot of gas in one series of tests.

The development of design equations for a centrifuge collector is relatively simple because its principle of operation is simple. Derivation of the design equation is much the same as for the gravity collecting chamber except that the gravitational force is replaced by a centrifugal force.

If it is assumed that the gas in the centrifuge is not turbulent, that the gas is stationary with respect to the rotating vanes of the centrifuge except for motion parallel to the axis of the vanes, that the gas velocity is independent of its position in the centrifuge, and that a modified form of Stokes' law applies, the smallest particle that can be completely collected by the centrifuge can be computed from

$$D_{pm} = \sqrt{\frac{18\mu v_o}{L(\rho_p - \rho)\omega^2} \ln \frac{R_2}{R_1}} \qquad (9)$$

By means of this equation it is possible to calculate D_{pm} for the centrifuge shown in Fig. 8. R_2 and R_1 are 6.5 in. and 4.0 in., respectively, and L, the length of the zone of centrifugal action, is approximately 29 in. If the collecting cylinder is operated at 2,500 rpm, the gas is air-delivered at 1,000 cfm at 70 F and atmospheric pressure, and the dust has a specific gravity of 2.0, then D_{pm} is 4 microns. If turbulence or gas circulation patterns exist in the gas passing through the centrifuge, the minimum-size particle completely collected is larger. There have not been enough data published to investigate this effect.

The operating time between cleaning periods can be computed readily from the quantity of dust that can be retained on the collecting cylinder between the airfoil stop rings. The

available volume is approximately 0.6 cu ft. If the dust packs to a concentration of approximately 60 per cent by volume, the dust load is 10 grains per cubic foot, and the dust density is 2.0 grams per cubic centimeter, the operating time will be approximately 30 min.

The derivation of equation (9) is as follows. The most difficult particles to collect are those which enter the centrifuge near the center tube because they are farthest from the collecting cylinder shell. Of these particles, the most difficult to collect are those having the smallest diameter. Consider a particle entering the centrifuge whose trajectory is such that it enters near the center tube and finally strikes the collecting cylinder just before the gas stream leaves the cylinder. This particle will be of the smallest size that can be removed completely from the gas stream. Any coarser particles will also be removed completely; finer particles will be only partially removed.

Assuming that gas-eddying has a negligible effect on the particle's motion, the motion of the particle can be computed from Newton's second law of motion, $F=\frac{ma}{g_c}$ (see Glossary). For this problem, Newton's equation becomes:

$$\frac{\pi D_{pm}^3}{6}\frac{\rho_p}{g_c}\frac{d^2r}{dt}=\frac{\pi D_{pm}^3}{6}(\rho_p-\rho)\frac{\omega^2 r}{g_c}-\frac{3\pi\mu D_{pm}}{g_c}\frac{dr}{dt} \qquad (10)$$

For problems of this type it is usually safe to assume that even though the velocity of the particle, $\frac{dr}{dt}$, is changing, the inertia term may be neglected. Assuming this and after algebraic manipulation, the equation becomes

$$\frac{dr}{dt}-\frac{D_{pm}^2(\rho_p-\rho)\omega^2 r}{18\mu}=0 \qquad (11)$$

With the initial condition that at $t=0$ the particle's position r is R_1, the solution of this equation is

$$r=R_1\exp\left[\frac{D_{pm}^2(\rho_p-\rho)\omega^2}{18\mu}t\right] \qquad (12)$$

Settling time, t, for the particle most difficult to collect is equal to the length, L, of the centrifuging zone divided by the velocity, v_o, of the gas flowing through it. Replacing t by $\frac{L}{v_o}$ and solving for D_{pm} yields the size that is most difficult to collect completely, i.e.,

$$D_{pm}=\sqrt{\frac{18\mu v_o}{L(\rho_p-\rho)\omega^2}\ln\frac{R_2}{R_1}} \qquad (9)$$

2.60 Impingement Separators

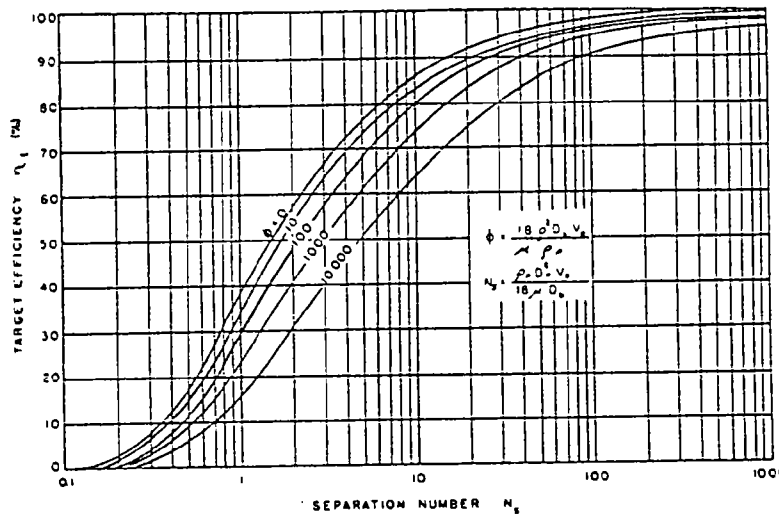
2.61 *Body Collectors*

If a dust-laden gas stream is forced to flow around an obstacle, a fraction of the dust particles will strike the obstacle because of their inertia and adhere to it, and will thus be removed from the gas stream. The most important collectors using this principle are scrubbers and fibrous filters, which are discussed by Gilbert[7] and Licht,[13] and impingement separators.

Impingement separators usually consist of a large number of vertical elements suspended in the path of the dusty gas stream. The elements are normally flat strips or cylinders, or, if they are not, they may usually be treated as though they were for estimating their performance. The width of the elements (perpendicular to the flow path) is on the order of 1 in. or more.

Impingement separators are normally designed for pressure drops on the order of 0.1 in. to 1.5 in. of water.[14] Their collection efficiency drops off rapidly for particles finer than approximately 20 microns. Therefore, they are used only for removing coarse particles. Rappers are frequently used to remove the collected dust from the impingement elements. If the dust is sticky, either because of elevated temperatures or because of moisture condensation, a circulating water film may be used to clean the elements. The chief advantage of these units is their adaptability to existing flues.

The capture of dust particles by impingement collectors can be treated in terms of "target" efficiencies. Target efficiency, η_t, is defined as the fraction of the particles in the gas volume swept by the collector element that impinge on the element. This efficiency is equal to the dust collection efficiency if all the particles that strike the element adhere to the element. For very fine particles (less than 1 to 5 microns) this assumption is probably safe because such particles adhere strongly to solid surfaces. Coarse particles (greater than 40 to 50 microns) will not adhere strongly and will tend to rebound from the collecting surface after striking it. Thus the collection efficiency will be lower than the target efficiency unless corrective measures are taken. One method is to wet the collector surface with a water film



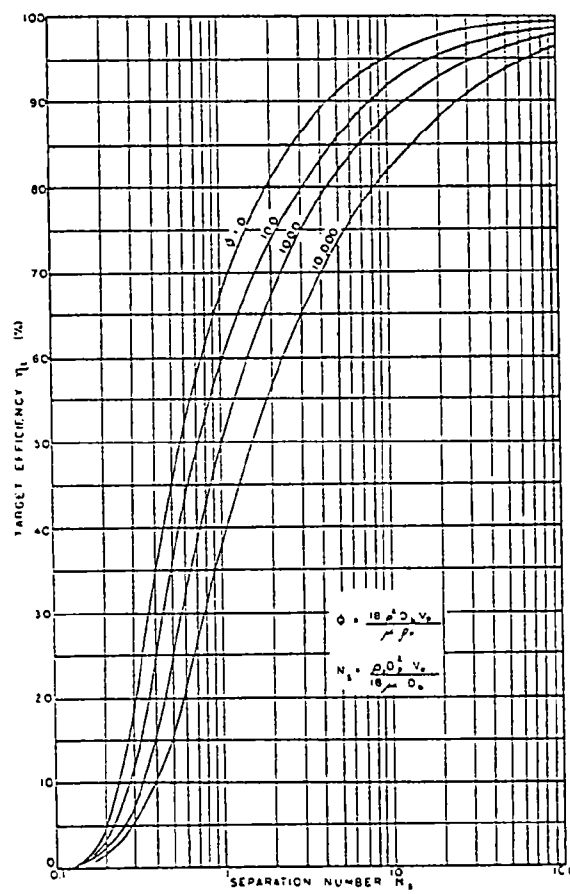
Courtesy of Langmuir and Blodgett.[12]

FIG. 9—Target Efficiencies for Cylinders.

which prevents particle rebound and also keeps the surface washed clean. A second method is the use of a hollow collecting element with an open front. The opportunity for a particle to rebound out of the collector is reduced by this arrangement. Furthermore, by continuously withdrawing a small amount of gas from the bottom of the hollow collecting element, the dust can be concentrated in a small amount of gas.

The work of Langmuir and Blodgett[12] may be used for estimating the performance of such collectors. They found that the target efficiency is a function of two dimensionless groups and that this function can be computed for a few simple geometric shapes. For the flow around an obstacle at a high Reynolds number, they assumed the gas could be treated as a non-viscous fluid in order to compute its flow lines around the obstacle. This is only an approximation but it is a reasonable one. The motion of the particles carried by the gas stream was then computed from the gas flow lines, from Newton's second law of motion, and from the correlation of the drag force acting on a sphere moving relative to a gas stream. Langmuir's and Blodgett's results are shown in Fig. 9 and 10 for cylinders and flat ribbons.

As an example of the use of their results, consider a dusty gas flowing around a flat strip 2 in. in width. Suppose that the gas is air at 60 F, 1 atm pressure, and is flowing with a velocity of 40 fps. Assume that the dust has



Courtesy of Langmuir and Blodgett.[12]

FIG. 10—Target Efficiencies for Flat Strips.

a density of 130 lb per cu ft and that the collection efficiency is equal to the target efficiency. The size particle that can be collected with a target efficiency of 50 per cent is calculated as follows.

First calculate ϕ as shown:

$$\phi = \frac{18\rho^2 D_b V_o}{\mu \rho_p} \qquad (13)$$

$$= \frac{(18)\left(\frac{29}{378}\right)^2\left(\frac{2}{12}\right)(40)}{[(0.0177)(0.672)(10^{-3})](130)}$$

$$= 445$$

For $\phi = 445$ and $\eta_t = 0.50$ the separation number, N_s, from Fig. 10 is 0.88; solving for D_p from

$$N_s = \frac{\rho_p D_p^2 V_o}{18\mu D_b} \qquad (14)$$

$$D_p = \sqrt{\frac{18\mu D_b N_s}{\rho_p V_o}}$$

$$= \sqrt{\frac{(18)[(0.0177)(0.672)(10^{-3})]\left(\frac{2}{12}\right)(0.88)}{(130)(40)}}$$

$$= \sqrt{(0.604)(10^{-3})}$$

$$= (0.78)(10^{-4})\ \text{ft}$$

$$= 24\ \text{microns}$$

From this calculation it is apparent that in order to achieve high collection efficiencies of fine particles it is necessary to use small-diameter obstacles. The equation indicates that increasing the gas velocity should also increase the efficiency. Unfortunately, re-entrainment of the deposited dust also increases, making it impractical to use gas velocities greater than 100 to 150 fps.

2.62 *Impingement Separators Using Jets*

In an interesting modification of the impingement separator, the gas stream is formed into a jet before it impinges upon a flat collector plate located from one to three jet widths away from the jet outlet (see Fig. 11). If small jet widths ($\frac{1}{32}$ in. to $\frac{1}{3}$ in.) are used, high collection efficiencies of fine particles can be achieved.

The jet can be formed by either a circular or a slit-shaped orifice. The experimental measurements of Ranz and Wong [12] (see Fig. 12) indicate that circular orifices produce a higher target efficiency than do slit-shaped orifices. The difference is not great enough to be the only criterion for choosing an optimum impingement separator design, however. Other factors such as pressure drop, simplicity of construction, and re-entrainment of the collected particles also must be considered before choosing the final design.

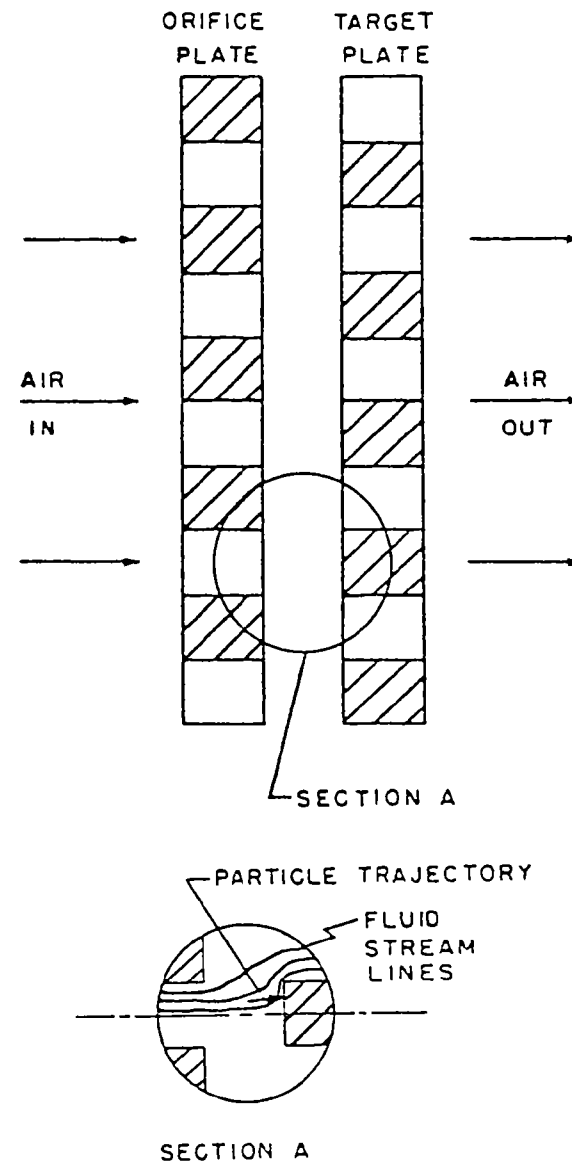


FIG. 11—Jet Impingement Separator.

As with the body collectors, re-entrainment is an important consideration. Dry, solid particles are more likely to rebound from the collecting surface than to adhere to it [11] unless they are very small (under 1 micron in size) or unless the collecting surface is coated with

a film of flowing water to trap and carry away the collected particles.

3.00 SONIC AGGLOMERATION

In 1860, Kundt discovered that a sound wave passed through an aerosol causes the aerosol particles to agglomerate. Practical application of this discovery has been made to agglomerate fine particles that are difficult to collect by conventional apparatus such as cyclone separators.[2, 4, 21]

The mechanism of sonic agglomeration is complex and includes the following factors:

1. Fine particles are acted upon by Brownian movement forces which, when the particles are in high concentration, cause them to collide frequently with one another.

2. Because of cohesive forces, fine particles tend to adhere to one another after collision.

3. Radiation pressure of a sound wave causes the particles to accumulate at the antinodes of the wave. The increased particle concentration at the antinodes increases the frequency of particle collisions.

4. Viscous forces tend to couple the motion of the particles to the oscillatory motion of the gas. Because of the particle inertia, the amplitude of oscillation of large particles is less than that of small particles. The difference in velocity of the particles increases the frequency of their collisions.

5. Bernoullian forces cause particles whose line of centers is at right angles to the direction of propagation of the sound wave to attract one another. This, too, increases the frequency of collisions.

Sonic agglomeration is only effective for aerosol concentrations greater than approximately 1 grain per cubic foot. For smaller concentrations it is necessary to increase the particle concentration by, for example, the injection of steam. The useful sound frequency range is from approximately 1 kc to 10 kc. The sound intensity required is 150 db or greater. This sound intensity causes serious problems because of its very high level. For people who are close to the apparatus, the sound level is above the threshold of pain. For those at a distance the high-pitched sound is a nuisance. The high-intensity sound can also have a serious effect on equipment—the vibration being able to produce fatigue failures of the equipment.

Several types of sound generators are available but currently only the gas siren generator[10] is capable of producing high-intensity sound at efficiencies which make sonic agglomeration economically practical.

There have been installed, in recent years, a small number of sonic agglomerators operated in series with cyclone collectors to recover materials such as carbon black, sulfuric acid mist, and soda ash fume. The number of industrial applications is still small because the use of sonic agglomeration has been recent; and a considerable amount of research and development remains to be done to satisfactorily establish suitable applications, optimum designs, and adequate design methods.

4.00 THERMAL PRECIPITATION

In 1870, Tyndall observed that if a dust-laden gas is brought into contact with a heated surface, a dust-free space develops between the surface and the cloud of dust particles. A theoretical analysis by Epstein[6] and experimental investigations by Rosenblatt and La Mer[20] and Saxton and Ranz[22] have shown that this phenomenon is a result of a force on the particles caused by a creeping motion of the gas from the cooler regions to the heated regions of the particles' surfaces. This force causes the particles to be repelled by heated surfaces and to be attracted by cooled surfaces.

Epstein's theory shows that the force is directly proportional to the gas temperature gradient and to the particle diameter. Since the motion of the particles is resisted by viscous drag forces which are also directly proportional to the particle diameter, the velocity of a particle moving through a gas temperature gradient should be independent of particle diameter.

Thus, a device consisting of two parallel plates—one heated, the other cooled—should act as a dust precipitator which is just as efficient for fine particles as for coarse particles. Such devices, called thermal precipitators, are used as instruments for atmospheric dust sampling. Thermal precipitation has had almost no industrial applications because of the high cost of maintaining the required temperature gradient and because of its large space requirements.

CYCLONE DUST COLLECTORS

(REPORT ON REMOVAL OF PARTICULATE MATTER FROM GASEOUS WASTES)

1.00 INTRODUCTION

1.10 Definition

A cyclone is a structure without moving parts which separates particulate matter from gas by transforming the velocity of an inlet gas stream into a vortex confined within the structure. A vortex is a helical form of rotation of fluid about an axis. In nature, the axis of a vortex is frequently curved, and although the axis of the confining structure might likewise be curved, it is in practice a straight line. Similarly, although the ideal structure would be one generated by a curved line revolved about the cyclone axis, practical cyclones employ confining structures generated by the revolution of straight lines about the axis, i.e., combinations of cylinders and cones (Fig. 1).

1.11 *Types of Cyclones*

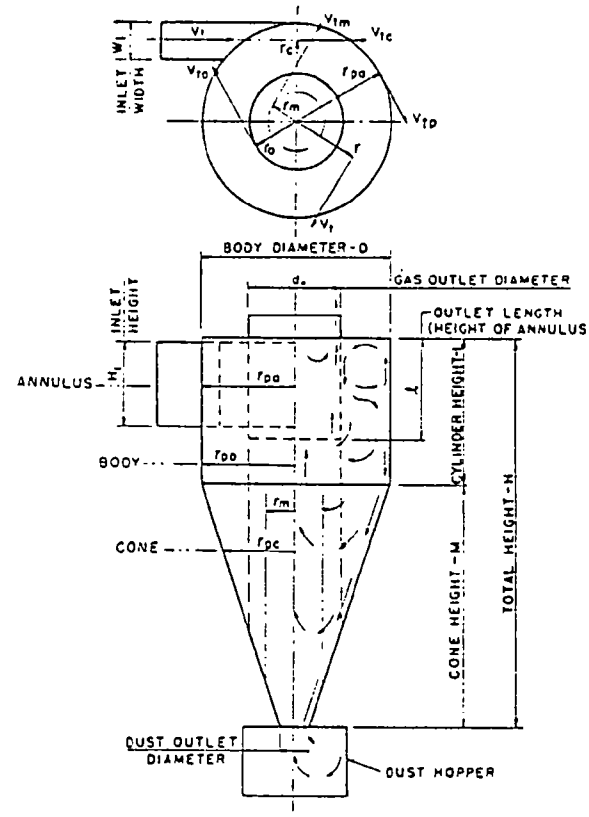
Structurally, a cyclone must have an axial gas outlet, a dust discharge, and a means for gas inlet which will produce the gas rotation necessary to create the vortex. These three elements may be combined in a number of different ways. Rotation may be produced by tangential gas entrance or by axial gas entrance through a set of swirl vanes. Separated dust may be removed either axially or tangentially from the periphery. Dust may be removed from either the end opposite to the axial gas outlet or from the same end. There may be either one or a multiplicity of tangential inlets. The cyclone body may be completely cylindrical, completely conical, or made of both cylinders and cones. The gas outlet may be either cylindrical or conical.

Cyclones in common use may be classified as follows:

1. Cyclones with tangential inlet and axial dust discharge.

   1*a*. Larger-diameter ("conventional") cyclones.

   1*b*. Small-diameter ("high efficiency") cyclones.



Typical Cyclone.

FIG. 1

2. Cyclones with tangential inlet and peripheral dust discharge.

3. Cyclones with axial inlet and axial dust discharge.

4. Cyclones with axial inlet and peripheral dust discharge.

Type 1*a* is the most commonly used type in which the total gas volume is handled through one cyclone body, although sometimes such cyclones are arranged in parallel (Fig. 1). The other types are usually of small capacity individually, and practical gas volumes are obtained by operating large numbers of individual units in parallel.

SOURCE: Cyclone Dust Collectors, Engineering Report Prepared for American Petroleum Institute, Washington, DC (1956).

1.20 Mechanism of Cyclone Operation

The cyclone separates particles from the gas by means of centrifugal force exerted on the particles in vortex flow, tending to drive the particles to the wall of the cyclone body. The particles at the wall move toward the dust discharge by virtue of the axial component of the vortex flow, aided, if the axis is vertical, by gravity. The magnitude of the radial forces acting on the particles depends on the nature of the vortex flow in the different sections of the cyclone. Counteracting forces, such as radial gas velocities, tend to offset the separating forces.

1.21 *Nature of Vortex Flow*

The inlet of a cyclone transforms linear flow into vortex flow. After the gas leaves the inlet annulus, it establishes a vortex with an axial component in the direction of the dust discharge.

1.211 FLOW IN THE MAIN VORTEX: The characteristic of the main vortex is that the tangential velocity at radius r (V_t) increases as r decreases from the radius of the confining structure r_p to a maximum V_{tm} at some intermediate radius r_m. As r further decreases from r_m to zero at the axis, V_t decreases from its maximum V_{tm} at r_m to zero at the axis. The zone between the axis and r_m is called the core of the vortex. In the outer zone of the vortex where V_t increases as r decreases, the flow obeys the equation:

$$V_t = V_{tp}\left(\frac{r_p}{r}\right)^n \qquad (1)$$

Where:

V_t = tangential velocity at radius r, in feet per second.
V_{tp} = tangential velocity at r_p, in feet per second.
r_p = radius confining structure, in feet.
r = radius, in feet.
n = exponent, dimensionless.

If $\frac{r}{rp} = r_f$, the ratio of the radius of rotation to the radius of the confining structure, equation (1) reduces to:

$$V_t = \frac{V_{tp}}{r_f^n} \qquad (2)$$

In an ideal gas, n would equal 1. Real values of n are less than 1, and at ordinary temperatures are greater than 0.5.

Alexander[23] presents an equation evaluating n for air at 10 C, as follows:

$$n = \frac{(24 r_p)^{0.14}}{2.5} \qquad (3)$$

For variations in gas temperature, he found n to vary as:

$$\frac{1 - n_T}{n_o} = \left(\frac{T_k}{283}\right)^{0.3} \qquad (4)$$

Where:

n_T = value of n at T Kelvin.
n_o = value of n at 283 K (10 C).
T_k = temperature, in degrees Kelvin.

Values of n computed from equations (3) and (4) are presented in Fig. 2. Individual values of n reported by other investigators are:

Shepherd and Lapple[18]	0.5
Stairmand[30]	0.5
Ter Linden[34]	0.52
Prockat[37]	0.7
First[16]	0.88

There is radial gas flow in the outer vortex zone. There has been much theory propounded on this point but little experimental measurement. The simplest theory, that of Feifel[14] for a simple cyclone with no gas-outlet extension into the body, assumes "sink" flow radially inward from inlet to outlet superimposed on tangential vortex flow. Unfortunately, however, the use of an outlet-duct extension into the cyclone body, and the presence of space below and above the inlet into which gas can flow, causes radial velocity to vary in a manner presently defying mathematical statement.

Radial velocity has been measured in a conventional cyclone with air and in a hydraulic cyclone with water. In the hydraulic cyclone the customary underflow (downflow through bottom of cone) was suppressed. Typical radial velocity profiles based on these findings show that from r_p to some intermediate radius there is inward radial velocity, but from the intermediate radius to the axis there is outward radial velocity (Fig. 4).

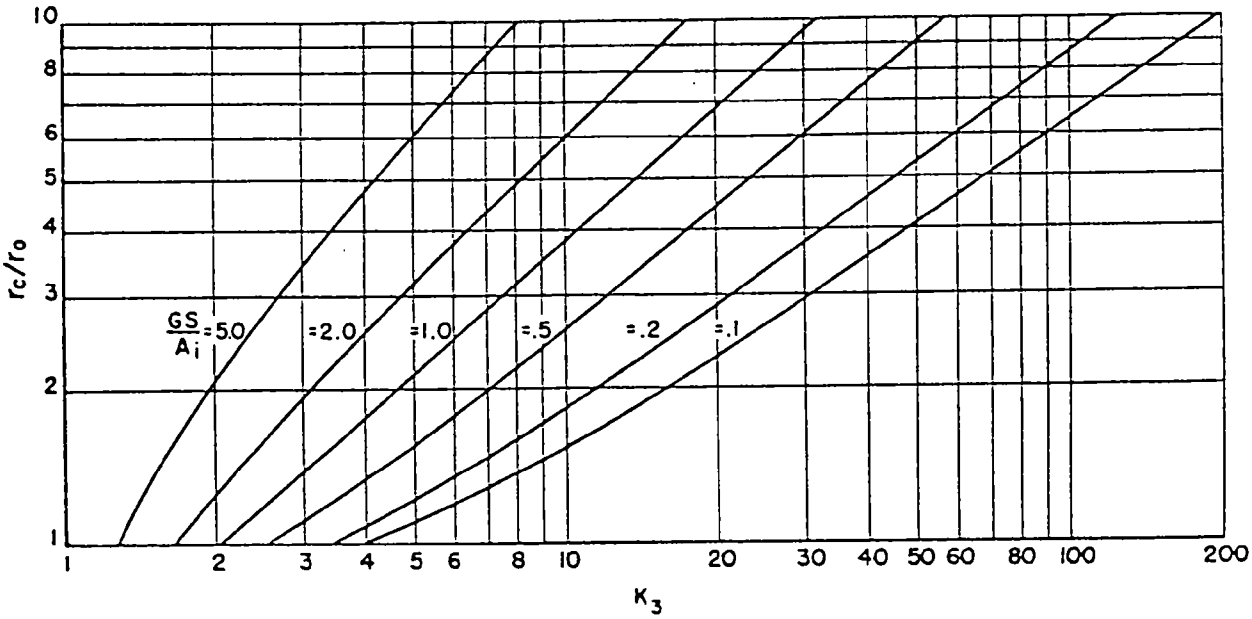
1.212 FLOW IN VORTEX CORE: Flow in the vortex core follows the equation:

$$V_t = Kr^q \qquad (5)$$

Where:

K = proportionality constant varying with V_p, r_m, and n.
q = velocity exponent.

* Figures refer to REFERENCES on p. 66.



Values of K_3 [See Equation (17)].

FIG. 6

and its helical pitch about 10.5 r_o. In extremely long cyclones, the eccentricity has been observed up to 50 r_o before disappearing.

As will be shown later (Sect. 2.31), cyclones of common design have a "natural length" on the order of 10 to 15 r_o.

At the vortex base there is a region of considerable turbulence and reversal in direction of axial flow, with a likelihood that the core eccentricity will bring this region into close proximity with, or in actual contact with, already-separated dust at the cyclone wall. It is for this reason that much attention should be devoted to the design of dust discharge, purge, and the like.

1.22 *Separation of Particles*

Particulate matter is separated from gas in a cyclone by centrifugal force, or radial force, tending to drive the particles (against the resistance of motion by the gas) to the cyclone wall. The radial force imparted to the particle is:

$$F_s = \frac{m_p V_p^2}{gr} \tag{6}$$

Where:

F_s = radial separating force, in pounds.
m_p = particle mass, in pounds.
V_p = tangential velocity of particle, in feet per second.
g = gravitational constant = 32.2 ft per sec per sec.

The tangential velocity of the particle is theoretically lower than that of the gas in which it is suspended; but, in considering fine particles, the two velocities are equal for all practical purposes and $V_p = V_t$. By combining equations (2) and (6):

$$F_s = \frac{m_p V_{tp}^2}{gr\, r_t^{2n}} \tag{7}$$

which has a maximum value:

$$F_{sm} = \frac{m_p V_{tm}^2}{g r_m r_{tm}^{2n}} \tag{8}$$

Where:

r_{tm} = radius ratio at r_m, dimensionless.
V_{tm} = maximum tangential velocity (at r_m), in feet per second.

The value m_p in the preceding equations is proportional to the cube of the particle diameter, thus:

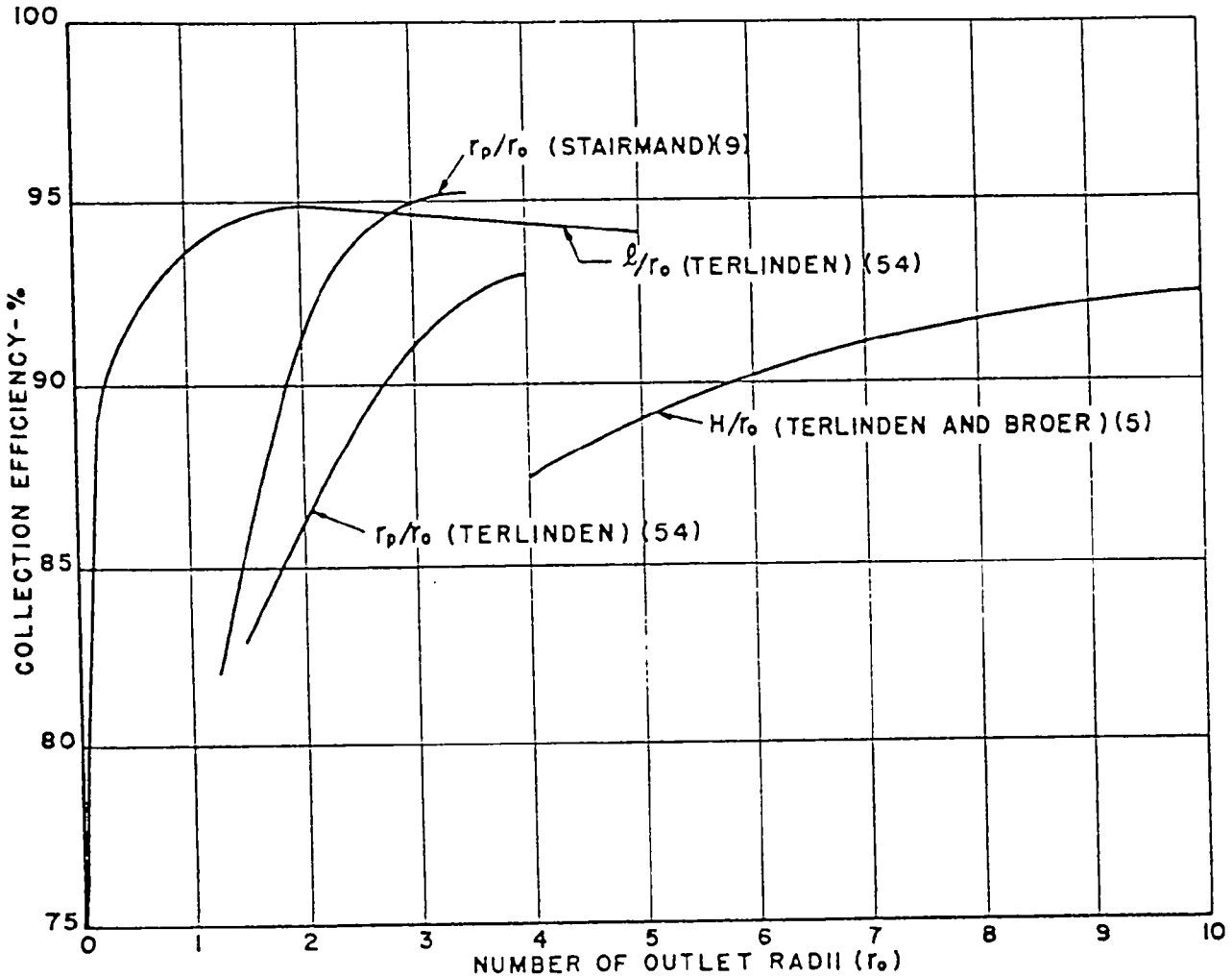
$$m_p = \beta \rho_p D_p^3 \tag{9}$$

Where:

β = volume shape factor, dimensionless.
ρ_p = particle density, in pounds per cubic foot.
D_p = particle diameter, in feet.

The separating force [equation (7)] becomes:

$$F_s = \frac{\beta \rho_p D_p^3 V_{tp}^2}{gr\, r_t^{2n}} \tag{10}$$



Dimension Ratios and Efficiency.

FIG. 7

It can be shown [26] that the force ("Stoke's Law force") resisting motion of a particle through a gas in the range of particle diameters from 3 to 100 microns is:

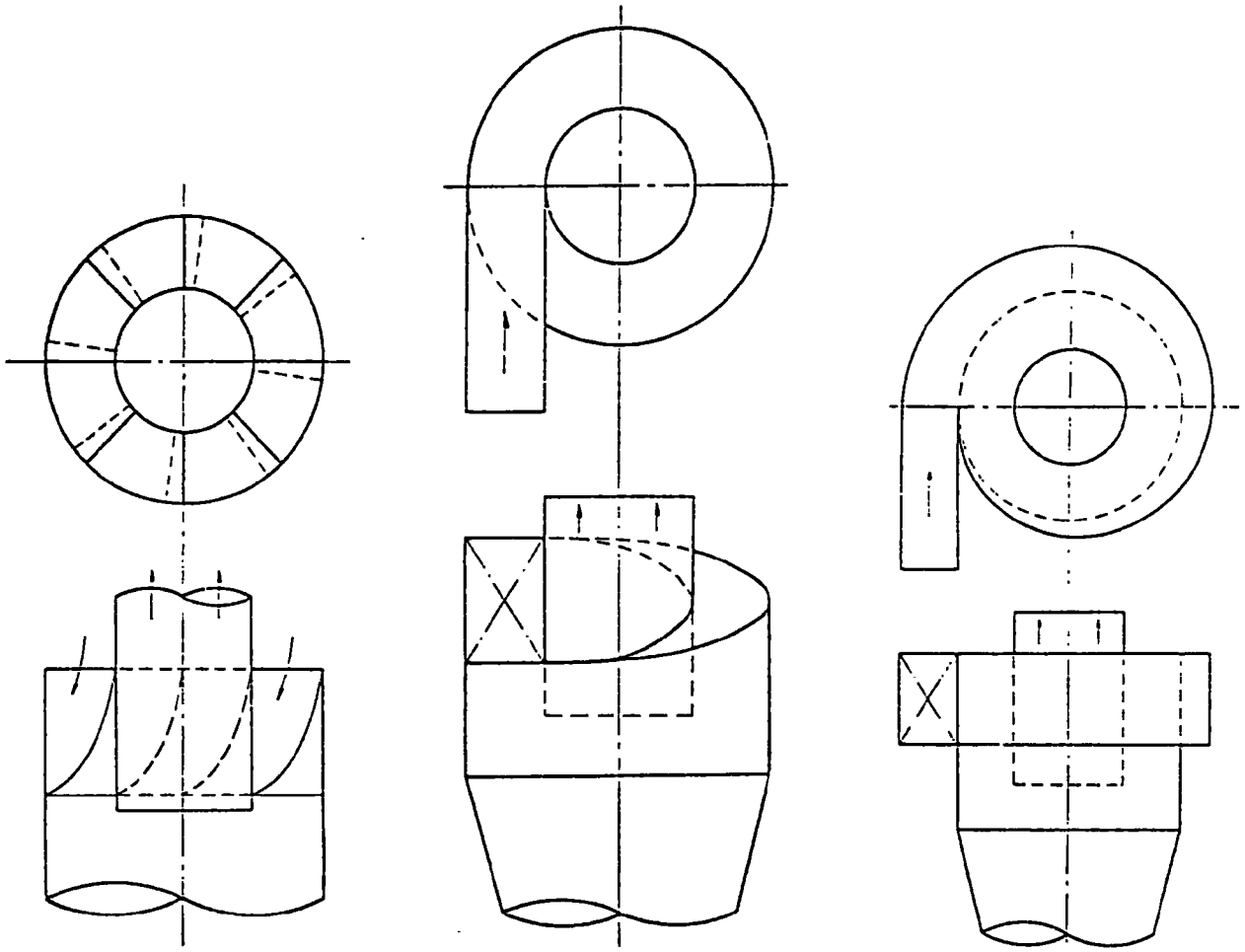
$$F_r = K_2 u D_p \mu \qquad (11)$$

Where:

F_r = frictional resistance to flow, in pounds.
K_2 = proportionality constant, dimensionless.
u = particle velocity with respect to gas, in feet per second.
μ = gas viscosity, in pounds per second per foot.

Comparison of equations (10) and (11) shows that the separating force varies with the cube of the particle diameter, whereas the resistance to flow varies only linearly. Thus large-diameter particles have a greater ratio of separating force to opposing force and are, therefore, more readily separated in a cyclone.

The velocity u of the particle with respect to the gas includes the radial as well as tangential components of gas flow (Sect. 1.211). The assumption of Feifel allows the computation of a "critical particle size" (D_{cr}) for any radius of rotation. D_{cr} may be considered the largest size of particle which is not separated from the gas stream. On the basis of this simplifying assumption, D_{cr} could be computed for r_o, and all particles larger than D_{cr} would be collected while all smaller particles would be lost into the outlet duct.



Cyclone Inlets.
FIG. 8

In fact, however, the radius at which a particle may be considered lost to the exit gases is not constant because the radial gas velocities vary along the axis of the cyclone. Since the radial velocity pattern has not yet been mathematically stated, there can be no reliable computation of critical particle size. In actual practice, the presence of the gas-outlet extension, the finite width of the entering gas stream, the random distribution of particles of various sizes across this width, the presence of major eddy currents, etc., all further obviate the value of any such theoretical computation.

Even were such a computation possible, it would be found that not one, but a series of critical sizes would be obtained for various increments of cyclone length and from one side to the other of the inlet. Therefore, it follows that a cyclone must be, and is, a poor classifier and does not make a sharp-size cut between particles separated and rejected. The cyclone has a curve rather than a straight line as its particle size-efficiency characteristic. Qualitatively, the predominant requirements for high collection efficiency of fine particles are that r_{fm} and r_m be low and V_{tm} high.

A number of authors have derived equations for D_{cr}, as shown in Table I. No critical evaluation has been made which would show one equation more nearly correct than another. The main value is to demonstrate the parameters involved and their qualitative relationships.

1.23 *Discharge of Separated Dust*

The separation of the dust from the gas stream is, in practical terms, only the first step

TABLE I

Formulae for Critical Particle Size

Reference	Formula	Special Units: Remarks
Davies[9]	$D_{cr} = a_{min} = \sqrt{\frac{9\mu r_p^2}{8(\rho_p - \rho) V_i H}\left[1 - \left(\frac{r_o}{r_p}\right)^4\right]}$	a_{min} = particle size above which efficiency will be 100 per cent in absence of re-entrainment.
Gardiner[63]	$D_{cr} = \sqrt{\frac{9\mu (D - d_o)}{2\pi N V_i (\rho_p - \rho)}}$	μ = viscosity, in pounds per second per foot.
Lapple[63]	$D_{cp} = \sqrt{\frac{9\mu W_i}{2\pi N_e V_i (\rho_p - \rho)}}$	μ = viscosity, in pounds per second per foot. D_{cp} = cut size, collected at 50-percent efficiency. N_e = "effective" number of turns in cyclone = 5 to 10 for typical cyclone (Sect. 2.31).
Shepherd[30]	$D_{cr} = \sqrt{\frac{9\mu d_o}{2\pi N V_i (\rho_p - \rho)}}$	μ = viscosity, in pounds per second per foot. For N, see reference.
Muhlrad[31]	$D_{cr} = \frac{3}{4}\sqrt{\frac{3g\mu D^2}{\pi \rho_p V_i r_c N}\left(\frac{1 - w^4}{1 + w + w^2}\right)}$	$w = \frac{do}{D}$. All units metric—see reference.
Rosin, Rammler, and Intelmann[34]	$D_{cr} = 3\sqrt{\frac{g\mu Y}{\pi \rho_p V_i N}\left(1 - \frac{Y}{D}\right)}$	$Y = \frac{D}{2} - r$ = instantaneous distance of particle from cyclone wall. All units metric—see reference.
Tarjan[32]	$d_{min} = \sqrt{\frac{9gA_i r}{\pi H_i V_i^2 r_p^2 \rho_p}}$	d_{min} = particle diameter at "blocking radius r." r = "blocking radius."

in a series intended to result in solids or liquid at rest in a container, and a gas stream cleaned of particulates to the desired degree. The concentrated dust layer swirling slowly (compared to the vortex) down the walls of the cyclone body must be conducted into the dust hopper, or its equivalent, with a minimum of re-entrainment into the base of the vortex. Factors affecting re-entrainment are:

a. The length, eccentricity, and diameter of the vortex core and its relation to the cyclone body walls.

b. The presence or absence of purge flow outward from the dust outlet.

c. Recirculation of gas, or infiltration of air, into the dust outlet.

d. Presence or absence of an air-lock material discharge valve or dip-leg.

e. Smoothness of the inner walls of the cyclone.

The two major types of discharge are axially through a core and peripherally. Both methods may be used with or without purge gas, or with various types of mechanical accessories. These methods, and their effect on efficiency, will be discussed in later sections.

The dust in the gas stream which escapes into the outlet duct tends to be concentrated toward the walls of the duct. Therefore, various devices for skimming off the outer layers of this vortex have an effect also on the overall performance of a cyclone.

1.30 Scope of the Cyclone in Field Use

1.31 *Typical Operating Ranges*

Cyclone collectors, as a class, are regarded as the lowest in first cost of equipment convention-

ally used for dust or droplet collection. They also, as a class, provide lower collection efficiency than other types of equipment, although there are, of course, exceptions to this generality. They are suitable for medium and coarse dusts and are unsuited for very fine dusts or metallurgical fumes. They have advantages, however, in that there are no moving parts, choice of materials of construction is wide, and maintenance costs are low. Power requirements (if reasonable efficiency on fine dust is required) are as high as, or higher than, most other types of equipment, although some types of wet scrubbers have even higher requirements.

1.32 *Efficiency in Field Use*

A clarification in terminology regarding efficiency will aid in this and later general discussions. Efficiency brackets are arbitrarily set as follows:

Collection Efficiency (Per Cent by Weight)	Efficiency Range	Amount Passing Collector (Per Cent)
Above 50 to 80	Low	Above 20 to 50
Above 80 to 95	Medium	Above 5 to 20
Above 95 to 99	High	Above 1 to 5
Above 99 to 99.99	Very high	Above 0.01 to 1
Above 99.99	Ultra high	Less than 0.01

On this basis, most cyclones as applied operate in the low and medium efficiency ranges. A well-designed but otherwise conventional cyclone may be expected to provide high efficiency for coarse particulate matter of the 40- to 50-micron diameter range: and small-diameter (less than 1-ft) "high efficiency" types may extend the high-efficiency range to particles as small as 15- to 20-micron sizes. Typical efficiency ranges for various particle size ranges are as follows:

Particle Size Range (Microns)	"Conventional" Cyclone Efficiency Range	"High Efficiency" Cyclone Efficiency Range
Less than 5	—	Low
5 to 20	Low	Medium
15 to 50	Medium	High
Greater than 40	High	High

For various practical reasons, efficiencies in the very high or ultra-high range are almost never achieved on industrial aerosols by cyclones.

1.33 *Pressure Drop in Field Use*

The loss in pressure of the gas stream flowing through a cyclone depends on a number of variables but, in practice, is usually found to be on the order of 1 to 4 inlet velocity heads. With velocities commonly used for handling dusty air, the velocity head will range from ¼ to 3 in., water gage. Thus the range of resistance would be from ¼ to 8 in., water gage. Where ordinary centrifugal blowers are used as the source of motive power for the air, a practical upper limit of resistance for the cyclone plus other system components is in the range of 15 to 16 in., water gage, although with other types of motive equipment this upper limit may be considerably higher. Efficiency increases with inlet velocity, as will be shown later, but at a lower rate than the pressure drop increases. Furthermore, for any given cyclone and dust combination, there is an inlet velocity beyond which turbulence increases more rapidly than separation, and efficiency begins to decrease. Thus, even aside from power cost considerations, there is little purpose in further increases in resistance. Most cyclones will be found to have from 2- to 7-in., water gage, resistance as operated.

1.34 *Dust Loading in Field Use*

There appears to be almost no practical upper limit of dust loadings to a properly designed cyclone. A cyclone can be designed to handle any amount of material which can be moved by gas flow and, in general, cyclone efficiency increases with increasing dust load. Since this ability is not possessed by many other types of collectors of inherently higher efficiency, cyclones are frequently used as precleaners for other types when dust loadings are too heavy for the secondary collector.

Conversely, cyclone efficiency decreases with decreasing dust load, and other types of collectors are well able to handle the lighter loads alone at higher efficiencies. As a result, cyclones are usually applied to dust loadings of 10 grains per cu ft or higher, and seldom are used below 1 grain per cu ft, unless the dust is unusually coarse or other factors of temperature, corrosion, and the like are overriding in importance.

1.35 *Range of Capacities*

Commercial cyclones are built in sizes having individual capacities of 30 to 30,000 cu ft per min. In general, the smaller units are more efficient but must be used in parallel to accommodate practical gas volumes.

1.36 *Range of Physical and Chemical Conditions*

Cyclones, as a class, can be designed to handle a wider range of chemical and physical conditions of operation than any other type of collection equipment. Any conditions of temperature, pressure, and corrosion for which structural materials are available can be met by a cyclone.

Erosion is sometimes troublesome, and some materials of construction necessary for temperature or corrosion conditions may not be especially desirable in erosion resistance.

The main limiting factor in conditions of cyclone application is the physical characteristic of the dust. A sticky, hygroscopic, or similar material may give difficulty in cyclone operation, and such materials are sometimes handled in cyclones operated wet, or in "wet collectors." Dusts which have a bad tendency to bridge, hang up, or cake may give difficulty at the dust outlet of small-diameter cyclones.

2.00 EFFICIENCY AND PRESSURE DROP

2.10 General Considerations of Efficiency

For high efficiency, the separating forces should be high, the number of gas revolutions large, the tangential velocity high, and the dust removal effective so that separated dust is not re-entrained.

Considerations governing the critical particle size D_{cr} have been presented previously. Since the particle size-efficiency performance of a cyclone is a curve rather than a straight line, there is no direct mathematical relation between efficiency η and D_{cr}. However, in a qualitative sense, those parameters tending to increase D_{cr} should decrease η for a given dust size distribution, and vice versa.

By inspection of Table I, it may be seen that efficiency will increase with an increase in the following:

Dust-particle density ρ_p.
Inlet velocity V_i.
Cyclone-body length H.
Number of gas revolutions N.
Ratio $\frac{D}{do}$.
Dust-particle size D_p.

Similarly, efficiency will decrease with an increase in the following:

Gas viscosity μ.
Cyclone diameter D.
Gas-outlet-duct diameter d_o.
Increase in inlet width W_i.
Inlet area A_i.
Gas density ρ.

Efficiency is also affected by various accessory devices not included in the mathematical relationships in Table I. It is obviously desirable to have smooth inner surfaces in the cyclone body in order to minimize projection of separated dust out into the air stream.

2.20 General Considerations of Pressure Drop

For a given cyclone handling clean air, the resistance varies with the square of the air volume Q, or similarly with the square of the inlet velocity V_i. Since the expression for velocity pressure h_v of a gas is:

$$h_v = 0.0030\rho v^2, \qquad (12)$$

h_v similarly varies with the square of the velocity. It therefore becomes convenient to express cyclone pressure drop in terms of number of inlet velocity heads, h_n, thereby making such equations independent of gas volume and inlet velocity.

It will be apparent from later discussion that a satisfactory method for predicting pressure drop from cyclone dimensions over a wide range of construction has not yet been developed. Pressure drop should preferably be determined experimentally on a geometrically similar prototype.

Most investigators agree that cyclone resistance is a function of gas-inlet area and outlet area of the form:

$$h_n = X\left(\frac{H_i W_i}{d_o^2}\right)^z \qquad (13)$$

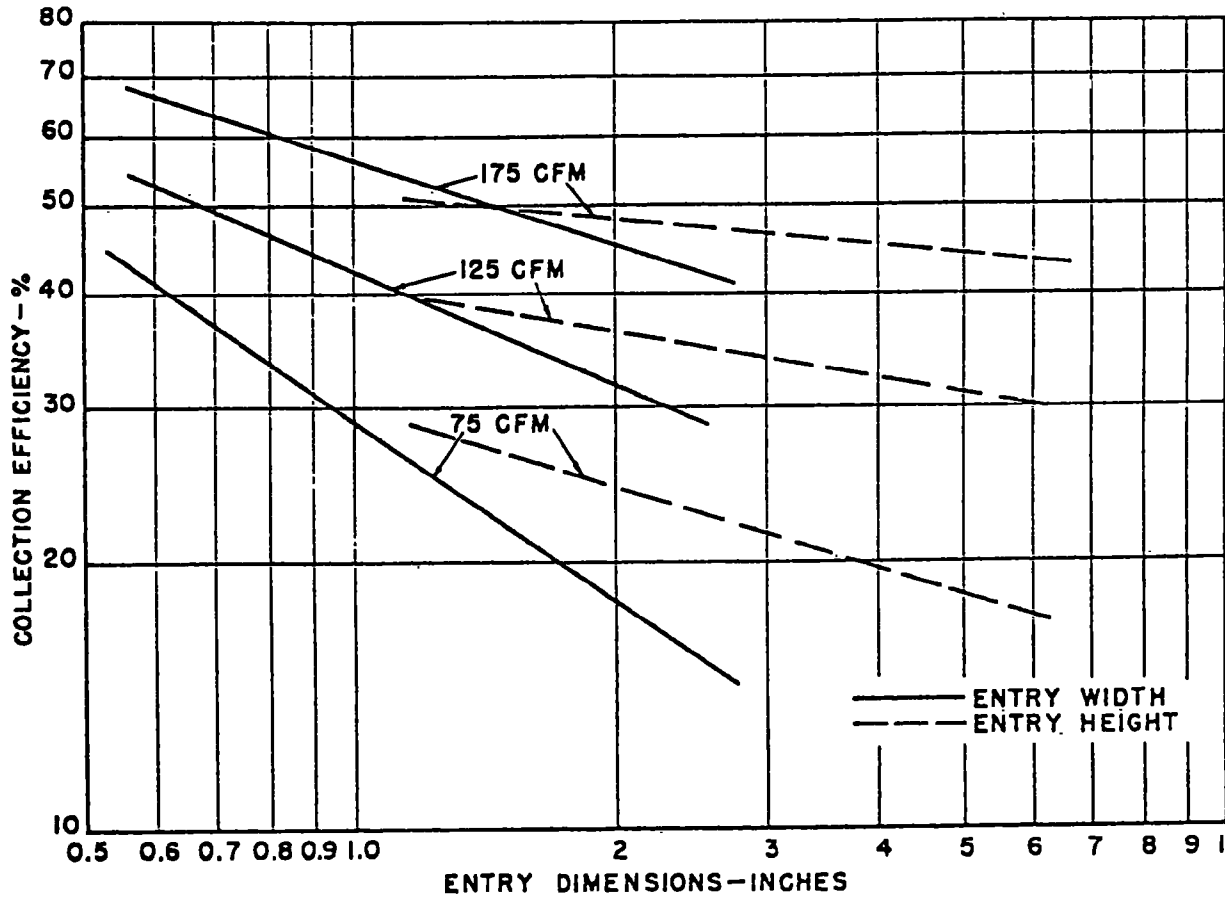
Where:

X = proportionality constant, dimensionless.
H_i = inlet height, in feet.
W_i = inlet width, in feet.
d_o = outlet diameter, in feet.
z = exponent, dimensionless.

Values for X are given as follows:

a. Ter Linden[66] states that for common cyclones with straight tangential inlets without inlet vanes $z=1$ and X is between 25 and 32, but that for involute inlets both z and X are lower. For a 180-deg involute inlet his data show $X=21.7$ if $z=1$ (Fig. 10).

b. Lapple[67] gives a value for X of 18.4 for a 360-deg involute inlet.



Entry Dimension Vs. Efficiency.

FIG. 9

c. For a cyclone having dimension ratios $\frac{r_p}{r_o}=$ 2 to 4, $\frac{H}{r_o}=8$, $\frac{l}{r_o}=6$, Shepherd and Lapple[43, 44] reported $z=1$ and $X=16$ without inlet vane, and 7.5 for an inlet vane which neither expanded nor contracted the entering gas and did not touch the outlet (a "neutral" vane). They also found that variations in $\frac{l}{r_o}$ from 6 to zero had no effect on X.

d. First[17] found that a reduction in $\frac{l}{r_o}$ from 2 to zero caused a 10-per-cent decrease in X $\left(\frac{r_p}{r_o}=2 \text{ and } \frac{H}{r_o}=5.8\right)$. In cyclones with $\frac{r_p}{r_o}=2$ and $\frac{l}{r_o}=2$ but with $\frac{H}{r_o}$ variable, First concluded that $z=1$, and derived an expression for X, as follows:

$$X=\frac{\frac{12}{Y}}{\left(\frac{L}{D}\right)^{\frac{1}{2}}\left(\frac{M}{D}\right)^{\frac{1}{2}}} \qquad (14)$$

Where:

Y = 0.5 for no inlet vane;
= 1.0 for neutral inlet vane;
= 2.0 for inlet vane that expands entering gas stream and touches outlet duct.
L = cyclone-cylinder length, in feet.
M = cyclone-cone length, in feet.
D = cyclone-body diameter, in feet.

Alexander[2] concluded that $z=1$, and derived an expression for X, as follows:

$$X=4.62\frac{r_o}{r_p}\left\{\left[\left(\frac{r_p}{r_o}\right)^{2n}-1\right]\left(\frac{1-n}{n}\right)+f\left(\frac{r_p}{r_o}\right)^{2n}\right\}, \qquad (15)$$

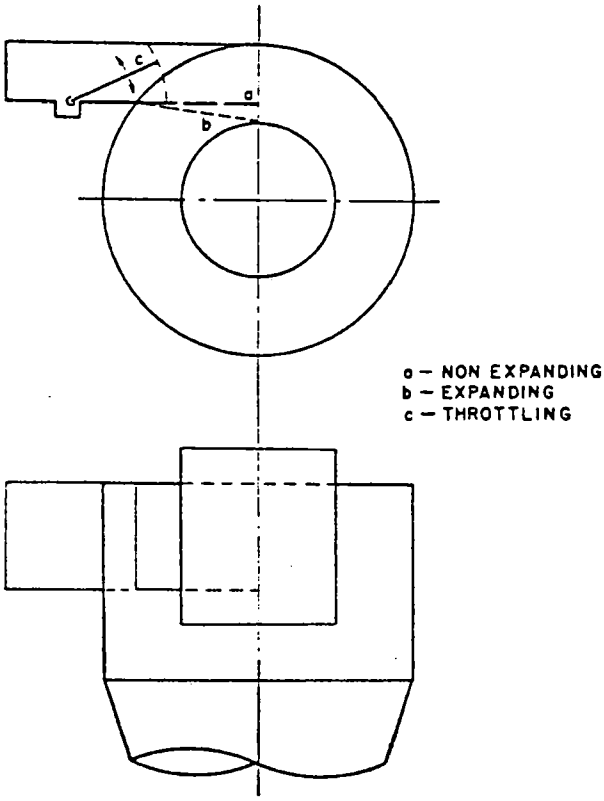
where f varies with n as follows:

n	0	0.2	0.4	0.6	0.8
f	1.90	1.94	2.04	2.21	2.40

Values of Alexander's function for X are plotted in Fig. 5. For values of n, see Fig. 2.

Stairmand has derived a theoretical expression for h_n, as follows:

$$h_n=K_3+3.24\left(\frac{A_1}{4r_o^2}\right)^2, \qquad (16)$$



Inlet Vanes.

FIG. 10

where:

$$K_3 = 1 + 2\left(\frac{V_{tc}}{V_i}\right)^2 \div \left(\frac{2r_c}{r_o} - 1\right) \qquad (17)$$

See Table II for computed values of $\frac{V_{tc}}{V_i}$, and Fig. 6 for plots of equation (17).

The effect on X of variations in $\frac{r_p}{r_o}$ and $\frac{H}{r_o}$ was investigated by Ter Linden and reported by Broer[5] as the following multiplying factors for correcting X:

$\frac{r_p}{r_o}$	Factor	$\frac{H}{r_o}$	Factor
1.5	0.91	4	1.17
2.0	1.00	6	1.08
2.5	1.08	8	1.00
3.0	1.19	10	0.96

A test of the results of these various equations has shown those based on equation (13) to have a higher order of reliability than those of equation (16); and, further, indicates that the exponent 2 in equation (16) is probably too high.

A summary of factors for application to equation (13) is presented in Table III.

An attempt has been made to analyze the

TABLE II

Calculated Values of $\frac{V_{tc}}{V_i}$ from Equation (20)

Ratio $\frac{r_c}{r_o}$ \ Ratio $\frac{GS}{A_i}$	0.10	0.20	0.50	1.0	2.0	5.0
	Calculated $\frac{V_{tc}}{V_i}$					
1	1.21	1.08	0.87	0.71	0.55	0.38
2	1.53	1.31	1.00	0.78	0.59	0.40
5	1.95	1.58	1.13	0.85	0.63	0.42
10	2.24	1.75	1.21	0.89	0.65	0.43
20	2.47	1.88	1.27	0.92	0.67	0.43

validity of equations (14) and (15), and the values cited by Shepherd and Lapple,[43, 44] by comparing calculated values of X with measured values of X. Three sets of data were available and are presented in Table IV. Group A was reported by Stairmand,[43] Group B by Stern,[51] and Group C represents field survey data previously unpublished. Since the three groups of data probably involve differences in the point and method of measuring static pressure, and it is known that in Group C it was not possible to determine the presence or absence of internal accessories, the three groups were analyzed separately.

Calculated X shows a large deviation from measured X in all three groups of data. The constant 16 proposed by Lapple gives less deviation for Groups A and C, while the Alexander equation gives lowest deviation for Group B. The data were further subjected to analysis of variance ratio,[50] with the result that, for Group A, all three methods of computation were found equally reliable; for Groups B and C, the Alexander method and the Lapple constant were equally reliable, while the First method was less reliable. For Groups A, B, and C as a whole, the Alexander and Lapple values were equally reliable, while the First method was less reliable. The results of this analysis may be summarized as follows:

Data Group	Best Method	Equally Good Methods
A	Lapple	First, Alexander
B	Alexander	Lapple
C	Lapple	Alexander
A, B, C	Lapple	Alexander

This analysis shows a constant value for X to be equally as good as, if not better than, equations for computing X based on cyclone-dimension ratios. It seems only reasonable to assume, however, that dimension ratios will affect X; in fact, this is proposed by the same authors who advocate a "constant" value (Table III).

TABLE III

Pressure-Drop Factors for Equation (13)

Source	$\frac{r_p}{r_o}$	$\frac{H}{r_o}$	$\frac{l}{r_o}$	Special Conditions	z	X
Ter Linden[64] . . .	2	8	—	No inlet vane	1	25 to 32
	2	8	—	180-Deg involute inlet	1 (Assumed)	21.7
Lapple[67]	1.62 to 3.25	—	1 (Approximately)	360-Deg involute inlet, step-tapered body	—	18.4
Shepherd and Lapple[43, 44] . .	2 to 4	8	6	No inlet vane	1	16
	2 to 4	8	6	Neutral inlet vane	1	7.5
Broer[5]	1.5 to 3.0	4 to 10	—	No inlet vane	—	See text for X correction factors
First[17]	2	Variable	2	$Y=0.5$ no inlet vane; $=1.0$ neutral inlet vane; $=2.0$ expanding inlet vane	1	$X=\frac{\frac{12}{Y}}{\left(\frac{L}{D}\right)^{\frac{1}{2}}\left(\frac{M}{D}\right)^{\frac{1}{2}}}$
Alexander[2]	—	—	—	—	1	$X=4.62\frac{r_o}{r_p}\left\{\left[\left(\frac{r_p}{r_o}\right)^{2n}-1\right]\frac{1-n}{n}+f\left(\frac{r_p}{r_o}\right)^{2n}\right\}$ (Fig. 5)
Lapple[67]	2	8	1.25	No inlet vane	—	8

TABLE IV

Analysis of Calculation Methods for X

Cyclone Diameter D (Feet)	Gas-Outlet Diameter d_o (Feet)	Gas-Outlet Extension l (Feet)	Cyclone Body L (Feet)	Cone Length M (Feet)	Inlet Height H_i (Feet)	Inlet Width W_i (Feet)	X Measured	Calculated Values of X: First [17]	Alexander [1]	Lapple [6, 14]	Deviations from Measured X: First	Alexander	Lapple
							Group A						
2.00	1.00	3.00	4.00	4.00	0.50	0.25	27.0	15	14	16	12.0	13.0	11.0
2.00	1.00	3.00	4.00	4.00	1.00	0.50	11.0	15	14	16	4.0	3.0	5.0
5.00	2.50	7.50	10.00	10.00	3.00	1.25	17.0	15	16	16	2.0	1.0	1.0
5.00	2.50	7.50	10.00	10.00	2.50	1.25	12.5	15	16	16	2.5	3.5	3.5
3.00	1.50	—	6.00	6.00	1.50	0.75	16.6	15	15	16	1.6	1.6	0.6
2.84	1.00	0.50	4.50	—	3.50	0.25	22.0	17.5	17.5	16	4.5	4.5	6.0
0.67	0.21	0.33	1.08	—	0.33	0.10	13.5 to 16.6	17.5	13	16	2.5	2.0	1.0
0.67	0.33	0.33	1.08	—	0.33	0.10	16.6 to 17.4	17.5	12.5	16	0.5	4.5	1.0
0.67	0.21	0.33	0.75	—	0.67	0.17	16 to 20	22	13	16	4.0	5.0	2.0
0.67	0.33	0.33	0.75	—	0.67	0.17	14.0	22	12.5	16	8.0	1.5	2.0
									Mean		4.2	4.0	3.3
							Group B						
0.98	0.38	0.83	0.46	1.46	0.25	—	11.5	27	14	16	15.5	2.5	4.5
1.00	0.50	1.17	1.33	1.85	0.62	0.23	6.5	18	13	16	11.5	6.5	9.5
0.67	0.38	—	0.44	0.97	0.25	—	8.1	24	12	16	15.9	3.9	7.9
1.33	0.75	0.81	1.17	0.0	0.33	—	19.8	26	12.5	16	6.2	7.3	3.8
1.58	0.83	1.00	0.62	2.16	0.50	—	12.3	29	13.5	16	16.7	1.2	3.7
0.75	0.43	0.67	0.98	1.48	0.50	0.25	9.1	18	12	16	8.9	2.9	6.9
1.10	0.62	1.00	1.50	1.50	0.67	0.35	11.9	20	12.5	16	8.1	0.6	4.1
									Mean		11.8	3.6	5.8

Group C																	
6.33	3.00	—	3.75	9.67	2.34	0.75	6.2	25	17	16	18.8	10.8	9.8
3.50	1.08	—	1.58	3.25	1.50	0.42	11.2	32	18	16	20.8	6.8	4.8
4.00	1.58	—	1.92	4.33	1.25	0.50	33.6	30	17	16	3.6	16.6	17.6
4.00	1.25	—	1.83	3.67	1.33	0.42	2.7	32	18	16	29.3	15.3	13.3
4.50	1.21	—	2.00	4.17	1.50	0.42	4.6	32	19	16	27.4	14.4	11.4
5.00	1.66	—	2.33	4.67	1.75	0.50	6.0	32	19	16	26.0	13.0	10.0
8.50	3.42	—	4.17	7.75	3.58	0.92	20.8	31	18.5	16	10.2	2.3	4.8
6.50	2.33	—	2.92	6.08	2.50	0.67	9.3	32	19	16	22.7	9.7	6.7
8.33	4.00	—	5.00	8.25	3.08	1.00	5.8	28	17	16	22.2	11.2	10.2
5.50	2.00	—	2.42	5.17	2.00	0.58	2.1	32	18	16	29.9	15.9	13.9
3.16	2.08	—	2.46	5.83	1.75	0.50	25.6	21	13	16	4.6	12.6	9.6
5.00	1.67	—	2.17	4.67	1.75	0.50	30.4	32	19	16	1.6	11.4	14.4
								Mean			18.0	11.7	10.5
								Total mean			11.8	7.1	6.9

It can only be concluded that a really satisfactory method for predicting cyclone pressure drop from cyclone dimensions over a wide range of construction has not yet been presented.

At the present state of the art, the best method of determining the pressure drop of a proposed cyclone is to depend on the measured pressure drop of a geometrically similar prototype, rather than to rely on a computed value.

2.30 Design Factors Affecting Pressure Drop and Efficiency

2.31 *Diameter and Dimension Ratios*

As has been described generally, the cyclone-diameter, inlet, and gas-outlet dimensions are of primary importance in efficiency and pressure-drop consideration.

A study has been made of 23 families of geometrically similar cyclones. The consensus design—the "average" dimension ratios of these families—is presented not as having any particular virtue, but as representing typical present practice, and thus serving as a starting point for discussion of variations in design. A widely recommended typical cyclone[13] has the following similar proportion ratios:

Cyclone Element	Ratio: $\frac{\text{Element}}{d_c}$ Consensus	Typical[13]
Body diameter D.....	2.0	2.0
Cylinder length L.....	1.5	4.0
Cone length M.....	2.5	4.0
Total length H.....	4.0	8.0
Outlet length l.....	1.25	1.25
Inlet height H_i.....	0.9	1.0
Inlet width W_i.....	0.4	0.5

A higher-efficiency (and higher-pressure-drop) design would have a larger length ratio, a smaller inlet-width ratio, and a larger body-diameter ratio with smaller body diameter.

The length of the cyclone body is of importance. Gas can be considered as flowing to the gas outlet from the main vortex zone through an imaginary cylindrical extension of the gas outlet down to the bottom of the cyclone, or to its intersection with a conical bottom. The area of this cylinder increases with the length of the main vortex zone. The mean inward gas velocity past it decreases with such increasing length. Since this mean inward gas velocity is one force opposing particle motion to the periphery, it follows that increasing length of the

TABLE XVII

Costs of Cyclone Dust Collectors

Size (Cubic Feet Per Minute)	Cost (Cents Per Cubic Foot Per Minute)					
	Kane[21] (1952)		Dallavalle[80] (1953)		Dorfan[81] (1950)	
	Standard	High-Efficiency	Light-Duty	Heavy-Duty[a]	Simple	Multiple
1,000	20	37 to 53	15	50	10	15
5,000	10	20 to 35	8	30	8	14
10,000	9	15 to 32	7	25	7	11
50,000	9	12 to 30	7	25	5	7
100,000	—	12 to 30	—	—	—	—

[a] Includes multitube units. Manifolding banks of multitube units may raise the cost to 60 cents per cubic foot per minute.[80]

efficiency collection is economical at dust loadings on the order of 1.0 grains per cu ft or greater. Cyclone collectors do not fall in this category, except for very coarse materials. They may still be used on collection of valuable materials, however, if the operating conditions are so rigorous as to preclude use of other, more efficient types.

Power costs will be rated on a pressure drop of approximately 0.25 hp per inch, water gage, per 1,000 cu ft per min.

No generalized data are available on special alloy construction or refractory, erosion-, or corrosion-resistant linings. Thin refractory and erosion linings are frequently estimated at $1 to $2 per square foot.

12.00 PRACTICAL CYCLONE DESIGN OR SELECTION

12.10 Steps in Design or Selection

1. Determine the following:

a. Volume rate of flow of gas and its chemical and physical properties.

b. Dust loading, dust particle size and density, and handling characteristics of dust.

c. Desired efficiency of collection.

d. Special problems of erosion, corrosion, or operational problems.

2. Determine from Sect. 1.32 what general type of cyclone is required.

a. If expected efficiency is lower than desired efficiency, consider other types of equipment if those types will withstand operating conditions.

b. If other types of equipment cannot be used, consider use of series operation, bottom purge, outlet skimmers, wet operation, etc., for improving efficiency.

3. Determine whether a commercial product is to be purchased or a cyclone designed and fabricated by the user. Multitube, small-diameter, "high efficiency" cyclones are generally purchased items.

a. If a commercial product is desired, obtain performance and efficiency data from the following:

Pilot test.
Laboratory test.
Similar experience data.

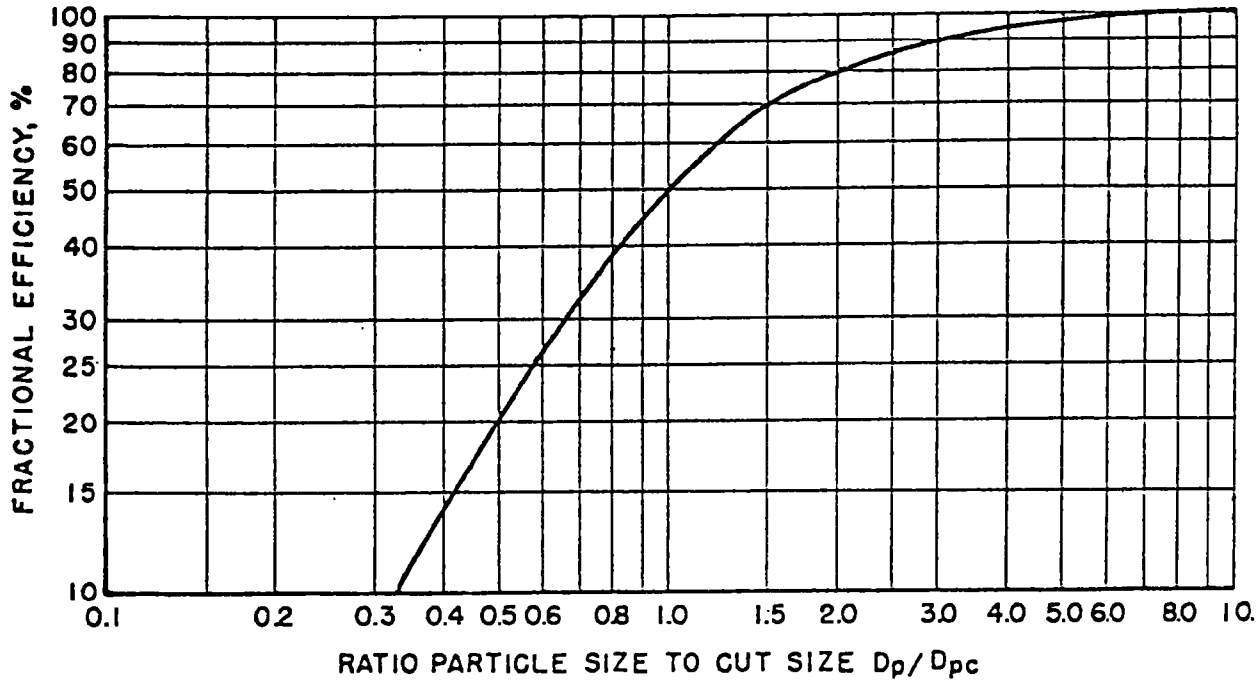
Correct as required to anticipated operating conditions.

b. If a cyclone is to be designed, calculate pressure drop and efficiency for a "typical" unit (Sect. 2.31), with an assumed inlet velocity of 50 ft per sec (normal range, 20 to 70 ft per sec). Efficiency may be evaluated from the curve of Fig. 36 showing efficiency vs. ratio $\frac{D_p}{D_{pc}}$ for this cyclone, and from a calculation of D_{pc} (Table I).

(1) If anticipated efficiency results are better than desired, a lower pressure drop may be obtained by reducing inlet velocity (enlarging the cyclone). Recalculate D_{pc} from new dimensions and check against Fig. 36 for desired efficiency.

(2) If anticipated efficiency results are poorer than desired, increase inlet velocity (reduce cyclone size), provide larger length ratio, smaller inlet-width ratio, larger body-diameter ratio with smaller body diameter, etc. Recalculate D_{pc} from new dimensions and check against Fig. 36 for desired efficiency. Consider the use of the following accessories or arrangements for improving performance:

Parallel operation of smaller units.
Series operation.
Purge from outlet.
Wet operation.



Fractional Efficiency of "Typical" Cyclone (See Sect. 2.31).

FIG. 36

(3) If efficiency is satisfactory but pressure drop too high, consider an outlet drum, etc., for pressure recovery.

4. Make adequate provision for preventing gas flow into dust outlet, positive removal of dust from cone, and prevention of hopper overfilling. In multitube or parallel operation, design to prevent recirculation between tube outlets.

5. If cyclone is to be operated wet, take necessary special precautions.

6. If erosion or fouling is likely, special design is needed. Consider special linings, scouring, etc.

7. If corrosive gases or materials are handled, consider special alloys, linings, wet operation, or prevention of condensation, as may be indicated.

12.20 Field Tests on Fluid Catalytic Crackers

Results of testing full-scale cyclones in fluid catalytic-cracker installations are tabulated in Table XVIII. The operating conditions and lack of access to the cyclones make such testing difficult and account for the missing values in the table for many tests.

Collection efficiency in such service is high, primarily on account of the high dust loadings and large particle size. Note that even with such efficiencies, losses are on the order of tons per day. Cyclones in ordinary service do not provide these high efficiencies.

TABLE XVIII

Field Tests on Full-Scale Fluid Catalytic Crackers [a]

Item No.:	1	2	3	4	5	6	7	8	9
Service	Regenerator	Regenerator	Regenerator	Reactor	Reactor	Regenerator	Regenerator	Regenerator	Regenerator
Number of sets in parallel	6	8	13	5	9	5	6	6	6
Number in series	1	2	2	1	2	3	8	2	2
Cyclone diameter, ft:									
Primary	Footnote [f]	Footnote [f]	3.0	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]
Secondary	Footnote [f]	Footnote [f]	3.0	Footnote [f]	Footnote [f]	3.0	Footnote [f]	Footnote [f]	Footnote [f]
Outlet diameter, ft:									
Primary	Footnote [f]	Footnote [f]	1.07	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	0.83	0.83
Secondary	Footnote [f]	Footnote [f]	1.07	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	0.83	0.83
Inlet conditions:									
Dust load, grains per cu ft at conditions	—	—	2,800	—	—	2,000	4,370	—	—
Mass median size, microns [a]	60 [b]	37 [d]	37 [d]	43 [b]	41 [b]	43 [b]	42 [b]	—	—
	1.0 [b]	1.0 [d]	1.0 [d]	1.5 [b]	1.8 [b]	1.5 [b]	1.0 [b]	—	—
Inlet velocity, ft per sec	—	—	80	—	—	60	78	57	84
Bed conditions:									
Density, lb per cu ft	30.5	27.7	31.9	32.2	40.1	35	32	—	—
Vapor velocity, ft per sec	1.70	2.28	2.33	1.70	1.65	—	—	—	—
Disengaging height, ft	25	22.3	20	25	30	—	—	—	—
Temperature, degrees fahrenheit	—	—	1,090	—	—	1,115	1,115	1,110	1,110
Pressure, psig	—	—	13.0	—	—	8.5	8.4	22.3	16.8
Outlet conditions:									
Load, grains per cu ft STP	—	—	0.85	—	—	0.01	0.50	0.78	0.57
Mass median size, microns [a]	4 [c]	33	—	14	11	12	10	15	—
	3.2 [c]	1.7	—	1.6	1.8	2.3	2.0	1.8	—
Efficiency, per cent by weight	—	—	99.98	—	—	99.976	99.994	—	—
Loss, tons per day	95	12.5	8.5	40	0.8	3.2	3.0	6.5	5.0
Gas volume, cu ft per sec STP	—	—	607	—	—	570	960	1,850	1,170
Remarks	Lined, ½-in. carbon steel	Unlined, ½-in. carbon steel	Primary: lined, ½-in. carbon steel Secondary: unlined, ½-in. carbon steel	Lined, ½-in. stainless steel	Lined, ½-in. carbon steel	Third-stage cyclone same as second-stage	Third-stage cyclone same as second-stage		

[a] Standard geometric deviation.
[b] Catalyst in bed.
[c] Includes Cottrell-precipitator return fines.
[d] Dilute phase 19 ft above dense bed.
[e] Courtesy Pan American Refining Corp., The Pure Oil Co., Union Oil Co. of California.
[f] Dimensions requested of vendors; to be forwarded when received.

CYCLONE DUST COLLECTORS

(REPORT ON REMOVAL OF PARTICULATE MATTER FROM GASEOUS WASTES)

1.00 INTRODUCTION

1.10 Definition

A cyclone is a structure without moving parts which separates particulate matter from gas by transforming the velocity of an inlet gas stream into a vortex confined within the structure. A vortex is a helical form of rotation of fluid about an axis. In nature, the axis of a vortex is frequently curved, and although the axis of the confining structure might likewise be curved, it is in practice a straight line. Similarly, although the ideal structure would be one generated by a curved line revolved about the cyclone axis, practical cyclones employ confining structures generated by the revolution of straight lines about the axis, i.e., combinations of cylinders and cones (Fig. 1).

1.11 *Types of Cyclones*

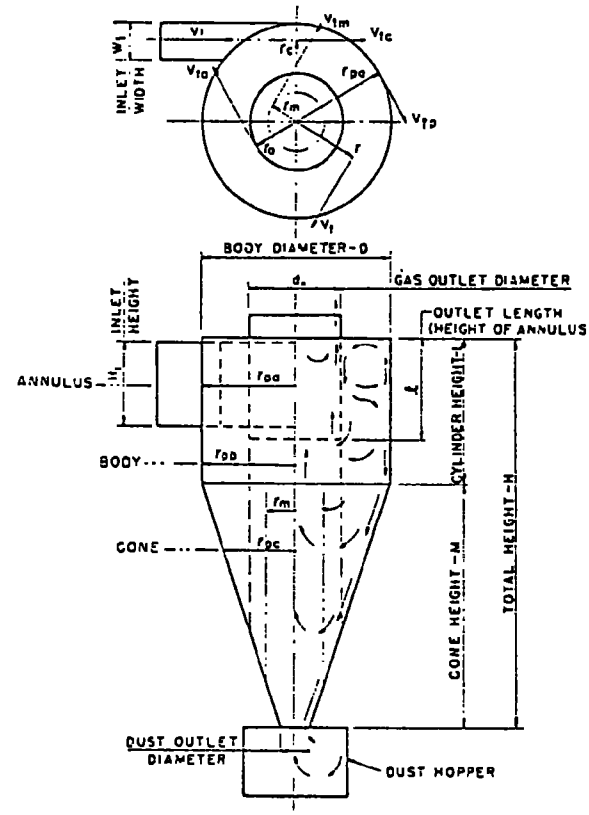
Structurally, a cyclone must have an axial gas outlet, a dust discharge, and a means for gas inlet which will produce the gas rotation necessary to create the vortex. These three elements may be combined in a number of different ways. Rotation may be produced by tangential gas entrance or by axial gas entrance through a set of swirl vanes. Separated dust may be removed either axially or tangentially from the periphery. Dust may be removed from either the end opposite to the axial gas outlet or from the same end. There may be either one or a multiplicity of tangential inlets. The cyclone body may be completely cylindrical, completely conical, or made of both cylinders and cones. The gas outlet may be either cylindrical or conical.

Cyclones in common use may be classified as follows:

1. Cyclones with tangential inlet and axial dust discharge.

   1*a*. Larger-diameter ("conventional") cyclones.

   1*b*. Small-diameter ("high efficiency") cyclones.



Typical Cyclone.

FIG. 1

2. Cyclones with tangential inlet and peripheral dust discharge.

3. Cyclones with axial inlet and axial dust discharge.

4. Cyclones with axial inlet and peripheral dust discharge.

Type 1*a* is the most commonly used type in which the total gas volume is handled through one cyclone body, although sometimes such cyclones are arranged in parallel (Fig. 1). The other types are usually of small capacity individually, and practical gas volumes are obtained by operating large numbers of individual units in parallel.

SOURCE: Cyclone Dust Collectors, Engineering Report Prepared for American Petroleum Institute, Washington, DC (1956).

1.20 Mechanism of Cyclone Operation

The cyclone separates particles from the gas by means of centrifugal force exerted on the particles in vortex flow, tending to drive the particles to the wall of the cyclone body. The particles at the wall move toward the dust discharge by virtue of the axial component of the vortex flow, aided, if the axis is vertical, by gravity. The magnitude of the radial forces acting on the particles depends on the nature of the vortex flow in the different sections of the cyclone. Counteracting forces, such as radial gas velocities, tend to offset the separating forces.

1.21 *Nature of Vortex Flow*

The inlet of a cyclone transforms linear flow into vortex flow. After the gas leaves the inlet annulus, it establishes a vortex with an axial component in the direction of the dust discharge.

1.211 FLOW IN THE MAIN VORTEX: The characteristic of the main vortex is that the tangential velocity at radius r (V_t) increases as r decreases from the radius of the confining structure r_p to a maximum V_{tm} at some intermediate radius r_m. As r further decreases from r_m to zero at the axis, V_t decreases from its maximum V_{tm} at r_m to zero at the axis. The zone between the axis and r_m is called the core of the vortex. In the outer zone of the vortex where V_t increases as r decreases, the flow obeys the equation:

$$V_t = V_{tp}\left(\frac{r_p}{r}\right)^n \qquad (1)$$

Where:

V_t = tangential velocity at radius r, in feet per second.
V_{tp} = tangential velocity at r_p, in feet per second.
r_p = radius confining structure, in feet.
r = radius, in feet.
n = exponent, dimensionless.

If $\frac{r}{rp} = r_f$, the ratio of the radius of rotation to the radius of the confining structure, equation (1) reduces to:

$$V_t = \frac{V_{tp}}{r_f^n} \qquad (2)$$

In an ideal gas, n would equal 1. Real values of n are less than 1, and at ordinary temperatures are greater than 0.5.

Alexander[23] presents an equation evaluating n for air at 10 C, as follows:

$$n = \frac{(24 r_p)^{0.14}}{2.5} \qquad (3)$$

For variations in gas temperature, he found n to vary as:

$$\frac{1 - n_T}{n_o} = \left(\frac{T_k}{283}\right)^{0.3} \qquad (4)$$

Where:

n_T = value of n at T Kelvin.
n_o = value of n at 283 K (10 C).
T_k = temperature, in degrees Kelvin.

Values of n computed from equations (3) and (4) are presented in Fig. 2. Individual values of n reported by other investigators are:

Shepherd and Lapple[13]	0.5
Stairmand[30]	0.5
Ter Linden[31]	0.52
Prockat[37]	0.7
First[16]	0.88

There is radial gas flow in the outer vortex zone. There has been much theory propounded on this point but little experimental measurement. The simplest theory, that of Feifel[14] for a simple cyclone with no gas-outlet extension into the body, assumes "sink" flow radially inward from inlet to outlet superimposed on tangential vortex flow. Unfortunately, however, the use of an outlet-duct extension into the cyclone body, and the presence of space below and above the inlet into which gas can flow, causes radial velocity to vary in a manner presently defying mathematical statement.

Radial velocity has been measured in a conventional cyclone with air and in a hydraulic cyclone with water. In the hydraulic cyclone the customary underflow (downflow through bottom of cone) was suppressed. Typical radial velocity profiles based on these findings show that from r_p to some intermediate radius there is inward radial velocity, but from the intermediate radius to the axis there is outward radial velocity (Fig. 4).

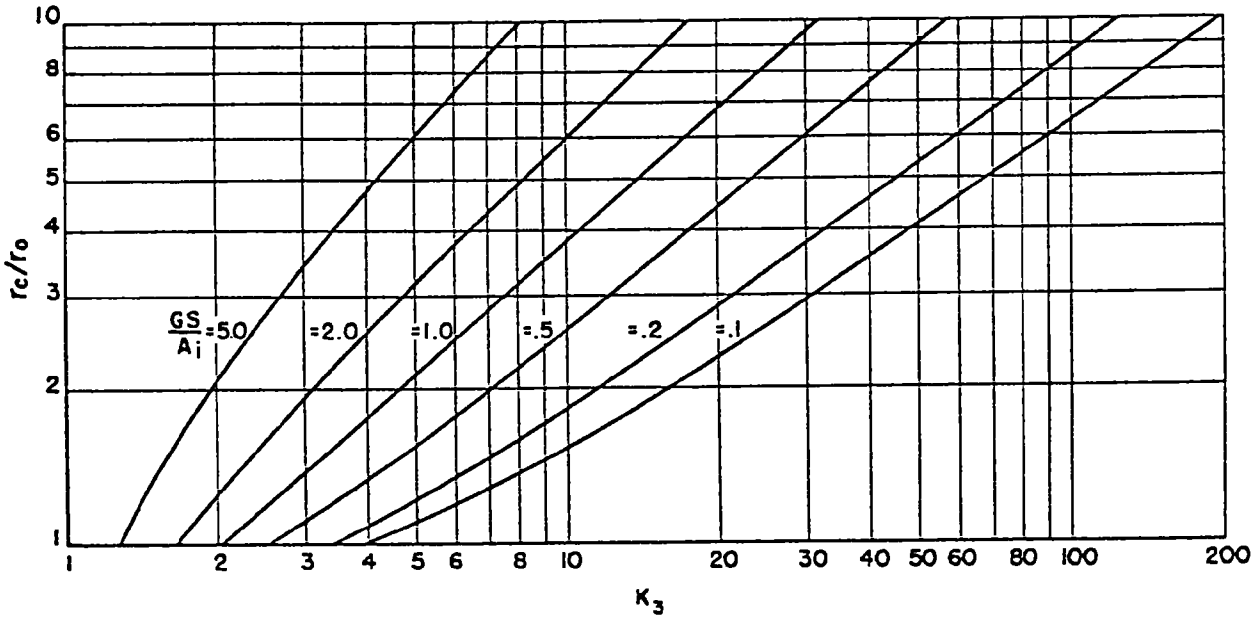
1.212 FLOW IN VORTEX CORE: Flow in the vortex core follows the equation:

$$V_t = Kr^q \qquad (5)$$

Where:

K = proportionality constant varying with V_p, r_m, and n.
q = velocity exponent.

[a] Figures refer to REFERENCES on p. 66.



Values of K_3 [See Equation (17)].

FIG. 6

and its helical pitch about 10.5 r_o. In extremely long cyclones, the eccentricity has been observed up to 50 r_o before disappearing.

As will be shown later (Sect. 2.31), cyclones of common design have a "natural length" on the order of 10 to 15 r_o.

At the vortex base there is a region of considerable turbulence and reversal in direction of axial flow, with a likelihood that the core eccentricity will bring this region into close proximity with, or in actual contact with, already-separated dust at the cyclone wall. It is for this reason that much attention should be devoted to the design of dust discharge, purge, and the like.

1.22 *Separation of Particles*

Particulate matter is separated from gas in a cyclone by centrifugal force, or radial force, tending to drive the particles (against the resistance of motion by the gas) to the cyclone wall. The radial force imparted to the particle is:

$$F_s = \frac{m_p V_p^2}{gr} \tag{6}$$

Where:

F_s = radial separating force, in pounds.
m_p = particle mass, in pounds.
V_p = tangential velocity of particle, in feet per second.
g = gravitational constant = 32.2 ft per sec per sec.

The tangential velocity of the particle is theoretically lower than that of the gas in which it is suspended; but, in considering fine particles, the two velocities are equal for all practical purposes and $V_p = V_t$. By combining equations (2) and (6):

$$F_s = \frac{m_p V_{tp}^2}{gr\, r_t^{2n}} \tag{7}$$

which has a maximum value:

$$F_{sm} = \frac{m_p V_{tm}^2}{g r_m r_{tm}^{2n}} \tag{8}$$

Where:

r_{tm} = radius ratio at r_m, dimensionless.
V_{tm} = maximum tangential velocity (at r_m), in feet per second.

The value m_p in the preceding equations is proportional to the cube of the particle diameter, thus:

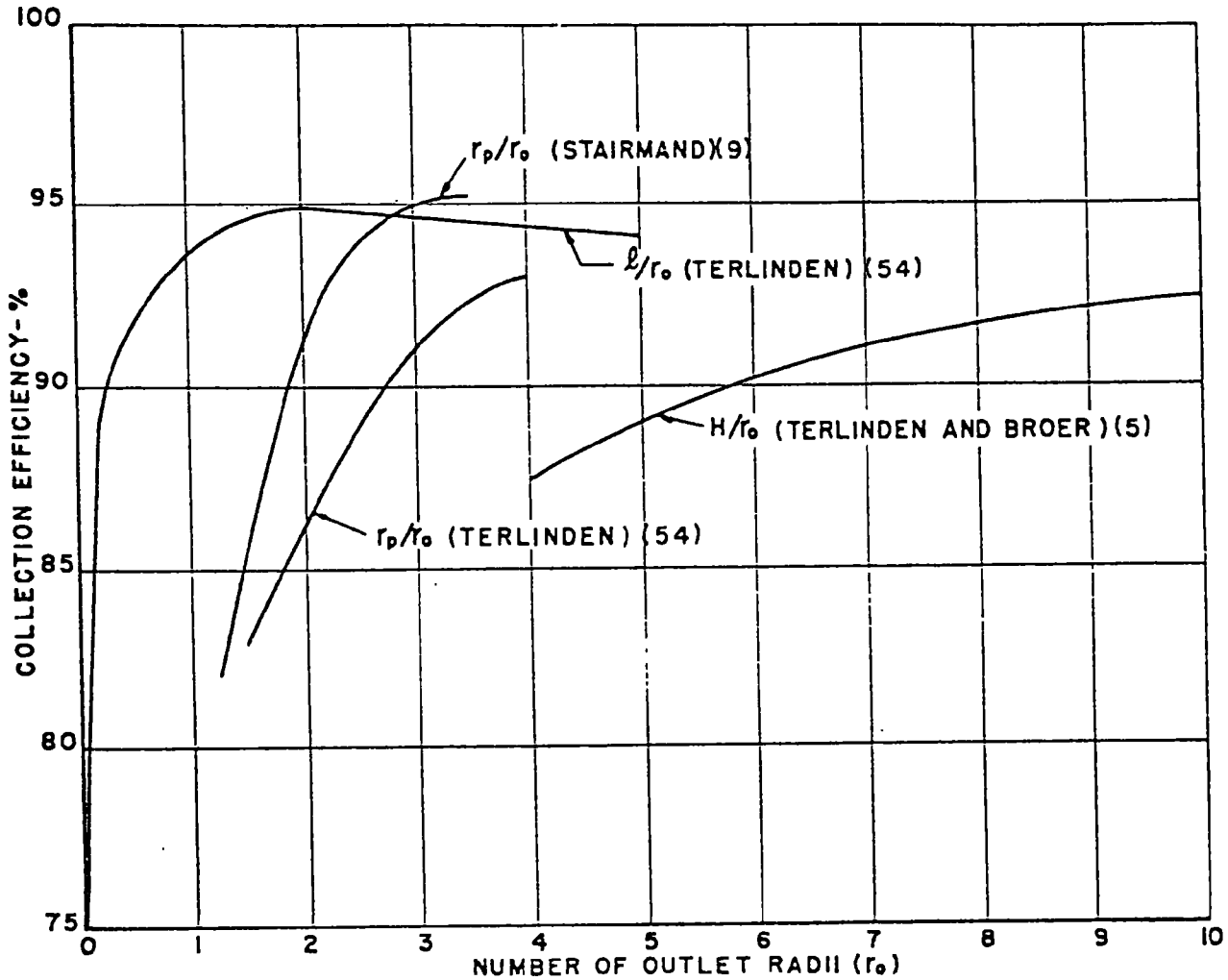
$$m_p = \beta \rho_p D_p^3 \tag{9}$$

Where:

β = volume shape factor, dimensionless.
ρ_p = particle density, in pounds per cubic foot.
D_p = particle diameter, in feet.

The separating force [equation (7)] becomes:

$$F_s = \frac{\beta \rho_p D_p^3 V_{tp}^2}{gr\, r_t^{2n}} \tag{10}$$



Dimension Ratios and Efficiency.

FIG. 7

It can be shown[26] that the force ("Stoke's Law force") resisting motion of a particle through a gas in the range of particle diameters from 3 to 100 microns is:

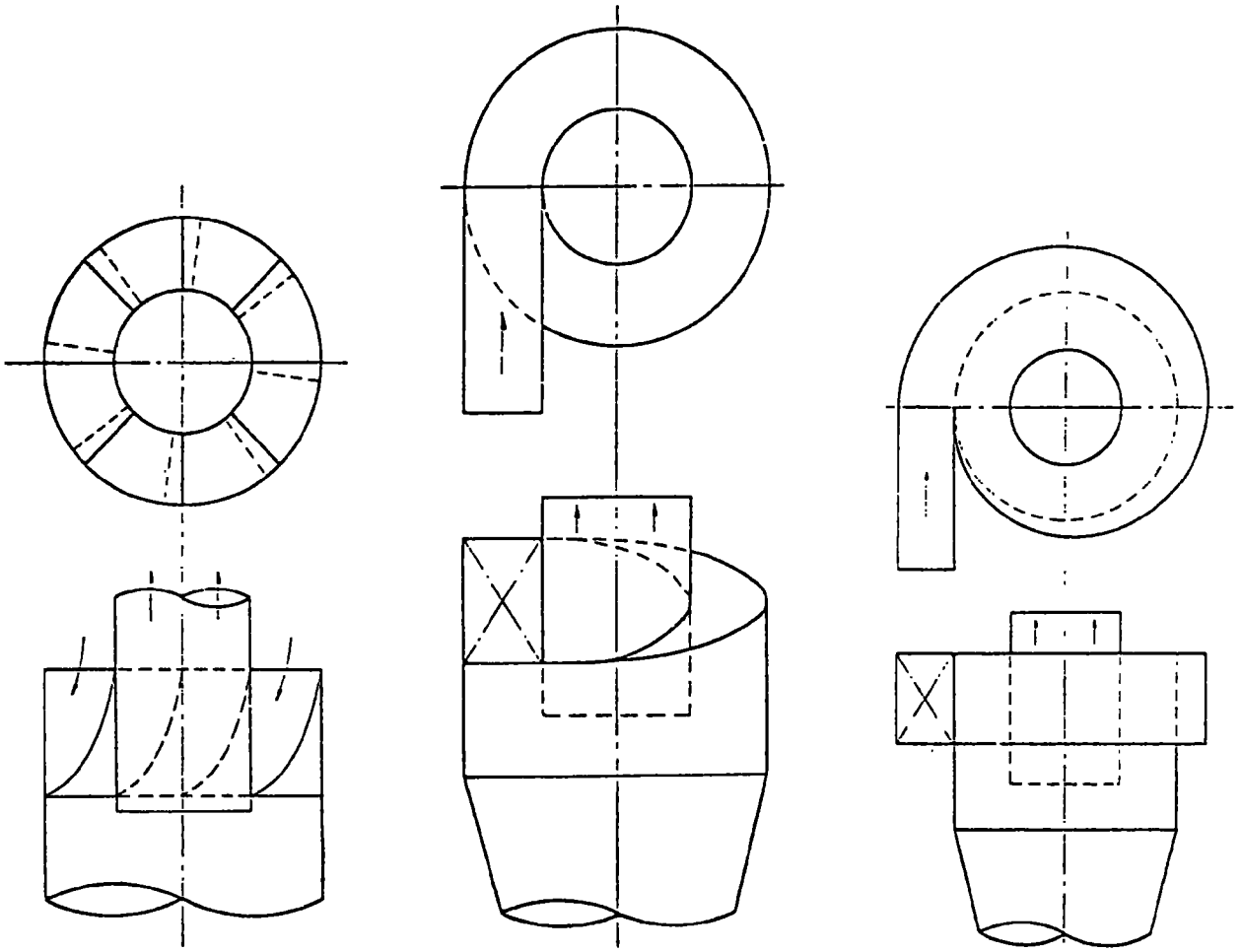
$$F_r = K_2 u D_p \mu \qquad (11)$$

Where:

F_r = frictional resistance to flow, in pounds.
K_2 = proportionality constant, dimensionless.
u = particle velocity with respect to gas, in feet per second.
μ = gas viscosity, in pounds per second per foot.

Comparison of equations (10) and (11) shows that the separating force varies with the cube of the particle diameter, whereas the resistance to flow varies only linearly. Thus large-diameter particles have a greater ratio of separating force to opposing force and are, therefore, more readily separated in a cyclone.

The velocity u of the particle with respect to the gas includes the radial as well as tangential components of gas flow (Sect. 1.211). The assumption of Feifel allows the computation of a "critical particle size" (D_{cr}) for any radius of rotation. D_{cr} may be considered the largest size of particle which is not separated from the gas stream. On the basis of this simplifying assumption, D_{cr} could be computed for r_o, and all particles larger than D_{cr} would be collected while all smaller particles would be lost into the outlet duct.



Cyclone Inlets.
FIG. 8

In fact, however, the radius at which a particle may be considered lost to the exit gases is not constant because the radial gas velocities vary along the axis of the cyclone. Since the radial velocity pattern has not yet been mathematically stated, there can be no reliable computation of critical particle size. In actual practice, the presence of the gas-outlet extension, the finite width of the entering gas stream, the random distribution of particles of various sizes across this width, the presence of major eddy currents, etc., all further obviate the value of any such theoretical computation.

Even were such a computation possible, it would be found that not one, but a series of critical sizes would be obtained for various increments of cyclone length and from one side to the other of the inlet. Therefore, it follows that a cyclone must be, and is, a poor classifier and does not make a sharp-size cut between particles separated and rejected. The cyclone has a curve rather than a straight line as its particle size-efficiency characteristic. Qualitatively, the predominant requirements for high collection efficiency of fine particles are that r_{fm} and r_m be low and V_{tm} high.

A number of authors have derived equations for D_{cr}, as shown in Table I. No critical evaluation has been made which would show one equation more nearly correct than another. The main value is to demonstrate the parameters involved and their qualitative relationships.

1.23 *Discharge of Separated Dust*

The separation of the dust from the gas stream is, in practical terms, only the first step

TABLE I

Formulae for Critical Particle Size

Reference	Formula	Special Units: Remarks
Davies[9]	$D_{cr} = a_{min} = \sqrt{\frac{9\mu r_p^2}{8(\rho_p - \rho) V_i H}\left[1 - \left(\frac{r_v}{r_p}\right)^4\right]}$	a_{min} = particle size above which efficiency will be 100 per cent in absence of re-entrainment.
Gardiner[63]	$D_{cr} = \sqrt{\frac{9\mu(D - d_o)}{2\pi N V_i(\rho_p - \rho)}}$	μ = viscosity, in pounds per second per foot.
Lapple[65]	$D_{cp} = \sqrt{\frac{9\mu W_i}{2\pi N_e V_i(\rho_p - \rho)}}$	μ = viscosity, in pounds per second per foot. D_{cp} = cut size, collected at 50-per-cent efficiency. N_e = "effective" number of turns in cyclone = 5 to 10 for typical cyclone (Sect. 2.31).
Shepherd[30]	$D_{cr} = \sqrt{\frac{9\mu d_o}{2\pi N V_i(\rho_p - \rho)}}$	μ = viscosity, in pounds per second per foot. For N, see reference.
Muhlrad[31]	$D_{cr} = \sqrt[3]{\frac{3g\mu D^2}{\pi\rho_p V_i r_v N}\left(\frac{1 - w^4}{1 + w + w^2}\right)}$	$w = \frac{do}{D}$. All units metric—see reference.
Rosin, Rammler, and Intelmann[38]	$D_{cr} = 3\sqrt{\frac{g\mu Y}{\pi\rho_p V_i N}\left(1 - \frac{Y}{D}\right)}$	$Y = \frac{D}{2} - r$ = instantaneous distance of particle from cyclone wall. All units metric—see reference.
Tarjan[33]	$d_{min} = \sqrt{\frac{9gA_i r}{\pi H_i V_i^2 r_p^2 \rho_p}}$	d_{min} = particle diameter at "blocking radius r." r = "blocking radius."

in a series intended to result in solids or liquid at rest in a container, and a gas stream cleaned of particulates to the desired degree. The concentrated dust layer swirling slowly (compared to the vortex) down the walls of the cyclone body must be conducted into the dust hopper, or its equivalent, with a minimum of re-entrainment into the base of the vortex. Factors affecting re-entrainment are:

a. The length, eccentricity, and diameter of the vortex core and its relation to the cyclone body walls.

b. The presence or absence of purge flow outward from the dust outlet.

c. Recirculation of gas, or infiltration of air, into the dust outlet.

d. Presence or absence of an air-lock material discharge valve or dip-leg.

e. Smoothness of the inner walls of the cyclone.

The two major types of discharge are axially through a core and peripherally. Both methods may be used with or without purge gas, or with various types of mechanical accessories. These methods, and their effect on efficiency, will be discussed in later sections.

The dust in the gas stream which escapes into the outlet duct tends to be concentrated toward the walls of the duct. Therefore, various devices for skimming off the outer layers of this vortex have an effect also on the overall performance of a cyclone.

1.30 Scope of the Cyclone in Field Use

1.31 *Typical Operating Ranges*

Cyclone collectors, as a class, are regarded as the lowest in first cost of equipment convention-

ally used for dust or droplet collection. They also, as a class, provide lower collection efficiency than other types of equipment, although there are, of course, exceptions to this generality. They are suitable for medium and coarse dusts and are unsuited for very fine dusts or metallurgical fumes. They have advantages, however, in that there are no moving parts, choice of materials of construction is wide, and maintenance costs are low. Power requirements (if reasonable efficiency on fine dust is required) are as high as, or higher than, most other types of equipment, although some types of wet scrubbers have even higher requirements.

1.32 *Efficiency in Field Use*

A clarification in terminology regarding efficiency will aid in this and later general discussions. Efficiency brackets are arbitrarily set as follows:

Collection Efficiency (Per Cent by Weight)	Efficiency Range	Amount Passing Collector (Per Cent)
Above 50 to 80	Low	Above 20 to 50
Above 80 to 95	Medium	Above 5 to 20
Above 95 to 99	High	Above 1 to 5
Above 99 to 99.99	Very high	Above 0.01 to 1
Above 99.99	Ultra high	Less than 0.01

On this basis, most cyclones as applied operate in the low and medium efficiency ranges. A well-designed but otherwise conventional cyclone may be expected to provide high efficiency for coarse particulate matter of the 40- to 50-micron diameter range; and small-diameter (less than 1-ft) "high efficiency" types may extend the high-efficiency range to particles as small as 15- to 20-micron sizes. Typical efficiency ranges for various particle size ranges are as follows:

Particle Size Range (Microns)	"Conventional" Cyclone Efficiency Range	"High Efficiency" Cyclone Efficiency Range
Less than 5	—	Low
5 to 20	Low	Medium
15 to 50	Medium	High
Greater than 40	High	High

For various practical reasons, efficiencies in the very high or ultra-high range are almost never achieved on industrial aerosols by cyclones.

1.33 *Pressure Drop in Field Use*

The loss in pressure of the gas stream flowing through a cyclone depends on a number of variables but, in practice, is usually found to be on the order of 1 to 4 inlet velocity heads. With velocities commonly used for handling dusty air, the velocity head will range from ¼ to 3 in., water gage. Thus the range of resistance would be from ¼ to 8 in., water gage. Where ordinary centrifugal blowers are used as the source of motive power for the air, a practical upper limit of resistance for the cyclone plus other system components is in the range of 15 to 16 in., water gage, although with other types of motive equipment this upper limit may be considerably higher. Efficiency increases with inlet velocity, as will be shown later, but at a lower rate than the pressure drop increases. Furthermore, for any given cyclone and dust combination, there is an inlet velocity beyond which turbulence increases more rapidly than separation, and efficiency begins to decrease. Thus, even aside from power cost considerations, there is little purpose in further increases in resistance. Most cyclones will be found to have from 2- to 7-in., water gage, resistance as operated.

1.34 *Dust Loading in Field Use*

There appears to be almost no practical upper limit of dust loadings to a properly designed cyclone. A cyclone can be designed to handle any amount of material which can be moved by gas flow and, in general, cyclone efficiency increases with increasing dust load. Since this ability is not possessed by many other types of collectors of inherently higher efficiency, cyclones are frequently used as precleaners for other types when dust loadings are too heavy for the secondary collector.

Conversely, cyclone efficiency decreases with decreasing dust load, and other types of collectors are well able to handle the lighter loads alone at higher efficiencies. As a result, cyclones are usually applied to dust loadings of 10 grains per cu ft or higher, and seldom are used below 1 grain per cu ft, unless the dust is unusually coarse or other factors of temperature, corrosion, and the like are overriding in importance.

1.35 *Range of Capacities*

Commercial cyclones are built in sizes having individual capacities of 30 to 30,000 cu ft per min. In general, the smaller units are more efficient but must be used in parallel to accommodate practical gas volumes.

1.36 *Range of Physical and Chemical Conditions*

Cyclones, as a class, can be designed to handle a wider range of chemical and physical conditions of operation than any other type of collection equipment. Any conditions of temperature, pressure, and corrosion for which structural materials are available can be met by a cyclone.

Erosion is sometimes troublesome, and some materials of construction necessary for temperature or corrosion conditions may not be especially desirable in erosion resistance.

The main limiting factor in conditions of cyclone application is the physical characteristic of the dust. A sticky, hygroscopic, or similar material may give difficulty in cyclone operation, and such materials are sometimes handled in cyclones operated wet, or in "wet collectors." Dusts which have a bad tendency to bridge, hang up, or cake may give difficulty at the dust outlet of small-diameter cyclones.

2.00 EFFICIENCY AND PRESSURE DROP

2.10 General Considerations of Efficiency

For high efficiency, the separating forces should be high, the number of gas revolutions large, the tangential velocity high, and the dust removal effective so that separated dust is not re-entrained.

Considerations governing the critical particle size D_{cr} have been presented previously. Since the particle size-efficiency performance of a cyclone is a curve rather than a straight line, there is no direct mathematical relation between efficiency η and D_{cr}. However, in a qualitative sense, those parameters tending to increase D_{cr} should decrease η for a given dust size distribution, and vice versa.

By inspection of Table I, it may be seen that efficiency will increase with an increase in the following:

Dust-particle density ρ_p.
Inlet velocity V_i.
Cyclone-body length H.
Number of gas revolutions N.
Ratio $\frac{D}{do}$.
Dust-particle size D_p.

Similarly, efficiency will decrease with an increase in the following:

Gas viscosity μ.
Cyclone diameter D.
Gas-outlet-duct diameter d_o.
Increase in inlet width W_i.
Inlet area A_i.
Gas density ρ.

Efficiency is also affected by various accessory devices not included in the mathematical relationships in Table I. It is obviously desirable to have smooth inner surfaces in the cyclone body in order to minimize projection of separated dust out into the air stream.

2.20 General Considerations of Pressure Drop

For a given cyclone handling clean air, the resistance varies with the square of the air volume Q, or similarly with the square of the inlet velocity V_i. Since the expression for velocity pressure h_v of a gas is:

$$h_v = 0.0030\rho V^2, \qquad (12)$$

h_v similarly varies with the square of the velocity. It therefore becomes convenient to express cyclone pressure drop in terms of number of inlet velocity heads, h_n, thereby making such equations independent of gas volume and inlet velocity.

It will be apparent from later discussion that a satisfactory method for predicting pressure drop from cyclone dimensions over a wide range of construction has not yet been developed. Pressure drop should preferably be determined experimentally on a geometrically similar prototype.

Most investigators agree that cyclone resistance is a function of gas-inlet area and outlet area of the form:

$$h_n = X\left(\frac{H_i W_i}{d_o^2}\right)^z \qquad (13)$$

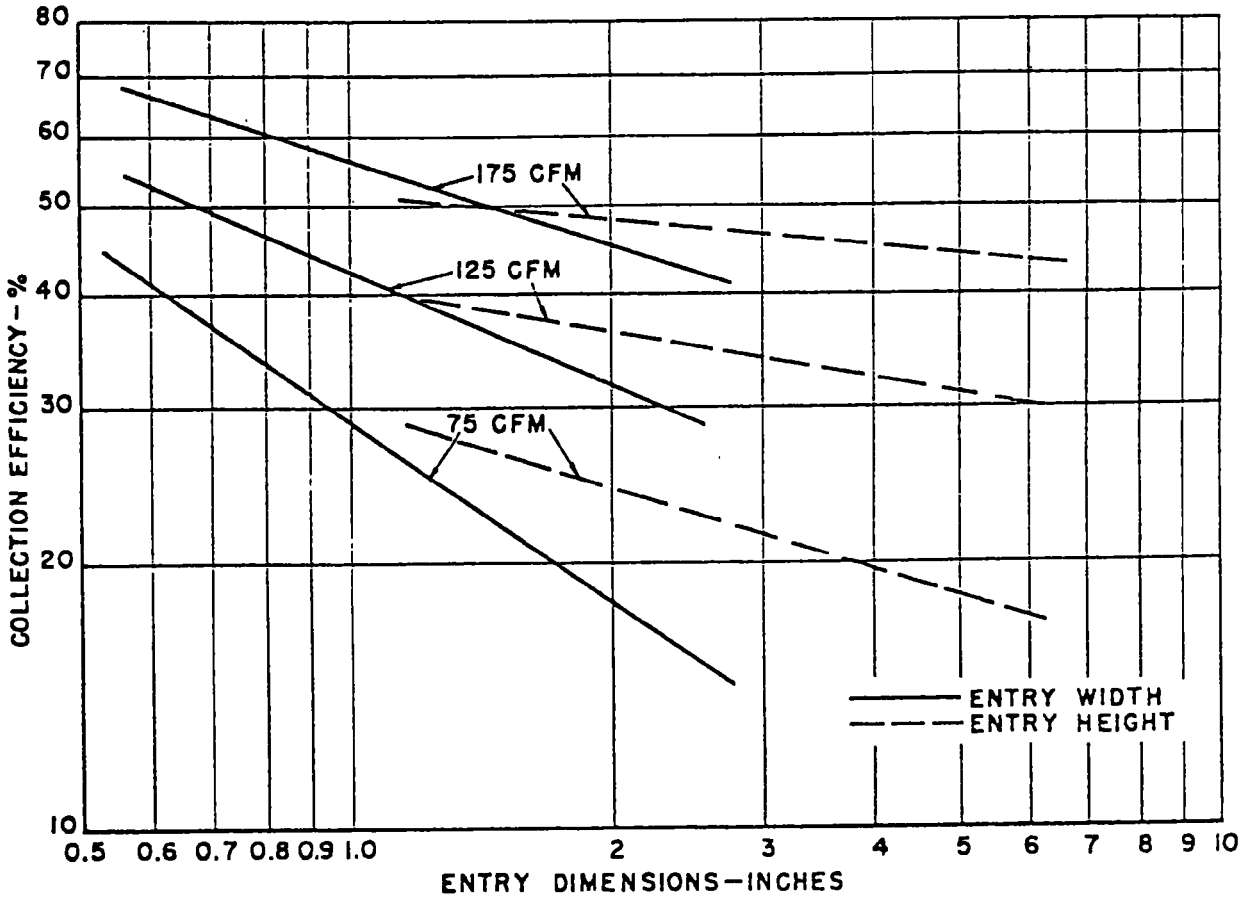
Where:

X = proportionality constant, dimensionless.
H_i = inlet height, in feet.
W_i = inlet width, in feet.
d_o = outlet diameter, in feet.
z = exponent, dimensionless.

Values for X are given as follows:

a. Ter Linden[66] states that for common cyclones with straight tangential inlets without inlet vanes $z=1$ and X is between 25 and 32, but that for involute inlets both z and X are lower. For a 180-deg involute inlet his data show $X=21.7$ if $z=1$ (Fig. 10).

b. Lapple[67] gives a value for X of 18.4 for a 360-deg involute inlet.



Entry Dimension Vs. Efficiency.

FIG. 9

c. For a cyclone having dimension ratios $\frac{r_p}{r_o}=$ 2 to 4, $\frac{H}{r_o}=8$, $\frac{l}{r_o}=6$, Shepherd and Lapple[43, 44] reported $z=1$ and $X=16$ without inlet vane, and 7.5 for an inlet vane which neither expanded nor contracted the entering gas and did not touch the outlet (a "neutral" vane). They also found that variations in $\frac{l}{r_o}$ from 6 to zero had no effect on X.

d. First[17] found that a reduction in $\frac{l}{r_o}$ from 2 to zero caused a 10-per-cent decrease in X $\left(\frac{r_p}{r_o}=2 \text{ and } \frac{H}{r_o}=5.8\right)$. In cyclones with $\frac{r_p}{r_o}=2$ and $\frac{l}{r_o}=2$ but with $\frac{H}{r_o}$ variable, First concluded that $z=1$, and derived an expression for X, as follows:

$$X=\frac{\frac{12}{Y}}{\left(\frac{L}{D}\right)^{\frac{1}{2}}\left(\frac{M}{D}\right)^{\frac{1}{3}}} \qquad (14)$$

Where:

Y = 0.5 for no inlet vane;
= 1.0 for neutral inlet vane;
= 2.0 for inlet vane that expands entering gas stream and touches outlet duct.
L = cyclone-cylinder length, in feet.
M = cyclone-cone length, in feet.
D = cyclone-body diameter, in feet.

Alexander[2] concluded that $z=1$, and derived an expression for X, as follows:

$$X=4.62\frac{r_o}{r_p}\left\{\left[\left(\frac{r_p}{r_o}\right)^{2n}-1\right]\left(\frac{1-n}{n}\right)+f\left(\frac{r_p}{r_o}\right)^{2n}\right\}, \qquad (15)$$

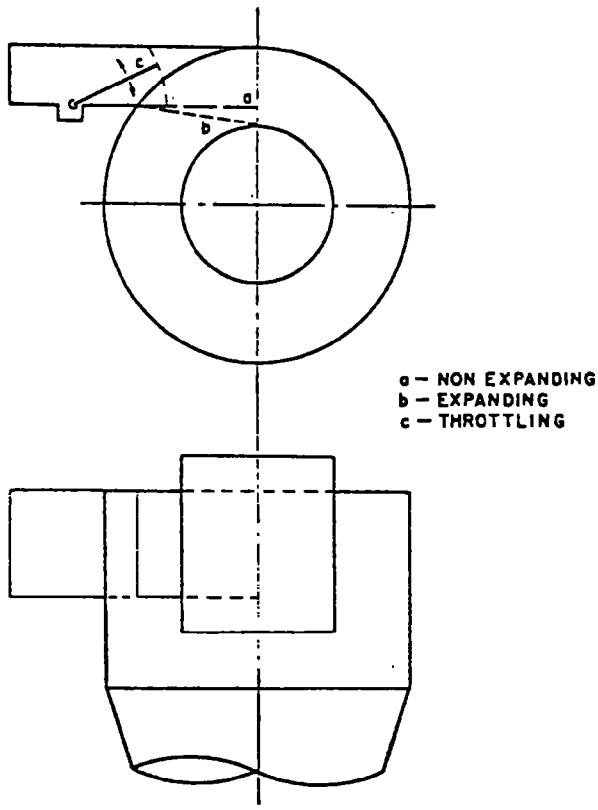
where f varies with n as follows:

n	0	0.2	0.4	0.6	0.8
f	1.90	1.94	2.04	2.21	2.40

Values of Alexander's function for X are plotted in Fig. 5. For values of n, see Fig. 2.

Stairmand has derived a theoretical expression for h_n, as follows:

$$h_n=K_3+3.24\left(\frac{A_i}{4r_o^2}\right)^2, \qquad (16)$$



Inlet Vanes.

FIG. 10

where:

$$K_3 = 1 + 2\left(\frac{V_{tc}}{V_i}\right)^2 \div \left(\frac{2r_c}{r_o} - 1\right) \qquad (17)$$

See Table II for computed values of $\frac{V_{tc}}{V_i}$, and Fig. 6 for plots of equation (17).

The effect on X of variations in $\frac{r_p}{r_o}$ and $\frac{H}{r_o}$ was investigated by Ter Linden and reported by Broer[5] as the following multiplying factors for correcting X:

$\frac{r_p}{r_o}$	Factor	$\frac{H}{r_o}$	Factor
1.5	0.91	4	1.17
2.0	1.00	6	1.08
2.5	1.08	8	1.00
3.0	1.19	10	0.96

A test of the results of these various equations has shown those based on equation (13) to have a higher order of reliability than those of equation (16); and, further, indicates that the exponent 2 in equation (16) is probably too high.

A summary of factors for application to equation (13) is presented in Table III.

An attempt has been made to analyze the

TABLE II

Calculated Values of $\frac{V_{tc}}{V_i}$ from Equation (20)

Ratio $\frac{r_c}{r_o}$ \ Ratio $\frac{GS}{A_i}$	0.10	0.20	0.50	1.0	2.0	5.0
	Calculated $\frac{V_{tc}}{V_i}$					
1	1.21	1.08	0.87	0.71	0.55	0.38
2	1.53	1.31	1.00	0.78	0.59	0.40
5	1.95	1.58	1.13	0.85	0.63	0.42
10	2.24	1.75	1.21	0.89	0.65	0.43
20	2.47	1.88	1.27	0.92	0.67	0.43

validity of equations (14) and (15), and the values cited by Shepherd and Lapple,[43, 44] by comparing calculated values of X with measured values of X. Three sets of data were available and are presented in Table IV. Group A was reported by Stairmand,[43] Group B by Stern,[51] and Group C represents field survey data previously unpublished. Since the three groups of data probably involve differences in the point and method of measuring static pressure, and it is known that in Group C it was not possible to determine the presence or absence of internal accessories, the three groups were analyzed separately.

Calculated X shows a large deviation from measured X in all three groups of data. The constant 16 proposed by Lapple gives less deviation for Groups A and C, while the Alexander equation gives lowest deviation for Group B. The data were further subjected to analysis of variance ratio,[10] with the result that, for Group A, all three methods of computation were found equally reliable; for Groups B and C, the Alexander method and the Lapple constant were equally reliable, while the First method was less reliable. For Groups A, B, and C as a whole, the Alexander and Lapple values were equally reliable, while the First method was less reliable. The results of this analysis may be summarized as follows:

Data Group	Best Method	Equally Good Methods
A	Lapple	First, Alexander
B	Alexander	Lapple
C	Lapple	Alexander
A, B, C	Lapple	Alexander

This analysis shows a constant value for X to be equally as good as, if not better than, equations for computing X based on cyclone-dimension ratios. It seems only reasonable to assume, however, that dimension ratios will affect X; in fact, this is proposed by the same authors who advocate a "constant" value (Table III).

TABLE III

Pressure-Drop Factors for Equation (13)

Source	$\frac{r_p}{r_o}$	$\frac{H}{r_o}$	$\frac{l}{r_o}$	Special Conditions	z	X
Ter Linden[64]	2	8	—	No inlet vane	1	25 to 32
	2	8	—	180-Deg involute inlet	1 (Assumed)	21.7
Lapple[67]	1.62 to 3.25	—	1 (Approximately)	360-Deg involute inlet, step-tapered body	—	18.4
Shepherd and Lapple[43, 44]	2 to 4	8	6	No inlet vane	1	16
	2 to 4	8	6	Neutral inlet vane	1	7.5
Broer[6]	1.5 to 3.0	4 to 10	—	No inlet vane	—	See text for X correction factors
First[17]	2	Variable	2	Y = 0.5 no inlet vane; = 1.0 neutral inlet vane; = 2.0 expanding inlet vane	1	$X = \frac{\frac{12}{Y}}{\left(\frac{L}{D}\right)^{\frac{1}{3}}\left(\frac{M}{D}\right)^{\frac{1}{3}}}$
Alexander[2]	—	—	—	—	1	$X = 4.62\frac{r_o}{r_p}\left\{\left[\left(\frac{r_p}{r_o}\right)^{2n} - 1\right]\frac{1-n}{n} + f\left(\frac{r_p}{r_o}\right)^{2n}\right\}$ (Fig. 5)
Lapple[67]	2	8	1.25	No inlet vane	—	8

TABLE IV

Analysis of Calculation Methods for X

Cyclone Diameter D (Feet)	Gas-Outlet Diameter d_o (Feet)	Gas-Outlet Extension l (Feet)	Cyclone Body L (Feet)	Cone Length M (Feet)	Inlet Height H_i (Feet)	Inlet Width W_i (Feet)	X Measured	Calculated Values of X: First [17]	Calculated Values of X: Alexander [8]	Calculated Values of X: Lapple [6, 4]	Deviations from Measured X: First	Deviations from Measured X: Alexander	Deviations from Measured X: Lapple
							Group A						
2.00	1.00	3.00	4.00	4.00	0.50	0.25	27.0	15	14	16	12.0	13.0	11.0
2.00	1.00	3.00	4.00	4.00	1.00	0.50	11.0	15	14	16	4.0	3.0	5.0
5.00	2.50	7.50	10.00	10.00	3.00	1.25	17.0	15	16	16	2.0	1.0	1.0
5.00	2.50	7.50	10.00	10.00	2.50	1.25	12.5	15	16	16	2.5	3.5	3.5
3.00	1.50	—	6.00	6.00	1.50	0.75	16.6	15	15	16	1.6	1.6	0.6
2.84	1.00	0.50	4.50	—	3.50	0.25	22.0	17.5	17.5	16	4.5	4.5	6.0
0.67	0.21	0.33	1.08	—	0.33	0.10	13.5 to 16.6	17.5	13	16	2.5	2.0	1.0
0.67	0.33	0.33	1.08	—	0.33	0.10	16.6 to 17.4	17.5	12.5	16	0.5	4.5	1.0
0.67	0.21	0.33	0.75	—	0.67	0.17	16 to 20	22	13	16	4.0	5.0	2.0
0.67	0.33	0.33	0.75	—	0.67	0.17	14.0	22	12.5	16	8.0	1.5	2.0
									Mean		4.2	4.0	3.3
							Group B						
0.98	0.38	0.83	0.46	1.46	0.25	—	11.5	27	14	16	15.5	2.5	4.5
1.00	0.50	1.17	1.33	1.85	0.62	0.23	6.5	18	13	16	11.5	6.5	9.5
0.67	0.38	—	0.44	0.97	0.25	—	8.1	24	12	16	15.9	3.9	7.9
1.33	0.75	0.31	1.17	0.0	0.33	—	19.8	26	12.5	16	6.2	7.3	3.8
1.58	0.83	1.00	0.62	2.16	0.50	—	12.3	29	13.5	16	16.7	1.2	3.7
0.75	0.43	0.67	0.98	1.48	0.50	0.25	9.1	18	12	16	8.9	2.9	6.9
1.10	0.62	1.00	1.50	1.50	0.67	0.35	11.9	20	12.5	16	8.1	0.6	4.1
									Mean		11.8	3.6	5.8

Group C																	
6.33	3.00	—	3.75	9.67	2.34	0.75	6.2	25	17	16	18.8	10.8	9.8
3.50	1.08	—	1.58	3.25	1.50	0.42	11.2	32	18	16	20.8	6.8	4.8
4.00	1.58	—	1.92	4.33	1.25	0.50	33.6	30	17	16	3.6	16.6	17.6
4.00	1.25	—	1.83	3.67	1.33	0.42	2.7	32	18	16	29.3	15.3	13.3
4.50	1.21	—	2.00	4.17	1.50	0.42	4.6	32	19	16	27.4	14.4	11.4
5.00	1.66	—	2.33	4.67	1.75	0.50	6.0	32	19	16	26.0	13.0	10.0
8.50	3.42	—	4.17	7.75	3.58	0.92	20.8	31	18.5	16	10.2	2.3	4.8
6.50	2.33	—	2.92	6.08	2.50	0.67	9.3	32	19	16	22.7	9.7	6.7
8.33	4.00	—	5.00	8.25	3.08	1.00	5.8	28	17	16	22.2	11.2	10.2
5.50	2.00	—	2.42	5.17	2.00	0.58	2.1	32	18	16	29.9	15.9	13.9
3.16	2.08	—	2.46	5.83	1.75	0.50	25.6	21	13	16	4.6	12.6	9.6
5.00	1.67	—	2.17	4.67	1.75	0.50	30.4	32	19	16	1.6	11.4	14.4
Mean											18.0	11.7	10.5
Total mean											11.8	7.1	6.9

It can only be concluded that a really satisfactory method for predicting cyclone pressure drop from cyclone dimensions over a wide range of construction has not yet been presented.

At the present state of the art, the best method of determining the pressure drop of a proposed cyclone is to depend on the measured pressure drop of a geometrically similar prototype, rather than to rely on a computed value.

2.30 Design Factors Affecting Pressure Drop and Efficiency

2.31 *Diameter and Dimension Ratios*

As has been described generally, the cyclone-diameter, inlet, and gas-outlet dimensions are of primary importance in efficiency and pressure-drop consideration.

A study has been made of 23 families of geometrically similar cyclones. The consensus design—the "average" dimension ratios of these families—is presented not as having any particular virtue, but as representing typical present practice, and thus serving as a starting point for discussion of variations in design. A widely recommended typical cyclone[15] has the following similar proportion ratios:

Cyclone Element	Ratio: Element / d_e — Consensus	Ratio: Element / d_e — Typical[15]
Body diameter D.....	2.0	2.0
Cylinder length L.....	1.5	4.0
Cone length M.....	2.5	4.0
Total length H.....	4.0	8.0
Outlet length l.....	1.25	1.25
Inlet height H_i.....	0.9	1.0
Inlet width W_i.....	0.4	0.5

A higher-efficiency (and higher-pressure-drop) design would have a larger length ratio, a smaller inlet-width ratio, and a larger body-diameter ratio with smaller body diameter.

The length of the cyclone body is of importance. Gas can be considered as flowing to the gas outlet from the main vortex zone through an imaginary cylindrical extension of the gas outlet down to the bottom of the cyclone, or to its intersection with a conical bottom. The area of this cylinder increases with the length of the main vortex zone. The mean inward gas velocity past it decreases with such increasing length. Since this mean inward gas velocity is one force opposing particle motion to the periphery, it follows that increasing length of the

TABLE XVII

Costs of Cyclone Dust Collectors

Size (Cubic Feet Per Minute)	Cost (Cents Per Cubic Foot Per Minute)					
	Kane[21] (1952)		Dallavalle[60] (1953)		Dorfan[61] (1950)	
	Standard	High-Efficiency	Light-Duty	Heavy-Duty[a]	Simple	Multiple
1,000	20	37 to 53	15	50	10	15
5,000	10	20 to 35	8	30	8	14
10,000	9	15 to 32	7	25	7	11
50,000	9	12 to 30	7	25	5	7
100,000	—	12 to 30	—	—	—	—

[a] Includes multitube units. Manifolding banks of multitube units may raise the cost to 60 cents per cubic foot per minute.[50]

efficiency collection is economical at dust loadings on the order of 1.0 grains per cu ft or greater. Cyclone collectors do not fall in this category, except for very coarse materials. They may still be used on collection of valuable materials, however, if the operating conditions are so rigorous as to preclude use of other, more efficient types.

Power costs will be rated on a pressure drop of approximately 0.25 hp per inch, water gage, per 1,000 cu ft per min.

No generalized data are available on special alloy construction or refractory, erosion-, or corrosion-resistant linings. Thin refractory and erosion linings are frequently estimated at $1 to $2 per square foot.

12.00 PRACTICAL CYCLONE DESIGN OR SELECTION

12.10 Steps in Design or Selection

1. Determine the following:

a. Volume rate of flow of gas and its chemical and physical properties.

b. Dust loading, dust particle size and density, and handling characteristics of dust.

c. Desired efficiency of collection.

d. Special problems of erosion, corrosion, or operational problems.

2. Determine from Sect. 1.32 what general type of cyclone is required.

a. If expected efficiency is lower than desired efficiency, consider other types of equipment if those types will withstand operating conditions.

b. If other types of equipment cannot be used, consider use of series operation, bottom purge, outlet skimmers, wet operation, etc., for improving efficiency.

3. Determine whether a commercial product is to be purchased or a cyclone designed and fabricated by the user. Multitube, small-diameter, "high efficiency" cyclones are generally purchased items.

a. If a commercial product is desired, obtain performance and efficiency data from the following:

Pilot test.
Laboratory test.
Similar experience data.

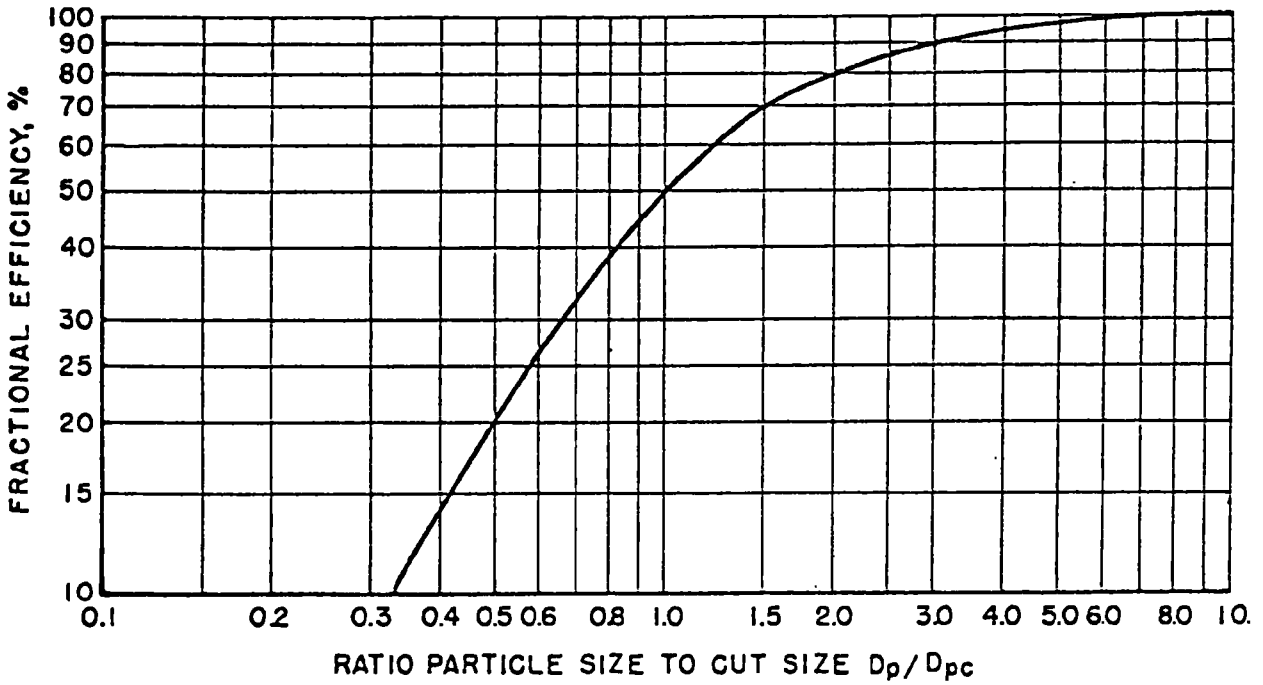
Correct as required to anticipated operating conditions.

b. If a cyclone is to be designed, calculate pressure drop and efficiency for a "typical" unit (Sect. 2.31), with an assumed inlet velocity of 50 ft per sec (normal range, 20 to 70 ft per sec). Efficiency may be evaluated from the curve of Fig. 36 showing efficiency vs. ratio $\frac{D_p}{D_{pc}}$ for this cyclone, and from a calculation of D_{pc} (Table I).

(1) If anticipated efficiency results are better than desired, a lower pressure drop may be obtained by reducing inlet velocity (enlarging the cyclone). Recalculate D_{pc} from new dimensions and check against Fig. 36 for desired efficiency.

(2) If anticipated efficiency results are poorer than desired, increase inlet velocity (reduce cyclone size), provide larger length ratio, smaller inlet-width ratio, larger body-diameter ratio with smaller body diameter, etc. Recalculate D_{pc} from new dimensions and check against Fig. 36 for desired efficiency. Consider the use of the following accessories or arrangements for improving performance:

Parallel operation of smaller units.
Series operation.
Purge from outlet.
Wet operation.



Fractional Efficiency of "Typical" Cyclone (See Sect. 2.31).

FIG. 36

(3) If efficiency is satisfactory but pressure drop too high, consider an outlet drum, etc., for pressure recovery.

4. Make adequate provision for preventing gas flow into dust outlet, positive removal of dust from cone, and prevention of hopper overfilling. In multitube or parallel operation, design to prevent recirculation between tube outlets.

5. If cyclone is to be operated wet, take necessary special precautions.

6. If erosion or fouling is likely, special design is needed. Consider special linings, scouring, etc.

7. If corrosive gases or materials are handled, consider special alloys, linings, wet operation, or prevention of condensation, as may be indicated.

12.20 Field Tests on Fluid Catalytic Crackers

Results of testing full-scale cyclones in fluid catalytic-cracker installations are tabulated in Table XVIII. The operating conditions and lack of access to the cyclones make such testing difficult and account for the missing values in the table for many tests.

Collection efficiency in such service is high, primarily on account of the high dust loadings and large particle size. Note that even with such efficiencies, losses are on the order of tons per day. Cyclones in ordinary service do not provide these high efficiencies.

TABLE XVIII

Field Tests on Full-Scale Fluid Catalytic Crackers [e]

Item No.:	1	2	3	4	5	6	7	8	9
Service	Regenerator	Regenerator	Regenerator	Reactor	Reactor	Regenerator	Regenerator	Regenerator	Regenerator
Number of sets in parallel	6	8	13	5	9	5	6	6	6
Number in series	1	2	2	1	2	3	8	2	2
Cyclone diameter, ft:									
Primary	Footnote [f]	Footnote [f]	3.0	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]
Secondary	Footnote [f]	Footnote [f]	3.0	Footnote [f]	Footnote [f]	3.0	Footnote [f]	Footnote [f]	Footnote [f]
Outlet diameter, ft:									
Primary	Footnote [f]	Footnote [f]	1.67	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	0.83	0.83
Secondary	Footnote [f]	Footnote [f]	1.67	Footnote [f]	Footnote [f]	Footnote [f]	Footnote [f]	0.83	0.83
Inlet conditions:									
Dust load, grains per cu ft at conditions	—	—	2,800	—	—	2,000	4,370	—	—
Mass median size, microns [a]	60 [b]	37 [d]	37 [d]	43 [b]	41 [b]	43 [b]	42 [b]	—	—
	1.9 [b]	1.6 [d]	1.6 [d]	1.5 [b]	1.8 [b]	1.5 [b]	1.0 [b]	—	—
Inlet velocity, ft per sec	—	—	80	—	—	60	78	57	84
Bed conditions:									
Density, lb per cu ft	30.5	27.7	31.9	32.2	40.1	35	32	—	—
Vapor velocity, ft per sec	1.70	2.28	2.33	1.70	1.05	—	—	—	—
Disengaging height, ft	25	22.3	20	25	30	—	—	—	—
Temperature, degrees fahrenheit	—	—	1,000	—	—	1,115	1,115	1,110	1,110
Pressure, psig	—	—	13.0	—	—	8.5	8.4	22.3	16.8
Outlet conditions:									
Load, grains per cu ft STP	—	—	0.85	—	—	0.91	0.50	0.78	0.57
Mass median size, microns [a]	4 [e]	33	—	14	11	12	19	15	—
	3.2 [e]	1.7	—	1.6	1.8	2.3	2.0	1.8	—
Efficiency, per cent by weight	—	—	99.98	—	—	99.976	99.994	—	—
Loss, tons per day	95	12.5	8.5	40	0.8	3.2	3.0	6.5	5.9
Gas volume, cu ft per sec STP	—	—	667	—	—	570	900	1,850	1,170
Remarks	Lined, ¼-in. carbon steel	Unlined, ¼-in. carbon steel	Primary: lined, ¼-in. carbon steel Secondary: unlined, ¼-in. carbon steel	Lined, ¼-in. stainless steel	Lined, ¼-in. carbon steel	Third-stage cyclone same as second-stage	Third-stage cyclone same as second-stage		

[a] Standard geometric deviation.
[b] Catalyst in bed.
[c] Includes Cottrell-precipitator return fines.
[d] Dilute phase 19 ft above dense bed.
[e] Courtesy Pan American Refining Corp., The Pure Oil Co., Union Oil Co. of California.
[f] Dimensions requested of vendors; to be forwarded when received.

REMOVAL OF PARTICULATE MATTER FROM GASEOUS WASTES

ELECTROSTATIC PRECIPITATORS

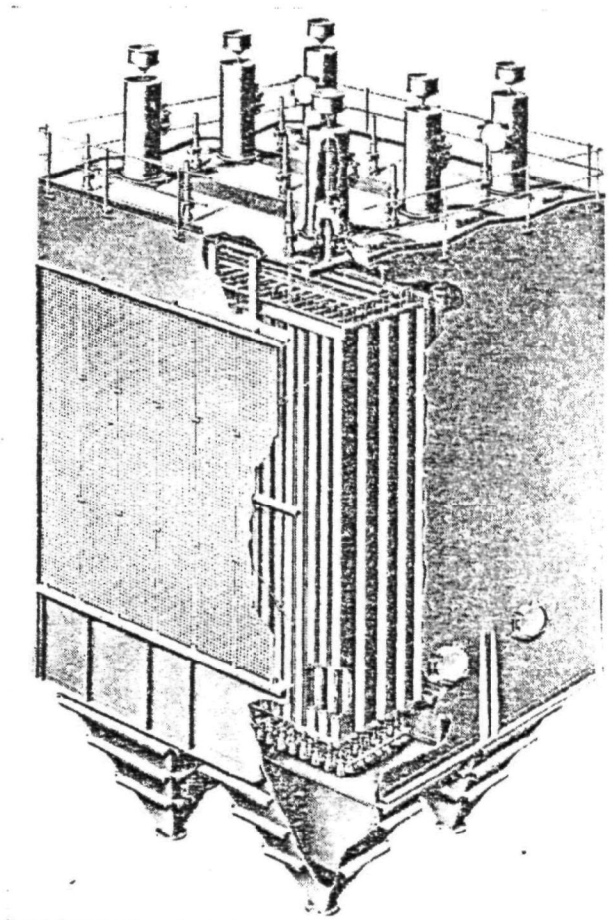
1.00 INTRODUCTION

The function of an electrostatic precipitator is to remove particles (solid or liquid) from gaseous streams. This is done by passing the gas between a pair of electrodes—a discharge electrode at a high potential and an electrically grounded collecting electrode. The potential difference must be great enough so that a corona discharge surrounds the discharge electrode. Under the action of the electrical field, gas ions formed in the corona move rapidly toward the collecting electrode and transfer their charge to the particles by collision with them. The electrical field interacting with the charge on the particles then causes them to drift toward, and be deposited on, the collecting electrode.

When the particles are liquid droplets, the collected droplets coalesce on the collecting electrode and drip off the bottom of that electrode into a collecting sump. When the particles are solid, the dust layer that forms on the collecting electrode is removed by intermittent rapping to cause the deposit to break loose from the electrode. In effect, this returns the dust to the gas stream, but not in its original finely divided state. As a result of cohesive forces developed between the particles deposited on the electrode, the dust is returned as agglomerates which are large enough so that gravity will cause them to fall into dust hoppers below the electrodes. Reduced to its essentials, the electrostatic precipitator acts as a particle agglomerator combined with a gravity settling chamber.

The electrical mechanisms for precipitation of particles are supplying: 1, an electrical charge to the particles; and, 2, the electrostatic force that causes the charged particles to drift toward the collecting electrode. In the usual industrial electrostatic precipitators, both are supplied simultaneously and the precipitator acts as a single-stage unit. Typical industrial precipitators are shown in Fig. 1 and 2. In the case of air conditioning applications and a few industrial applications,[5a, 27] however, a two-stage precipitator is used in which the two mechanisms are separated. One set of electrodes supplies the electrical charge to the particles, and a second set supplies the electrostatic force which precipitates the charged particles.

Another interesting difference that exists between industrial and air conditioning precipitators is the polarity of the discharge elec-



Courtesy of Research-Cottrell, Inc.

FIG. 1—A Plate-Type Precipitator.

[a] Figures refer to REFERENCES on p. 42.

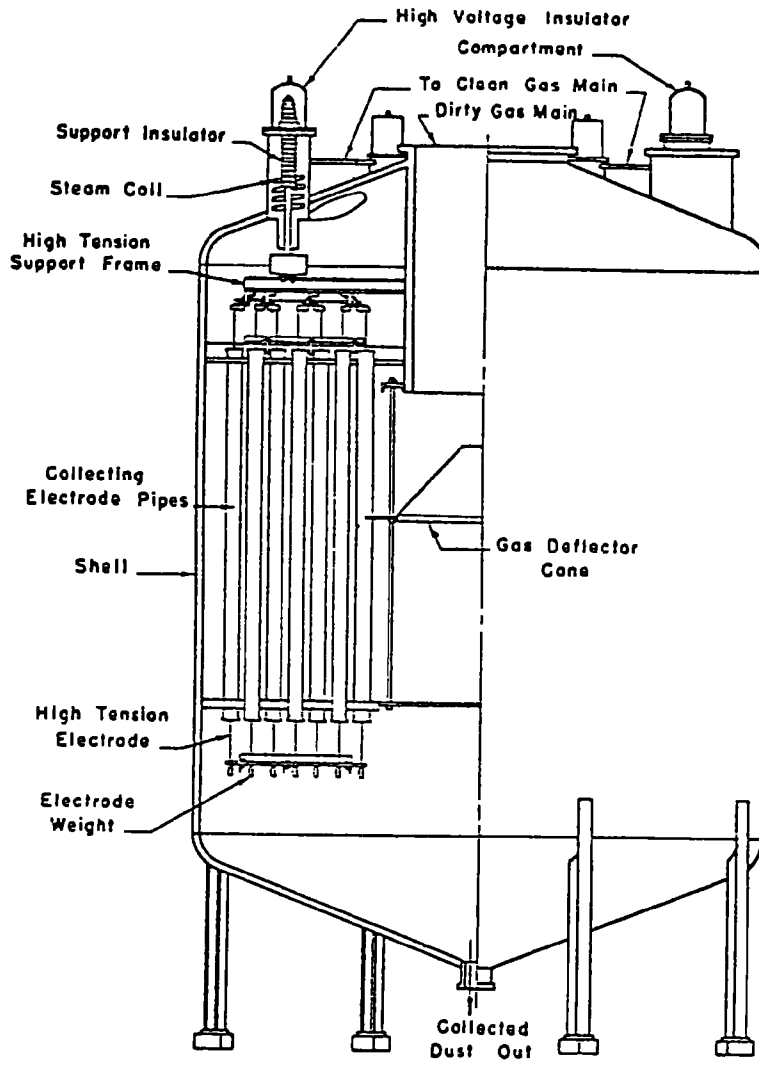
SOURCE: Removal of Particulate Matter From Gaseous Wastes--Electrostatic Precipitators, Engineering Report Prepared for American Petroleum Institute, New York, NY (1961).

trodes. The industrial precipitator almost invariably employs a negative polarity discharge electrode, because a higher voltage drop can be used before the disruptive effect of sparking between the electrodes occurs. The higher voltage makes it possible to charge the particles to a higher level and also makes the electrical field strength greater for precipitation. A positive polarity discharge electrode is used in air conditioning, however, because less ozone is produced. Since the amount of ozone which can be tolerated in air conditioning applications is limited, design efficiency is sacrificed to some extent for reduced ozone production in such applications.

The essential components of the electrode system are a fine "wire" discharge electrode and an extended-surface collecting electrode. Although hereinafter referred to as a wire, the discharge electrode may take forms other than finely drawn wire (see page 6). The usual electrode arrangements are:

1. Wires suspended along the centerline of vertical, tubular collecting electrodes. The tubes range from 6 in. ID by 6 ft in length to 12 in. ID by 15 ft in length.

2. Vertical wires suspended midway between parallel-plate collecting electrodes. The plates are spaced 6 in. to 12 in. apart and are up to 20 ft in height.



Courtesy of Western Precipitation Corporation.

FIG. 2—A Tube-Type Precipitator.

The wires are suspended from an insulated hanger at the top and kept under tension by weights attached to their lower ends. To reduce swinging of the wires, groups of the wire weights are usually tied together by a frame to increase the effective mass of the system.

For the wire-and-tube electrode system, the gas flow path is down around the outside of the tubes and then up through the inside of the tubes. For the wire-and-plate electrode system, the gas flow can also be vertically upward between the plates, but is usually horizontal between the plates. Both the collecting electrode surfaces and the wires must be vertical where gravity collection of liquid droplets or agglomerated dust is employed. Even if gravity removal of collected solid or liquid were not a consideration, vertical orientation of the wires would be desirable to simplify maintenance of wire location and wire tension.

The electrostatic precipitator is only one of many types of particulate-collecting devices available. However, one of the electrostatic precipitator's striking characteristics is its high collection efficiency for fine dusts. In the petroleum industry, collection efficiencies of over 99.5 per cent (based upon the catalyst lost from the cyclone separators) are not uncommon for the recovery of fluid cracking catalyst.

Briefly stated, the precipitator's advantages are:

1. It can handle large volumes of high-temperature gases.

2. It has an almost negligibly small pressure drop.

3. It has a high collection efficiency for a wide range of particle sizes and concentrations.

4. Its operating and maintenance costs are low.

Its disadvantages are: 1, the large space required for its installation; 2, its high initial cost; and, 3, the possible explosion hazard when the gas or particles collected are combustible.

The usual applications for dust collectors are:

1. Recovery of a valuable material such as the catalyst in a fluid catalytic cracking process.

2. Purification of gases to be used in processes, such as blast furnace gases to be used for power or heating.

3. Prevention of air pollution by dust-laden gases vented to the atmosphere.

4. Cleaning of ventilation air.

The justification for choosing a particular dust collector—e.g., an electrostatic precipitator—depends upon what must be removed from the gas. The precipitator is not justified if the gas contains a relatively coarse dust, because a cyclone can do the job at a lower cost. If the gas contains a vapor which has to be removed as well as dust, a scrubber is probably called for, because the precipitator will not remove the vapor. But, if the dust is fine and must be removed with a high collection efficiency and low pressure drop, very often the precipitator is the only collector which can do the job. That this situation is common is apparent from the large number of precipitators which have been installed in this country.

2.00 ELECTRICAL THEORY

2.10 Basic Mechanisms

Several electrical processes are important in the operation of an electrostatic precipitator. These are:

1. Ionization of the gas by means of a corona discharge.

2. Charging of the dust particles by means of ion bombardment of the particles and ion diffusion to the particles.

3. Drift of the charged dust particles to the collecting electrode caused by the electrical field existing between the electrodes and resisted by the fluid drag on the particles.

4. Removal of the electrical charge from the dust particles on the collecting electrode by conduction through the dust layer.

5. Momentum transfer from the ions streaming from the discharge electrode to the collecting electrode. This produces a lateral motion of the gas stream called the electric wind. At one time this was thought to be the basis for the operation of the precipitator, but now it is believed that the electric wind does nothing more than increase the turbulence in the gas stream.

2.20 The Corona

In order for particles to be precipitated out of the gas stream, it is essential that they be electrified so that they will be acted upon by the electrical field. Most particles entering a precipitator already have a small amount of charge previously accumulated by frictional electrification and sometimes by flame ionization, but this charge is not large enough for economical operation of an electrostatic precipitator. Some additional method of electrification is required. The method that is used in all com-

mercial operations is electrification by corona discharge.

The corona is generated by applying a direct-current electrical field between a pair of electrodes, one having a small radius of curvature (the discharge electrode), and the other having a large radius of curvature (the collecting electrode). As the field strength is increased between the electrodes, no current passes between them until the corona starting voltage is reached. At this point an electrical breakdown (ionization) of the gas occurs, causing a hissing sound and a blue glow around the discharge electrode. As the voltage is raised further, the current passing between the electrodes increases rapidly and the corona glow about the discharge electrode (or electrodes) increases in brightness and volume until sparkover voltage is reached. A corona can also be formed by an alternating-current voltage, but this does not produce a satisfactory field for particle precipitation.

The distinguishing characteristic between corona discharge and sparking discharge is that the corona discharge corresponds to an intense electrical breakdown of the gas in a small space around the discharge electrode, whereas, in sparking discharge, the gas breaks down electrically in narrowly confined paths extending from the discharge electrode to the collecting electrode.

The field strength, E, of the electrical field between the electrodes is defined as the derivative of the voltage, V, with respect to distance, r, i.e., the voltage gradient.

Expressed mathematically, the field strength is:

$$E = -\frac{dV}{dr} \qquad (1)$$

From this it follows that, if the voltage difference between the electrodes is V, then

$$V = -\int_{R_1}^{R_2} E\,dr \qquad (2)$$

Where:

r, R_1, and R_2 = distances measured from the centerline of the discharge electrode, with R_1 representing the position of the outer surface of the discharge electrode and R_2 representing the position of the inner surface of the collecting electrode.

FUGITIVE DUST EMISSIONS AND CONTROL

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ABSTRACT

Many Air Quality Control Regions (AQCR's) do not meet ambient air quality standards for particulates. In a majority of these AQCR's (92 percent), the emissions from fugitive dust sources are higher than those from nonfugitive sources. In most cases, unpaved roads are the largest source of fugitive dust, while agricultural tilling and construction also contribute substantial amounts. The reentrainment of particles from paved roads can also provide large quantities in urban areas.

Present control techniques for fugitive dust are inadequate. Estimates of the relative effectiveness of control techniques are presented in this paper. If the emissions were controlled to the levels reported in the literature, 87 percent of the AQCR's would still show fugitive sources as greater contributors than other sources.

INTRODUCTION

Many Air Quality Control Regions (AQCR's) do not meet the primary and/or secondary standards for total suspended particulates (TSP). This study provides an estimate of the impact of fugitive dust emissions (i.e., nonducted emissions) on the TSP in these AQCR's. In making this estimate, the relationships between fugitive dust emissions and emissions from other sources were examined in each AQCR. The relationship of emissions to ambient concentrations is not explored except in a general fashion by examining published information on this relationship.

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Existing control technologies for fugitive dust sources are examined for effectiveness when applied to various sources. Available data on fractional efficiency of control are presented.

FUGITIVE EMISSIONS ASSESSMENT

Area Sources

The 150 AQCR's that do not meet the total suspended particulate standards were identified from a published report.[1] Emission source categories in each were then examined for relative importance. The categories examined were those over which man has some control, and included fugitive and point sources. Classified as area sources under the National Emissions Data System (NEDS), fugitive emissions sources include dirt roads, landings and take offs from dirt airstrips, agricultural tilling, construction, open burning, slash fires, and coal refuse fires. For the first four sources, emissions data were taken from an updated NEDS card file that used countywide emission factors and activity levels. These data are thought to be more accurate than the data derived from nationwide emissions factors because they are corrected by local silt content, precipitation/evaporation indexes, and dry days per year. Of course, other area sources such as paved roads should also be considered. However, data on these types of emissions could not be obtained on a nationwide basis.

The data for coal refuse piles were generated using an emission factor of 10 kg/m^3 (17 lb/yd^3) and assuming that 5 percent of the pile burns each year.[2] The data for the dirt road emissions were calculated by multiplying the number of vehicle miles traveled by a local emission factor. The vehicle miles traveled were based on a nationwide population extrapolation of data from Kansas where an accurate accounting has been made. A check of these data with results from St. Louis indicated that rural data were within approximately 50 percent while urban data could be as much as two orders of magnitude high.[3] In view of this, the computed values for dirt roads were arbitrarily reduced by one order of magnitude.

This analysis provides annual area emissions levels for the seven source categories. The results for the individual AQCR's are not presented here but can be found in the project report for the study.[4]

INDUSTRIAL SOURCES

Some industrial sources have the potential to contribute significant fugitive dust emissions. A list of these sources is given in the project report.[4]

Within these industries, some of the most important sources of fugitive emissions include raw material and product piles, waste heaps, materials handling equipment, comminution equipment, furnaces, and dryers.

A search of the NEDS file provided data on the total emissions, number of industrial sources, and the percentage of the sources that are controlled in each of the AQCR's that do not meet the TSP standards. The data are presented in the project report.[4]

PAVED ROADS

Paved roads have been shown only recently to be significant contributors to particulate emissions. A study conducted in Seattle's Duwamish Valley compared dust emissions from paved and unpaved roads to emissions from industry and other sources.[5] The results follow:

Source	Emissions (tons/yr)	Percent of Total Emissions
Heavy industry	1200	24.5
Vessels, trains, auto tailpipes, home heating	1000	20.4
Gravel roads (19 mi)	2100	42.9
Paved roads (110 mi)	600	12.2

Other data presented in this study showed that a car driven 12 km (7.5 mi) at 16 km/h (10 mph) on a wet gravel road picked up 36 kg (80 lb) of mud. Average pickup from dirt parking lots was 0.34 kg (0.74 lb) per vehicle. Thus, mud pickup from unpaved roads and parking lots can contribute significantly to the amount of material that is deposited on paved roads.

Another study examined the contribution of various sources including paved roads to the total particulate emissions in three counties in North Carolina.[6] The results are shown in Table 1.

Tire wear debris has been examined as a source of airborne particulate. Pierson and Brachaczek estimated that this debris was a relatively minor source, accounting for 2 to 3 percent of the suspended particulate associated with vehicles.[7]

TABLE 1. COMPARISON OF THE CONTRIBUTION OF SOURCE CATEGORIES TO TOTAL EMISSIONS IN THREE COUNTIES OF NORTH CAROLINA FOR 1973

	EMISSIONS BY SOURCE CATEGORY (% OF TOTAL EMISSIONS)		
Source	Mecklenburg County	Forsyth County	Guilford County
Point	74.0	8.7	9.6
Unpaved Roads	14.9	77.8	76.6
Paved Roads	5.6	7.2	6.8
Other Area Sources	5.5	6.3	7.0

THE MAGNITUDE OF THE EMISSION PROBLEM

To estimate the magnitude of the emission problem associated with fugitive dust, the fugitive emissions were compared to the total point source emissions for each of the AQCR's that did not meet either the primary or the secondary TSP standards. The results are shown below.

	Number of AQCR's	% of Total
Point Source > Area Source	9	6.7
Area > Point	139	92.0
Area 5 times greater than point	97	64.7
Area 10 times greater than point	58	38.7
Data Missing	2	1.3
Totals	150	100.0

As a further illustration of the magnitude of these area source emissions, examine the effect of cutting them in half. Even with this, area source emissions in 129, or 86 percent of the AQCR's are still greater than the total point source emissions. With cutting them to 0.1, 57, or 38 percent are still greater.

IMPACT OF EMISSIONS ON TSP

The evaluation of the impact of emissions on air quality requires a complicated, site-specific calculation that is beyond the scope of this report. Therefore, this report must concentrate on published results to evaluate fugitive dust impacts.

In a recent paper describing the impact of fugitive emissions on TSP, it was stated that in a large industrial city where the TSP loading was influenced by fugitive emissions, the TSP on an annual basis averaged 25 $\mu g/m^3$ higher than industrial areas not influenced by fugitive emission sources.[8] This paper also stated that the results from 20 sites in five heavily industrialized cities indicated that fugitive emissions increased TSP by 10 $\mu g/m^3$.

In discussions with various EPA personnel, it was brought out that fugitive dust emissions from dirt roads have a relatively minor effect on TSP. This statement was based on the assumption that the particle size of the dust from dirt roads is such that most particles fall out of the air within short distances from the dirt roads and that most dirt roads are located in rural areas away from the sampling stations. However, the study performed in Seattle showed that 27 percent of the dust from vehicles traveling over dirt roads at 32 km/h (20 mph) was suspendable (less than 10 μm in size), while 41 percent was suspendable at 48 km/h (30 mph).[5]

Further evidence of the substantial impact of fugitive dust emissions comes from Massachusetts. An item appearing in a weekly publication reported that the air of southeastern Massachusetts had been declared a hazard to public health and that 80 percent of the particulates came from windblown sand and road dirt.[9] A followup discussion with Massachusetts officials indicated that the episodes occurred during the winter months and were the result of the reentrainment of sand that was used for vehicle skid control.[10]

A study of air quality maintenance areas in North Carolina found that the emissions inventories for particulate matter in several counties did not provide enough emissions to account for the ambient air quality measurements obtain in urban areas.[6] The study concluded that paved roads contributed the substantial amount of emissions necessary to make up the difference in TSP observations in urban sections. To account for this difference, the emission factor that was based on the Seattle study[5] was raised by a factor of 2.3 for Mecklenburg County where vacuum street cleaning is used and by 3.5 for Forsyth and Guilford Counties where no vacuum street cleaning is used. As a result, an acceptable calibration of the Air Quality Display Model (AQDM) was achieved.

The data on both emission quantities and impact of emissions on TSP imply a strong relationship between fugitive dust emissions and nonattainment in many AQCR's. It must be emphasized that the precision and reliability of the data base used for this analysis are unknown, basically because of the inconsistencies in sampling, testing, and recording methodologies used throughout the network. However, NEDS is the only data base available for a study of this type. Therefore, the approach has been to rely on a comparison of relative magnitudes and not on an exact quantification of each piece of data.

FUGITIVE DUST CONTROL TECHNIQUES

Currently control of fugitive dusts from area sources is predominantly by prevention rather than capture and separation. Measures are adopted to prevent the dust from becoming airborne. There are four preventive technologies: wetting, physical stabilization, chemical stabilization, and vegetative stabilization. Industrial operations such as mining and beneficiation, included in this study, tend to make moderate use of capture technologies.

Control technologies were examined to estimate their relative effectiveness and to comment on their limitations. Their applications were considered with respect to eight source categories: agriculture, transportation, materials handling, stockpiles and waste heaps, mining operations, beneficiation, construction, and miscellaneous sources (e.g. open burning, incineration, cooling-tower drift).

Wetting

Wet suppression of dust using either water or water plus a wetting agent can be employed for temporary control of fugitive dust from some agricultural activity, cattle feedlots, unpaved roads, transport of raw materials or products, materials handling and beneficiation, stockpiles, waste heaps, and mining and construction activities. The temporary nature of wet suppression restricts its usefulness. In cases when there is continual activity at the source, the suppressive must be repeatedly applied to be useful. This is due to the continual exposure of dry surfaces to climatic elements and is applicable to agricultural activity, unpaved roads, and stockpiles.

Water has proven to be a poor suppressive due to its high surface tension. The high surface tension interferes with the wetting, spreading, and penetrating necessary for effective suppression.

Surface tension can be reduced by the addition of wetting agents. These agents increase the effectiveness of wet suppression by:[14]

1. allowing particles to penetrate the water droplet, and thus exposing a larger water surface;

2. agglomerating particles in the droplet;

3. increasing the number of droplets per unit volume, the surface area, and the contact potential through increased efficiency of atomization; and

4. causing the liquid to wet faster and deeper and spread farther.

In addition to being a temporary control measure, wet dust suppression cannot be used where either the product or the next stage of processing will not tolerate a wet product. Examples of these instances include grain processing and certain beneficiation processes that require dry classification. Drying steps can be taken but present additional environmental problems as well as added costs.

The wet suppression of dust is usually accomplished by spraying the water either with or without a surfactant onto the surface of the exposed material. For many mining and construction roads and other surfaces, this is usually done by a special truck equipped with a tank for the liquid and a series of spray nozzles in the front and back. For the transport of products and raw materials, the carrier vehicle is usually passed under a series of spray bars where the liquid is dispersed onto the surface of the material. For materials handling and beneficiation sources, nozzles located at transfer points and at equipment intakes spray the liquid on the material. For stockpiles, nozzles spray the liquid onto either the pile or the material as it is being transferred. For feedlots, a spray system is also appropriate.

The application of wet dust suppression to many fugitive dust sources is not feasible. These sources include some agricultural activity, unpaved roads, and waste heaps. Reasons for the infeasibility include the potential shortages of water, magnitude of source, lack of suitable equipment for transporting and dispersing water, and the temporary nature of the control method.

In recent years, a new wet dust suppression system has been introduced. The use of foam systems has become an important dust suppression method. Foam systems have been successfully applied to both hard rock drilling operations and transfer points of conveyors.[11,12] These systems have advantages over untreated water in that they increase the wettability, thus requiring a smaller supply of wetting fluid; and in the case of drilling operations, they prevent overinjection of water into the hole which in turn can cause collaring of the bit and decreased penetration rates.

Data on the control efficiency of wet dust suppression is minimal. One reference cites as much as 80 percent control for cattle feedlots, but this is very much dependent on soil conditions, local climatic conditions, number of cattle, activity level, and many other things.[14] This same reference reported efficiencies of 30 to 67 percent for highly disturbed to nondisturbed storage piles, and efficiencies of 0 to 70 percent for construction site watering.[13]

Observations of several North Carolina granite quarries have shown substantially reduced emissions from processing plants, haulage roads, and drilling rigs using wet dust suppression with surfactants.[14]

Control efficiencies from drilling storage piles and construction sites will depend on many factors, including type of material and percentage of fines, local climatic conditions, type of equipment being used, moisture, and activity rate.

A recent study has examined the use of water sprays and foam on materials handling processes.[12] At a coal chain feeder-to-conveyor transfer point with a 3-ft material drop, water controlled 70 percent of the emissions while the foam spray controlled 91 percent. These numbers represent control with a spray under the belt as well as at the transfer point. Under-the-belt sprays were shown by this report to be effective in controlling dust at conveyor transfer points when used in conjunction with transfer point sprays.

Physical Stabilization

Physical stabilization methods can be used for controlling fugitive dust from inactive waste heaps, unpaved roads, and other sites. Physical stabilization requires the covering of the exposed surface with a material that prevents the wind from disturbing the surface particles.

Common physical stabilizer materials for inactive waste heaps and steep slopes include rock, soil, crushed or granulated slag, bark, wood chips, and straw that are harrowed into the top few inches of the material.[16] For dirt roads, paving is a common practice. However, paving is expensive and, in most cases, must be preceded by roadbed buildup and improvement to prevent overdriving by vehicle operators. Other methods of physical stabilization of these sources include covering with elastomeric films, asphalt, wax, tar, oil, pitch, and other cover materials.

Very little information is available on the effectiveness of physical control methods. One reference cites an 85-percent control efficiency with paving and right-of-way improvement on dirt roads.[13] This control efficiency is dependent on how much dirt is brought onto the road and later reentrained by passing vehicles.

Chemical Stabilization

Chemical stabilization requires the use of binding materials that, upon drying, bind with surface particles to form a protective crust. It acts in much the same way as physical controls by isolating the surface from climatic factors and is often used in combination with vegetative stabilization. Applications of chemical stabilization are found on agricultural fields, unpaved roads, waste heaps, and excavation heaps.

Evaluations of the suitability of various chemical stabilizing materials have been reported in the literature. In one study evaluating the cost and effectiveness of 34 stabilizers,[15] the evaluation criteria

were cost, prevention of wind erosion, effect on plant germination and growth of tomatoes and beans, and ease of application. Those stabilizers that proved effective for reducing wind erosion from the piles for 180 days are ranked in Table 2.

TABLE 2. MATERIALS THAT REDUCED SOIL LOSS FOR 180 DAYS RANKED BY 1971 COST

Product	Manufacturer	Nonerosion Rate (per acre)	1971 Cost ($)	Ranked Effectiveness
Elvanol 50-42 Technical Protein Colloid	E. I. du Pont	13 lb	8.20	6
5-V	Swift & Co.	108 lb	34.60	5
Geon 652	Goodrich Chemical	17 gal	51.20	8
Aquatain	Larutan Corp.	68 gal	172.50	7
ORTHO Soil Mulch	Chevron Chemical	681 gal	242.20	1
Anionic Asphalt Emulsion	Phillips Petro.	1226 gal	436.70	3
AGRI-MULCH	Douglas Oil	954 gal	445.70	4
Soil Erosion Control Resin Adhesive Z-3876	Swift & Co.	571 gal	1159.90	2

A later report presented the results of the Bureau of Mines tests on 70 different chemicals.[15] Water and wind erosion tests were performed in the laboratory on applications of these chemicals to various types of mill tailings. The more effective chemicals of those tested are listed below in order of their relative effectiveness based upon the cost required to stabilize 1 yd^2.[12] Long-term effectiveness to wind erosion was not measured.

1. COHEREX - good wind resistance at coverage of 240 gal/acre at cost of $65/acre, good water-jet resistance at cost of $650/acre.

2. Calcium, sodium, ammonium lignosulfonates - effective stabilizers at coverage of 2400 lb/acre at cost of $130 to $170/acre.

3. Compound SP-400, Soil Gard, and DCA-70 - wind and water resistant surfaces at coverage of 55, 90, and 50 gal/acre, respectively. Cost of about $130/acre.

4. Cement and milk of lime - effective stabilization at costs of about $190/acre.

5. Paracol TC 1842 - effective stabilizer at cost of about $250/acre.

6. Pamak WTP - effective at cost of $250/acre.

7. Petroset SB-1 - effective at cost of $250/acre.

8. Potassium silicate (SiO_2 to K_2O ratio of 2.5) - effective at $450 to $950/acre.

9. PB-4601 - effective at $500/acre.

10. Cationic neoprene emulsion and Rezosol - effective at $500/acre.

11. Dresinol TC 1843 - effective at $500/acre.

12. Sodium silicates (SiO_2 to Na_2O ratios of 2.4 to 2.9 to 1) - effective at about $200/acre, with calcium chloride additive, amount of sodium silicate was reduced.

One reference has estimated control efficiencies of chemical stabilization on a number of sources.[13] Examples of these estimates are as follows:

Source	Efficiency (%)
Unpaved roads	50
Construction - completed cuts and fills	80
Agricultural fields	40
Tailings piles	80
Continuous spray of aggregate as it is piled	90
Cattle feedlots	40

The effectiveness of chemical stabilization of unpaved roads would seem to be extremely variable based on the amount of traffic. Heavy traffic would tend to break up the surface crust, pulverize particles, and eject them into the atmosphere in much the same manner as if the road were untreated. Likewise, with cattle feedlots, the effectiveness would seem to be heavily dependent on the activity in the feedlot. It would seem that the effectiveness of continuous spraying of aggregate as it is piled could be highly variable depending on such things as the quantity of fines in the mix, type of stone, etc. In addition, the activity level of the storage pile is also important.

Vegetative Stabilization

Vegetation can be effectively used to stabilize a variety of exposed surfaces. In many cases, modifications must be made to the

surface or the surrounding terrain before effective stabilization can occur (e.g., fertilization, pH modification, and slope reduction).

Vegetative stablization for the control of fugitive dust is restricted to inactive areas where the vegetation will not be mechnically disturbed once it is started. These sources can include refuse piles (coal and mineral) and road shoulders.

Coal Refuse Piles--

Coal mining and preparation usually produce both fine and coarse waste materials. These materials consist of low grade coal, ash, carbonaceous and pyritic shale, slate, clay, and sandstone.[17]

The principal problems encountered in the vegetative stabilization of coal refuse piles occur as a result of the acidic nature of the wastes and from the slopes of the piles' sides. Thus, chemical or physical treatment of the piles' components must be accomplished prior to effective stabilization. Chemical treatment usually involves the addition of a soil neutralizing material such as agricultural limestone. Other materials such as fly ash, mines phosphate rock, and treated municipal sewage sludge have also been used.[17] Even with a neutralization pretreatment, it is recommended that acid-tolerant vegetative species be used for stabilization because the sulfide materials in the waste can oxidize the acid sulfates and thus lower the pH of the soils.

Physical treatment of the piles usually involves such things as the burying of high pyritic materials, covering the piles with a layer of topsoil, or grading to reduce slopes of the piles.[17] A good premining restoration plan can be effective for efficient physical treatment methods.

Many species of plants have been used for the stabilization of coal mine refuse piles: grasses, legumes, trees, shrubs, and vines. For a detailed discussion of these plants and their uses, refer to Reference [17].

Mineral Refuse Piles--

Mineral mining and beneficiation produce wastes in the form of overburden, gangue, and tailings. Overburden and gangue do not usually present problems to vegetative stabilization. However, tailings can present varied and extreme problems due to a deficiency of nutrients, saline or toxic properties, and variable pH.[17]

Most tailings stabilization is accomplished by first covering the waste with a layer of topsoil and then by establishing a vegetative cover. Without the topsoil cover, vegetation usually requires the assistance of other wind erosion preventatives such as mulches, chemical coatings, rapidly established plant covers, and watering.[17] However, even with these aids, stabilization of many mineral wastes has

not been effective. Most species are very site-specific, and small changes in topography, climate, and tailings composition affect their growth success.

Copper Tailings--

The establishment of vegetation on copper tailings is very site-specific. Even with piles in the same general geographic area, it is often difficult to establish the same type of vegetation.

In the western United States, copper tailings have been stabilized with vegetation. In most cases, maintenance in the form of liming, fertilizing, and irrigating after planting is required. However, at Magma, Utah, a form of permanent vegetative stabilization seems to have been established with natural vegetation invading the pile.[17]

Uranium Tailings--

Uranium tailings in Colorado have been stabilized using sweet brome, sweetclover, cereal rye, barley, alfalfa, and various wheat grasses.[17] There has been very little invasion by natural species, and continual maintenance is required.

Iron Tailings--

The vegetative stabilization of iron tailings in Pennsylvania and Minnesota has been relatively successful. Initial stabilization with grasses and legumes followed by the planting of woody plants seems to have been successful.[17] Invasion by native vegetation heightens the prospect of a permanent, maintenance-free stabilization site.

Other Metallic Tailings--

In most cases, plants tolerant to specific conditions must be applied to metallic tailings piles. Some success has been demonstrated with varieties of grasses on gold mining slimes and sands; some species of grasses have been found to be tolerant to lead and zinc; but little long-term success has been demonstrated with rye on molybdenum tailings.[17]

Control Efficiency--

The control efficiency of vegetative stabilization should vary considerably with differences in the amount and type of cover established on the tailings piles. One report estimates a control efficiency of from 50 to 80 percent.[13] This estimate was made using the wind erosion equation and is not based on a measured efficiency. This same report estimates a 93-percent reduction in windblown emissions with a combined chemical/vegetative stabilization program.

It would seem reasonable to assume that these control efficiencies could be achieved. In fact, efficiencies of 100 percent should be approached with complete vegetative covering on some sources.

OTHER CONTROL METHODS

Numerous other control methods are available for various sources of fugitive emissions. Some of the most important include speed reduction on unpaved roads, street cleaning of paved roads, reduction of fall distances for materials handling, and enclosure, hooding, and ducting.

Speed Reduction

Reducing the speed of vehicles traveling over unpaved roads has been shown to reduce the dust emissions from such travel. A reduction in vehicle speed reduces both the pulverization of road material and the turbulent wake of the vehicle. A well-quoted source has shown the following results from vehicle travel at various speeds on dirt roads. (Table 3).[11]

TABLE 3. EFFECT OF SPEED REDUCTION ON EMISSIONS

Average Vehicle Speed (mph)	Dust Emissions (lb/vehicle mile)	Emissions Compared to Those at 40 mph (%)
40	2.50	100.0
35	1.47	58.8
25	0.70	28.0
15	0.48	19.2

In another report, the results of a study in Seattle's Duwamish Valley have shown comparatively higher emissions.[5] In addition, this study showed significant reductions in the quantities of suspendable particulates with speed reduction. The results are shown in Table 4.

TABLE 4. EFFECT OF SPEED REDUCTION ON EMISSIONS IN SEATTLE'S DUWAMISH VALLEY

Vehicle Speed (mph)	Total Emissions (lb/vehicle mile)	Suspendable Emissions (lb/vehicle mile)	Total Emissions Compared to Those at 30 mph (%)	Suspendable Emissions Compared To Those at 30 mph (%)
30	22.2	9	100.0	100.0
20	7.0	2	31.5	22.2
10	3.5	0.5	15.8	0.1

Street Cleaning

With the recent interest on reentrained dust from paved roads as a source of air pollution, attention has been focused on street cleaners as dust control devices. Essentially three types of cleaners are now in use: broom sweepers, flushers, and vacuum and regenerative air sweepers. Their effectiveness has not been overwhelmingly demonstrated. Streetside samples have shown concentration reductions but regional samplers have shown no reductions.

Broom sweeping has been shown to reduce the average concentration of dust in one study but has been shown to be ineffective in two others.[18] It has been estimated that this type of sweeper picks up 20 percent of the material below 140 μm.[19] Also, while recovering this paltry amount of material, the sweeper can actually generate air pollution by stirring up the dust and by moving the material from the curbs into the middle of the road where it can be reentrained by passing vehicles.

Flushing showed significant particulate reduction in two studies and no effect in two other studies. In a fifth study, flushing showed no reduction in the average monthly concentration but did show reduction on days when flushing took place.[18]

Vacuum and regenerative air sweepers have been shown to be ineffective.[18]

Two studies on mud carryover control showed substantial reductions in particulate concentrations.[18] These studies involved manual cleaning at a construction site egress and strip paving and oiling of unpaved parking lots, roads, and shoulders on an areawide basis.

Reduction of Fall Distances

During the transfer of dusty materials from a conveyor or stacker to another location such as another conveyor or a stockpile, the

separation of the fine materials from the large materials can be caused by wind and/or the falling action of the material. A simple method to reduce dusting from these operations is to reduce the fall distances by using hinged-boom conveyors, rock ladders, telescoping chutes, lowering wells, or other devices.[14] The hinged-boom conveyor can raise or lower the conveyor belt and thus reduce the fall distance at the transfer point. Rock ladders allow the material to fall small distances in a step-like fashion. By reversing the direction of travel on successive steps, the momentum that the material receives from the previous fall and the dusting are reduced.

Telescoping chutes carry the material from the discharge point to the receiving point. Thus, the material is not exposed. Lowering wells, or perforated pipes, allow material to flow out of the pipe above the pile surface. The dusting from the impact of the falling material is retained inside the pipe, and the material is protected from wind action.

Enclosure

Simple enclosure of a fugitive dust source is an effective control method in some cases. It has been applied to a number of sources including storage of products, loading and unloading operations, product bagging operations, and classification operations. In process operations, periodic cleaning is necessary and may preclude application.

The enclosure of sources without providing adequate exhaust is not applicable to sources where abrasive materials are handled. This is especially true in hard rock processing plants where a high quartz content of the rock abrades the equipment. Enclosure is also not applicable to sources whose dust would present the danger of explosion such as in many grain handling operations.

Exhaust Systems

Many process sources of fugitive dust emissions can be controlled by the use of exhaust systems in combination with full or partial enclosure or full- or partial-coverage hoods and the associated ducting. Examples of sources amenable to this type of control include materials handling (i.e., conveyors, elevators, feeders, loading and unloading, product bagging, and stockpiling), solids beneficiation (i.e., crushing, screening, and other classifying), mining operations (i.e., drilling), and others (i.e., furnaces and dryers).

Complete enclosure of conveyors, elevators, or feeders has been practiced. Another alternative is to enclose the transfer points. Hoods as well as enclosures can be used on many loading and bagging operations.

For solid beneficiation processes, both enclosures and hoods are used. For drilling operations, enclosure of the drill hole and ducting to a baghouse mounted on the drill rig is used.[14]

Effectiveness of control is highly variable and dependent on many variables. Efficiencies of 90 percent and greater are considered appropriate. For example, 90 percent efficiency is attainable on the enclosure of BOF furnaces.[20]

No attempt has been made to provide detailed descriptions of ventilation practices. However, several excellent references are available on this subject (see References 21 and 22).

EFFECTIVENESS OF CONTROLS

Based on the foregoing discussions and comparisons, the relative effectiveness of the five types of control technologies as applied in the eight source categories is summarized in Table 5. The comparative effectiveness is indicated by VP (very poor, less than 20 percent efficiency); P (poor, about 30 percent efficiency); F (fair, about 50 percent efficiency); G (good, perhaps up to 85 percent efficiency). These efficiencies may be substantially less than indicated, depending upon the circumstances of application. Additional symbols used are: NR (not rated, usually because no application could be cited); VAR (variable); UPR (unpaved roads); PR (paved roads). More extensive tables showing ratings by individual source within each category are given in the project report.[4]

TABLE 5. RELATIVE EFFECTIVENESS OF FUGITIVE DUST CONTROL TECHNOLOGIES, BY SOURCE

Control Technology	Source Category: Agriculture	Transportation UPR	Transportation PR	Materials Handling	Stockpiles, Waste Heaps	Mining Operations	Beneficiation	Construction	Miscellaneous open burning	Miscellaneous incineration	Miscellaneous cooling tower drift
Physical stabilization	NR	G	F	NR	F,G	NR	NR	F,G	-	-	-
Wetting, wet application	F	VP	P	FG	P,F	VP	P,F	VP,P	-	-	-
Chemical stabilization	P	P	F	NR	P	NR	NR	NR	-	-	-
Vegetative stabilization	VP		G	NR	FG	NR	NR	F,G	-	-	-

TABLE 5. (Continued)

Control Technology	Source Category: Agriculture	Transportation UPR	Transportation PR	Materials Handling	Stockpiles, Waste Heaps	Mining Operations	Beneficiation	Construction	Miscellaneous open burning	Miscellaneous incineration	Miscellaneous cooling tower drift
Special											
control device										FG	
speed reduction		Var									
enclosure				F							
exhausting				F,G		G	F,G				
reduction of fall				F-P							
wind screen					VP						

F = fair ~ 50% G = good ~ 85% P = poor ~ 20% VP = very poor < 20%

UPR = unpaved roads NR = not rated Var = variable
PR = paved roads

Conclusions

While fair control of some agriculture emissions may be obtained by wetting, this source lacks good controls. Physical stabilization remains practically untried, chemical stabilization is rated poor, and vegetative stabilization very poor.

Physical stabilization of dirt roads (that is, paving) is the only good control. Paved roads benefit from vegetative stabilization of shoulders. Materials handling operations can attain fair to good control by wetting when the techniques can be used. Other technologies remain unexploited at this time.

Stockpiles benefit from physical and vegetative stabilization.

Mining operations benefit from exhausting techniques, while wetting is very poor and the stabilization technologies have not been rated, and may not work well.

Exhausting has been fair to good for control of beneficiation emissions, while wetting has been poor to fair, and stabilization unrated.

Physical and vegetative stabilization is fair to good in construction operations, while wetting is poor, and chemical stabilization is not rated.

None of these technologies are effective in open burning or on industrial cooling towers. Incinerators, if properly designed, can be effective as control devices.

EFFECT OF FUGITIVE EMISSION REDUCTION ON AQCR'S

To examine the effects of fugitive dust emissions reduction on total AQCR emissions, emissions from unpaved roads, agricultural tilling, and construction were reduced by appropriate measures reported in the literature. The reductions used were 50 percent for unpaved roads and 40 percent for agricultural tilling (chemical stabilization effectiveness), and 30 percent for construction (wetting).

The results of the emissions reduction are shown in the following summary:

	Before Emissions Reduction	After Emissions Reduction
Total number of AQCR's not meeting TSP Standards	150	150
Point > Area	9	17
Area > Point	139	131
Area 5x > Point	97	68
Area 10x > Point	58	38
Data Missing	2	2

CONCLUSIONS

1. Fugitive dust sources are significant emitters of particulates in a majority of the AQCR's. Of the 150 AQCR's that do not meet the TSP standards, fugitive dust emissions exceed point source emissions in 139 AQCR's, or 92 percent. In fact, fugitive emissions are 10 times greater than point source emissions in 58, or 39 percent, of the AQCR's.

2. In most cases, unpaved roads provide the largest source of particulate emissions in the AQCR's. Agricultural tilling and construction sources are also very important and in some cases are the largest emitters.

3. The reentrainment of particles from paved roads is a source of large quantities of particulates in many AQCR's.

4. Industrial sources of fugitive emissions are plentiful and can have a substantial impact on surrounding areas.

5. Fugitive dust sources can contribute significantly to the TSP burden of an entire AQCR as well as have an impact in a localized area.

6. The relationship between pollutant exposure and human health has been demonstrated. Increased hospitalization rates have been observed with increased particulate pollutant exposure.

7. More attention should be given to the control of fugitive dust emissions because of their contribution to ambient dust loadings.

8. Control effectiveness for fugitive sources is highly variable and depends on such things as type of control, characteristics of the source, local climatic conditions, and source activity.

9. Present control technology for unpaved roads, agricultural tilling, and construction activity is inadequate. Reducing the emissions from these activities by the amounts reported in the literature has only a small influence on fugitive emissions in most AQCR's.

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EPA BUBBLE

STEEL INDUSTRY EXAMPLE OF BEST USE OF BUBBLE

Iron Oxide Sources	Emission (ton/yr)	Possible Controls	Reduction %	(ton/yr)	Cost $ Millions	Cost per Annual Ton
Storage-Pile Wind Loss	473	Spray System	60	(284)	0.2	$ 704
Blast-Furnace Cast House	309	Hoods and Baghouse	95	(294)	2.5	8,520
BOF Charging and Tapping	326	Hoods and Baghouse	90	(293)	4.0	13,630
Open-Hearth Charging and Tapping	140	Hoods and Baghouse	80	(112)	4.0	35,710

SOURCE: Armco Steel Corp., Middletown, Ohio.

REMOVAL OF PARTICULATE MATTER FROM GASEOUS WASTES

WET COLLECTORS

1.00 INTRODUCTION

1.10 Definitions

Wet collectors comprise all units in which a liquid, usually water, is employed to achieve or assist in the removal of dispersoids from gases. As used in this report, the term "dispersoid" will include dust, spray, fume, and mist. Lapple [41] places all dispersoids into two general categories: "mechanical dispersoids" and "condensed dispersoids." Mechanical dispersoids are formed by comminution, decrepitation, or disintegration of larger masses of material, or by the grinding of solids or spraying of liquids. A wide range of particle sizes usually is involved. Mechanical dispersoids are further classified as "dust" and "spray," referring to dispersed solids and liquids, respectively.

Condensed dispersoids are formed by condensation of the vapor phase or as the product of a vapor phase reaction. Particles thus obtained usually are characterized by a relatively narrow size distribution. Further classification of condensed dispersoids into "fume" and "mist" refers to solid and liquid dispersed phases, respectively.

The sizes of dispersed particles generally are related to the manner in which they are formed. The following tabulation summarizes the classification and presents representative size ranges of gas dispersoids:

Dispersoids	Approximate Particle Diameter (Microns)
Mechanical:	
Dust	> 1
Spray	>10
Condensed:	
Fume	< 1
Mist	<10

The size ranges indicated in this tabulation are representative of most typical cases; they are not intended to be mutually exclusive nor are they intended to serve as rigid definitions of dispersoids which may be encountered in practice. For example, condensed dispersoids generally tend to agglomerate into particles of large size, which may actually exceed the size of many industrial dusts. A fine atmospheric mist, commonly called "fog," agglomerates into rather large rain drops.

The term "aerosol" frequently is used in technical literature to designate the dispersion of solid or liquid particles in a gas. The properties of an aerosol thus involve the properties of dispersed particles or dispersoids as well as those of the gas phase. A summary of properties of typical aerosols, which is widely quoted and frequently reproduced by a number of authors, was compiled by C. E. Miller [43] and is reproduced as Fig. 1. Further references to Miller's chart will be made throughout this report.

For reasons of simplicity and convenience herein, the term "aerosol" will be used to indicate the more or less stable dispersions of solids and liquids in a gas; another term, "particulates," will be used to denote the dispersed particles, both solid and liquid. In consonance with this terminology, the present report will attempt to present information on the theory and practice of the separation of particulates from aerosols by methods which utilize a liquid to achieve or assist in the separation.

1.20 Classification of Wet Collectors

The unit operation by which particulate matter is removed from a stream of gases may be viewed as a sequence of three steps:

1. Conditioning of particulate matter.
2. Disengagement or separation of the particulate phase from the carrier gas.
3. Removal of the separated particulates from the collector.

In the industrial equipment, step 1 may be absent altogether; may be accomplished separately; or may be combined with disengagement, step 2.

In wet collectors, as defined in Par. 1.10, the particulate matter leaves the collector as a

SOURCE: Removal of Particulate Matter From Gaseous Wastes--Wet Collectors, Engineering Report Prepared for American Petroleum Institute, New York, NY (1961).

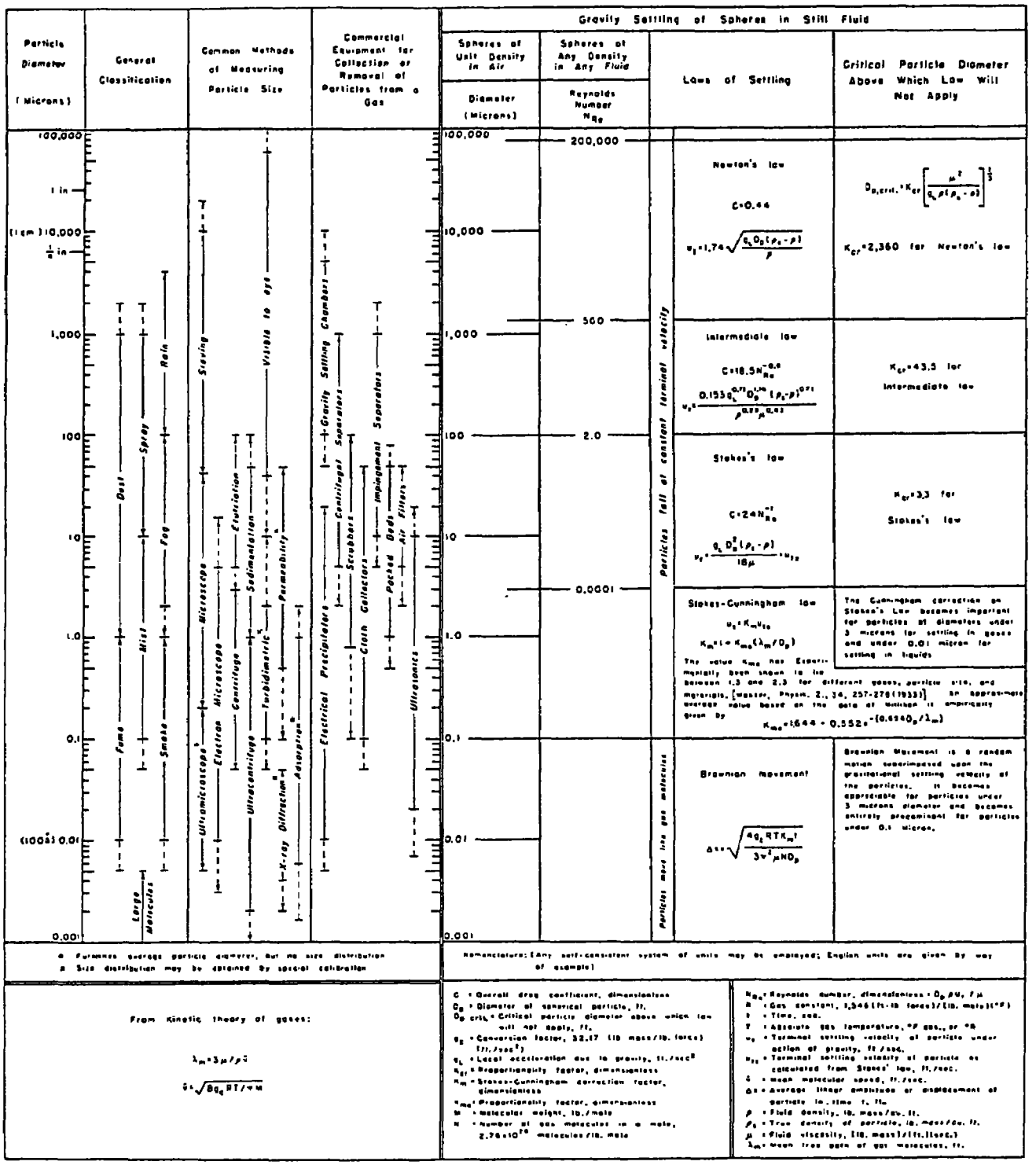


FIG. 1—Summary of Properties of Some Typical Aerosols.

slurry or in a dissolved state. It is either discarded to waste or is subjected to a separation procedure—intended to recover the particulates, if economically justified, or to permit recirculation of the scrubbing liquid.

Conditioning of the particulate matter, step 1, and its disengagement from the carrier gas, step 2, in wet collectors may involve one or more of several mechanisms. These mechanisms, discussed at greater length in Sect. 2.00, may be listed as follows:

1. Impingement (impaction) and interception.
2. Brownian motion diffusion.
3. Humidification of gas.
4. Condensation of liquid on particles.
5. Agglomeration of particles.
6. Electrostatic precipitation.

Although it would appear, at a first glance, that a classification of wet collectors based upon the preceding mechanisms might be feasible, in almost all instances commercial equipment utilizes more than one of the mechanisms listed and thus precludes such a classification. The wide variety of scrubbers and the many possible combinations of functional mechanisms make it difficult to develop a comprehensive and mutually exclusive classification of types.

A classification used by Lapple[41, 42] enjoys wide acceptance and is adopted in the present report. A summary of this classification of wet collectors, which is used as the basis for presentation of material in Sect. 3.00, is presented as follows:

1. Chamber scrubbers.
2. Cyclonic scrubbers.
3. Inertial scrubbers.
4. Mechanical scrubbers.
5. Packed scrubbers.
6. Film scrubbers.
7. Miscellaneous scrubbers.

The several categories used in this classification are briefly described as follows:

1. Chamber scrubbers are devices in which the dust-laden gas simply enters and leaves a chamber where one or more spray nozzles are mounted. The chamber may be large in order to slow down the gas flow (conventional spray washer), or it may be in the form of a venturi to speed up the gas flow. The spray nozzles may be operated at a high pressure to produce a fog or the liquid may be introduced into the throat of an ejector to provide the draft for the movement of the gas.

2. Cyclonic scrubbers contain structural characteristics, which impart centrifugal forces to the aerosol. The centrifugal action may be induced by a tangential entrance of the dust-laden air, by forcing the gas through specially shaped vanes, or by constraining the gas to a spiral-shaped chamber. The scrubbing liquid is introduced in various manners, and vanes and baffles frequently are used to facilitate disengagement of the collecting liquid from the gas stream before the latter leaves the scrubber.

3. Inertial scrubber is the term applied to those devices in which the energy of the dust-laden gas stream primarily is used to expand the surface area of the scrubbing liquid and thus obtain liquid contact.

In a venturi scrubber, a popular and effective scrubber in the inertial group, scrubbing liquor enters the throat of a venturi at a relatively low velocity but encounters a high-velocity flow of gas in the throat. In another type of wet inertial scrubber, gas jets produced by an orifice plate entrain the scrubbing liquor, which flows over the orifice plate, and the mixed spray impinges upon properly located target plates. In still another type of inertial collector, the scrubbing liquor is contacted with dust-laden gas when the latter is forced through suitably restrictive passages submerged in the liquor. Other specific examples of the inertial scrubber are described in Sect. 3.00.

4. Mechanical scrubbers are characterized by the presence of some mechanical devices for producing the spray. Thus, in one model of a mechanical scrubber, widely used in blast furnace gas cleaning, the dust-laden gas and scrubbing liquid are passed outward through a series of rotating and stationary arms. In another group of devices of the same general type, dust-laden gas is scrubbed with liquor dispersed by means of various shaped rotors dipping into the liquid.

5. Packed scrubbers are conventional towers packed with raschig rings, berl saddles, grids, and so forth operated with liquor loadings well below flooding point. In these scrubbers the liquor primarily serves to wash the dust off the surfaces and to avoid re-entrainment of the dust.

6. Film scrubbers comprise those units in which the scrubbing liquid is present only as a film on collecting surfaces. In such units, except for collection resulting from humidification and

condensation, the liquid serves merely to keep the collecting surface free of solids and to prevent re-entrainment of collected dust.

7. *Miscellaneous scrubbers* include a number of wet collectors which are not conveniently classified under the preceding categories.

1.30 Range of Application

Wet collectors as a class provide a moderate cost, high-efficiency method for removal of particulates. Their use is indicated as a potential means for the collection of particulates [42] when:

1. Addition of liquid to the gas stream is not objectionable.
2. Particulate matter is very fine—diameters predominantly ranging between 10 and 0.1 microns.
3. A moderately high collection efficiency is required.
4. Gas must be cooled.
5. Vapors or gaseous contaminants must also be removed from the air stream.

The use of a wet collector is not advisable when a less expensive device, such as a cyclonic scrubber, will perform satisfactorily. Wet collectors normally are competitive with cloth collectors (bag filters), although they may be used to handle dust-laden gases under conditions where bag filters are not applicable because of temperature, moisture conditions, explosion hazards, and so forth.

The use of wet collectors presents a number of problems under certain conditions. Silverman [64] lists these conditions and resultant problems as follows:

1. Soluble particulates for recovery must be recrystallized and may become contaminated during collection.
2. Collector requires means of disposal for the sludges, e.g., sludge ponds, tailing piles, etc., some of which may create a source of secondary contamination.
3. Recovery of insoluble product requires a dewatering step.
4. Low removal efficiency for particles smaller than 1 micron in diameter.
5. Removal of soluble contaminants by the scrubbing liquor may introduce corrosion problems.
6. Liquid entrainment in the effluent gas stream represents a source of contamination.
7. Freezing problems in cold weather.

Wet collectors are used in many chemical and process industries.

1.40 Comparison with Other Types of Collectors

Kane [82] qualitatively compares the characteristics of five principal types of dust collectors: cyclones, high-efficiency cyclones, wet collectors, fabric collectors, and high-voltage electrostatic precipitators. The usual relationships between the basic groups of collector designs are shown in Appendix A; exceptions for specialized designs are permissible.

The use of the collectors, representative of the five basic groups in a number of industrial processes, is summarized in Appendix B. Although the ratings—usual, frequent, considerable, occasional, etc.—are qualitative and may be expected to reflect the personal opinions of the compiler,[32] the tabulation nevertheless is believed to be useful as a check list against conclusions reached by analysis of several factors influencing collector selection.

2.00 REMOVAL OF SMALL PARTICLES FROM MOVING GAS STREAM

2.10 General Considerations

As stated in Par. 1.20, as a class, wet collectors are distinguished by the employment of liquid to achieve or assist in the removal of particulate matter from gases. In most of the wet collectors described in this report the liquid is dispered through the gas and the collection of the particles is the result of their interaction with dispersed droplets of the scrubbing liquid. Thus, the effectiveness of the removal of particles is the sum of interactions of all the droplets with the particles of the aerosol. These interactions are involved in both particle conditioning and particle precipitation.

The several mechanisms of particle-droplet interaction will be examined quantitatively in the following paragraphs.

2.20 Particle Flocculation

The increase in the average size of the particles as a result of flocculation makes the subsequent collection of particles much easier. Flocculation occurs when small particles engaged in Brownian motion collide. The collisions are inelastic and if the particles are solid —e.g., fumes of lead, oxides of zinc, magnesium, iron—chainlike aggregates are formed. Liquid particles coalesce into a single drop.

Since Brownian motion is a result of the impact of molecules upon the particles, the extent of this motion and, therefore, the importance of flocculation in collection of particulates increases with the temperature of the aerosol. However, this is significant only for those particles which are sufficiently small to be influenced by molecular impacts. Thus, the phenomenon of flocculation is of importance with submicron sizes only, 0.1 micron or less. A high concentration of particles, by increasing the likelihood of collisions, similarly increases the extent of flocculation.

The flocculation rate is given quantitatively by an expression for the rate of decrease of the particle concentration with time. Junge [30] presents the flocculation rate for a homogeneous aerosol composed of spherical particles in still air as follows:

$$-\frac{dc}{dt}=\frac{4R'T}{3\mu N}\left(1+K_{me}\frac{\lambda_m}{D_p}\right)c^2 \qquad (1)$$

Where:

$\frac{dc}{dt}$ = flocculation rate, in particles per unit volume per unit time.

R' = gas constant = $8.3(10^7)$, in dyne-centimeters per (gram-mole) (degrees Kelvin).

T = absolute temperature, in degrees Kelvin.

μ = gas viscosity, in poises or dyne-seconds per square centimeter.

N = Avogadro's number = $6.02(10^{23})$ molecules per gram-mole.

K_{me} = correction factor (1.72 for air).

λ_m = mean free path of gas molecules, in microns (0.1 for air).

D_p = diameter of particles, in microns.

c = concentration, in particles per cubic centimeter.

Flocculation is of some importance in the conditioning of metallic fume particles before removal in settling chambers or by bag filters. In the case of wet collectors, where the usual range of applications is in the micron range or higher, Brownian diffusion and flocculation do not contribute significantly to the collection efficiency. Moreover, the interaction of particulates with droplets of the liquid predominates to such an extent that contribution of collisions between particles themselves to the phenomenon of conditioning is reduced further. The occurrence of flocculation, nevertheless, must be kept in mind when describing the average particle size entering any collector, if the process generating the aerosol gives rise to a high concentration of submicron particles of appropriate nature.

A substantial amount of flocculation may be produced if an aerosol is exposed to sound waves of high frequency such as from a siren. The process is not well understood nor is it possible to calculate accurately the coagulation rate from theory.[59, 60] In general, the particles must be smaller than 10 microns and their concentration greater than 1 grain per cubic foot.

The process has been tried on a fair-sized scale in the collection of carbon black [69] and for the collection of sulfuric acid,[13] but has not as yet been established on a firm design basis.

2.30 Impaction of Particles on Liquid Droplets

Fundamental analysis of wet collectors requires an analysis of impaction of small particles upon droplets of the collecting liquid with which the collector, or a portion of it, is filled. Such an analysis must include consideration of all of the forces that operate between the particles and the droplets. For particles of normal density in the micron and submicron ranges of size, the primary mechanisms by which collection may take place are:

1. Inertia.
2. Interception.
3. Settling.
4. Brownian motion.
5. Electrostatic attraction.

In the case of inertia, a particle carried along by the gas stream, on approaching an obstruction (liquid droplet), tends to follow the stream but may strike the obstruction because of its inertia. In Fig. 2 solid lines represent the fluid streamlines around a droplet of diameter D_b and the dotted lines represent the paths of particles which initially followed the fluid streamlines.

For a flow around a spherical collector the quantity $\frac{X}{D_b}$, where X is the distance between limiting streamlines A and B, represents the fraction of particles initially present in a volume swept by the droplet which will be removed by inertial impaction.

In interception, the trajectory of the center of a relatively large particle, although not intersecting the collecting surface, may pass close enough for the surface of the particle to touch the collecting drop and be arrested by it. Also, the particle may be encouraged to impact upon the collecting surface by an actual or induced electrostatic force between the particle and collector.

In the case of settling, particles in a slowly moving air stream may settle out on the collecting surface under the influence of gravity. For particles smaller than 0.1 micron, Brownian diffusion becomes significant.

Impaction of aerosol particles on body collectors, such as cylinders and spheres, was studied theoretically by Albrecht,[2] Landahl and Herrmann,[39] Langmuir and Blodgett,[40] and by Sell,[63] all of whom considered inertia as the only mechanism of collection. Because of the complicated nature of the problem, the results of these authors were not in good agreement, particularly with regard to the question of whether a minimum particle size exists below which impaction cannot occur.

Ranz and Wong [56] developed a mathematical statement of the problem of impaction without restricting their consideration to a single mechanism. They carried out limiting solutions and made order-of-magnitude calculations, which establish the nature and the importance of the several mechanisms of impaction.

Through evaluation of the forces which affect the motion of the particles and cause them to move across the streamlines to the collecting surface provided by liquid droplets, Ranz and Wong [56] defined the following parameters:

1. Inertial parameter, $\psi = \frac{C\rho v_o}{18 D_b \mu (10^4)} D_p^2$

Where:

C = empirical correction factor for resistance of a gas to movement of small particles, dimensionless =

$$1 + \frac{2\lambda}{D_p}\left[1.23 + 0.41 \exp\left(\frac{-0.44 D_p}{\lambda}\right)\right] \text{for } 0.1 < \frac{2\lambda}{D_p} < 134$$

ρ = particle density, in grams per cubic centimeter.

v_o = velocity of aerosol stream, in centimeters per second.

D_p = diameter of aerosol particle, in microns.

D_b = diameter of droplet, in microns.

μ = viscosity of gas, in poises.

$\lambda = \frac{2\mu}{\bar{v}}$, mean free path of gas molecules, in centimeters.

$\bar{v}$ = average molecular velocity of gas molecules,* in centimeters per second.

Parameter ψ may be considered to be the ratio of the force necessary to stop a particle initially traveling at velocity v_o in the distance $\frac{D_b}{2}$, to the fluid resistance at a relative particle velocity of v_o. It is also the ratio of the stopping distance—i.e., the distance a particle will penetrate into still gas when given an initial velocity of v_o—to the diameter of the liquid droplet.

2. Interception parameter, $R = \frac{D_p}{D_b}$

Parameter R is the ratio of the particle diameter to the diameter of the liquid droplet.

3. Settling parameter,

$$F = \frac{C\rho_p g_L D_p^2}{18\mu v_o} = \left(\frac{g_L D_b}{v_o^2}\right)\psi$$

Where:

ρ_p = particle density, in gram mass per cubic centimeter.

g_L = absolute value of local acceleration of gravity, in centimeters per second per second.

Parameter F is the ratio of the force of gravity to the fluid resistance at a relative particle velocity of v_o. It is also the ratio of the

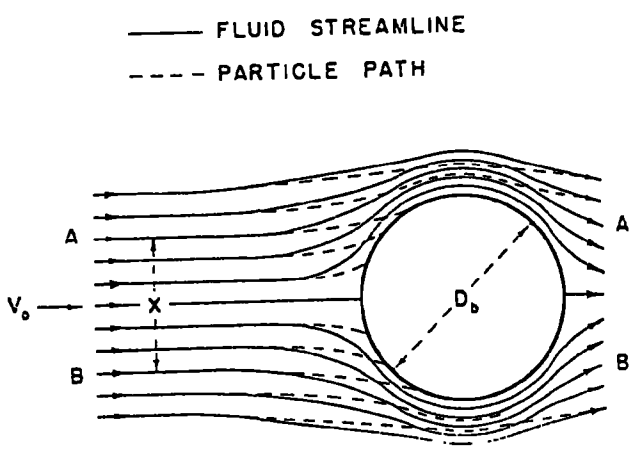


FIG. 2—Inertial Impaction upon Single Droplet.

* $\bar{v}$ is the square root of the mean square velocity of the molecular, the expression for which is given in all standard treatments of kinetic theory; see for example, Samuel Glasstone, *Textbook of Physical Chemistry*, D. Van Nostrand Co., Inc., New York, 247 (1940).

free-settling velocity of the particle to the stream velocity.

4. Brownian motion diffusion parameter,

$$\theta = \frac{3D_{BM}}{v_o D_b} = \frac{CR'T}{\mu D_b D_p v_o}$$

Where:

D_{BM} = diffusivity, in square centimeters per second.
R' = gas constant.

Parameter θ is the ratio of diffusive force caused by random thermal motion to the fluid resistance.

5. Electrostatic attraction.

Two parameters are defined describing: 1, the interaction of a positively charged particle and droplet, K_E; and 2, the interaction between a charged droplet and a dielectric particle on which the droplet charge induces a charge, K_I. These parameters are:

$$K_E = \frac{Cq_p q_{ac}}{3\pi\mu\epsilon_o D_p v_o}$$

$$K_I = \frac{2}{3}\left(\frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + 2\epsilon_2}\right)\left(\frac{CD_p^2 q_{ac}^2}{\epsilon_o \mu v_o D_b}\right)$$

Where:

q_p = electric charge on particle, in coulombs.
q_{ac} = electric charge on droplet, in coulombs per square centimeter.
ϵ_o = permittivity of free space.
ϵ_1 = dielectric constant of aerosol particle.
ϵ_2 = dielectric constant of gas.

Both K_E and K_I are the ratios of the electrical force at the surface of the droplet to the fluid resistance caused by a relative particle velocity of v_o with respect to the droplet. Positive values of K_E indicate decreased collection efficiency (charges are of the same sign), and negative values indicate increased efficiency.

The extent to which the several interaction mechanisms operate under a given set of conditions is determined by the magnitudes of the described parameters. It can be shown that the efficiency of collection by any of these mechanisms is negligible when the corresponding parameter is much less than 10^{-2}, and is of the order of unity when the parameter is of the order of unity. Johnstone, et al.,[27] cite the results of a calculation of parameters for several aerosols in a throat of a venturi in which a gas velocity of 500 fps was maintained. These results are given in Table 1.

It is seen that the inertial forces are by far the most important of those considered as possible

TABLE 1—Collection Parameters at Venturi Throat

(Gas velocity at throat = 500 fps)

	Ammonium Sulfate	Ammonium Chloride	Dibutyl Phthalate
Particle size, microns	1.22	0.27	0.58
Particle density, g per cu cm or ml.	1.5	1.5	1.0
Parameters:[a]			
Inertial, ψ	36.5	1.8	8.2
Electrostatic, K_E	$(13)(10^{-3})$	$(5)(10^{-3})$	$(7)(10^{-3})$
Induction, K_I	$(7.5)(10^{-4})$	$(4.7)(10^{-5})$	$(1.7)(10^{-4})$
Diffusion, θ	$(5)(10^{-4})$	$(26)(10^{-4})$	$(11)(10^{-4})$

[a] Calculations of the dimensionless parameters are based on the mean diameters of the particles and water droplets. The parameters for the electrostatic forces are based on a maximum charge density of $(2.65)(10^{-9})$ coulombs per square centimeter for charged surfaces in air. Higher charges will leak away through air ionization and corona discharge. The dielectric constant[27] for the ammonium salts was taken as 6.3 and for the dibutyl phthalate as 6.

mechanisms of collection. At lower velocities, electrostatic forces may become important if particles are charged artificially. Collection by Brownian diffusion is negligible even for the 0.27-micron ammonium chloride aerosol. This parameter becomes important when the particles are smaller than 0.1 micron and when the relative velocity between the droplets and particles is small.

The inertial impaction of aerosol particles upon droplets of scrubbing liquid is discussed in the following paragraphs.

2.40 Efficiency of Collection by Impaction on a Single Droplet

The removal of aerosol particles through impaction on droplets of collecting liquid has been the subject of a number of theoretical and experimental studies.[2, 21, 28, 39, 40, 56, 63] Efficiency of impaction, also termed "target efficiency," η_t, may be considered as the ratio of the area of the aerosol tube—from which all particles are removed—to the projected frontal area of the droplet. In terms of Fig. 2, if X is the limiting width of the initial streamlines, in which all particles collide with and are impacted upon the droplet of diameter D_b, the efficiency of impaction is:

$$\eta_t = \frac{X^2}{D_b^2} \tag{2}$$

The several studies (see references cited), notably that by Langmuir and Blodgett,[40] established that the target efficiency should be a function of the dimensionless group

$$\frac{u_t V_o}{g_L D_b} \tag{3}$$

varies linearly with the specific area of the droplets.

2.60 Grade-Efficiency Curves for Collectors

Although the material presented in the preceding paragraphs is indicative of the effect of particle size, droplet size, specific surface area, properties of the gas phase, etc. on the collection efficiency, more dependable methods of predicting collector efficiencies must be based on actual performance data. Unfortunately, the collection of accurate performance data is time-consuming, expensive, and is subject to a number of uncertainties involved in accurate characterization of the particulates in the inlet and outlet of a collector. Moreover, isolated data for plant performance on different duties are difficult to compare.

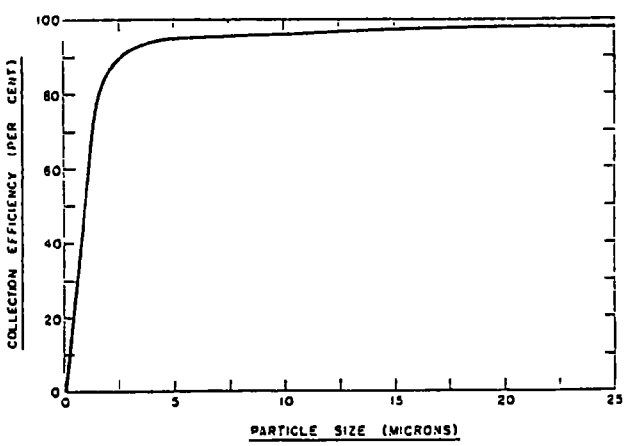
Stairmand [67] proposed a method for practical evaluation of performance of collectors and in a subsequent publication [68] cited a number of examples drawn from extensive tests conducted on large-scale industrial dust collection equipment.

Stairmand describes the performance of a number of dust collectors in terms of a "grade-efficiency" curve characteristic for each type of equipment. In such curves, the collection efficiency for particles having an "effective density" of 2.7 g per cu cm is plotted against the particle size in microns. Fig. 6, reproduced from Stairmand,[68] is an example of such curves and is based upon a large industrial spray tower processing 70,000 cfm of gas.

In addition, Stairmand [63] describes a method for direct comparison of different collector types based on the use of their characteristic grade-efficiency curves. This method consists in calculating the overall collection efficiency of particulates from a standard-test aerosol. It is exemplified in Table 2, in which the overall collection efficiency of a spray tower, with a grade-efficiency curve as shown in Fig. 6, is computed for three dusts which have the same grading as shown in the first two columns of the table. Table 2 also includes a prediction of the grading of dust in the outlet gas. It is assumed that the spray tower operates under essentially the same conditions as those for which the grade-efficiency curve was established.

The calculations summarized in Table 2 illustrate the effect of particle-size distribution upon the overall collection efficiency of the scrubber. The presence of sizable particles results in a large predicted overall removal efficiency (approximately 92 per cent for minus 150-micron dust), whereas the fine dust can be removed much less efficiently (77 per cent for minus 10-micron dust).

The method described by Stairmand [63] and illustrated in Table 2 can be used to compare directly the performance of different types of collectors by computing in a similar manner the expected overall collection efficiencies of the standard dust by the different collectors. It should be noted that the comparison depends upon the availability of experimentally determined relations of the grade efficiencies versus particle size for conditions of gas flow, droplet size, and so forth for which comparison is to be made.



Courtesy of C. J. Stairmand and The Institute of Fuel (London).

FIG. 6—Grade-Efficiency Curve for Spray Tower.

3.00 INDUSTRIAL WET COLLECTORS

3.10 Chamber Scrubbers

Chamber scrubbers represent a class of wet collectors in which dust-laden gas simply enters and leaves a chamber where one or more spray nozzles are mounted. There are many industrial variations of this class of collectors. These range from a stack spray arrangement, in which a single spray is installed in a stack carrying exhaust gases from a furnace, to much more complicated, specially designed towers, where a series of baffles is used to impart to the gas a tortuous path and provide for repeated contact of the dust-laden gas with scrubbing liquor. Several examples of chamber scrubbers are described herein.

TABLE 2—Prediction of Overall Efficiency of a Spray Tower and Grading of Exit Dust

1	2	3[a]	4[b]	5[c]	6[d]
				Grading of Exit Dust	
Size of Grade (Microns)	Per Cent by Weight in Grade at Inlet	Efficiency at Mean Size of Grade (Per Cent)	Overall Collection (Per Cent)	As Per Cent of Inlet	Actual Per Cent
Dust A (Minus 150 Microns)					
104 to 150	3	100	3.00	0.00	0.0
75 to 104	7	99.5	6.97	0.03	0.4
60 to 75	10	99.1	9.91	0.09	1.1
40 to 60	15	98.7	14.81	0.19	2.4
30 to 40	10	98.3	9.83	0.17	2.2
20 to 30	10	97.9	9.79	0.21	2.7
15 to 20	7	97.2	6.80	0.20	2.6
10 to 15	8	97.0	7.76	0.24	3.1
7.5 to 10.0	4	95.5	3.82	0.18	2.3
5.0 to 7.5	6	94.5	5.67	0.33	4.2
2.5 to 5.0	8	93.0	7.44	0.56	7.2
1.0 to 2.5	5	85.0	4.25	0.75	9.6
0.5 to 1.0	4	42.0	1.68	2.32	29.6
0.0 to 0.5	3	15.0	0.45	2.55	32.6
	100		92.18	7.82	100.0
Dust B (Minus 40 Microns)					
30 to 40	15	98.3	14.75	0.25	2.1
20 to 30	15	97.9	14.69	0.31	2.6
15 to 20	11	97.2	10.69	0.31	2.6
10 to 15	12	97.0	11.64	0.36	3.0
7.5 to 10.0	6	95.5	5.73	0.27	2.3
5.0 to 7.5	10	94.5	9.45	0.55	4.7
2.5 to 5.0	12	93.0	11.16	0.84	7.1
1.0 to 2.5	8	85.0	6.80	1.20	10.2
0.5 to 1.0	6	42.0	2.52	3.48	29.4
0.0 to 0.5	5	15.0	0.75	4.25	36.0
	100		88.18	11.82	100.0
Dust C (Minus 10 Microns)					
7.5 to 10.0	13	95.5	12.42	0.58	2.5
5.0 to 7.5	21	94.5	19.85	1.15	5.0
2.5 to 5.0	25	93.0	23.25	1.75	7.6
1.0 to 2.5	17	85.0	14.45	2.55	11.1
0.5 to 1.0	13	42.0	5.46	7.54	33.0
0.0 to 0.5	11	15.0	1.65	9.35	40.8
	100		77.07	22.92	100.0

[a] Column 3: Read off from Fig. 6.

[b] Column 4: $\frac{(\text{Column 3})(\text{Column 2})}{100}$.

[c] Column 5: Column 2–Column 4.

[d] Column 6: $\frac{(\text{Column 5})(100)}{\text{Total of Column 5}}$.

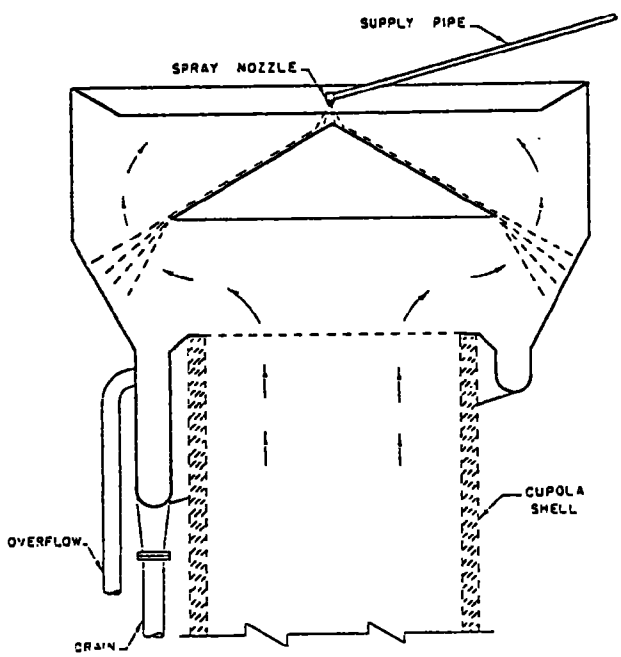
3.11 *Gravity Spray Towers*

The use of sprays located on top of foundry cupolas for control of cupola emission is described by Brechtelsbauer.[8] The final arrangement recommended as a result of operating experience is shown in Fig. 7. Here the flue gas is deflected by means of a conical baffle and is forced to flow through the annulus. A single spray delivers water onto the top of the conical baffle; the water flows across the top of the baffle and contacts the gas in the annular space between the edge of the baffle and the enclosing shroud. The flow of water over the conical baffle also serves to cool the baffle and extends the life of the cone. The tests indicate that the dust content of the outlet gas can be reduced to approximately 0.2 grain per cubic foot of gas, measured at standard conditions, with liquid

consumption of approximately 6 gpm per sq ft of cross-sectional stack area. The installation[8] is inexpensive and this degree of scrubbing is stated to meet the code requirements in many areas of the country.

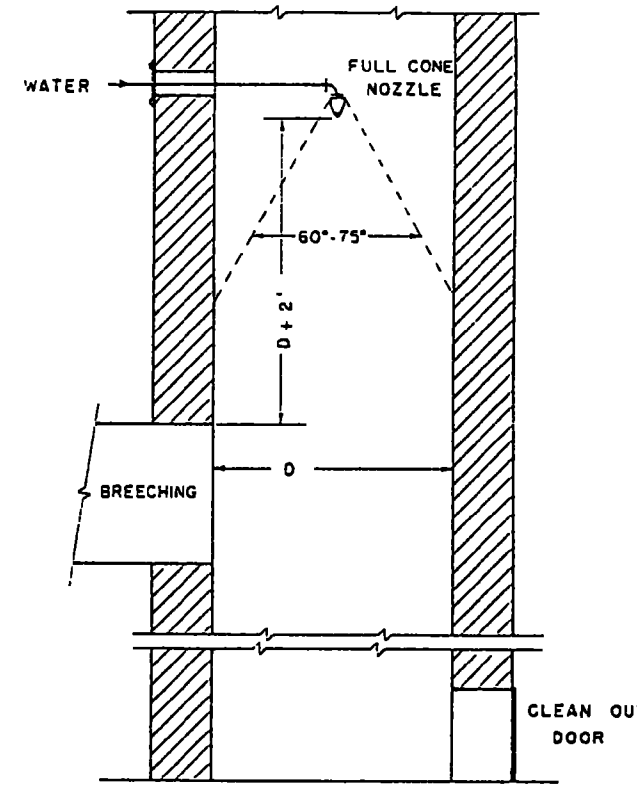
Updegraff[72] reports the results of a laboratory study on collection of fly ash and dust from boiler stacks during soot-blowing and fire-cleaning periods by means of a single nozzle installed centrally in the stack. An arrangement recommended by Bituminous Coal Research, Inc.,[66] is illustrated in Fig. 8. The spray collection efficiency was shown to be influenced primarily by the water rate. A rate of 0.4 gpm per sq ft of stack area appeared to be optimum, giving a collection of 60 to 70 per cent of the dust. The selection of a proper nozzle is based on water pressure available; nozzles which deliver the recommended volume of water are easily selected from manufacturers' catalogs.

An example of a considerably more complicated spray tower is described by Ashman,[5] see Fig. 9. The dust-laden gas is made to follow an upward tortuous path during which phase it is contacted by liquid introduced at the top of the tower and is cascaded downward over the baffles. Primary sprays located near the gas inlet are used to reduce the temperature of gas and to facilitate dust removal. The mechanism of dust collection is principally the inertial impaction of the dust on wetted surfaces, although some



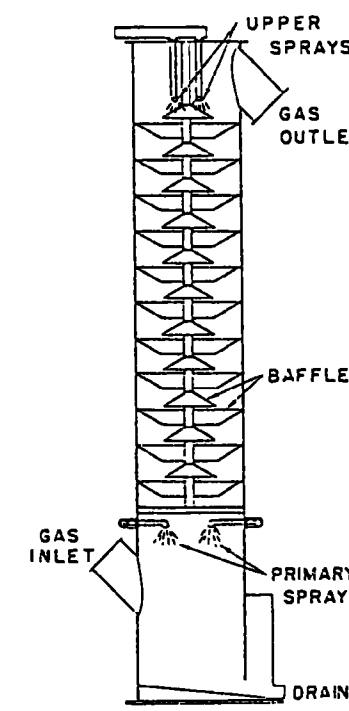
Courtesy of American Foundrymen's Association.

FIG. 7—Cupola Gas Scrubber.



Courtesy of Bituminous Coal Research, Inc.

FIG. 8—Furnace Stack Spray Scrubber.



Courtesy of R. Ashman and Institution of Mechanical Engineers (London).

FIG. 9—Gravitational Spray Scrubber.

impaction on water droplets cascading from the edges of baffles undoubtedly also occurs.

The only data of sufficiently general interest on the collection efficiency of gravity spray towers is that given by Stairmand;[68] see Par. 2.60 and Fig. 6. The data refer to performance of a large industrial spray tower, handling approximately 70,000 cfm of gas. The tower is 22 ft in diameter by 66 ft high and uses 75,000 gph of water, about 18 gal per 1,000 cu ft of gas. The pressure drop is stated to be negligible, less than 1 in. of water. The efficiencies of removal of particulates in such a tower range from 99+ per cent for particles 60 microns or larger to 55 per cent for 1-micron particles, see Fig. 6. An overall efficiency of removal of particles in a test aerosol containing solid particles of sizes up to 150 microns is approximately 92 per cent, decreasing to 77 per cent for a test aerosol containing solid particles of sizes up to 10 microns only, see Table 2.

Although the gravity spray tower is to some extent tending to become obsolete because of its relatively high cost, it is often used as a precooler where very large quantities of gas are involved, e.g., in blast furnace operation. Another advantage is that no very fine clearances are involved, thus it can handle relatively high concentrations of dust without chokage. As indicated in Par. 2.40, because very small spray droplet sizes are not called for, the spray nozzles need not produce fine jets and reliability is improved, with the added advantage that the spray water can be recirculated until it contains quite a high concentration of suspended solids, which simplifies the effluent treatment and disposal problems.

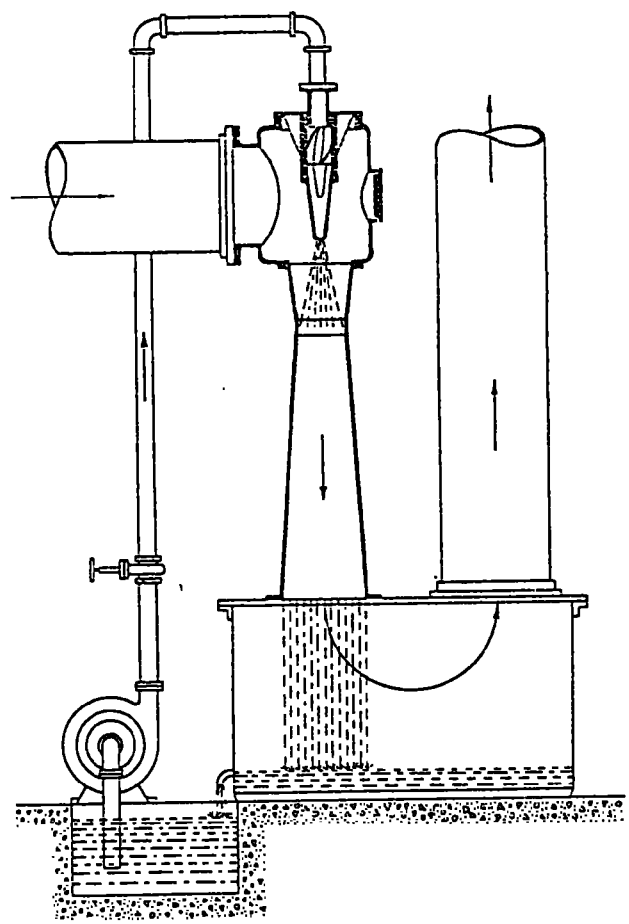
The grade-efficiency curve for a spray tower, see Fig. 6, shows that the collection efficiency of a spray tower decreases rapidly for particles smaller than approximately 2 microns. The consideration of the effect of droplet size on target efficiency also shows that there is little point in decreasing the droplet size, even if it could be accomplished economically. Thus, inherently, the use of spray towers is limited to cases where a high collection efficiency of particles in sizes below 2 microns is not required.

3.12 *Water-Jet Scrubbers*

In an effort to increase the relative velocity between the droplets of the scrubbing liquor and the aerosol, the scrubbing liquor may be supplied in the form of a high-velocity jet directed along the axis of a venturi nozzle. In the usual industrial construction the water-jet is utilized both as a means for moving the dust- or fume-laden air and for removal of particulates. A typical water-jet scrubber is shown in Fig. 10.

Manufacturers' catalogs [23, 26] provide pertinent data on the sizes of units and nozzles, water consumption as a function of the water pressure available, and the amount of gas to be passed through the unit. The literature [23] states that standard units permit a reduction of 70 to 95 per cent of particulates with a single unit and a reduction of 80 to 99 per cent in a bank of four units placed in series for particles larger than 5 microns. Where the particle size is less than 5 microns, much higher velocities and turbulences are required for adequate collection. No other information on collection efficiencies has been published.

As is shown in Fig. 10, in addition to the jet, a water-gas separating device, which may be a simple gas reversal chamber, sometimes



Courtesy of Schutte and Koerting Company.

FIG. 10—Typical Water-Jet Scrubber.

equipped with baffles, must be provided on the outlet side. Sizes ranging from 3 in. to 72 in. in inlet diameter are available with capacities up to 110,000 cfm (at 1-in draft, water pressure is 200 psig, and water flow through the nozzle is 10,000 gpm).

3.13 *Chamber Scrubbers with Mechanical Spray Generators*

Kristal, et al.,[38] describe a wet chamber scrubber consisting of single or multiple collection stages, each containing a venturi tube and two mechanical spray generators. An experimental unit, tested by the authors, consisting of four similar collection stages is diagramed in Fig. 11; the individual stages are contained in quadrants of a cylindrical housing, and not in a simplified structure as is schematically indicated. In each stage the aerosol encounters a spray in the plenum chamber, passes through the venturi section and again is contacted with a spray in a plenum chamber following the venturi section. In multistage units, the spray generators are used as indicated in Fig. 11.

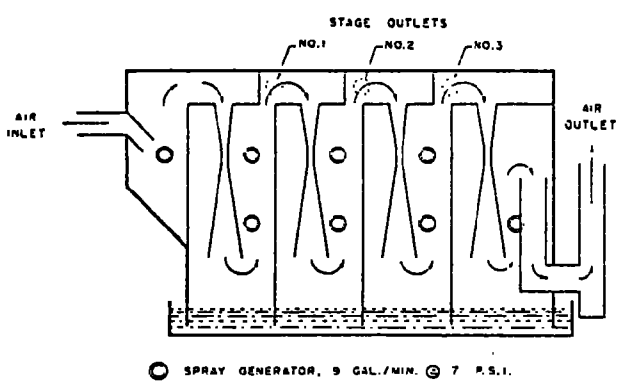
The spray generators are of mechanical design: water jets produced by relatively large orifices ($\frac{1}{16}$-in. diameter) impinge upon a motor-driven, rapidly rotating disk (3,300 rpm) equipped with beveled vanes. The rotation of the disk produces a fine spray of water droplets with a linear velocity initially approaching that of the vane tips (approximately 150 fps). The droplet size is of the order of magnitude of 100 to 400 microns and depends upon the amount of water supplied, speed of the disk rotation, orifice size, and so forth.

In operation, dust-laden gas enters the plenum chamber of the first stage where it encounters the first-spray generator. Collisions between spray droplets and particles in this zone, followed by inertial separation of large drops (prior to entering the venturi tube), afford a considerable degree of dust removal. The aerosol then enters the first-stage venturi tube in which additional collisions occur. Here, because of an increase in approach velocity between the relatively large water droplets and the small dust particles in the accelerating air stream, significant target efficiencies are obtained. The velocity of small particles remains essentially the same as that of the gas so that they pass through a zone of relatively slow-moving, large droplets, which increases the probability of capture by impaction. A small temperature drop, produced by rapid (adiabatic) expansion, occurs in the water-saturated gas stream as it traverses the expanding portion of the venturi. Contrary to the expectation of the designers, the condensation of water vapor on dust particles serving as nuclei, which would "condition" the particles, is not an important mechanism of collection because of the very brief retention time.

After leaving the venturi tube the aerosol enters a second plenum where it passes over the second-spray generator. For single-stage operation the aerosol is then withdrawn through a droplet eliminator. For multistage operation the cycle is repeated as shown in the schematic diagram, Fig. 11.

The collection efficiency of the device depends upon the aerosol size, the number of stages, and the rate of gas flow. Significant improvement was observed by using a second stage, but use of additional stages produced only minor improvement. Efficiencies determined for a single stage varied from 99 per cent by weight for resuspended fly ash (median diameter—count basis, 0.6 micron; mass basis, 14.3 microns) to 22 per cent for iron oxide fume (median diameter—count basis, 0.03 micron; mass basis, 0.6 micron).

The device is characterized by rather high pressure loss, approximately 7 in. of water per stage, and large power and water requirements compared to other wet collectors capable of similar performance. The mechanical spray generator, however, is nonclogging; its use may eliminate the need for elaborate filtering apparatus and thus permit the economic recycling of the spent spray water in regions of sparse water supply.



Courtesy of the Harvard Air Cleaning Laboratory and U.S. Atomic Energy Commission.

FIG. 11—Experimental Four-Stage Wet Collector Equipped with Mechanical Spray Generators.

3.20 Cyclonic Scrubbers

This group of wet collectors includes several types of units in which scrubbing is combined with cyclonic action. In these units, the action of water droplets conditions the aerosol particles by a combination of impaction, humidification, and condensation. The centrifugal motion of the aerosol is utilized to separate the conditioned particles from the gas phase by an inertial mechanism. The numerous industrial modifications differ in the methods of introducing the scrubbing liquor, inducing centrifugal motion of the aerosol, arrangements for reducing entrainment, and in details of removing the sludge from the unit.

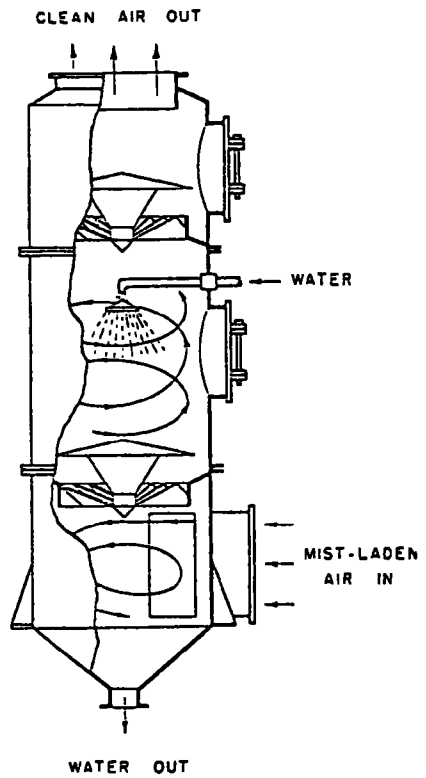
Several typical industrial modifications of cyclonic scrubbers are discussed in the following sections and illustrated in schematic drawings. All of these units can be used to clean hot gases; scrubbing liquor usually is recirculated, provided appropriate arrangements for removing the collected solids are made; and soluble constituents of the gas phase are absorbed in the scrubbing liquor.

3.21 *Cyclonic Scrubbers Equipped with Vane Baffles*

These units are cylindrical towers with a tangential entry of the aerosol. Several typical units are illustrated in Fig. 12 through 17.

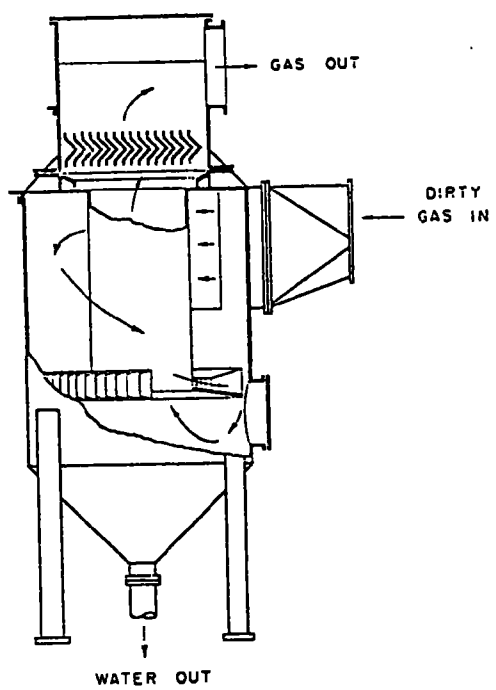
The cyclonic wash scrubber, illustrated in Fig. 12, accomplishes scrubbing [11, 47] of an aerosol by a combination of inertial and impaction mechanism. The unit is an arrangement of one or more washing stages followed by an eliminator stage, as shown in Fig. 12. Centrifugal motion is imparted to the gas stream both by the tangential inlet and by the vanes. Washing liquid usually is introduced through nozzles above the top washing stage. In a multistage arrangement the lower stages may be supplied with additional liquid, this arrangement is recommended for high dust loadings to maintain desired slurry characteristics and also for prehumidification where elevated temperatures are encountered.

In operation, the dust-laden air enters the lower chamber. The centrifugal motion aided by initial wetting removes the relatively large particles from the air stream. The air stream then is accelerated by passing through the vanes of the washing stage where particulates impinge upon wetted surfaces of the vanes. The accelerated, centrifugally moving air stream then contacts the washing liquid in the center spray



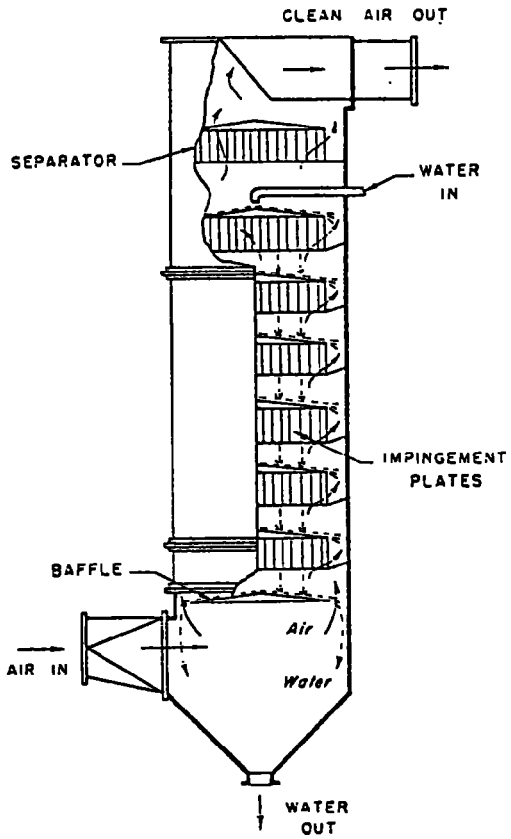
Courtesy of C. F. Montross and *Chemical Engineering*.

FIG. 12—Cyclonic Wash Scrubber.



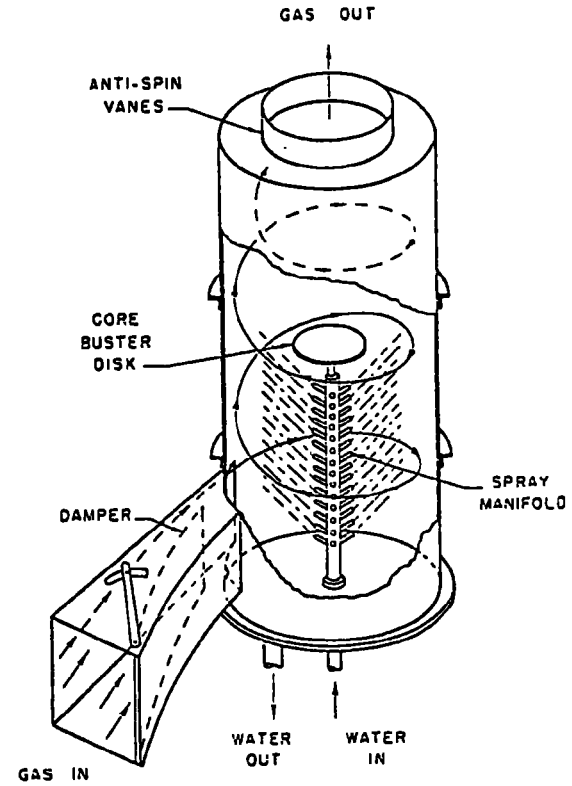
Courtesy of C. F. Montross and *Chemical Engineering*.

FIG. 13—Cyclonic Baffle Scrubber.



Courtesy of C. F. Montross and *Chemical Engineering*.

FIG. 14—Cyclonic Multiple-Baffle Scrubber.



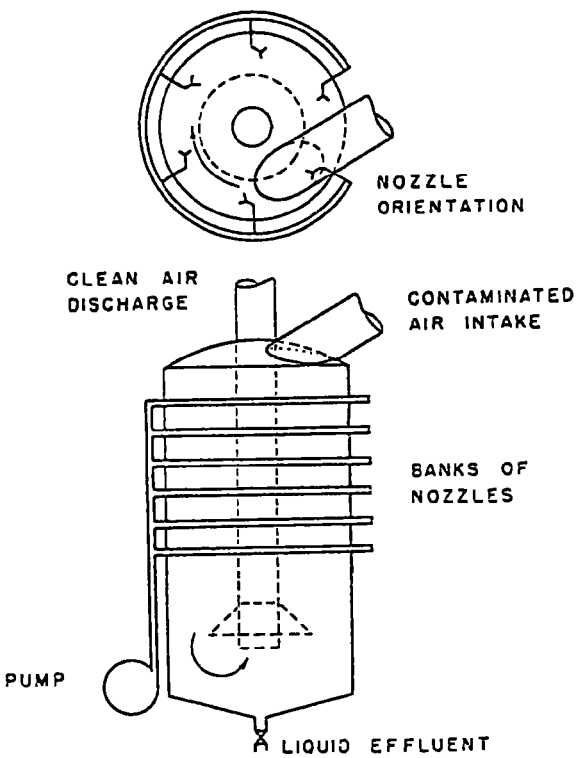
Courtesy of C. F. Montross and *Chemical Engineering*.

FIG. 15—Cyclonic Spray Scrubber I.

chamber, where the particles are impacted upon the liquid droplets and the latter are separated from the gas stream by centrifugal motion. A shielded-cone baffle prevents formation of a vortex in the air stream, and directs the liquid onto the vanes and into the centrifugal path of the air stream.

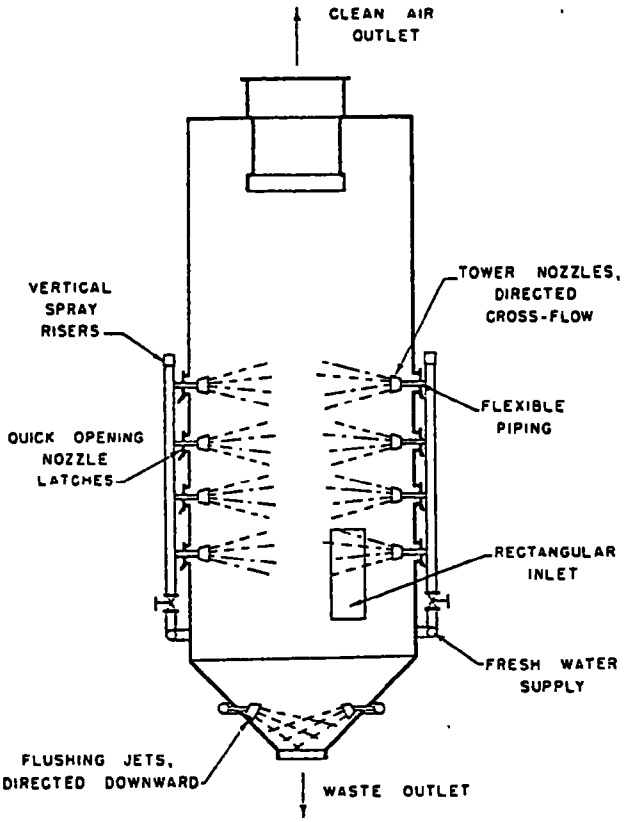
A set of vane baffles is provided at the top of the tower to reduce the entrainment of liquid. To increase the efficiency of removal, two or more washing stages of similar design may be required. For removal of submicron particles, multivane designs are used; in these, two rows of vanes are mounted inversely against each other and are spaced more closely to provide a larger surface area for impingement.

Units are designed with capacities ranging from 500 cfm to 40,000 cfm of gas. Normal water requirements for units having a single washing stage are approximately 2 gal per 1,000 cu ft of gas. The pressure drop ranges from 1½ in. to 3 in. of water. Units employing more than one washing stage are characterized by a higher water requirement and pressure drop.



Courtesy of D. G. Hudson and *Heating and Ventilating*.

FIG. 16—Cyclonic Spray Scrubber II.



Courtesy of Buffalo Forge Company.

FIG. 17—Cyclonic Spray Scrubber III.

One manufacturer [11] states that collection efficiencies of 98 to 99 per cent by weight can be realized in most cases. Friedlander, et al.,[22] reports a weight collection efficiency of 74 per cent, when the effluent from a dry-cyclone installation was washed in a hydraulic scrubbing tower of the design described herein. The two figures are not necessarily contradictory. The higher efficiency refers to collection of particulates from usual industrial effluents in which a fairly wide range of particle sizes is encountered; the lower efficiency refers to secondary treatment of an effluent with low loading (5.8 grains per cubic foot) and particle size of 1.5 microns and less.

Performance efficiency data of wider applicability which would relate the collection efficiency with particle size, such as is illustrated in Fig. 6, is not available. It would be expected, however, that a properly designed unit of this type would give a grade-efficiency curve intermediate between that of a spray tower and that of a wet-impingement scrubber, approaching the latter. As is shown in Fig. 6 and 23, a recovery of 98 per cent is not unlikely for the hydraulic scrubbing tower combining the cyclonic and impingement effects.

Essentially the same principles are utilized and comparable effectiveness of operation is realized in other multistage towers with a somewhat different design of vane baffles, see Fig. 13 and 14.

3.22 *Cyclonic Scrubbers with Radial Spray Injection*

Another widely used wet collector, a cyclone spray scrubber, based on the scrubbing of a centrifugally moving gas stream with a liquid spray,[23, 34, 36] is illustrated in Fig. 15. In this unit dust-laden gas enters tangentially at the bottom of a cylindrical tower and pursues an upward spiral path. No baffles are used. Spray is introduced into rotating gas from an axially located manifold in the lower part of the unit. A core-buster disk is located usually above the sprays to prevent formation of a vortex. The spray droplets sweep across the path of the gas stream and, because of the centrifugal motion imparted to them by the gas stream, impinge upon the wall of the tower, run down and out the bottom of the unit together with the collected particulates.

The cyclone spray scrubber is an efficient device for removing small particles from gases when the particles are larger than 2 microns. For smaller particles the efficiency of the cyclone spray falls off rapidly as the particle size decreases, unless extremely high ratios of the scrubbing liquid to gas are used. This decrease in efficiency of deposition of the small particles has been ascribed to streamlining of particles around the drops.[36]

Kleinschmidt [34] and Kleinschmidt and Anthony [36] developed an equation for the overall efficiency of removal of dust particles by a scrubber of the type described as a function of:

D = diameter of tower, in inches.
W = effective volume of the scrubbing liquid, in cubic feet per minute.
d = diameter of droplets formed, in inches.
G = volume of gas scrubbed, in cubic feet per minute.

For example, for an 8-ft-diameter cyclone in which 25,000 cfm of gas tangentially enter through a 4-in. by 2-in. inlet, the centrifugal force is approximately 27.5 times gravity and

the target efficiencies of individual droplets of 100-micron diameter are estimated to be:

Particle Size (Microns)	Target Efficiency
5	0.98
2	0.32
1	0.11
0.5	0.0
0.2	0.0

Equation (6), developed in Par. 2.50, relates the overall effectiveness of particle removal to the conditions of scrubbing by including the target efficiency in the exponent of *e:*

$$E = 1 - e^{-\frac{3}{4}\eta_t \frac{P'W}{dG}}$$

Thus, the overall efficiency of a cyclonic scrubber is affected by all of the factors which determine the value of η_t:

1. Particle size.
2. Relative velocity between particles and spray droplets.
3. Density of particles.
4. Viscosity of gas.
5. Droplet size.

In a cyclonic scrubber the relative velocity between particles and spray droplets varies continuously as the droplet traverses the path from the nozzle to the wall; the distribution of droplet diameters is determined by the nozzle design, pressure of liquid, rate of liquid, and so forth. A theoretical construction of a grade-efficiency curve thus becomes very difficult; experimental data on effectiveness of cyclonic scrubbers are fragmentary and meager. An empirical method of scrubber design based on performance of a small scrubber, or a large scrubber operating under different conditions, is described by Kleinschmidt.[24]

The overall efficiencies typical of a number of industrial installations are assembled below; these efficiencies apply only to specific installations described in the references cited:

Cyclonic spray scrubbers require from 2 to 10 gal of water per 1,000 cu ft of gas. The pressure drop is usually in the range of 1 in. to 4 in. of water. A variety of corrosion-resistant materials is used in cyclonic spray scrubber construction to permit its use for the scrubbing of gases containing soluble and corrosive components.

3.23 *Cyclonic Scrubbers with Circumferential Spray Injection*

In another version of a cyclonic spray tower, described by Hudson [24] and Thomas,[70] the spray nozzles are placed in several parallel banks throughout the height of a vertical tower. The nozzles are arranged to discharge at a common angle and are directed nearly tangentially to aid in imparting a centrifugal motion to the aerosol traversing the tower. A spray tower of this design is shown in Fig. 16. The dust-laden gases enter at the top of the tower, spiral downward through the tower, and exit through a central duct, concentric with the tower.

A spray tower of a similar design [23] features a construction with easily accessible nozzles, permitting inspection and replacement of the nozzles while the unit is in operation. In this design, shown in Fig. 17, the aerosol enters at the bottom of the tower through a rectangular tangential port and exits from the top of the tower.

In both designs the scrubbing liquid is introduced through the nozzles at high pressures, 400 psig to 600 psig, in an effort to improve the collection of small particles. Information on droplet size in a spray thus produced is not available, although Silverman and Davidson [65] give indirect evidence that at 400 psig the droplet size is less than 50 microns. In a fog-like spray the droplet size is well below the optimum size needed for impaction. The droplets quickly approach the same velocity as the suspended aerosol particles and thus high impaction efficiencies cannot be realized. The increased spe-

Dust	Particle Size Range (Microns)	Dust Loading (Grains per Cubic Foot) Inlet	Dust Loading (Grains per Cubic Foot) Exit	Removal Efficiency (Per Cent)	Reference No.
Lime	2.0 to 40.0	9.2	0.08	99	51
Lime	1.0 to 25.0	7.7	0.25	97	51
Lead compounds	0.5 to. 2.0	...	...	97	51
Iron ore, coke, etc.	0.5 to 20.0	3.0 to 24.0	0.03 to 0.08	98	51
Ammonium nitrate	(Unstable)	...	...	99+	51
Chemical fume	0.5 to 3.5	17.0	1.02	94	36
Chemical fume	0.2 to 2.0	2.25	0.79	65	36
Boiler fly ash	2.0 to 5.0	0.25 to 2.5	0.045 to 0.125	82 to 95	36

cific surface area of the fine droplets, however, would tend to counteract this effect and facilitate impaction. In addition, Brownian motion diffusion would become operative and submicron particles would collide with and impact upon the fog droplets. This consideration of mechanisms of collection suggests that fog-producing nozzles would add to the effectiveness of collection of submicron particles. In the units diagramed in Fig. 16 and 17, larger particles would be collected by inertial forces induced by the centrifugal motion of the gas, and the submicron particles would be collected by combination of diffusion and inertial impaction.

Collectors of the type described herein sometimes are referred to as "fog filters." [24, 70] The fog filter, because of its limitations and the great diversity of engineering processes, must be engineered to the job. It appears to be more effective on aerosols containing particles less than 10 microns in diameter; presence of a large proportion of larger particles requires the use of a companion unit such as a dry cyclone. Performance data for the fog filter on some industrial gases given by Thomas [70] indicate a 100-per-cent removal of sulfuric acid mist, 90.0- to 99.4-per-cent removal of solids from fertilizer mixing plants, and approximately 90-per-cent removal of low-density organic solids, such as phthalic and maleic anhydrides.

A composite efficiency tabulation for a similar scrubber using 400 psig sprays, cited by a manufacturer,[25] is as follows:

Size Fraction (Microns)	Efficiency (Per Cent by Weight)
0.0 to 0.5	78.6
0.5 to 1.0	83.4
1.0 to 2.0	89.7
2.0 to 3.0	94.0
3.0 to 4.0	96.4
4.0 to 6.0	97.5
6.0 to 8.0	98.6
8.0 to 10.0	99.2

These data are presented also in the form of a grade-efficiency curve in Fig. 18 by plotting the efficiencies versus the average of size fractions.

For scrubbers of this type, collection efficiencies can be brought to almost any desired level for many materials by the following means: [70]

1. Increasing tower height.
2. Compounding stages.
3. Controlling gas volumes.
4. Regulating liquid flow.
5. Regulating spray pressures.

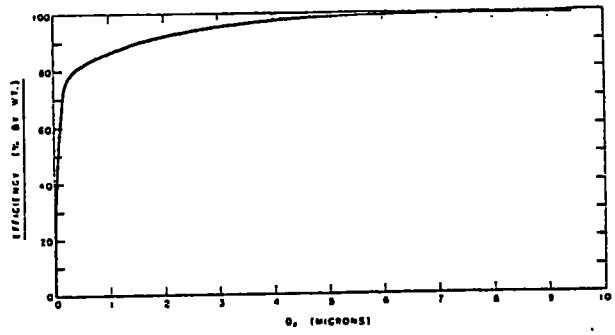


FIG. 18—Grade-Efficiency Curve for Cyclonic Spray Scrubber.

The presence of certain dissolved salts, and suspended solids, tends to clog the small orifice nozzles, therefore making it necessary to adequately provide for filtration of scrubbing liquor, if re-used, and to flush and clean the nozzles with greater frequency than would be the case for nozzles with larger orifices. Although the pressure drop across a typical tower is low (1 in. to 4 in. of water) compared to those found in most high-efficiency collectors, the use of high-pressure nozzles involves a high rate of energy use for pumping the water through the nozzle. Manufacturers' catalogs offer rating tables relating the pressure-volume characteristics for a number of sizes available. The towers are manufactured for gas flows between 2,500 cfm and 50,000 cfm.

3.24 *Air Tumbler*

Another device in which centrifugal force is combined with scrubbing action of a liquid is diagramed in Fig. 19. The manufacturer describes this unit as a wet dynamic dust collector,[1, 6] which separates the dust from the gas by centrifugal action, while the water wets and entraps the dust. The interior of the unit is a stationary screw within a horizontal, pear-shaped barrel.

The dust-laden gas enters at one end of the barrel under the suction of an exhaust fan connected to the outlet at the opposite end. During the flow through the barrel, the dust particles are continually centrifuged through four revolutions along a helical path formed by the screw. The lower portion of a horizontal barrel contains water and the surface of the water is swept by the gas stream. The angular impingement of the friction of the gas against the surface of the water induces a sheet of water to flow around the periphery of the barrel. Thus, the collector is not unlike a wetted-wall cyclone; also, it is similar to dynamic col-

APPENDIX A

DUST COLLECTOR CHARACTERISTICS (ACCORDING TO KANE[22])

Item	Cyclones	High-Efficiency Cyclones	Wet Collectors	Fabric Collectors	High-Voltage Electrostatic Precipitators
Effect of Dust Variations					
Efficiency, particles:					
< 1 micron	Poor	Poor	Poor to fair	Good	Good
1 to 10 microns	Poor	Poor to fair	Fair to good	Good	Good
10 to 20 microns	Poor	Good	Good	Good	Good
> 20 microns	Fair to good	Good	Good	Good	Good
Abrasion resistance	Fair	Fair	Good	Good	Good
Ability to handle sticky, adhesive materials	Fair	Poor	Poor to good	Poor	Poor
Bridging materials give trouble	Slight	Yes	No	Yes	Yes
Fire or explosion hazard minimized	Fair	Fair	Good	Poor	Poor
Can handle hygroscopic materials	Yes	Fair	Yes	With care	With care
Large foreign materials cause plugging	Seldom	Yes	Seldom to yes	Seldom	Yes
Effect of Gas Stream Variations					
Maximum temperature (deg F), standard construction	750	750	No limit	180 to 275	750
Troubles from condensed or entrained mists or vapors	Slight	Considerable	Slight	Considerable	Some
Corrosive gases attack standard construction	Slight	Slight	Severe	Slight	Slight
Collector					
Space	Large	Modest	Modest	Modest to large	Large
Pressure drop	1 in. to 2 in.	3 in. to 5 in.	3 in. to 6 in.	2 in. to 6 in.	1 in. to 2 in.
Reduced volume adversely affects collection efficiency	Yes	Yes with most designs	Depends on design	No	No

APPENDIX B

USUAL AIR CLEANER SELECTIONS FOR INDUSTRIAL PROCESSES (ACCORDING TO KANE[32])

Operation	Concentration	Particle Sizes	Collector Types Used in Industry: Cyclones	High-Efficiency Cyclones	Wet Collectors	Fabric Arresters	High-Voltage Electrostatic Precipitators	See Remark No.*
Ceramics								
Raw product handling	Light	Fine	Rare	Seldom	Frequent	Frequent	No	1
Fettling	Light	Fine to medium	Rare	Occasional	Frequent	Frequent	No	2
Refractory sizing	Heavy	Coarse	Seldom	Occasional	Frequent	Frequent	No	3
Glaze and vitreous enamel spray	Moderate	Medium	No	No	Usual	Occasional	No	
Chemicals								
Material handling	Light to moderate	Fine to medium	Occasional	Frequent	Frequent	Frequent	Rare	4
Crushing, grinding	Moderate to heavy	Fine to coarse	Often	Frequent	Frequent	Frequent	No	5
Pneumatic conveying	Very heavy	Fine to coarse	Usual	Occasional	Rare	Usual	No	6
Roasters, kilns, coolers	Heavy	Medium to coarse	Occasional	Usual	Usual	Rare	Often	7
Coal Mining and Power Plant								
Material handling	Moderate	Medium	Rare	Occasional	Frequent	Frequent	No	8
Bunker ventilation	Moderate	Fine	Occasional	Frequent	Occasional	Frequent	No	9
Dedusting, air cleaning	Heavy	Medium to coarse	Frequent	Frequent	Occasional	Often	No	10
Drying	Moderate	Fine	Rare	Occasional	Frequent	No	No	11
Fly Ash								
Coal-burning:								
Chain grate	Light	Fine	No	Rare	No	No	No	
Stoker fired	Moderate	Fine to coarse	Rare	Usual	No	No	Rare	12
Pulverized fuel	Heavy	Fine	Rare	Frequent	No	No	Frequent	13
Wood-burning	Varies	Heavy	Occasional	Occasional	No	No	No	14
Foundry								
Shake out	Light to moderate	Fine	Rare	Rare	Usual	Rare	No	15
Sand handling	Moderate	Fine to medium	Rare	Rare	Usual	Rare	No	16
Tumbling mills	Heavy	Medium to coarse	No	No	Frequent	Frequent	No	17
Abrasive cleaning	Moderate to heavy	Fine to medium	No	Occasional	Frequent	Frequent	No	18

Grain Elevator, Flour and Feed Mills								
Grain handling	Light	Medium	Usual	Occasional	Rare	Frequent	No	19
Grain dryers	Light	Coarse	No	No	No	No	No	20
Flour dust	Moderate	Medium	Usual	Often	Occasional	Frequent	No	21
Feed mill	Moderate	Medium	Usual	Often	Occasional	Frequent	No	22
Metal Melting								
Steel blast furnace	Heavy	Varied	Frequent	Rare	Frequent	No	Frequent	23
Steel open hearth	Moderate	Fine to coarse	No	No	Doubtful	Possible	Probable	24
Steel electric furnace	Light	Fine	No	No	Considerable	Frequent	Rare	25
Ferrous cupola	Moderate	Varied	Rare	Rare	Frequent	Occasional	Occasional	26
Nonferrous reverberatory	Varied	Fine	No	No	Rare	...	...	27
Nonferrous crucible	Light	Fine	No	No	Rare	Occasional	...	28
Metal Mining and Rock Products								
Material handling	Moderate	Fine to medium	Rare	Occasional	Usual	Considerable	...	29
Dryers, kilns	Moderate to heavy	Medium to coarse	Frequent	Frequent	Frequent	Rare	Occasional	30
Cement rock dryer	Moderate	Fine to medium	Rare	Frequent	Occasional	No	Occasional	31
Cement kiln	Heavy	Fine to medium	Rare	Frequent	Rare	No	Considerable	32
Cement grinding	Moderate	Fine	Rare	Rare	No	Frequent	Rare	33
Cement clinker cooler	Moderate	Coarse	Occasional	Occasional	...	...	...	34
Metal Working								
Production grinding, scratch brushing, abrasive cutoff	Light	Coarse	Frequent	Frequent	Considerable	Considerable	No	35
Portable and swing frame	Light	Varied	Frequent	Rare	Frequent	Rare	No	
Buffing	Light	Varied	Frequent	Rare	Frequent	Rare	No	36
Toolroom	Light	Fine	Frequent	Frequent	Frequent	Frequent	No	37
Cast iron machining	Moderate	Varied	Rare	Frequent	Considerable	Considerable	No	38
Pharmaceutical and Food Products								
Mixers, grinders, weighing, blending, bagging, packaging	Light	Medium	Rare	Frequent	Frequent	Frequent	...	39
Coating pans	Varied	Fine to medium	Rare	Rare	Frequent	Frequent	No	40
Plastics								
Raw material processing			(*See comments under chemicals*)					41
Plastic finishing	Light to moderate	Varied	Frequent	Frequent	Frequent	Frequent	No	42
Rubber Products								
Mixers	Moderate	Fine	No	No	Frequent	Usual	No	43
Batchout rolls	Light	Fine	No	No	Usual	Frequent	No	44
Talc dusting and dedusting	Moderate	Medium	No	No	Frequent	Usual	No	45
Grinding	Moderate	Coarse	Often	Often	Frequent	Often	No	46
Woodworking								
Woodworking machines	Moderate	Varied	Usual	Occasional	Rare	Frequent	No	47
Sanding	Moderate	Fine	Frequent	Occasional	Occasional	Frequent	No	48
Waste conveying, hogs	Heavy	Varied	Usual	Rare	Occasional	Occasional	No	49

* For Remarks see p. 44.

REMOVAL OF PARTICULATE MATTER FROM GASEOUS WASTES

FILTRATION

1.00 INTRODUCTION

1.10 Definition

Filtration is an operation in which a stream of gas carrying suspended particulate matter (dust, fume, fog, mist, or aerosol) is passed through a porous medium in such a way that the particles impinge on, and adhere to, the medium and are thereby removed from the gas which freely passes on through the filter. In many filters the deposit of dust so collected becomes, in turn, the filtering medium for succeeding particles.

As the deposit accumulates, inevitably the porosity of the medium is reduced, eventually to the point where the flow of gas becomes so restricted as to require either: 1, removal of the deposit in order that the medium can be re-used; or, 2, discarding of the clogged filter and replacement with new medium. It is an inherent feature of filtration that arrangements must be provided to accomplish one of these alternatives either periodically or continuously.

1.20 Types of Filters

A variety of filter arrangements and many kinds of porous media may be used. Possible arrangements include passing the dust-laden gas through:

1. A flexible sheet, layer, tube, or bag, as of woven fabric, felt, or paper.
2. A semirigid supported fabric or nonwoven mat of fibrous material.
3. A rigid porous solid.
4. A fixed or packed bed of dry granular particles.*
5. A fluidized or moving bed of granules or fibers.

Fibers used to make fabrics or mats may be of wool, cotton, metal (e.g., steel wool), asbestos, cellulose, fiberglas, Fiberfrax (ceramic), Orlon, Nylon, or other synthetic polymers. They may be used in the natural (dry) condition or treated—as with resins, in order to give them an electrostatic charge; or with a viscous oil, in order to make them sticky. Rigid solids include metal screens, porous metals, or porous ceramics. Fixed or moving beds may be composed of granules of sand, coke, slag wool, crushed rock, and other materials.

The material and type of filter to be used in a given application must be selected with due regard for the composition, temperature, and moisture content of the gas stream; particle size and nature of the dust; corrosion and abrasive effects which may be present; collection efficiency desired; and economic aspects of the operation, including possible recovery of the dust, re-use of the filter, or both.

Filters may be classified in various ways according to type of media, arrangement of support, cleaning mechanisms, etc. A full discussion of filter media and filter arrangements is given in Sect. 3.00. However, it should be pointed out here that a very basic distinction is made between two general modes of filter collection:

1. The medium itself is the essential separation mechanism.
2. The medium acts primarily as support for the collected particles, which become the effective filter.

Auxiliary equipment, such as dust removal and filter removal devices, blowers, ducts, and stacks, is usually involved. There may also be the need for coolers and other gas-conditioning devices before the filtration proper. Sometimes another type of particle-collecting equipment may also be used in series with a filter.

1.30 Range of Application

Dalla Valle has stated: "It is possible to secure almost any kind of filter for handling any type of particle with any desired degree of effi-

* The usual wet-packed tower is considered a wet collector rather than a filter.

SOURCE: Removal of Particulate Matter From Gaseous Wastes--Filtration, Engineering Report Prepared for American Petroleum Institute, New York, NY (1961).

ciency. This can be said of no other method of particle collection known."[23a]

This statement indicates the most important advantage of filtration as a method of particle collection—that it is capable of high-efficiency collection of very small particles. Its use is to be considered whenever a very low dust loading of the effluent gas stream is required, and especially when the particles to be removed are in the range of from 10 microns down to less than 1 micron in size.

On the other hand, filtration is a relatively expensive gas-cleaning operation with several important limitations. If the dust load of the gas to be treated is high, it may be necessary to use another type of collector as a preliminary stage ahead of the filter. Certain filters require a rather low lineal gas velocity for effective operation, and this may, in turn, call for a very large area of filter surface. A relatively large pressure difference is required to force the gas stream through the filter, and this involves large energy consumption in the blower or compressor. Cleaning and renewal devices involve mechanical apparatus requiring careful maintenance. Most filter media must be used at relatively low temperatures and on relatively dry gas in order to avoid excessive deterioration. Many of them have rather limited resistance to corrosion and rather low mechanical strength, which limits the amount of handling they can withstand. Special media have been developed to overcome some of these disadvantages, but their higher cost may not be warranted in many applications.

The following are examples of situations in which filters have been used with satisfactory results:

1. Removing dust from atmospheric air (as used in heating or ventilating systems) by panel filters made up of mats of glass, metal, vegetable fibers, animal hair, etc.; often coated with some oily or adhesive substance or resin (to impart electrostatic charge); usually discarded and replaced when dirty; sometimes washed, retreated, and re-used.[105]

2. Collecting oxide, ash, and carbon fumes from gray iron or nonferrous cupolas in Orlon, wool, or silicone-treated glass wool bag filters, cleaned by periodic manual shaking.[20, 114]

3. Removing sand and stone dust from kiln stack gas leaving a bituminous mix asphalt plant, by filtration through dense wool felt bags (following a preliminary cyclone collector), cleaned continuously by a flow of air from a "reverse jet" traveling over the obverse surface of the bag.[55]

4. Cleaning blast furnace gas by bag filters made of a specially woven fabric of asbestos and glass fibers, mounted in a special way to minimize the deterioration due to the shaking necessary for cleaning.[70]

5. Removing fine radioactive or other particles with very high efficiency (99.99 per cent) from exhaust or supply ventilation air by a soft felt-like asbestos-bearing cellulose paper formed in thin pleated sheets, used until dirty, and then discarded.[91]

6. Cleaning dust (including carbon particles from generator brushes) from fresh and recirculated air supplied to "motor rooms" by a vertical endless-belt type of continuously traveling screen, self-cleaning and oiled as it dips into a pan of oil at the bottom of the belt.[155]

7. Removing air-borne bacteria in order to produce sterile air in industrial fermentation plants (e.g., in penicillin manufacture), by filtration through thick beds of slag or glass wool, "cleaned" *in situ* by sterilization with dry heat a large number of times before replacement becomes necessary.[18]

8. Carrying fine particles of valuable catalyst from a fluidized bed and recovering them by passing the exhaust gas through porous stainless steel filters made by sintering powdered metal, cleaned by automatic blowback.[92]

9. Removing iron oxide dust in stack gases from an open-hearth furnace by filtration through a horizontally moving bed of fine-fiber slag wool, continuously reclaimed by passing through a washing, drying, and bed-reforming system.[119]

10. Removing coal dust from synthesis gas streams passed countercurrently upward to a vertically moving bed of granular coke, periodically removed from the bottom, washed, drained, and returned to the top.[36]

11. Removing sulfuric acid mist from air by passing it through a fluidized bed of porous silica gel or alumina particles revivified by washing with water and drying for re-use.[36]

The foregoing examples were selected only to give a general idea of the possible applications of filtration methods of particle collection; they are not intended to form a comprehensive survey of the field. They do serve to indicate two broad classes of filter duty, which may be defined roughly as:

1. The air-cleaning range, characterized by a relatively low dust loading of the carrier gas, e.g., less than 1 grain per 1,000 cu ft.

[a] Figures refer to REFERENCES on p. 54.

2. The dust-collecting range, with loading of the carrier gas ranging upward from 1 grain per 1,000 cu ft to as high as (5) (10^4) grains per 1,000 cu ft.

In general, the nonrenewable mat, pad, paper or bed type of filter will be used for air cleaning (examples 1, 5, 7), with a cleanable type used in some cases (example 6). The heavier loadings involved in dust collecting usually require renewal of the filter by cleaning, either to recover valuable material in the dust (example 8) or to prevent excessive cost of filter replacement where the main purpose of collection is to reduce air pollution (examples 2, 3, 9, 11) or process gas contamination (examples 4, 10).

1.40 The Role of Filters in Collection

The position of filtration in comparison with other methods of particle collection is a question of relative effectiveness and relative cost. This is indicated in a general way by the classifications given by Kane [66]:

1. High-efficiency, high-cost collectors:
   a. Electrostatic precipitators.
   b. Sonic agglomerators.
2. High-efficiency, moderate-cost collectors:
   a. Fabric or fibrous filters.
   b. Wet collectors, packed towers, scrubbers, and centrifugals.
3. Low-cost, lower efficiency designs:
   a. Cyclones and dry centrifugals.
   b. Dry dynamic.
   c. Inertial.

A chart presented by Stairmand [131] based upon actual operating data generally supports the foregoing classifications, although showing venturi scrubbers as being most costly and electrostatic precipitators as less efficient than filters (see Sect. 4.00, Fig. 11).

The important effect of particle size upon collector performance is illustrated by the charts presented by Kane [66] and McCabe.[93] These indicate that filters retain their high-efficiency characteristics down to finer particle sizes than any other collectors except electrostatic precipitators.

These general results are supported by many tests reported in the literature. They serve to substantiate the statement that filtration is a moderate- to high-cost method of collection, capable of the highest efficiency, and particularly effective in dealing with fine particles.

It should be noted that these statements refer mainly to fabric and fibrous filters, inasmuch as the position of porous solid, packed-bed, and moving-bed filters is not indicated in these classifications. This is because these methods are of rather recent development and there is insufficient experience available from commercial installations to judge their ultimate role. Most of the pilot plant or developmental type of studies which have been reported, however, indicate that such filters are all also capable of high efficiency, but probably at higher cost—which may be justifiable in special applications.

2.00 THEORY OF FILTRATION

A comprehensive theory of the operation of filters should deal with the mechanism and efficiency of particle collection, the life of the filter medium, and the pressure drop through the filter. Each of these questions will be considered in turn. For the reader who does not wish to consider theory in detail, the following paragraphs will give the highlights of the theoretical approach and sources of the practical results obtained: 2.11, 2.127 (p. 12, 15), 2.133, and 2.30.

Theoretical developments have for the most part been limited either to the performance of a "clean" filter, i.e., at the beginning of the collection of a homogeneous dust, or to one on which a homogeneous dust has collected in a uniform manner. That actual filter behavior may be more complex than is contemplated in these simplified models is pointed out in several places in the following discussion.

2.10 Particle Collection

In order for a particle to be removed from the gas stream, it is first necessary that it collide with the surface of an element (e.g., fiber or granules) of the filter and then adhere to this element, at least until it is desired to clean the filter. The theory must therefore deal first with the interaction between individual particles and individual filter elements, and then with the composite effect of all the elements making up the filter medium.

2.11 *Basic Mechanisms for Collision*

Stoppage of particles by direct sieving action is seldom an important aspect of dust filtration as the spaces between the filter elements are usually much larger than the particles collected. If this were not the case, clogging would occur

rapidly, with an attendant severe rise in pressure drop across the filter.

Other mechanisms must be relied upon to cause the particles to collide with the obstacle, which the filter element represents, in their path. These have been identified as:

1. Direct interception or flow line interception.
2. Inertial deposition or impaction.
3. Diffusional deposition or Brownian movement.
4. Gravity settling.
5. Electrostatic precipitation.
6. Thermal precipitation.

Direct interception, or flow line interception, occurs whenever the fluid streamline along which a particle approaches a filter element passes within a distance from the element equal to one-half the particle diameter. If the particle has a very small mass, although of finite size, it will not deviate from the streamline as the latter curves around the obstacle and will therefore collide if the streamline passes sufficiently close. This is illustrated by path A in Fig. 1.

Inertial impaction occurs when the mass of the particle is great enough that it cannot follow the streamline rapidly curving around the obstacle but tends to continue along a path of lesser curvature. This brings the particle closer to the filter element than it would have approached along the streamline. Collisions may therefore occur due to this inertial effect, even when flow line interception would not take place (see path B in Fig. 1).

Brownian movement will be superimposed upon the flow motion of very small particles. This may cause a particle to diffuse toward, and contact the surface of, a filter element as it flows by. The particle must pass sufficiently close to the obstacle for a long enough time in order for the relatively slow diffusional velocity to bring about a collision. The process is akin to mass transfer by molecular diffusion.

Gravity settling onto the filter surface may result from vertical motion of a particle due to its weight as it passes through the filter.

Electrostatic precipitation will occur as a result of electrostatic forces drawing particle and filter element together whenever either or both possess a static charge. These forces may be either direct attraction, where both particle and filter are charged, or induced, if only one of them is charged. Such charges are usually not present unless deliberately introduced during the manufacturing of the filter. They must be strong enough to draw a particle out of its flow path to the filter surface during the time the particle passes nearby.

Thermal precipitation may occur whenever there is a temperature gradient between the gas stream and the filter surface. Particles may thus be caused to migrate toward a cold surface or away from a warm one. Thermal gradients do not exist in normal practice, and this principle has not yet found industrial application. It will not be discussed further in this report.

All of these mechanisms are not usually in effect at the same time in a given filtration sit-

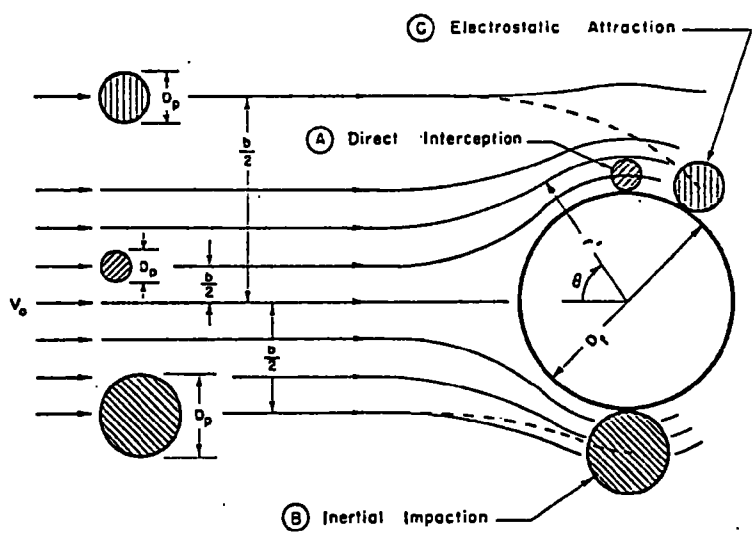


FIG. 1—Streamlines and Particle Trajectories Approaching Filter Element.

uation. Only one, or a combination of just two or three of them, may be involved. It is necessary to analyze each filter application to determine the controlling mechanisms present, in order that the filter may be operated to the best advantage. Which mechanisms are important in a given case will be determined by such factors as: size and density of particles, size and nature of filter elements, velocity and pattern of fluid flow, temperature, nature of gas, existence of electric fields, etc.

Each mechanism may be characterized by a basic dimensionless parameter which may be calculated with reference to a single aerosol particle and an individual filter element. From the magnitude of these parameters, the importance of each mechanism may be judged in a given case and its contribution to the efficiency of the filter estimated. These parameters are discussed in detail hereinafter.

2.12 *Collection Efficiency of Individual Filter Elements*

There are principally two kinds of elements used to make up aerosol filters: fibers and granules. The theoretical ideal model of a filter element may therefore be regarded as either a cylinder (representing a fibrous element) or a sphere (representing a granular element). Granular filters (e.g., deep-bed, fluidized-bed, moving-bed) have not as yet come into widespread use for various reasons; therefore, the spherical model collecting element has been the subject of little or no theoretical investigation as applied to dry filters. For wet collectors of the spray type, the spherical model represents the individual drop of liquid as the collecting element and, therefore, has been studied extensively.

The pattern of theoretical investigation of the various mechanisms is much the same for cylindrical and spherical collectors, with due allowance for the consequences of the geometrical differences. For the reasons just mentioned, only the theory of cylindrical elements will be presented here. A review of the theory of spherical elements may be found in the report *Wet Collectors* by Gilbert, which is another in this API series on dust collection.

In theory, the idealized aerosol particle is always regarded as a sphere. Assuming that each such particle which collides with a filter element adheres to it and therefore may be regarded as "collected," the single-element efficiency of collection or "target" efficiency is defined as

$$\eta = \frac{\text{cross-sectional area of fluid stream from which particles are removed}}{\text{cross-sectional area of filter element projected in direction of flow}}$$

or,

$$\eta = \frac{b}{D_f} \tag{1}$$

In Fig. 1, $\frac{b}{2}$ is shown as the initial distance from the central streamline of particles which just graze the surface of the element, and D_f is the diameter of that element. The value of b, and the resulting target efficiency, must be considered for each mechanism separately and for various combinations of mechanisms operating simultaneously.

Since any particle passing by whatever mechanism within distance $\frac{D_p}{2}$ of the element $\theta = \frac{\pi}{2}$ will be collected, the efficiency can also be calculated as a flow ratio:

$$\eta = \frac{Q}{v_0 \frac{D_f}{2}} \tag{2}$$

Here Q represents the volumetric rate of flow per unit length of cylinder in the space within a distance of $\frac{D_p}{2}$ of the surface at $\theta = \frac{\pi}{2}$. Q is found from the velocity profile $v_{\frac{\pi}{2}}$ at $\theta = \frac{\pi}{2}$ according to

$$Q = \int_{\frac{D_f}{2}}^{\frac{D_f + D_p}{2}} (v_{\frac{\pi}{2}})\,(dr') \tag{3}$$

2.121 DESCRIPTION OF FLOW PATTERN: A description of the pattern of streamlines around a filter element is evidently needed in developing the theory of collection by any of the mechanisms. For a cylinder, exact mathematical descriptions taking into account the boundary layer and separation lines are available but very complicated. It has been assumed that the equations of streamlines relatively close to, and in front of, the cylinder are all that is needed. On this basis, two simplified descriptions have been used: 1, ideal fluid; and, 2, viscous fluid.

Ideal fluid: At high Reynolds numbers (strictly, as $N_{Re} \rightarrow \infty$) the flow in front of a

ZIEGLER, F. G.

D_f. At medium velocities, direct interception is important; and the smaller D_f, the higher the filtration criterion.

3. For the same D_f, D_p, and β: The filtration criterion decreases at first, remains fairly constant, and then increases as V increases.

4. For the same D_f, V, and β: At the high values of V, the filtration criterion increases with increasing D_p. At medium values of V, the filtration criterion remains essentially constant. At high values of V, the filtration criterion increases with decreasing D_p.

There are really no quantitative theoretical methods to predict filter life or the optimum time of effective performance. The experimental data of Rowley and Jordan,[107] for example, show that η_e may remain essentially constant for some time after Δp begins to increase appreciably. When Δp is increasing more rapidly than the penetration, the filtration criterion begins to decrease rapidly. At this point, it is necessary to stop and either clean or renew the filter. However, this point can be determined only by trial under operating conditions.

3.00 INDUSTRIAL DUST FILTERS

Industrial dust filters may be classified according to their construction and mode of operation by the following scheme:

Cloth or Fabric Collectors

A. Intermittent—operation interrupted by cleaning:

1. Bags, bag houses, tubes, hoses.
   a. Cleaned by shaking or rapping.
   b. Cleaned by reverse flow of air.
2. Screen-supported envelopes.
   a. Cleaned by shaking or rapping.
   b. Cleaned by reverse flow of air.

B. Continuous—cleaning continuous during operation:

1. Multiple sections of A-1 and A-2.
2. Reverse-jet filters.
3. Nonshaking types.

Fixed Beds or Layers

A. Granular—deep beds of coke, sand, etc.

B. Fibrous:

1. Air filters—mats of fibers for air cleaning.
   a. Viscous impingement—fibers coated by fluid adhesive: 1, disposable; 2, renewable; 3, washable; 4, automatic self-cleaning (see *Moving Beds*, B-1).
   b. Dry: 1, disposable; 2, renewable; 3, washable; 4, automatic self-cleaning (see *Moving Beds*, B-1).
2. Mats or pads for dust recovery.
   a. Dry, through flow.
   b. Radial flow, variable compression.
   c. Treated—electrostatic, etc.
3. Papers.
   a. High efficiency: cellulose, asbestos, glass, plastic.
   b. Multiple plies.

C. Rigid porous:

1. Porous metal.
2. Plastic.
3. Porous ceramic.

Moving Beds

A. Granular:

1. Gravity flow of collector granules.
2. Fluidized bed of collector granules.

B. Fibrous:

1. Self-cleaning air filters.
2. Traveling mat of collector fibers.

The construction, operation, applications, and performance of each of the foregoing types of filters will be described briefly.

3.10 Cloth or Fabric Collectors

The collecting medium is a woven or felted fabric which first collects particles by the various mechanisms of impingement until a layer or floc of dust is formed. This, in turn, acts as the medium to collect additional particles by sieving action. The collection becomes more efficient, but the pressure drop increases ever more rapidly as the operation proceeds. Cleaning removes most of the floc but leaves a basic layer in the fibers so that efficiency increases after new cloth is installed, and the layer of dust is an essential feature in obtaining high efficiency. For this reason, best results are obtained on gas streams carrying a high load of dust. There are two general designs available: the tube or bag type, and the cloth screen type.

3.11 *Bags, Bag Houses, and Tube Filters*

The filter fabric is in the form of a bag, tube, or hose, either cylindrical or oblong, and suspended vertically. Many such bags are operated

in parallel, all confined in one structure called a bag house. This is possibly the oldest type of filter.

In Bennett's description[7] of one installed in 1906, it is stated that there were 1,920 bags, each 18 in. in diameter by 28 ft 8 in. in length, housed in a reinforced concrete building approximately 90 ft by 126 ft by 60 ft high. These bags were suspended from their closed top ends, with the open bottom ends held in place by rings set in a concrete floor. Dust-laden hot gases from a lead smelter were blown, at the rate of 55,000 cfm, by an enormous fan into a chamber below the bag floor, where much of the coarser and heavier particles settled out. The remaining finer particles were carried up inside the bags by the gas flow and trapped on the inner surface, the clean gas passing through the bags and out to a common flue and stack. Periodically the bags were shaken—apparently manually—to dislodge the collected dust, which then fell into the chamber below. With reduction in size, and improvements in capacity and cleaning methods, this type of filter is still in use today.

Present-day versions of the bag house arrangement include one or more of the following modifications:

1. A mechanical shaking device to agitate the top hanger.

2. Subdivision of the bag house into units which may be closed off individually for cleaning while the remainder continues to operate, thus giving essentially steady continuous operation.

3. Increase of gas pressure on the external side during cleaning in order to cause a reverse flow which aids in removing the dust loosened by shaking.

4. Induced flow of gas by exhaust fans on the clean side, where the dust cannot affect the fan operation.

5. Automatic timing of the filtering and shaking periods; and automatic control of the switchover from one to the other, which may be activated pneumatically by the increase in pressure drop across the fabric as the dust collects.

6. A precoat of filter-aid on the inside of the bag to promote the highest collection efficiency from the very beginning of the collection period.

7. Completely enclosed units for indoor use.

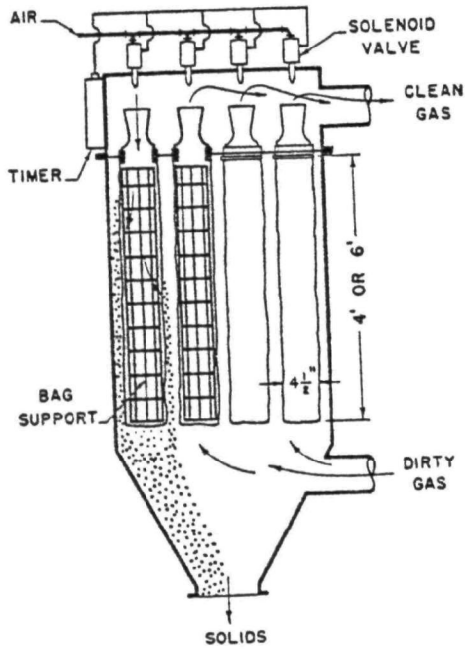
8. Envelope- or oblong-shaped bags for more compact utilization of space.

Standard sizes of bag units are available from a number of manufacturers.[46, 117] Bags are usually made with a length-to-diameter ratio of less than 20 to 1, often in the neighborhood of 16 to 1, a fairly common size being 6 in. in diameter by 8 ft long. Standard units contain anywhere from just a few bags up to as many as 1,300 bags and are capable of filtering up to 60,000 cfm of gas at standard conditions. A variety of fabrics is used, each having certain desirable properties for certain applications. Fabrics are discussed in detail in Par. 3.14.

Operating conditions are fairly standardized with regard to velocity and pressure drop. The value of V, referred to as the air-to-cloth ratio or filter ratio (cfm flow per square foot of filter surface), usually ranges from 2.0 to 5.0 fpm and occasionally as high as 10 or 12 fpm. Pressure drop, Δp, is on the order of 0.2 to 0.5 in. of water for a clean filter, and 2.0 to 5.0 in. of water for a "dirty" one. Operation is always at or near atmospheric pressure, with allowable temperatures depending upon the fabric used. Obviously, the chemical nature of the dust and gas must also be considered in the choice of fabric.

It is generally considered[30, 43, 46, 117, 118] that the most appropriate range of dust loading for bag filters is for $0.1 < c_M < 10$ grains per cubic foot. Tests are cited in the foregoing references which indicate that collection efficiencies of better than 99 per cent by weight are easily obtained on particles coarser than a few microns, and over 90 per cent for particles of approximately 1 micron or finer.

A recent innovation[4] in bag filters is one in which the bags are suspended from a ring holding the open end at the top, with the closed end at the bottom. Fig. 7 shows the arrangement and flow of gas. Cleaning is accomplished by an air jet mounted above each bag. Once a minute, a blast of air from a jet spurts into each bag for $\frac{1}{10}$ sec, entraining some cleaned air, inflating the bag slightly, and shaking it so that dust falls off the outside and drops into the collection chamber below. The dust enclosure is thus free of any moving parts, which helps to keep maintenance low. Filtration is continuous at a uniform pressure drop, as the bags are cleaned sequentially. It is claimed that the filter rate is higher than for other bag houses, and that the operating cost is lower. Per 1,000 cu ft of gas cleaned, only 1 cfm to 2 cfm of air at 40 psig to 80 psig is needed for



Courtesy of *Chemical Engineering*.

FIG. 7—Bag Filters Cleaned by Air Jets.

the cleaning jets. Standard sizes handling up to 5,000 cfm per unit are offered.

Bag houses are used in industry for a wide variety of filtration purposes. Their application is limited chiefly by the range of temperature and moisture content of the gas and by the degree of shaking which available fabrics can withstand. For this reason, gas conditioning (cooling, and reduction of moisture content) prior to filtration is often necessary. Fabric properties are discussed in Par. 3.14 and gas conditioning in Par. 3.42.

With proper precooling of the gas, bag houses have been very successfully used to clean the hot gases arising out of a variety of metallurgical operations such as those performed in gray iron cupolas,[80] electric steel foundries,[40] open-hearth steel furnaces,[95] lead blast furnaces,[6] copper-base alloy smelters,[112] and the like. When strict air pollution control was put in force in Los Angeles County in the early 1950's, bag houses were the only answer to the dust recovery problems of many foundries.[20] Summaries of such applications are given in a number of articles.[75, 97, 114] A typical example is that of the Alhambra Foundry, described by Siechert and Menardi,[116] data for which are tabulated as follows:

Particulate emission: inert ash, silica, and iron oxide—0.8 to 1.6 grains per cubic foot, 25 per cent finer than 325-mesh.
Gas volume: 13,100 cfm at 400 F.
Bag house: four compartments, 112 bags each —each bag 11 in. in diameter by 15 ft long.
Fabric: silicone-treated glass wool—total area 4,835 sq ft.
Filter ratio: 2.7 fpm.
Operating conditions: 400 F; $\Delta p = 3$ in. to 4 in. of water.
Shaking: manual, by compartment, every 90 min..
Collection efficiency: 99+ per cent.

Applications to nonmetallurgical operations, usually but not always involving gases at ordinary temperatures, are also common. Goldfield[51] describes an enormous bag house of 48 compartments, each containing 1,200 bags 5 in. in diameter by 14 ft long, for filtration of *90 tons per minute* of air in an asbestos mill. Many uses are found in connection with crushing and grinding operations such as are associated with mining, materials preparation, and the various mineral industries.[47, 98] Sand-handling equipment in foundries, coal grinding,[93] and similar operations produce dust often recovered by bag houses. A typical example of a small-scale operation is cited by Silverman[118]:

Particulate emission: dust from hydrated lime packing operation — 7 grains per cubic foot; 100 per cent finer than 37 microns, 43 per cent finer than 13 microns.
Gas volume: approximately 1,200 cfm to 1,500 cfm.
Bags: cotton fabric, 340 sq ft total surface.
Filter ratio: 3 fpm to 5 fpm.
Operating conditions: room temperature; $\Delta p = 2$ in. to 5.2 in. of water.
Shaking: once every 4 hr.
Collection efficiency: 99+ per cent.

Aside from the limitations imposed by fabric properties, bag house filters also suffer from the disadvantages of low filter ratio which requires large filtering surface and a large amount of space for installation. Various other cloth fil-

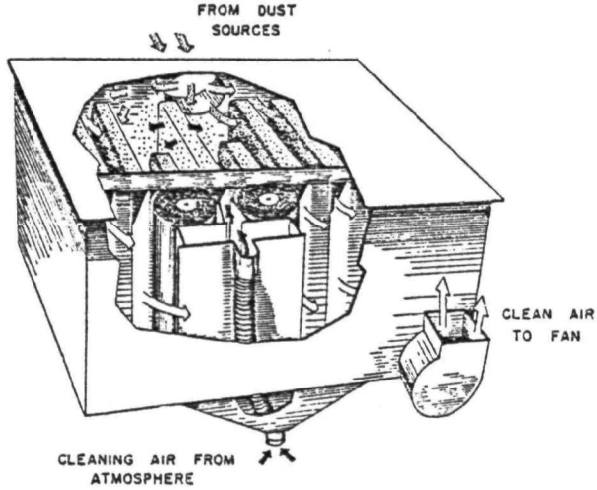
ter arrangements, which represent attempts to overcome some of these problems, are discussed in the succeeding sections.

3.12 *Screen-Supported Envelopes*

In this arrangement the filtering surface consists of a number of bags, each shaped as a rectangular envelope open on one end. Each bag or envelope is slipped over a wire screen or similar supporting framework so that the fabric is stretched taut. That end of the screen where the envelope is open is attached to a rack which holds a number of similar screens in parallel. The envelope is always mounted so as to stand on edge, but its long dimension may be either in a horizontal or a vertical direction. Fig. 8 shows a typical arrangement.

Dust-laden gas flows inward around the outside of the envelopes, and the dust collects on their outer surfaces. The clean gas passes through the fabric, flows inside the screen support, then out the open end to a manifold and gas discharge duct. Therefore, the rack which holds the screens also serves as a connection to the clean-gas discharge system.

Cleaning of the bags is accomplished by shaking the screen supports, by a reverse flow of clean air through them, or by a combination of the two actions. If the bags are to be shaken, the supporting rack is attached to a motor-driven vibrating system or to a device which raps the rack intermittently with a series of sharp blows. If a reverse flow of air is to be used, a valve system must shut off the flow of dirty air to a group of bags and, simultaneously, admit clean air into the open end of the envelopes. Ingenious arrangements are available for doing either of these things continuously and automatically over all of the bags in the filter in sequence, thus giving an essentially uninterrupted steady filtering operation. In one make of filter, where a suction fan is installed in the clean-gas duct to induce the flow, the same suction is used to create the flow of the cleaning air, as shown in Fig. 8.



Courtesy of W. W. Sly Manufacturing Company.

FIG. 8—Screen Cloth Filter.

In this type of filter the volume of space needed for a given area of filter surface is much less than in a bag house, because the flat envelopes can be arrayed more compactly than bags or tubes. The filter unit thus requires less room and less floor space, and may be installed in locations where other filters would not fit.

Since the fabric remains taut and is not subjected to flexing (except for a slight ballooning action in reverse-flow cleaning), it need not have as much mechanical strength as that used in bags. Certain fibers may therefore be used which have excellent heat- or corrosion-resistant properties, but which could not withstand the shaking action in a bag house. The shaking mechanism for the screen supports would necessarily be heavier and more powerful than for flexible bags. For this reason, the reverse-flow cleaning is preferable, provided it can be made to dislodge the dust as effectively.

Operating conditions for bag houses and screen filters are very similar. A series of comparative tests conducted by Dennis, et al.,[30] showed essentially the same ranges of filter ratio, pressure drop, inlet dust loading, and collection efficiencies for both types. Standard screen filters are available in capacities ranging from a few hundred cubic feet per minute for self-contained unit filters of less than 10 bags to upwards of 60,000 cfm for filters of 600 to 700 bags.

Despite the advantages cited in the foregoing, the cloth screen seems not to be as widely used as the bag house. There are many more articles in the literature describing specific bag house installations than those describing cloth screen filters. There also seem to be more manufacturers of the bag type, according to Silverman.[117] The reason apparently is that many types of dust particles are particularly difficult to dislodge on cleaning, and the cleaning of the cloth screen is not effective enough to prevent clogging in these cases.

reverse-jet filter (see Par. 3.13) the traveling jet mechanism can be set in operation whenever, and only so long as, the pressure differential is above this limit. Bag-shaking devices may also be operated automatically in this way. Such control is especially desirable whenever the dust loading or volume of gas flowing fluctuates very much. However, whenever a steady condition of rate of flow and dust concentration prevails, the cleaning cycle may be controlled simply by a program timer. This will automatically, and regularly, cut the filter to be cleaned out of operation for a fixed period of time, during which the cleaning mechanism operates. In this way a large bag house, for example, can give overall continuous operation as different sections of it are cleaned in turn.

3.45 *Safety Measures*

The principal hazard in connection with dust filters is that of explosion and fire whenever the dust consists of a combustible material. Other hazards may arise in special cases depending upon the nature of the dust, e.g., health hazards such as silicosis, radiation injury from radioactive substances, infectious diseases from air-borne bacteria, etc. In these cases, the filter is itself the principal safety device acting to remove injurious substances from the air. Therefore, the principal precaution to be taken is the elimination of all leaks from the filtration system to avoid recontamination of the air. An electric-eye dust detector may be installed in the clean-gas discharge ducts or stack to detect bag failures or leaks automatically.

Mumford, et al.,[89] in discussing the application of cloth filters to the collection of coal dust, give a good summary of safety measures to be taken against explosion and fire. These include:

1. Flameproofing of filter fabric.
2. Installation of explosion vents on each filter compartment.
3. Elimination of horizontal runs of duct work wherever possible.
4. Provision of access doors and cleanout plugs in all locations where dust might settle in the system.
5. Elimination of all possible sources of sparks or static electrical discharges.

Jameson[63] points out the fire hazard inherent in the use of oil-film air cleaners and indicates that an oil or adhesive substance of fire-resistant properties should be used. The automatic self-cleaning type of continuous air filter should be equipped with its own automatic fire-extinguishing system.

3.50 Operating and Maintenance Problems

Throughout the literature the theme expressed in the following quotation from Kane[66] is found over and over again:

"Because dust collection equipment is not truly production machinery, it has too often been installed in a place that is inaccessible with the unfounded hopes that once installed it can be forgotten. Nothing is further from the truth and the more effective the design, the more complicated will be the collector construction and the more frequent need for inspection, servicing and preventative maintenance."

Accordingly, it is important to consider plans by which dust filters may be kept in smooth, trouble-free operation. Such planning should be kept in mind from the very beginning of the design of the installation and should be based upon a careful study of the filter manufacturer's instructions for installation operation and maintenance. This should result in the establishment of a servicing schedule setting forth the operations to be performed and their frequency.

Several lists of items to be included in such a servicing schedule have been proposed in connection with installations in different industries by Bolt,[10] Kidder,[68] Smith,[127] Mumford, et al.,[89] Swift,[141] and Harris and Mason,[54] in addition to the general comments of Kane.[64, 66] The following list of problems and comments represents a composite digest of these references:

Leakage through the filter: This is perhaps the most important service problem. Bag filters must be regularly inspected for holes or tears in the fabric and fiber filters for channeling or leaks around the edges between the bed and frames. Regular measurement of the downstream dust concentration serves as a check on faulty filtration. An electronic-eye dust detector may be installed in the outlet duct to warn of an increase in dust content of this stream. A visual inspection on the clean-air side of the filter may reveal staining of parts by leaked dust.

Ordinarily, a set of bags should last several years if the proper fabric has been selected for the operating conditions. Labbe and Donoso[75] recommend a monthly test of the acid content and tensile strength of a fabric sample from

the bags in service. Howat [80] suggests that bags be washed every three or four months. Care should be taken that the thread used to sew the seams in bags is also of the proper material; otherwise, splitting of the seams may be a source of trouble.

Lubrication of moving parts: Fan motors and fan bearings, shaking mechanisms, reverse-jet blow rings, valves, dampers, etc. must be lubricated regularly and checked for wear. To avoid serious delays and shutdowns, worn parts should be replaced before they fail in service.

Plugging of filter: This will be indicated by abnormal pressure drop across the filter, reduced rate of flow, or both. It may be due to improper performance of the cleaning system, too high humidity in the dust stream, foreign substances carelessly added to the gas, or a sudden increase in dust load beyond the design capacity of the filter. Constant monitoring of the pressure differential gage is important.

Improper accumulation of dust: This may occur in ducts, on fan blades, in hoppers, etc.—in many locations where dust is not supposed to accumulate. In time, this results in malfunction of the system, excessive wear, and possibly a fire hazard. There should be provision for frequent inspection of such locations, and cleaning whenever indicated. Sudden increases in gas velocity may stir up such dust and cause overloading and plugging of the filter.

Wear of metal parts: There should be regular inspection of ducts, hoods, framework, housings, etc. for signs of wear due to corrosion, erosion, excessive heat, excessive moisture, etc. Leaks which may develop in this way may release hazardous dusts into the atmosphere and defeat the purpose of the filtering system. Regular painting of the metal surfaces is insurance against some of this sort of trouble.

Electrical overloading: The current through motors should be checked regularly for indication of overloading. Temperature of motors and bearings should likewise be checked frequently.

Improper tension in belt devices: The tension in belt devices should be measured regularly and adjusted before belts fail in service. Improper speed of fans may result from incorrect belt tension and this, in turn, may cause an incorrect velocity of gas through the filter. Thus, the collection efficiency could be impaired even though there was no obvious malfunction of the equipment.

Convenience of inspection and servicing: To insure that workmen assigned to maintenance work will follow the schedule of inspections and servicing, it is desirable to make it as convenient as possible. Outdoor locations should be sheltered, service points should be readily accessible, and necessary tools and testing equipment should be kept in good repair.

Instrumentation checkup: Pressure gages, thermocouples, flow meters, and all other instruments must be constantly checked to insure that they are giving accurate readings. This is basic to the use of instrumentation for the control of any operation.

Precautions against fire: Fire-fighting apparatus should always be kept in working order and regularly inspected and tested. During repair work particular care should be taken against sources of ignition such as welding torches. Routine care against improper accumulation of dust will also remove a possible source of fire by spontaneous combustion.

As an illustration of a service schedule, the following abbreviated version of the preventive maintenance program followed by Bolt [10] is given:

At beginning of each 8-hr shift:
- Empty collectors of accumulated dust.

Every 24 hr:
- Check temperature of motors and bearings.
- Check all machinery for proper lubrication.

Weekly:
- Check current in motors, for overloading.
- Check tension on belt drives.
- Clean out underground tunnels.
- Inspect fire control equipment.

Every three weeks:
- Clean overhead duct work.

Every four weeks:
- Scrape blades of fans, and fan housings.
- Change lubricant in all bearings.

Every three months:
- Complete inspection of entire system.

Every year (during summer vacation shutdown):
- Overhaul entire system.

4.00 COST DATA

Specific and up-to-date cost data are, of course, not obtainable from the general technical literature. The only way to find the exact cost of a piece of equipment at any given time is to solicit price quotations from the manufacturers. The best that can be done in a general survey of this kind is to indicate general trends in costs, relative costs in comparison with other types of dust collectors, and those

Repair materials and replacement parts (bags, filter panels, etc.)
Dust disposal
Depreciation of equipment
Other fixed charges—insurance, taxes, etc.

The United States Atomic Energy Commission's *Handbook on Air Cleaning* [46] states that for metallurgical bag filters total operating costs are divided roughly as follows: 38 per cent for labor; 25 per cent for power; 12 per cent for bag renewal; 7 per cent for supervision; and the remaining 18 per cent for fuel, tools and supplies, laundry, power shovel and engine, and car service. No mention is made of fixed charges. This handbook also cites quite a number of specific cost data for a variety of collectors; however, inasmuch as it dates from 1946 to 1950, the figures are no longer valid.

A useful source of current information on costs and chemical engineering economics in general is the annual review, "Chemical Cost and Profitability Estimation," published in *Industrial and Engineering Chemistry* in the May or June issue. This is a survey and bibliography of the literature which has appeared during the previous calendar year, with a subject index. "Dust collectors" and "Filters, air" are the appropriate listings in the index.

5.00 PRACTICAL CONSIDERATIONS IN FILTER SELECTION

In the approach to any dust collection problem there are always two basic considerations to be taken into account:

1. What is the character of the gas-dust stream to be dealt with? This must include a complete description of all its properties: dust size distribution, dust concentration, temperature, moisture content, chemical composition of dust and gas, physical nature of dust, etc.

2. What is to be accomplished by the collection operation? The requirements to be met by the collection equipment must be specified in terms of effluent dust loading; particle size, re-use, or disposal of collected dust; and quantity to be handled.

Answers to the two foregoing questions will generally lead to a preliminary selection of the method of dust collection to be employed. In fact, consideration of only particle size, particle concentration, and desired collection efficiency is often sufficient to indicate the kind of equipment to be used, or at least to narrow the choice down to between two or three types. Attention may then be given to detailed selection of a specific unit.

5.10 Selection of Collectors in General

A number of aids are available in undertaking such preliminary selection studies. One of these is a chart prepared by Sylvan of the American Air Filter Company, Inc., presented by Kane,[66] with a more detailed explanation of its use given by Kayse.[67] This chart shows the collection efficiency to be expected from any particular type of equipment operating upon a stream of specified concentration (in grains per cubic foot) of dust having a given mean particle size (in microns). Typical ranges of particle size and concentrations encountered in various practical situations are also shown.

Stairmand [133] lists the calculated collection efficiency of a number of devices on a standard test dust, W.C.3 silica powder, which has about the same size distribution as typical fly ash from a pulverized fuel boiler. A few values selected from his table are listed in Table 11.

Other useful aids are the check list and tables of Kane,[64] the tabulation of First and Silverman,[43] and the general discussions by Hedberg [56] and Lapple.[51] These indicate that the following factors should all be considered in selecting the method of dust collection and specific equipment to be used:

Mean dust-particle size and range
Dust concentration or loading
Abrasive characteristics of dust
Adhesive characteristics of dust
Bridging characteristics of dust
Fire or explosion hazard
Corrosive nature of gases
Volume of gases to be handled
Gas temperature and pressure
Condensable vapors present in gas
Possible fluctuations in operating conditions
Collection efficiency required
Method of dust disposal or recovery
Collector size, location, and space required
Collector cost, initial and operating
Collector installation work required
Collector servicing and maintenance required
Need for make-up air supply

Kane's tables summarize the operating characteristics of different types of collecting equipment with regard to many of these points. They also show the collector types commonly used for a wide range of industrial processes.

TABLE 11—Collection Efficiency on W.C.3 Test Dust [133]

Collector	Overall Efficiency (Per Cent)	Efficiency at 5 Microns (Per Cent)	Efficiency at 1 Micron (Per Cent)
Cyclone, medium efficiency	65.3	27	8
Cyclone, low-pressure drop	74.2	42	13
Electrostatic precipitator	94.1	92	70
Fabric filter	99.9	99.9	99
Spray tower	96.3	94	55
Venturi scrubber	99.7	99.6	97

A discussion of all of the factors listed in the foregoing paragraph with reference to all kinds of collectors is, of course, not within the scope of this report. Such discussions for individual types will be found in each of the reports in this series prepared for the American Petroleum Institute. The remainder of this section will be devoted to the interpretation of such problems in terms of the use of filters of various kinds.

5.20 Selection of Filters

The general place of filters in the scheme of dust collectors has been indicated in Sect. 1.00. They are characterized as high-efficiency, moderate-cost devices capable of application to a wide variety of problems by virtue of the many different kinds of filter media available, and especially useful on medium- to very small-sized particles. Assuming that it has been decided to use a filter, the next question to be answered is: What kind of filter shall it be? The check list given in Par. 5.10 should be repeated, this time with reference to the various possibilities of filters. The order of importance of these items is not necessarily as they are listed. Possibly, the first consideration should be given to the range of dust concentration.

There are two broad classifications of filters to be considered at the outset, based upon dust concentration. If this is less than, roughly, 1 to 3 grains per cubic foot, an air filter such as is discussed in Par. 3.221 (stationary) or Par. 3.322 (movable) is indicated. If the concentration is higher, a "dust collector" filter (industrial) is indicated. This may be of the fabric type (Par. 3.10), the fibrous bed type (Par. 3.223 or 3.321), or the granular bed type (Par. 3.21 or 3.31).

The selection of air filters is discussed by May [55] and Rowe.[105] The small unit or panel type, with either disposable or renewable media, will be preferred for small volumes of gas where a minimum of attention is desirable, for the collection of a dust which is not to be recovered. For large volumes of air one of the automatic cleaning types will be more suitable, especially if the filter has to be located in a relatively inaccessible place or it is desirable to reduce maintenance requirements to a minimum. Collection efficiency is moderate, dust-holding capacity high, and pressure drop low. The dust-holding capacity may be defined as the weight of dust accumulated either before the pressure drop across the filter reaches a specified maximum or before its collection efficiency drops below a specified minimum. Rowe recommends a maximum pressure drop of 0.2 in., water gage, for small units (such as a home furnace) and 0.5 in., water gage, for heavy-duty installations (such as industrial filter banks). Table 5 summarizes many of the selection criteria involved. As the name implies, such filters are principally used in general ventilation work for the protection of people and machinery from air-borne contaminants.

In the realm of dust collectors general discussions of cloth filters are given by Stern [136] and Ebeling,[35] and of porous materials by Silverman.[117, 118] The general range of performance to be expected from each type has been cited herein in the sections dealing with each one. Extensive specific performance test data are cited for cloth bags, screens, and reverse jets by Dennis, et al.[30]; and for unit collectors of the screen, bag, or air filter type by Stern, et al.[137] For other types, less extensive data are indicated in the references cited under each type. Such performance data must be at hand, either from the literature or from the manufacturer, before a filter selection can be made.

Often the choice between cloth filter and fiber mat may be resolved by the ultimate destination of the dust. It is almost impossible to recover dust out of a fiber mat for some re-use purpose. Dust which has a re-use value must be collected as a cake which can readily be freed from the collecting medium.

The next step in filter selection is to determine the volume of gas to be handled. This will, in turn, fix the total area of filter needed on the basis of the value of lineal velocity V, or filter ratio, appropriate to the type selected. Typical values of V have been cited in the description of each kind of filter given herein. As consideration proceeds to the other items on the check list, the size of filter and the space it will require can be kept in mind.

Particle size range and collection efficiency required to produce the desired effluent concentration should be considered next. If legal factors such as air pollution code requirements are involved, they must, of course, be investigated and taken into account. If possible, an analysis of the dust size distribution on a weight basis should be obtained. Knowing the collection efficiency as a function of particle size according to the collection mechanisms involved, one can then calculate the size distribution of the effluent dust (or of that collected) on a weight basis. Stairmand [132, 133] gives examples of such calculations. To do this, one must also know the size of fibers to be used in the filter contemplated. The finer the dust, the finer the fibers needed.

If the size range is broad and includes an appreciable amount of particles over 10 microns in diameter, the possibility of preceding the filter by a primary collector of another type should not be overlooked. Coarser particles are easily and efficiently removed by less expensive collectors, which will reduce the duty of the filter. Two kinds of filters may also be used in series where the second is of a higher efficiency than the first and is to be used for the ultimate collection of very fine particles (such as radioactive dusts) which cannot, under any circumstances, be permitted to escape in the effluent gas stream.

Next, all the properties of the gas and dust which will have an influence upon the filter medium must be taken into account. Foremost among these is temperature. The allowable range of temperature for each of the various fabrics, fibers, and other media has been given herein. The possible need for cooling apparatus must be contemplated. Abrasive, corrosive, and flammability characteristics will also influence the choice of filter medium.

Flexibility of operation may be very important in some cases. If a plant is to operate intermittently, or if there are likely to be surges in the dust or gas flow rates, provision must be made to handle the worst set of operating conditions. Filters which are primarily designed to operate continuously under steady conditions on a regular cleaning cycle will obviously not be appropriate.

Consideration of all of the aforementioned factors will probably lead to a tentative selection of a filter. Before a final decision is made, however, the warnings against overlooking questions of location, accessibility, servicing and maintenance needs, installation problems, and disposal methods must be heeded in order that costly mistakes be avoided and smooth operation assured. The size of the proposed filter installation, including auxiliaries, must now be definite in order to plan on location and layout.

Finally, the question of cost must be raised and answered. The ratio of pressure drop to efficiency will be a useful criterion here as it represents a ratio of operating cost (in a general sense) to unit of achievement.

There are many references in the literature to individual problems connected with the selection and use of filters in specific industries, and examples of how these problems have been met in certain cases. Following is a representative list:

Air-borne bacteria [18, 24, 61]
Coal dust [93]
Fluid catalyst fines [92]
Foundry and cupola fumes [20, 80]
Hot gases [95, 130]
Metallurgical dusts [6]
Protection of electrical equipment [63, 103, 140, 155]
Radioactive dusts [9, 12, 87]

6.00 PROBLEMS IN PERFORMANCE TESTING

In testing the performance of a filter, there are essentially three quantities to be checked: pressure drop, gas flow rate, and collection efficiency. Pressure drop and flow rate are fairly easy to measure by standard techniques. The matter of collection efficiency, however, raises certain problems.

A statement of the collection efficiency, or per-cent penetration, is meaningless without an accompanying description of the method of determination employed. Different methods have been used, and they give different results upon the same filter. If, in the specifications for the purchase of a filter, a statement or guarantee of collection performance is to be included, it will be very important to agree with the manufacturer upon the method by which this performance is to be rated. The statement of the test method should include a complete description of the particle size distribution and chemical composition of the dust which will be used for performance testing.

IV. SO_x

Fluidized Bed Combustion Update

The most recent research on fluidized bed combustion has developed several possiblities for improving both the efficiency and emission control of coal-fired power plants. These include primarily the method of feeding the coal to the fluidized bed and the efficiency of the sulfate sorbent.

Washed Coal Feed

The standard fluidized bed combustion system has a deep fluidized bed and a tall combustion chamber to ensure efficient combustion of finer coal particles present in the crushed coal feed. It has recently been shown that the coal does not have to be crushed before introduction to the fluidized bed combustion chamber.

The main reason for firing crushed coal is the need to maintain an effective fluidized bed in the combustion chamber. The burning coal, ash, and SO_2 sorbent must remain suspended in the upward airflow forming a violently churning layer of particles. However, during normal operation, the fluidized bed contains only a very small amount of coal (1-5 percent) and consists mostly of ash and sorbent particles.

To maintain effective fluidization, particles in the bed must be less than approximately 5 mm in size. Coal, however, often contains rocks and stones up to 2 in. in diameter. If these were introduced to the combustion chamber they would sink through the fluidized bed and deposit on the bottom of the chamber. The coal crushing process assures that the stone contained in the coal remains fluidized.

If the coal is washed, however, the more dense stones can be easily separated from the coal. Coal washing also removes much of the inorganic sulfur contained in the coal, and reduces the amount of ash. One-half to 1 in. size coal can be burned in a fluidized bed as small as 15 cm high to achieve a combustion efficiency of 97 percent.

Fluidized bed combustion boilers using this method of fuel feed are currently in use in both the United States and Great Britain.[1]

Sorbents

Much current research is being devoted to the improvement of SO_2 sorbent efficiencies and regeneration. Currently, limestone is being used as the SO_2 sorbent without regeneration. In this process, the limestone is fed to the fluidized bed along with the feed coal. The carbon dioxide is quickly driven off or calcined, leaving a porous CaO structure (Figure 1). The SO_2 then deposits on the surface of the remaining stone as calcium sulfate ($CaSO_4$). Normally, from 20 to 25 percent of the calcium in the limestone feed can be converted to calcium sulfate by this method.

It recently has been found that the limestone efficiency can be improved either by adding a small amount of sodium chloride with the limestone or by hydrating the calcium sulfate in a regeneration process. Both of these processes increase the pore diameter and prevent sealing off of the small micropores present in the nonmodified calcined limestone. (See Figure 1.) Up to 50 percent conversion has been obtained by adding sodium chloride[2] to the limestone (see Figure 2), while 85 percent calcium conversion has been obtained with successive cycles of hydration.[3]

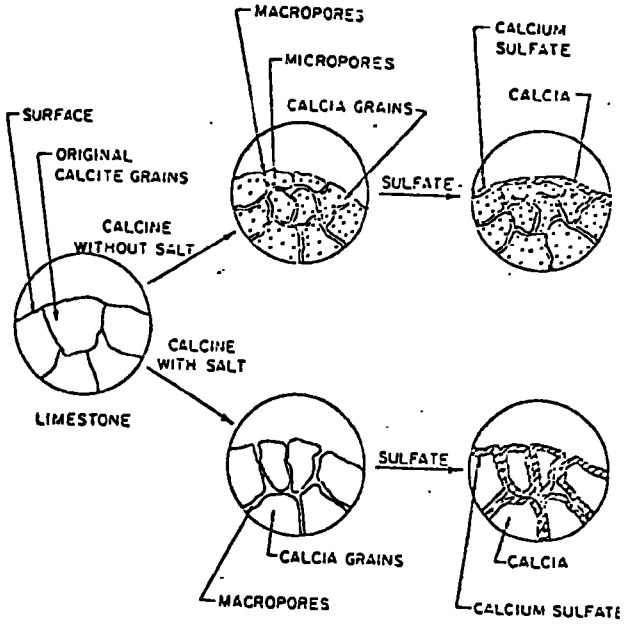


Figure 1 Magnified cross-section comparison of limestone calcinatio and sulfation, with and without salt (schematic)

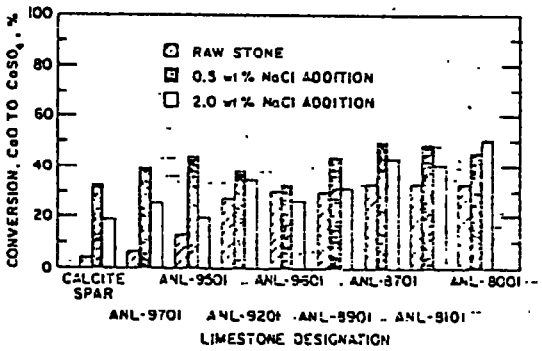


Figure 2. The effect of 0.5 and 2.0 wt % NaCl treatment on limestone subsequently precalcined and sulfated at 650 °C for 5 hr in 0.3% SO_2, 5% O_2, 20% CO_2, balance N_2

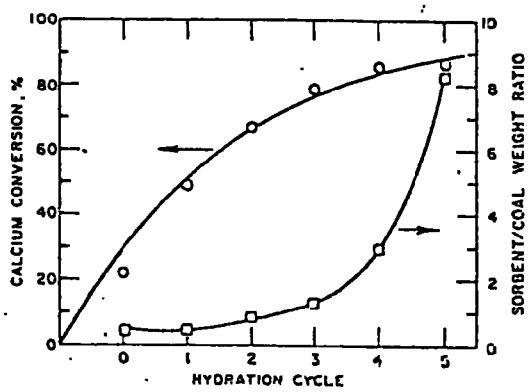


Figure 3 Calcium conversion of the steady-state product as a function of hydration cycle. (Hydration cycle 0 represents the initial sulfation).

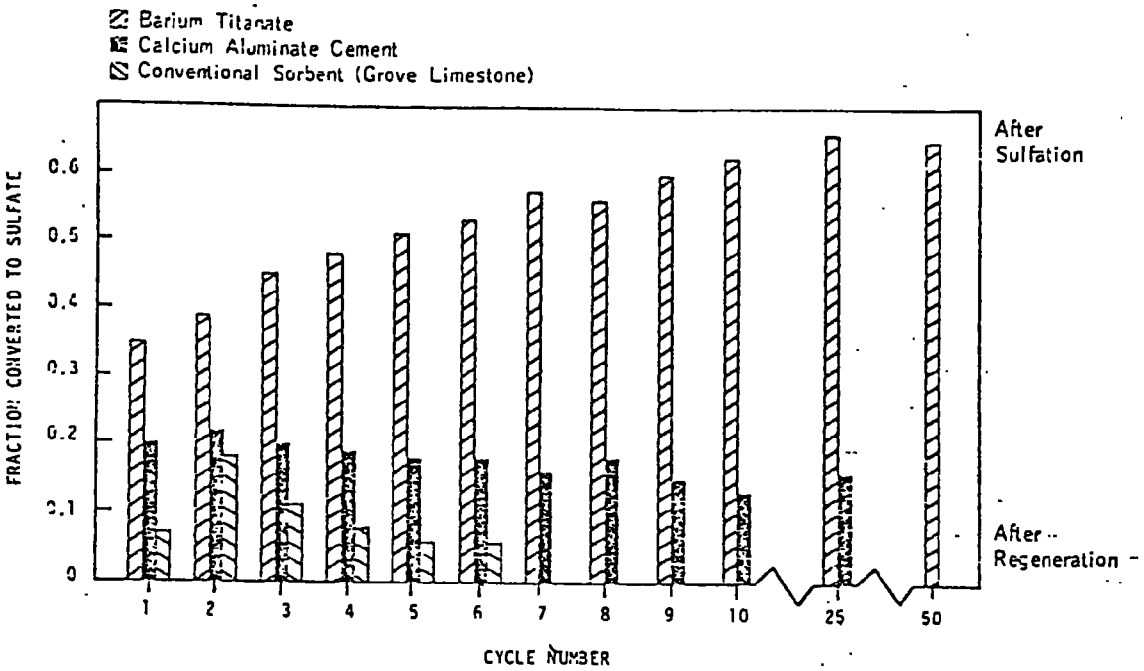


Figure 4 Comparison of new regenerable sorbents and limestone

A major problem with using limestone as a sorbent in a regeneration cycle, however, is a rapid loss or attrition through erosion in the fluidized bed. Also, the regeneration process involves high temperatures which rapidly deactivate the limestone after only a few cycles.

Two additional minerals have shown promise as possible SO_2 sorbents in the fluidized bed process.[4] They are barium titanate and calcium aluminate cement. Both of these minerals have shown acceptable conversion to sulfate as well as erosion resistance. Preliminary economic assessment indicates that either of these may be feasible on a commercial basis.

Regeneration of the SO_2 sorbent used in fluidized bed combustion is not currently practiced. However, research indicates that regeneration will greatly reduce the solid waste associated with SO_2 removal as well as possibly providing a commercially usable sulfuric acid by-product.

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[1] Env. Sci. & Tech., Vol. 14, No. 3, pp. 270-288 (1980).
[2] Ibid., Vol. 14, No. 9, pp, 1113-1118 (1979).
[3] J.A.P.C.A., Vol. 30, No. 6, pp. 684-688 (1980).
[4] Env. Sci. & Tech., Vol. 13, No. 6, pp. 715-720 (1979).

2. The FGD System

The R-C/Bahco facility operating at RAFB is a calcium-based throwaway FGD and particulate removal system. Either pebble lime (CaO) or ground limestone ($CaCO_3$) can be used for SO_2 removal to produce mixtures containing calcium sulfite ($CaSO_3$), gypsum ($CaSO_4$), and fly ash. The overall chemical reactions for the respective reagents are shown in Table 1.

The scrubbing system comprises the following major components:

- Flue-gas-handling equipment
- R-C/Bahco scrubber
- Reagent-handling and -storage equipment
- Sludge disposal equipment

The entire FGD system (Figure 1) is served by a centrally located control room and is operated, part time, by heat plant personnel.

Flue-Gas-Handling Equipment

The flue-gas-handling equipment includes a flue gas header, bypass stack, mechanical collector, and booster fan. Flue gas from as many as eight stoker-fired hot water generators—up to 108,000 actual ft^3/min (51 m^3/s)—passes into the header and mechanical collector where coarse particulate matter is removed before it enters the booster fan and scrubber. Removing particulate minimizes erosion of the fan and other scrubber components and reduces the amount of wet solids handled by the scrubbing system. The ash is disposed of via the existing ash-handling system. A bypass stack in the carbon steel flue gas header serves two purposes: it serves as a fail-safe emergency bypass, and it permits air to enter the system at low loads to maintain gas velocity through the mechanical collector and scrubber to maximize collection efficiency.

Gas Flow

As shown in Figure 2, the R-C/Bahco scrubber, which is fabricated from 316L stainless steel, is a two-stage inverted venturi unit specifically designed to operate with slurries containing calcium sulfite, calcium sulfate (gypsum), calcium carbonate, calcium hydroxide, and fly ash. All of the internal gas flow passages are large, unobstructed, and well irrigated with circulating slurry or makeup water to essentially eliminate the possibility of serious plugging problems.

Hot flue gas from the booster fan enters the first stage, where it impinges on the surface of the slurry, creating a cascade of droplets that it carries into the throat of the lower venturi. The droplets, containing SO_2 scrubbing reagent, cool the gas to its saturation temperature, absorb sulfur dioxide, and trap particulate

Table 1.

Chemical Reactions for Lime and Limestone in SO_2 Removal

Reagent	Reaction
Lime:	
Lime slaking	$CaO + H_2O \longrightarrow Ca(OH)_2$
SO_2 absorption	$Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 + H_2O$
Sulfite oxidation	$CaSO_3 + \frac{1}{2}O_2 \longrightarrow CaSO_4$ (gypsum)
Limestone:	
SO_2 absorption	$CaCO_3 + SO_2 \longrightarrow CaSO_3 + CO_2$
Sulfite oxidation	$CaSO_3 + \frac{1}{2}O_2 \longrightarrow CaSO_4$ (gypsum)

SOURCE: "Capsule Report--Bahco Flue Gas Desulfurization and Particulate Removal System," EPA 625/2-79-022 (July 1979).

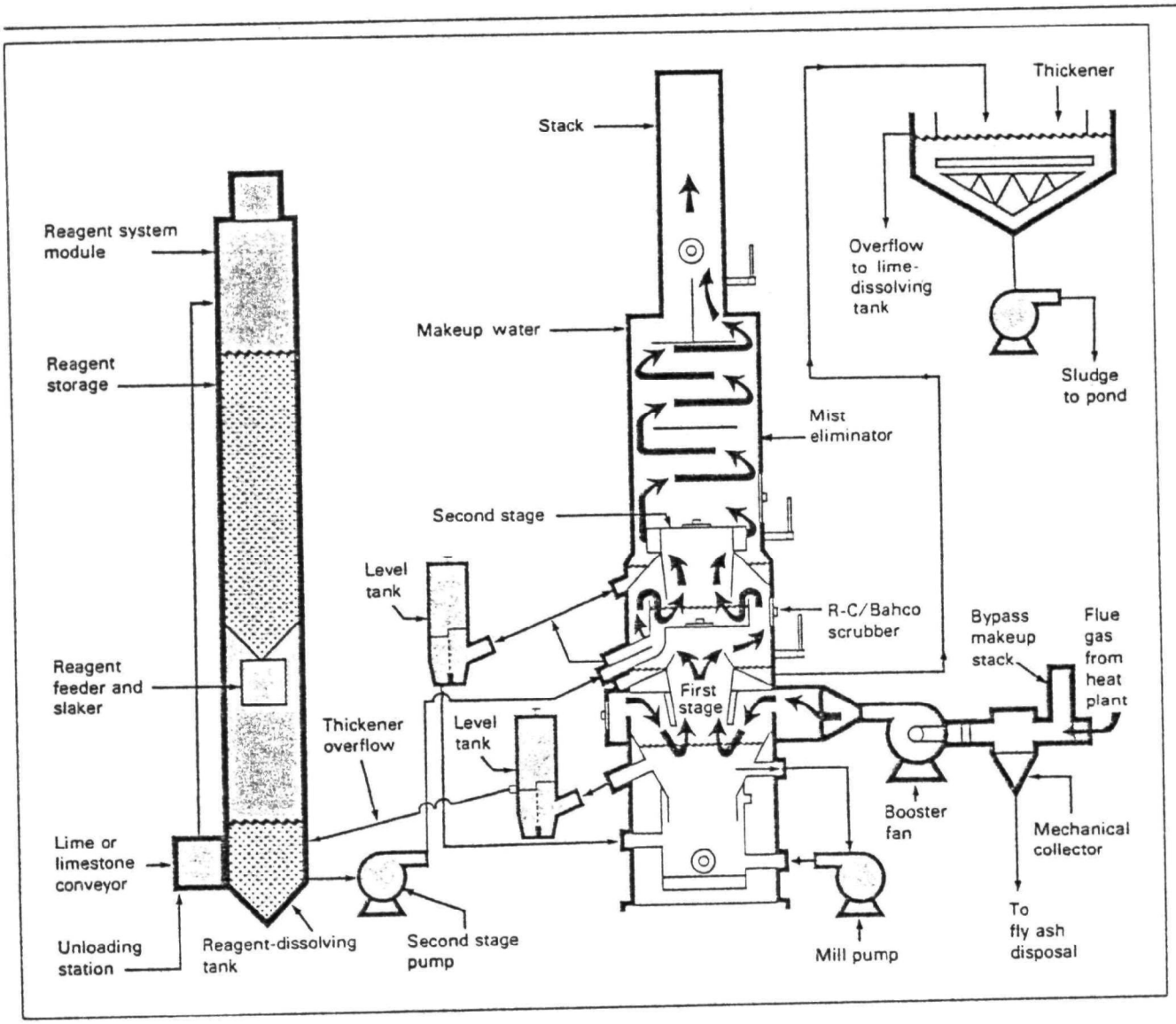


Figure 1.

R-C/Bahco Scrubber System

matter. Above the first venturi, the gas stream is turned downward by the bottom of the pan in the second stage venturi causing most of the droplets to fall out. In the second stage, or upper venturi, the process of impinging the gas stream on the surface of a slurry is repeated. Here the gas/droplet mixture passes up through the throat of the upper venturi where final SO_2 absorption and particulate removal are accomplished. A cyclonic mist eliminator above the upper venturi imparts a spinning motion to the gas stream, causing the droplets to move toward the wall where they coalesce and drain from the scrubber. From the mist eliminator, clean gas, which is not reheated, enters the surrounding atmosphere via the stack.

Slurry Flow

Two techniques of handling slurry flow in the system are used to eliminate or minimize the plugging and erosion problems often associated with calcium-based FGD systems: maintaining essentially constant slurry flow rates through the scrubber, and eliminating turndown in slurry bleed streams by operating in an

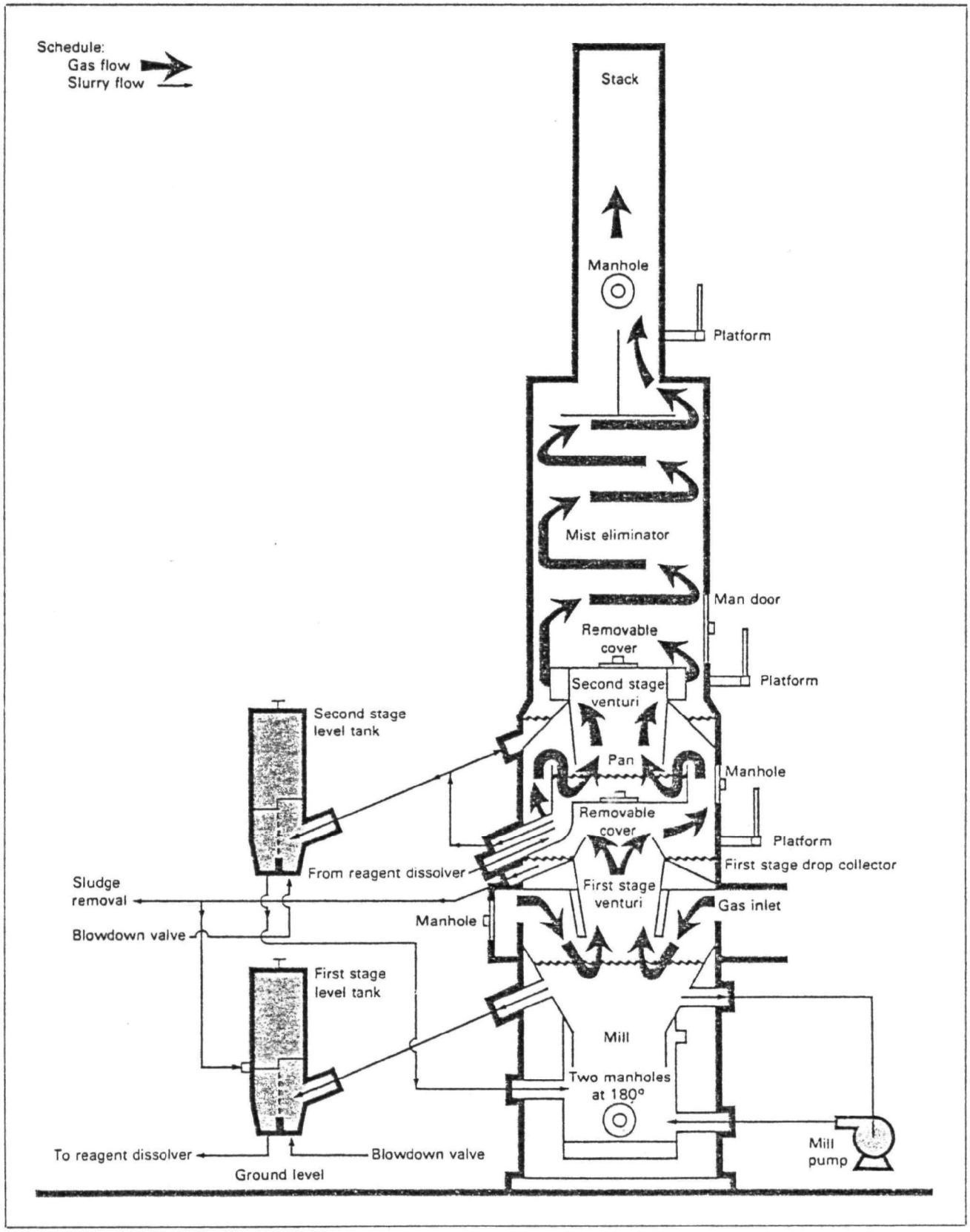


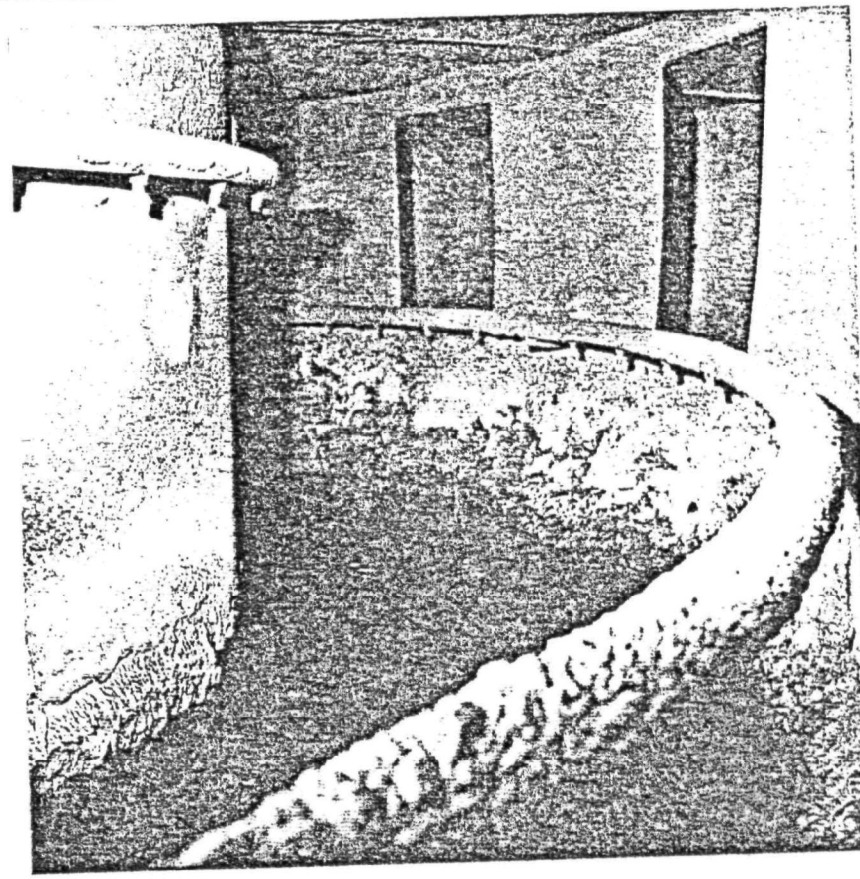
Figure 2.

R-C/Bahco Scrubber

on-and-off mode with water flushing after slurry flow is interrupted.

Slurry flows by gravity from top to bottom in the scrubber, counter-current to the gas flow. Slurry from the reagent dissolver (which is also of 316L stainless steel) contains makeup reagent—either lime or ground limestone. The slurry enters the pan in the upper venturi. Slurry level in the pan determines the upper venturi pressure drop; the level is set by adjusting a weir in the level tank located outside the scrubber.

Slurry streams from the mist eliminator and the pan are combined in the level tank before flowing by gravity to the mill under the lower venturi, where another level tank is used to set the pressure drop in the lower venturi. Part of the slurry collected in the area between the upper and lower venturis, the part that has contacted the gas stream twice, flows by gravity to the sludge disposal system. In the first-stage level tank this slurry is combined with overflow from the mill and is returned to the reagent dissolver. More reagent is added in the dissolver before the slurry is recycled to the upper venturi. The fluid mill is powered by an external pump and is used to grind coarse limestone or other large particles in the system.



First-stage venturi, showing gas inlets and makeup water spray manifolds

Reagent-Handling and -Storage Equipment

The reagent system installed at RAFB is capable of handling both 0.75-inch (1.9-cm) pebble lime and 200-mesh ground limestone. Primary components include truck-unloading equipment, a steel silo with 3 weeks' storage capacity at winter load conditions, a weigh belt feeder, and a lime slaker. The silo, feeder, slaker, and reagent-dissolving tank are integrated into a single module to minimize materials handling, supports, and space requirements. Lime or limestone drops directly out of the silo into the feeder-slaker and overflows into the reagent-dissolving tank directly under the slaker.

Sludge Disposal Equipment

Calcium sulfite, gypsum, and fly ash collected in the scrubber are concentrated from 10 percent to approximately 40 percent solids (by weight) in a thickener. The overflow from the thickener is returned by gravity to the reagent-dissolving tank. The underflow from the thickener is pumped underground to a hypalon-lined storage pond.

3. The Test Program

The R-C/Bahco FGD system test program, carried out at RAFB between March 1976 and June 1977, incorporated the following categories:

- Material balance
- Lime reagent process variable
- Lime reagent verification
- Particulate collection efficiency
- Limestone reagent process variable
- Sludge characterization
- Scrubber reliability monitoring

Material balance tests were conducted to establish the range of operating conditions over which the R-C/Bahco scrubber could be operated and to verify performance at design conditions by completing material balances. Maximum and minimum gas flow rates, pressure drops, and slurry circulation rates were determined and preliminary SO_2 and the particulate performance data at the limits of the system's capabilities were obtained. The system was operated at the design gas rate of 50,000 stdft^3/min (25 normal m^3/s) and complete material balances on calcium, sulfur, and total solids were performed.

Statistically designed lime process variable tests helped to establish the quantitative effect of the following process variables on SO_2 removal: gas flow rate, first- and second-stage pressure drops, mill and second-stage slurry rates, lime:SO_2 stoichiometric ratio, slurry inventory, and slurry solids concentration.

Lime reagent verification tests were undertaken to verify the results obtained in the lime process variable tests, and to determine the effect of very dilute scrubber slurry (2 percent solids) on system performance.

Particulate collection efficiency tests were a continuation of the particulate tests initiated during the earlier sampling phase. Relationships were determined between system variables, including particle size distribution and particulate removal efficiency.

Limestone process variable tests were completed using the same statistically designed test plan used for lime. The effect of system variables on SO_2 removal efficiency and reagent use was determined.

Sludge samples generated at RAFB were tested to determine dewatering, transport, and disposal characteristics (sludge characterization). Samples of sludge from lime as well as limestone scrubbing were tested.

The R-C/Bahco system was monitored from March 1976 to June 1977, to document its operating and maintenance history and to obtain data for a cost analysis. Data were gathered on reagent, coal, water, and power consumption as well as on operating and maintenance labor requirements.

Throughout the test program samples were taken of slurry, flue gas, lime, limestone, and coal, often in duplicate, for chemical analyses, particulate loading, and particle size distribution. A field analytical laboratory was established, and especially developed and highly efficient test methods using thermogravimetric analysis were employed extensively.

4. Test Results

Capacity/Material Balance Tests

Performance of the size 50 R-C/Bahco scrubber at RAFB is measured by its ability to handle variations in system operating parameters while reducing SO_2 and particulate emissions to the limits allowed by the applicable regulations, without exceeding the capacity of the system. Regulations applicable to RAFB limit SO_2 emissions to 2.2 lb/10^6 Btu (3.96 g/10^6 cal) and particulate to 0.16 lb/10^6 Btu (0.29 g/10^6 cal). Table 2 lists maximum, minimum, and optimum operating levels determined for the system at RAFB. The cost of reducing emissions to meet requirements will be minimized at optimum operating levels.

Lime Tests

The SO_2 removal capabilities of the R-C/Bahco system using pebble lime were characterized in two steps. First, a series of screening tests determined the effects of slurry rates, gas rate, venturi pressure drops, slurry density, system volume, and lime stoichiometry on SO_2 removal.

Tests results indicated that lime stoichiometry—the ratio of lime feed in the system to SO_2 in the flue gas—was the only variable controlling SO_2 removal as long as the system was operated within the limits outlined in Table 2.

A second group of tests, in which the effects of the gas flow, slurry rates and slurry density were determined, confirmed the initial findings that stoichiometry alone controlled SO_2 removal.

Results of these verification tests are shown in Figure 3. The figure also shows that lime use is essentially 100 percent—that is, no excess lime is needed—up to 90 percent SO_2 removal. Figure 4 illustrates system performance when SO_2 removal is above 90 percent—that is, when SO_2 emissions at RAFB were reduced below 0.6 lb/10^6 Btu (1.08 g/10^6 cal). The figure indicates that over 98 percent of the SO_2 corresponding to 0.1 lb SO_2/10^6 Btu (0.18 g SO_2/10^6 cal), can be

Table 2.

R-C/Bahco Scrubber Operating Levels

Variable	Minimum	Maximum	Optimum
Gas rate (actual ft^3/min)	35,000	55,000	40,000-50,000
Slurry circulation rate (gal/min)	1,500	3,000	2,300
Venturi pressure drop for each stage (inches H_2O)	6	12	7-10
Slurry concentration (wt % solids)	2	25	10
Reagent:SO_2 stoichiometry (moles reagent:moles SO_2, based on inlet SO_2 levels):			
Lime	0.45	1.05	0.7
Limestone	0.55	1.2	0.75
SO_2 removal efficiency (percent):			
Lime	45	98+	70
Limestone	40	85	70
SO_2 emission (lb/10^6 Btu):			
Lime	3.7	0.1	2.0
Limestone	4.0	1.0	2.0
Particulate emission (lb/10^6 Btu)	0.2-0.3	0.14	0.16

achieved with a stoichiometry of 1.1—that is, 10 percent excess lime. The SO_2 emission rates shown in Figure 4 are well below the required 2.2 lb/10^6 Btu (3.96 g/10^6 cal) and the guarantee level of 1.0 lb/10^6 Btu (1.8 g/10^6 cal).

From the lime tests it is concluded that lime:SO_2 stoichiometry is the controlling factor in determining SO_2 removal efficiency. Virtually any desired SO_2 removal efficiency can be achieved when lime is used in the R-C/Bahco scrubber, simply by adjusting the lime:SO_2 stoichiometry. Lime use approaches 100 percent at stoichiometric ratios up to about 0.9. At stoichiometric ratios up to 1.1, producing up to 99 percent removal, lime use is above 90 percent. Because most SO_2 regulations for industrial boilers permit emissions in the range of 1.0 to 2.0 lb/10^6 Btu (1.8 to 3.6 g/10^6 cal), lime, with its high removal capabilities, can be used to obtain offset credits in a nonattainment area to apply toward an expansion or new facility. No further capital expenditure need be made, because the R-C/Bahco system normally would be designed to handle lime as well as limestone, and switching from limestone to lime will increase the annual operating costs only by about 15 percent.

Limestone Tests

System performance with ground limestone was determined in a series of screening tests very similar to those used for pebble lime. These tests indicated that slurry circulation in addition to limestone stoichiometry controls SO_2 removal efficiency.

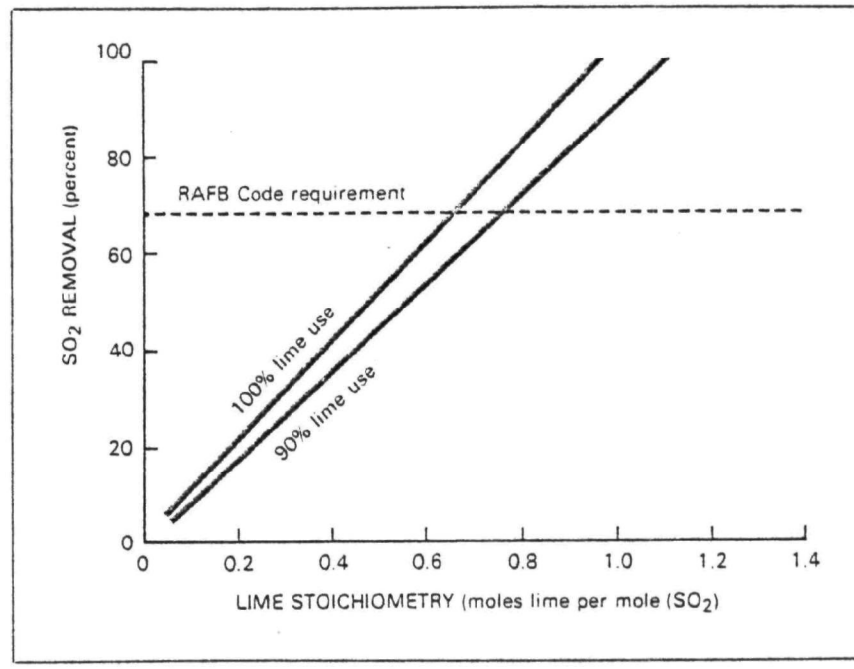
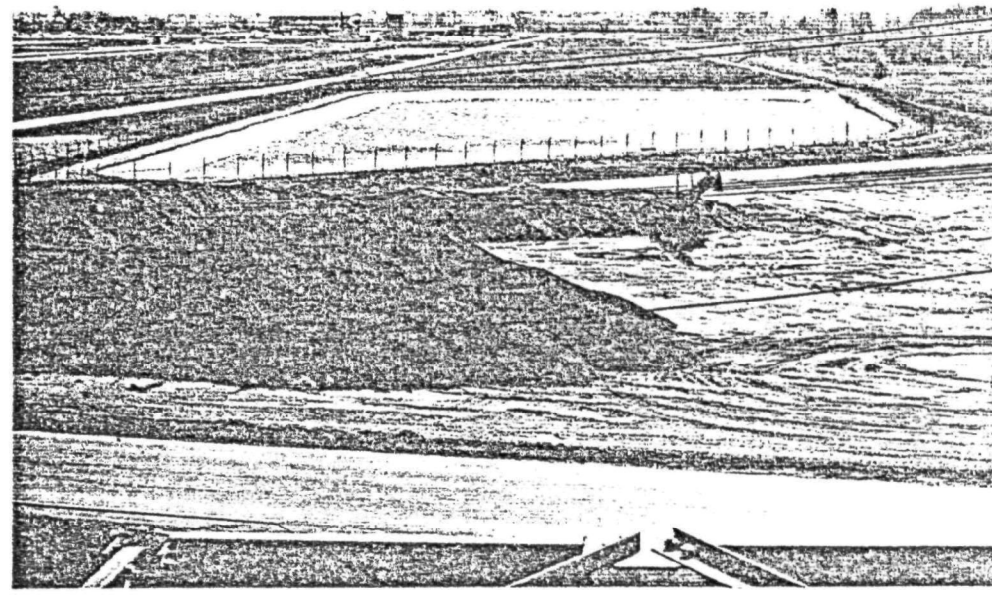


Figure 3.

SO_2 Removal Efficiency as a Function of Lime Stoichiometry



Hypalon-lined storage pond

Figure 5 shows the results of the tests and gives limestone use data. At a stoichiometry of 1.0 and slurry circulation of 2,300 gal/min (0.14 m^3/s), slightly over 80 percent SO_2 removal is possible with 80 percent limestone use. A practical limit for limestone is 80 percent SO_2 removal, because higher removals result in substantial reductions in limestone use.

Operation with limestone at RAFB produced sludge that contained much more gypsum than did operation with lime. That is, there was more oxidation of $CaSO_3$ to $CaSO_4$. Table 3 shows an average gypsum ($CaSO_4 \cdot 2H_2O$) and calcium sulfite ($CaSO_3 \cdot \frac{1}{2}H_2O$) content of 33 and 55 percent, respectively, when lime was used. The limestone slurry was almost completely oxidized and contained 78 percent sulfate and less than 1 percent sulfite. The comparison of average lime and limestone slurry analyses during similar boiler load periods listed in Table 3 indicates that the oxidation trend is probably attributable to the lower slurry pH encountered when using limestone, because all other operating conditions were essentially the same.

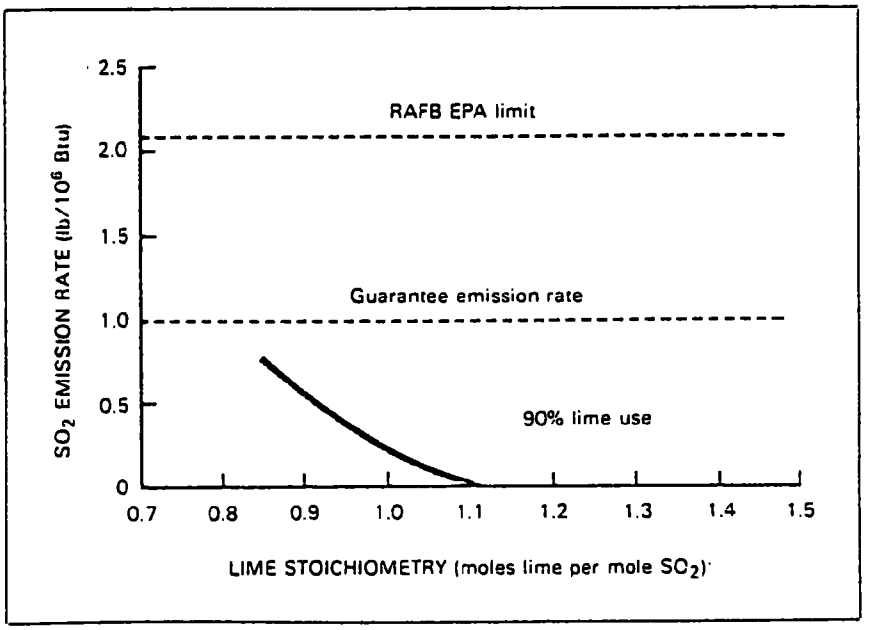


Figure 4.

Relationship Between SO_2 Emission Rates and Lime:SO_2 Stoichiometry

Particulate Removal Efficiency

Particulate Removal Tests. Initial particulate removal tests on the R-C/Bahco scrubber, performed in March, April, and May of 1976, revealed the presence of substantial amounts of soot in the stack gas. The average particulate emission rate for these tests was 0.23 lb/10^6 Btu (0.42 g/10^6 cal).

Overall particulate removal averaged 93 to 94 percent. Ohio emission standards require an overall removal efficiency of 96 percent at a particulate inlet loading of 1.5 gr/stdft^3 dry (3.4 g/normal m^3 dry) to achieve an emission rate of 0.16 lb/10^6 Btu (0.29 g/10^6 cal). Venturi pressure drops were increased to nearly double the design value of 7 inches (18 cm) H_2O to reduce these emissions. Below approximately 18 inches (46 cm) H_2O total pressure drop, particulate emissions increased rapidly. The amount of soot present in the flue gas at RAFB is higher than in other stoker-fired generators similar to the Rickenbacker boiler.

The Air Force has undertaken an extensive program to upgrade the heat plant at RAFB. Data obtained during this test program contributed substantially to information used to plan the upgrading program, and so far the following modifications have been completed:

- Installation of a new 60-Btu/h (18-Watt) generator to replace the two old units
- Replacement of hot water distribution piping
- Installation of flue gas oxygen monitoring equipment
- Repair of firing air distribution equipment and fire box pressure controls in the generators

- Rebuilding mechanical collectors and induced draft fans on the generators
- Replacement of burned out ledge plates, which regulate combustion air flow around the grates
- Repair of traveling grates

The problem with soot at RAFB points up a critical aspect of a successful emission control project—namely, that proper operation of all equipment, boilers as well as the scrubber, is essential to maintain satisfactory emission levels. Inadequate combustion or inadequate air can be as detrimental to emission control as improper scrubber operation.

Slurry Entrainment and Gas Bypassing. During the particulate tests, two phenomena were observed when the system was operated above its capacity limits. The first, called entrainment, occurs at very low venturi pressure drops—that is, under 6 inches (15 cm) H_2O involves small droplets of slurry carrying through the second-stage mist eliminator and out the stack. The second, called bypassing, is characterized by pulsations in the gas flow through the scrubber; the result is low collection efficiency in all particle size ranges. The second phenomenon takes place when relatively high pressure drops—that is, 12 inches (30 cm) H_2O or more in either venturi—are coupled with slurry flows under 150 gal/min (0.01 m^3/s) to the scrubber.

Conclusion. The particulate removal efficiency of the R-C/Bahco scrubber is comparable to that of low energy venturi scrubbers for particles larger than 1 μm, and appears to be better for particles smaller than 1 μm. In an R-C/Bahco scrubber, the second stage is the primary collector of fine particles. Slurry carryover and

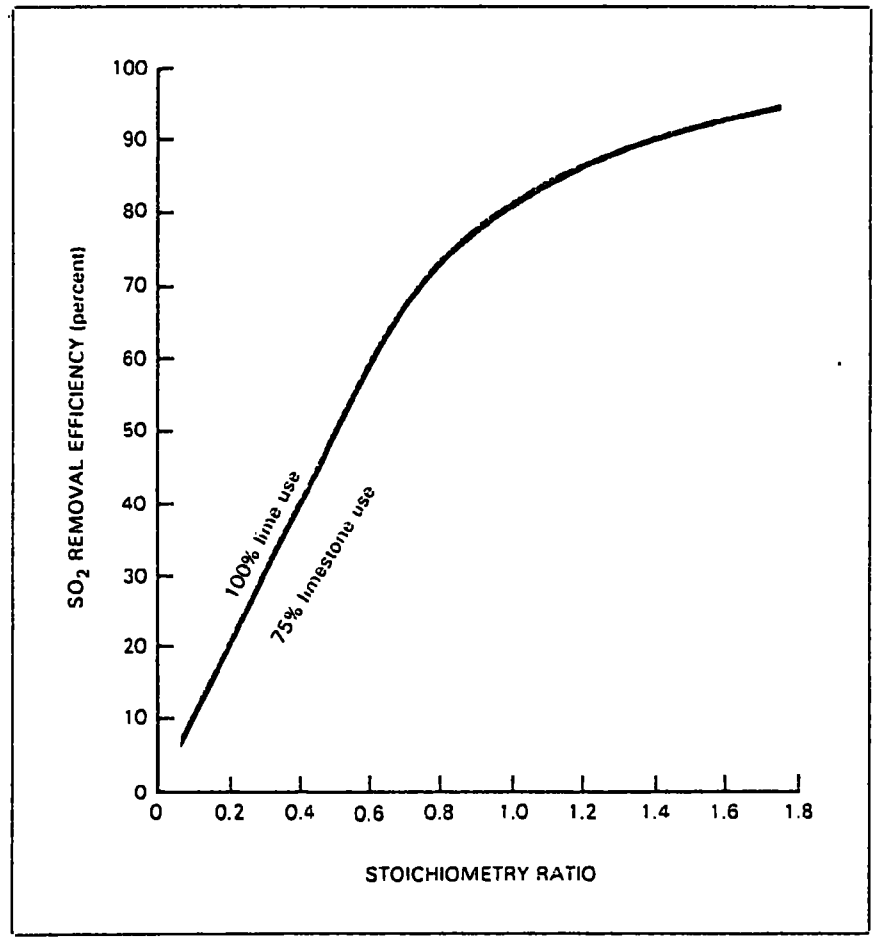


Figure 5.

SO_2 Removal Efficiency as a Function of Limestone:SO_2 Stoichiometry

Table 3.

Lime and Limestone Slurry Analyses

Slurry solids	Lime slurry (wt%)	Limestone slurry (wt%)
$CaSO_4 \cdot 2H_2O$	33.4	77.5
$CaSO_3 \cdot \frac{1}{2}H_2O$	54.5	1.0
$CaCO_3$	3.7	17.3
$MgCO_3$	—	0.8
Acid insolubles	4.6	3.4
Total	96.2	100.0

gas bypassing limit particulate collection in an R-C/Bahco scrubber operated outside the levels shown in Table 1. Particulate emissions from stoker-fired coal-burning equipment can be reduced to levels required by regulatory agencies if excessive soot formation is prevented.

Sludge Characterization

A series of scrubber sludge characterization tests was carried out at the Research-Cottrell laboratories to:

- Determine scrubber sludge dewatering characteristics
- Evaluate transportability of dewatered sludge
- Determine physical/structural properties of dewatered sludge
- Measure sludge leachate properties

Slurry Dewatering. A series of settling, centrifuge, and filter leaf tests was run on lime and limestone slurry samples. The results are summarized in Table 4.

The settling tests showed that limestone slurries settle more rapidly and produce denser settled layer than lime slurries. Flocculation improved the settling of limestone slurries, but not that of lime slurries.

Table 4.

Dewatering Test Results

Test	Slurry type	Feed solids (wt%)	Final solids (wt%)	Rate at 35 percent solids
Settling	Lime	16.2	44	22 lb/d/ft^2
	Limestone	16.7	58	164 lb/d/ft^2
	Limestone[a]	16.7	58	578 lb/d/ft^2
Centrifuge	Lime	26.3	51	—
	Lime	38.4	56	—
	Limestone	37.4	65	—
Filter leaf	Lime	24.6	58	70 lb/h/ft^2
	Lime	41.5	59	124 lb/h/ft^2
	Limestone	37.4	74	64 lb/h/ft^2

[a]With 5 ppm flocculant.

Table 5.

Sludge Leachate Analysis

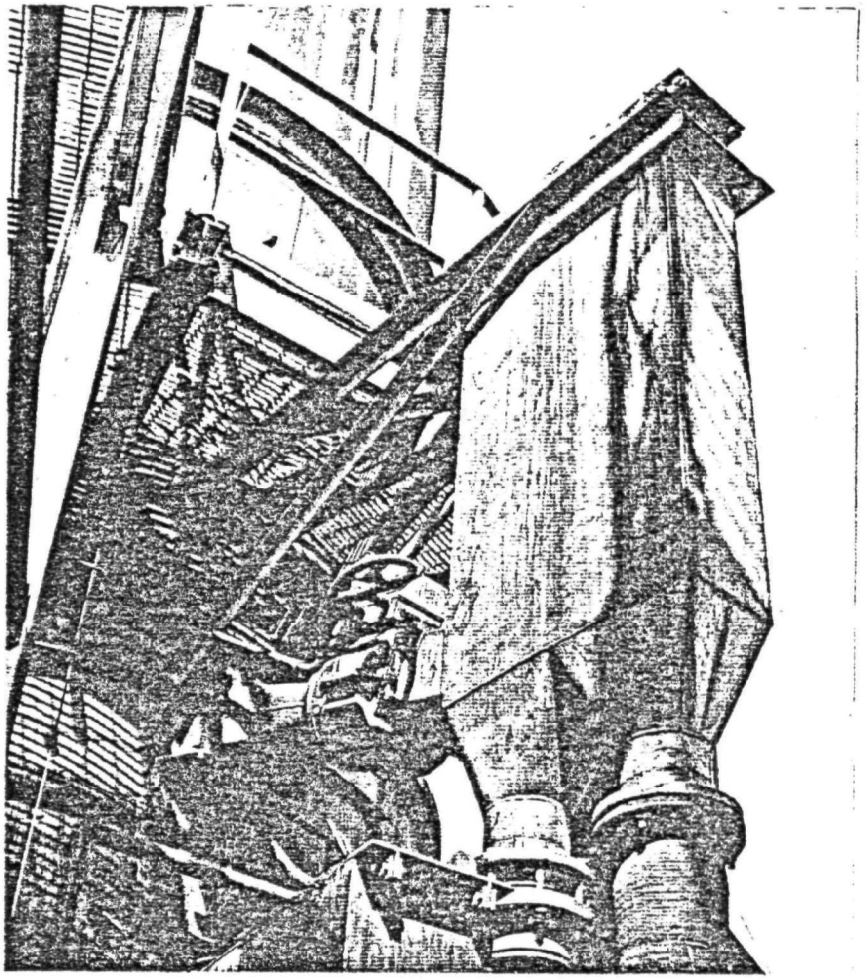
Analysis	Lime leachate	Limestone leachate
TDS (mg/l)	2,960	2,760
SO_4 (mg/l)	1,810.6	1,613.1
COD (mg/l)	8.4	6.8
Cl (mg/l)	72.52	48.04
Pb (ppb)	<100	<100
Cd (ppb)	<10	<10
Cr (ppb)	50	50
Hg (ppb)	<25	<25

The centrifuge tests indicated that final cake density increased as the solids concentration in the feed was increased, and that limestone slurries produced higher cake densities than did lime slurries.

Filter leaf tests showed that limestone slurry filtration rates were significantly lower than lime slurry rates. However, limestone again produced a denser cake.

Leachate Tests. Leachate tests were performed on samples of lime and limestone sludges. The results are listed in Table 5.

Leachate compositions from lime and limestone sludges are essentially the same. Total dissolved solids (TDS) in the range of 2,500 to 3,000 mg/l and sulfate levels of 1,600 to 1,800 mg/l indicate that the leachates were saturated with respect to $CaSO_4$. Both sulfites in the sludge and organic matter in the fly ash contribute to the chemical oxygen demand (COD) levels observed. Although the chloride level in the lime leachate is somewhat higher than the limestone leachate, the other trace elements are present in similar concentrations in both leachates. The constituents found in these leachates are similar in type and concentration to those reported in other studies. If a disposal site is placed so as to avoid infiltration of leachate into ground water, and if sludge and soil cover are placed properly to avoid excessive contamination of runoff, leachate from these sludges will not present an environmentally unacceptable disposal problem.



First-stage level tank

5. Operating Experience

Since startup in March 1976, the R-C/Bahco system has performed well in all areas essential to successful FGD, including:

- SO_2 removal
- Particulate removal
- Scrubber reliability
- Minimal routine maintenance
- Moderate operating costs
- Ease of operation

During the test period of about 11,000 hours, the scrubbing system operated for 6,194 hours. The operation is summarized in Figure 6. It is of interest that from December 1976 to February 1977 (when severe winter weather was encountered), no outages resulted from failure of auxiliary equipment. There were a few brief shutdowns caused by frozen air and water lines during this period, but system availability was over 95 percent.

Downtime is summarized in Table 6. This table shows the amount of time required to obtain parts as well as the actual time for repair work. Spare parts were not kept on hand during the test period, and this resulted in substantial unnecessary downtime. Since completion of the test program, a full supply of spares has been procured. Table 6 also shows that booster fan repair time accounted for 90 percent of the downtime caused by repairs. The booster fan operates on the inlet side of the scrubber, downstream from the mechanical collector, and handles only hot dry flue gas with moderate amounts of fine fly ash. Modifications to the fan wheel and bearings, completed in May 1977, have eliminated the recurring failures associated with this piece of equipment.

Total downtime, exclusive of fan repairs and procurement, was 1,845 hours, or 17 percent of the test period. During routine operation, the system availability should be over 95 percent, based on the factors observed during the test program.

Scrubber inspections were an integral part of the program to monitor scrubber performance. A thorough internal inspection was made in April 1976, approximately 1 month after startup. A followup inspection was made 2 months later, with subsequent inspections during outages up to the end of the test program in June 1977. These inspections confirmed the effectiveness of the water makeup system in keeping key areas of the scrubber clean.

Accumulations of solids were detected at seven locations within the scrubber (Figure 7). Accumulations in four areas—1, 5, 6, and 7—had no impact on scrubber performance. Problems of solids buildup in Areas 2, 3, and 4 were easily corrected, as follows:

In the first few months after startup, the first-stage venturi overflowed into the inlet manifold, Area 2, resulting in an accumulation of dried slurry in the bottom of that area. Subsequent investigation revealed that operation of the first-stage at pressure drops above 12 inches (30 cm) H_2O coupled with a second-stage slurry pumping rate more than 50 percent higher than the design rate of 2,600 gal/min (0.16 m^3/s), caused flooding when the gas flow was reduced below 35,000 stdft^3/min (17 normal m^3/s) or the booster fan was shut down. This problem was eliminated by decreasing the speed of the slurry pump to reduce the flow to design levels, and by adding an interlock to stop the pump when the booster fan is shut down. The accumulated material was removed during subsequent heat plant outages.

Areas 3 and 4 were affected twice during the test by accumulations of a coarse sandy material. The first incident, which occurred shortly after startup, was caused by inadequate removal of grit from the lime slaker. The material in the pan was removed and the slaker was readjusted to eliminate the problem. The second accumulation took place during the winter of 1976-77 when the air lines, which activated the blowdown valves on the first- and second-stage level tanks, froze and rendered these valves inoperative.

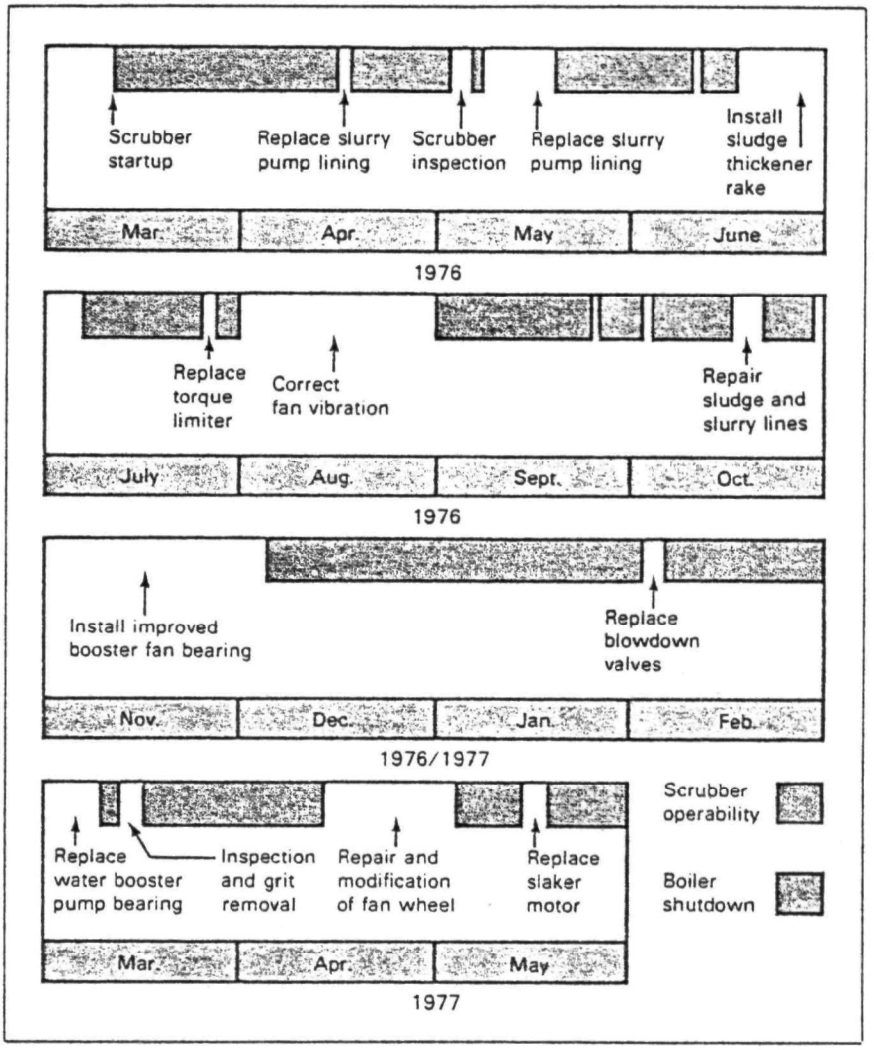


Figure 6.

Downtime Related to Auxillary Equipment

Table 6.

Downtime Summary

Item	Hours			Percent of test period
	Procurement	Repairs	Downtime	
Booster fan	514	2,252	2,766	25.1
Thickener	471	8	479	4.4
Slurry pump	252	18	270	2.5
Water booster pump	190	16	206	1.9
Lime slaker	122	11	133	1.2
Modifications	—	—	388	3.5
Routine maintenance	—	—	139	1.3
Loss of utilities	—	—	116	1.1
Miscellaneous	56	58	114	0.9
Total	1,605	2,363	4,611	41.9

The results of this part of the test program demonstrated that there are situations that can result in deterioration of scrubber performance, including:

- Infiltration of grit into the system through the lime slaker
- Inadequate operation of the scrubber blowdown valves
- Slow accumulation of solids in the straightening vanes in the stack

The infiltration of grit can be kept to a minimum by paying close attention to the operation of the lime slaker grit removal circuit.

The blowdown valves should be operated two to four times a shift, depending on scrubber load, to avoid accumulations of solids in the slurry outlets.

The straightening vanes at the base of the stack, which serve only to minimize spin in the gas stream leaving the scrubber, may accumulate some material and should be checked twice a year. The possibility of accumulations taking place can be minimized by operating the scrubber within the limits outlined in Section 3 to avoid slurry carryover. Obviously, elimination of the vanes would prevent the problem entirely, but accurate outlet particulate sampling would then be difficult.

The RAFB operating experience indicates that there are no significant problems related to the accumulation of solids in the R-C/Bahco system. The scrubber can tolerate substantial accumulations of solids resulting from external operating problems before performance is adversely affected. Any deterioration in performance that does occur is gradual and can be rectified at a convenient time.

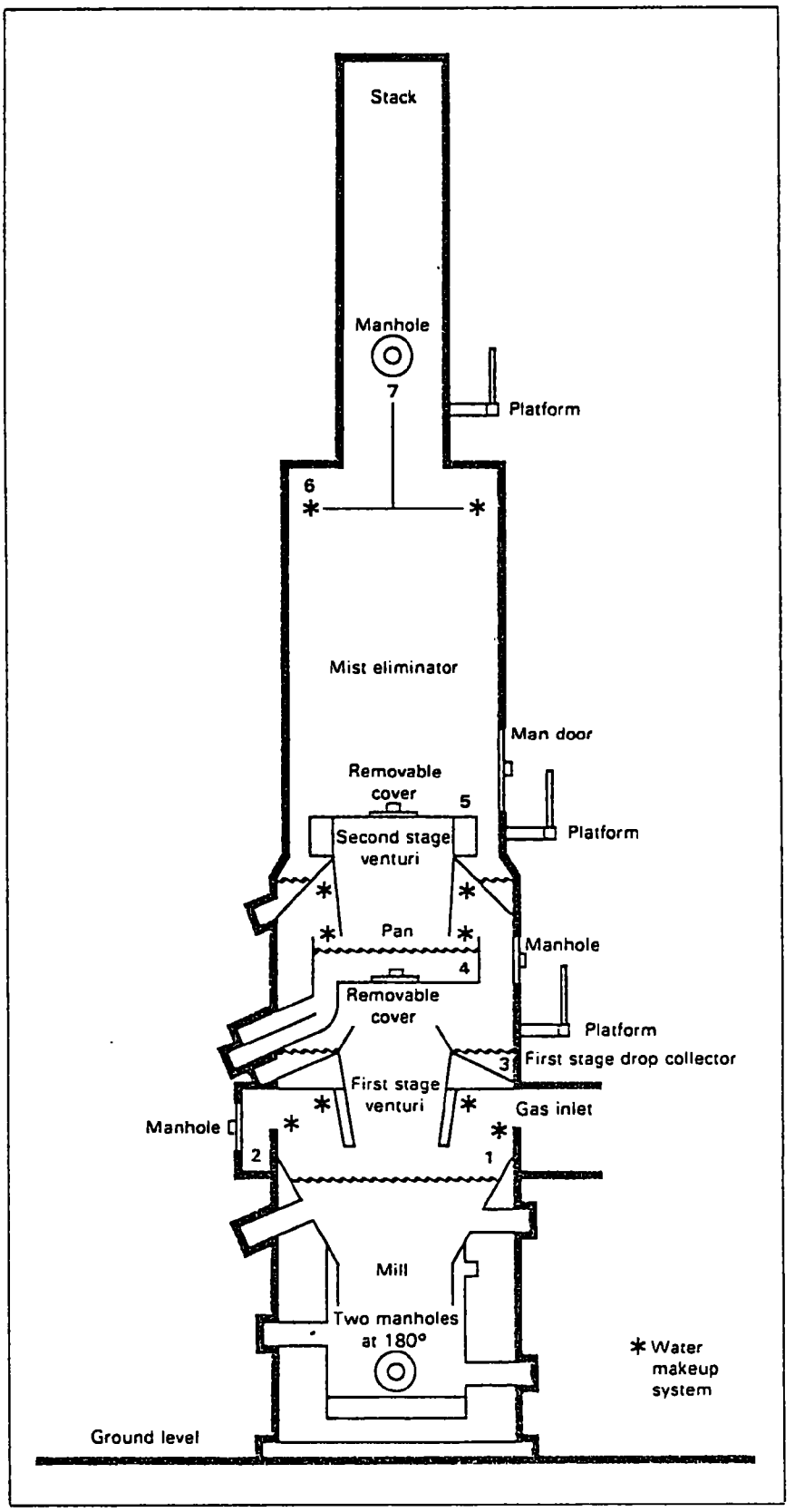


Figure 7.

R-C/Bahco Scrubber Module

Burning coal in

E. C. McKenzie, Woodall-Duckham Ltd., Babcock & Wilcox Group

☐ Today, many plant operators must specify new boilers that will have a life expectancy of 30 years or more. Which fuels will be available for these plants, particularly in their later years of operation? What environmental restrictions will be imposed on emissions?

The trend is toward the prohibition of oil and natural gas as boiler feeds. This has come about via either legislation or problems with fuel availability and cost. Let us, therefore, assume that the fuel for these boilers will be coal. We will first examine options on the design of a boiler and its fuel-preparation and firing equipment, using the technology available prior to fluidized-bed combustion. Then we will compare this technology to that of a fluidized bed.

Assume that the boiler output is greater than 400,000 lb/h of evaporation, so that we will be considering a pulverized fuel-firing system.

For a conventional boiler, we must next decide what type of coal will be used, since a boiler can handle only a limited range of fuel.

Bituminous-coal-fired boilers

Fig. 1 shows a sectional elevation of a 300-MW_e (megawatts, electrical) boiler designed for firing bituminous coal. The coal usually is ground into particles, 70% of which are less than 75 μm, typically in a vertical spindle mill. The mill is swept with sufficient heated air to dry the coal and convey the ground material directly to the burners. Power consumed in this process is about 18 kW/long ton of coal fired, i.e., the mill power plus the fan power.

Furnace volume and shape are determined by the heat absorption required to meet the design-furnace exit gas-temperature, if there is no concern about NO_x emissions. This temperature is set below the coal-ash melting point to prevent slagging on subsequent convection banks.

The size and number of burners are chosen to provide complete combustion within the furnace. A typical such pulverized-coal burner is shown in Fig. 2. Primary air and pulverized coal enter a tube fitted concentrically in a cylindrical secondary-air-register. The amount of swirl given to the secondary air is controlled by vanes on the periphery of the register. A smaller tube, located in the center of the coal/primary-air inlet, has an impeller that diverts the coal into the secondary-air stream. Inside this small tube is an oil burner for lighting up the coal flame, and a gas torch for igniting the oil burner. Both are withdrawn to a cool zone after they have been used.

The impeller acts also as a bluff-body stabilizer (a nonstreamlined object placed in the gas stream to inhibit flow) along with the flow-reversal mechanism set up by the swirled secondary air. The burners are positioned on the front wall (or on the front and rear walls for large boilers), so as to yield a near-uniform heat release over the furnace plan-area and minimize ash deposits on the walls.

The turndown on a mill and its associated burners is limited to approximately 50% by the need to (1) maintain velocity in the fuel pipes to prevent fallout of the coal, and hence plugging and (2) restrict maximum velocity so as to control erosion. Hence, the boiler load is controlled by varying the number of mills and burners in service. For safety, the oil burners are lit usually during load changes or when mills are put in or out of service, and are maintained in operation when the boiler is on low load.

The spacing of the platens is fixed to ensure that slag accumulations will not cause blockages. (If the platens are too close together, slag will bridge the spaces between them.) The velocity through the convection banks is limited by the abrasive properties of the ash particles, in order to prevent erosion of the tubes. The degree of abrasion with any given ash is proportional to the cube of the particle velocity. Normally, the boiler can accept a wide range of ash properties in bituminous

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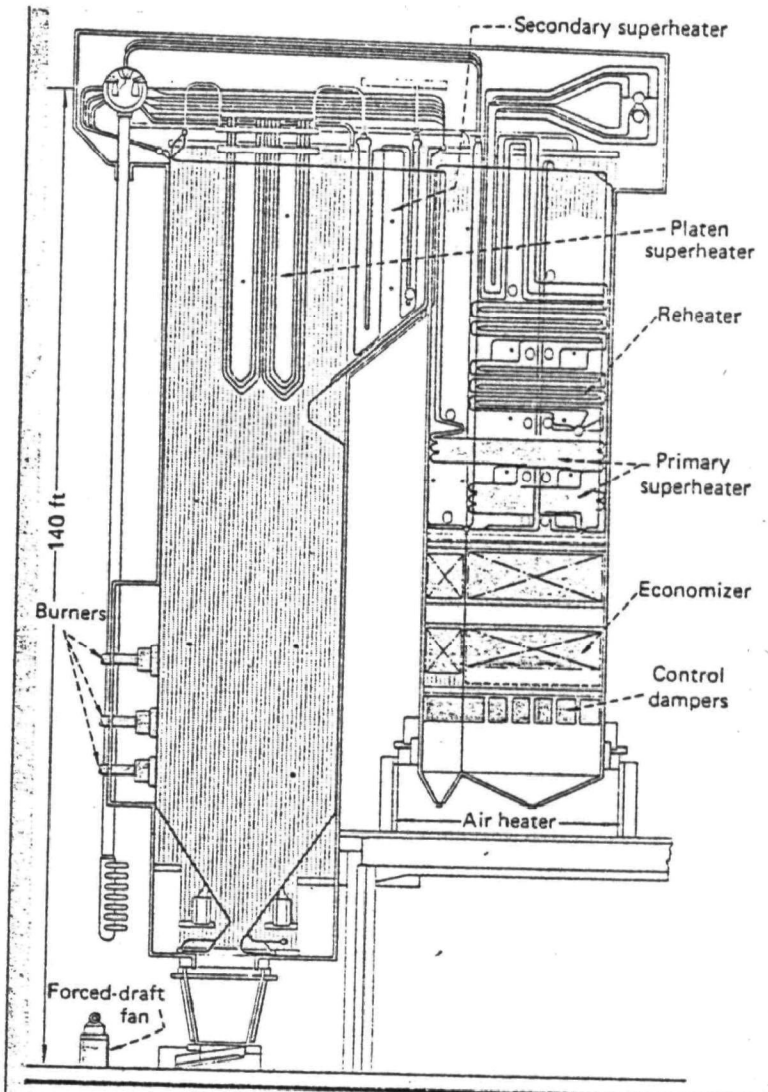
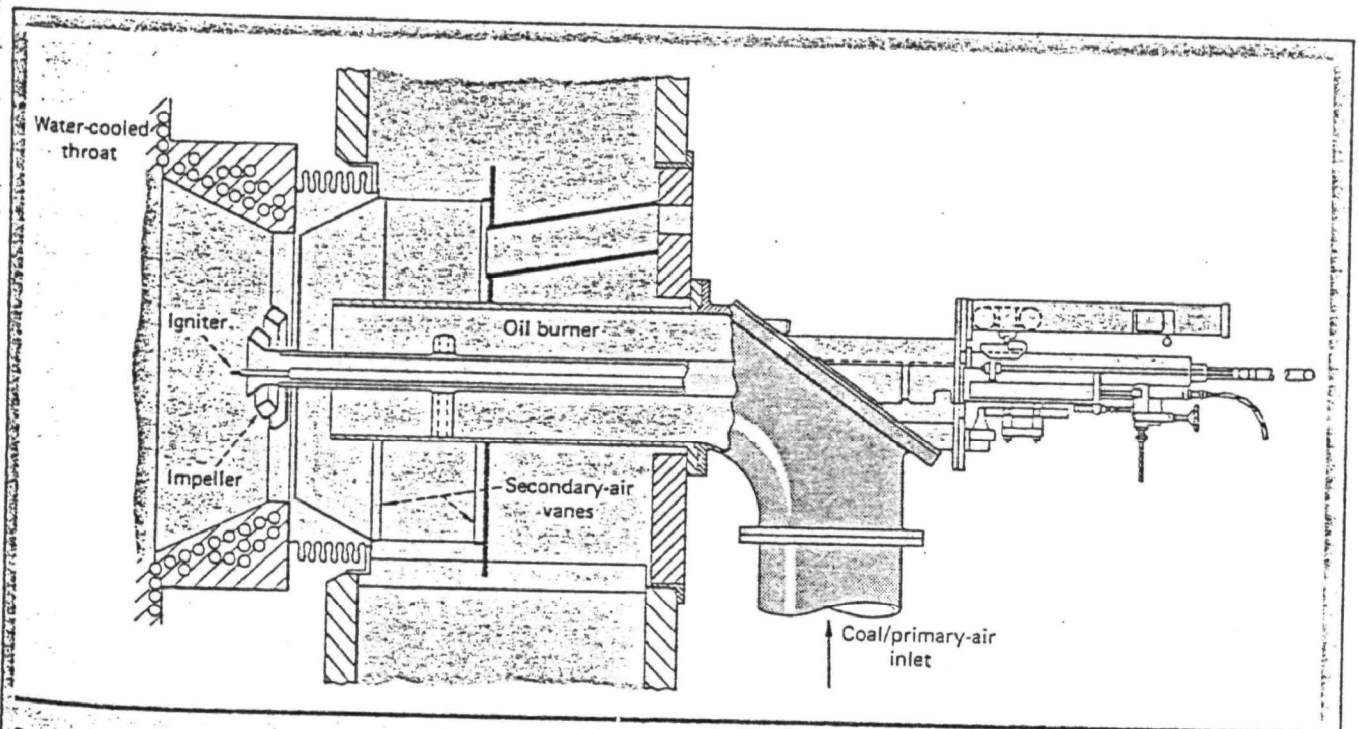
fluidized beds

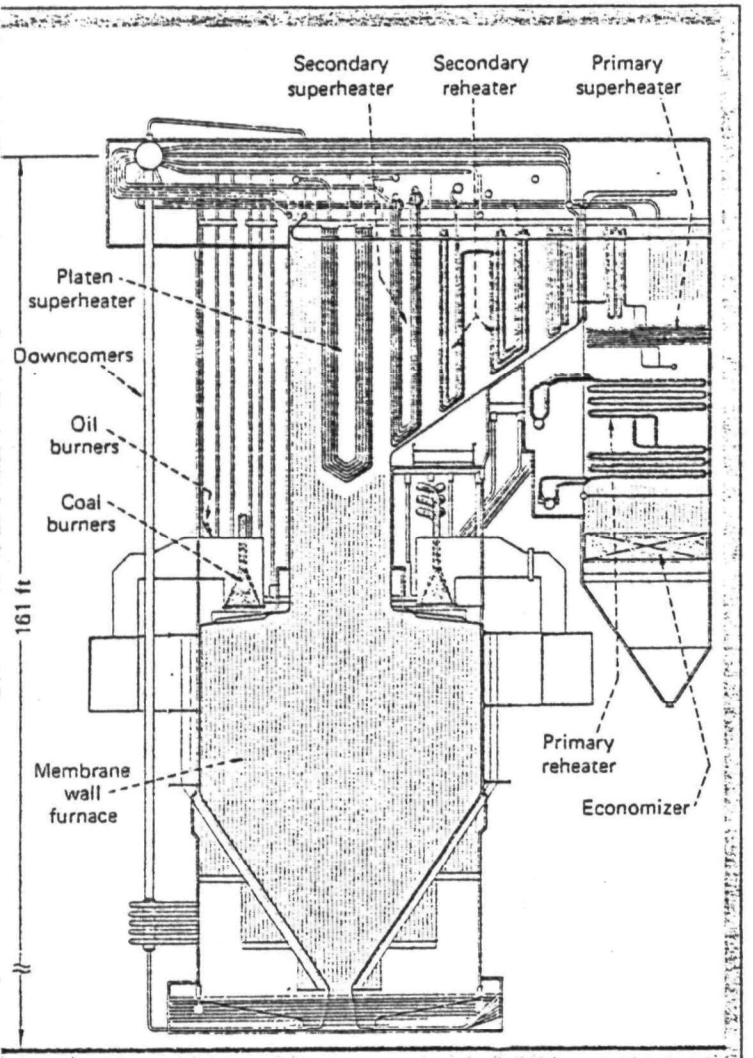
fter setting the stage with a review the operation of conventional al-fired boilers, this report discusses e use of fluidized beds, including pics such as coal preparation, load ntrol and emissions control.



Conventional 300-MW_e boiler that handles bituminous coal affords complete combustion Fig. 1



Burner for firing pulverized bituminous coal can be withdrawn from furnace Fig. 2



Designed for low-volatility, pulverized coal, 300-MW_e boiler requires high mill-power Fig. 3

coals. If a much different rank of fuel is used, such a boiler and firing system are no longer suitable.

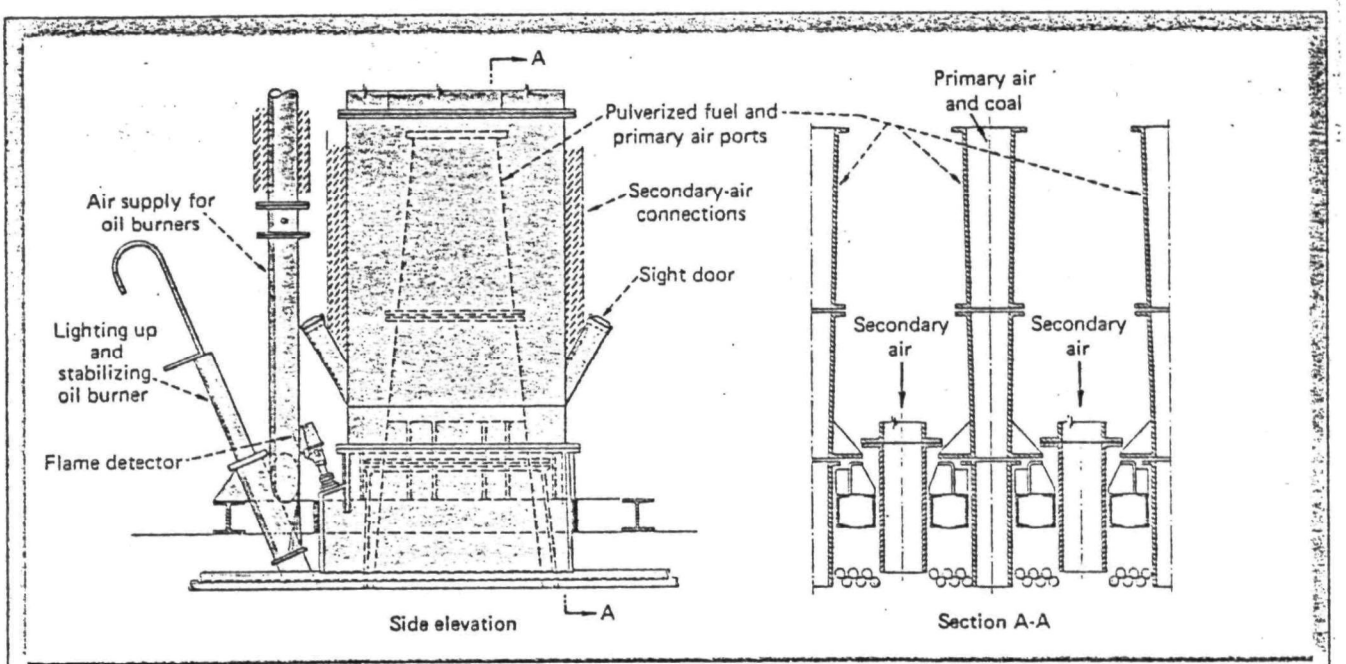
Low-volatility coal boilers

Figs. 3 and 4 show the boiler (also 300 MW_e) and burner systems for low-volatility coal. Here, one can no longer use a turbulent burner. To assist ignition, the coal is ground typically into particles, 85% of which are less than 75 μm. Compared with bituminous coal, the mill power-requirement is increased by about 50%. The burners are set in the roof of the combustion chamber. Primary air and coal are fired through rectangular slots, and the secondary air through adjacent slots. The relative velocities are designed so that once ignition is established, the secondary air mixes with the fuel at a rate that supports combustion but does not quench it. The absolute velocities are designed to yield long flames that sweep down into the lower part of the combustion chamber and then turn up to enter the center pass at the convection banks.

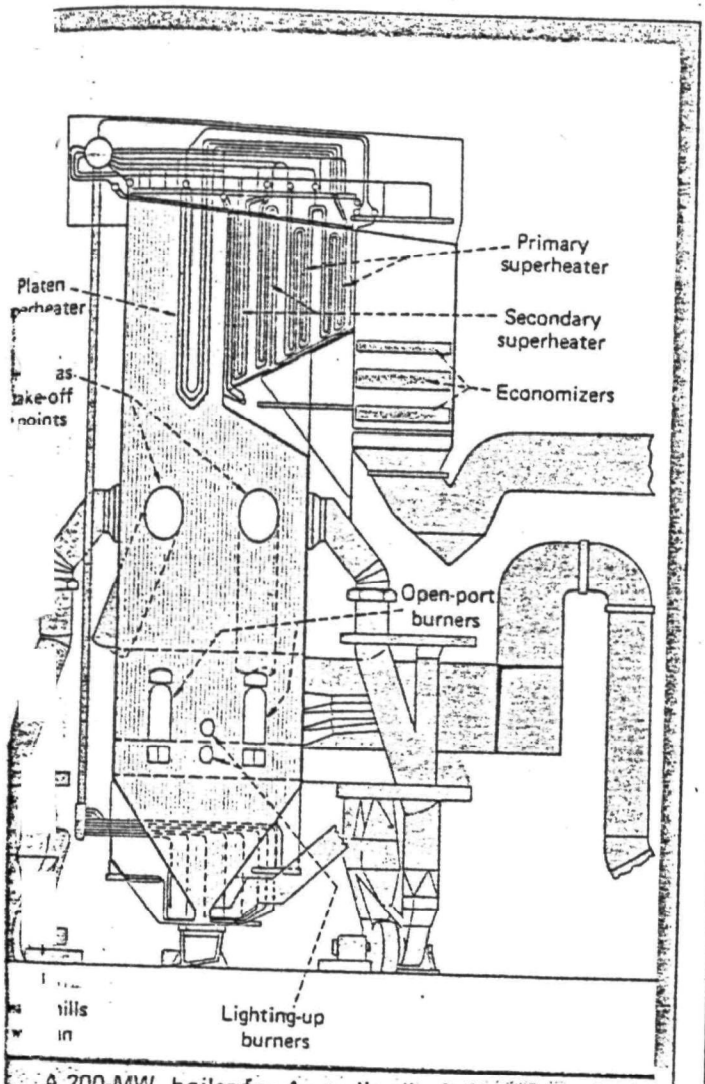
Mill and burner turndown are the same as for bituminous-coal systems, but due to the relatively poor reactivity of low-volatility coals, oil support is needed earlier than it is with bituminous coal as the boiler load is reduced from its normal maximum rating. These supporting burners are often placed in the side walls.

Fig. 5 shows a 200-MW_e boiler designed for Australian lignite. This fuel has a moisture content of about 70%, but when dry is extremely reactive. Usually, 99% of the particles must be less than 1 mm, requiring a mill power input of about 2kW/long ton. Also, the coal leaving the mill must be dried to about 20% moisture to ensure stable ignition in the boiler. To achieve this, gases from the furnace at about 1,000°C pass through the mill with the raw-coal feed.

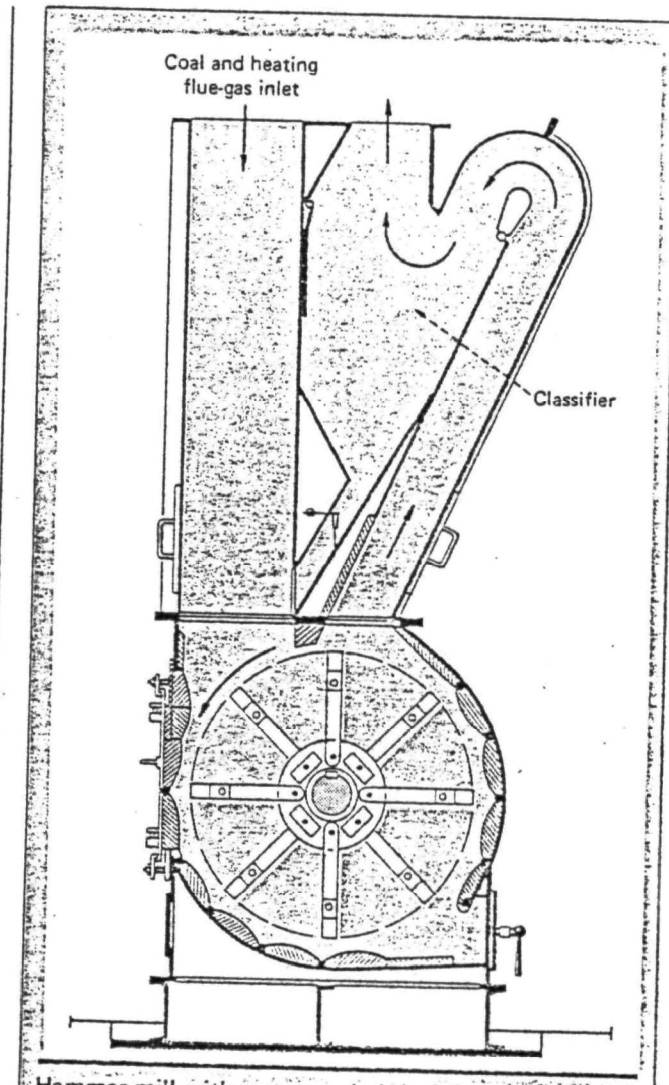
A hammer mill with a water-cooled shaft is the only type of mill suited for these conditions (see Fig. 6). Since



Nonturbulent burners for low-volatility coal. Units are set in chamber's roof Fig. 4



A 200-MW_e boiler for Australian lignite, which is dried by flue gases to 20% moisture Fig. 5



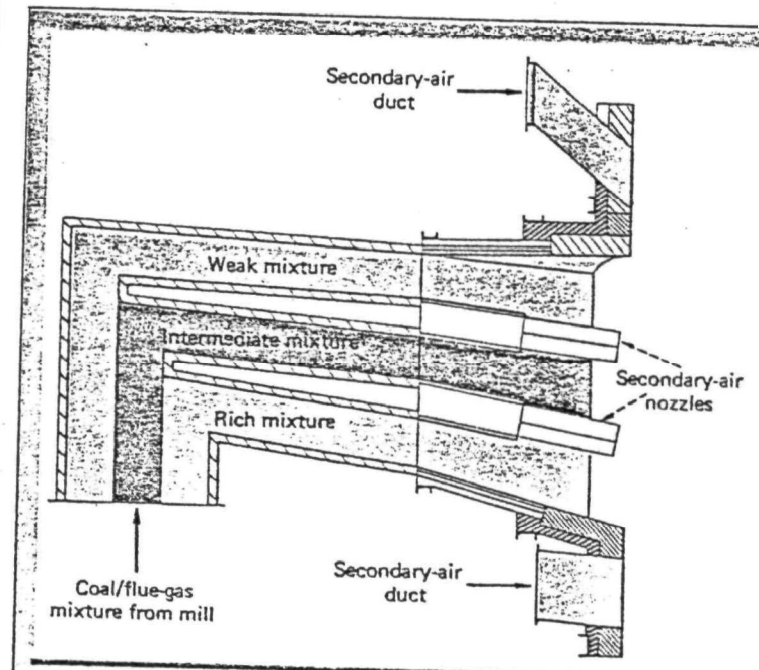
Hammer mill with water-cooled shaft is used to grind lignite for boiler in Fig. 5 Fig. 6

relatively coarse product is acceptable, a simple classi-
r can be used to return oversized particles to the mill.
ases leaving the mill are heavily laden with water vapor. The fuel and gases are partially separated in the ict carrying the coal to the burner, which is a series of orizontal slots alternately containing fuel-and-gas mixture and air.

A fuel-rich mixture is fired in the lower slot of the irner, as shown on Fig. 7, to improve ignition stabil-. The combustion chamber may be in the form of an octagon, with one burner, served by one mill, firing ch of the eight sides. The combustion chamber is ge compared with chambers for higher-grade coals.

The above brief survey on pulverized-coal firing illustrates the variety of boiler, fuel-preparation and ng systems necessary to suit the grade of the coal. ne of these systems can control SO_2 emissions and this must be done separately.

Also, because of its highly turbulent burner and conuently high flame temperature, the bituminous-l-fired boiler produces high NO_x emissions. If NO_x is to be controlled, whether by two-stage combustion, -gas recirculation, or both, then the combustion-mber volume becomes much greater and the boiler



Burner for separation firing of lignite alternates layers of air with coal/flue-gas Fig. 7

more expensive. Anthracite and lignite boilers are likely to produce much less NO_x because of their lower flame temperatures and, in the case of the lignite boiler, because of the high percentage of water in the fuel.

Fluidized-bed combustors

With fluidized-bed combustion, on the other hand, a boiler and its fuel-preparation and firing equipment can be designed to suit any type of fuel, whether solid, liquid or gaseous. This is provided that the fuel has a net calorific value greater than that required to heat both it and the makeup air to the bed temperature. Obviously, fuel-handling systems must suit the various forms of fuel, as well as have large enough capacities for the lowest-calorific-value fuels foreseeable.

The major advantage of fluidized beds, therefore, is that they allow the development of standard-design boilers and combustion systems to a degree not possible before. Fluidized beds also permit the use of low-grade coal, even at low loads, without the need for expensive support fuels to ensure stable ignition. Another advantage is that the relatively low combustion temperature results in low NO_x emissions and provides optimum conditions for the retention of sulfur by limestone or dolomite in the bed.

Principles of fluidized-bed combustion

The bed, which may be sand, firebrick, limestone or coal ash, is fluidized by blowing evenly distributed air through it. Both bed material and the coal fired to it are crushed to a size compatible with the chosen fluidizing velocity, i.e., a size that minimizes loss by elutriation. The fluidizing velocity is calculated from the quantity of air at bed temperature and pressure, and from the bed's superficial area:

$$v_f = \frac{W}{C\rho_0} \times \frac{T_b + 273}{273} \times \frac{1}{A}$$

where v_f = fluidizing velocity, ft/s
W = air quantity, lb/s
T_b = bed temperature, °C
ρ_0 = air density at 0°C, lb/ft^3
A = bed area, ft^2
C = bed pressure, atm

At a given excess-air level, heat-release rate per unit area of the bed is a linear function of the fluidizing velocity. The heat-absorption surface is immersed in the bed and is matched to the heat input, so that the bed temperature can be controlled between chosen limits. Since the heat input is proportional to the fluidizing velocity, as the latter increases, the amount of installed surface increases to keep within the design's maximum bed-temperature.

Furthermore, McLaren and Williams [1] have shown that as the bed's mean particle size becomes greater to suit higher fluidizing velocities, the heat-transfer coefficient between the bed and the immersed surface decreases. Hence, two factors determine the area of heat-absorbing surface required as the fluidizing velocity increases. Since, for a given tube arrangement, additional surface can only be provided by deepening the bed, an optimization study has to be made between the capital cost of the bed area and the operating cost of higher fan power needed for the deeper bed. Although the combustion-air fan power requirement is considera-

How is fluidized-bed combustion technology developing?

Companies involved with this knowhow must choose among a variety of options; such as: Should the bed's operating pressure be atmospheric or elevated? Technological controversies now exist, and are examined here in an excerpt from a new report, "Fluidized-Bed Energy Technology: Coming to a Boil," by Walter C. Patterson and Richard Griffin. Issued by Inform, 25 Broad Street, New York, N.Y. 10004, a nonprofit research organization, the report is available for $45.

☐ Energy planners all over the world are looking to coal as the one essential fuel.

Actually, all but the most single-minded coal enthusiasts will concede that, given the choice, oil and natural gas are more-satisfactory fuels than coal, and that solar energy is even better in some cases. Interest in advanced coal-technologies stems from the premise that oil or natural gas is no longer reliably available, that nuclear power carries high environmental risks and provokes strong public opposition, and that solar technology is not available or economical for certain important applications, particularly those requiring intense heat.

Thus, an increasing use of coal, especially over the next few years, seems inevitable. If so, the potential advantages of fluidized-bed systems warrant serious study by those involved in energy-use and -supply decision-making.

Opinions about fluidized-bed technology differ widely among specialists but all agree that the basic concept is sound. Three U.S., one Norwegian, and three British companies are offering fluidized-bed combustors for small-scale industrial use, and a number of test systems are already functioning. A typical capacity is 100,000 lb/h of steam. When it comes to development

ble, it is largely offset by savings in mill and primary-air n power, when compared with conventional pulverized bituminous or anthracite units for beds under 3 ft.

Choosing the maximum, rated bed-temperature depends on several factors. First, the maximum temperature at which the bed can function is limited by the ash sion characteristics. Obviously, when firing coal, no matter what the starting bed material is, the bed will ultimately consist only of coal ash, and this must not be lowed to sinter. So far, it has been found that trouble ll not occur if the bed temperature is at least 200°C below the ash's initial deformation-temperature. Operating at the maximum permissible bed temperature hieves the highest combustion efficiency within the d, the highest heat flux to the immersed surface, and the widest boiler-load control that can be practiced by d-temperature control.

Combustion efficiency in the bed and the freeboard is itten high enough that sufficient carbon is burned up so that any carbon in the precipitators can be ignored. In ne cases, it may be necessary to refire a selected part the solids carried over to achieve an acceptable unburned loss. As fluidized-bed boilers become bigger, and ltiple beds are employed, there will be increased dom in choosing bed temperature and fluidizing ocity for the refired grits.

Boiler load is controlled by bed temperature and the nber of bed zones in operation. To reduce the load, bed temperature is lowered by reducing the amount of incoming fuel and air. This is limited by the onset of significant drop in combustion efficiency. At that nt, selected zones will have the fuel and air cut off so t the zones slump.

When this happens, the heat-transfer coefficient from bed to tubes virtually instantaneously falls to zero, resulting in a step change in load. The bed adjacent to the tubes cools to the temperature of the tubes, but only a small part of the bed is cooled, because of its insulating properties. The heat loss from the zone is so small that after several hours' idleness, the zone may be reactivated simply by restoring the air and fuel supply.

The extent of the load change by temperature control is a function of the temperature range through which the bed operates and the surface temperature of the tubes immersed in the bed.

For example, consider a bed with a maximum load temperature of 950°C, a tube surface temperature of 400°C, and a minimum bed temperature of 750°C at which combustion efficiency begins to deteriorate. Assuming half the heat flux is through convection and half through radiation, then reducing bed temperature from 950°C to 750°C would achieve an about 50% cut in the work done in the bed. If, however, for any reason, such as sulfur retention, it would be necessary to limit the maximum operating temperature to 850°C, lowering the temperature to 750°C would reduce the work done in the bed by only 30%. Thereafter, load reduction would be by slumping selected zones. The number of zones required is such that by a combination of temperature control and zone slumping, all of the stipulated load range could be covered.

The rate at which the load is changed by temperature control is very fast, as shown in Fig. 8. It will be seen that by turning off the fuel and leaving on the fluidizing air, the temperature drops from 850°C to 750°C in 100 s, even with a fluidizing velocity as low as 4 ft/s.

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of larger, more-efficient or more-sophisticated systems, nions differ.

The most fundamental difference is between those who feel that others are proceeding too fast, and those feel that others are doing the opposite. In general, companies feel that European firms are moving quickly, while Europeans believe the U.S. companies are lagging behind.

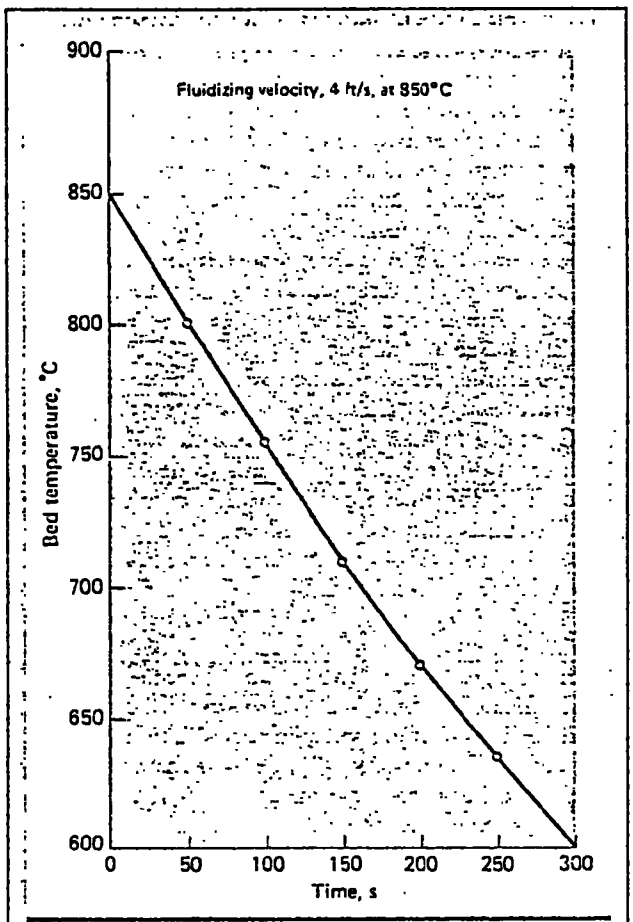
Another disagreement, more technical in nature, is ther to use atmospheric or pressurized systems. Some companies, such as Pope, Evans & Robbins, Inc. (New York City), are concentrating entirely on atmospheric systems; others such as Curtiss-Wright Corp. (Wood-Ridge, N.J.), are concentrating on pressurized systems. Still others, such as Babcock & Wilcox Ltd. (London), are actively involved in both lines of development.

Companies pursuing both lines feel that atmospheric fluidized-bed combustion will be preferred for industrial-sized boilers, and that utilities will prefer pressurized systems, which can be adapted to combined-cycle use. For a large utility plant, about 200 MW, important capital-cost savings will be realized by the pressurized fluidized-bed combustor's smaller size (for the same amount of output). Also, improved efficiency is achieved through combined cycles.

Much of the controversy on how fast to proceed stems from uncertainty as to scaleup and the usefulness of pilot-plant data. Some U.S. research laboratories carry out exhaustive small-scale investigations into emissions and their control, sorbent behavior, and other fluidized-bed phenomena. Others, however, especially those in Europe, insist that small-scale results will not apply to scaled-up units. Such companies, including Stal-Laval Turbin (Finspong, Sweden) and Babcock & Wilcox Ltd., feel that enough data already exist to permit construction of major prototype facilities.

A different opinion is held by those involved in a pressurized demonstration plant to be built at Grimethorpe, England, by the British government's National Coal Board. The 80-MW_t (megawatts, thermal) unit will be of prototype size but will be used purely for research. It is expected to be more flexible than a commercial unit and should better lend itself to full-scale experimentation.

Researchers at Grimethorpe doubt there are enough relevant data available to successfully design and operate full-scale, pressurized, fluidized-bed-combustor/



In fluidized-bed combustion, temperature dips rapidly as fuel is cut off Fig. 8

Obviously, by modulating the fuel input rather than cutting it off, the rate can be made slower.

Separately slumping each zone is equivalent to turning off a burner group served by one mill in a conventional pulverized-coal-fired boiler. There is, therefore, much similarity in the boiler load-control systems, in that the same sort of functions have to be performed. In a pulverized-coal boiler, the removal of a mill and burner group is dictated by its turndown capability, which is defined for the operator. In a fluidized-bed-fired boiler, the removal of coal feed and air from a zone is dictated by the lowest temperature that provides good combustion and maintains sulfur retention. Fluidized-bed firing has the advantage that once a bed is at its operating temperature, an expensive fuel-oil support system is not needed during load changes or at low load operation, even with very-low-grade coal.

The author has described [2] the first year's experience with a 40,000-lb/h boiler that was converted to fluidized-bed firing. In subsequent trials with a coal containing 60% ash, the boiler load was controlled from 46,000 lb/h of evaporation to 12,000 lb/h, with no support fuel required. This is readily understandable, as the coal in the bed is less than 1% by weight of the bed, even at maximum load.

Atmospheric-pollution control

The main pollutants in the stack gases from current conventional high-temperature combustion systems are ash, sulfur oxides and nitrogen oxides. There is, however, a growing concern about the emission of trace elements such as arsenic, antimony and mercury.

Ash is trapped with acceptable efficiency by precipi-

gas-turbine systems. However, Stal-Laval Turbin and Babcock & Wilcox, Ltd., among others, disagree. The Grimethorpe team considers it premature to tackle both the problem of a pressurized fluidized-bed combustor and that of coupling such a combustor to a gas turbine.

On the other hand, the Stal-Laval/Babcock & Wilcox team feels that the Grimethorpe unit will be "reinventing the wheel," carrying out research on a noncommercial unit that might perfectly well be done by building a commercial prototype and acquiring the desired experience in actual service. Some U.S. experts feel that the Stal-Laval/Babcock & Wilcox team is overlooking the problems of gas-turbine-blade corrosion due to sodium and potassium in the coal.

One project, considered already obsolete by some, is a 30-MW_e (megawatts, electrical) prototype atmospheric unit, built in Rivesville, W. Va., by Pope, Evans & Robbins for the former U.S. Office of Coal Research, now part of the U.S. Dept. of Energy (DOE). The project was an attempt to develop a cheap coal-fired boiler for power generation. Contracted for in 1972, before the oil price-rise, the system was supposed to compete with then-cheap oil.

The plant is a multi-cell fluidized-bed unit, consisting of four separate beds. The first bed boils the water, the second heats the resulting steam, the third superheats the steam, and the fourth burns up unburned carbon. Problems have been encountered, particularly with coal-handling and coal-feed systems. One persistent problem is clogging of coal in feed lines, blocking the fuel supply.

Critics feel these problems are partly due to tight specifications laid down when the objective was to build a very inexpensive boiler.

Today, DOE is primarily concerned with sulfur-oxide emissions control. Fluidized-bed combustors must compete economically not with oil-fired boilers but with conventional coal-fired boilers using scrubbers. Pope, Evans & Robbins concedes that times and priorities have changed. However, the company questions a wholesale switch to pressurized fluidized-bed combustion. It believes that money saved by smaller-size units for the same output will be offset by the additional cost of coping with the higher pressures, especially for feeding coal and removing solid waste. Atmospheric systems are thought preferable for all sizes.

Stal-Laval believes that pressurized systems may be preferable for medium-to large-scale applications. The firm cites the advantage of being able to double a pressurized system's useful energy output by using com-

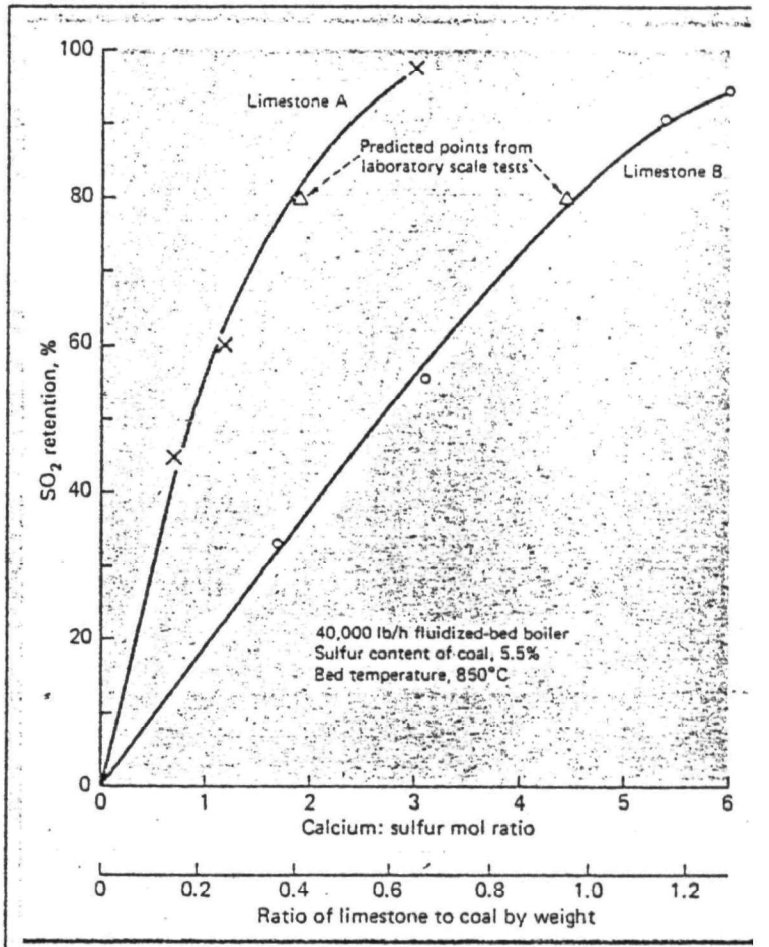
tators. Sulfur oxides can be controlled by burning low-sulfur fuels, which command high prices, unless they are coals of the sub-bituminous types, such as those found in the western U.S. and in south Australia, that have a high alkali content and give rise to severe slagging and fouling.

For high-sulfur fuels, expensive scrubbing systems may be used. A popular method is to scrub the gases with a limestone slurry. But this has two disadvantages. First, it creates a residual pollution problem in disposing of the spent limestone, unless an expensive recovery plant is installed to regenerate the limestone and recover the sulfur, which has a doubtful market value. Second, scrubbing carries a penalty of at least 4% on gross thermal efficiency because, after scrubbing, the gases have to be reheated before entering the stack.

Nitrogen oxides are generally controlled by interfering with the combustion process, again with attendant penalties.

With fluidized-bed firing, when there is no restriction on sulfur oxides emission, the removal of particulate matter from the gases is somewhat easier than it is for pulverized-coal firing. This is because, in a fluidized bed, for a given coal less goes to the precipitators, and the mean particle size is much greater. Where sulfur retention is practiced, adding limestone (or dolomite) makes the dust burden greater and changes the character of the dust to be caught. Opinions among the makers of electrostatic precipitators appear to be rather mixed. Some claim that enough is known to permit the design of satisfactory precipitators, while others regard this area as still developmental.

Garner, Howe and Dzierlenga [3] list proposals of



Better than 90% retention of sulfur is achieved even when using high-sulfur coal Fig. 9

bined cycles or cogeneration. The company believes this will be the most effective lever in persuading industries to convert their boilers to ones that use pressurized fluidized-bed coal firing.

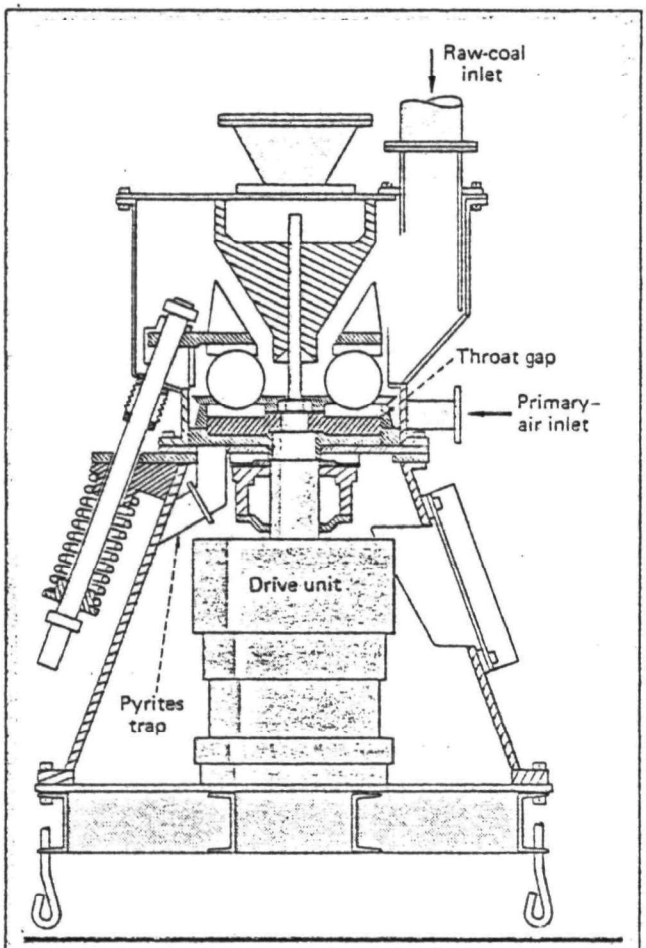
Art Fraas, a consultant to the Oak Ridge National Laboratory (Oak Ridge, Tenn.), points out that using a closed-circuit hot-air turbine system makes it possible to combine atmospheric fluidized-bed combustion and combined cycles or cogeneration.

Steven Freedman, director of DOE's fluidized-bed program, feels that industrial-sized atmospheric fluidized beds are closest to becoming commercial. These systems' greatest advantage, he believes, is their fuel-use flexibility. Freedman sees utility systems as a longer-term proposition. DOE hopes to have both large atmospheric and large pressurized fluidized-bed plants online by 1984, so utilities can choose between the two systems. It sees advantages in both approaches: atmospheric is simpler and more reliable, while pressurized has a slightly higher efficiency and produces slightly fewer sulfur-dioxide emissions.

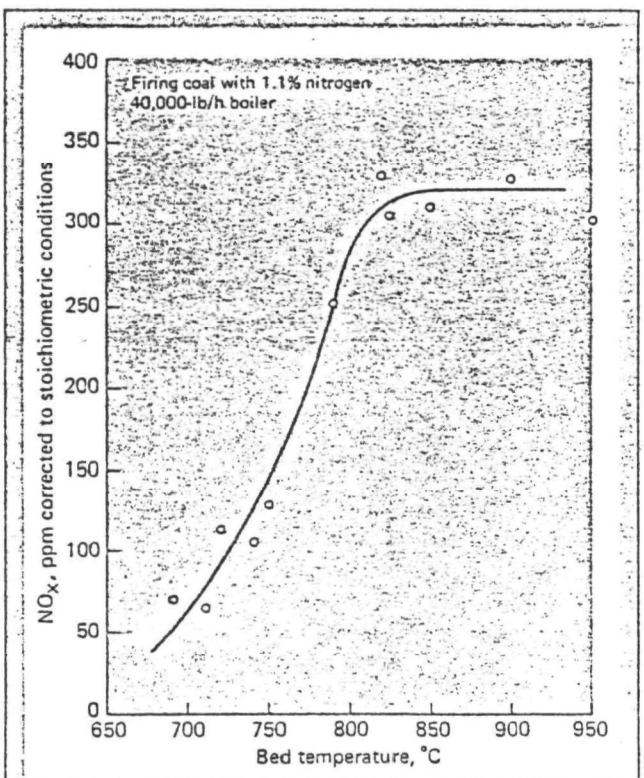
Other differences of opinion exist. Battelle Memorial Institute (Columbus, Ohio) and various U.S. researchers are concerned about possible corrosion of boiler tubes. Others, especially those in Europe, see nothing at all to suggest that such problems will arise.

Coal feed has caused continuous trouble at the Rivesville unit, and several U.S. firms are also concerned about feed problems, while the Europeans see no such troubles. The general European view seems to be that coal can be fed from above the bed, within it or under it; and that the easiest way, from above, is satisfactory. Coal fed from above remains within the bed long enough to burn completely without undue carry-over of unburned particles into the flue gases. Europeans feel that if a company uses a special carbon burnup cell for unburned particles when moving to large-scale applications (as is the case at Rivesville), this indicates the design of the main bed is not optimum.

Still another difference of technical opinion concerns unit size. Some favor cell and bed dimensions small enough to permit prefabrication in the manufacturer's shop, while others favor larger units. The smaller-scale (or modular) approach offers the advantages of replication, and of stable working conditions in an established shop. However, Babcock & Wilcox, Ltd., and others believe the modular design may not be as flexible in actual operation as the custom-built large-scale bed, which may be subdivided into separate cells with separate air and fuel feed.



Mill modified to operate as a crusher. Unit separates out pyrites as well Fig. 10



NO_x emissions level off above 800°C to value below current U.S. legal maximum Fig. 11

three U.S. boiler makers. Two propose to trap larger particles in multitube cyclones and do the final cleanup in a baghouse. The third proposes using two hot-side electrostatic precipitators, one to trap the coarse material for possible reinjection and the other for final cleaning. There is no doubt that baghouses can now be used to meet particulate-emission limits. Precipitators, however, may turn out to be the most economical way to control particle emissions.

Limestone efficiency

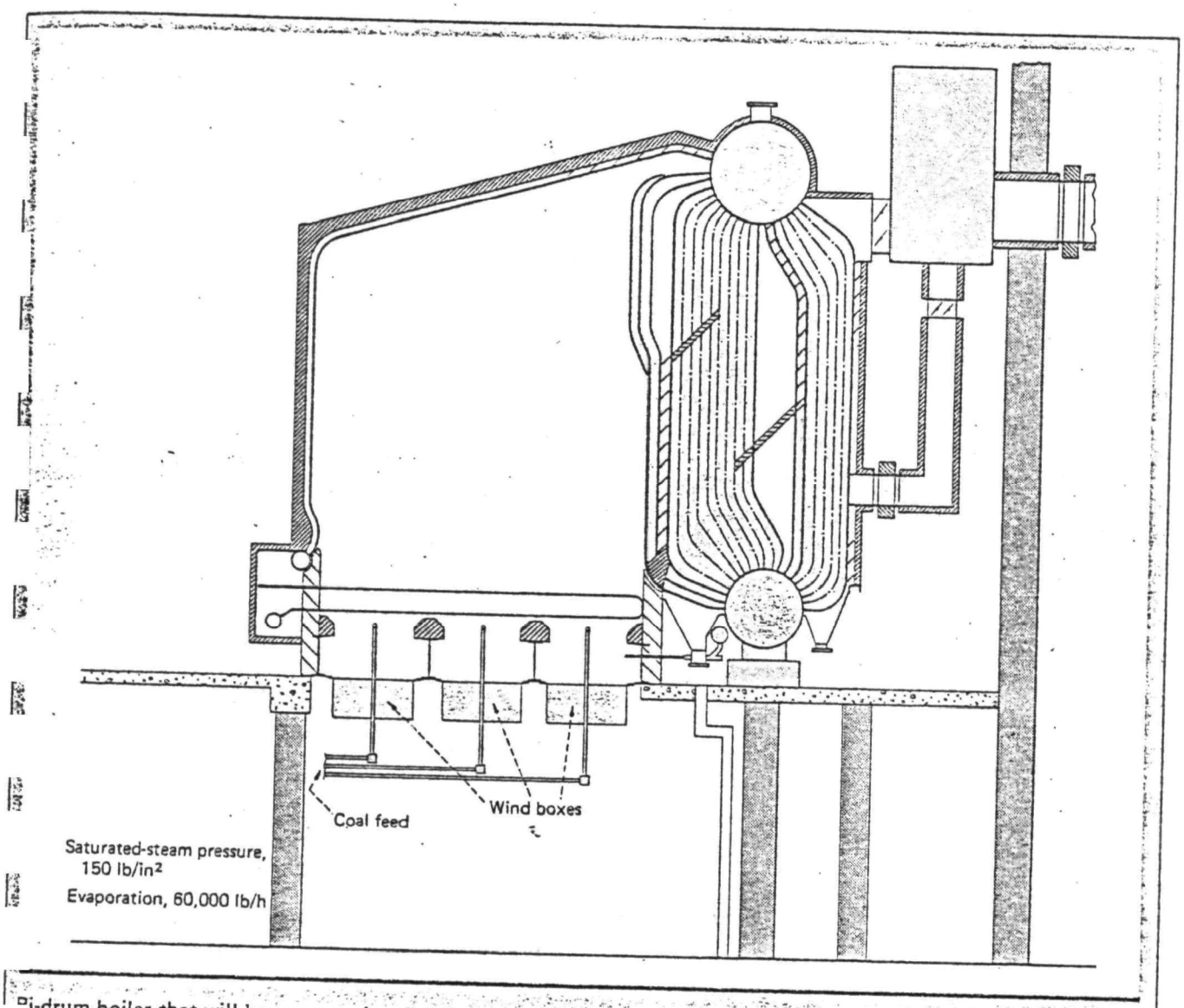
Fig. 9 shows the effect of the limestone/coal ratio on sulfur retention for two different limestones. Although these have the same chemical composition, their efficiency in reacting with sulfur is different, probably due to differences in their porous structures. These results show two other features: (1) even with very-high-sulfur coal, retentions better than 90% are achieved; and (2) small-scale tests can accurately predict the Ca:S ratio required to yield the desired performance in a boiler. Ehrlich [4] shows the effect of bed temperature on sulfur capture and concludes that the optimum temperature at atmospheric pressure is near 800°C. A fluidized-bed combustor operating between 850°C and 750°C would probably provide the optimum in sulfur retention and boiler load-modulation by bed temperature control.

Sulfur occurs in coal in organic and inorganic form. The inorganic is mainly pyrites, an iron sulfide having a specific gravity of 5.0. Coal has a specific gravity of about 1.3, while that for coal ash or limestone is around 2.7. In low-sulfur coals, the organic form predominates. As the total sulfur increases, more of it becomes pyrites. This is separated out in some types of mills.

Fig. 10 shows a sectional elevation of such a mill. The air for drying and conveying the coal through the mill enters a plenum chamber under the yoke and then passes through slots in the throat ring into the mill. The velocity through these slots keeps coal particles in the mill, while heavier particles (pyrites) fall through the slots. The rejected material is then swept by ploughs to a reject box. The high-sulfur coal used in Fig. 9 may have half of its sulfur as pyrites. The more discrete the distribution of the pyrites, the greater the proportion will be rejected and, accordingly, the greater the savings in limestone needed to reach the acceptable SO_2 emission level.

With coals having a modest sulfur content, the calcium oxide in the coal ash may be sufficient to reduce SO_2 emissions without requiring the addition of limestone to the bed.

In Fig. 11, NO_x emissions from a Babcock boiler that is firing a coal containing 1.1% nitrogen are shown as a function of bed temperature. The analyses were done by the chemiluminescence method. The maximum effluent level is well below the current limit of 525 ppm at 3% excess oxygen set by the U.S. Environmental Protection Agency for new coal-fired plants. In fluidized-bed combustion, it is now generally accepted that most of the NO_x formed comes from the nitrogen in the fuel and not from the atmosphere. The maximum figure of 325 ppm shown on Fig. 11 corresponds to the conversion of about 30% of the nitrogen in the coal.



Bi-drum boiler that will be converted to fluidized-bed firing

Fig. 12

Fluidized-bed advantages

Further advantages are apparent when comparing idized-bed combustors with other furnaces:

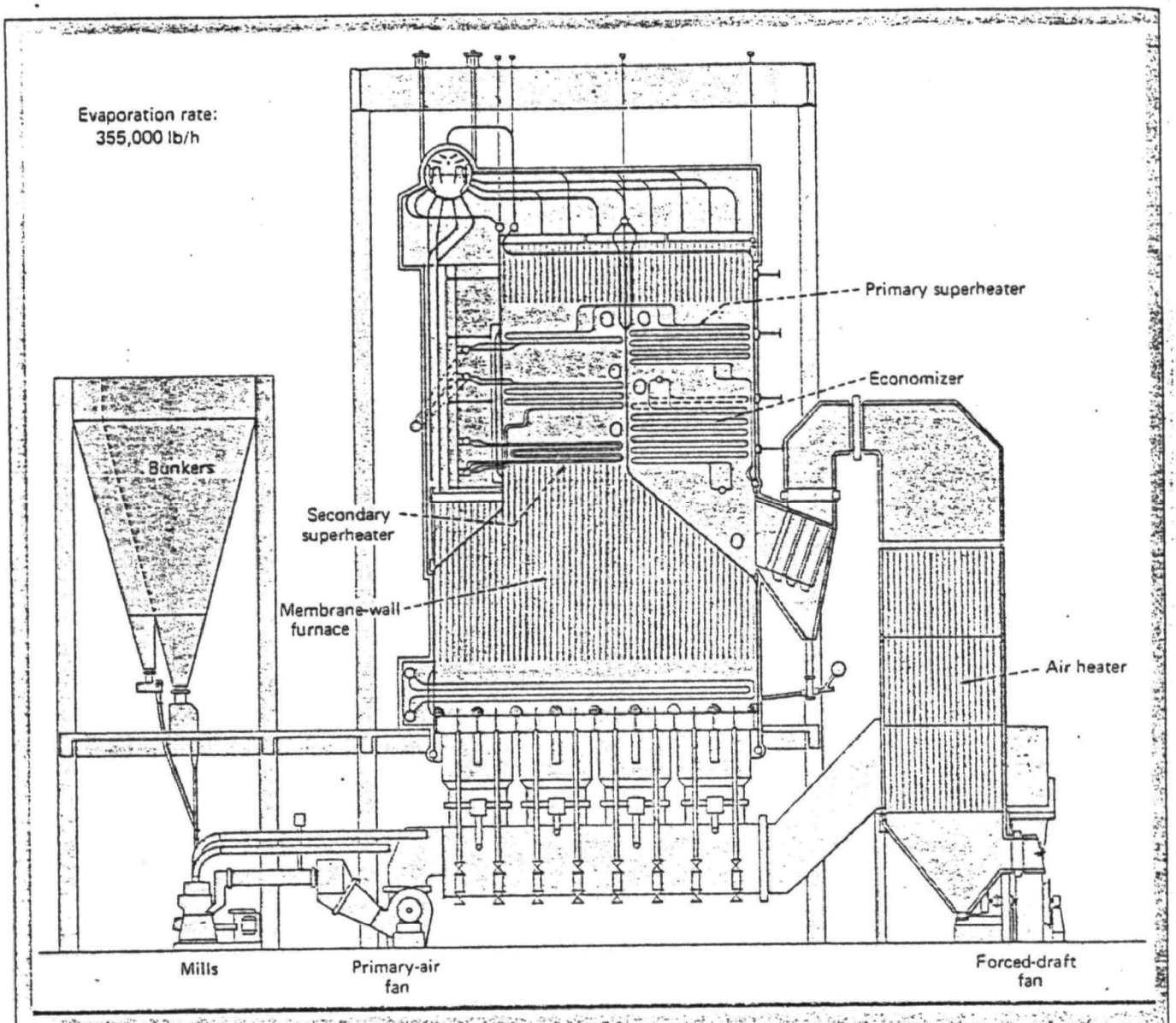
Because combustion is carried out at a relatively low iperature, the coal-ash particles are kept below their ening temperature, preventing slagging and ...ded-deposit formation. Hence, the need for soot-blowing is reduced. On the 40,000-lb/h boiler, the soot-wers that were in place before conversion have never ded to be used in over 6,000 h of operation. This should allow for more-compact convective-heat-transfer banks, thereby increasing heat-transfer coefficients and imizing the surface area.

Very-high heat-transfer coefficients are obtained between the bed material and the immersed surface, so t although the temperature differential is lower than i pulverized-coal- or oil-fired boiler, the overall heat flux is greater. Therefore, less surface is required. Further, there is relatively little variation in the heat flux o all the immersed surface, so there is small risk of t failure due to high local heat flux which can lead to departure from nucleate boiling in the tubes.

The low combustion temperature leads to markedly reduced vapor pressures of alkali metal sulfates and chlorides. Thus, the greater part of these harmful constituents remain in the bed. This is true also of vanadium and sodium salts when heavy fuel-oil is fired in a fluidized bed. Cooke and Rogers [5] report the results of corrosion trials on a number of low-chromium and austenitic steels. They conclude that all the materials would provide satisfactory service under normal fluidized-bed operating conditions, if used at the temperatures employed in a conventional plant. Even with that limitation, however, the fluidized-bed system has an advantage. Because of the high rate of mixing in the bed, all the tubes will be at the same temperature, so there is no need to add temperature margins in design.

Current designs of fluidized boilers

In the U.K., fluidized-bed-fired boilers having an evaporation rate to 500,000 lb/h are being offered. The upper limit of evaporation is fixed at a level that is achieved economically in a single bed, at fluidizing velocities up to 10 ft/s. Above that size, multiple beds



Two-pass, radiant fluidized-bed boiler uses convection banks for superheating Fig. 13

are used. Not enough time has yet been devoted to seeking the optimum arrangements for multiple beds. Garner, *et al.* [3] describe conceptual designs for 500-MW_e boilers by three U.S. boiler makers in conjunction with two architectural engineering firms, and sponsored by the U.S. Dept. of Energy. In the U.K., an order has been received for an 80,000-lb/h boiler for a chemical process company. It is a standard bi-drum boiler with conventional oil burners in its front wall. However, provision has been made for conversion within five years to coal firing with a fluidized bed.

Two other projects are illustrated. Fig. 12 shows another bi-drum boiler, which will be converted from spreader/stoker firing to a fluidized bed. Conversion must be looked at carefully, since it may be more economical to install a new boiler, depending on the state of the plant and the original fuel for which the plant was designed. Conversion of spreader/stoker firing to a fluidized bed can be attractive, since the combustion rate per unit area and the freeboard shape and size can be the same for the two systems. Only three separate slumped zones are required to meet the load changes demanded by this system.

Fig. 13 shows a design for the 30- to 40-MW_e range. In this unit, all the superheating is done in convection banks, so that only generating tubes are immersed in the bed. Also, the boiler plan area is reduced and divided to provide the gas velocities required to reach adequate convection-heat-transfer coefficients. When boilers demanding multiple tiered beds are called for, the plan area will not need as much, if any, reduction.

Fluidized beds are used in the marine field [6]. The ability of an oil-fired fluidized bed to retain vanadium and sodium is being applied to raise superheat and reheat temperatures to 600°C in steam turbines for ship propulsion. Hitherto, such temperatures have been forbidden with conventional oil firing by high-temperature corrosion of superheater and reheater tubes.

Pressurized fluidized beds

So far, we have concentrated on atmospheric fluidized-bed boilers, principally because their development

is more advanced. There is, however, a great deal of work going on in pressurized fluidized beds—which promise these further advantages:

1. For a given duty, the bed area is inversely proportional to the absolute pressure; thus the plant can be compact and comparatively lightweight.
2. Combustion efficiency within the bed is such that good design should eliminate the need for grit recycling.
3. Using dolomite, sulfur retention is improved with pressurization. (Unfortunately, limestone effectiveness decreases at increased pressures.)
4. NO_x emissions are reduced further by pressure.

Pressurized combustion should permit the development of combined gas and steam-turbine cycles, which hitherto have been limited by the necessity to employ clean fuels for the gas turbine. A gas turbine should operate for long periods without significant fouling, corrosion or erosion, due to the non-erosive nature of the coal ash, the ability of the bed to retain alkali metals and sulfur, and the effectiveness of mechanical removal of particulate matter from the gases with an acceptable pressure drop. Roberts, *et al.* [*7*] describe the experimental work and the types of cycle that may be employed. Thurlow [*8*] mentions some design studies currently in progress, and describes the application of fluidized-bed combustion to boilers smaller than those discussed here.

Conclusions

It has been said that there would be no interest in fluidized-bed combustion if it were not for the stringent regulations concerning the emission of sulfur oxides and nitrogen oxides. This is extremely difficult to believe. While atmospheric pollution is important—and it has been amply demonstrated that these beds can control it—surely an important factor is the ability to operate a plant at its design capacity, no matter how the fuel supply may change during its life.

Another important factor is energy conservation. Since the Industrial Revolution, coal mining has rejected combustible material consumers would not take, either because consumers could not use it or because it was uneconomical to do so. For similar reasons, there are large quantities of high-ash coal deposits in the world that have been left in the ground. In the U.K., large amounts of the heat content of the total coal mined has been lost to pit spoil-heaps. [*9*]. The world can no longer afford to squander or neglect its energy resources that way.

Cost comparisons between fluidized-bed combustion and present conventional units are not made here because the costs of the latter vary so much with the type of coal being fired. Thurlow gives the results of some studies both for atmospheric and pressurized applications. Generally, these favor fluidized beds, particularly if flue-gas cleaning is taken into consideration.

There is continuing development in atmospheric and pressurized fluidized-bed combustors. In atmospheric units, the emphasis is on increasing combustion efficiency in the bed to reduce the need for refiring carbon-loaded grits. In pressurized designs, emphasis is on the development of power turbines and control systems that can be successfully integrated with the combustor.

It is hoped that this report has shown that atmospheric fluidized-bed boilers are gaining acceptance; any operator with a new plant in mind should give the system careful study.

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V. NO_x

5.2 COMBUSTION PROCESS MODIFICATION TECHNOLOGY

As a result of emission control regulations for new and existing stationary sources, NO_x control techniques have been developed and implemented in the past 10 years. Nearly all current NO_x control applications use combustion process modifications. Other approaches, such as modifying or switching fuels, using alternate energy systems, and treating post-combustion flue gas, as well as more advanced combustion process modifications are being evaluated for potential future use. Experience has shown that the applicability and effectiveness of combustion process modifications depend on the specific equipment/fuel combination to be controlled, and on whether the control is to be applied to existing field equipment or new units. Accordingly, control development is focusing on specific equipment categories and fuel types. In general, the following sequence of control development is being pursued for each major equipment/fuel category:

- Minor operational adjustments
- Minor retrofit modifications

SOURCE: "Environmental Assessment of Stationary Source NO_x Control Technologies: First Annual Report," EPA-600/7-78-046, U.S. EPA, Research Triangle Park, NC (March 1978).

- Extensive hardware changes, either retrofit or factory-installed on new units of conventional design

- Major redesign of new equipment

Progress made in this sequence varies with the importance of the source in local and national NO_x regulatory strategies.

Currently, modifying combustion process conditions is the most effective and widely-used technique for achieving 20- to 70-percent reduction in combustion-generated oxides of nitrogen. These modifications include:

- Low excess air firing

- Flue gas recirculation

- Off-stoichiometric combustion

- Load reduction

- Burner modifications

- Water injection

- Reduced air preheat

- Ammonia injection

The following paragraphs summarize the status of each of these controls.

Low Excess Air Firing

Changing the overall fuel-air ratio is a simple, feasible, and effective technique for controlling NO_x emissions from all stationary sources of combustion except gas turbines. For some sources, such as utility boilers, low excess air (LEA) firing is currently a routine operating procedure and is incorporated in all new units. Since it is energy efficient and easy to implement, LEA firing will be increasingly used in other sources. However, most sources will have to use other control methods, in conjunction with LEA, to meet NO_x emissions standards. In such cases, the extent to which excess air can be lowered will depend upon the other control techniques employed. Virtually all programs for developing advanced NO_x controls are emphasizing operating at minimum levels of excess air. Thus, LEA will be an integral part of nearly all combustion modification NO_x controls, both current and emerging, to be assessed in the NO_x E/A.

Flue Gas Recirculation

The primary near-term application of flue gas recirculation (FGR) is in gas- and oil-fired utility boilers. Future applications are limited. FGR may be used in industrial boilers as a retrofit or in new designs, but

alternate approaches, such as low-NO_x burners and off-stoichiometric combustion, also are being evaluated and may prove more attractive. Techniques other than FGR are more effective for coal-fired utility boilers, gas turbines, and warm air furnaces. The effectiveness of FGR with process furnaces is under evaluation.

Off-Stoichiometric Combustion

Off-stoichiometric combustion (OSC) is a widely used technique for controlling thermal and fuel NO_x from large boilers. Near-term uses of OSC to be considered in the NO_x E/A include retrofitting on gas-, oil- and coal-fired utility boilers and using factory-installed equipment on new coal-fired utility boilers. Potential future applications to be considered include using factory installations on new industrial boilers and using advanced staging techniques for major redesigns of utility or industrial boilers.

Load Reduction

Load reduction/enlarged firebox techniques may be used in the near term as retrofits to gas- and oil-fired utility boilers and as new designs for coal-fired utility boilers. Load reduction also may be used on new and existing industrial boilers as standards are set. Because of economic and operational penalties, load reduction for existing boilers is unattractive, and is used only as a last resort to achieve compliance with standards.

Burner Modifications

New, optimized-design burners appear to be capable of reducing NO_x emissions 40 to 65 percent with gas and oil fuels. Similar, or greater, reductions are being demonstrated on prototype coal-fired units. The new low-NO_x burners are designed to mix fuel and air in a controlled pattern that sustains local fuel-rich regions, keeps the flame temperature down, and dissipates the heat quickly. Improved burner designs may well replace the external combustion modifications now in use and produce significantly lower NO_x emissions. Thus, although low-NO_x burners have limited use currently, they will be emphasized in the NO_x E/A for both near- and far-term application.

Water Injection

Water injection has been found to be effective in suppressing NO_x emissions from gas turbines and IC engines. However, water injection may decrease thermal efficiency, increase equipment corrosion, and cause other undesirable operating conditions. Therefore, it is anticipated that water injection will be replaced by advanced combustor design in the long term.

Reduced Air Preheat

Reduced air preheat for gas turbines and for boilers is not a practical way to control NO_x unless the energy in the exhaust gases can be used effectively for other purposes, such as in combined gas-steam turbine cycles. Reduced air preheat will thus be accorded low priority in the NO_x E/A because of associated efficiency losses.

Ammonia Injection

Ammonia injection does not appear to have significant near-term application for NO_x control in the U.S. However, it shows promise for far-term applications and will be given primary emphasis in the NO_x E/A for assessment of advanced concepts for the 1980's and 1990's.

5.3 ALTERNATE CONTROL TECHNIQUES

In addition to combustion modifications, NO_x can be controlled by one or more of the following techniques: flue gas treatment, fuel denitrification, fuel additives, alternate or mixed fuels, or advanced, low-NO_x combustion concepts. Each of these is briefly discussed below.

Flue Gas Treatment

The dry flue gas treatment (FGT) techniques used in Japan -- notably selective catalytic reduction with ammonia -- can probably be applied to gas- and oil-fired sources in the U.S. However, more pilot and full scale demonstration tests are needed before full application of dry processes is possible on these sources. Dry processes have yet to be demonstrated on coal-fired sources, although pilot-scale tests are currently planned. Wet processes are less well developed and more costly than dry FGT processes; however, wet processes have the potential to remove NO_x and SO_x simultaneously. Again, pilot-scale research and field tests are needed to determine costs, secondary effects, reliability, and waste disposal problems. Flue gas treatment holds some promise as a control technique if very stringent emissions standards make it necessary to greatly reduce NO_x. However, even in these instances FGT will probably be employed to supplement combustion modification.

Fuel Denitrification

Fuel denitrification of coal or heavy oils could, in principle, be used to control the component of NO_x emissions produced by the conversion of fuel-bound nitrogen. The most likely use of fuel denitrification would be to supplement combustion modifications that reduce thermal NO_x. Currently denitrification occurs only as a side effect of pretreating fuel to remove sulfur, ash, or other pollutant precursors. Preliminary data indicate that 30- to 40-percent reductions in fuel nitrogen result from oil desulfurization (Reference 22). Since these processes produce low denitrification efficiencies,

SOURCE: Technical Assessment of Thermal $DeNO_x$ Process--Interagency Energy/Environment R&D Program Report, EPA-600/7-79-117, U.S. EPA, Research Triangle Park, NC (May 1979).

SECTION 2

PAST EXPERIENCE

The noncatalytic reduction of NO by the Thermal $DeNO_x$ Process was discovered in August 1972 by Exxon Research and Engineering Co. (ER&E). Since then, numerous laboratory, pilot, and full-scale tests have further investigated the Thermal $DeNO_x$ Process. These tests have been designed to understand the critical process parameters and how they can be used to control NO_x emissions from both stationary and mobile sources.

ER&E, developer of the Process and patent holder, has done most of the laboratory research and field studies. However, Exxon's tests were limited to gas- and oil-fired facilities, except for full-scale tests on a solid waste incinerator. KVB Inc., under contract to ER&E and EPRI has recently studied the use of Thermal $DeNO_x$ on a 3×10^6 Btu/hr coal-fired test boiler. KVB has also conducted the only domestic full-scale application of NH_3 injection. This was on a thermal oil recovery steam boiler.

Table 2-1 presents a summary of all commercial installations utilizing noncatalytic decomposition of NO_x by ammonia. All of these installations use Exxon's ammonia injection technology except for one Japanese source noted. Detailed information on all installations using Exxon's Thermal $DeNO_x$ Process is not available. However, depending on the source and its operation, NO_x reductions as high as 70 percent have been achieved.

TABLE 2-1. SUMMARY OF COMMERCIAL APPLICATIONS OF EXXON'S THERMAL $DeNO_x$ PROCESS

Source	Fuel Burned	Location	Initial Nitric Oxide Emissions (ppm as measured)[a]	$DeNO_x$ Rate (Percent)	Additive[b]	Comments
Steam Boiler 45 MW heat input	Gas/oil	Japan	120-150	60	Yes	No reduction obtained at full load
Incinerator 7 ton/hr	Waste	Japan	100-180	20-70	NA[c]	Difficult source to retrofit because of constant change in fuel
Crude heater 150 x 10^3bbl/day	Gas/oil	Japan	150	35-65	Yes	Best reductions achieved at high load
Steam boiler 76 MW heat input	Gas/oil	Japan	95-145	35-50	NA	No details of retrofit system are available
Utility boiler 275 MW heat input	Gas/oil	Japan	80-120	60	NA	No details of retrofit system are available
Utility boiler 275 MW heat input	Gas/oil	Japan	80-120	50-60	NA	No details of retrofit system are available
Crude heater 150 x 10^3bbl/day	Gas/oil	Japan	80-85	40-65	NA	Best reductions achieved at high loads
Thermal recovery heater	Oil	USA-California	260	50-70	NA	First commercial U.S. installation
Utility boiler 375 MW	Residual oil	Japan	NA	40	No	Does not use Exxon NH_3 injection technology -- NH_3 emission limited to 10 ppm

[a]Excess oxygen varied between 3-5 percent for all sources
[b]"Yes" indicates that hydrogen was injected together with NH_3 to obtain reported NO_x reduction performances
"No" indicates that no additive was used
[c]NA = no data are available

Based on these full-scale results, Exxon has commercialized the process and will license it upon request on gas- and oil-fired boilers. Additionally, they are continuing to study the feasibility of full-scale applications on coal-fired boilers. These studies are aimed at maximizing NO_x reduction and cost effectiveness, and exploring and defining potential operating problems.

This section summarizes the status of Thermal $DeNO_x$ Process developments. Results from gas and oil combustion in laboratory and pilot-scale studies are discussed in Section 2.1. Section 2.2 presents results from ammonia injection in a coal-fired pilot-scale facility. Results from ER&E's full-scale commercial demonstration of the process are described in Section 2.3.

2.1 SUBSCALE TESTING -- GAS AND OIL

ER&E discovered a new reaction which is the basis of the Process in research done in a laboratory flow reactor. Based on the observed kinetics of this reaction Lyon proposed the following mechanism (Reference 2-1):

$$NH_2 + NO \longrightarrow N_2 + H + OH$$

$$NH_2 + NO \longrightarrow N_2 + H_2O$$

$$H + O_2 \longrightarrow OH + O$$

$$O + NH_3 \longrightarrow OH + NH_2$$

$$OH + NH_3 \longrightarrow H_2O + NH_2$$

$$H + NH_3 \longrightarrow N_2 + NH_2$$

To further explore this reaction mechanism, ER&E conducted tests on a small 0.3 MW (10^6 Btu/hr commercial size boiler). These tests investigated how key operating variables such as reaction temperature,

NH_3 injection rate and flue gas residence time influence the NO_x reduction effectiveness.

Additional tests were conducted on a 9 MW (30 x 10^6 Btu/hr) test furnace to optimize mixing and injection methods and to evaluate problems such as corrosion and fouling which may be encountered during full-scale application. ER&E also evaluated the economics of full-scale application of the process for oil- and gas- firing. KVB Inc. has also considered the effects of Thermal $DeNO_x$ on key operating parameters. Both ammonia and a proprietary ammonia-based compound were investigated as NO reducing agents for product gases from the combustion of gas and oil.

The Exxon and KVB test results reveal the following key operating variables and constraints which affect the efficiency of the Thermal $DeNO_x$ Process:

- Reaction temperature
- Ammonia injection rate
- Mixing technique and reaction time
- Hydrogen and other additive injection
- Byproduct and ammonia emissions

The following sections briefly describe these key parameters and their effects on the $DeNO_x$ Process.

2.1.1 Reaction Temperature

The temperature of the flue gas at the point of NH_3 injection is a key process condition because the reaction between NO and NH_3 in the presence of O_2 is extremely temperature sensitive, i.e., the temperature range in which ammonia is effective in reducing NO concentrations is small. This characteristic, therefore, governs how the process can be applied.

Lyon reported that the reaction temperature of about 955°C (1750°F) results in the largest NO reduction. At temperatures higher than approximately 1100°C (2010°F), the oxygen present in the flue gas oxidizes the injected ammonia producing a net increase in NO. Below 900°C (1650°F), the reaction of NH_3 with NO is slowed considerably causing less NO reduction and more NH_3 emission from unreacted gases. Figure 2-1 shows how the reaction temperature affects the performance of the Thermal $DeNO_x$ Process.

This strong dependence of Thermal $DeNO_x$ performance on reaction temperature can limit the use on some systems. For example, the required temperature window in gas turbines and IC engines is located where a very short residence time is available for reaction with NH_3. Thus, Thermal $DeNO_x$ may not be suited to these sources. In large steam generators, the optimum temperatures and residence times for noncatalytic reduction of NO are usually accessible in the boiler convective section. However, cross-sectional temperature gradients as high as 200°C (360°F) often exist making ammonia injection considerably less effective for some areas of the flue gas ducts. Load variations also shift the temperature profile causing the temperature window to move in the convective section.

These problems could theoretically be solved by installing more than one injection stage to account for the shift in the temperature window. However, additives have also been evaluated as methods to accommodate temperature variations and unfavorable location of the temperature window. For example, hydrogen additive is a demonstrated alternative for controlling or shifting the injection points to the optimum temperature location for the Thermal $DeNO_x$ Process. Additive injection is discussed in Section 2.1.3.

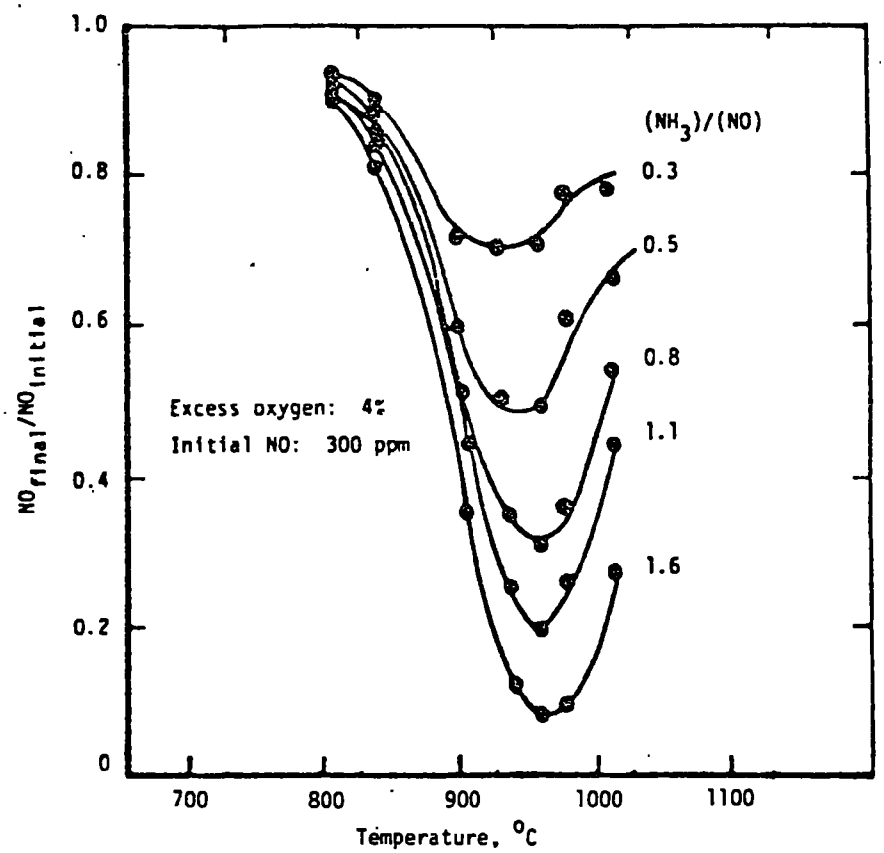

Figure 2-1. Effect of flue gas temperature on Thermal $DeNO_x$ performance (Reference 2-2).

2.1.2 Ammonia Injection Rate

Ammonia efficiently reduces NO_x because of its ability to react selectively with nitric oxide regardless of the amount of oxygen present in the treated gas. Thus, the amount of ammonia required in the Thermal $DeNO_x$ Process is on the order of the initial NO concentration. Other additives, such as methane and ethane also can be used to reduce NO in hot flue gases. However, because these reagents are nonselective, they do not react with nitric oxide alone. That is, all the free oxygen present in the hot gases must first be consumed by the reagents before the NO can be reduced. Therefore, more hydrocarbons are necessary, thus causing these additives to be economically unattractive.

Experiments conducted by ER&E and KVB show that for typical conditions, an ammonia injection rate of 2.0 (molar ratio of NH_3 to initial NO concentration, (NH_3/NO)) achieves the optimum maximum process efficiency. Figure 2-2 shows that minimal additional NO reduction is obtained by increasing the ammonia injection rate beyond the NH_3/NO molar ratio of 2.0.

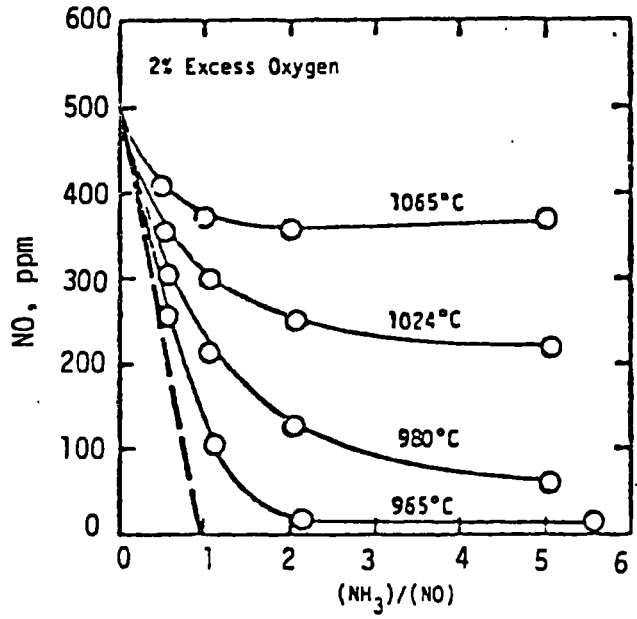

Figure 2-2. Effect of NH_3 injection rate on NO emissions (Reference 2-2).

Ammonia injection rates depend on the initial concentration of nitric oxide. Experimental data illustrated in Figure 2-3 show that lower molar ratios of NH_3/NO are needed to achieve a given process efficiency when the initial NO concentration is greater than 400 ppm. These experimental data further indicate that the percent oxygen in the flue gas may also have some effect on required NH_3 injection rates. Minimum amount of dilution with excess air decreases the volume of flue gas to be

treated and increases initial NO concentration thus possibly reducing the amount of NH_3 needed.

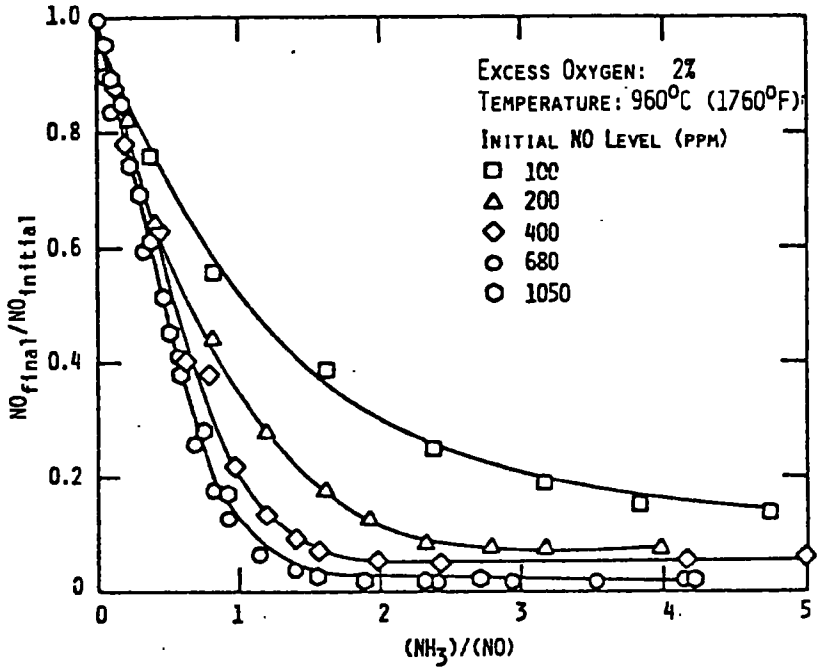

Figure 2-3. Effect of initial nitric oxide concentrations on reductions with ammonia injection (Reference 2-2).

The ammonia injection rate, the reaction temperature and the residence time are critical in maintaining ammonia emissions at minimum levels. Test data depicted in Figure 2-4 indicate that the level of unreacted ammonia at the injection temperature of 965°C (1770°F) increases significantly only at NH_3/NO ratios greater than 2.0, as expected. When the reaction temperature is lowered to 870°C (1600°F) the level of ammonia carryover is substantially increased because of the slower chemical reaction. Therefore, the ammonia emission level can be controlled by allowing the reaction to occur at slightly higher temperatures than the optimum 955°C (1750°F). In fact, NH_3

injection, at temperatures above 1000°C (1830°F) virtually all NH_3 breakthrough is eliminated.

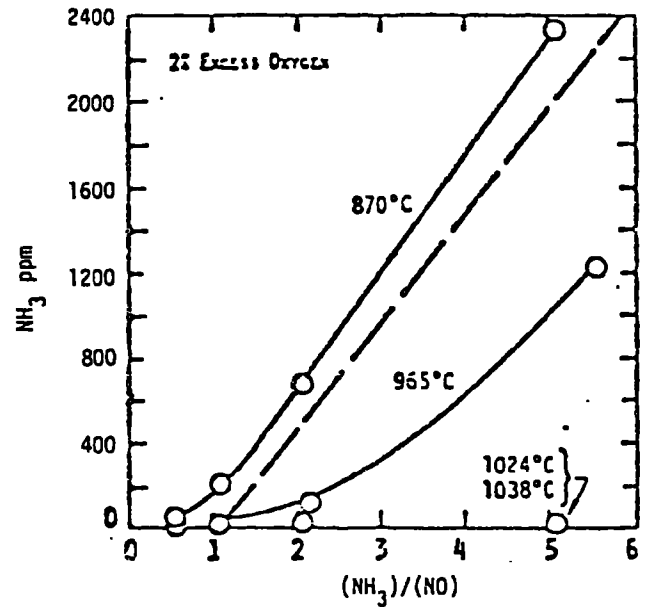

Figure 2-4. Effect of NH_3 injection rate on NH_3 carryover emissions (Reference 2-2).

Poor mixing of ammonia with the flue gas may cause ammonia carryover to occur also at NH_3/NO molar ratios much lower than 2.0. In fact, large scale applications of the Thermal $DeNO_x$ Process have shown that NH_3/NO ratios in nonideal gas conditions generally should be lower than 1.5 to maintain minimum NH_3 emissions. High levels of ammonia breakthrough were caused by high ammonia injection rates combined with ineffective mixing or low flue gas temperatures.

In summary, NH_3/NO molar ratios can vary from 1.0 to 2.0 in large scale applications of the Thermal $DeNO_x$ Process. The actual injection rate used will depend on the desired NO_x reduction and could be limited by ammonia breakthrough. Therefore, the injection rate is the result of

an optimization performance study taking into account flue gas conditions and source configurations.

2.1.3 Hydrogen and Other Additives

The Thermal $DeNO_x$ Process can be applied over a greatly widened range of temperatures if certain additives are injected with the ammonia. Of the many additives investigated, hydrogen is the most effective over the temperature range from 700 to 1010°C (1290 to 1850°F). Figure 2-5 shows the shifting effect of hydrogen injection on optimum reaction temperature measured in a commercial size firetube boiler. The magnitude of this shift depends on the amount of H_2 injected relative to the NH_3. For example, at H_2/NH_3 molar ratios on the order of 2:1 selective noncatalytic reduction of NO_x can be made to occur at 700°C (1290°F). Thus, by carefully selecting the H_2 injection rate, flue gas treatment can be controlled over a wide temperature range.

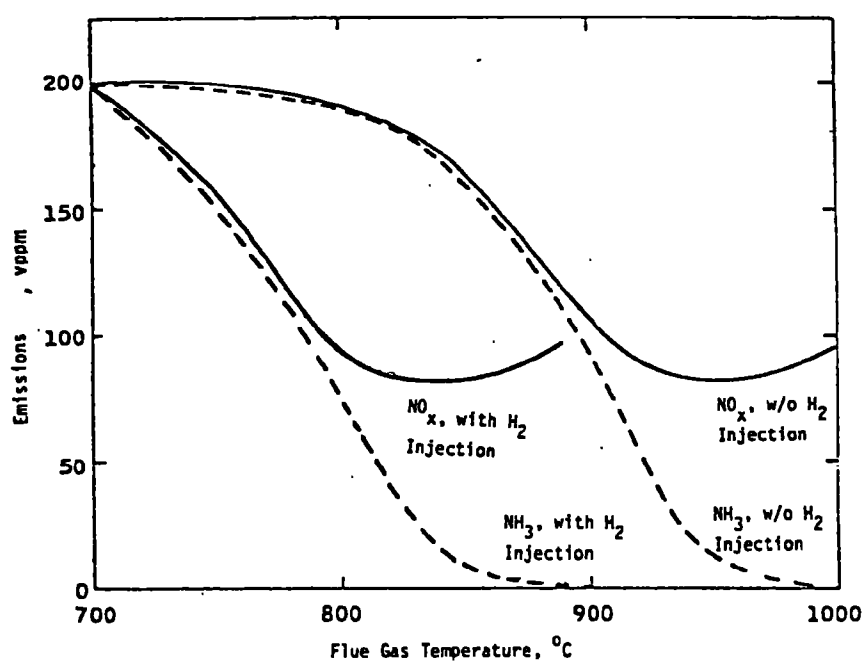

Figure 2-5. Thermal $DeNO_x$ reaction products as functions of temperature with and without hydrogen injection (Reference 2-3).

Exxon also investigated the use of combined additives. A mixture of 50 percent hydrogen and 50 percent methane was found to be more effective than either hydrogen or methane alone. However, the introduction of methane in combustion gases, especially at low excess air levels, increased cyanide emissions by a few ppm.

Additive injection can also be used to control ammonia breakthrough emissions to concentrations lower than 10 ppm. For example, small amounts of H_2 injection with ammonia would lower the optimum reaction temperature from 955°C (1750°F) to 945°C (1733°F). This 10°C (18°F) temperature differential is sufficient to deplete some excess NH_3 which would otherwise exit from the stack.

Because H_2 can control the temperature of the NH_3-NO-O_2 reaction, Thermal $DeNO_x$ is technically feasible for most boilers provided that the hardware can be installed within the boiler configuration. However, the cost of the $DeNO_x$ Process is greatly increased because of the large volumes of hydrogen needed. This is especially the case for very low temperature such as 760°C (1400°F).

Until recently, the NH_3 injection was limited to boiler cavities. Thus if the optimum reaction temperature of about 955°C did not occur in an isothermal cavity, NH_3 was injected at temperatures below this level. This situation warranted the use of an additive to maximize the efficiency of the $DeNO_x$ Process. The in-tube bank injection of NH_3, recently demonstrated by Exxon, has diminished the dependence of the process efficiency on the use of an additive. $DeNO_x$ rates of 60 to 70 percent were achieved by injecting NH_3 in tube banks without the use of an additive.

2.1.4 Byproduct Emissions

The Exxon Thermal $DeNO_x$ Process may form byproduct pollutants directly or indirectly from the presence of NH_3 in the combustion gas. Potential byproduct emissions suggested by ER&E are NH_3, CO, HCN and N_2O and, when sulfur-bearing fuel is burned, NH_3 and SO_3 combine to form ammonium bisulfate, NH_4HSO_4.

Ammonium bisulfate is a viscous liquid from 147°C to about 450°C (300-840°F). It has been known to cause corrosion of metal surfaces. Thus far, however, no increase in metal corrosion attributable to ammonium bisulfate has been identified when Thermal $DeNO_x$ has been used. The formation of NH_4HSO_4 can be controlled by limiting the amount of NH_3 carryover. This can be accomplished by NH_3 injection at a temperature slightly higher than optimum or by using an H_2 additive. In general, ammonium bisulfate is considered the most serious byproduct and one which could effect the use of the Thermal $DeNO_x$ Process.

Carbon monoxide emissions may also be promoted by ammonia injection because the Thermal $DeNO_x$ reaction inhibits the oxidation of CO to CO_2. Thus, if there is unburned CO at the point of NH_3 injection, the CO may not be oxidized, but will be discharged to the atmosphere. Under normal operating conditions, CO levels are not usually significant in steam generators. Using hydrocarbons as additives to control the NH_3-NO-O_2 reaction increases the concentration of CO in the flue gas. Exxon reported that as much as 50 percent of the hydrocarbons may be oxidized to CO. This CO may then be emitted to the atmosphere because the ammonia inhibits the $O_2 + CO \rightarrow CO_2$ reaction.

HCN is formed only if hydrocarbons are present in the region in which NH_3 is injected. Under normal boiler operation, gaseous

hydrocarbons are not present unless they are injected along with the NH_3. KVB reported that for gas, oil and coal firing, HCN was present in the untreated flue gas at 3 to 10 ppm concentration, depending on excess air level. Injection of NH_3 did not measurably affect the HCN level.

The reduction of NO by NH_3 and O_2 forms N_2O as a minor byproduct. However, less than 2 moles are generated for every 100 moles of NO reduced, according to ER&E experimental data. All the available evidence indicates that N_2O is relatively harmless at those levels, and does not represent an environmental concern.

2.2 SUBSCALE TESTING -- COAL

Recently, KVB has conducted a pilot-scale investigation of the Thermal $DeNO_x$ Process to reduce NO levels from combustion of coal (Reference 2-4). The work was sponsored by the Electric Power Research Institute (EPRI) and Exxon Research and Engineering (ER&E).

The major objective of this investigation was to determine the level of NO_x reduction which is achievable in flue gas resulting from coal combustion. The primary variables investigated were the injection temperature, the NH_3/NO ratio, and the coal type. Additionally, a hydrogen additive was used to lower the temperature range for NO removal. Four different coals were investigated; three coals were bituminous and one subbituminous. Byproduct emissions were also measured at different NH_3 injection rates.

The combustion facility consisted of a 0.9 MW (3×10^6 Btu/hr) firetube boiler equipped with a ring-type natural gas burner and a scaled down version of a commercial coal burner presently used in utility boilers firing Western coal. The NH_3 injection system consisted of five

injectors located at the end of the firetube section distributing the ammonia and nitrogen (carrier gas) counter-flow to the flue gas stream. The injectors were designed to be movable so that they could be positioned axially along the length of the firebox thus providing for evaluation of the effectiveness of different temperature profiles. The injection method was a result of an optimization study in which the injection grid and nozzles were designed to provide substantial NO_x reductions that allowed a valid comparison between the various coal types and natural gas. Since the injection method directly affects the efficiency of the Thermal $DeNO_x$ Process, the results achieved by KVB do not necessarily represent the maximum NO_x reductions achievable with coal combustion.

This section discusses the results of this investigation. These results can be used to compare noncatalytic NO reductions and byproduct emissions between coal and the gaseous and liquid fuels previously investigated. Key parameters considered here are again:

- Reaction temperature
- Ammonia injection rate
- Hydrogen and other additive injection
- Byproduct emissions

2.2.1 Reaction Temperature

The temperature at which ammonia is injected into the flue gas is the primary variable which determines the amount of NO removed with the Thermal $DeNO_x$ Process. A major objective of the KVB study was to determine whether the additional pollutants resulting from combustion of coal, such as SO_2 and particulates, would influence the temperature dependence of the process or reduce the process efficiency. Figure 2-6 shows the effect of reaction temperature on NO reduction for the four

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National Fertilizer Development Center
Muscle Shoals AL 35660

TVA Y-134

Impact of Ammonia Utilization by NO_x Flue Gas Treatment Processes

Interagency Energy/Environment R&D Program Report

INTRODUCTION

Of the five most common air pollutants released in the United States, nitrogen oxides (NO_x) are the only ones projected to increase significantly in the future. The total emission of the other four pollutants [particulate matter, sulfur oxides (SO_x), hydrocarbons, and carbon monoxide (CO)] has decreased during the past 6 yr and is expected to decline further in the future as more point sources are equipped with more efficient control systems. With most public attention focused on these other pollutants which are typically emitted at higher rates than NO_x, the development of equipment and techniques for controlling NO_x has lagged behind. However, recently more attention has been given to the possible health effects of NO_x emissions. Although the NO_x emission from each source appears to be small, the cumulative total is measured in millions of tons annually and is increasing substantially from year to year due to the increasing number of sources.

NO_x emissions are divided into two classes, mobile or stationary, depending on the source. The mobile class, as its name implies, includes sources such as automobiles, trucks, buses, trains, and planes. Attempts at controlling the NO_x emissions from these sources have been delayed due to both technical and economic considerations. Stationary sources, which release about 56% of the total amount of NO_x emitted in the United States (an estimated 11.15 Mtons in 1975), are split into three groups: combustion sources, industrial processes, and other miscellaneous sources. In 1975 combustion sources contributed approximately 93% of all stationary source emission (an estimated 10.4 Mtons) of which nearly two-thirds came from fossil fuel-fired boilers (approximately 7.0 Mtons). If these boilers are further divided according to size (heat rate of the boiler), large boilers [i.e., greater than 250 MBtu/hr (25 MW equiv)] release 45% of al NO_x emitted from stationary combustion sources. Figure 1 and Table 1 show the relative contributions from mobile sources and each type of stationary source to the total NO_x emissions in the United States during 1975. Since the mobile source standards are not expected to become more stringent in the near future, restricting the amount of NO_x emissions from stationary sources, particularly large fossil fuel-fired boilers, may become necessary since these boilers are the second largest source of NO_x emissions in the U.S. The reason for the possibility of stricter NO_x emission control on large boilers are threefold. The emissions from these boilers are projected to increase at about 4.9% annually over the next decade (doubling every 15 yr) assuming present control levels. Secondly, assuming the application of combustion modification which is now considered the best available control technology (about 30% decrease in the NO_x formation), the amount of NO_x emitted by large boilers will increase from 4.7 Mtons in 1975 to 6.6 Mtons in 1985 (50). And thirdly, although the total amount of NO_x emitted by these boilers is only approximately one-half that of mobile sources, there are orders-of-magnitude fewer boilers and hence each boiler source emits significantly more NO_x than each individual mobile source.

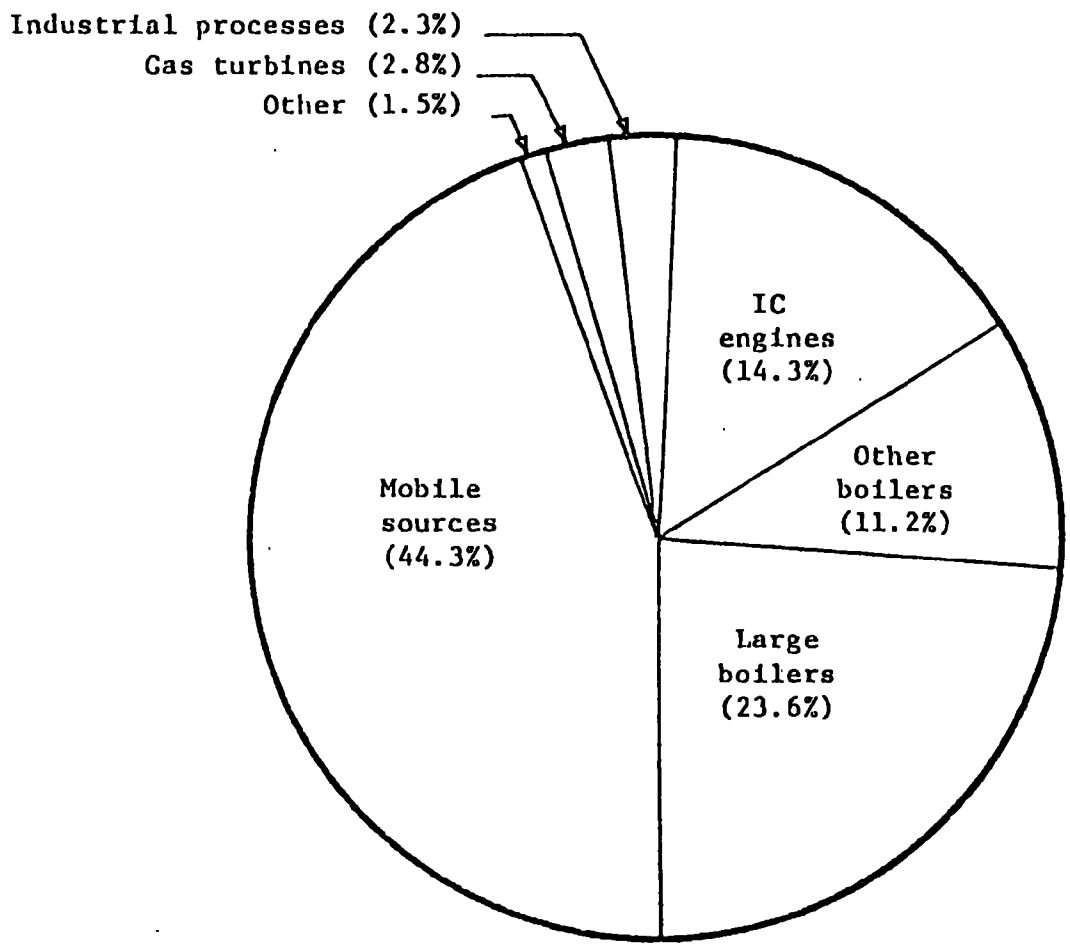


Figure 1. Breakdown of the total U.S. NO_x emissions by original source (45).

Therefore, it is expected that based on each ton of NO_x removed it will be more cost-effective to reduce NO_x emissions from large boilers than from individual mobile sources.

TABLE 1. NO_x EMISSIONS BY SOURCE IN 1975 (45)

	Annual amount, ktons
Mobile sources	8,850
Stationary sources	
Large boilers	4,728
Other boilers	2,238
IC engines	2,849
Gas turbines	566
Incinerators	39
Industrial processes	454
Field burning	290
Total	20,000

FORMATION OF NO_x IN LARGE BOILERS

NO_x is formed during high-temperature combustion operation and can be produced by either of two mechanisms. The first method of formation is thermal fixation or "thermal NO_x" and involves the reaction of molecular nitrogen (N_2) and oxygen (O_2) at high temperatures. The second method is the oxidation of chemically bound nitrogen within the fuel and is called "fuel NO_x." In oil- or coal-fired boilers, NO_x is formed by both mechanisms, but in natural gas-fired boilers the NO_x is formed only by thermal fixation since natural gas contains no fuel-bound nitrogen.

POTENTIAL NO_x CONTROL METHODS FOR LARGE BOILERS

Two potential methods of reducing NO_x emissions from fossil fuel-fired boilers are undergoing extensive research and development. In the United States, combustion modification techniques to reduce the amount of NO_x formed during combustion are being emphasized; while in Japan, mainly because of more stringent NO_x emission regulations, the emphasis is on flue gas treatment (FGT).

Combustion modification techniques attempt to prevent the formation of NO_x by altering the reaction conditions inside the boiler. Since thermal fixation is primarily a function of the temperature (i.e., the rate of formation increases with temperature) and the concentration of O_2 in the boiler, reducing either of these parameters will decrease the amount of thermal NO_x formed. These same boiler modifications which reduce the O_2 concentration in the boiler can also reduce the amount of fuel NO_x formed since the conversion of fuel-bound nitrogen is a strong function of the O_2 concentration. Various combustion modification techniques, which are currently undergoing development work in the United States, are compared in Table 2 for the three types of fossil fuel-fired boilers. Combustion modifications are shown to be the most effective on gas- and oil-fired boilers where a major portion of the NO_x is formed by the thermal mechanism. For coal-fired boilers where much of the NO_x comes from fuel-bound nitrogen, the available combustion modification techniques are limited to about 40% reduction in NO_x.

Although the resulting reduction in the total NO_x emissions from large boilers would appear to be significant, a recent study (45) has determined that, even with combustion modifications on all new large fossil-fueled boilers, the expected growth rate for new large boilers will result in a significant increase in the total NO_x emissions from these boilers, rising from 4.73 Mtons in 1975 to 6.56 Mtons in 1985. Unfortunately, combustion modifications also have undesirable side effects of reducing boiler efficiency, increasing the potential for flame instability, and increasing the soot, CO, and particulate loadings in the flue gas. For these reasons, an alternative method of NO_x control technology, FGT, has recently begun to receive more attention. Although probably more expensive than combustion modification, FGT allows normal operation of the boiler and can remove at least 90-95% of the NO_x from the flue gas. Many different types of FGT systems are currently undergoing development work in Japan and the United States, but the most technically advanced type for removing NO_x from power plant stack gas is now selective catalytic reduction (SCR) (30). In this type, ammonia (NH_3) is injected into the flue gas ducts and the mixture of NH_3 and flue gas passes through a catalytic reactor containing a base-metal catalyst. The NO_x is selectively reduced to molecular N_2 by the following reactions:

$$4NH_{3(g)} + 4NO_{(g)} + O_{2(g)} \rightarrow 4N_{2(g)} + 6H_2O_{(g)} \quad (1)$$

$$4NH_{3(g)} + 2NO_{2(g)} + O_2 \rightarrow 3N_{2(g)} + 6H_2O_{(g)} \quad (2)$$

Although these SCR processes are still in early stages of development (most have not been tested either on coal-fired flue gas or on a large scale unit), they are receiving considerable attention because of both the potentially low capital investment and the fact that they generate molecular N_2 directly without further chemical processing.

TABLE 2. EFFECTS OF BOILER MODIFICATIONS TO REDUCE NO_x EMISSIONS BY FOSSIL FUEL TYPE (30)

Boiler modification	Percent decrease of NO_x formation in boilers by fuel type		
	Gas	Oil	Coal
Prevention of thermal NO_x by:			
Flue gas recirculation	60	20	Not effective
Reduced air preheat	50	40	Not competitive
Steam or water injection	60	40	Not competitive
Prevention of both thermal and fuel NO_x by:			
Staged combustion	55	40	40
Low excess air	20	20	20
Reduced heat release rate	20	20	20
Combination of stage combustion, low excess air, and reduced heat release rate	50	35	40
Prevention of fuel NO_x by:			
Change to fuel with lower percent nitrogen	Not applicable	40	20

A primary consideration in the widespread application of these SCR processes in the United States is the potential availability and the cost of NH_3 in the future. Since nearly all of the NH_3 produced in the United States is made from natural gas, there are serious concerns over the potential impact of widespread use of NH_3 in FGT applications. The availability and cost of both natural gas and NH_3 may be affected. Would this additional demand for NH_3 create shortages in NH_3-based fertilizers and thus increase food costs? Will there be sufficient natural gas available for meeting this demand for NH_3? If not, what other methods and feedstocks are available for generating NH_3? This report will attempt to provide insights into these questions.

NH_3 REQUIREMENTS FOR NO_x CONTROL

NH_3 REQUIREMENTS FOR TYPICAL POWER PLANT APPLICATIONS

Any evaluation of the impacts of the additional NH_3 demand for power plant FGT systems must begin with a determination of the magnitude of the additional demand. In order to calculate the NH_3 requirements for typical fossil fuel-fired boilers, it is necessary to presuppose future NO_x standards for large stationary source boilers.

Although the future NO_x emission limits have not been published, for the purposes of this study the following scenario has been hypothesized. Since the SCR and other FGT processes are still in the early stages of development in the United States, strict Federal NO_x emission regulations of 90% removal from large stationary sources will probably not be enforced until 1985. Since Federal new-source performance standards (NSPS) apply only to new sources, existing sources will not be required to meet these standards but existing sources converted from gas or oil to oil or coal after 1985 will be. Between the present and 1985, the NO_x emission limits may be reduced but only to the extent that combustion modifications can be used to meet the newer regulations.

Two possible methods would be available for meeting these emission regulations of 90% NO_x removal, (1) the installation of an SCR system designed for 90% NO_x removal or (2) the use of combustion modifications to cut NO_x emissions from the boiler by 50% with the additional installation of an SCR system designed for 80% NO_x removal to give an overall NO_x removal efficiency of 90%. The impacts of each of these methods are considered in later sections.

The typical fossil fuel-fired boilers included in this study were 500-MW coal- and oil-fired boilers with the flue gas compositions shown in Table 3. Gas-fired boilers were not considered since they are not expected to be built after 1985. For the two alternative cases, the uncontrolled conventional 500-MW coal-fired boiler would release about 600 ppm NO_x in the flue gas (3009 lb/hr), would require an SCR system capable of a 90% NO_x removal efficiency, and would release only approximately 60 ppm NO_x (300 lb/hr) of NO_x after FGT control. Through the use of combustion modification techniques in the second coal-fired case, the boiler would emit 300 ppm NO_x (1504 lb/hr) and the additional SCR system would remove 80% of the remaining NO_x to obtain a total of 90% NO_x removal. In a similar manner, the uncontrolled 500-MW oil-fired boiler releasing 200 ppm NO_x in the flue gas (856 lb/hr) would be required to have 90% NO_x removal, i.e., down to 20 ppm (86 lb/hr) NO_x. Again this could be obtained either by an SCR system designed for 90% removal or through combustion modification to lower boiler emissions to 100 ppm NO_x and then an 80% efficient SCR system.

TABLE 3. FLUE GAS COMPOSITIONS FROM 500-MW

COAL- AND OIL-FIRED BOILERS

Constituent	Flue gas composition from Oil-fired boiler Vol, %	Lb/hr	Coal-fired boiler Vol, %	Lb/hr
N_2	73.60	2,929,000	73.76	3,450,000
O_2	2.54	115,400	4.83	258,200
CO_2	11.96	747,900	12.31	904,200
SO_2	0.13	12,060	0.24	25,130
SO_3	0.0013	151	0.0024	317
NO_x	0.02	856	0.06	3,009
HCl	-	-	0.01	661
H_2O	11.75	300,800	8.79	264,500
	100.00	4,106,000	100.00	4,906,000
Fly ash, gr/sft^3 (wet)		0.032		6.06

The catalytic reduction reactor used in the SCR processes is typically either a fixed-bed reactor incorporating a catalyst or reactor design to prevent plugging by entrained particulates or a moving-bed reactor. The normal operating conditions inside this reactor are a temperature of about 350-400°C (662-752°F) and a space velocity ranging from 5,000-10,000 hr^{-1}. Within these specified conditions the NO_x removal efficiency can be altered by changing the NH_3:NO_x mol ratio as shown in Figure 2. Between 0-90% NO_x removal, the NO_x removal efficiency is nearly a linear function of the NH_3:NO_x mol ratio entering the reduction reactor. Above about 93% NO_x removal the curve becomes asymptotic and greater NO_x removal requires large excesses of NH_3. Thus, for 90% NO_x removal, an NH_3:NO_x mol ratio of about 0.95:1 would be required while for 80% NO_x removal an NH_3:NO_x mol ratio of approximately 0.83:1 would be needed. These mol ratios are based on either laboratory or pilot-plant work of various process developers and most of them recommended operating at a mol ratio in the range of 1.0-1.1:1 for 90% NO_x removal in a commercial system (30).

For this reason the assumed NH_3:NO_x mol ratios for the 90% and the 80% NO_x removal systems were assumed to be 10% higher than that used in the pilot-plant work, i.e., 1.05:1 and 0.91:1 respectively. Once this mol ratio has been estimated, the annual NH_3 consumption for the particular power plant can be obtained from Figure 3. This figure shows the annual NH_3 consumption as a function of the NH_3:NO_x mol ratio for the four hypothesized cases based on the premises given in Table 4: (1) 500-MW coal-fired boiler without combustion modification, (2) 500-MW coal-fired boiler with combustion modification, (3) 500-MW oil-fired boiler without combustion modification, and (4) 500-MW oil-fired boiler with combustion modification. The estimated annual NH_3 consumption for each of these

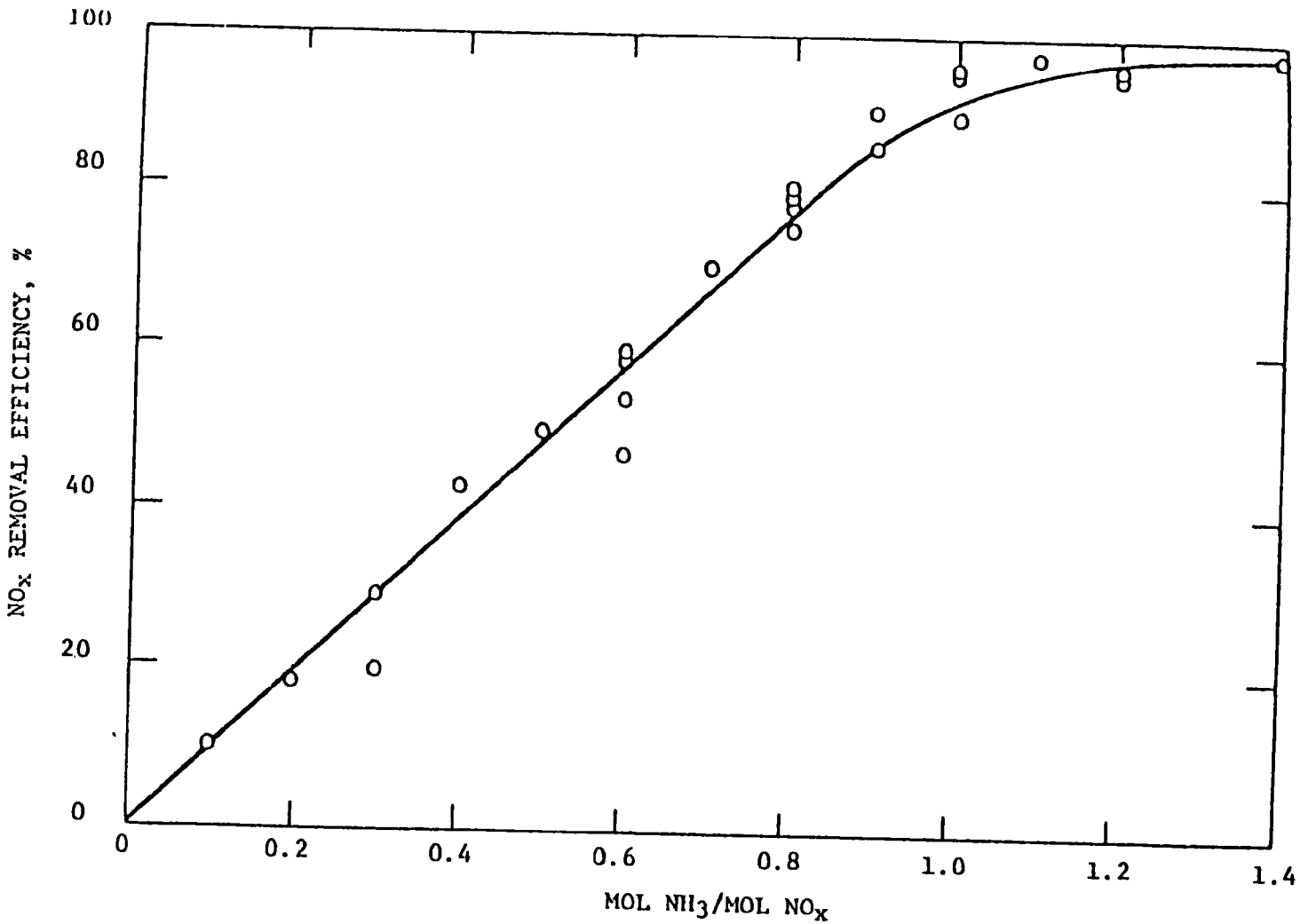


Figure 2. NO_x removal efficiency as a function of NH_3:NO_x mol ratio.

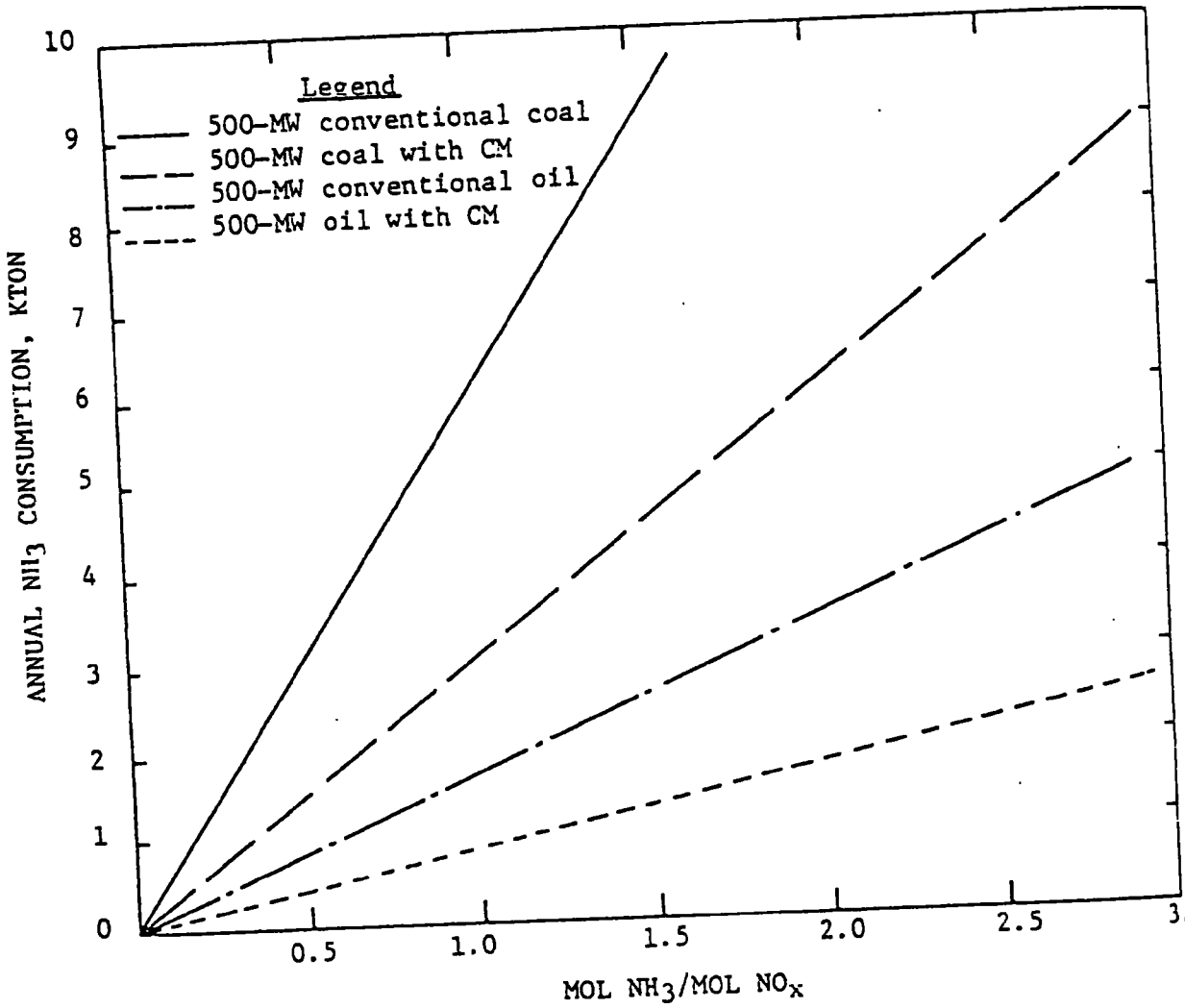


Figure 3. Annual NH_3 consumption for selected 500-MW boilers for NO_x FGT as a function of NH_3:NO_x mol ratio.

four cases is listed in Table 5. The values range from a high of 6266 tons of NH_3/yr for the 500-MW conventional coal-fired boiler without combustion modifications to a low of 772 tons of NH_3 annually for the 500-MW oil-fired boiler with combustion modifications.

TABLE 4. PREMISES FOR THE CALCULATION OF ANNUAL NH_3 CONSUMPTION FOR 500-MW FOSSIL-FIRED BOILERS

Parameter	Value
Heat rate, Btu/kWh	9,000
Heating value	
Coal, Btu/lb	10,500
Oil, Btu/gal	144,000
Availability, hr/hr	7,000

TABLE 5. NH_3 CONSUMPTION FOR TYPICAL 500-MW COAL- AND OIL-FIRED BOILERS

Fuel	NO_x treatment scheme	NO_x concentration in flue gas, ppm	Mols NH_3 per mol NO_x	NH_3 consumption, tons/yr
Coal	SCR[a]	600	1.05	6,266
Coal	CM & SCR[b]	300[c]	0.91	2,715
Oil	SCR	200	1.05	1,781
Oil	CM & SCR	100[c]	0.91	772

a. Selective catalytic reduction.
b. Combustion modification followed by selective catalytic reduction.
c. Combustion modification was assumed to be 50% efficient in controlling NO_x emissions.

The economics of present-day NH_3 generating plants dictate a minimum capacity of 1,000 tons of NH_3/day (330,000 tons/yr) and thus local, small NH_3 plants at each boiler would be highly unlikely. Even with large 2,500-MW coal-fired power plants, the annual NH_3 requirement of 31,000 tons would not justify a captive NH_3 plant. Thus it is assumed that for all NO_x FGT applications the NH_3 would be purchased from existing fertilizer plants already producing NH_3 and shipped to the power plant and stored in large tanks onsite.

VI. HYDROCARBONS

HYDROCARBONS

SOURCES

Hydrocarbons by definition contain the elements hydrogen and carbon. In addition, naturally-occurring, processed, and synthetic hydrocarbon molecules may contain other elements such as oxygen, nitrogen, sulfur, and halogens.

The health effects of hydrocarbon and organic solvent emissions are of two types, direct and indirect. Direct effects are caused by the original, unaltered emissions, and indirect effects are caused by substances formed by photochemical reactions of the original emissions with other substances in the atmosphere.

Generally, hydrocarbon materials at levels encountered in the ambient air have no direct health or welfare effects and the prime reason for controlling hydrocarbon emissions is to prevent their participation in atmospheric photochemical reactions. Olefins are regarded as being the most reactive of the organic compounds in photochemical smog formation, although reactivity varies widely with chemical structure.

As in the case of nitrogen oxides and carbon monoxide, the largest single source of hydrocarbons is transportation. Stationary sources of hydrocarbon emissions include petroleum refining, gasoline distribution and marketing, chemical manufacturing, coal coking, fuel burning, waste disposal, and food processing. Sources of organic solvent emissions include manufacture and application of protective coatings, manufacture of rubber and plastic products, degreasing and cleaning of metal parts, dry cleaning operations, printing, and manufacture of chemicals. A summary of total nonmethane hydrocarbon emissions by source is given in Table I.

From the production of crude oil to the marketing of finished products, the petroleum industry has the potential for emitting significant quantities of

hydrocarbon gases and vapors. These emissions are often undesirable since they may be precursors of photochemical smog. Crude oil is first produced from the ground. Then the liquid hydrocarbons are separated from the gases, light hydrocarbon vapors, and water. Finally, the crude oil is stored until it is removed to the refinery where it is converted to salable products. In crude oil production, most of the emissions are due to evaporation of hydrocarbons from storage tanks.

The design of a refinery depends on the kind of crude oil it processes and on the final products it manufactures. Refinery operations are most easily discussed, therefore, in terms of their similar functions.

Since crude oil as it is produced has few uses, it is processed to obtain salable products, such as gasoline, kerosene, fuel oil, petrochemical raw materials, waxes, lubricating oils, and asphalt. Processing involves four major steps: separation, conversion, treatment, and blending.

The first refining step, separation by distillation within a specific temperature range, yields fractions, the relative volumes of which are determined by the nature of the crude oil. These fractions are usually further refined to meet the demands for the various petroleum products. These processes are outlined below.

Conversion by cracking is employed to convert high-molecular-weight hydrocarbons into products of lower molecular weights. For example, cracking partially converts heavy gas oil to gasoline. If a catalyst is used (the more usual case), it is called catalytic cracking, if not, it is thermal cracking. Thermal cracking requires higher temperatures and pressures than those required to catalytic cracking.

Gasoline yield and quality can be improved by several other processes. In catalytic reforming, the molecules of the gasoline feed stock are rearranged and dehydrogenated to produce high-octane gasoline blending stocks.

Isomerization rearranges molecules to increase the octane number; it also increases molecular branching, but it does not add to or remove anything from the original material. In still other conversion processes, liquid gasoline is made from the hydrocarbon gases generated during cracking. Polymerization joins an olefin with a branched chain paraffin to yield a saturated hydrocarbon.

Treatment steps are used to purify the material or to prevent an undesirable reaction with an impurity. For example, during selective hydrogenation, sulfur and nitrogen as impurities in the feed stocks are converted to hydrogen sulfide and ammonia, respectively. In addition, olefins and aromatic compounds may be hydrogenated to partial or complete saturation. Three types of treatment employed are acid treatment, "sweetening," and solvent extraction. Petroleum fractions may be brought into contact with concentrated sulfuric acid to remove sulfur, nitrogen, and undesirable unsaturated compounds and to improve color and odor. Sweetening converts mercaptans to disulfides and this improves odor. Sodium plumbite (doctor), lead sulfide, hyprochlorite, and copper chloride are common sweetening agents. In solvent extraction, solvents are used to remove undesired contaminants or to concentrate desired components.

Physical treatments such as absorption, air-blowing, electrical coalescence, and filtration are used in intermediate refining processes to remove contaminants.

Another commonplace activity at refineries is the blending of base stocks to produce a wide variety of finished products.

A list of equipment, facilities, and processes likely to produce organic emissions in crude oil production and in refining includes:

1. Storage.
2. Pressure relief valves.
3. Blowdown systems.
4. Flares.
5. Catalytic cracking units.
6. Asphalt oxidation.

7. Chemical treatment.
8. Loading facilities.
9. Oil-water separators.
10. Pumps.
11. Valves.

REGULATIONS

Hydrocarbon emission standards for refineries and related petroleum industry facilities were not included in the performance standards for new stationary sources which were issued in December, 1971, by the Federal Environmental Protection Agency. The EPA has indicated, however, that petroleum refineries will be a source classification in the next group of standards issued and that hydrocarbon emission standards will be included for all types of producing and refining activities. It is anticipated that proposed standards will be issued before mid-1972.

To assist the state regulatory agencies in preparation of implementation plans, the EPA included extensive model regulations for control of hydrocarbon emissions in the proposed implementation plan guidelines which were issued in April, 1971. The model regulations, which were patterned quite closely after the Los Angeles County hydrocarbon emission regulations, require that:

1. Storage facilities for volatile hydrocarbons (> 1.5 psia) larger than 40,000 gallons must be equipped with floating roofs, vapor recovery systems, or other control devices to control evaporative emissions. Further, the use of floating roofs is limited to hydrocarbons with a vapor pressure of less than 11.0 psia.

2. Storage tanks for volatile hydrocarbons larger than 250 gallons must be equipped with a permanent submerged fill pipe or other evaporative control device to reduce hydrocarbon emissions during filling operations.

3. Loading facilities for volatile hydrocarbons must be equipped with a vapor collection and disposal or recovery system to control losses during

loading operations.

4. Oil-water separators which receive more than 200 gallons per day of volatile hydrocarbons must be equipped with a solid cover, floating roof, vapor recovery system or other means to prevent hydrocarbon losses.

5. Pumps and compressors handling volatile organic materials must have mechanical seals to keep leakage to a minimum.

6. Hydrocarbon gases from vapor blowdown systems must be burned in smokeless flares.

7. Emissions of organic solvents from numerous varied operations must be controlled through the use of such methods as incineration, carbon adsorption, and vapor recovery.

In the final implementation plan guidelines issued by EPA in August, 1971, the model hydrocarbon emission regulations were not significantly modified. It was emphasized, however, in the final guidelines that the major reason for controlling hydrocarbons is to prevent photochemical oxidant production and that control of stationary hydrocarbon sources would be necessary only in areas where the anticipated reduction obtained from the motor vehicle standards would not be sufficient to result in attainment of the oxidant ambient air quality standard.

Virtually all states have proposed or already adopted some hydrocarbon emission regulations primarily based on the EPA model standards. The petroleum industry, through the state petroleum councils and individual company statements, has presented extensive testimony at state hearings which have been held on the proposed hydrocarbon regulations. Principle points covered by the industry include requests that:

1. Applicability of any hydrocarbon regulations be limited to those areas where the photochemical oxidant standard is met or exceeded. This would limit

imposition of costly control requirements to those major metropolitan areas where there currently is a photochemical smog problem and would be consistent with latest EPA recommendations.

2. The definition of volatile hydrocarbon be changed to mean any material with a vapor pressure of over 2.5 psia instead of 1.5 psia. This would except JP-4 jet fuel, heavy naphtha solvents and feed stocks and kerosene-type materials from the requirement of being stored in floating roof tanks and being loaded in facilities with vapor recovery systems. This change could also make a difference in the number of oil-water separators which need to be covered.

3. The use of floating roofs be allowed for hydrocarbons with a vapor pressure of up to 12.5 psia instead of 11.0 psia. This would eliminate the need to store materials such as LVN and LCN in pressure tanks during the summer.

4. The requirement for vapor recovery at loading facilities be limited to larger facilities which load more than 20,000 gallons per day. This would except bulk plants which typically load only several truckloads per day.

5. The requirement for mechanical seals be limited to rotary and centrifugal pumps and compressors since mechanical seals are not applicable to reciprocal units.

6. A differentiation be made between vapor blowdown systems and emergency relief devices and that the requirement for smokeless flares be limited to blowdown systems. This change would preclude the need to connect emergency pressure relief valves, which are infrequently, if ever, used, to the blowdown and flare system, which is normally used during startups, shutdown, and minor upsets.

Some of the industry recommendations have been accepted by some of the states. In others, compromise versions have been adopted or the application of the most stringent regulations has been limited to new facilities. It is likely, when all the states have completed adoption of regulations and implementation

plans later this year, that the hydrocarbon emission regulations will vary considerably from state to state and that these variations will be disconcerting to multiple-facility companies attempting to comply with regulations in several states.

STORAGE

Storage is potentially the most important source of hydrocarbon emissions in the petroleum industry. Vapors can be emitted when storage tanks "breathe," when vapors are displaced during filling, and when liquids evaporate. Tanks "breathe" due to the expansion and contraction of their contents with the heat of the day and the cool of the night. When the contents expand, air mixed with hydrocarbon vapors is forced out of the tank. Methods have been developed to estimate losses and to minimize these losses from storage tanks.

Even in the most modern petroleum refineries and petrochemical plants, storage facilities must be provided for large volumes of liquids and gases. These facilities can be classified as closed-storage or open-storage vessels. Closed-storage vessels include fixed-roof tanks, pressure tanks, floating-roof tanks, and conservation tanks. Open-storage vessels include open tanks, reservoirs, pits, and ponds.

Closed-storage vessels are constructed in a variety of shapes, but most commonly as cylinders, spheres, or spheroids. Steel plate is the usual material of construction though concrete, wood, and other materials are sometimes used. Before modern welding methods, the sections of the tank shell were joined by rivets or bolts. Welded joints are now used almost universally except for the small bolted tank found in production fields. Capacities of storage vessels range from a few gallons up to 500,000 barrels, but tanks with capacities in excess of 150,000 barrels are relatively rare.

Open-storage vessels are also found in a variety of shapes and materials of construction. Open tanks generally have cylindrical or rectangular shells

of steel, wood, or concrete. Reservoirs, pits, ponds, and sumps are usually oval, circular, or rectangular depressions in the ground. The sides and bottom may be the earth itself or may be covered with an asphalt-like material or concrete. Any roofs or covers are usually of wood with asphalt or tar protection. Capacities of the larger reservoirs may be as much as 3 million barrels.

Vapors, gases, aerosols, and odors are examples of air contaminants emitted from storage facilities. In most cases, practical and feasible air pollution control measures are available to reduce the emissions.

Pressure Tanks and Fixed-Roof Tanks

Pressure tanks and fixed-roof tanks are grouped together because, in a sense, pressure tanks are special examples of fixed-roof tanks designed to operate at greater than atmospheric pressure. Horizontal, cylindrical (bullet) pressure tanks are the most common pressure tanks. Other types of pressure tanks include spheres, plain and noded spheroids, and noded hemispheroids. Maximum capacities of these pressure tanks are as much as 30,000 barrels for spheres and hemispheroids, and 120,000 barrels for noded spheroids. Spheres can be operated at pressures up to 217 psi; spheroids, up to 50 psi; noded spheroids, up to 20 psi; and plain or noded hemispheroids, up to 15 and 2-1/2 psi, respectively. Horizontal, cylindrical pressure tanks are constructed with various capacities and pressures.

Typical storage tanks are vertical, cylindrical, fixed-roof tanks. This type of storage facility operates at or within a few ounces of atmospheric pressure and may have a flat, recessed flat, conical, or domed roof. The term gastight, often applied to welded tanks, is misleading. Many of the roofs of the welded tanks have free vents open to the atmosphere. Others are equipped with conservation vents that open at very slight positive pressures. A tank also has many standard appurtenances including gaging hatches, sample hatches, relief vents, and

foam mixers. Any of these accessories may fail in service and result in vapor leaks.

The operating pressure of a tank is limited by the thickness (weight) of the roof. A cone roof tank may be operated at higher pressures, if necessary, by structural reinforcement or weighting of the roof. Safe operating pressures up to 4 ounces can be realized by this added expense. Use of unsupported dome-shaped roofs is another method of increasing the allowable operating pressure of the fixed-roof tank.

Floating-Roof Tanks

Floating-roof storage tanks are used for storing volatile material with vapor pressures in the lower explosive range, to minimize potential fire or explosion hazards. These vessels also economically store volatile products that do not boil at atmospheric pressures or less and at storage temperatures or below. These tanks are subclassified by the type of floating-roof section as pan, pontoon, or double-deck floating-roof tanks.

Pan-type floating-roof tanks were placed in service more than 50 years ago. These roofs require considerable support or trussing to prevent the flat metal plate used as the roof from buckling. These roofs are seldom used on new tanks because extreme tilting and holes in the roof have caused more than one-fifth of installed pan roofs to sink, and because their use results in high vaporization losses. Solar heat falling on the metal roof in contact with the liquid surface results in higher than normal liquid surface temperatures. Hydrocarbons boil away more rapidly at the higher temperatures and escape from the opening around the periphery of the roof.

To overcome these disadvantages, pontoon sections were added to the top of the exposed deck. Better stability of the roof was obtained, and a center drain with hinged or flexible connections solved the drainage problem. Center-weighted

pontoons, double pontoons, and high- and low-deck pontoon floating-roof tanks are available today. Current practice is to use the pontoon roof on tanks with very large diameters. Included with some pontoon roof designs is a vapor trap or dam installed on the underside of the roof. This trap helps retain any vapors formed as a result of localized boiling and converts the dead vapor space into an insulation medium. This dead vapor space tends to retard additional boiling.

The more expensive double-deck floating roof was eventually introduced to reduce the effect of solar boiling and to gain roof rigidity. The final design generally incorporates compartmented dead-air spaces more than 12 inches deep over the entire liquid surface. The top deck is generally sloped toward the center or to a drainage area. Any liquid forming or falling on the roof top is drained away through a flexible roof drain to prevent the roof from sinking. The bottom deck is normally coned upwards. This traps under the roof any vapors entrained with incoming liquid or any vapors that might form in storage. A vertical dam similar to those used on pan or pontoon floating roofs can also be added to retain these vapors.

Conservation Tanks

Storage vessels classified as conservation tanks include lifter-roof tanks and tanks with internal, flexible diaphragms or internal, plastic, floating blankets. The lifter roof or, as more commonly known, gas holder, is used for low-pressure gaseous products or for low-volatility liquids. This type of vessel can be employed as a vapor surge tank when manifolded to vapor spaces of fixed-roof tanks.

Two types of lifter-roof tanks are available. One type has a dry seal consisting of a gastight, flexible fabric; the other type employs a liquid seal. The sealing liquid can be fuel oil, kerosene, or water. Water should not be

employed as a sealing liquid where there is danger of freezing.

The physical weight of the roof itself floating on vapor maintains a slight positive pressure in the lifter-roof tank. When the roof has reached its maximum height, the vapor is vented to prevent overpressure and damage to tank.

The conservation tank classification also includes fixed-roof tanks with an internal coated-fabric diaphragm. The diaphragm is flexible and rises and falls to balance pressure changes.

Two basic types of diaphragm tanks are the integrated tank, which stores both liquid and vapor, and the separate tank, which stores only vapor. Common trade names for integrated tanks are "diaflote," "dialift," and "vapor-mizer" tanks, or they may be referred to as vapor spheres or vapor tanks. The separate type of tank offers more flexibility and does not require extensive alteration of existing tanks.

Open-Top Tanks, Reservoirs, Pits, and Ponds

The open-top tank is not used as extensively as in the past. Safety, conservation, and housekeeping are factors affecting the elimination of open vessels. Even tanks that require full access can and should be equipped with removable covers. The open vessels generally have a cylindrical shell, but some have a rectangular shell.

Reservoirs were devised to store the large quantities of residual oils, fuel oils, and, sometimes, crude oils resulting from petroleum production and refining. Safety considerations, larger fixed-roof tanks, and controlled crude oil production have reduced the number of reservoirs in use today. Even when covered, reservoirs have open vents, which maintain atmospheric pressures in the reservoir. Windbreaks divert the windflow pattern over a large roof area and prevent the roof from raising and buckling.

Open ponds or earthen pits were created by diking low areas or by excavation. These storage facilities served for holding waste products, refinery

effluent water, or inexpensive oil products for considerable periods of time. In these, oils "weathered" extensively, leaving viscous, tar-like materials, and water seeped into the lower ground levels. As the pond filled with solids and semisolids, the contents were removed by mechanical means, covered in place, or the pond was simply abandoned. The use of these ponds has diminished, and the remaining ponds are usually reserved for emergency service.

Smaller ponds or sumps were once used extensively in the crude oil production fields. This use was primarily for drilling muds though oil-water emulsions and crude oil were also stored by this method. Their use is gradually disappearing because unattended or abandoned sumps cause nuisance problems to a community.

Control of air pollution originating from storage vessels serves a threefold purpose: (1) elimination or reduction of air contaminants, (2) elimination or reduction of fire hazards, and (3) economic savings through recovery of valuable products. Methods of control include use of floating roofs, plastic blankets, spheres, variable vapor space systems, various recovery systems, and altered pumping and storage operations.

Seals for Floating-Roof Tanks

The principle by which a floating roof controls emissions from a volatile liquid is that of eliminating the vapor space so that the liquid cannot evaporate and later be vented. To be successful the floating roof must completely seal off the liquid surface from the atmosphere. The seal for the floating roof is therefore very important. The floating section is customarily constructed about 8 inches less in diameter than the tank shell. A sealing mechanism must be provided for the remaining open annular gap. The seal also helps keep the roof centered.

Conventional seals generally consist of vertical metal plates or shoes connected by braces or pantograph devices to the floating roof. The shoes are

suspended in such a way that they are forced outward against the inner tank wall. An impervious fabric bridges the annular area between the tops of the shoes contacting the tank wall and the circumference of the floating roof. To reduce emissions, a secondary seal or wiper blade has been added to the floating-roof design by extending the fabric seal or by adding a second section of fabric. This seal remains in contact with the tank wall. Its flexibility allows it to make contact even in rivet head areas of the inner shell or in places where the shell might be slightly out of round. This improvement lowers hydrocarbon emissions further by reducing the effect of wetting and wicking associated with floating-roof tanks.

Recently, other types of sealing devices to close the annular gap which have been marketed include filled tube seals. These devices consist of a fabric tube that rests on the surface of liquid exposed in the annular space. The fabric tube is filled with air, liquid or plastic material. The pneumatic, inflated seal is provided with uniform air pressure by means of a small expansion chamber and control valves. The sides of the tube remain in contact with the roof and inner shell. The liquid-filled tube holds a ribbed scuff band against the tank wall. The ribbed band acts as a series of wiper blades as well as a closure. All tubes are protected by some type of weather covering.

A weather covering can also be added to protect the sealing fabric of the conventional seals. The covering includes flat metal sections held in place by a metal band. The metal protects the fabric seal from the elements. When floating-roof sections are added to older tanks constructed of riveted sections, better contact of the shoes with the shell can be ensured by guniting or plastic coating the inner shell. The wetting condition of gunited walls may, however, offset the gain of better contact.

Floating Plastic Blankets

A floating plastic blanket, operates on the same principle of control as a floating roof. The blanket is usually made of polyvinyl chloride but can be made of other plastics such as polyvinyl alcohol, superpolyamides, polyesters, fluoride hydrocarbons, and so forth. The blanket's underside is constructed of a large number of floats of the same plastic material. The blanket is custom manufactured so that only a 1-inch gap remains around the periphery. A vertical raised skirt is provided at the edge of the blanket to serve as a vapor seal over the annular area. Once this area is saturated, further evaporation diminishes. The only remaining loss is gaseous diffusion. The seal is made as effective as possible by using an elastic, Z-shaped skirt.

Provisions are made in the blanket for openings fitted with vertical sleeves for measuring and sampling operations. These openings have a crosscut, flexible inner diaphragm to minimize exposure of the liquid surface. Small holes with downspouts to effect a liquid seal are used to provide drainage of any condensate from the top of the blanket. Another feature includes a stainless steel cable grid to prevent a buildup of static charges. The grid is closely attached just under the blanket in parallel lines and connected to the tank shell by a flexible conductor cable. Installation of a plastic blanket is convenient for both new and existing tanks. The blanket is made in sections and can be introduced into a tank through a manhole.

A rigid foam-plastic cover constructed of polyisocyanate foam is also available to equip small fixed-roof tanks with a floating cover. The cover is manufactured in radial sections, each equipped with a flexible neoprene seal attached on the outer edge. The sections are easily installed through roof manholes and assembled with slip-fit joints.

Plastic Microspheres

An outgrowth of application of plastic material provides another type of control mechanism. This type of control is also similar to the floating roof and involves the use of a phenolic or urea resin in the shape of tiny, hollow, spherical particles. This material has the physical properties necessary to form a foam covering over the denser petroleum products. The fluidity of the layer enables it to flow around any internal tank parts while keeping the liquid surface sealed throughout any level changes. These plastic spheres are known under their trademark names of microballoons or microspheres. These coverings have proved to be effective controls for fixed-roof crude oil tanks. Excessive amounts of condensation or high turbulence should be avoided. The plastic foam has not proved as satisfactory for one-component liquid or gasoline products.

A 1/2-inch layer of foam has been found sufficient for crude oil where pumping rates do not exceed 4,000 barrels per hour. A layer 1 inch thick is recommended for pumping rates up to 10,000 barrels per hour. In order to overcome wall holdup in smaller tanks, it is suggested that a 1-inch layer be used regardless of pumping rates. For tanks storing gasoline, the recommended foam thickness is 2 inches for tanks up to 40 feet in diameter, and 1 inch for all larger diameter vessels.

Various methods can be used to put the foam covering on the crude oil. One method is to inject the plastic spheres with the crude oil as it is charged to the tank. Spheres are added by means of an aspirator and hopper similar to equipment used in fire-fighting foam systems. The spheres can also be added by placing the desired quantity on the clean, dry floor of the tank just before the crude oil is charged. A wetting agent must be used when the foam covering is to be used on gasoline products. This is accomplished by slurrying the plastic spheres, wetting agent, and gasoline in a separate container. The slurry is then injected into the tank. Changes in tank operation are not necessary except

for gaging or sampling. A floating-type well attached to a common-type gaging tape allows accurate measurement of the tank's contents. A sample thief with a piercing-type bottom is needed for sampling.

Protection against excessive loss of the plastic spheres is necessary because of the relative value of the foam covering. Precaution must be taken against overfilling and pumping the tank too low. Standard precautions against air entrainment in pipelines normally safeguard against the latter. Overfilling can be prevented by automatic shutoff valves or preset shutoff operations. Low-level shutoff should prevent vortices created during tank emptying. Other than loss of the foam, no trouble should be encountered if the spheres escape into process lines. The plastic material is not as abrasive as the sand particles normally found entrained in crude oil. Excessive pressures crush the spheres and the plastic settles in the water or sediment. At high temperatures, the thermo-setting resins soften, liquefy, and mix with the fuel oil, asphalt, or coke.

Plastic microspheres have proved to be effective for control of evaporative losses from fixed-roof crude oil storage tanks but do not reduce emissions from gasoline storage tanks as effectively as other devices.

Vapor Balances Systems

Variable vapor space or vapor balance systems are designed to contain the vapors produced in storage. They do not achieve as great a reduction in emissions as an appropriately designed vapor recovery system does. A well-planned unit includes storage of similar or related products, and uses the advantage of in-balance pumping situations. Only the vapor space of the tanks is manifolded together in these systems. Other systems include a vapor reservoir tank that is either a lifter-roof type or a vessel with an internal diaphragm. The latter vessel can be an integrated vapor-liquid tank or a separate vaporsphere.

The manifold system includes various sizes of lightweight lines installed to effect a balanced pressure drop in all the branches while not exceeding allowable pressure drops. Providing isolating valves for each tank so that each tank can be removed from the vapor balance system during gaging or sampling operations is also good practice. Excessive vapors that exceed the capacity of the balance system should be incinerated in a smokeless flare or used as fuel.

Vapor Recovery Systems

The vapor recovery system is in many ways similar to and yet superior to a vapor balance system in terms of emissions prevented. The service of this type of vapor recovery system is more flexible as to the number of tanks and products being stored. The recovery unit is designed to handle vapors originating from filling operations as well as from breathing. The recovered vapors are compressed and charged to an absorption unit for recovery of condensable hydrocarbons. Noncondensable vapors are piped to the fuel gas system or to a smokeless flare. When absorption of the condensable vapors is not practical from an economic standpoint, these vapors, too, are sent directly to the fuel system or incinerated in a smokeless flare.

The recovery system, like the vapor balance system, includes vapor lines interconnecting the vapor space of the tanks that the system serves. Each tank should be capable of being isolated from the system. This enables the tanks to be sampled or gaged without a resulting loss of vapors from the entire system. The branches are usually isolated by providing a butterfly-type valve, a regulator, or a check valve. Since the valves offer more line resistance, their use is sometimes restricted. Small vessels or knockout pots should be installed at low points on the vapor manifold lines to remove any condensate.

In some vapor recovery systems, certain tanks must be blanketed with an inert atmosphere in order to prevent explosive mixtures and product contamination. In other, larger systems, the entire manifolded section is maintained

under a vacuum. Each tank is isolated by a regulator-control valve. The valves operate from pressure changes occuring in the tank vapor space.

Because the vapor-gathering system is based upon positive net vapor flow to the terminus (suction of compressors), the proper size of the vapor lines is important. Sizing of the line, as well as that of the compressors, absorption unit, or flare, is based upon the anticipated amount of vapors. These vapors are the result of filling operations and breathing. The distance through which the vapors must be moved is also important.

Miscellaneous Control Measures

Recent tests have shown that breathing emissions from fixed-roof tanks can be reduced by increasing the storage pressure. An increase of 1 ounce per square inch was found to result in an 8 percent decrease in emissions due to breathing. Tanks operated at 2-1/2 psig or higher were found to have little or no breathing emissions. The pressure setting, however, should not exceed the weight of the roof.

Another method of reducing breathing losses is based upon the degree of saturation in the vapor space. A baffle located in a horizontal position immediately below the vent directs entering atmospheric air into a stratified layer next to the top of the tank. Since this air is lighter, it tends to remain in the top area; thus, there is less mixing of the free air and any of the rich vapor immediately above the liquid surface. The top stratified layer is first expelled during the outbreathing cycle. Test data indicate a reduced surface evaporation of 25 to 50 percent.

Hydrocarbon emissions can be minimized further by the proper selection of paint for the tank shell and roof. The protective coating applied to the outside of shell and roof influences the vapor space and liquid temperatures. Reflectivity and glossiness of a paint determine the quantity of heat a vessel

can receive via radiation. A cooler roof and shell also allows any heat retained in the stored material to dissipate. Weathering of the paint also influences its effectiveness. Vapor space temperature reductions of 60°F. have been reported with proper selection of paint color. Similarly, liquid-surface temperature reductions of 3 to 11 degrees have been achieved. Data gathered by the American Petroleum Institute on hydrocarbon emissions indicate breathing emission reductions of 25 percent for aluminum over black paint and 25 percent for white over aluminum paint. All paints revert to "black body" heat absorption media in a corrosive or dirt-laden atmosphere.

Insulation applied to the outside of the tank is one method of reducing the heat energy normally conducted through the wall and roof of the vessel. Another method of controlling tank temperatures is the use of water. The water can be sprayed or retained on the roof surface. The evaporation of the water results in cooling of the tank vapors. Incressed maintenance and corrosion problems may, however, be encountered.

Storage temperatures may be reduced by external refrigeration or autorefrigeration. External refrigeration units require the circulation of the refrigerant or of the tank contents. Autorefrigeration is practical in one-component liquid hydrocarbon storage where high vapor pressure material is involved. The pressure in the tank is reduced by removing a portion of the vapor. Additional vapor is immediately formed. This flash vaporization results in lowering the temperature of the main liquid body.

Routine operations can be conducted in such a manner as to minimize other emissions associated with storage tanks. Use of remote-level reading gages and sampling devices reduces emissions by eliminating the need to open tank gage hatches. Emissions can be further reduced by proper production scheduling to (1) maintain a minimum of vapor space, (2) pump liquid to the storage tank during cool hours and withdraw during hotter periods, and (3) maintain short periods

between pumping operations.

Using wet scrubbers as control equipment for certain stored materials that are sufficiently soluble in the scrubbing media employed is both possible and practical. The scrubbers can be located over the vent when the scrubbing medium, for example, a water scrubber for aqua ammonia storage, can be tolerated in the product. In other cases, the vent of one or more tanks can be manifolded so that any displaced gas is passed through a scrubbing unit before being discharged to the atmosphere. A typical example is a scrubber packed with plastic spirals that serves ketone storage vessels. The scrubbing liquid is water, which is drained to a closed waste effluent disposal system.

Properly designed condensers can be used to reduce the vapor load from tank vents in order that smaller control devices can be employed.

Costs of Storage Vessels

The installed costs of various types of hydrocarbon storage tanks are summarized in Table I. Included in these costs are standard tank accessories such as manholes, vents, ladders, stairways, drains, gage hatches, and flanged connections.

WASTE-GAS DISPOSAL SYSTEMS

Large volumes of hydrocarbon gases are produced in modern refinery and petrochemical plants. Generally, these gases are used as fuel or as raw material for further processing. In the past, however, large quantities of these gases were considered waste gases, and along with waste liquids, were dumped to open pits and burned, producing large volumes of black smoke. With modernization of processing units, this method of waste-gas disposal, even for emergency gas releases, has become less acceptable to the industry. Moreover, many local governments have adopted or are contemplating ordinances limiting the opacity of smoke from combustion processes.

Nevertheless, petroleum refineries are still faced with the problem of safe disposal of volatile liquids and gases resulting from scheduled shutdowns and sudden or unexpected upsets in process units. Emergencies that can cause the sudden venting of excessive amounts of gases and vapors include:

1. Failure of the cooling water supply.
2. Failure of a reflux system.
3. Entrance of a more volatile fluid into the equipment.
4. Vapor generation due to fire exposure.
5. Excessive heat inputs other than from fire.
6. Accumulation of noncondensible gases.
7. Closed or plugged equipment outlets.
8. Failure of automatic flow, temperature, or pressure control equipment.
9. Internal explosions.
10. Uncontrolled chemical reactions.
11. Failure of heat exchanger internals.
12. Power failure.
13. Thermal expansion.
14. Compressor failure.

A system for disposal of emergency and waste refinery gases consists of a manifolded pressure-relieving or blowdown system, and a blowdown recovery system or a system of flares for the combustion of the excess gases, or both. Many refineries, however, do not operate blowdown recovery systems. In addition to disposing of emergency and excess gas flows, these systems are used in the evacuation of units during shutdowns and turarounds. Normally a unit is shut down by depressuring into a fuel gas or vapor recovery system with further depressuring to essentially atmospheric pressure by venting to a low-pressure flare system. Thus, overall emissions of refinery hydrocarbons are substantially reduced.

Refinery pressure-relieving systems, commonly called blowdown systems, are used primarily to ensure the safety of personnel and protect equipment in the event of emergencies such as process upset, equipment failure, and fire. In addition, a properly designed pressure relief system permits substantial reduction of hydrocarbon emissions to the atmosphere.

The equipment in a refinery can operate at pressures ranging from less than atmospheric to 1,000 psig and higher. This equipment must be designed to permit safe disposal of excess gases and liquids in case operational difficulties or fires occur. These materials are usually removed from the process area by automatic safety and relief valves, as well as by manually controlled valves, manifolded to a header that conducts the material away from the unit involved. The preferred method of disposing of the waste gases that cannot be recovered in a blowdown recovery system is by burning in a smokeless flare. Liquid blowdowns are usually conducted to appropriately designed holding vessels and reclaimed.

A blowdown or pressure-relieving system consists of relief valves, safety valves, manual bypass valves, blowdown headers, knockout vessels, and holding tanks. A blowdown recovery system also includes compressors and vapor surge vessels such as gas holders or vapor spheres. Flares are usually considered as part of the blowdown system in a modern refinery.

The pressure-relieving system can be used for liquids or vapors or both. For reasons of economy and safety, vessels and equipment discharging to blowdown systems are usually segregated according to their operating pressure. In other words, there is a high-pressure blowdown system for equipment working, for example, above 100 psig, and low-pressure systems for those vessels with working pressures below 100 psig. Butane and propane are usually discharged to a separate blowdown drum, which is operated above atmospheric pressure to increase recovery of liquids. Usually a direct-contact type of condenser is used to permit recovery of as much hydrocarbon liquid as possible from the blowdown vapors.

The noncondensibles are burned in a flare.

Design of Pressure Reflief System

The design of a pressure relief system is one of the most important problems in the planning of a refinery or petrochemical plant. The safety of personnel and equipment depends upon the proper design and functioning of this type of system. The consequences of poor design can be disastrous.

A pressure relief system can consist of one relief valve, safety valve, or rupture disc, or of several relief devices manifolded to a common header. Usually the systems are segregated according to the type of material handled, that is, liquid or vapor, as well as to the operating pressures involved.

The several factors that must be considered in designing a pressure relief system are (1) the governing code, such as that of ASME (American Society of Mechanical Engineers, 1962); (2) characteristics of the pressure relief devices; (3) the design pressure of the equipment protected by the pressure relief devices, (4) line sizes and lengths, and (5) physical properties of the material to be relieved to the system.

Safety Valves

Nozzle-type safety valves are available in the conventional or balanced-bellows configurations. Backpressure in the piping downstream of the standard-type valve affects its set pressure, but theoretically, this backpressure does not affect the set pressure of the balanced-type valve. Owing, however, to imperfections in manufacture and limitations of practical design, the balanced valves available vary in relieving pressure when the backpressure reaches approximately 40 percent of the set pressure. The actual accumulation depends upon the manufacturer.

Until the advent of balanced valves, the general practice in the industry was to select safety valves that start relieving at the design pressure of the vessel and reach full capacity at 3 to 10 percent above the design pressure.

This overpressure was defined as accumulation. With the balanced safety valves, the allowable accumulation can be retained with smaller pipe size.

Each safety valve installation is an individual problem. The required capacity of the valve depends upon the condition producing the overpressure.

Rupture Discs

A rupture disc is an emergency relief device consisting of a thin metal diaphragm carefully designed to rupture at a predetermined pressure.

The obvious difference between a relief or safety valve and a rupture disc is that the valve reseats and the disc does not. Rupture discs may be installed in parallel or series with a relief valve. To prevent an incorrect pressure differential from existing, the space between the disc and the valve must be maintained at atmospheric pressure. In some cases a rupture disc may be used to supplement a relief or safety valve. In an installation such as this, the relief or safety valve is sized by conventional methods and the rupture disc is usually designed to relieve at 1.5 times the maximum allowable working pressure of the vessel.

In determining the size of a disc, three important effects that must be evaluated are low rupture pressure, elevated temperatures, and corrosion. Manufacturers can supply discs that are guaranteed to burst at plus or minus 5 percent of their rated pressures.

The corrosive effects of a system determine the type of material used in a disc. Even a slight amount of corrosion can drastically shorten disc life. Discs are available with plastic linings, or they can be made from pure carbon materials.

FLARES

The air pollution problem associated with the uncontrolled disposal of waste gases is the venting of large volumes of hydrocarbons and other odorous gases

and aerosols. The preferred control method for excess gases and vapors is to recover them in a blowdown recovery system and, failing that, to incinerate them in an elevated-type flare. Such flares introduce the possibility of smoke and other objectionable gases such as carbon monoxide, sulfur dioxide, and nitrogen oxides. Flares have been further developed to ensure that this combustion is smokeless and in some cases nonluminous. Luminosity, while not an air pollution problem, does attract attention to the refinery operation and in certain cases can cause bad public relations.

Smoke from Flares

Smoke is the result of incomplete combustion. Smokeless combustion can be achieved by: (1) adequate heat values to obtain the minimum theoretical combustion temperatures, (2) adequate combustion air, and (3) adequate mixing of the air and fuel.

An insufficient supply of air results in a smoky flame. Combustion begins around the periphery of the gas stream where the air and fuel mix, and within this flame envelope the supply of air is limited. Hydrocarbon side reactions occur with the production of smoke. In this reducing atmosphere, hydrocarbons crack to elemental hydrogen and carbon, or polymerize to form heavier hydrocarbons. Since the carbon particles are difficult to burn, large volumes of carbon particles appear as smoke upon cooling. Side reactions become more pronounced as molecular weight and unsaturation of the fuel gas increase. Olefins, diolefins, and aromatics characteristically burn with smoky, sooty flames as compared with paraffins and naphthenes.

A smokeless flame can be obtained when an adequate amount of combustion air is mixed sufficiently with the fuel so that it burns completely and rapidly before any side reactions can take place.

Types of Flares

There are, in general, three types of flares for the disposal of waste gases: elevated flares, ground-level flares, and burning pits.

The burning pits are reserved for extremely large gas flows caused by catastrophic emergencies in which the capacity of the primary smokeless flares is exceeded. Ordinarily, the main gas header to the flare system has a water seal bypass to a burning pit. Excessive pressure in the header blows the water seal and permits the vapors and gases to vent a burning pit where combustion occurs.

The essential parts of a flare are the burner, stack, seal, liquid trap, controls, pilot burner, and ignition system. In some cases, vented gases flow through chemical solutions to receive treatment before combustion. As an example, gases vented from an isomerization unit that may contain small amounts of hydrochloric acid are scrubbed with caustic before being vented to the flare.

Elevated Flares

Smokeless combustion can be obtained in an elevated flare by the injection of an inert gas to the combustion zone to provide turbulence and inspirate air. A mechanical air-mixing system would be ideal but is not economical in view of the large volume of gases handled. The most commonly enountered air-inspirating material for an elevated flare is steam. Three main types of steam-injected elevated flares are in use. These types vary in the manner in which the steam is injected into the combustion zone.

In the first type, there is a commercially available multiple nozzle which consists of an alloy steel tip mounted on the top of an elevated stack. Steam injection is accomplished by several small jets placed concentrically around the flare tip. These jets are installed at an angle, causing the steam to discharge in a converging pattern immediately above the flare tip.

A second type of elevated flare has a flare tip with no obstruction to flow, that is, the flare tip is the same diameter as the stack. The steam is injected

by a single nozzle located concentrically within the burner tip. In this type of flare, the steam is premixed with the gas before ignition and discharge.

A third type of elevated flare is equipped with a flare tip constructed to cause the gases to flow through several tangential openings to promote turbulence. A steam ring at the top of the stack has numerous equally spaced holes about 1/8 inch in diameter for discharging steam into the gas stream.

The injection of steam in flares may be automatically or manually controlled. Most flares are instrumented to the extent that steam is automatically supplied when there is a measurable gas flow. In most cases, the steam is proportioned automatically to the reate of gas flow; however, in some installations, the steam is automatically supplied at maximum rates, and manual throttling of a steam valve is required for adjusting the steam flow to the particular gas flow rate. There are many variations of instrumentation among various flares, some designs being more desirable than others. For economic reasons, all designs attempt to proportion steam flow to the gas flow rate.

Steam injection is generally believed to result in the following benefits: (1) energy available at relatively low cost can be used to inspirate air and provide turbulence within the flame, (2) steam reacts with the fuel to form oxygenated compounds that burn readily at relatively low temperatures, (3) water-gas reactions also occur with this same end result, and (4) steam reduces the partial pressure of the fuel and retards polymerization. (Inert gases such as nitrogen have also been found effective for this purpose; however, the expense of providing a diluent such as this is prohibitive.)

Ground-Level Flares

Ground-level flares are of four principal types: horizontal venturi, water injection, multijet, and vertical venturi.

A horizontal venturi-type flare system utilizes groups of standard venturi burners. In this type of burner, the gas pressure inspirates combustion air for

smokeless operation.

A water-injection flare consists of a single burner with a water spray ring around the burner nozzle. The water spray inspirates air and provides water vapor for the smokeless combustion of gases. Water is not as effective as steam for controlling smoke with high gas-flow rates, unsaturated materials, or wet gases.

A multijet ground flare uses two sets of burners, one for normal gas release rates and both for higher flaring rates.

A vertical, venturi-type ground flare also uses commercial-type venturi burners. This type of flare is suitable for relatively small flows of gas at a constant rate.

Ground-level flares are seldom used today in refineries because of space limitations, the inability to safely dissipate heat generated, and the difficulty of diffusing any vapors that may be emitted.

Effect of Steam Injection

A flare installation that does not inspirate an adequate amount of air or does not mix the air and hydrocarbons properly emits dense, black clouds of smoke that obscure the flame. The injection of steam into the zone of combustion causes a gradual decrease in the amount of smoke, and the flame becomes more visible. When trailing smoke has been eliminated, the flame is very luminous and orange with a few wisps of black smoke around the periphery. The minimum amount of steam required produces a yellowish-orange, luminous flame with no smoke. Increasing the amount of steam injection further decreases the luminosity of the flame. As the steam rate increases, the flame becomes colorless and finally invisible during the day. At night this flame appears blue.

The injection of an excessive amount of steam causes the flame to disappear completely and be replaced with a steam plume. An excessive amount of steam may extinguish the burning gases and permit unburned hydrocarbons to discharge to

the atmosphere. When the flame is out, there is a change in the sound of the flare because a steam hiss replaces the roar of combustion. The commercially available pilot burners are usually not extinguished by excessive amounts of steam, and the flame reappears as the steam injection rate is reduced. As the use of automatic instrumentation becomes more prevalent in flare installations, the use of excessive amounts of steam and the emission of unburned hydrocarbons decrease and greater steam economies can be achieved. In evaluating flare installations from an air pollution standpoint, controlling the volume of steam is important. Too little steam results in black smoke, which, obviously, is objectionable. Conversely, excessive use of steam produces a white steam plume and an invisible emission of unburned hydrocarbons. A condition such as this can also be a serious air pollution problem.

Design of a Smokeless Flare

The choice of a flare is dictated by the particular requirements of the installation. The usual flare system includes gas collection equipment, the liquid knockout tank preceding the flare stack. A water seal tank is usually located between the knockout pot and the flare stack to prevent flashbacks into the system. Flame arrestors are sometimes used in place of or in conjunction with a water seal pot. The flare stack should be continuously purged with steam or refinery gas to prevent the formation of a combustible mixture that could cause an explosion in the stack.

The preferred method of inspirating air is injecting steam either into the stack or into the combustion zone. Water has sometimes been used in ground flares where there is an abundant supply. There is, however, less assurance of complete combustion when water is used, because the flare is limited in its operation by the type and composition of gases it can handle efficiently.

The diameter of the flare stack depends upon the expected emergency gas flow rate and the permissible backpressure in the vapor relief manifold system.

The stack diameter is usually the same or greater than that of the vapor header discharging to the stack and should be the same diameter as or greater than that of the burner section. The velocity of the gas in the stack should be as high as possible to permit use of lower stack heights, promote turbulent flow with resultant improved combustion, and prevent flashback.

Adequate stack heights must be provided to permit safe dispersion of toxic or combustible material in the event of pilot burner failure.

The structural support of an elevated-flare stack over 40 to 50 feet high requires the use of guy wires. A self-supporting stack over 50 feet high requires a large and expensive foundation. Stacks over 100 feet high are usually supported by a steel structure.

The amount of steam required for smokeless combustion varies according to the maximum expected gas flow, the molecular weight, and the percent of unsaturated hydrocarbons in the gas. Actual tests should be run on the various materials to be flared in order to determine a suitable steam-to-hydrocarbon ratio. In the typical refinery, the ratio of steam to hydrocarbon varies from 0.2 to 0.5 pound of steam per pound of hydrocarbon.

Pilot Ignition System

The ignition of flare gases is normally accomplished with one of three pilot burners. A separate system must be provided for the ignition of the pilot burner to safeguard against flame failure. In this system, an easily ignited flame with stable combustion and low fuel usage must be provided. In addition, the system must be protected from the weather.

On elevated flares, the pilot flame is usually not visible, and an alarm system to indicate flame failure is desirable. This is usually accomplished by installing thermocouples in the pilot burner flame. In the event of flame failure, the temperature drops to a preset level, and an alarm sounds.

Instrumentation and Control of Steam and Gas

For adequate prevention of smoke emission and possible violations of air pollution regulations, an elevated, smokeless flare should be equipped to provide steam automatically and in proportion to the emergency gas flow.

Basically, the instrumentation required for a flare is a flow-sensing element, such as a pitot tube, and a flow transmitter that sends a signal (usually pneumatic) to a control valve in the steam line. Although the pitot tube has been used extensively in flare systems, it is limited by the minimum linear velocity required to produce a measurable velocity head. Thus, small gas flows will not actuate the steam control valves. This problem is usually overcome by installing a small bypass valve to permit a constant flow of steam to the flame burner. A more sensititve type of flow-measuring device is the inverted weir. A variation of the inverted weir is the slotted orifice.

The hot-wire flow meter has also been used in flare systems. The sensing element is basically a heat loss anemometer consisting of an electrically heated wire exposed to the gas stream to measure the velocity. The gas flow is perpendicular to the axis of the hot wire. A conventional recorder is used with this probe, modified for the resistance bridge circuit of the gas flow meter. As the flow of gas past the probe varies, the heat loss from the hot wire varies and causes an imbalance of the bridge circuit. The recorder then adjusts for the imbalance in the bridge and indicates the gas flow. This type of installation provides sensitivity at low velocities, and the gas flow measurement can be made without causing an appreciable pressure drop. This is an important advantage in a system using constant backpressure-type relief valves. The hot-wire flow meter can be used as a primary flow-sensing element or as a leak detector in laterals connected to the main flare header.

Maintenance of Flares

Most refineries and petrochemical plants have a fixed schedule for inspection and maintenance of processing units and their auxiliaries. The flare system should not be exempted from this practice. Removal of a flare from service for maintenance requires some type of standby equipment to disperse emergency gas vents during the shutdown. A simple stack with pilot burner should suffice for a standby. Coordinating this inspection to take place at time when the major processing units are also shut down is good practice.

Flare instrumentation requires scheduled maintenance to ensure proper operation. Most of the costs and problems of flare maintenance arise from the instrumentation.

Maintenance expenses for flare burners can be reduced by constructing them of chrome-nickel alloy. Because of the inaccessibility of elevated flares, the use of alloy construction is recommended.

PROCESS OPERATIONS

Catalytic Cracking Units

Petroleum fractions are cracked to produce compounds of lower molecular weight. Catalysts in the form of powders or beads are utilized. The catalyst particles become coated with carbon and high-molecular-weight compounds. These materials must be burned off the catalyst in order to maintain its activity. The catalyst continuously circulates from the reactor chamber to the regenerator chamber. In the regenerator, a controlled amount of air is admitted to burn off the coatings. This causes the formation of CO and hydrocarbons. Typical hydrocarbon emissions from the regenerators of catalytic cracking units are estimated to be 220 lbs./1,000 barrels of fresh feed for fluidized units and 87 lbs./1,000 barrels of fresh feed for moving bed units.

Hydrocarbon emissions from regenerators of catalytic cracking units are generally of secondary importance compared to the carbon monoxide emissions and

their control is incidental to CO control. A waste heat or CO boiler will provide essentially a 100 percent reduction in hydrocarbon emissions as well as controlling CO emissions. The internal CO combustion technique also results in significant reduction in hydrocarbon emissions but data are incomplete as to the exact percentage reduction which can be obtained with this technique.

Asphalt Oxidation

Asphalt is a dark brown to black, solid or semisolid material found in naturally occurring deposits or as a colloidal suspension in crude oil. Analytical methods have been used to separate asphalt into three component groups--asphaltenes, resins, and oils. A particular grade of asphalt may be characterized by the amounts of each group it contains. The asphaltene particle provides a nucleus about which the resin forms a protective coating. The particles are suspended in an oil that is usually paraffinic but can be naphthenic or naptheno-aromatic.

Over 90 percent of all asphalt used in the United States is recovered from crude oil. The method of recovery depends upon the type of crude oil being processed. Practically all types of crudes are first distilled at atmospheric pressure to remove the lower boiling materials such as gasoline, kerosene, diesel oil, and others. Recovery of nondistillable asphalt from selected topped crudes may then be accomplished by vacuum distillation, solvent extraction, or a combination of both.

A vacuum distillation unit uses a heater, preflash tower, vacuum vessel, and appurtenances for processing topped crudes. Distillation of topped crude under a high vacuum removes oils and wax as distillate products, leaving the asphalt as a residue. The amount of oil distilled from the residue asphalt controls its properties; the more oil and resin or oily constituents removed by distillation, the harder the residual asphalt. Residual asphalt can be used as

paving material or it can be further refined by airblowing.

Asphalt is also produced as a secondary product in solvent extraction processes. This process separates the asphalt from remaining constituents of topped crudes by differences in chemical types and molecular weights rather than boiling points as in vacuum distillation processes. The solvent, usually a light hydrocarbon such as propane or butane, is used to remove selectively a gas-oil fraction from the asphalt residue.

Economical removal of the gas-oil fraction from topped crude, leaving an asphaltic product, is occasionally feasible only by airblowing the crude residue at elevated temperatures. Excellent paving-grade asphalts are produced by this method. Another important application of airblowing is in the production of high-quality specialty asphalts for roofing, pipe coating, and similar uses. These asphalts require certain plastic properties imparted by reacting with air.

Airblowing is mainly a dehydrogenation process. Oxygen in the air combines with hydrogen in the oil molecules to form water vapor. The progressive loss of hydrogen results in polymerization or condensation of the asphalt to the desired consistency. Blowing is usually carried out batchwise in horizontal or vertical stills equipped to blanket the charge with steam, but it may also be done continuously. Vertical stills are more efficient because of longer air-asphalt contact time. The asphalt is heated by an internal fire-tube heater or by circulating the charge material through a separate tubestill. A temperature of 300° to 400°F. is reached before the airblowing cycle begins. Air quantities used range from 5 to 20 cubic feet per minute per ton of charge. Little additional heat is then needed since the reaction becomes exothermic.

Effluents from the asphalt airblowing stills include oxygen, nitrogen and its compounds, water vapor, sulfur compounds, and hydrocarbons as gases, odors, and aerosols. Discharge of these vapors directly to the atmosphere is objectionable

from an air pollution control standpoint. The disagreeable odors and airborne oil particles entrained with the gases result in nuisance complaints. Disposal methods are available that can satisfactorily eliminate the pollution potential of the effluents.

Control of effluent vapors from asphalt airblowing stills has been accomplished by scrubbing and incineration, singly or in combination. Most installations use the combination. For scrubbing alone to be effective, a very high water-to-gas ratio of about 100 gallons per 1,000 scf is necessary.

Where removal of most of the potential air pollutants is not feasible by scrubbing alone, the noncondensibles must be incinerated. Essential to effective incineration is direct-flame contact with the vapors, a minimum retention time of 0.3 second in the combustion zone, and maintenance of a minimum combustion chamber temperature of 1,200°F. Other desirable features include turbulent mixing of vapors in the combustion chamber, tangential flame entry, and adequate instrumentation. Primary condensation of any steam or water vapor allows use of smaller incinerators and results in fuel savings. Some of the heat released by incineration of the waste gases may be recovered and used for generation of steam.

Catalytic fume burners are not recommended for the disposal of vapors from the airblowing of asphalt because the matter entrained in the vapors would quickly clog the catalyst bed.

Chemical Treating Processes

In acid treatment, emissions can be reduced by substituting continuous mechanical mixing for batch-type agitators that employ airblowing for mixing. Acid regeneration can also be used instead of the hydrolysis-concentration method of acid recovery. Gases emitted during acid-sludge recovery can be vented to caustic scrubbers to remove sulfur dioxide and odorants. Gases from scrubbers can then be vented to a firebox or flare. For new installations,

acid treatment can also be replaced by catalytic hydrogenation or by other processing techniques that may prove to be more effective.

In doctor treating, the doctor solution can be steam-stripped to recover hydrocarbons prior to airblowing for regeneration. The effluent from airblowing can then be incinerated to destroy hydrocarbon vapors.

In the disposal of spent caustic, entrained hydrocarbons are often removed by stripping with inert gases. The vapors removed in this stripping operation can be vented to a flare or to a furnace firebox.

Whenever hydrocarbons are removed in air or gasblowing operations, the effluent hydrocarbons can be destroyed by incineration.

LOADING FACILITIES

Gasoline and other petroleum products are distributed from the manufacturing facility to the consumer by a network of pipelines, tank vehicle routes, railroad tank cars, and oceangoing tankers.

As integral parts of the network, intermediate storage and loading stations receive products from refineries by either pipelines or tank vehicles. If the intermediate station is supplied by pipeline, it is called a bulk terminal, to distinguish it from the station supplied by tank vehicle, which is called a bulk plant. Retail service stations fueling motor vehicles for the public are, as a general rule, supplied by tank vehicle from bulk terminals or bulk plants. Consumer accounts, which are privately owned facilities operated, for example, to fuel vehicles of a company fleet, are supplied by tank vehicles from intermediate bulk installations or directly from refineries.

Gasoline and other petroleum products are loaded into tank trucks, trailers, or tank cars at bulk installations and refineries by means of loading racks. Bulk products are also delivered into tankers at bulk marine terminals.

When a compartment of a tank vehicle or tanker is filled through an open overhead hatch or bottom connection, the incoming liquid displaces the vapors

in the compartment to the atmosphere. Except in rare instances, where a tank vehicle or tanker is free of hydrocarbon vapor, as when being used for the first time, the displaced vapors consist of a mixture of air and hydrocarbon concentration, depending upon the product being loaded, the temperature of the product and of the tank compartment, and the type of loading. Ordinarily, but not always, when gasoline is loaded, the hydrocarbon concentration of the vapors is from 30 to 50 percent by volume and consists of gasoline fractions ranging from propane through hexane.

The volume of vapors produced during the loading operation, as well as their composition, is greatly influenced by the type of loading or filling employed. The types in use throughout the industry may be classified under two general headings, overhead loading and bottom loading.

Overhead loading, presently the most widely used method, may be further divided into splash and submerged filling. In splash filling, the outlet of the delivery tube is above the liquid surface during all or most of the loading. In submerged filling the outlet of the delivery tube is extended to within 6 inches of the bottom and is submerged beneath the liquid during most of the loading. Splash filling generates more turbulence and therefore more hydrocarbon vapors.

Bottom loading has been introduced by a number of oil companies for new facilities. The equipment required is simpler than that used for overhead loading. Loading by this method is accomplished by connecting a swing-type loading arm or hose at ground level to a matching fitting on the underside of the tank vehicles. Aircraft-type, quick-coupling valves are used to ensure a fast, positive shutoff and prevent liquid spills. Several companies experienced in aircraft-fueling operations have developed fully automatic bottom-loading systems. All the loading is submerged and under a slight pressure; thus, turbulence and resultant

production of vapors are minimized.

Loading losses for splash filling typically range from 0.2 to 0.35 percent depending on loading rate, RVP and temperature of product, and degree of saturation of the displaced vapors. Loading losses for bottom loading and submerged filling are roughly equivalent with values ranging from 0.06 to 0.23 percent depending on conditions.

The method employed for loading marine tankers is essentially a bottom-loading operation. Liquid is delivered to the various compartments through lines that discharge at the bottom of each compartment. The vapors displaced during loading are vented through a manifold line to the top of the ship's mast for discharge to the atmosphere.

In addition to the emissions resulting from the displacement of hydrocarbon vapors from the tank vehicles, additional emissions during loading result from evaporation of spillage, drainage, and leakage of product.

An effective system for control of vapor emissions from loading must include a device to collect the vapors at the tank vehicle hatch and a means for disposal of these vapors.

Overhead Loading

Four types of vapor collectors have been developed for use during overhead loading operations. All are essentially plug-shaped devices that are inserted into a fitting for the hatch opening. Gasoline flows through a central channel in the device into the tank vehicle compartment. This central channel is surrounded by an annular space into which vapors enter through openings on the bottom of the hatch fitting. The annular space is in turn connected to a hose or pipe leading to a vapor disposal system.

The Mobil Oil Corporation device is connected to a vapor chamber with a transparent section to allow the operator to see the calibrated capacity markers

located within the tank compartment. This closure has adjustable height. It requires a constant downward force to keep it firmly in place during filling. It is built to fit only hatches 8 to 10 inches in diameter.

The Chiksan device incorporates the hatch closure, the vapor return line, and the fill line into an assembled unit. This unit has features to prevent overfills, topping off, or filling unless the assembly is properly seated in the tank hatch.

The Greenwood vapor closure developed by the Vernon Tool Company, also requires downward force during filling. It ordinarily does not have a transparent vapor chamber. This closure has an adapter for hatches larger than 10 inches.

The fourth device was developed by Standard Oil Company of California and has a positive clamp for the hatch opening, which, when closed automatically actuates the vapor chamber. It also has a safety shutoff float that senses the gas level and prevents overfilling. These SOCO devices can be used with adapters for hatches larger than 8 inches in diameter.

The slide positioner of the Mobil Oil Corporation device can be a source of vapor leaks and requires close attention by the operator during adjustments for fitting and submerged loading. The inner valves of the SOCO devices make them considerably heavier than other types. This device increases pressure drop and slows the loading rates. Mobil and Greenwood devices both require check valves in the vapor-gathering lines to prevent the vapor from discharging back to the atmosphere when the assembly is withdrawn. In addition, these devices require nearly vertical entry of the loading tube into the hatch opening in order to provide a tight seal against vapor leaks. An assembly is available to assure that the Greenwood device maintains this vertical position.

Bottom Loading

Bottom loading permits easier collection of displaced vapors. Because the filling line and the vapor collection line are independent of each other, collection during bottom loading is relatively easy. The vapor collection line consists of a flexible hose or swing-type arm connected to a quick-acting valve fitting on the dome of the vehicle. A check valve must, of course, be installed on the vapor collection line to prevent backflow of vapors to the atmosphere when the connection to the tank is broken.

In designing for complete vapor pickup at the tank vehicle hatch, several factors, including tank settling, liquid drainage, and topping off must be considered.

The settling of a tank vehicle due to the weight of product being added requires that provision be made for vertical travel of the loading arm to follow the motion of the vehicle so that the vapor collector remains sealed in the tank hatch during the entire loading cycle. Two solutions to the problem of settling have been used. The first, applicable to pneumatically-operated arms, includes the continuous application of air pressure to the piston in the air cylinder acting on the arm. The arm is thus forced to follow the motion of the vehicle without need for clamping or fastening the vapor collector to the tank vehicle. The second solution, employed on counterweighted and torsion spring loading arms, provides for locking the vapor collector to the tank vehicle hatch. The arm then necessarily follows the motion of the vehicle. The second solution is also applicable to vapor collection arms or hoses that are connected to the top of a tank vehicle during bottom loading.

The second problem, that of preventing considerable liquid drainage from a loading arm as it is withdrawn after completion of filling operations, has been adequately solved. The air valve that operates the air cylinder of pneumatically

operated loading arms may be modified by addition of an orifice on the discharge side of the valve. The orifice allows 30 to 45 seconds to elapse before the loading assembly clears the hatch compartment. This time interval is sufficient to permit complete draining of liquid into tank compartments from arms fitted with loading valves located in an outboard position. Loading arms with inboard valves require additional drainage time and present the problem of gasoline retention in the horizontal section of the arm. To prevent drainage the SOCO vapor collection closure is fitted with an internal shutoff valve that is closed before the loading arm is withdrawn from the tank hatch. Providing for thermal expansion has been found necessary when an inboard valve and a SOCO vapor closure are used. This has been accomplished by installing a small expansion chamber at the normal position of the loading arm's vacuum breaker. In bottom loading, the valve coupling at the end of the loading arm or hose, as well as the mating portion of the valve on the trucks, is self-sealing to prevent drainage of product when the connection is made or broken.

The third factor to be considered in the design of an effective vapor collection system is topping off. Topping off is the term applied to the loading operation during which the liquid level is adjusted to the capacity marker inside the tank vehicle compartment. Since the loading arm is out of the compartment hatch during the topping operation, vapor pickup by the collector is nil. Metering the desired volumes during loading is one solution to the problem. Metered loading must, however, be restricted to empty trucks or to trucks prechecked for loading volume available. Accuracy of certain totalizing meters or preset stop meters is satisfactory for loading without the need for subsequent open topping. An interlock device for the pneumatic-type loading arms, consisting of pneumatic control or mechanical linkage, prevents opening of the loading valve unless the air cylinder valve is in the down position. Thus, open topping is theoretically impossible.

Topping off is not a problem when bottom loading is employed. Metered loading, or installation of a sensing device in the vehicle compartments that actuates a shutoff valve located either on the truck or the loading island, eliminates the need for topping off.

Vapor Disposal

The methods of disposing of vapors collected during loading operations may be considered under three headings: using the vapors as fuel, processing the vapors for recovery of hydrocarbons, effecting a vapor balance system in conjunction with submerged loading, or simple incineration of generated vapors.

The first method of disposal, using the vapors directly as fuel, may be employed when the loading facilities are located in or near a facility that includes fired heaters or boilers. In a typical disposal system, the displaced vapors flow through a drip pot to a small vapor holder that is gas blanketed to prevent forming of explosive mixtures. The vapors are drawn from the holder by a compressor and are discharged to the fuel gas system.

The second method of disposal uses equipment designed to recover the hydrocarbon vapors. Vapors have been successfully absorbed in a liquid such as gasoline or kerosene. If the loading facility is located near a refinery or gas absorption plant, the vapor line can be connected from the loading facility to an existing vapor recovery system through a regulator valve.

Vapors are recovered from loading installations distant from existing processing facilities by use of package units. One such unit that absorbs hydrocarbon vapors in gasoline has been developed by the Superior Tank and Construction Company. This unit includes a vaporsphere or tank equipped with flexible membrane diaphragm, saturator, absorber, compressor, pumps, and instrumentation. Units are available to fit any size operation at any desired loading location since they use the gasoline product as the absorbent.

Explosive mixtures must be prevented from existing in this unit. This is accomplished by passing the vapors displaced at the loading rack through a saturator countercurrently to gasoline pumped from storage. The saturated vapors then flow to the vaporsphere. Position of the diaphragm in the vaporsphere automatically actuates a compressor that draws the vapors from the sphere and injects them at about 200 psig into the absorber. Countercurrent flow of stripped gasoline from the saturator or of fresh gasoline from storage is used to absorb the hydrocarbon vapors. Gasoline from the absorber bottoms is returned to storage while the tail gases, essentially air, are released to the atmosphere through a backpressure regulator. Some difficulty has been experienced with air entrained or dissolved in the sponge gasoline returning to storage. Any air released in the storage tank is discharged to the atmosphere saturated with hydrocarbon vapors. A considerable portion of the air can be removed by flashing the liquid gasoline from the absorber in one or more additional vessels operating at successively lower pressures.

Another type package unit is offered by Parker-Hannifin. This unit does not utilize a vaporsaver to level off the vapor flow rate to the compressor and, therefore, requires a larger compressor and higher power usage. The unit also incorporates a refrigeration unit in conjunction with the absorber. Costs of the two systems are comparable since the savings from eliminating the vaporsaver is offset by the cost of the larger compressor and refrigeration unit.

A third type of package unit adsorbs the hydrocarbon vapors on activated carbon. The application of this type of unit is presently restricted to loading installations that have low throughputs of gasoline, since the adsorbing capacity and the life of the carbon are limited. Units of this type find application in control of vapors resulting from fueling of jet aircraft.

The vapors displaced during bottom filling are minimal. Data indicate a volume displacement ratio of vapor to liquid of nearly 1:1. A closed system can

then be employed by returning all the displaced vapors to a storage tank. The storage tank should be connected to a vapor recovery system.

For medium-sized terminals loading less than about 1.8 million barrels per year of gasoline, extensive recovery facilities such as those described above cannot be economically justified and the preferred emission control method is incineration. For small facilities such as bulk plants which handle only several truck loads per day, even incineration cannot be justified and a requirement for emission controls would result in closing of the facility and reorganization of the gasoline distribution system.

OIL-WATER SEPARATORS

A typical waste-water gathering system for a modern refinery usually includes gathering lines, drain seals, junction boxes, and pipes of vitrified clay or concrete for transmitting waste water from processing units to large basins or ponds used as oil-water separators. These basins are sized to receive all effluent water, sometimes even rain runoff; they are constructed as earthen pits, concrete-lined basins, and steel tanks.

Liquid wastes discharging to these systems originate at a wide variety of sources such as pump glands, accumulators, spills, cleanouts, sampling lines, and relief valves.

Organic compounds can escape to the atmosphere from openings in the sewer system, channels, vessels, and oil-water separators. The large exposed surface area of these separators can result in large hydrocarbon emissions to the atmosphere.

The most effective means of control of hydrocarbon emissions from oil-water separators has been the covering of forebays or primary separator sections. Either fixed roofs or floating roofs are acceptable covers. Separation and skimming of over 80 percent of the floatable oil layer takes place in the covered sections. Thus, only a small amount of oil is contained in the effluent water,

which flows under concrete curtains to the open afterbays or secondary separator sections.

Satisfactory fixed roofs have been constructed by using wooden beams for structural support and asbestos paper as a cover. A mastic-type sealing compound is then used to seal all joints and cracks. Although this form of roof is acceptable for the control of pollutants, in practice a completely vaportight roof is difficult to achieve. The resultant leakage of air into the vapor space, and vapor leakage into the atmosphere are not desirable from standpoints of air pollution or safety.

The explosion hazard associated with fixed roofs is not present in a floating-roof installation. These roofs are similar to those developed for storage tanks. The floating covers are built to fit into bays with about 1 inch of clearance around the perimeter. Fabric or rubber may be used to seal the gap between the roof edge and the separator wall. The roofs are fitted with access manholes, skimmers, gage hatches, and supporting legs. In operation, skimmed oil flows through lines from the skimmers to a covered tank or sump and then is pumped to demulsifying processing facilities.

A simpler type of floating cover can be provided by Foamglas slabs which can be used to cover the primary section of the oil-water separator. This material has been used to cover the oil-water separators at Wood River where it is estimated that evaporation losses have been by 100 to 600 B/D depending on the season and slop oil composition. Estimated efficiency is 80 to 90 percent.

Any type of floating cover on an oil-water separator will interfere with skimming operations if the separator is equipped with flight skimmers. This problem can be overcome by increasing the weir level so that the flights are completely submerged. This will result in constant retention of a layer of oil several inches deep in the separator at all times.

The installed cost of Foam glas slabs is roughly $.50/ft.^{2} compared to $1.00-3.00/ft.^{2} for other types depending on the elaborateness of the cover.

In addition to covering the separator, open sewer lines that may carry volatile products can be converted to closed, underground lines with water-seal-type vents. Junction boxes can also be vented to vapor recovery facilities, and steam can be used to blanket the sewer lines to inhibit formation of explosive mixtures.

PUMPS

Pumps are used in every phase of the petroleum industry. Their applications range from the lifting of crude oil from the depths of a well to the dispensing of fuel to automobile engines. Leakage from pumps can cause air pollution wherever organic liquids are handled.

Pumps are available in a wide variety of models and sizes. Their capacities may range from several milliliters per hour, required for some laboratory pumps, to 3/4 million gallons per minute, required of each of the new pumps at Grand Coulee Dam.

Materials used for construction of pumps are also many and varied. All the common machinable metals and alloys, as well as plastics, rubber, and ceramics, are used. Pumps may be classified under two general headings, positive displacement and centrifugal.

Positive-displacement pumps have as their principle of operation the displacement of the liquid from the pump case by reciprocating action of a piston or diaphragm, or rotating action of a gear, cam, vane, or screw. The type of action may be used to classify positive-displacement pumps as reciprocating or rotary. When a positive-displacement pump is stopped, it serves as a check valve to prevent backflow.

Centrifugal pumps operate by the principle of converting velocity pressure generated by centrifugal force to static pressure. Velocity is imparted to the

fluid by an impeller that is rotated at high speeds. The fluid enters at the center of the impeller and is discharged from its periphery. Unlike positive-displacement pumps, when the centrifugal type of pump is stopped there is a tendency for the fluid to backflow.

Other specialized types of pumps are available, but, generally, the pumps used by the petroleum industry fall into the two categories discussed.

Power for driving the various types of pumps is usually derived from electric motors, internal combustion engines, or steam drives. Any one of these sources may be adapted for use with either reciprocating pumps or centrifugal pumps. Most rotary pumps are driven by electric motor.

Operation of various pumps in the handling of fluids in petroleum process units can result in the release of air contaminants. Volatile materials such as hydrocarbons, and odorous substances such as hydrogen sulfide or mercaptans are of particular concern because of the large volumes handled. Both reciprocating and centrifugal pumps can be sources of emissions.

The opening in the cylinder or fluid end through which the connecting rod actuates the piston is the major potenial source of contaminants from a reciprocating pump. In centrifugal pumps, normally the only potential source of leakage occurs where the drive shaft passes through the impeller casing.

Several means have been devised for sealing the annular clearance between pump shafts and fluid casings to retard leakage. For most refinery applications, packed seals and mechanical seals are widely used.

Packed seals can be used on both positive displacement and centrifugal type pumps. Typical packed seals consist of a stuffing box filled with sealing material that encases the moving shaft. The stuffing box is fitted with a takeup ring that is made to compress the packing and cause it to tighten around the shaft. Materials used for packing vary with the product temperature, physical and chemical properties, pressure, and pump type. Some commonly used materials are metal,

rubber, leather, wood, and plastics.

Lubrication of the contact surfaces of the packing and shaft is effected by a controlled amount of product leakage to the atmosphere. This feature makes packing seals undesirable in applications where the product can cause a pollution problem. The packing itself may also be saturated with some material such as graphite or oil that acts as a lubricant. In some cases cooling or quench water is used to cool the impeller shaft and the bearings.

The second commonly used means of sealing is the mechanical seal, which was developed over a period of years as a means of reducing leakage from pump glands. This type of seal can be used only in pumps that have a rotary shaft motion. A simple mechanical seal consists of two rings with wearing surfaces at right angles to the shaft. One ring is stationary while the other is attached to the shaft and rotates with it. A spring and the action of fluid pressure keep the two faces in contact. Lubrication of the wearing faces is effected by a thin film of the material being pumped. The wearing faces are precisely finished to ensure perfectly flat surfaces. Materials used in the manufacture of the sealing rings are many and varied. Choice of materials depends primarily upon properties of fluid being pumped, pressure, temperature, and speed of rotation. The vast majority of rotating faces in commercial use are made of carbon.

Emissions to the atmosphere from centrifugal pumps may be controlled in some cases by use of the described mechanical-type seals instead of packing glands. For cases not feasible to control with mechanical seals, specialized types of pumps, such as canned, diaphragm, or electromagnetic, are required.

The canned-type pump is totally enclosed, with its motor built as an integral part of the pump. Seals and attendant leakage are eliminated. The diaphragm pump is another type devoid of seals. A diaphragm is actuated hydraulically, mechanically, or pneumatically to effect a pumping action. The electromagnetic pumps use an electric current passed through the fluid, which is in the presence

of a strong magnetic field, to cause motion.

A pressure-seal-type application can reduce packing gland leakage. A liquid, less volatile or dangerous than the product being pumped, is introduced between two sets of packing. This sealing liquid must also be compatible with the product. Since this liquid is maintained at a higher pressure than the product, some of it passes by the packing into the product. The pressure differential prevents the product from leaking outward, and the sealing liquid provides the necessary lubricant for the packing gland. Some of the sealing liquid passes the outer packing (hence the necessity of low volatility), and a means should be provided for its disposal.

This application is also adaptable to pumps with mechanical seals. A dual set of mechanical seals similar to the two sets of packing is used.

Volatile vapors that leak past a main seal may be vented to vapor recovery by using dual seals and a shaft housing.

Other than the direct methods used to control leakage, operational changes may minimize release of contaminants to the atmosphere. One desireable change is to bleed off pump casings during shutdown to the fuel gas system, vapor recovery facilities, or a flare instead of directly to the atmosphere.

VALVES

Valves are employed in every phase of the petroleum industry where petroleum or petroleum product is transferred by piping from one point to another. There is a great variety of valve designs, but, generally, valves may be classified by their application as flow control or pressure relief.

Manual and automatic flow control valves are used to regulate the flow of fluids through a system. Included under this classification are the gate, globe, angle, plug, and other common types of valves. These valves are subject to product leakage from the valve stem as a result of the action of vibration, heat, pressure, corrosion, or improper maintenance of valve stem packing.

Pressure relief and safety valves are used to prevent excessive pressures from developing in process vessels and lines. The relief valve designates liquid flow while the safety valve designates vapor or gas flow. These valves may develop leaks because of the corrosive action of the product or because of failure of the valve to reseat properly after blowoff. Rupture discs are sometimes used in place of pressure reflief valves. Their use is restricted to equipment in batch-type processes. The maintenance and operational difficulties caused by the inaccessibility of many pressure relief valves may allow leakage to become substantial.

Obviously, the controlling factor in preventing leakage from valves is maintenance. An effective schedule of inspection and preventive maintenance can keep leakage at a minimum. Minor leaks that might not be detected by casual observation can be located and eliminated by thorough periodic inspections. New blind designs are being incorporated in refinery pipeline systems in conjunction with flow valves. This is done to ensure against normal leakage that can occur through a closed valve.

Emissions from pressure relief valves are sometimes controlled by manifolding to a vapor control device. Normally, these disposal systems are not designed exclusively to collect vapors from relief valves. The primary function of the system may be to collect off gases produced by a process unit, or vapors released from storage facilities, or those released by depressurizing equipment during shutdowns.

Another method of control to prevent excessive emissions from relief valve leakage is the use of a dual valve with a shutoff interlock. A means of removing and repairing a detected leaking valve without waiting until the equipment can be taken out of service is thus provided. The practice of allowing a valve with a minor leak to continue in service without correction until the operating unit

is shut down for general inspection is common in mny refineries. This practice should be kept at a minimum.

A rupture disc is sometimes used to protect against relief valve leakage caused by excessive corrosion. The disc is installed on the pressure side of the relief valve. The space between the rupture disc and relief valve seat should be protected from pinhole leaks that could occur in the rupture disc. Otherwise, an incorrect pressure differential could keep the rupture disc from breaking at its specified pressure. This, in turn, could keep the relief valve from opening, and excessive pressures could occur in the operating equipment.

One method of ensuring against these small leaks in rupture discs is to install a pressure gage and a small manually operated purge valve in the system. The pressure gage would easily detect any pressure increases from even small leaks. In the event of leaks, the vessel would be removed from service, and the faulty rupture disc would then be replaced. A second, but less satisfactory method from an air pollution control standpoint, is to maintain the space at atmospheric pressure by installing a small vent opening. Any minute leaks would then be vented directly to the atmosphere, and a pressure increase could not exist.

TABLE I

SUMMARY OF HYDROCARBON EMISSIONS (1968)

Source		Percent of Total
Transportation		51.9
Motor Vehicles	48.7	
Aircraft	1.0	
Railroads	1.0	
Vessels	0.2	
Other	1.0	
Fuel Combustion		2.2
Industrial Processes		14.4
Solid Waste Disposal		5.0
Miscellaneous		26.5
Forest Fires	6.9	
Organic Solvent	9.7	
Gasoline Marketing	3.8	
Agricultural Burning	5.3	
Other	0.8	
		100.0

Total Emissions - 32.0×10^6 Tons/Year

TABLE II

INSTALLED COSTS OF STORAGE TANKS (1972)

Type	Cost ($/B)		
	20,000 B	40,000 B	80,000 B
Cone Roof	2.20	1.85	1.60
Floating Roof			
a) Pontoon-Type	2.90	2.20	1.75
b) Double-Deck	3.20	2.80	1.90
Hemispheroids (2.5 psi)	4.00	2.90	-
Spheroids (5 psi)	5.60	4.00	-
(15 psi)	6.40	4.90	-
Spheres (30 psi)	7.20	6.00	-
(50 psi)	10.40	8.30	-

EVAPORATION LOSS IN THE PETROLEUM INDUSTRY—CAUSES AND CONTROL

CHAPTER 1—SOURCES OF EVAPORATION LOSS

Evaporation loss is the natural process whereby a liquid is converted to a vapor which subsequently is lost to the atmosphere. The liquid may be unconfined or may be enclosed in a container such as an oil-storage tank. By definition, evaporation loss occurs only when the vapors reach the atmosphere.

Evaporation loss is common to all branches of the petroleum industry. Because tanks are used similarly throughout the industry, sources of loss from tanks are discussed first. Other sources of evaporation loss associated with operational features of each branch are then considered. To further emphasize true sources of loss, conditions which can falsely indicate loss are also discussed.

A. Loss in Storage

Six kinds of evaporation loss occur from petroleum in storage: breathing loss, standing-storage loss, filing loss, emptying loss, wetting loss, and boiling loss.

Breathing Loss: Vapors expelled from a tank because of the thermal expansion of existing vapors, and/or expansion caused by barometric pressure changes, and/or an increase in the amount of vapor from added vaporization in the absence of liquid-level change, except that which results from boiling, is defined as breathing loss. The term *vapor* is used herein to denote any mixture of hydrocarbon vapor and air. The term *hydrocarbon* vapor refers to hydrocarbons in the gaseous state independent of the presence or absence of air.

Breathing loss takes place in most types of tanks and occurs when limits of pressure or volume change are exceeded. Fixed-roof tanks, herein denoting ordinary storage tanks designed for only a few inches of water pressure or vacuum, suffer relatively large breathing losses. Tanks protected from a loss or gain in heat by reflective coatings, burying, insulation, or shading experience less breathing loss. Pressure tanks which operate at 2½ psig or higher, normally experience relatively little or no breathing loss. Variable-vapor-space-tank systems also normally experience little or no breathing loss. Floating-roof tanks almost eliminate vapor spaces, and little or no breathing loss occurs past the seals.

Standing-Storage Loss: Vapor from tanks, which results from causes other than breathing or change in liquid level, is defined as standing-storage loss. For floating-roof tanks, the largest potential source of standing-storage loss is attributed to an improper fit of the seal and shoe to the shell. This condition exposes some liquid surface to the atmosphere; wind affects this source of loss. Also, a small amount of vapor may permeate through the flexible membrane that seals the space between the shoes and the roof. The permeation of flexible membranes, or absorption in liquid seals, may also be a source of loss from variable-vapor-space tanks. Other sources of standing-storage loss are vapor escape from open hatches or other openings, glands, valves, and fittings.

Filling Loss: Vapors expelled from a tank as a result of filling, irrespective of the exact mechanism by which the vapors are produced, is defined as filling loss. This loss is common to all types of tanks except the floating-roof tank and closed-system pressure storage, such as for liquefied petroleum gas (LPG). It occurs when the pressure inside the tank exceeds the relief pressure. For fixed-roof tanks, the relief pressure is low, therefore the filling loss is relatively high. Filling loss from pressure and variable-vapor-space tanks is somewhat less because these tanks have added vapor-storage-capacity. The pressure tank also promotes condensation of hydrocarbon vapors during filling.

Emptying Loss: Vapors expelled from a tank after the liquid is removed is defined as emptying loss. Because vaporization lags behind the expansion of the vapor space during such withdrawal, the partial pressure of the hydrocarbon vapor drops. Enough air enters during the withdrawal to maintain total pressure at atmospheric pressure. When vaporization into the new air reaches equilibrium, the vapor volume exceeds the capacity of the vapor space. This increase in vapor volume causes the expulsion.

Emptying loss is common to all types of tanks except the floating-roof tank and closed-system pressure storage. Fixed-roof tanks are most vulnerable to this loss. Pressure tanks and variable-vapor-space tanks are less subject to this loss but will encounter it if the vapor-storage capacity is exceeded.

In the loading of transportation vessels the definition of emptying loss is restricted: The transporter considers emptying loss to be only that portion which evaporates into the vapor space of the tank during the actual withdrawal, that is, between the opening and closing of the gages.

Wetting Loss: Vaporization of liquid from a wetted-tank wall, exposed when a floating roof is lowered by withdrawal of liquid, is defined as wetting loss. This source of evaporation loss is small.

Boiling Loss: Vapors expelled from a tank as a result of boiling of the liquid is arbitrarily defined as boiling loss. Boiling loss may occur from any tank. The fixed-roof tank is more subject to this loss than the pressure tank. The earliest floating-roof tank, the pan type, is especially vulnerable to boiling loss because heat is readily conducted through the roof directly to the liquid and no vapor-storage capacity exists under the deck.

B. Loss in Production

Production entails three operations which contribute to evaporation loss: gas-oil separation, emulsion treating, and lease-tank operation.

In gas-oil separation, the oil may be rich in light components, which later are lost from the usual fixed-roof lease tank. In a recovery system, butanes and pentanes may not be completely extracted from the gas and may be lost. A true evaporation loss occurs when the gas is flared or vented. In addition to the loss in crude-oil volume, the API gravity is decreased.

In emulsion treating, heat is applied and released vapors may be vented. Also, the crude oil reaching the lease tank at elevated temperature contributes to the evaporation loss.

At the lease tank, splashing may occur as oil is introduced; in such cases vaporization and evaporation loss are accelerated. Dark-colored tanks contribute further to evaporation loss.

C. Loss in Refining

Refining involves three operations which are sources of evaporation loss: treating and blending in freely vented vessels, such as an agitator; pressure systems which may leak; and sewers, ponds, and open separators.

Use of air and agitation can result in high-evaporation loss from vessels which are not part of a closed system. Sweetening naphtha in agitators and blending volatile components in a semiopen vessel are potential examples of this source of evaporation loss.

Pressure systems, common to refineries and natural-gasoline extraction plants, may have sources of evaporation loss from leaking exchangers, glands, valves, and fittings. Hydrocarbon vapor may leak directly to the atmosphere. Also, liquid may leak and evaporate rapidly if volatile at the operating temperature. Besides outward leaks, inward leaks of air, such as at pump suctions, are sources of loss because this air becomes at least partially saturated before venting.

Sewers, ponds, and open separators are sources of evaporation loss if volatile liquids are permitted to reach them. Such liquids usually encounter high turbulence in sewers and collect in thin layers offering large exposures for evaporation. The recovered skimmings from ponds and separators require demulsification involving heat and constitute another source of loss from the recovery equipment.

D. Loss in Transportation and Marketing

Transportation includes pipeline shipments and the loading, transit, and unloading of transport vessels from which evaporation loss can occur. Pipelines are subject to loss from air eliminators used in metering systems and from leaking glands, valves and fittings, and corroded pipes.

Filling and emptying losses occur from nonpressure tankers, barges, tank cars, and trucks in much the same manner as from tanks. If tank cars and trucks are top-loaded with a short filling pipe, the undue splashing not only accelerates vaporization but also produces small droplets which may be lost by entrainment. Air inspired during loading can be an added source of evaporation loss because such air becomes at least partially saturated with hydrocarbons before it is vented; loosely connected, submerged loading spouts are sources of such inspiration.

In-transit losses from transport vessels are essentially breathing losses. Excessive heating of crude oil in marine vessels is a potential source of evaporation loss during transit.

Marketing operations entail many of the previously discussed sources of loss, particularly those discussed in Par. A, "Loss in Storage."

E. False Indications of Loss

Under certain conditions a loss appears to have occurred which actually did not. Being aware of these conditions and being able to distinguish between an "actual" and a "false" loss is important, otherwise corrective efforts may be directed toward conditions where no real improvement can result. Conversely, these conditions may balance out and cover up an actual loss, with the result that necessary corrective action is overlooked. Five such conditions are: inaccurate measurement, gravitation between tanks, inaccurate volume of supply lines, inaccurate calibration of meters, and physical changes in volume.

Inaccurate Measurement: Apparent gains or losses can result from inaccurate measurement, either of average liquid temperature, height of liquid, or incorrect calibration of containers. Other sources of error would be the failure to correct all volumes to a common temperature base by use of the unabridged Table 6, "Reduction of Volume to 60 F Against API Gravity at 60 F," of the *ASTM-IP Petroleum Measurement Tables* (1953).

Gravitation Between Tanks: Any leakage past a valve believed to close a line between two tanks results in gravitation—a loss of product in one tank results in a gain in the other tank which may not be observed.

Inaccurate Volume of Supply Lines: If the volumes of the supply lines are not known accurately, or if lines

are not in the full or empty condition which is assumed, unrealistic losses or gains may be indicated.

Inaccurate Calibration of Meters: The inaccurate calibration of meters can result in apparent losses, which may be attributed incorrectly to evaporation—or in apparent gains which may conceal actual evaporation losses.

Physical Changes in Volume: Certain processing operations, such as cracking, polymerization, and the blending and separation of light and heavy stocks, result in physical changes in volume even when full correction is made for changes in temperature. For example, in a cracking process, where small molecules are produced from large ones, the products will occupy a greater volume than the charge. In a polymerization process, where large molecules are produced from small ones, the product volume shrinks. With such volume changes API gravity always changes but the total weight, before and after the volume change, is the same.

CHAPTER 2—FACTORS AFFECTING EVAPORATION LOSS FROM TANKS

The total amount of evaporation loss depends upon the rate of loss and the period of time involved. Primary factors affecting the rate of loss are: true vapor pressure of the liquid, temperature changes in the tank, tank outage, tank diameter, schedule of tank fillings and emptyings, tank condition, and type of tank. Saturation and diffusion effects are only a part of the mechanism of the loss and are classed as dependent, or secondary, variables. Although quantitative-loss relationships for the primary factors are not yet available, a fair understanding based on theory and practice can be gained by considering the mechanism of loss from fixed-roof tanks. With such understanding, the advantages of floating-roof, variable-vapor-space, and pressure-tank systems will readily be apparent.

A. True Vapor Pressure of the Liquid

True vapor pressure affects the rate of loss because it is the basic force causing vaporization. It varies with liquid composition and temperature. True vapor pressure at storage temperature is all important. For hydrocarbon mixtures, this pressure decreases with evaporation because of the change in liquid composition. True vapor pressure usually is determined from correlations relating it to Reid vapor pressure (RVP). Such relationships are illustrated in nomograph form in Appendix V.

The effect of true vapor pressure on rate of breathing loss from a fixed-roof tank involves at least two internal considerations—the saturation concentration and the diffusion and convection factor. The maximum concentration of hydrocarbons which can be present in expelled vapor, known as the saturation concentration, increases in direct proportion to true vapor pressure. It follows that if vented vapors were fully saturated, evaporation loss would increase rapidly as true vapor pressure approaches the tank relieving pressure (a boiling condition). However, another mechanism—the diffusion and convection of hydrocarbon vapor from the liquid surface through the vapor space is too slow to fully saturate it. Experience shows that vapors vented during normal breathing are usually only 80 per cent to 90 per cent saturated. Thus, the driving force to overcome resistance to diffusion factors and convection through the vapor space is one of the controlling factors. Such driving force can be looked upon as being the true vapor pressure of the liquid minus the partial pressure of hydrocarbons in the vapor space. As true vapor pressure rises, this driving force would rise in direct proportion if percentage saturation in the vapor space remains constant. Thus, both the saturation consideration and the diffusion and convection consideration suggest that actual loss is at least directly proportional to rising true vapor pressure.

Filling or emptying losses from fixed-roof tanks are directly proportional to increasing true vapor pressure because of the relationship between true vapor pressure and saturation concentration.

This concept does not apply when true vapor pressure exceeds the absolute tank pressure because boiling occurs and losses may be large. Then, the main controlling factor is heat input.

In terms of total loss over a period of time, the effect of true vapor pressure depends upon the composition of the stock. For example, two crude oils of identical true vapor pressure may weather at different rates. One crude oil may contain a relatively high per cent of volatile propane and ethane; for a specific starting loss rate, the vapor pressure will drop rapidly and the loss rate will drop shortly thereafter. The other crude oil may derive vapor pressure from relatively high concentrations of less-volatile pentanes and butanes; for the same starting loss rate, the vapor pressure will drop less rapidly but the loss rate will remain higher for a longer period. This consideration is particularly significant for newly produced crude oils at leases and pipeline storage terminals where true vapor pressures may be close to atmospheric pressure.

B. Temperature Changes in the Tank

Internal temperature changes, brought about by atmospheric and solar heat, tend to cause the tank vapor space to breathe. During the day, heat flowing through the roof and upper walls raises the vapor temperature and expands the volume. The pure thermal effect is augmented by vaporization of hydrocarbons from the tank contents during the same period. The heat input also may increase the liquid-surface temperature and accelerate vaporization. At night, reverse processes shrink the vapor and cause an intake of air.

Atmospheric and solar heat also cause forced convection in the vapor space which promotes evaporation from the liquid surface and aids in the dispersion of the hydrocarbon vapor.

Although efforts have been made to develop more precise criteria, the average daily change in atmospheric temperature is still the only accepted way to characterize atmospheric and solar-heat effects. Monthly meteorological data for various locations in the United States and Canada are presented in Appendix VI.

Theoretical considerations do not permit good estimation of how much loss will increase with increasing atmospheric temperature change; however, it prob-

ably will be somewhat less than directly proportional to the increase in atmospheric temperature change.

C. Tank Outage

The volume of most vapor spaces is directly proportional to outage—the height of the vapor space. For a fixed-roof tank, higher outage means greater loss because the larger volume will breathe more. However, when outage is increased heat input is not increased in direct proportion. Heat enters the vapor space through the tank wall, the area of which increases in direct proportion, and through the tank roof, the area of which remains unchanged. Furthermore, with added height of vapor space, resistance to transfer of hydrocarbon vapors from the liquid surface to the vent increases. Therefore, the average concentration of hydrocarbons in vented vapor should fall. Experience has confirmed that loss will increase less than directly proportional to increasing outage.

D. Tank Diameter

Tank diameter influences the volume of the vapor space and the liquid-surface conditions. Breathing is less than directly proportional to increase in vapor volume because of the less than proportional increase in area for heat transfer into the vapor space. Furthermore, increasing diameter should reduce the temperature rise of the liquid surface because the rising hot stock, in contact with the tank wall, must spread in a thinner film over the surface area. Assuming constant tank height, total breathing loss, therefore, increases at a rate less than directly proportional to tank volume.

E. Schedule of Tank Fillings and Emptyings

Over a period of time, the frequency of stock turnover and the average outage affect total loss. Operations that promote high outages may result in relatively high breathing losses. Fillings and emptyings scheduled to compensate the daily temperature changes may reduce breathing loss. The time interval between emptying and filling may have a significant effect on loss. For a system of tanks connected with vapor lines, simultaneously filling one tank while emptying another maintains the vapor-storage capacity relatively constant and filling loss is reduced.

F. Tank Condition

Tank condition is another factor affecting loss rate; however, quantitative effects cannot be predicted. Open vents result in high loss when gusty or turbulent winds cause rapid pressure changes in tanks in which volatile liquids are stored. Rapid breathing occurs as short puffs. Any hole in a tank roof, diaphragm, seal, or accessory results in the same type of loss.

Where there are two or more openings in the tank, loss is further increased. Pressure differences, which result from wind or thermal effects, cause a constant flow of air through some openings into the vapor space and an outflow of vapor through other openings.

G. Type of Tank

The type of tank or storage system will affect the evaporation loss experienced. The amount of loss depends upon the volume of the vapor space available and the pressure limitations of the equipment.

If tanks have their vapor spaces interconnected, vapor-space volume can be controlled to a limited extent by scheduling fillings and emptyings, where feasible.

If the vapor space is allowed to change volume at constant pressure, breathing loss can be practically eliminated and filling loss can be reduced. The extent of the reduction in loss is dependent upon the amount of variable vapor space provided.

CHAPTER 3—TANKS AND EQUIPMENT TO CONTROL EVAPORATION LOSS

The industry may choose from four basic types of tanks for storage of petroleum and its products: fixed-roof tanks, floating-roof tanks, variable-vapor-space tanks, and pressure tanks. Each type is designed for specific storage requirements, the actual storage problem should determine the type selected. In many instances, the most economical tank can be selected only after a detailed study comparing loss from, and the cost of different tanks. For stocks having a low true vapor pressure, less than 2 psia, the fixed-roof tank generally will be the most economical selection. For stocks of motor-gasoline range of volatility at high throughputs, the floating-roof tank generally will be the best choice, but at lower throughputs the variable-vapor-space tank generally will be better. For stocks which boil at atmospheric pressure and storage temperature, pressure tanks are best generally; however, in some cases use of the fixed-roof tanks in conjunction with a vapor-recovery system may offer more advantages.

The tendency to boil in storage is a function of vapor pressure, altitude, barometric pressure, and liquid-surface temperature. Maximum liquid-surface temperatures vary throughout the United States. For the indicated temperatures, the maximum Reid vapor pressures (RVP) of stocks which can be stored at atmospheric pressure without general boiling (but at the expense of high-loss rates) are:

Area	Maximum Liquid-Surface Temperature * (Degrees Fahrenheit)	Maximum Reid Vapor Pressure * (Pounds)
West Coast (tempered by Pacific Ocean)	80	18
	90	15.5
Gulf Coast, Atlantic Seaboard, and northern Middle West	100	13.5
	110	11.5
Mid-Continent area and arid Southwest	115	11
	120	10

* The limits must be reduced for locations at higher altitudes to account for lower barometric pressure.

Effective loss-control operation of each tank is dependent upon certain accessory items, such as breather valves and automatic gages. Continued effective operation is dependent upon a program to maintain the tank and accessories in a gastight condition.

Choice of paint color may be an important factor in reducing loss. In special instances, loss may be reduced by use of a floating plastic blanket; or, by employing insulation, a shading device, water sprays, mechanical cooling, or by burying the tank. In some cases, it may be possible to reduce loss further by specially scheduling fillings and emptyings.

A. Fixed-Roof Tanks

The minimum accepted standard for storage of volatile oils is the fixed-roof tank. It can sustain an internal pressure, or vacuum, of only an ounce or two per square inch. Being susceptible to sizable breathing and filling losses, this type of tank is used most frequently for services which cannot economically justify a conservation tank.

Design of Tank: The fixed-roof tank, the predecessor of conservation tanks, came into being during the early days of the petroleum industry. Wooden barrels were used at first, but they could not keep up with the rising flood of oil that poured from the Pennsylvania wells. As production increased, open pits and diked areas were used, but they were hazardous. Wooden tanks, caulked with oakum and held together with iron hoops, first appeared in 1861. The capacity of these tanks ranged between 500 bbl and 1,000 bbl.

The first iron tank with a wooden, gravelled roof appeared in 1864; it provided larger and safer storage. Shortly after the Civil War, bolted- and riveted-steel tanks came into use. They ranged in size up to 35,000 bbl. After 1915 capacities were increased and in 1919 the first 80,000-bbl tank was erected. The introduction of electric welding, in 1923, made possible the fabrication of welded roofs and bottoms. The welded tank was introduced in 1927.

Fixed-roof tanks built today usually are welded throughout, but many riveted tanks are still used and bolted tanks are common in the smaller sizes. Whereas the seams of welded tanks are almost inherently gastight, the seams of bolted and riveted tanks frequently require additional maintenance. In some areas, particularly on leases where corrosion is a problem, wooden roofs, which are seldom of gastight construction, are still in use. Loss from these tanks is much greater than from steel-roof tanks.

If a fixed-roof tank is found to be the best type for a particular storage problem, careful consideration should be given to the size before the final selection is made. Because the loss rate increases significantly with outage and tank diameter, the use of the smallest tank possible for the given storage requirement results in a minimum loss. For further insight as to the outage and diameter effects, refer to Chapter 2, "Factors Affecting Evaporation Loss from Tanks."

Maintenance of Tank: To maintain a gastight condition, tanks should be inspected at regular intervals and repaired as necessary. The frequency of inspections usually is determined by experience. Riveted-roof tanks, because of their greater tendency to develop leaks, should be inspected more frequently than welded-roof tanks.

When the tank is under pressure, five ways in which leaks may be detected are:

1. Observation of heat-wave-like trails of the escaping vapors.
2. Hearing the hiss of escaping vapors.
3. Smelling the vapors.
4. Use of gas testers or "sniffers."
5. Applying soap solution or linseed oil to seams.

Also, stains on the painted surfaces frequently indicate leaks.

Design of Accessory Equipment: The fixed-roof tank has several openings in roof for venting, gaging, and sampling. To maintain a gastight roof, accessory equipment of a gastight design must be provided for these openings.

The accessory for the vent opening is called a breather valve, pressure-vacuum relief valve, or conservation vent. When operating properly, this device prevents either the inflow of air or the escape of vapors until some preset vacuum or pressure is developed. Most breather valves, especially the metal-to-metal types, allow some leakage below the pressure or vacuum setting. A tight breather valve is important in reducing evaporation loss. The actual magnitude of the savings will depend upon such factors as vapor pressure of stock stored, weather conditions, paint color, and allowable working-pressure range. However, the savings realized usually will pay for the installation. The breather valve also contributes to safe operation by keeping the tank vent closed to the atmosphere most of the time.

The pressure and vacuum settings of a breather valve are dictated by the structural characteristics of the tank and should be within safe operating limits. A certain amount of pressure and vacuum beyond these settings is necessary to overcome pressure drop in order to obtain required flow. Proper size and settings can best be determined by reference to *API Std 2000: Venting Atmospheric and Low-Pressure Storage Tanks* (1968) and to the manufacturer's tank data determined in accordance with this publication. The pressure setting for vent valves to be installed on large tanks constructed in accordance with *API 12D: Specification for Large Welded Production Tanks* (1957) usually is limited to ½ oz because roof plates will start to shift when the pressure rises much above 1 oz. For small tanks, and all tanks having special structural features, the pressure range can be increased in accordance with the manufacturer's recommendations.

Breather valves should be designed to give:

1. High-flow capacity at relatively small pressure or vacuum above the setting.
2. A gastight seal.
3. Freedom from sticking or freezing.
4. Easy access to all parts for inspection and maintenance.

Diaphragm and liquid-seal valves have less leakage than metal-to-metal types. For dependable service, diaphragms should be resistant to tank vapors.

Open vents of the mushroom or return-bend type should not be used on fixed-roof tanks storing volatile oils as they permit high loss. These vents are merely hooded openings equipped with protective screens. The opening is turned down to prevent any blockage by ice or snow.

Venting accessories sometimes used are: flame arrestors, flame snuffers, and flash screens. They usually have little effect on vapor loss except when they are installed between the tank and vent valve and must be removed for cleaning.

Some vapor loss is inherent in manual gaging and sampling methods which necessitate opening a tank to the atmosphere each time these operations are performed. This loss can be minimized through the use of automatic gaging equipment, double-closure gaging locks, and a system of thermometers and sample valves in the tank shell.

Accessories which help to reduce evaporation loss from lease tanks include:

1. Pressure-vacuum thief hatch and vent-line valve.
2. Automatic-closing valve in the equalizer line which closes when the gage hatch is opened.
3. A diagonal-slotted downcomer type of fill line to minimize free fall and splashing.

Maintenance of Accessory Equipment: To maintain accessories in a gastight condition they should be inspected and restored periodically. Pallets of the metal-to-metal breather valves which become warped in service must be machined to restore a gastight fit. Defective diaphragms of diaphragm breather valves should be replaced.

Liquid-seal breather valves may be affected by dilution or loss of liquid and may have to be inspected and maintained more frequently as determined by experience. A loose fitting gage-hatch lid can be made nearly gastight by replacing the gasket or by machining the seating surface.

Flame arrestors and flash screens can become clogged with dust, rust, and ice. Such obstructions in the venting system can cause severe damage to the tank from excessive internal pressure or vacuum. These accessories should be inspected and cleaned frequently.

Choice of Paint: Tank painting is important in reducing evaporation loss as well as in preserving the tank. An adequate paint program, using reflective paints, will minimize the heat input to the tank by reducing the metal temperature of the tank.

White paint is a simple and effective means for reducing evaporation loss. The additional low cost of maintaining a clean white surface on a tank frequently has an attractive economic return. Recent data indicate that painting the tank roof and shell white, rather than

gray, reduces the evaporation-loss rate by at least 20 per cent.

Use of Insulation: Insulation on the roof and shell of a storage tank tends to reduce heat input and heat loss; this tendency toward constant temperature reduces breathing loss. However, when stock at higher than normal storage temperature is added to an insulated tank, the average tank temperature increases, which in turn increases true vapor pressure and promotes a higher concentration of hydrocarbons in the vapor space. This condition may increase filling loss somewhat and breathing loss to a lesser degree. Insulation usually is expensive to install and may involve considerable maintenance. Unless moisture is prevented from entering the insulation, loss of insulation effect as well as corrosion of the tank shell may result.

Use of Shade: Shading of a storage tank from direct sunlight reduces heat input, but generally does not reduce normal heat loss. Hence, compared to a bare tank, shading provides less variation in internal temperature and, usually, results in a lower average stock temperature. Although the installation of shades generally has not been considered economical, usually the maintenance is not an expensive factor.

Use of Flexible Blanket on Liquid Surface: Evaporation loss in fixed-roof tanks can be reduced with the use of flexible blankets which float directly on the liquid surface. The blanket acts in the same manner as a floating roof. There are two types of flexible blankets: one is a foam blanket made up of plastic spheres; the other is a blanket or raft made from plastic sheeting. The latter type has not been tested extensively in this country.

The floating plastic-foam blanket consists of microscopically small, hollow, plastic, gas-filled spheres. This material has been used extensively on fixed-roof storage tanks in crude-oil service. Tests made in this country and Canada have indicated that under favorable conditions evaporation loss on crude oil can be reduced from 50 per cent to 70 per cent in working tanks and from 70 per cent to 90 per cent in static tanks. A ½-in. thickness usually is used on static tanks. A 1-in. thickness is used on working tanks to avoid breaking up the complete foam layer during filling and emptying. Gaging difficulties with the plastic foam have been minimized by the use of a portable type of gage well carried on a gage tape.

Loss of the plastic spheres can occur if tanks are pumped to low levels at high pumpout rates. The operation of mixers must be controlled to prevent the plastic spheres from being dispersed in the oil and then pumped out during emptyings.

Not enough information is available to estimate accurately the service life of the spheres. However, reports received indicate that the material has operated satisfactorily for two and one half years. The spheres should not be installed in tanks containing liquids subject to boiling; water also may damage the plastic spheres, especially, if agitation promotes contact of moisture with the spheres.

B. Floating-Roof Tanks

The floating-roof tank is an effective conservation device for stocks of motor-gasoline volatility. The basic design virtually eliminates the vapor space, which results in low losses both from breathing and filling. The exceptionally low losses from filling brought this tank into widespread use. Other advantages of this tank are excellent fire protection and corrosion resistance. Ignition may occur only in the seal area; being confined to this localized area, the fire normally is easy to extinguish. However, should the stock boil, the fire may be difficult to extinguish. Excellent protection from sour or corrosive stocks is afforded by floating roofs which are in contact with the entire liquid surface.

Design of Tank: There are three basic designs of floating-roof tanks in operation: the pan type, pontoon type, and double-deck type.

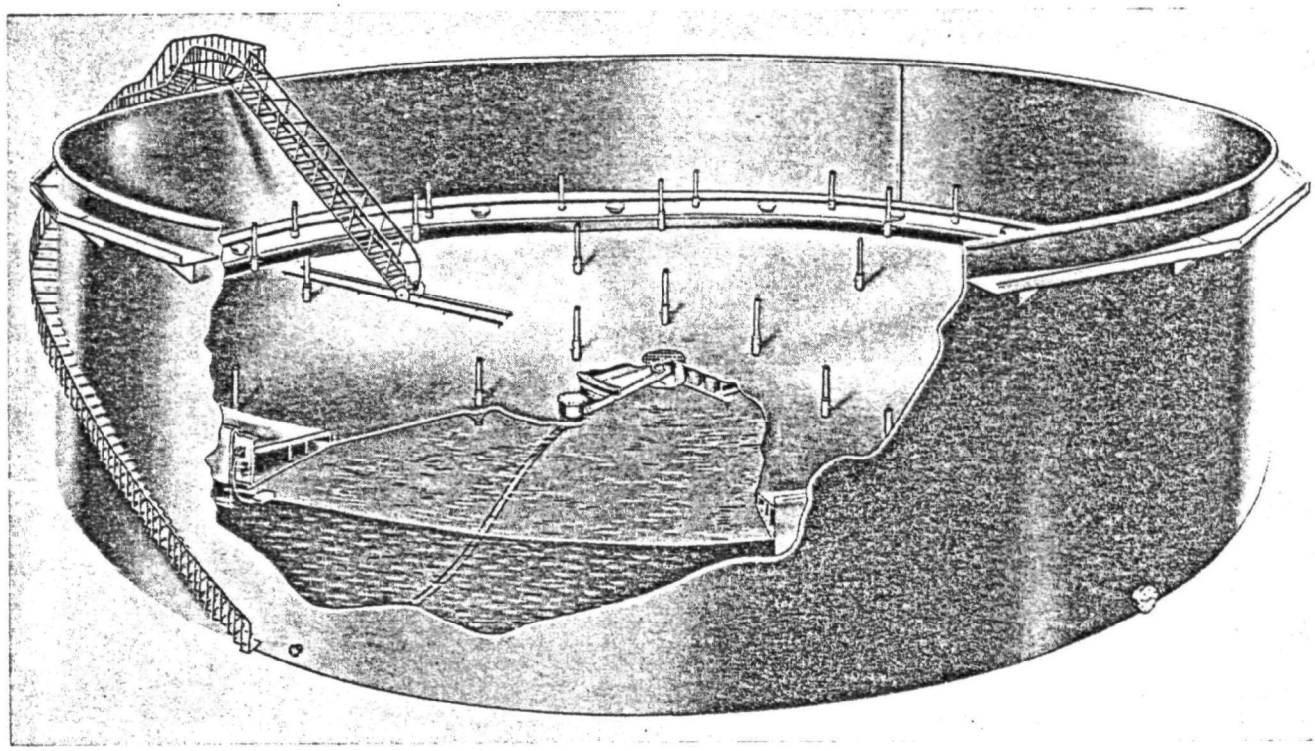
The first successful floating-roof tank, the pan type, was built in Cushing, Oklahoma, in 1922. A typical example of a pan-type floating roof in operation today is shown in Fig. 1. A single deck covers most of the liquid surface and a seal is attached to the rim of this deck. The deck slopes to the center for drainage.

This roof has three disadvantages which account for its limited use. The single deck is exposed to the sun during the middle of the day. Because the deck is held forcibly in contact with the liquid, heat is transferred directly to the liquid surface. The liquid-surface temperature rises appreciably. Sometimes the product boils and losses of gasoline and similar stocks may result. The pan roof also may tip and sink under heavy loads of water or snow, or from leaks which may develop in the deck.

The pontoon roof was developed in 1928 by adding pontoons to the pan-type roof to give it greater stability and bouyancy. Thus, the pontoon roof has a single deck over only a part of the total area, closed pontoons cover the remaining area. Pontoon-type roofs are illustrated in Fig. 2 and Fig. 3. The pontoons are arranged and compartmented to provide floating stability under heavy loads of water or snow. Enough bouyancy normally is provided so that the roof will not sink when the single-deck area leaks or the drain fails. Properly compartmented, the pontoons can be partially flooded without endangering the roof structurally.

A pontoon roof having a single deck, which can rise above the liquid surface when boiling starts, provides an insulating vapor space and reduces the heat transfer from the sun to the liquid surface. Boiling losses usually will not occur with stocks in the motor-gasoline range of volatility.

In the mid 1940's the double-deck roof was offered, which in effect made the entire roof a series of pontoons, see Fig. 4. Circular and radial bulkheads divide



Courtesy: Graver Tank and Manufacturing Company, Inc.

FIG. 3—Pontoon-Type Floating Roof.

the space between the two decks into compartments; this design can give good stability and load-carrying capacity and provides an insulating air space over the entire area. Boiling losses usually will not occur with stocks in the motor-gasoline range of volatility.

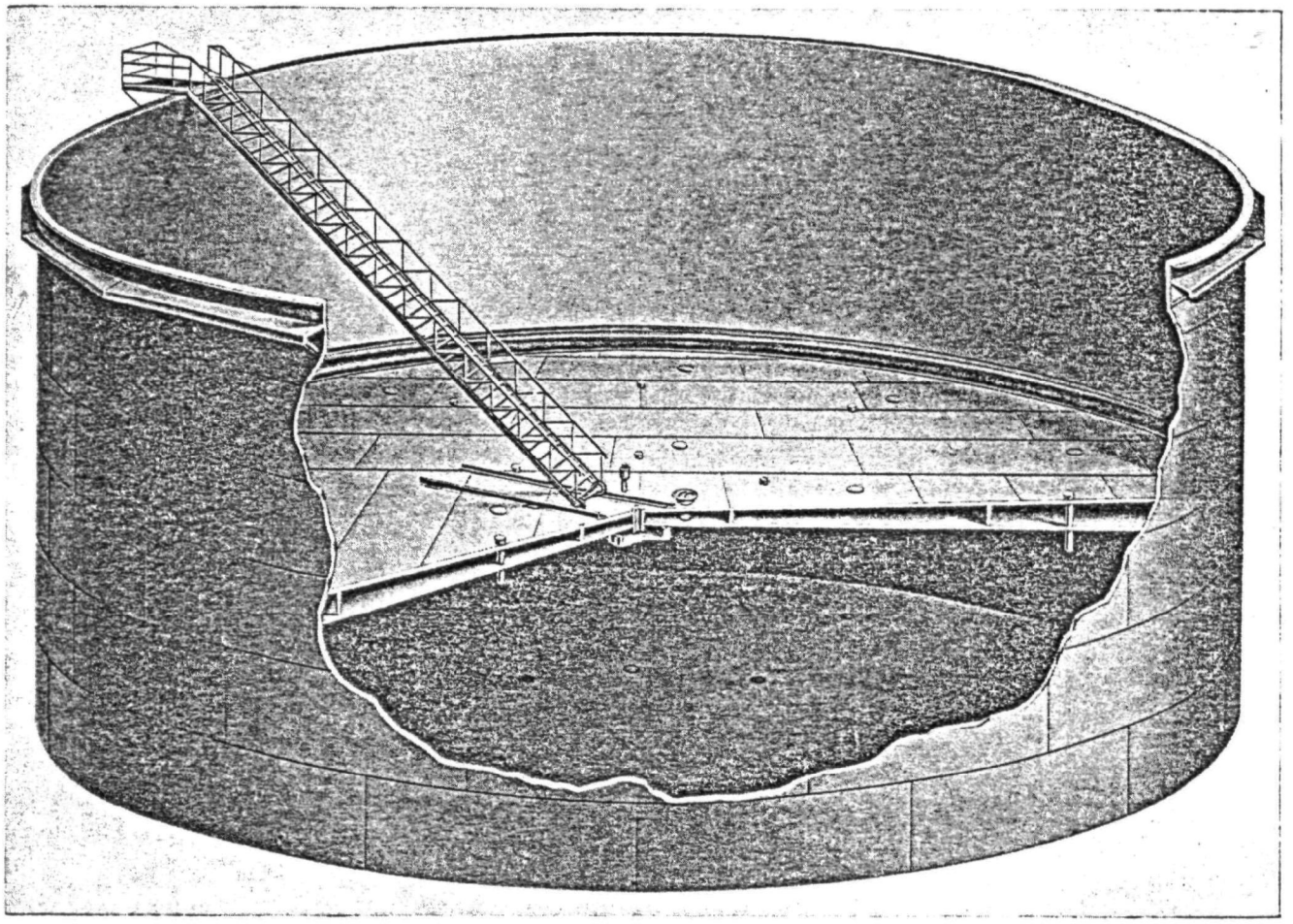
The usual seal in a floating-roof tank consists of a relatively thin-gage shoe or sealing ring supported against the tank shell around the edge of the floating roof. The bottom of the sealing ring is below the liquid surface, and the top is a few inches above the top rim of the roof. A piece of flame-retardant rubberized cloth closes the space between the sealing ring and the roof. Another type of seal consists of a flexible tube, fastened to the roof and occupying the annular space between the roof and shell. The tube, filled with a nonfreezing liquid, is held on the liquid surface and completely eliminates the vapor space. In tanks with riveted shells, abnormally high losses of the more volatile stocks occur because the rivet heads and overlapping steel plates hold the sealing ring away from the tank shell. Thus, it is advisable to use a secondary seal on riveted tanks. This type of seal consists of a strip or loop of rubber adapted to cover the slot at the top of the sealing ring. The value of a secondary seal for welded tanks is uncertain.

Maintenance of Tank: Efficient and safe operation of any mechanical device which moves intermittently requires inspection and maintenance at regular intervals; the floating-roof tank is no exception. Shoes must fit well, seals must be in good condition, the roof should be level at all times, and the breather valve and bleeder vent must operate satisfactorily.

Before the tank is put into service the opening between tank shell and shoe should be minimized by adjusting shoe springs or hangers. If the liquid surface is plainly visible between shoes and shell, after all adjustments are made, the tank may be out-of-round caused by faulty construction or uneven settling. Because this condition leads to large losses it should be corrected. Shoe fit should be checked periodically; at the same time, the above-deck hangers should be serviced to keep them in an operating condition.

The primary and secondary seals should be inspected periodically for tightness and general condition. Sections of the primary seal which have deteriorated and have weakened should be replaced. Holes that appear in sections of good material may be repaired by patching. The secondary seals are subject to considerable abrasive wear and are not amenable to patching, such worn-out seals should be replaced.

The floating position (the level) of a roof depends upon the weight of the load supported and how easily the roof can move up and down. With riveted tanks, shoes occasionally bear unevenly on the shell of the tank. Inspection for this condition should be made periodically and shoes adjusted as necessary. After every rain, drainage from the roof should be checked and any debris clogging the screened roof drains should be



Courtesy: Hammond Iron Works.

FIG. 4—Double-Deck Floating Roof.

removed. Although a snow load is not serious for the pontoon or double-deck roofs it can be with the pan-type roof. When more than a foot of snow accumulates on a roof of any type, it should be removed, particularly if it drifts unevenly.

Design of Accessory Equipment: Two accessories are necessary to the operation of a floating-roof tank: a breather valve for the rim space and a bleeder vent for the roof. One breather valve, sometimes two, is provided at the outer edges of all types of floating-roof tanks; it is similar in design to that used on fixed-roof tanks. The bleeder vent for the pontoon and double-deck tanks allows air trapped under the roof to escape before the roof floats and prevents a vacuum as the roof comes to rest on its supports.

Maintenance of Accessory Equipment: The following accessories should be inspected regularly and repaired as necessary: breather valves (rim vents), bleeder vents, sample and gage hatches, and any other openings from which vapors might escape.

Choice of Paint: The value of a highly reflective paint in reducing evaporation loss from floating-roof tanks is questionable. Although the floating-roof tank is a very efficient conservation device, savings effected through the use of a particular color of paint will be less than for other types of tanks. Reflective paint on the pan-type roof may be justified because it will reduce the chance for boiling. It is not so important on the pontoon and double-deck roofs because these roofs are designed to provide insulating barriers to heat transfer. Reflective paint on the shell of these tanks may be justified because it may reduce boiling in the seal area and it will help maintain a lower liquid temperature throughout the tank. Such reductions are beneficial particularly for the older riveted tanks where it is difficult to maintain a good fit between the shoes and shell.

C. Variable-Vapor-Space Tanks

The variable-vapor-space tank is an effective conservation device particularly suited to reducing breathing losses. Expanding vapors are stored temporarily in a gasholder device and vented to the atmosphere only

E. Vapor-Recovery Systems

Design of System: Vapor-recovery systems collect vapor from storage tanks and send it to a gas-recovery plant. These systems have sensitive pressure-vacuum controls and remove vapor as pressures build up during pumping into the tanks or during breathing. The vapor is collected, compressed, and then recovered by absorption or condensation; with lease tanks, however, the compressed gas normally is discharged into an extraction-plant gathering system. A properly designed system should eliminate most of the evaporation loss, but because of control difficulties the efficiency actually is somewhat lower.

Refinery or natural gas is sometimes used for repressuring the vapor spaces of tanks when air or a corrosive atmosphere is undesirable in the vapor-recovery system. The vapors are withdrawn from the tank as the internal pressure increases, and the repressuring gas is admitted to the tank when air normally would be drawn in. Some provision must be made to prevent collapse of the tanks when insufficient gas evolves to maintain pressure in the tanks.

Where it is uneconomical to design a tank or a storage system to operate at pressures high enough to make evaporation loss negligible, various vapor-recovery methods can be utilized. To recover vapor by condensation, one or a combination of four methods may be used:

1. Absorption may be accomplished in a suitable liquid of higher molecular weight than that of the vapors being recovered. This rich oil must be reprocessed if it is desired to separate the absorbed vapors. The liquid from which the vapors originally escaped also can be used as the absorption medium and then the enriched liquid can be returned to the storage tank without further processing. Vapor usually is absorbed under pressure.

2. Compression of the vapors, under suitable temperature conditions, will condense part or all of the vapors.

3. Cooling, alone or in combination with compression, can return vapors to the liquid state.

4. Adsorption in suitable material, such as activated charcoal or silica gel, is a means of collecting the hydrocarbon vapors if they have been mixed with noncondensables, such as air or other gases. Further processing by heat will remove the hydrocarbons from the adsorbent material; the vapors may then be condensed to the liquid state by cooling, for return to the tank.

Maintenance of System: Vapor-recovery systems require that all the tanks be kept gastight and that the instrumentation and fittings be adequately maintained.

Vapor lines should be sloped to a low spot to collect condensate. Condensed vapors and moisture should be drained periodically from each line. If vapor lines are underground, the low spot should be in a pit and it may be necessary to pump the condensate.

F. Other Ways to Control Loss

Special techniques that reduce heat input minimize evaporation loss. Before one of the techniques is used, it should be considered in relation to the specific problem; the reduction in breathing loss anticipated should be related to the cost of the technique adopted, i.e., that an economic payout be obtained.

Water Sprays: Water sprays cause cooling due to absorption of heat to vaporize the water.

Mechanical Cooling: In mechanical cooling, cooling coils or refrigeration units are used to reduce the effect of heat input. This technique is probably most commonly used for condensing vapors.

Underground Storage: In underground storage, the earth eliminates absorption or emission of radiant energy to or from the tank. Breathing effects are, therefore, greatly minimized. Accordingly, where underground storage is used for any reason, evaporation loss is minimized. Burying tanks near hot lines should be avoided.

Schedule of Tank Fillings and Emptyings: Breathing loss sometimes can be minimized where conditions permit coordinating tank filling and tank emptying with the daily breathing cycle. This is accomplished by filling during a normal period of inbreathing and emptying during a normal period of outbreathing. The compensating effects of breathing will partially cancel out filling losses. Inbreathing normally begins when the tank starts to cool in the afternoon; outbreathing normally begins when the tank starts to warm up in the morning.

Pumpings to fixed-roof tanks should be scheduled to maintain minimum average outage. If volatile stock accumulates in a group of non-interconnected tanks, only one of which is a conservation-type, this tank might be used for daily accumulation; enough stock periodically would be transferred from it to completely fill one of the fixed-roof tanks. Another method to minimize average outage is to refill a tank as soon as possible after emptying. This procedure also tends to reduce filling loss. Immediately after a tank is emptied the vapor space is lean in hydrocarbon. Refilling within a day expels vapor which is lean in hydrocarbon. A delay of three days may nullify most of the advantage.

Evaporation loss from a variable-vapor-space system can be minimized by balancing fillings and emptyings. Filling into one tank should be scheduled when vapor expansion is at a minimum or when another tank is being emptied.

Filling loss from pressure tanks can be minimized by controlling the fill rate in order to avoid pressure build up; this allows time for condensation of vapor and equilibrium is maintained. If heat of condensation cannot be dissipated as fast as condensation occurs, a rise in internal temperature will result in a higher internal pressure.

SECTION 1.0
INTRODUCTION

The specific objectives of the study were to:

1) Assess the feasibility of applying vapor control technology for benzene transfer operations including tank cars, railcars, barges, tankers, storage tanks, and pipeline operations.
2) Determine the achievable emission level and emission reduction for each vapor control alternative.
3) Determine any secondary emissions that would result from applying each vapor control alternative.
4) Quantify the capital and annualized costs of the control alternatives.

Visits were made to the plants of two benzene producers to gather information on liquid benzene storage and transfer operations. A literature search was conducted to obtain data on benzene handling and storage, as well as to investigate technological alternatives to control emissions. This activity was brief because of the desire to evaluate technologies that could readily be applied to industry. Equipment manufacturers were consulted to determine the state-of-art of commercially available equipment and ascertain the effectiveness, cost, and operating history of their treatment units. Three technologies exhibited promise as effective methods to reduce benzene emissions, and were selected for further study. These were a refrigeration and lean oil absorption unit, vacuum regenerated carbon adsorption, and thermal incineration.

Hypothetical models were prepared to represent a typical current-day benzene producer, and two benzene consumers. These models serve as base cases for the study. Six control schemes were developed and applied to the base cases. Four were applied to the producer, and two to the consumers. Each of the three control technologies discussed above were applied utilizing their respective achievable emission levels to the control schemes resulting in 16 case studies. The cost effectiveness of each case study was calculated, and the technologies rated.

SECTION 2.0
SUMMARY

The three control technologies evaluated were:

1) Condensation of benzene vapors by refrigeration followed by absorption of benzene vapors in an oil absorbing/stripping system.

2) Carbon adsorption beds regenerated by vacuum.

3) Thermal incineration using supplemental fuel.

Other technologies were considered, but dropped because of lack of design information and/or commercial availability.

The control technologies were evaluated by applying them in various configrations to hypothetical models which were prepared to represent facilities and operations typical of current-day producers and consumers of benzene.

Each of the technologies embody basic principles whose successful application to hydrocarbon processing has been well demonstrated, and for which large data bases exist. Their application to benzene emission control is very limited and actual performance data was not available. The transfer of technology from other hydrocarbons services to benzene service is not expected to create unusual problems. All of the technologies are currently being applied to gasoline emission control, and this experience is useful.

The claimed removal efficiencies of the three technologies studied are all high. The predicted benzene emission concentration levels that are practical to achieve are:

Refrigeration-absorption	-	1000 ppm
Carbon adsorption	-	10 ppm
Thermal incineration	-	10 ppm

The technologies were evaluated using the above emission levels. The economic penality for installing and operating a thermal incinerator at 10 rather than 1000 ppm is small. This is not the case with carbon adsorption and a meaningful economic comparison of this technology can only be made when it and competing technologies are evaluated at the same emission concentration level. Using the above emission levels, refrigeration-absorption has a cost effectiveness very close to that of thermal incineration. Average cost effectiveness of the refrigeration-absorption systems is $3.83/lb reduction, while that of thermal incineration is $3.78/lb reduction. (Note: Units used in this report are the same as used by suppliers of raw data. A metric conversion chart is contained in Appendix A.) This is a negligible difference. A slight rise in the value of benzene and/or the cost of natural gas relative to electricity would make refrigeration-absorption the most cost effective. Although there is no single component in the system that is unique; i.e., closed loop refrigeration vapor scrubbing tower, gas-oil separation by distillation; the combination of these components into a single package for remote automatic efficient operation is not yet demonstrated. This system is thought to need more control and fine tuning than the other technologies to achieve efficient operation. A great deal more operating experience would likely be required to make this technology widely accepted. What makes refrigeration-absorption particularly attractive is its potential to be the most cost effective and its conservation of benzene.

Thermal incinerator technology has been used more in the control of storage and transfer emissions than the other two technologies. The transfer of gasoline handling knowledge to benzene handling is much more direct than that of the other technologies. The state of the art for thermal incineration is at a high level, and potential improvements are possible with energy recovery by heat exchangers. Advantage was not taken for heat recovery in the case study models. Also the particular commercially available thermal incinerators investigated did not offer heat recovery as a regular option. If heat recovery is a possibility for any particular plant, thermal incineration would be even more cost effective. Standard thermal incineration units are available as "off the shelf" items from at least two manufacturers.

Vacuum regenerated carbon adsorption with 10 ppm emissions was calculated to be the least cost effective means of controlling benzene emissions but at 1000 ppm emissions may be competitive with other technologies. On a functional basis, carbon adsorption stands out as the most attractive technology. It has a very high efficiency of benzene recovery and removal, relatively simple operation well suited for automation, and wide turndown ranges. Experience with benzene is presently limited to extrapolation of results gained from gasoline service with gasoline containing benzene. Substantial advancement in the state of the art is expected as more experience is obtained.

Steam regenerated carbon systems have wide experience in the treatment and recovery of solvents from solvent contaminated air in extremely dilute concentrations. These units are available from several manufacturers as standard package items. However, no experience was found pertaining to benzene, gasoline, or high concentration hydrocarbon usage. No pricing estimates for

benzene applications of steam regenerated systems were available. Some means for disposal of benzene contaminated condensate is necessary for this type system.

Calculations revealed that there is considerably more benzene lost as a result of loading and storage (per unit of benzene handled) by producers than for consumers. The emission factor for the base case producer is 2.608 $lb/10^3$ gallons compared to .468 for the consumer case. Floating roof tanks represent a high level of control. (Texas state regulations require floating roof tanks for the base case.) Conversely if a plant has cone roof tanks, the first efforts should be directed to reducing storage losses by conversion to either open floating roof or internal floating cover depending on their relative cost effectiveness. Either method is highly cost effective.

When the implementation of carbon adsorption technology is desired, the most cost effective design will incorporate features to reduce the capacity (in terms of benzene loading and volumetric flowrate) of the individual treatment units, permit higher ppm emissions, and minimize the number of units required. Capacity reducing features might include vapor holders to act as flow equalizers and displacement of vapor from tank to tank or carrier to tank. The additional cost due to capacity reducing measures will be more than offset by the savings in capital costs of the carbon adsorption units. Capacity reducing measures do not provide similar cost effectiveness gains for refrigeration-absorption and thermal incineration technologies. The increased cost of the capacity reduction measures outweighs the cost savings obtained by reducing the size and number of treatment units.

SECTION 3.0
CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations are:

1) It is concluded that thermal incineration offers the best means for control of benzene vapor to levels of 10 ppm benzene. The risk in applying this technology to benzene service is considered to be low. Thermal incineration systems have the distinct advantage of being able to dispose of other pollutants.
2) Thermal incineration at the level of 10 ppm benzene emission and refrigeration-adsorption at 1000 ppm are equal in cost effectiveness.
3) Carbon adsorption is not as cost effective as thermal incineration when both are compared at 10 ppm.
4) The cost of carbon adsorption is sensitive to final benzene emission level and a true cost comparison to other technologies can only be made when all technologies are evaluated at the same emission level.
5) Benzene emission control efforts are more cost effective in producer rather than consumer facilities. Plants with cone roof storage tanks should receive attention before those using floating roof tanks. When the producer plant is equipped with floating roof tanks, the priority shifts to controlling the loading losses.
6) Modifications to carriers to reduce transit losses (defined as breathing losses during shipment) should receive the lowest priority. Modifications to carriers

should be limited to those which are required to reduce loading losses.

7) Secondary emissions for the control systems evaluated were low, and do not present a significant problem.

8) Air-benzene mixtures in pipe lines to recovery systems introduce significant explosion hazards, and designs must incorporate equipment to avoid this hazard. (This was done for designs evaluated in this report.)

VII. MOBILE SOURCE/CO

(ORAL PRESENTATION)

Oxidation of CO in the Exhaust Gas

Exhaust manifold air injection, thermal reactors, and catalytic converters all control CO emissions by oxidizing CO in the exhaust to CO_2. The gas temperature, oxygen concentration, catalyst parameters and CO concentration are the important operating variables. Secondary air injection and temperature control are often required. Two kinds of thermal reactors have been developed for automotive (gasoline spark ignition) engines: the Rich Thermal Reactor (RTR) for fuel rich air/fuel ratios and the Lean Thermal Reactor (LTR) for lean ratios. The thermal reactor is a container which, by its size and configuration, increases the residence time and turbulence of exhaust gases, thereby providing a chamber for the high-temperature oxidation reaction. High temperatures are maintained by the exothermic oxidation of CO and HC in the exhaust gas. The rich thermal reactor operates at temperature from 870 to 1,040^{o}C (1,600 to 1,900^{o}F) and is designed for fuel rich operation. At rich air/fuel ratios of 11-12 to 1, NO_x emissions are reduced to less than 6 g/kwhr (4.5 g/hphr), but fuel consumption penalties are incurred. Secondary air injection is normally injected into the thermal reactor for complete oxidation, and construction materials such as Inconel 601 are needed for the inner core, bafflers and port liners. Temperature control devices are required to protect the reactor construction materials against overtemperature.

Reference: Control Techniques for Carbon Monoxide Emissions, EPA-450/3-79-006 (June 1979).

The lean thermal reactor operates at higher air/fuel ratios (17-19 to 1) and lower operating temperatures, 760-870°C (1,400 to 1,600^{o}F), than the rich thermal reactor. Secondary air-injection is not usually required and construction materials have less severe durability requirements than do the materials for rich thermal reactors. Oxidation catalysts and 3-way catalysts are being used extensively in the control of CO from automotive engines. This CO control strategy can be equally effective in the control of CO from stationary engine sources. Recent literature describes a patented platinum catalyst on a ceramic honey comb support that has withstood 50,000 hours of stationary engine testing. The catalytic converter has also been used for small Diesel, LP gas, and gasoline engines in sizes up to 13.1 litres (800 cu in.) displacement and is applicable to 2- and 4-cycle naturally aspirated or turbocharged engines. Applications include Diesel powered mining and tunneling equipment, locomotives, loaders, fork-lift trucks operated in enclosed spaces, and electric generators located near airconditioning intakes. For oxidation catalysts to be an effective means of controllilng CO and HC emissions, the engine must be properly tuned and unleaded fuel must be used. Also, the control system should ideally be adjusted to preclude the formation of sulfate emissions which can be formed in the catalyst due to excess oxygen in the exhaust gases and sulfur content of the fuel. Alternatively, sulfur can be removed from the fuel. In the case of 3-way catalysts, rich mixtures are conducive to the formation of HCN and ammonia.

Air injection into the exhaust manifold can reduce CO emissions by a factor of 55 percent from baseline emissions on some engines with modifications to the air/fuel ratio, compression ratio, and spark ignition timing schedule.

Design Changes and Operating Adjustments

The air/fuel ratio is the operating variable that determines CO emissions, and it has a significant effect on NO_x emissions. Operation at air/fuel ratios that produce low CO emissions can produce high or low NO_x emissions depending on the exact value of the air/fuel ratio used. Since NO_x emissions from stationary reciprocating internal combustion engines are considered more of a problem than CO emissions, design and operating changes are expected to be made in these sources primarily for NO_x control. Care must be taken to ensure that the entire emission control system provides adequate control of all emissions that need to be controlled. This sometimes leads to more sophisticated systems.

VIII. EMISSION CONTROL/ENVIRONMENTAL ANALYSIS

SECTION 1

SUMMARY

The Industrial Environmental Research Laboratory is responsible for performing the research and development required to assess the impacts of pollution from a variety of industries and to evaluate the applicability of various control technologies for these industries. Pollution control options must be evaluated for efficiency, reliability, economics, and energy consumption. If secondary pollutants are generated by the cleanup of the original pollutant, their impact must also be assessed. This report on acrylonitrile plants addresses these aspects of control technology evaluation.

The purpose of the report is to provide data for making decisions about control technology. Control technologies are identified and ranked in terms of efficiency, cost, and energy requirements. Control technology demonstration opportunities in the acrylonitrile industry are also identified.

There are six operating acrylonitrile plants in the U.S. Each has several air pollutant emission sources. The effluent streams addressed in this report are:

- The absorber vent gas stream
- The liquid waste streams that go to the holding ponds and deep-well ponds

- The HCN and acetonitrile incinerators and their off-gas streams
- The reactor startup emission streams

The absorber vent gas stream, when unabated, emits large quantities of hydrocarbons. Thermal incineration is used for abatement of this stream at one acrylonitrile plant, and catalytic incineration is used at another plant. Data for these streams and their abatement by the incineration processes were available from EPA contractors. Using these data, the effectiveness of catalytic and thermal incineration was evaluated. A quick review of the literature showed other methods to be unsuitable: carbon adsorption because the pollutants are too low in molecular weight, and hydrocarbon absorption because the stream is too dilute. It was concluded that thermal incineration with waste heat recovery is the best method for abatement of this stream; catalytic incineration has a high unburned-hydrocarbon passthrough rate.

High levels of hydrocarbon emission occur from the holding ponds. There are no reasonable pollution control technologies for open ponds, but there are control technologies for hydrocarbon removal from waste water on its way to the ponds. A review of studies and demonstration projects on solvent extraction of organic nitrogen containing waste waters was made. In addition, a patent for changing the acrylonitrile processing to eliminate water scrubbing of the product was reviewed. This would also eliminate most of the waste water production. These methods are still in the research and development stage, and conclusions about their efficacy cannot be drawn.

All acrylonitrile plants have HCN and acetonitrile thermal incinerators; the emissions data available (from other EPA contractors) for the exit streams from these incinerators showed 0.6 percent conversion

of fuel nitrogen to NO_x. A review of the combustion literature revealed that 20 to 80 percent of conversion of fuel nitrogen to NO_x could be expected. (This discrepancy should be resolved by further study.) Catalytic incinerators were evaluated as replacements for the existing incinerators; a literature review shows that similar levels of NO_x production could be expected.

When reactors at acrylonitrile plants are started up, the emissions from these reactors are vented directly to the atmosphere. To control this intermittent pollution stream, which contains up to 10,000 lbs of acrylonitrile per reactor per emission, flares and carbon adsorption were evaluated. Flares (and other combustion methods) form unacceptable amounts of NO_x. Carbon adsorption, and wet scrubbing followed by carbon adsorption, appear to be more effective.

This report presents the following conclusions:

- Absorber vent stream: Thermal incineration is an acceptable and efficient control method. Thermal incinerators are currently in use, and no further development is required.
- Holding pond: Extraction of hydrocarbons from the waste water before it is sent to a holding pond is the most desirable control method. Bench and pilot-plant scale research on carbon adsorption and hydrocarbon absorption (solvent extraction) is recommended. A literature review of the waste water control methods in use in Europe (e.g., the Montecatini plant) is also recommended.
- Hydrogen cyanide/acetonitrile incinerators: Investigation of the NO_x production of the existing incinerators is recommended. Threre is a potential for high levels of NO_x

emissions from these incinerators. A feasibility study of advanced incineration techniques -- two-stage (low NO_x) thermal and catalytic incinerators -- is also recommended.

- Startup emissions: A study of the feasibility of routing startup emissions to the absorber tower for scrubbing and a demonstration of a combined wet-scrubber and carbon adsorption abatement technique are recommended.