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Wet Scrubber Inspection and Evaluation Manual

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

GLOSSARY*

ADIABATIC SATURATION.[1] A process by means of which an air or gas stream is saturated with water vapor without adding or subtracting heat from the system.

AERODYNAMIC DIAMETER. The diameter of a unit density sphere having the same aerodynamic properties as an actual particle. It is related to the physical diameter according to the equation below:

$$d_{pa} = d_p \, (\rho C)^{1/2}$$

where: d_{pa} = aerodynamic diameter

d_p = physical diameter

ρ = particle density

C = Cunningham correction factor

AIR, DRY. Air containing no water vapor.

ATOMIZATION. The reduction of liquid to a fine spray.

BAROMETRIC SEAL.[1] A column of liquid used to hydraulically seal a scrubber, or any component thereof, from atmosphere or other part of the system.

BURNER.[1] A device for the introduction of fuel and air into a furnace at the desired velocities, turbulence, and concentration to establish and maintain proper ignition and combustion of the fuel.

CASCADE IMPACTOR. A particle-sizing device in which progressively increasing inertial forces are used to separate progressively smaller particle sizes.

CHEVRON MIST ELIMINATOR.[1] Series of diagonal baffles installed in a gas stream, designed to separate fine droplets of liquid from the gas by means of inertial impaction on the surfaces of the baffles.

COCURRENT. Flow of scrubbing liquid in the same direction as the gas stream.

COLLECTION EFFICIENCY.[1] The ratio of the weight of pollutant collected to the total weight of pollutant entering the collector.

CONDENSATION.[1] The physical process of converting a substance from the gaseous phase to the liquid or solid phase via the removal of heat, the application of pressure, or both.

CROSSFLOW. Flow of scrubbing liquid normal to the gas stream.

CUNNINGHAM CORRECTION FACTOR. A correction factor to account for slippage of fine particles moving through a discontinuous gaseous medium.

*If not specified, definition taken from U.S. Environmental Protection Agency, Control Techniques for Particulate Emissions from Stationary Sources, Volume I. EPA-450/3-81-005a, September, 1982.

CYCLONE. A device in which the velocity of an inlet gas stream is transformed into a confined vortex from which inertial forces tend to drive particles to the wall.

DAMPER.[2] An adjustable plate installed in a duct to regulate gas flow.

DEHUMIDIFY.[1] Reduction of water vapor content of a gas stream.

DEMISTER. A mechanical device used to remove entrained water droplets from a scrubbed gas stream.

DENSITY.[2] The ratio of the mass of a specimen of a substance to the volume of the specimen. The mass of a unit volume of a substance.

DIFFUSION (AEROSOL). Random motion of particles caused by repeated collisions of gas molecules.

DIFFUSIOPHORESIS. Force acting on a particle, effecting movement due to a vapor condensation gradient, resultant of differences in molecular impacts on opposite sides of a particle.

DRAFT.[1] A gas flow resulting from the pressure difference between the incinerator, or any component part, and the atmosphere, which moves the products of combustion from the incinerator to the atmosphere. (1) Natural draft: The negative pressure created by the difference in density between the hot flue gases and the atmosphere. (2) Induced draft: the negative pressure created by the vacuum action of a fan or blower between the incinerator and the stack. (3) Forced draft: the positive pressure created by the fan or blower, which supplies the primary or secondary air.

DRAG FORCE. Resistance of a viscous medium due to relative motion of a fluid and object.

DUST.[2] Solid particles less than 100 micrometers created by the attrition of larger particles.

DUST LOADING.[2] The weight of solid particulate suspended in an airstream (gas), usually expressed in terms of grains per cubic foot, grams per cubic meter, or pounds per thousand pounds of gas.

EXCESS AIR.[1] Air supplied for combustion in excess of that theoretically required for complete combustion; usually expressed as percentage of theoretical air (130% excess air).

FEEDSTOCK.[1] Starting material used in a process. Can be raw material or an intermediate product that will undergo additional procesing.

GRAVITY, SPECIFIC.[2] The ratio of the mass of a unit volume of a substance to the mass of the same volume of a standard substance at a standard temperature. Water is usually the standard substance. For gases, dry air at the same temperature and pressure as the gas is often the standard substance.

GRID.[1] A stationary support or retainer for a bed of packing in a packed bed scrubber.

HEADER.[1] A pipe used to supply and distribute liquid to downstream outlets.

HUMIDITY, ABSOLUTE.[2] The weight of water vapor carried by a unit weight of dry air or gas.

HUMIDITY, RELATIVE.[2] The ratio of the absolute humidity in a gas to the absolute humidity of a saturated gas at the same temperature.

HYDROPHILIC MATERIAL. Particulate matter that adsorbs moisture.

INERTIA. Momentum; tendency to remain in a fixed direction, proportional to mass and velocity.

INTERCEPTION. A type of aerosol collection related to impaction, in which an aerosol impacts the side of an obstacle because of reduced mobility across streamlines.

ISOKINETIC SAMPLING. Matching the gas velocity at the sampling probe entrance to the gas velocity of the localized gas stream to collect a representative particle size distribution.

LIQUOR.[1] A solution of dissolved substance in a liquid (as opposed to a slurry, in which the materials are insoluble).

LOG-NORMAL DISTRIBUTION. A series of points that can be defined by a geometric mean value and a geometric standard deviation.

MEAN FREE PATH. The average distance between successive collisions of gas molecules; related to molecular size and number per unit volume.

OPACITY. Measure of the fraction of light attenuated by suspended particulate.

PARTICLE. Small discrete mass of solid or liquid matter.

PARTICLE SIZE. An expression for the size of liquid or solid particle.

PARTICULATE MATTER. As related to control technology, any material except uncombined water that exists as a solid or liquid in the atmosphere or in a gas stream as measured by a standard (reference) method at specified conditions. The standard method of measurement and the specified conditions should be implied in or included with the particulate matter definition.

PARTICULATE MATTER, ARTIFACT. Particulate matter formed by one or more chemical reactions within the sampling train.

PENETRATION. Fraction of suspended particulate that passes through a collection device.

pH.[1] A measure of acidity-alkalinity of a solution; determined by calculating the negative logarithm of the hydrogen ion concentration.

POLYDISPERSITY. A particle size distribution consisting of different size particles.

PRESSURE, STATIC. The pressure exerted in all directions by a fluid; measured in a direction normal to the direction of flow.

PRESSURE, TOTAL. The algebraic sum of the velocity pressure and the static pressure.

PRESSURE, VELOCITY. The kinetic pressure in the direction of gas flow.

PRIME COAT (PRIMER).[1] A first coat of paint applied to inhibit corrosion or to improve adherence of the next coat.

QUENCH.[1] Cooling of hot gases by rapid evaporation of water.

REYNOLDS NUMBER, FLUID. A dimensionless quantity in fluids to describe the ratio of inertial to viscous forces.

REYNOLDS NUMBER, PARTICLE. A dimensionless quantity in aerosol science to describe the ratio of inertial to viscous forces relative to the particle.

SATURATED GAS.[1] A mixture of gas and vapor to which no additional vapor can be added, at specified conditions. Partial pressure of vapor is equal to vapor pressure of the liquid at the gas-vapor mixture temperature.

SIZE DISTRIBUTION. Distribution of particles of different sizes within a matrix of aerosols; numbers of particles of specified sizes or size ranges, usually in micrometers.

SLURRY.[1] A mixture of liquid and finely divided insoluble solid materials.

SMOKE. Small gasborne particles resulting from incomplete combustion; particles consist predominantly of carbon and other combustible material; present in sufficient quantity to be observable independently of other solids.

SPECIFIC GRAVITY.[1] The ratio between the density of a substance at a given temperature and the density of water at 4°C.

SPRAY NOZZLE.[1] A device used for the controlled introduction of scrubbing liquid at predetermined rates, distribution patterns, pressures, and droplet sizes.

STOKES NUMBER. Descriptive of the particle collection potential of a specific system; the ratio of particle-stopping distance to the distance a particle must travel to be captured.

STREAMLINE. The visualized path of a fluid in motion.

TEMPERATURE, ABSOLUTE.[2] Temperature expressed in degrees above absolute zero.

TERMINAL SETTLING VELOCITY. The steady-state speed of a falling particle after the equilibration of gravitation, drag, and buoyant forces has occurred.

VAPOR. The gaseous form of substances that are normally in the solid or liquid state and whose states can be changed either by increasing the pressure or by decreasing the temperature.

WET/DRY LINE.[1] The interface of hot, dry particulate-laden gas and cooling or scrubbing liquid, at which an accumulation of solids can occur.

GLOSSARY REFERENCES

1. Industrial Gas Cleaning Institute. Wet Scrubber Terminology. Publication WS-1, July 1975.

2. Industrial Gas Cleaning Institute. Fundamentals of Fabric Collectors and Glossary of Terms. Publication F-2, August 1972.

scrubbers, plate-type scrubbers, packed tower scrubbers, and spray tower scrubbers. Emphasis is given to the gas-atomized scrubbers since these are the most common type used for large air pollution control systems.

1.0 INTRODUCTION

The Stationary Source Compliance Division of the U.S. Environmental Protection Agency has sponsored the development of this manual. The purpose of the manual is to assist EPA personnel, State and local agency personnel, and operating personnel in the routine evaluation of wet scrubbers in order that abnormal operating conditions contributing to excessive emissions can be identified and rectified as rapidly as possible. It covers the inspection and evaluation of particulate wet scrubbers installed at stationary sources. And its scope includes gas-atomized scrubbers, plate-type scrubbers, packed tower scrubbers, and spray tower scrubbers. Emphasis is given to the gas-atomized scrubbers since these are the most common type used for large air pollution control systems.

This manual presents specific evaluation techniques for identifying and assessing wet scrubber operating problems. It is not intended to be an exhaustive survey of operation and maintenance (O&M) practices for wet scrubbers or a summary of design principles; this material is already available in commercial literature and in numerous EPA publications.

In the past, regulatory agencies and operators alike have used emission correlations based on wet scrubber performance parameters as an indirect measure of performance. Generally, this practice has meant simply evaluating the pressure drop and comparing it with pressure drops generally experienced in the specific industry. Among the numerous problems encountered with this approach is plant-to-plant particle size differences. In many scrubber applications, emissions sometimes vary substatially without a major change in the observed pressure drop. Thus, an evaluation approach based only on pressure drop is not adequate. In addition, simply recording the values indicated by the differential pressure gauges installed on wet scrubber systems can lead to erroneous conclusions, as they are sometimes not operating correctly.

In the evaluation approach proposed in this manual, current performance parameters are evaluated against their site-specific baseline values for the wet scrubber being evaluated. The influence of important variables or parameters that cannot be measured, such as the degree of maldistribution during liquid-gas contact and the particle size distribution, is thereby taken into account. An additional noteworthy aspect of the proposed approach is that parameters beside pressure drop must be considered. The available literature has been reviewed to identify those variables having a significant impact on scrubber performance.

2.0 BASIS FOR SELECTION OF SCRUBBER PARAMETERS USED IN PERFORMANCE EVALUATION

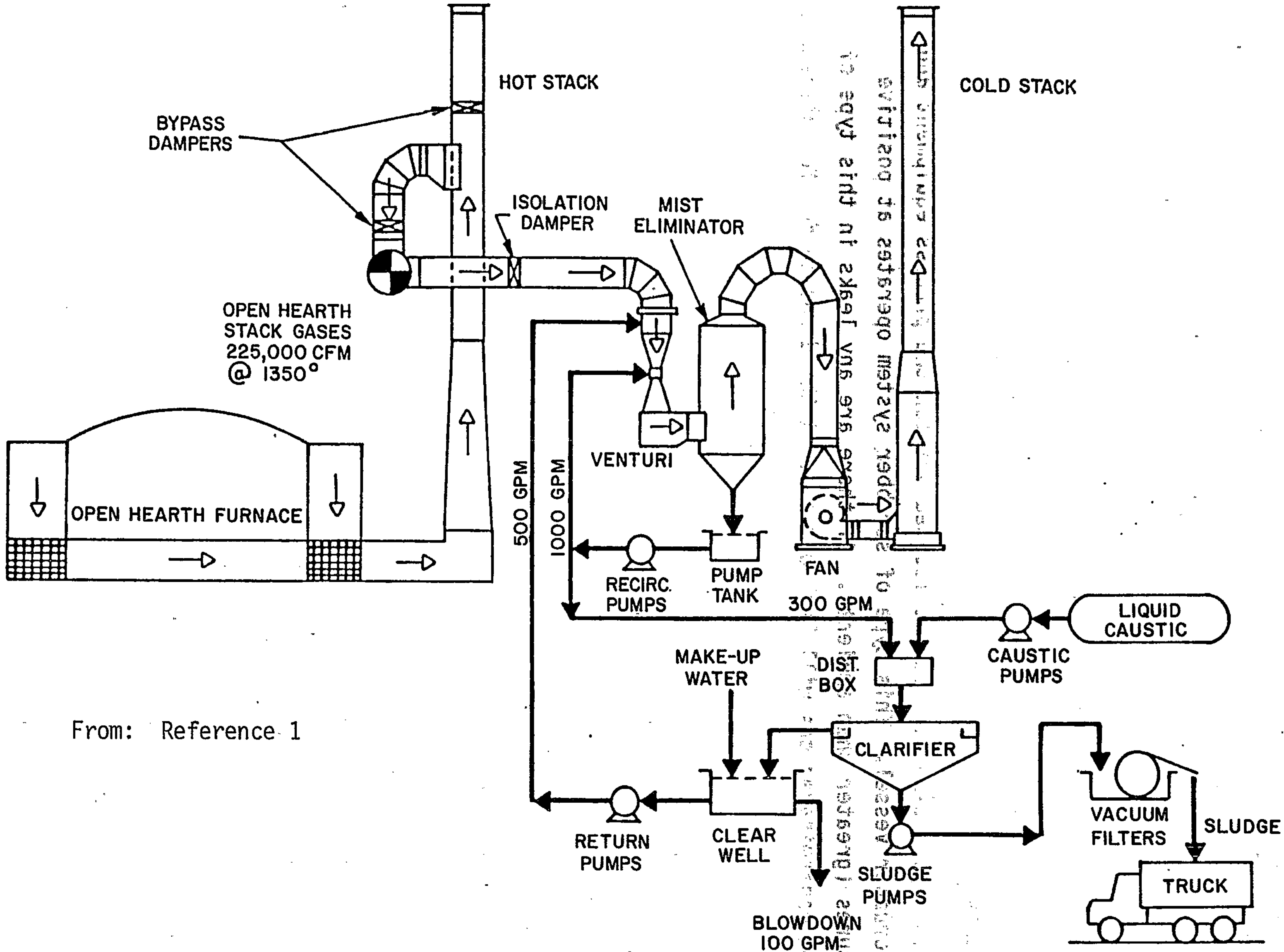
Routine evaluation of particulate wet scrubbers depends on the assessment of scrubber operating variables that are both meaningful and measurable. Description of such a performance evaluation approach must start with the identification and understanding of the functions of scrubber system components and a comprehension of the significant operating variables. These are discussed in the subsequent sections.

2.1 WET SCRUBBER SYSTEM COMPONENTS

Because operating problems affecting performance of wet scrubbers originate not only in the scrubber vessel, but also in the process equipment and in the independent components of the scrubber system, the scrubber vessel must be evaluated as part of the larger system into which it is integrated, and not as an isolated piece of equipment. A wet scrubber system is composed of a large number of individual components all of which must work properly even when process conditions vary. A simplified flowchart of one wet scrubber system is shown in Figure 2-1. Individual components which make up this particular system are listed below:

1. Scrubber vessel
2. Demister
3. Fan
4. Recirculation tank
5. Recirculation pumps
6. Presaturator
7. Bypass duct and dampers
8. Alkaline additive system
9. Clarifier
10. Vacumn filter
11. Purge and make-up systems
12. Stack
13. Flow monitors
14. pH monitors
15. Static pressure monitors

There is considerable diversity in the design of wet scrubber systems due to the different control requirements, different water availabilities and qualities, and process related factors.



From: Reference 1

Figure 2-1. Example wet scrubber system.

Gas movement through the wet scrubber system is maintained by the use of a fan (except for a few systems in which the process equipment pressure is sufficient to move the gas). If the process equipment and the scrubber vessel are located before the fan, as shown in Figure 2-2a, then the entire system operates at pressures lower than ambient. This is termed "negative" static presure (static pressure is simply the pressure exerted by a gas in all directions, measured normal to the direction of flow, if any). With the fan in this position, ambient air will leak into the ductwork and scrubber if there are any holes, open access hatches, or weld gaps.

In Figure 2-2b, the fan is located between the process equipment and the scrubber vessel. This type of scrubber system operates at positive pressures (greater than ambient). If there are any leaks in this type of system contaminated gas will leak outward. A third option for fan placement is a push-pull arrangement with fans placed before and after the scrubber. This arrangement is often used when the scrubber has been added to an existing control system.

The pressure drop across the scrubber vessel is an important operating variable since it is often related to the effectiveness of particulate capture. The pressure drop is simply the mathematical difference between the static pressures before and after the scrubber. Both of the examples shown in Figure 2-2 have a pressure drop of 14.5 inches water.

The liquor flow, through the scrubber can either be "once-through" or recirculated. Most wet scrubber systems have a recirculating liquor system to reduce the volume of water needed, and to reduce the cost of treating the scrubber effluent liquor. Both liquor systems are illustrated in Figure 2-3.

Obviously the recirculating liquor circuit is more complicated than the once-through system. The addditional components required include the recirculation tank, the purge stream controls, and the makeup stream controls. The recirculating system is prone to buildup of solids and corrosive agents, while the once-through system is free of these potential problems as long as there is a sufficient supply of high quality water. The advantages of the recirculating liquor system include lower operating cost (in most situations) and the opportunity to neutralize and treat the liquor prior to entry to the scrubber vessel.

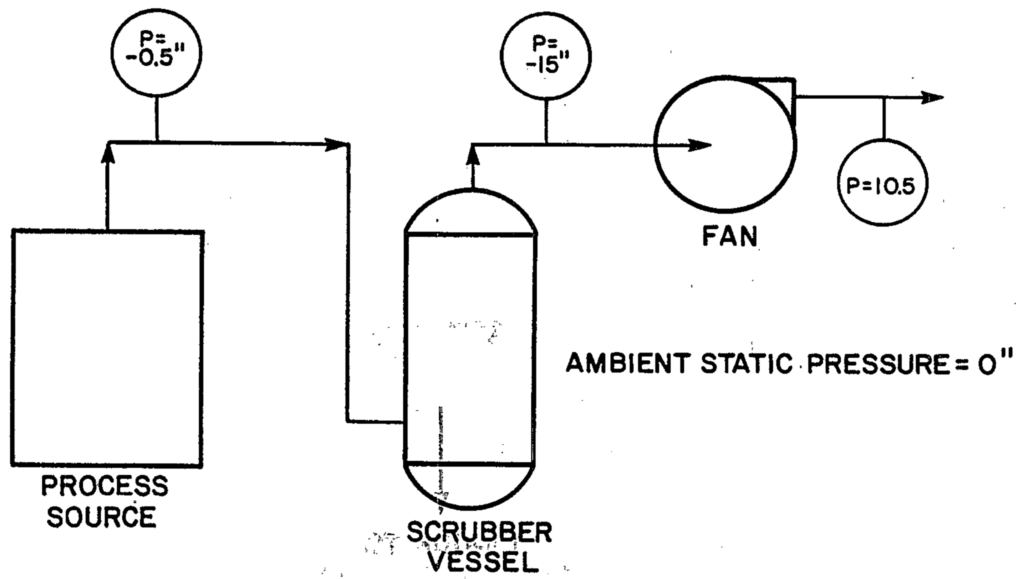


Figure 2-2a. Negative pressure system.

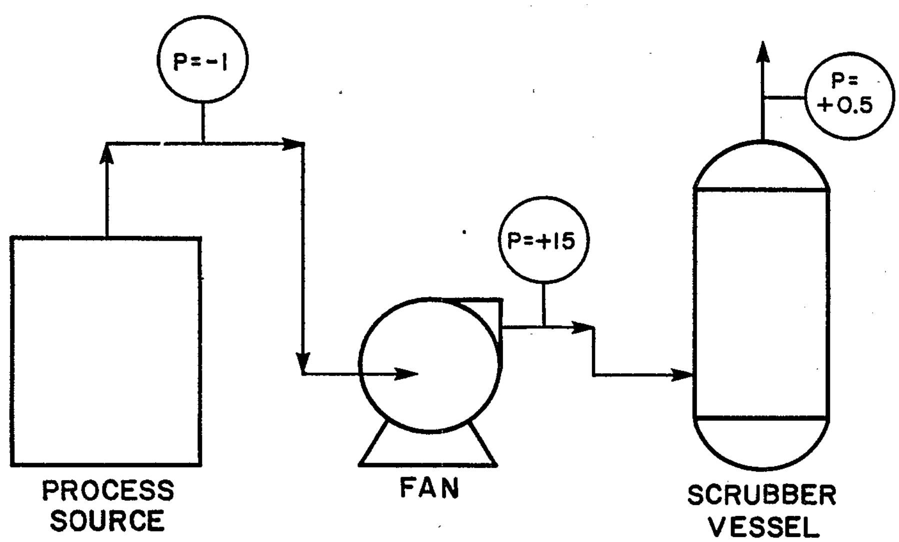


Figure 2-2b. Positive pressure system.

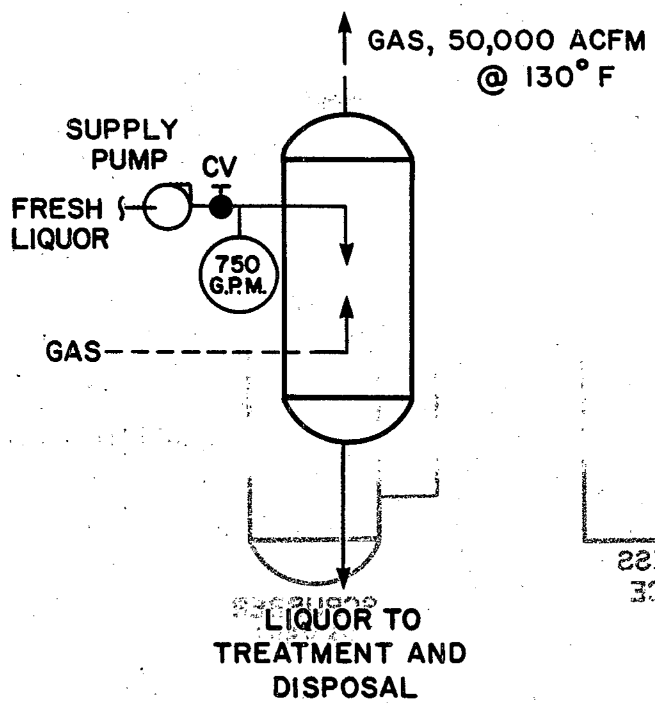


Figure 2-3a. Once-through liquor system.

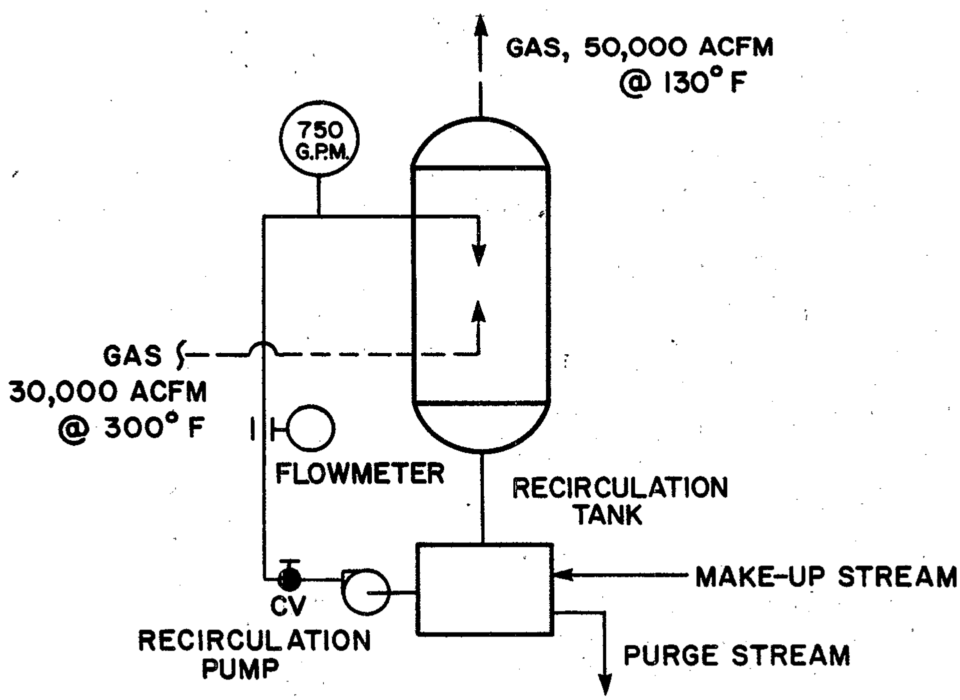


Figure 2-3b. Recirculating liquor system.

A useful measure of the quantity of liquor being used by the scrubber system is the liquid-to-gas ratio which is normally abbreviated as L/G. This ratio is usually (but not always) defined as the total volume (in gallons) of liquor entering the scrubber divided by the outlet gas flow rate (in thousands of ACFM). The outlet gas flow rate is used as the basis of the parameter since this easier to measure than the inlet gas flow rate. For the scrubber illustrated in Figure 2-3a, the liquid-to-gas ratio is 750 gallons per minute divided by 50 X 10^3 ACF per minute, or 15.

As indicated earlier, a recirculating liquor system must have some form of temporary liquor storage, such as the recirculation tank shown in Figure 2-3b, a pond, or perhaps a small section at the bottom of the scrubber vessel itself. The recirculation tank or pond provides a good location for the addition of neutralizing agents, surfactants, and/or anti-foaming agents. Often the pond or tank is the site of makeup water addition and/or drawing off of a purge stream.

Because of the buildup of solids in the scrubbing liquor and the need to minimize the concentration of chlorides and dissolved compounds, a portion of the recirculation liquor is often drawn off for disposal or further treatment. This purge stream usually consists of 2% to 5% of the total recirculation stream rate. In scrubber systems without a purge stream, all of the liquor within the system is replaced on a regular basis. Depending on the frequency of replacement, the liquor quality varies considerably.

To maintain the desired recirculation flow rate, sufficient liquor is added to (1) account for that removed in the purge stream and (2) make up the liquor lost to evaporation and that lost with the wet sludge (if any). This makeup stream is usually fresh process water, well water, or municipal water. The makeup stream can be added at a number of points in the scrubber system with the most common point of addition being the recirculation tank or pond.

If the temperature of the gas stream entering the scrubber is very hot (greater than 300° F), the gas stream is often cooled prior to entry to the scrubber. Cooling the gas stream protects the scrubber vessel materials of construction, especially the corrosion and abrasion resistant linings. If the cooling is done by the evaporation of liquor, the increased gas stream humidity also enhances the particle capture mechanisms.

The gas stream can be cooled in an evaporative cooler or in a presaturator or quencher. The latter is simply a small chamber immediately before the scrubber in which clean liquor is sprayed. Because of the short residence time within the presaturator or quencher, many of the droplets do not have time to evaporate completely; therefore, more than the minimum quantity of liquor is used. The evaporative cooler is usually a tall cylindrical vessel with liquid or air atomizing nozzles located near the top. The use of nozzles optimizes droplet evaporation due to smaller water droplet sizes created. At least 85% of the liquor injected into the evaporative coolers evaporates; therefore, the effluent liquor stream is quite small. The locations of evaporative coolers and presaturators in a wet scrubber system are shown in Figures 2-4a and b.

Alkaline material is often added to the scrubber liquor circuit in order to maintain the pH in a range in which corrosion is not a problem. The materials most frequently used include, limestone, dolomite, soda ash, and sodium hydroxide. The rate of feed of the alkaline material is controlled by a pH meter within the scrubber system, as shown in Figure 2-5. Another means of adding a neutralizing material is illustrated in Figure 2-1. When lime is used, a slaker is also required.

The liquor treatment system reduces the total solids content of the liquor prior to return of the liquor to the recirculation circuit. Common equipment for this purpose includes a clarifier and a rotary vacumn filter. Flocculant is added to the clarifier to improve the settling characteristics of the solids. The reduction in solids content reduces the potential for pump impeller erosion, nozzle erosion, and pipe pluggage. The clear effluent from the clarifier is returned to the main liquor circuit either at the recirculation tank or at the scrubber itself.

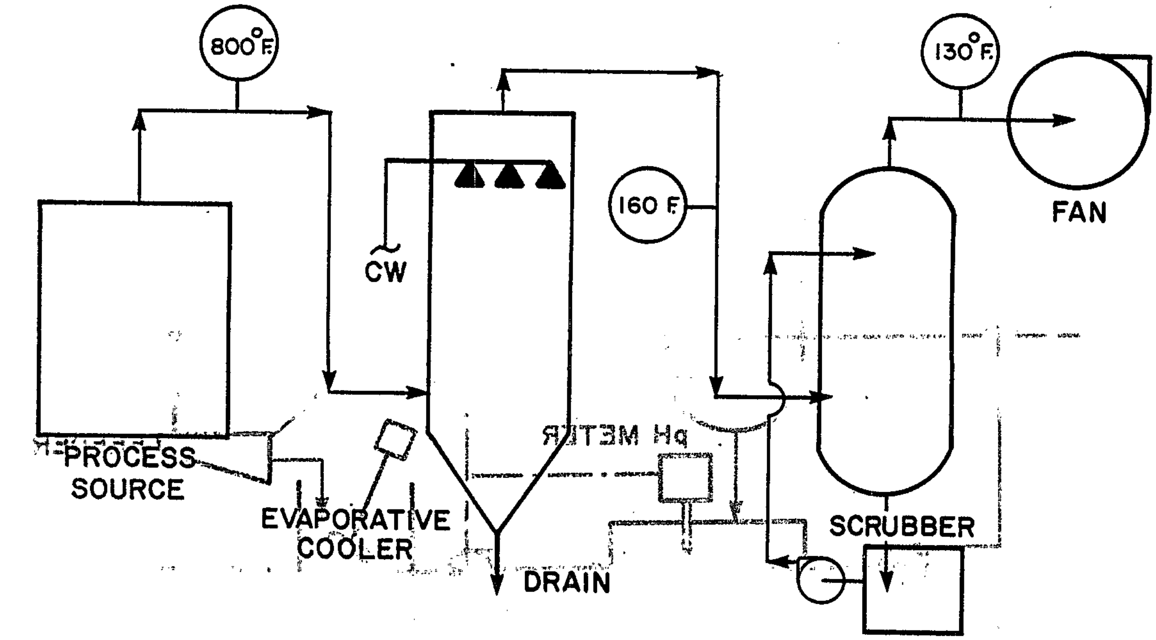


Figure 2-4a. Scrubber system with evaporative cooler.

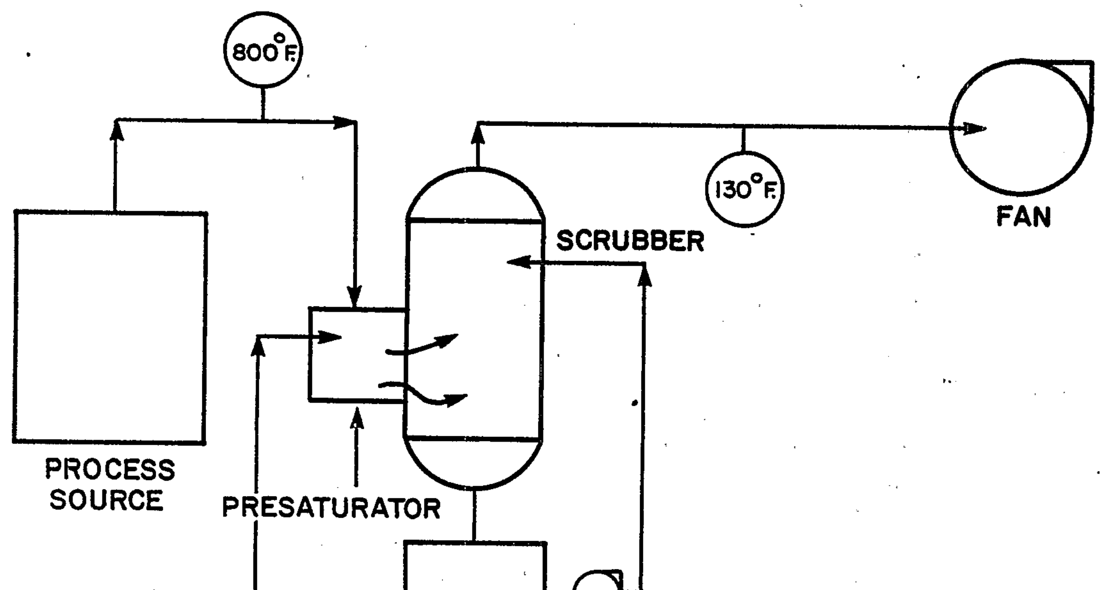


Figure 2-4b. Scrubber system with presaturator.

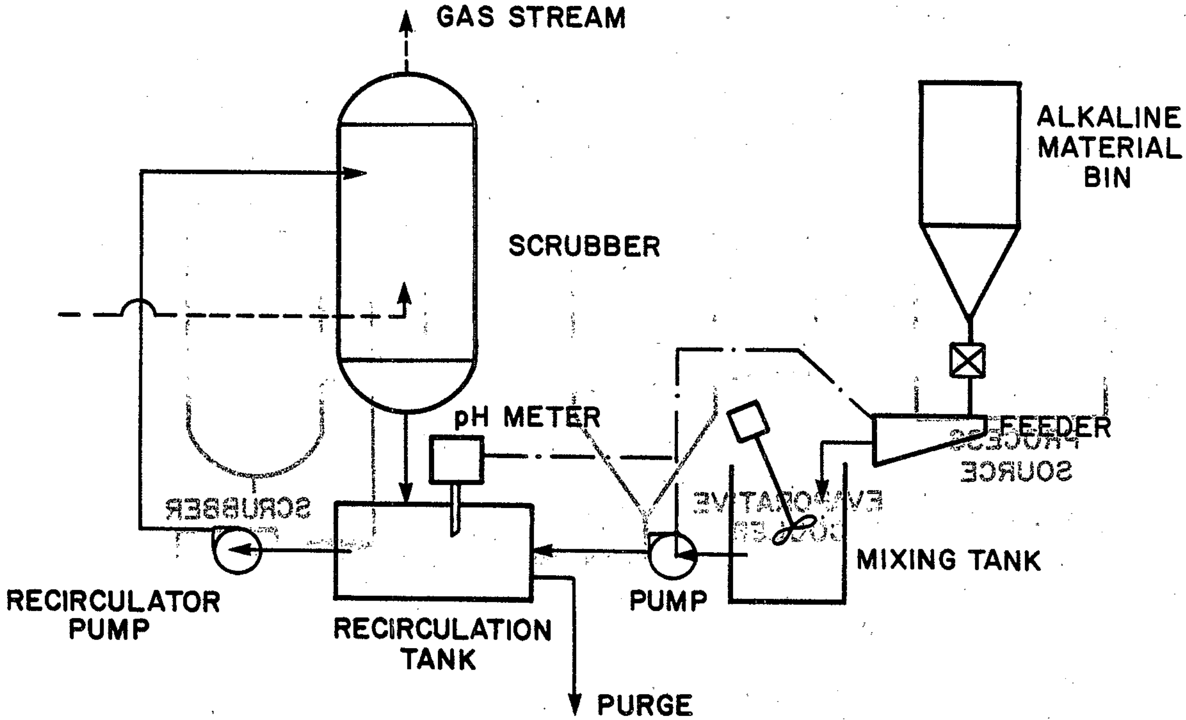


Figure 2-5. Neutralization system.

Many scrubber systems incorporate a bypass duct to protect the process equipment in the case of a major upset and the scrubber in the event of the loss of liquid flow. A set of dampers are used to prevent inadvertent leakage of untreated gas through the duct.

Flow of liquor through the system is maintained by pumps. The most common type of pump in wet scrubber systems is the centrifugal pump. If the liquor contains abrasive or corrosive materials, the pumps are fitted with protective liners.

2.2 IMPORTANCE OF PARTICLE SIZE DISTRIBUTION

The performance of all types of particulate wet scrubbers is highly dependent on the inlet particle size distribution. The importance of the particle size distribution is a result of the strong particle size dependence of the fundametal particle capture mechanisms used in scrubbers, namely, inertial impaction and to a lesser extent, Brownian diffusion.

Unfortunately, there are substantial differences in particle size distribution on a plant-by-plant basis. The particle size distribution can also have temporal variations at a specific scrubber system under different process operating conditions or due to process upsets. In some cases, the operating conditions of the scrubber itself can modify the inlet particle size distribution. Particle size is difficult to measure during routine evaluations and, therefore, less direct indications of a shift in particle size must be used.

2.2.1 Particle Capture Mechanisms

The key step involved in wet scrubbing is the capture of the particle into either liquid droplets, sheets, or jets. The principal physical mechanism used in commercially available systems is inertial impaction. Other physical phenomena aiding capture include: Brownian diffusion, diffusiophoresis, and thermophoresis. Electrostatic attraction may contribute to capture in certain cases such as venturi scrubbers where liquid atomization can result in static electrical charge buildup. These physical capture mechanisms are briefly reviewed to illustrate the sensitive relationship between scrubber performance and particle size.

2.2.1.1 Inertial Impaction. Entrained particles have a much greater mass and, therefore, a much greater inertia when in motion, than the surrounding gas. As a gas stream approaches an obstacle, the gas molecules pass on either side on it, leaving the particle propelled toward the obstacle by its inertia.

The typical droplet sizes in wet scrubbers range from 100 to 800 micrometers,[2,3] while the particle sizes of most interest are in the 0.1 to 10 micrometer range. There is normally a large difference in the initial relative velocity between the droplet and the particle. The effectiveness of impaction is proportional to the Stokes Number (K_I) defined in Equation 2-1.

$$K_I = \frac{C\, d_p^2\, \rho_p\, V}{18\, \mu\, D_c} \qquad \text{Equation 2-1}$$

where:

K_I = Stokes Number, dimensionless

C = Cunningham Slip Correction Factor, dimensionless

d_p = particle diameter, mA $(g/cm^3)^{0.5}$

ρ_p = particle density, g/cm^3

V = relative velocity between particle and droplet

D_C = diameter of droplet or collector water layer

μ = gas viscosity, k_g/m-s

The Stokes Number is proportional to the particle diameter squared. This relationship means that as the particle diameter increases, the ease of impaction increases substantially. Impaction is directly related to the particle density, which can vary from 0.2 g/cm^3 for hollow particles and flocculants to 3.0 g/cm^3 for certain types of metallic particles. There is a slight temperature dependence of the Stokes Number due to the temperature dependence of the viscosity term. The Cunningham Slip Correction Factor in Equation 2-1 is simply an adjustment for the discontinuous nature of gas resistance to particle movement for particles having sizes of less than 2 micrometers.

Scrubber design and operating conditions have a direct effect on the relative velocity term (V) and the collector diameter term (D_C), in Equation 2-1. The greater the relative velocity, the better the impaction. This arrangement may be achieved by introducing the liquid in a counterflow manner or by injecting the liquid in a rapidly moving gas stream and allowing the droplets formed to accelerate gradually up to the prevailing gas stream velocities. Impaction is inversely proportional to the size of the impaction target, such as the droplet.

2.2.1.2 Brownian Diffusion. Very small particles move randomly across gas streamlines because they collide with individual gas molecules. This movement can result in particle capture as a particle passes near a water droplet or sheet. This mechanism is only important for particles below 0.2 micrometer in diameter and becomes progressively more important as the particle size decreases from 0.2 micrometer. The effectiveness of diffusion is proportional to the absolute gas temperature.

2.2.1.3 Diffusiophoresis. As water vapor condenses on the surfaces of existing droplets, there is a net flow of material toward the surface of the droplets. The difference in the mass concentration as a function of the distance from the surface leads to an imbalance in the molecular collisions on a particle close to the surface of the droplet. This imbalance causes the particle to migrate toward the site of the condensation. The opposite effect occurs when the droplet is undergoing evaporation.

2.2.1.4 Thermophoresis. When there is a distinct temperature gradient, there is an imbalance between the forces exerted on the sides of a particle by the molecular collisons. The molecules on the higher temperature side have a greater velocity and thereby transfer more momentum to the particle when colliding than those molecules on the colder side. The result is a net movement toward the colder temperatures.

2.2.2 Dependence of Scrubber Performance on Particle Size

Because of the combined action of impaction and diffusion, the penetration curve as a function of the particle size generally appears as shown in Figure 2-6. The peak penetration corresponds to the 0.2 to 0.5

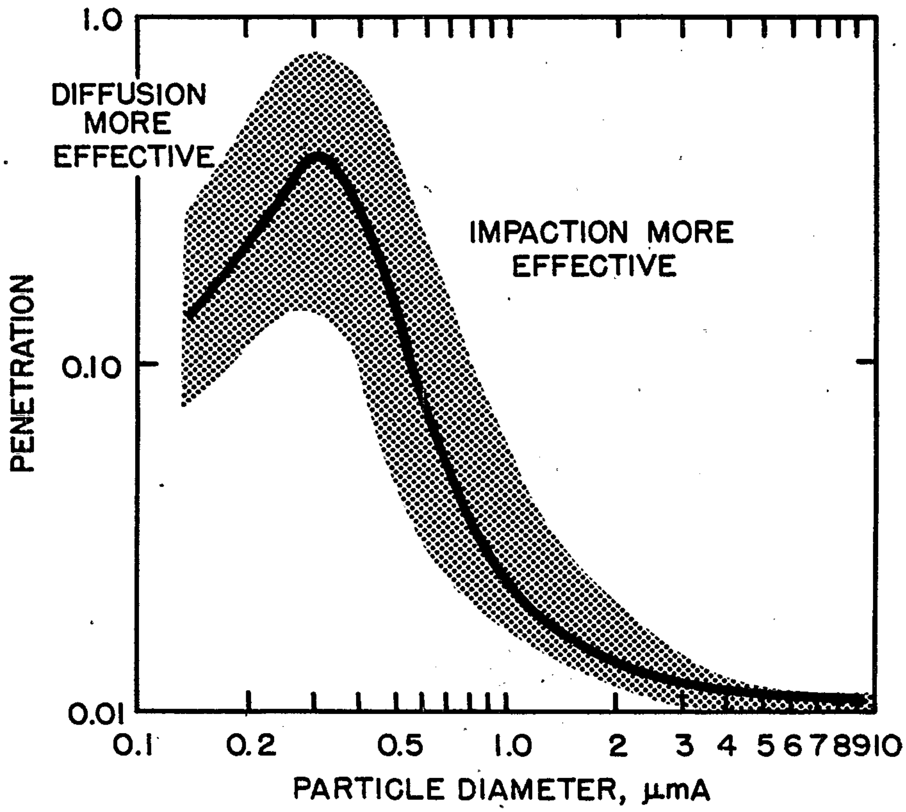


Figure 2-6. Hypothetical curve illustrating general relationship between penetration and particle size.

micrometer size range, in which inertial impaction is relatively ineffective and the particles are too large for significant diffusional capture.

The emissions from a given scrubber system depend primarily on the quantity of particulate matter in the size range from 0.1 to 5 micrometers and the penetration level achievable for the particle sizes. The latter is generally considered to be a function of the total power input into the scrubber and the type of scrubber itself.

The particle size dependence of venturi scrubbers is illustrated in Figure 2-7. The highest penetration is for particles of 0.5 micrometers in size. The beneficial effect of Brownian diffusion on penetration is not apparent in this figure. Most stack sampling techniques for particle sizing determine mass concentrations as the total mass with diameters less than a specific size (e.g., total less than 0.2 μmA). If the effect of Brownian diffusion had been included, the curve shown in Figure 2-7 would begin

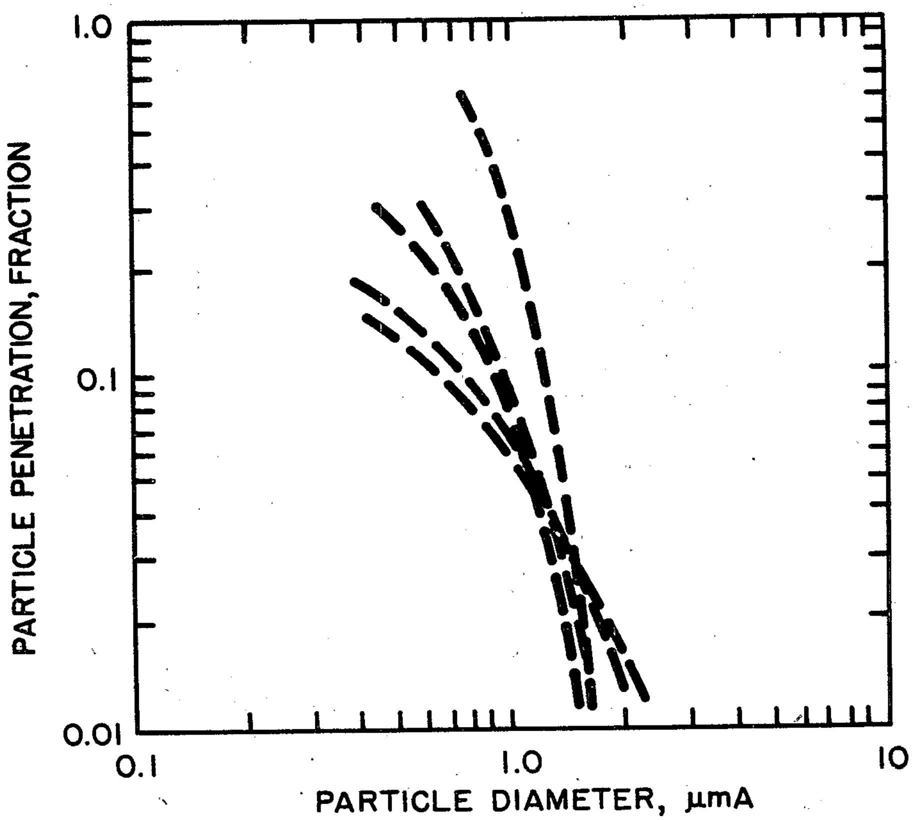


Figure 2-7. Fractional efficiency curve for venturi scrubbers.[7]

to resemble the curve presented in Figure 2-6. A number of similar particle size-penetration curves are presented in references 3, 4, and 5.

On a given scrubber system a shift in the particle size distribution in the gas stream has a major impact on the performance. The can be illustrated by use of the venturi scrubber model described in references 6 through 9. For a hypothetical set of operating conditions, the model was used to calculate the penetration. The mass mean particle size was varied from 5 to 20 micrometers and a standard deviation of 2.5 was used in all three cases. The results are shown in Figure 2-8. The predicted penetration increases by a factor of 3 when the size distribution shifts from a mass mean of 15 micrometers

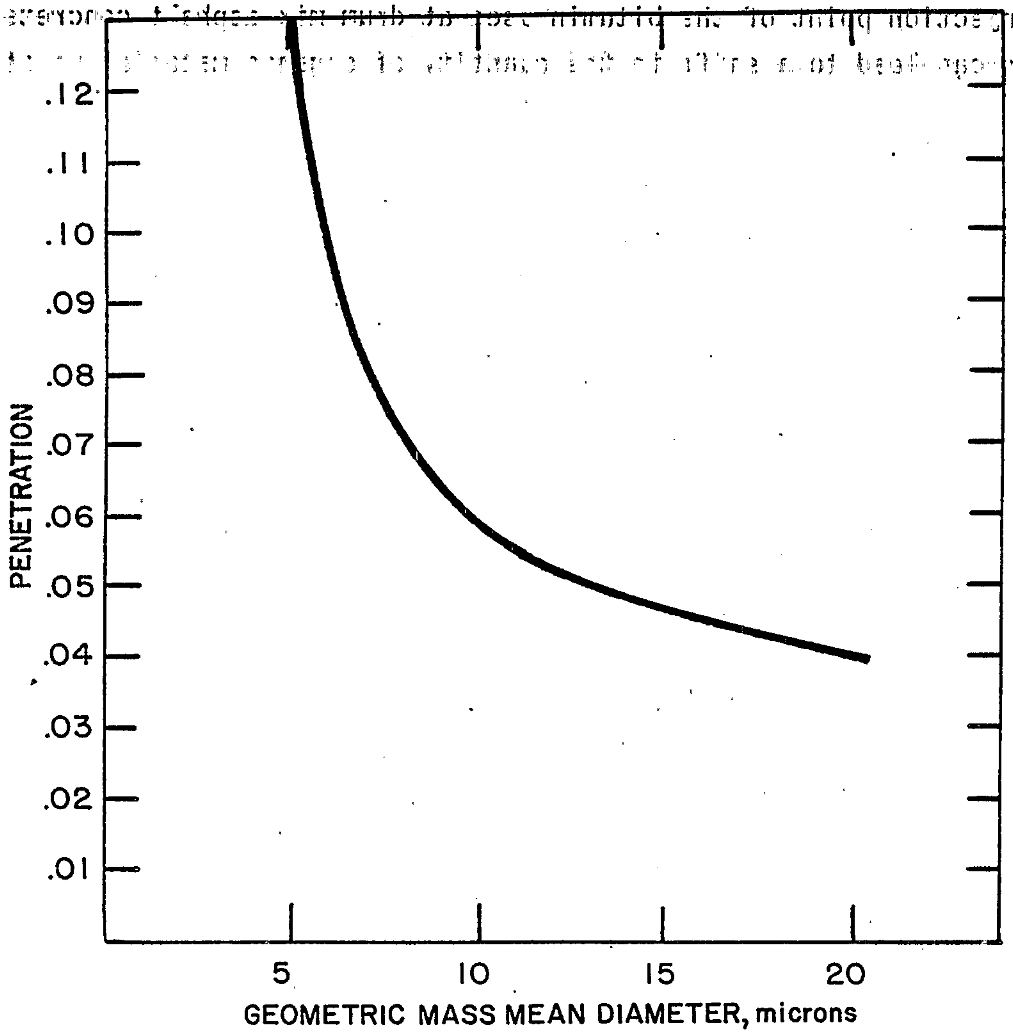


Figure 2-8. Predicted relationship between overall penetration and particulate mass mean diameter.

2.2.3 Factors That Modify Particle Size

Numerous process-related operating factors and upset conditions affect the particle size distribution at the scrubber inlet. Thus a wet scrubber system cannot be considered as a separate entity operating independently of the process it serves.

2.2.3.1 Process Operational Change. Any change that modifies the quantity of particulate and vaporous materials evolved from the process can cause a decrease in the particle size distribution. For example, an increase in the sodium content of the lime sludge feed to a lime kiln at a kraft pulp mill would substantially increase the quantity of 0.2 to 2 micrometer size particulate matter entering the scrubber. The change in the injection point of the bitumin used at drum-mix asphalt concrete plants can lead to a shift in the quantity of organic material volatilized and thereby increase the quantity of of very fine hydrocarbon aerosol particulate which must be removed.

The indications of a change in the process operation may include some of the following: a major increase or decrease in the gas temperature entering the scrubber, a change in the types of raw materials (to the extent this can be determined), an increase in the residual opacity of the plume downstream from the scrubber (bluish white material), and a change in the fuel characteristics. As many symptoms as possible should be considered together to reliably identify process changes as responsible for a particular shift in the particle size disbribution.

2.2.3.2 Evaporative Release. Many commercial wet scrubbers are preceded by a quench tower which serves to cool the gas stream to the 125° to 200°F temperature range prior to its entry into the scrubber. This is necessary to protect scrubber internal parts and may also improve particle capture.

The liquor quality used in the quench tower (or presaturator) varies from source to source depending on the types of spray nozzles used in the quench tower and the need to recycle liquor to minimize treatment costs. The total solids content can sometimes be as high as 15% by weight. Since a major portion of the liquor injected into the quench tower and/or presaturator evaporates, some of the solids entering as suspended and dissolved solids in the liquor are released as particulate matter.

Kalika has presented some calculated effects of evaporative release based on conditions observed at an incinerator scrubber.[10] The results are provided in Table 2-1. In preparing these data, he assumed an incinerator exit temperature of 1600°F with a humidity of 0.08 pound water per pound of dry air. He also assumed that 85% of the quench water droplets evaporate to dryness.

TABLE 2-1. EFFECT OF RECIRCULATION LIQUOR SOLIDS[10]

Solids in Recirculated Water, %	Water Recirculated to Quench, Gpm	Outlet Dust Loading, Lb./Min.	Apparent Scrubber Efficiency, %
-	0	0.032	98.0
2	22	0.114	92.9
5	25	0.259	83.9
10	26	0.512	68.2

As the solids content of the liquor is increased to 10% by weight, the emissions from the scrubber are predicted to increase by more than an order of magnitude. These data provide only a rough guide to the potential effect; the actual effect will depend on the droplet size distribution in the quench tower, the gas temperature at the quench tower inlet, the liquid-to-gas ratio at the quench tower, the residence time within the quench tower, and the manner in which the droplets shatter during the later stages of evaporation. A droplet must be completely evaporated before the suspended and dissolved particulate matter are released.

At the present time, the extent to which evaporative release contributes to additional particulate matter emissions is not well documented. Considerable study will be necessary to determine the evaporative conditions within a quench tower and the effect of the released material on the particle size distribution.

Indirect indications of potential or actual evaporative release include: high turbidity liquor going to the quench tower, frequent pluggage problems with the quench tower nozzles, high gas inlet temperatures, and high residual opacity.

2.2.3.3 Vapor Condensation. Some industrial sources generate organic and/or metallic vapor in addition to particulate matter. If these vaporous materials begin to condense in a homogeneous manner while passing through the scrubber, very little of this material will be captured. To the extent possible, the condensation process should be initiated as far upstream of the scrubber as possible to enhance heterogenous condensation on the surfaces of existing aerosols.

Symptoms of increased vapor condensation aerosol include a change in the process operating temperature, a change in the use of raw materials and/or corrosion inhibitors, and increased residual opacity plume downwind of the stack exit.

2.3 PRESSURE DROP AS A PERFORMANCE PARAMETER

The static pressure drop of the gas stream passing through a particulate wet scrubber is used extensively by both operators and inspectors to evaluate scrubber performance. In some cases, conclusions regarding adequacy of performance have been based solely on these data. The uses and limits of pressure drop as a performance parameter are examined in this section.

2.3.1 Definition of Pressure Drop

Pressure drop is the reduction in potential energy (through conversion to kinetic energy) of the gas stream as it passes from one point to another. It results from frictional losses on the ductwork and scrubber internal components, from acceleration of the gas and liquid streams, from the atomization of the liquor, and from any changes in elevation of the gas and liquid streams.

The scrubber pressure drop is simply the arithmetic difference between the static pressures of the gas stream at the inlet and at the outlet of the collector. If there are two collectors in series, the total pressure drop across the system is the sum of the two individual pressure drops. The additive nature of static pressure drop (P_t) is illustrated in Equation 2-2.

$$P_t = P_1 + P_2 + \ldots + P_n \qquad \text{Equation 2-2}$$

where:

P_t = total pressure drop of system

P_1 = pressure drop across unit 1

P_2 = pressure drop across unit 2

P_n = pressure drop across unit n

The same concept applies to a single scrubber with multiple trays. The pressure drop across the scrubber is the sum of the pressure drops across each tray plus the pressure drop across the demister.

If there are two scrubbers in parallel on a given effluent stream, as shown in Figure 2-9, the pressure drop across the system is equivalent to the pressure drop across either unit. In other words, the pressure drop along each path must be identical. The equivalent nature of static pressure along parallel paths is illustrated in Equation 2-3.

$$P_t = P_2 - P_1 = P_4 - P_3 \qquad \text{Equation 2-3}$$

where:

P_t = total pressure drop of system

P_1 = static pressure at inlet of path A

P_2 = static pressure at outlet of path A

P_3 = static pressure at inlet of path B

P_4 = static pressure at outlet of path B

While the pressure drops across each path must be identical, the pressure drops across each scrubber may not be identical. If one of the paths has longer ductwork, more elbows, or a flow restriction such as a damper or solids deposit, then the pressure drop of the scrubber on this path will be less than that in the other path. This difference is illustrated in Figure 2-10.

With certain types of venturi scrubbers, there is static pressure recovery in the divergent section; in other words, the pressure drop across the throat is greater than the pressure drop across the entire venturi section (convergent section - throat - divergent section). This occurs in units where the divergent section expansion angle is equal to

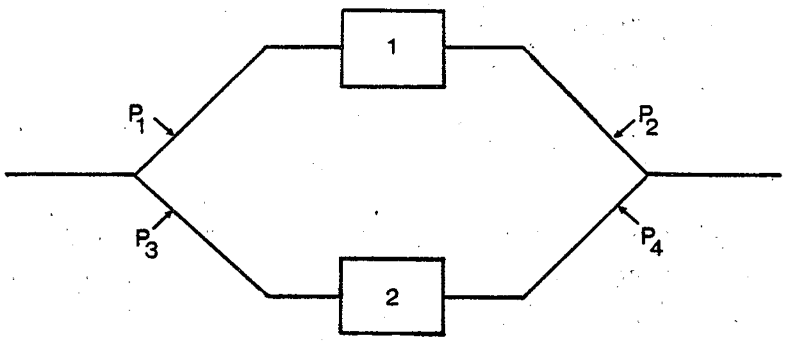


Figure 2-9. Parallel scrubber trains.

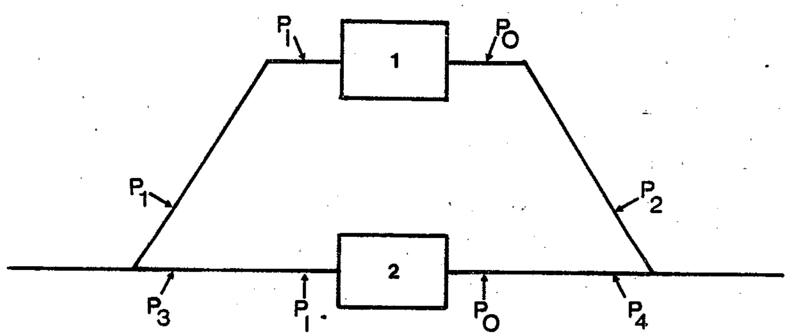


Figure 2-10. Parallel scrubber trains with unequal duct resistance.

or less than 7.5 degrees as shown in Figure 2-11. With units of this type, boundry layer separation probably does not occur.[11] Pressure recovery can also occur in scrubbers with a slightly greater expansion angle; however, the extent of the gain would be slight. Most commercial designs have a divergent angle (β) of greater than 25° and many are in the 35° to 45° range. A few types do not even include a divergent section to the venturi; pressure recovery in these would be negligible.

In order to properly define the pressure drop, it is very important to specify the locations where the "inlet" and "outlet" measurements are made. A sketch of the system showing the scrubber, all major internal parts, and flow restrictions of the inlet and outlet ductwork is helpful in avoiding misinterpretation of the pressure drop value.

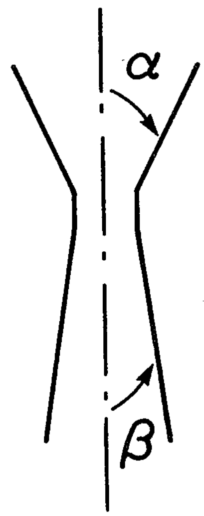


Figure 2-11. Converging and diverging venturi angles.

2.3.2 Relationship Between Penetration and Pressure Drop

There is a useful relationship between the collection efficiency of a particulate wet scrubber and the pressure drop of the gas stream passing through it. For this reason, operators have been using pressure drop as an indicator of scrubber performance for a long time.

In 1956, Kemack and Lapple proposed that penetration is a function of the total energy consumption within the scrubber, not just the energy loss represented by the gas phase pressure drop.[12] This theory was expanded and stated in its present form by Semrau in 1960.[13] (See also references 14-16.) Referred to as the Contact Power Theory, it has enjoyed broad acceptance by both operators and regulatory agencies. Since much of the available data are presented in the Contact Power format, the basis of this theory is briefly examined.

According to the Contact Power Theory, scrubber efficiency is directly related to the total energy consumption of the system. The power can be expended by the gas stream, the liquid stream, by a mechanical rotor, or by a combination of all three. Other variables such as collector size, scrubber design characteristics, liquid-to-gas ratio, liquor surface tension, and gas velocity are assumed to have no independent effect on the scrubber performance. Accordingly, it should be possible to quantify the emissions from a specific wet scrubber system using only those parameters with an effect on the power input.

The Contact Power Theory has also been used to compile industry-by-industry mass emission-contact power curves. In this section, the adequacy of these unit specific and the industry wide applications of the theory are evaluated .

The Contact Power equations commonly presented in the literature are reproduced below. These apply to all particulate wet scrubbers.*

$$P_G = 0.158 \ \Delta P \qquad \text{Equation 2-6}$$

$$P_L = 0.583(Q_L/Q_G) \qquad \text{Equation 2-7}$$

$$P_T = P_G + P_L \qquad \text{Equation 2-8}$$

$$N_t = \alpha (P_T)^{\beta} \qquad \text{Equation 2-9}$$

$$\eta = 1 - e^{(-N_t)} \qquad \text{Equation 2-10}$$

$$P = 1 - (\eta/100) \qquad \text{Equation 2-11}$$

where:

ΔP = gas phase pressure drop, inches w.c.

P = penetration

η = collection efficiency, percent

N_t = number of transfer units, dimensionless

α, β = empirical constants, dimensionless

P_t = total power input, hp/1000 ACF

P_L = power input from liquid stream, hp/1000 ACF

P_G = power input from gas stream, hp/1000 ACF

Q_L/Q_G = liquid-to-gas ratio, gal/1000 ACF

The constants α and β are functions of the particle size and particle characteristics. Equations 2-10 and 2-11 simply indicate the relationship between transfer units, efficiency, and penetration.

The derivation of these equations, which was only briefly described by Semrau,[14] was apparently based on a mechanical energy balance across the scrubber. To fully evaluate the adequacy of these equations and the means to apply the Contact Power approach, the derivation was reconstructed. It is presented below. The starting point is the basic Bernoulli Equation for incompressible flow.

*An additional term for shaft power would be required if a mechanical rotor were included in the scrubber.

$$\left[\frac{P_1 - P_2}{\rho_G}\right]G + \frac{g}{g_c}\left[Z_1 - Z_2\right] G + \left[\frac{a_1 V_1^2 - a_2 V_2^2}{2\ g_c}\right] G + W_p - h_{f_G} = 0$$

Equation 2-12

$$\left[\frac{P_p - P_2}{L}\right] L + \frac{g}{g_c}\left[Z_p - Z_2\right] L + \left[\frac{{}_pV_p^2 - {}_2V_2^2}{2\ g_c}\right] L + W_p - h_{f_L} = 0$$

Equation 2-13

where:

P_1 = gas static pressure at point 1 (upstream)
P_2 = gas static pressure at point 2 (downstream)
ρ_G = gas density
G = gas stream flow rate
g = gravitation acceleration
g_c = conversion factor, 32.17 ft-lb/lbf-sec
Z_1 = gas stream elevation at point 1
Z_2 = gas stream elevation at point 2
a_1, a_2 = flow angles
V_1, V_2 = gas stream velocities at points 1 and 2
W_p = shaft work
h_{f_G} = fraction loss of gas stream on scrubber walls
h_{f_L} = fraction loss of liquid
P_p = liquid pressure in pump or nozzle
Z_p = elevation of liquid at point of injection
L = liquid flow rate

The equations can be simplified by deletion of the terms relating to shaft work. They have also been rearranged to resemble the Contact Power equations (Equations 2-6, 2-7, and 2-8).

$$P_G = \left(\frac{\Delta P}{\rho_G}\right) G = h_{f_G} - \frac{g}{g_c}\left[Z_1 - Z_2\right] G - \left[\frac{a_1 V_1^2 - a_2 V_2^2}{2 g_c}\right] G$$

Equation 2-14

$$P_L = \left(\frac{\Delta P_L}{\rho_L}\right) L = h_{f_L} - \frac{g}{g_c}\left[Z_p - Z_2\right] L - \left[\frac{\alpha_p V_p^2 - \alpha_2 V_2^2}{2g_c}\right] L$$

Equation 2-15

$$P_T = P_G + P_L = \left(\frac{\Delta P_G}{\rho_G}\right) G + \left(\frac{\Delta P_L}{\rho_L}\right) L$$

Equation 2-16

$$P_T = \left[\left(\frac{\Delta P_G}{\rho_G}\right) + \left(\frac{\Delta P_L}{\rho_L}\right) (L/G)\right] G$$

Equation 2-17

Since the liquor pressure is zero psig, ΔP_L is equivalent to P_L.

$$\frac{P_T}{G} = \frac{\Delta P_G}{\rho_G} + \left(\frac{P_L}{\rho_L}\right) (L/G)$$

Equation 2-18

The left hand term, P_T/G is identical to the contact power form of horsepower per 1000 ACF. To convert the gas phase energy term, P_G/ρ_G, to the form of Equation 2-6, the gas density at 70^oF, 14.7 psia must be inserted. This reconstructed derivation is intended to demonstrate a very important point, namely that total energy input is a function of gas density. Too often Equation 2-6 has been used without questioning the applicability of the "constant," 0.158. The actual gas density can vary substantially as a function of the inlet gas temperature, the scrubbing liquor inlet temperature, the liquid-to-gas ratio, and the outlet static pressure.

As stated earlier, the form of the Bernoulli Equation used in the derivation of the Contact Power equation applies only to incompressible flow. Since it is conceivable that the gas density varies more than 10% while passing through some types of scrubbers, these equations would not be strictly applicable.[17] Gas density data at various humidities, temperatures, and static pressures are presented in the Appendix A to illustrate the degree of variability possible.

The presssure drop term in Equation 2-18 applies only to the throat in a venturi scrubber. If there is some degree of pressure recovery in the divergent section of the venturi, the observed pressure drop will be lower than that used in this equation.

Despite the theoretical limits of the Contact Power Theory, there appears to be a number of cases in which it provides reasonable correlations between performance and energy input. A number of correlations originally compiled by Semrau are provided in Figures 2-12, 2-13, 2-14, and 2-15.[13] The gas phase pressure drop is probably the dominant energy loss in these correlations.

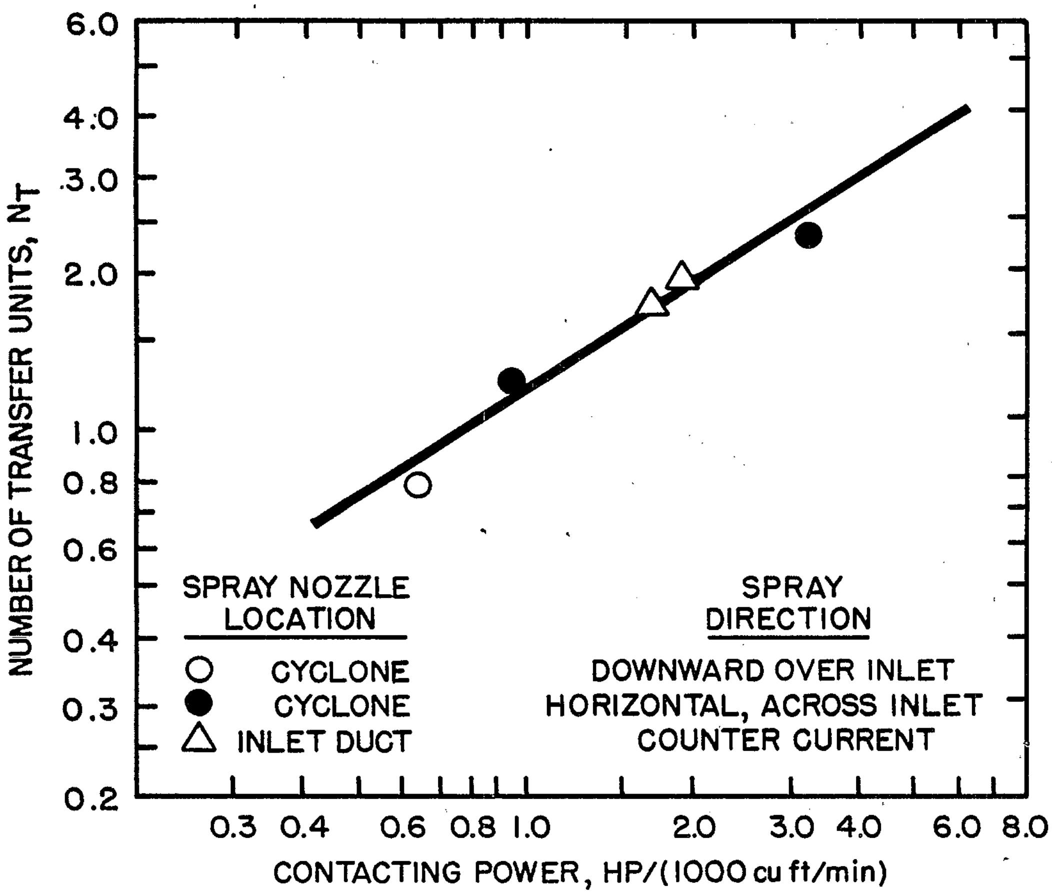


Figure 2-12. Contact power curve for a cyclone scrubber controlling talc dust.[13]

All of these data are from very early studies and were obtained with test methods that are not as accurate as current methods. However, the data do support the contention that emissions corelations can be developed for a group of similar sources using only the power input and possibly just the pressure drop.

Figure 2-15 is presented specifically to demonstrate that the liquid-to-gas ratio does not have any independent effect.[13] Semrau qualifies the statement, however, by suggesting that some effect may occur at very low liquid-to-gas ratios of 1 to 3 gallons per 1000 ACFM.[18] No data in this range was apparently available when the data in Figure 2-15 was originally compiled.

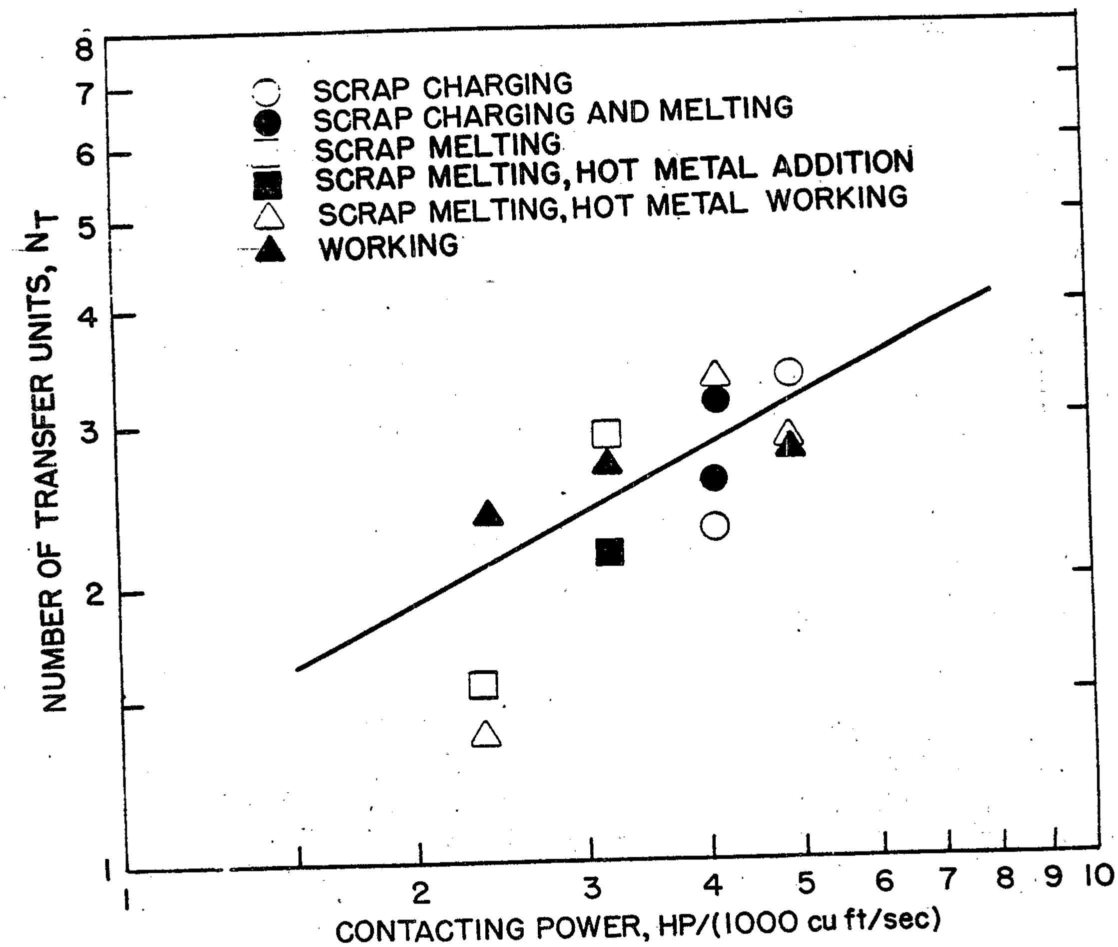


Figure 2-13. Contact power curve for venturi scrubbers on open hearths.[13]

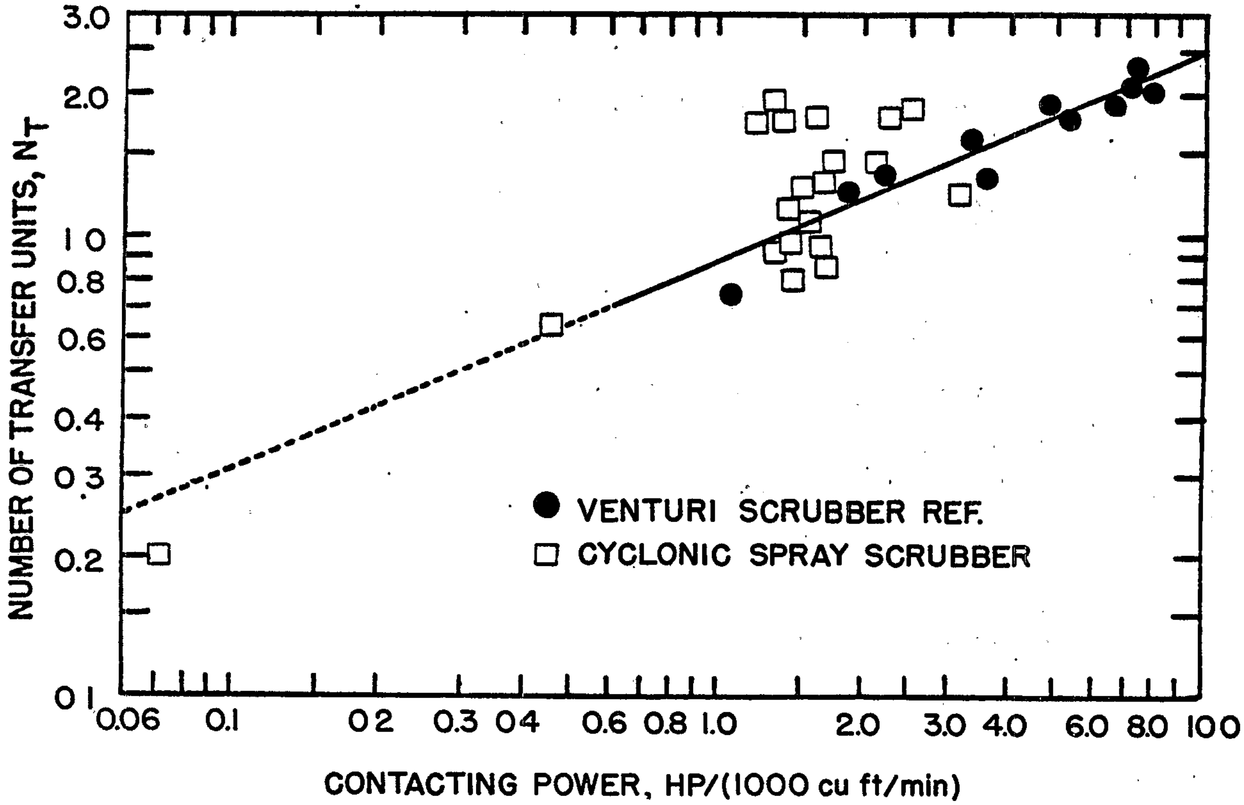


Figure 2-14. Contact power curve scrubbers controlling ferrosilicon furnace fume.[13]

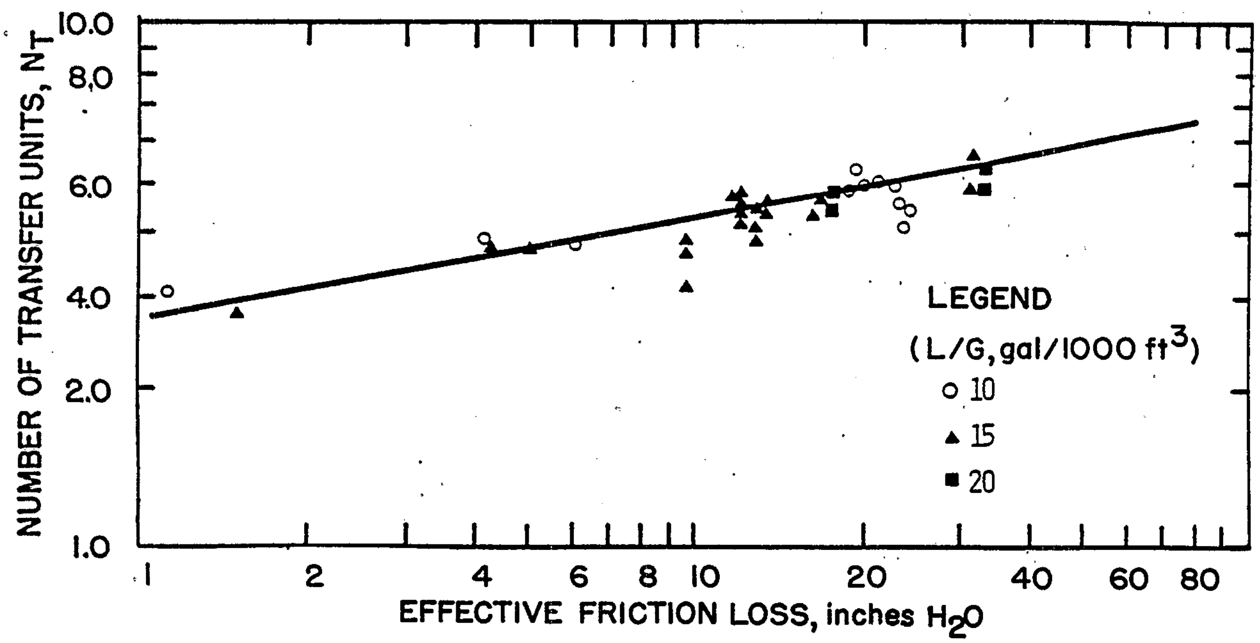


Figure 2-15. Contact power curve for venturi scrubbers illustrating lack of independent effect of the liquid-to-gas ratio.[18]

Walker and Hall[19] have compiled a contact power correlation for flooded disc venturi scrubbers serving four commercial lime kilns. Data from a pilot plant were also included in the data set. The resulting emissions-power input correlation presented in Figure 2-16 suggests a linear relationship between the pressure drop (the only significant energy input is the gas phase) and the measured emissions. To further evaluate its usefulness, the curve has been replotted (see Figure 2-17) into a more conventional format and the confidence interval prepared (using the procedures presented in Appendix B).

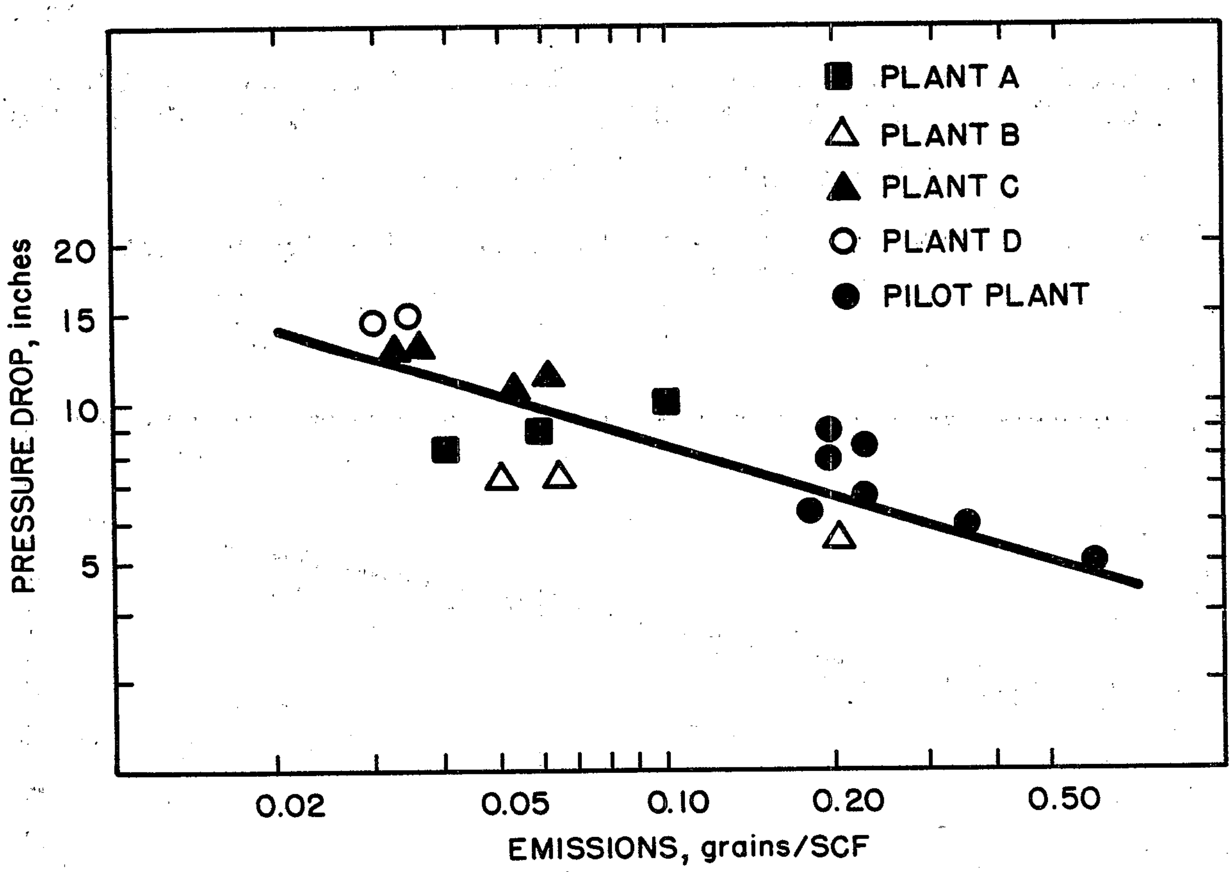


Figure 2-16. Relationship between pressure drop and emissions for flooded disc scrubbers on lime kilns.

It is readily apparent in the modified curve of Figure 2-17 that there is considerable scatter in this correlation. For example, at a pressure drop of 9 inches, the emissions can vary from 0.075 grain per ACF to as high as 0.20 grain per ACF. Obviously, the degree of scatter would preclude application of this type of curve for the purposes of evaluating compliance with an emission standard. During the preparation of this curve, it was not possible to determine whether individual site-specific correlations would have less scatter, because the raw data was not included in reference 19.

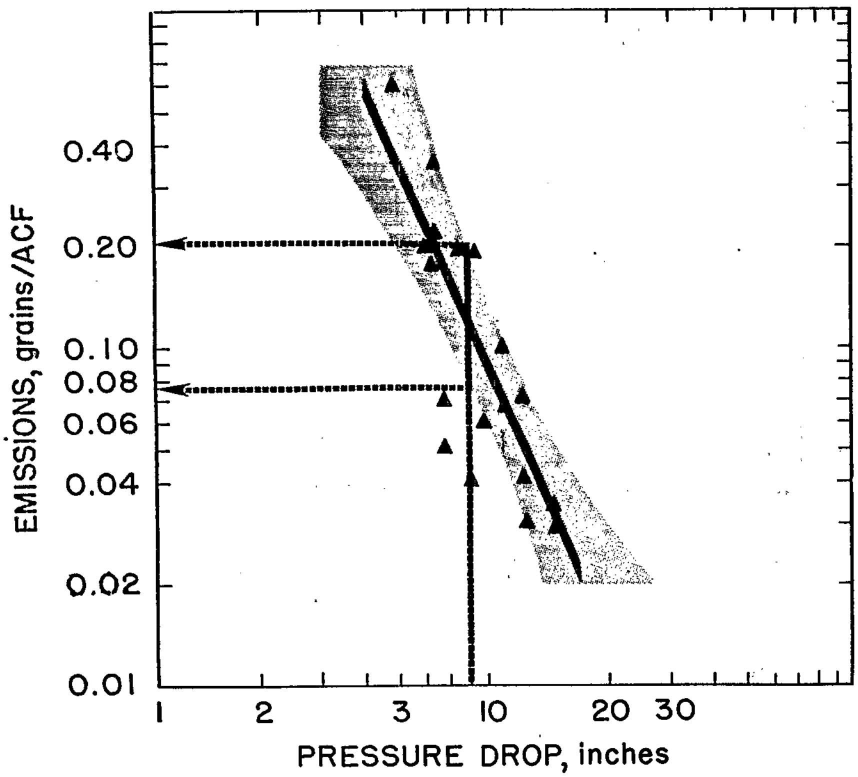


Figure.2-17. Replotted Walker and Hall data; 90% confidence interval is denoted by shaded area.

Kashdan and Ranade have summarized emissions data and contact power levels (uncorrected for saturated gas density) for pulverized coal and lignite-fired utility boilers [20]. The modest degree of scatter in Figure 2-18 is due in part to the inclusion of data from various types of scrubber systems incuding the Krebs Preformed scrubber, the UOP Turbulent

Contact Absorber, and several major types of venturi scrubbers. Considering the diversity of scrubber designs and the major differences in the fuel characteristics, it is remarkable that any correlation is apparent.

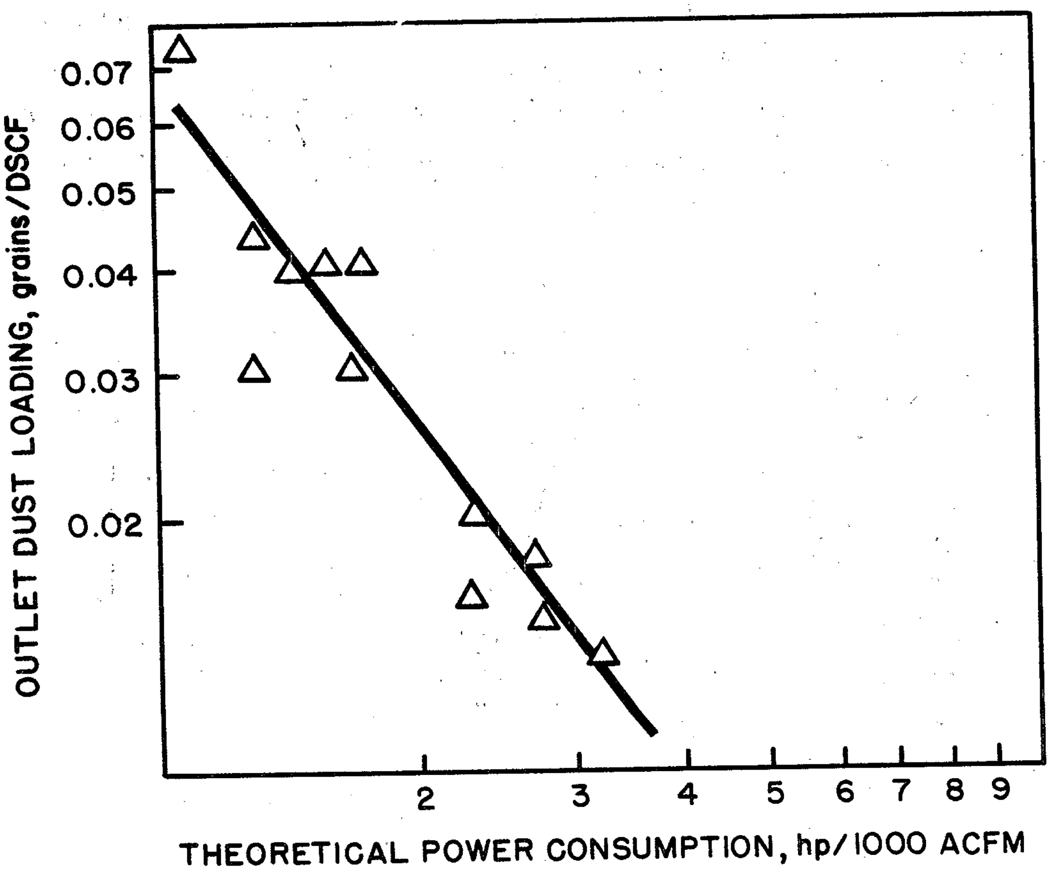


Figure 2-18. Pressure drop versus emission for wet scrubbers serving coal-fired utility boilers.[20]

A subset of Kashdan and Ranade's data was used to prepare a contact power curve for power plants using only venturi-type scrubbers (see Figure 2-19). It is apparent that the scatter is substantially reduced. The range of variables for this subset of data is presented along with the curve to demonstrate that even with this small data group, there is considerable variation. Additional testing and evaluation is necessary to confirm that a curve representing all types of coal-fired boilers with venturi scrubbers can be prepared. Data from Kansas City Power's LaCygne Station are considerbly higher than the other points.

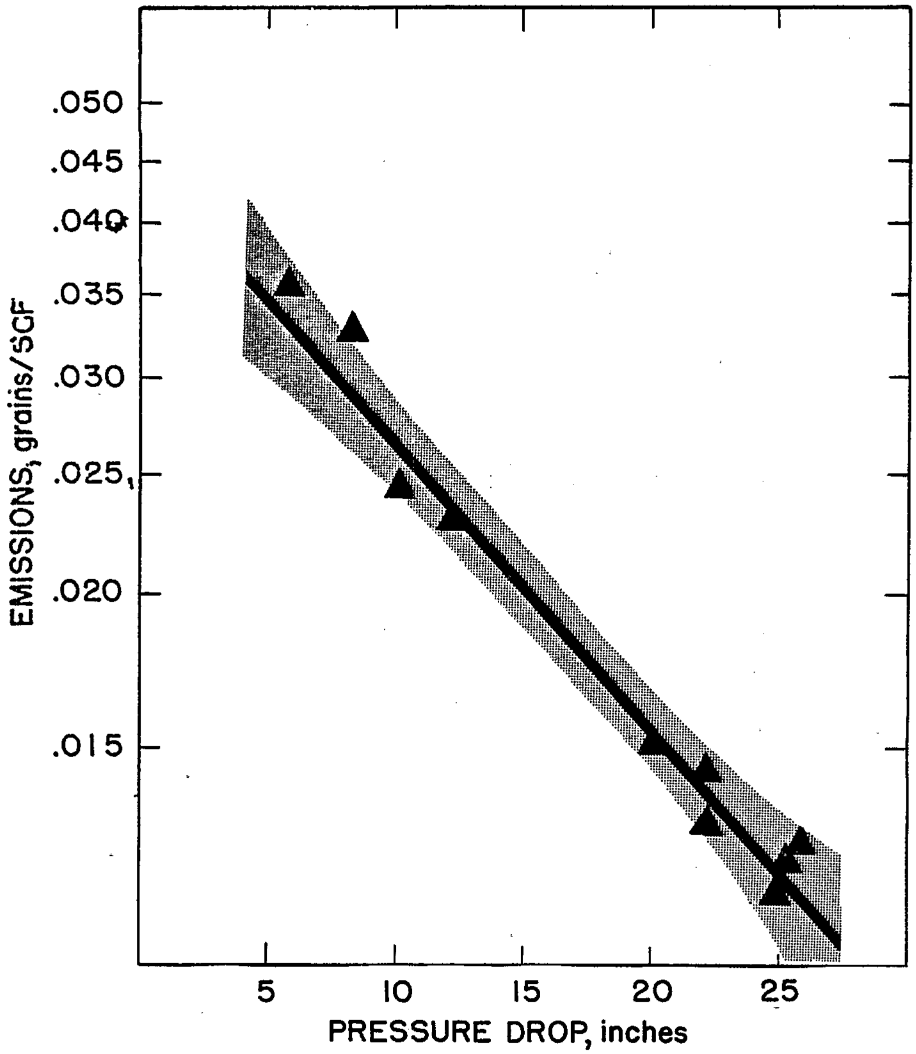


Figure 2-19. Replotted data of Kashdan and Ranade using only scrubbers; 90% confidence interval is denoted by shaded area.

Genoble, et al. have collected a number of emission-contact power correlations, two of which are shown in Figures 2-20 and 2-21.[16] In both of these cases, there is considerable scatter in the data. The scatter in the data set for the coal preparation plant thermal dryers has been partially attributed to differences introduced by the various organizations conducting these tests.

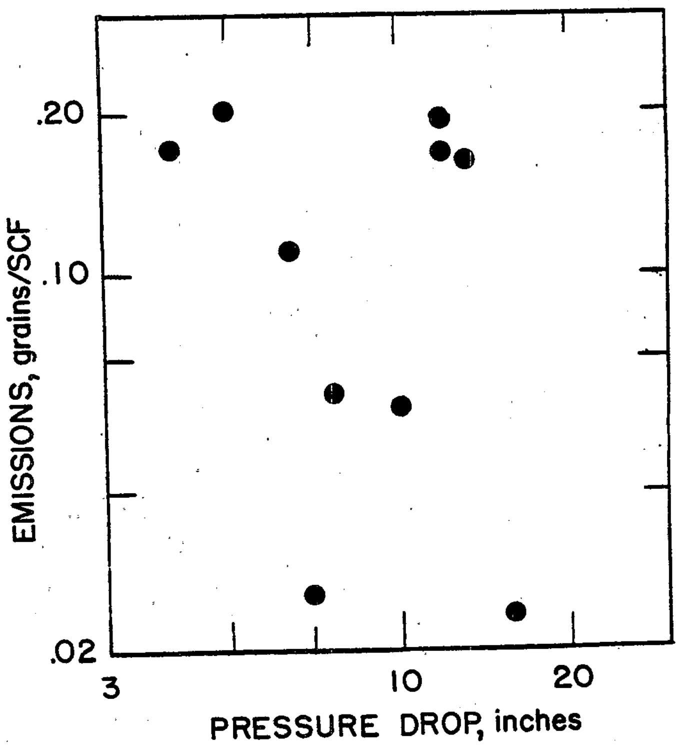


Figure 2-20. Pressure drop versus emissions data for venturi scrubbers serving asphalt plants.[16]

The data scatter in the asphalt concrete plant curve, the thermal dryer curve, and many of the curves presented earlier, is evidence of the weakness of industry wide correlations. These correlations inherently cannot take into account the numerous important site-specific variables which include, but are not limited to, particle size distribution, particle size distribution, particle surface characteristics, liquid-to-gas ratio, gas-liquor maldistribution, and liquor droplet size. Correlations prepared on a site-specific basis should be less vulnerable to these variables and hence, should be more useful for evaluating scrubber performance.

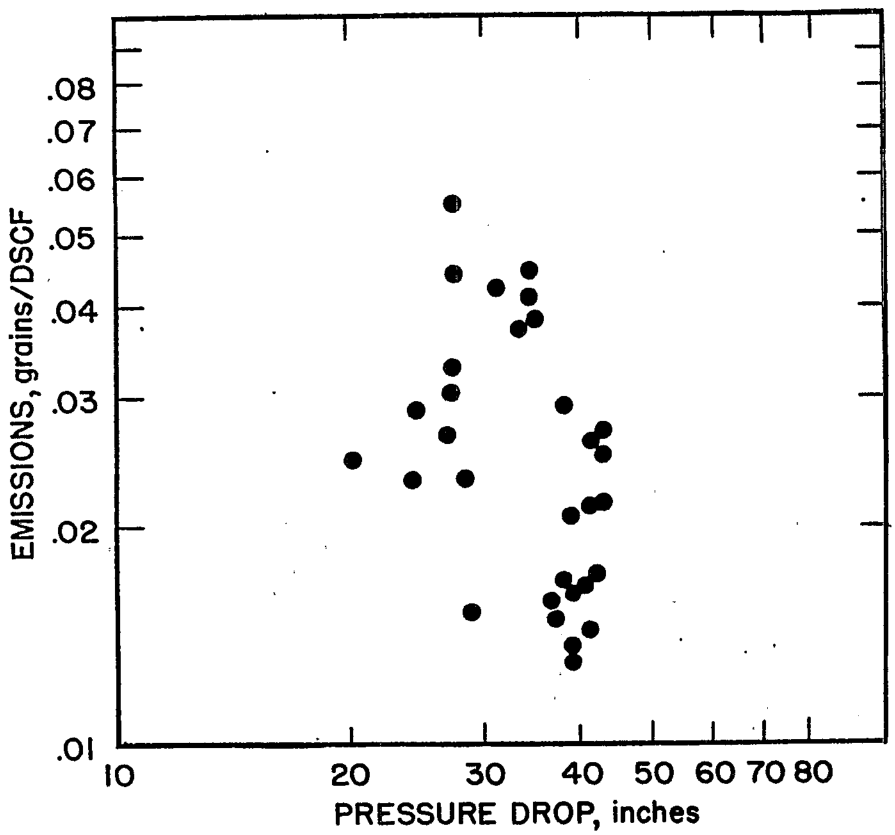


Figure 2-21. Pressure drop versus emissions data for venturi scrubbers serving coal thermal dryers.[16]

Site-specific data are very limited since few operating wet scrubber systems have been tested enough times for an emissions - contact power correlation to be prepared. Available data are usually limited to pilot scale equipment.

Pilot plant wet scrubber data for the Minnesota Power and Light system have been reported by Johnson and also by Nixon and Johnson.[21] The scrubber tested handled a 3200 ACFM slip stream from the Clay Boswell Station, Unit No. 3. Emission tests conducted during periods when two different coal supplies were being burned are summarized in Figure 2-22. The data for the scrubber are very consistent, despite the slight differences apparently introduced by the coal supplies.

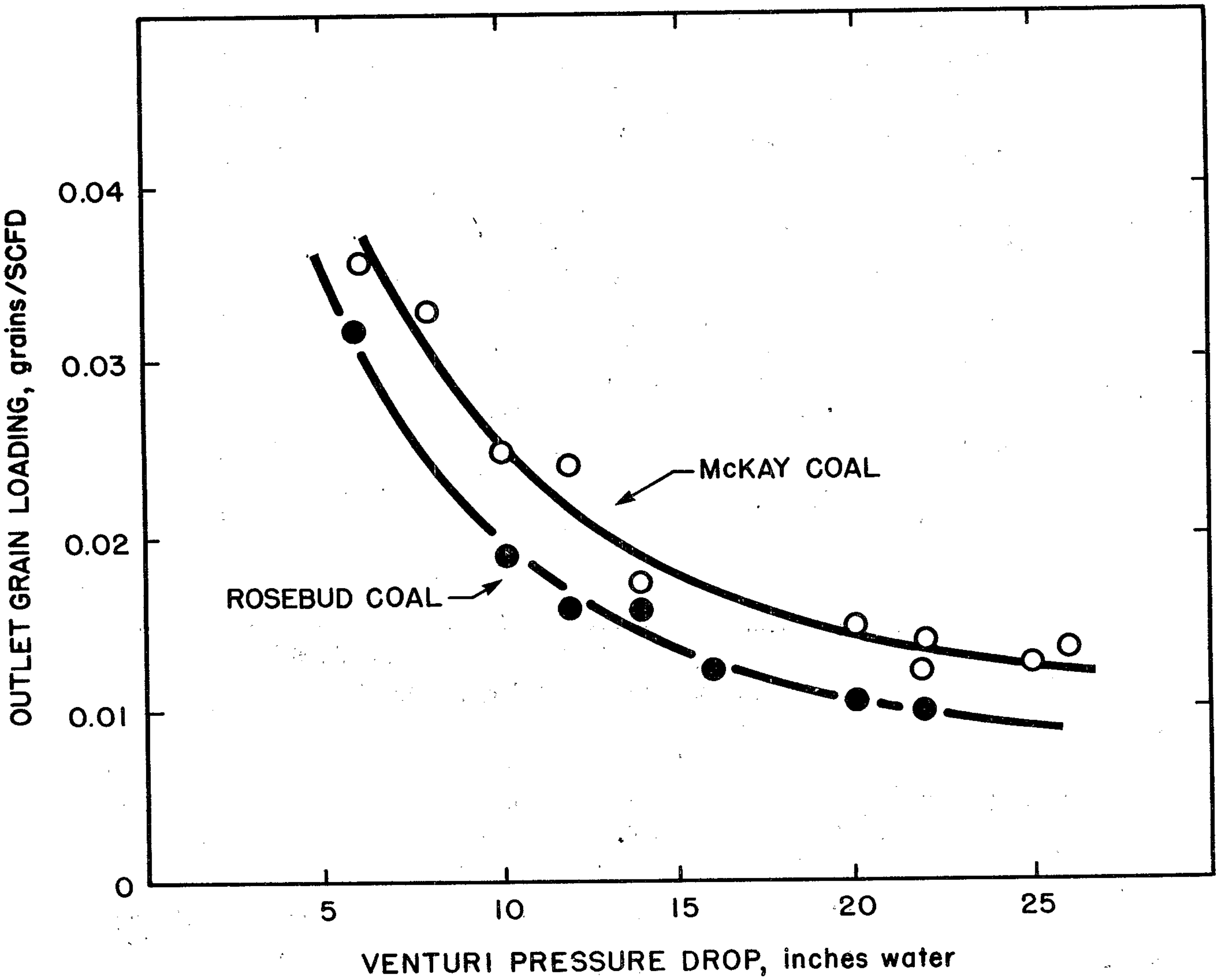


Figure 2-22. Relationship between pressure drop and emissions for a pilot scale venturi scrubber on a coal-fired boiler slip stream.

A contact power relationship for a full scale Q-Basic Oxygen Process (Q-BOP) furnace is presented in Figure 2-23. It was prepared from a tabulated data set provided by Kemner and McIlvaine.[22] The data are for three identical vessels controlled by adjustable throat Baumco venturies in series with venturi prequenchers.

The values shown on Figure 2-23 represent the average pressure drops during the period of 5 to 11 minutes into the oxygen blow. The pressure drop variation during cycle is due to the rate of gas evolution. The pressure drop values have not been corrected for gas density since the necessary temperature data were not included.

The correlation between the average pressure drop and the outlet dust loading has very little scatter. This may be partially due to the identical design and operating conditions of the three vessels. A site-specific relationship of this type would be adequate for an emissions correlation. The relationship, however, wuold probably not be applicable to other basic oxygen furnaces because of the significant differences made by the various types of hooding and process conditions on the particle characteristics.

Since performance is affected by so many variables, from a number of different scrubbers should not be grouped into a single correlation. It would be preferable to use the contact power approach only on a site-specific basis. Even in this case, it would be necessary to confirm that there have been no major operating changes that would invalidate the mass emission-power correlation.

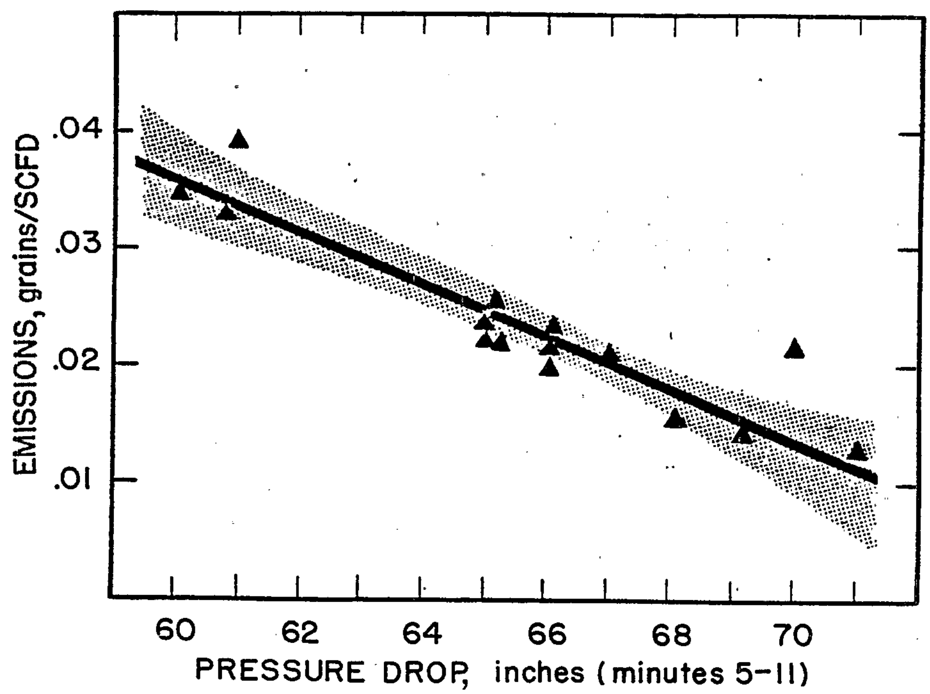


Figure 2-23. Pressure drop versus emissions data for venturi scrubbers serving three Q-BOP furnaces (plotted using data of Kemner and McIlvaine).[22]

2.4 PLUME AND BREECHING OPACITIES AS PERFORMANCE PARAMETERS

Regulatory agencies and control equipment operators routinely use plume opacity as an indicator of the particulate matter removal performance. In the case of wet scrubbers, however, the use of opacity has been limited by the practical problems created by the condensation of water droplets in the plume.

Theoretically, opacity could be a meaningful operating indicator since particles that scatter visible light most effectively are in the range of 0.2 to 2 micrometers and this coincides with the peak penetration range for the particles treated in a wet scrubber system (as was shown in Figure 2-6.) Thus, as the penetration through the scrubber system increases in this important size range, the opacity should also increase substantially.

Mass emission-opacity correlations have rarely been developed based on manual observations. This is partially due to the lack of sufficient emission test data and partially due to the difficulty in making these observations. For example, in compiling these correlations it is important that the observational path length through the plume remain the same. This is possible only when the condensation of water droplets occurs at a point downstream of the stack. Under these somewhat unusual conditions, it is possible to make the observation of opacity at a point directly above the stack, where tne path length is known. Observation of the residual opacity of a plume downwind of the stack is not as useful since the path length at this point can be highly variable due to meteorological conditions and dilution of the plume becomes a factor.

As early as 1963, an extractive instrument was tested as a means to evaluate the stack opacity without interference from water condensation.[23] The device consisted of a photocell mounted in a flow-through gas cell. The source of light was a simple flashlight bulb. The sample was extracted through a heated sample line to prevent condensation, and the instrument was calibrated using neutral density filters. While successful performance was claimed, it is doubtful that this instrument could satisfy the specification requirements of present day transmissometers.

In some cases, a conventional transmissometer has been successfully utilized as a continuous monitor. Very often condensation of water droplets downsteam of the scrubber does not occur in the ductwork. Therefore, a transmissometer installed in these locations should perform satisfactorily. A study by Nixon and Johnson at the Minnesota Power and Light plant using a pilot scale scrubber system included the evaluation of the plume opacity as a function of the mass concentration in the effluent.[21] The opacity was determined using a Lear Siegler RM41 transmissometer mounted along a 6'6" section of the outlet duct. As seen in Figure 2-24, the study showed a linear relationship between the mass concentration and the opacity. This supports the logical presumption that opacity should be a useful indicator of mass emissions when the opacity can be accurately determined.

More recent test work has been done using a heated extractive sample line similar in concept to this early instrument.[24] The opacity monitor in this case, however, is a Nephleometer which measures light scatter. Test work done at a kraft pulp mill recovery boiler equipped

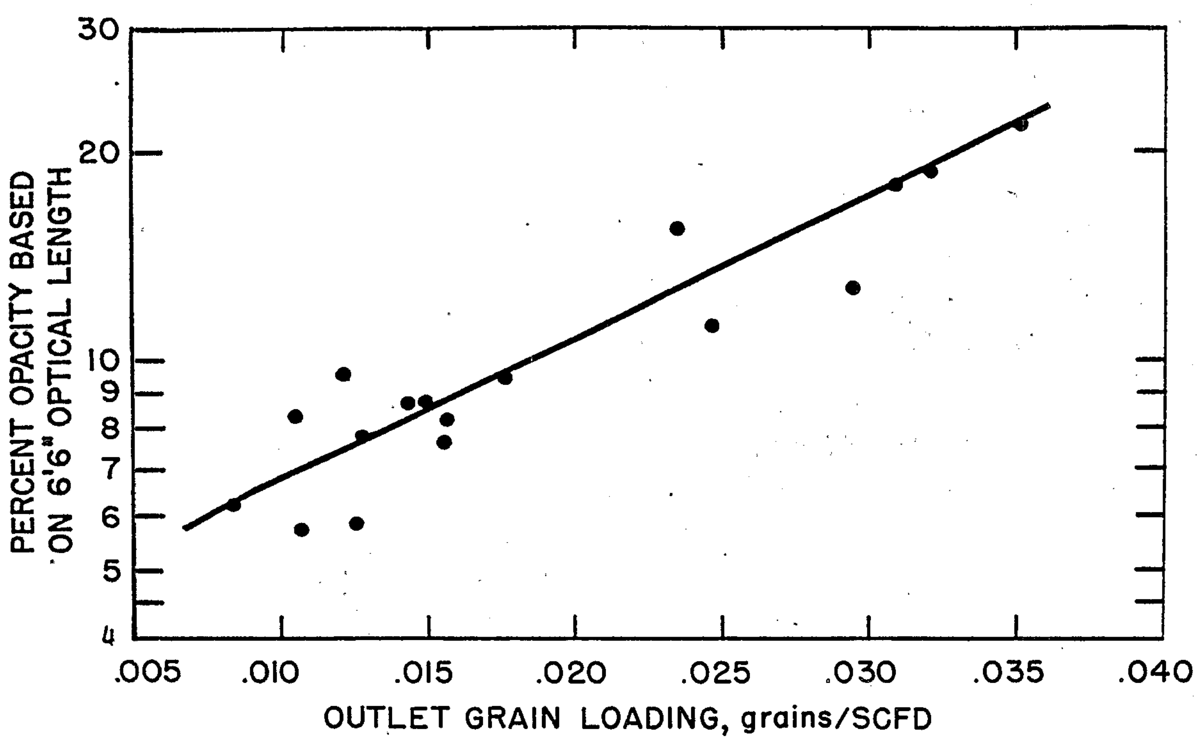


Figure 2-24. Opacity versus emissions data for a venturi scrubber on a coal-fired boiler slip stream.[21]

with a venturi scrubber was encouraging. With certain refinements, this approach may soon provide a convenient means to continuously monitor the performance of wet scrubbers.

2.5 LIQUID-TO-GAS RATIOS AS PERFORMANCE PARAMETERS

The liquid-to-gas ratio has a significant impact on the penetration through a wet scrubber. However, it is questionable whether the effect of the liquid-to-gas ratio needs to be considered independently of the pressure drop, because, for most types of wet scrubbers, the pressure drop is linearly related to the liquid-to-gas ratio.[7,8]

The possible effect of the liquid-to-gas ratio has been examined using the venturi scrubber analytical model discussed earlier. The penetration was calculated for a number of combinations of gas velocities and liquid-to-gas ratios. Then the penetration and corresponding pressure drop data was plotted using the liquid-to-gas ratio as a parameter. The results are illustrated in Figure 2-25.

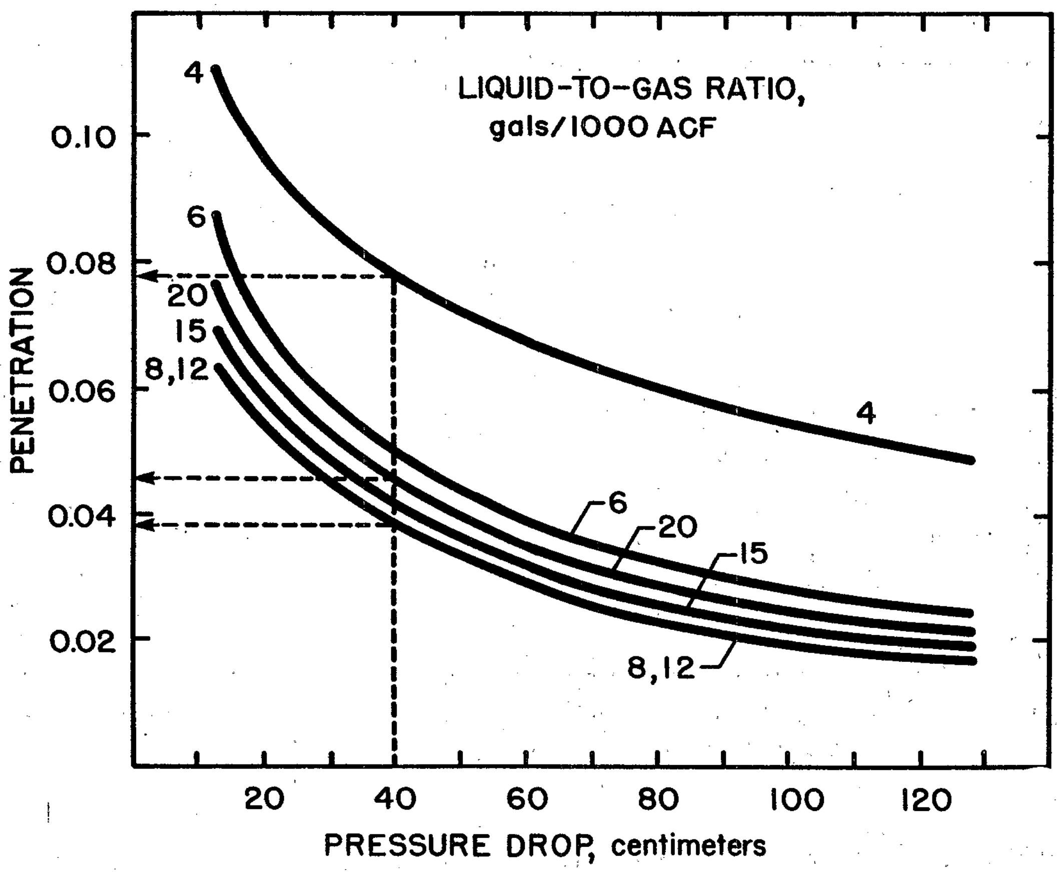


Figure 2-25. Predicted effect of liquid-to-gas ratio on penetration as calculated using the venturi scrubber model.

Based on the model predictions, the optimum liquid-to-gas ratio is between 8 and 12 gallons per thousand ACFM. At this rate, the penetration is lowest at a given pressure drop as illustrated by the dotted line at 40 centimeters of water. There is only a slight difference in performance as the liquid-to-gas ratio varies over the range of 6 to 20 gallons per thousand ACFM. The model suggests that there is essentially no independent effect over this range, which is the most common operating range of commercial wet scrubber systems.

At very low liquid-to-gas ratios, the venturi scrubber model predicts that there is an effect which is independent of the pressure drop. The 4 gallon per thousand ACFM curve is significantly higher than the other liquid-to-gas ratio curves. This prediction is consistent with the observations of Semrau and others during the testing of operating systems.[14] At low liquid-to-gas ratios, it would be necessary to monitor the liquid flow rate since a change of plus or minus 1 gallon per thousand ACFM would have a major impact on scrubber performance.

As normally used, the liquid-to-gas ratio applies to the entire scrubber. In other words, the liquid-to-gas ratio is the total recirculation liquor flow divided by the total scrubber outlet gas flow rate. Unfortunately, the distribution of the liquor across the gas stream is not entirely uniform; therefore, there can be significant variation in the local liquid-to-gas ratios. This variation can have a significant impact on the penetration without a proportional impact on the pressure drop. It is very difficult to identify the maldistribution problems.

Poor gas-liquid distribution is often the result of improper treatment of the recirculation liquor. Excessive suspended solids can lead to pluggage of the spray nozzles, the main liquor pipes, and the strainer before the pump. In some spray tower scrubbers, as many as half of the nozzles have been found to be plugged by suspended solids in the liquor. In venturi scrubbers and traytype scrubbers, scaling of the scrubber internals can also result in serious gas-liquor maldistribution. To minimize scaling, it is important to maintain a proper pH (generally below 10) and a proper purge/blowdown rate.

Buildup of material in the wet-dry interface can lead to maldistribution, too. To prevent buildup of material in this location, the gas approach must be wetted.

2.6 EFFECT OF LIQUOR SURFACE TENSION

The surface tension of the scrubbing liquor can potentially affect the penetration rate whenever impaction on droplets is an important unit mechanism. This is true for gas atomized scrubbers such as venturis and orifice units, impingement plate and sieve plate scrubbers, mechanically aided scrubbers, and spray tower scrubbers. Low surface tension reduces the liquor droplet size and improves coalescence (the inclusion of the particle into the droplet). In one study by Hesketh, it was found that lowering the surface tension from 50-60 dynes per centimeter to 10 dynes per centimeter reduced the penetration by 50%.[25]

The impact of reduced droplet size can be predicted using the venturi scrubber analytical model developed by Calvert et al.[7] The data presented in Table 2-2 was computed by Woffinden, Markowski, and Ensor[26] using the Calvert Model and the conditions of an 8000 cm/sec throat velocity and a monodisperse aerosol of 1 μmA. The model suggests no improvement if the droplet diameter without surfactant is below approximately 50 micrometers. This is not a commercially important case since the large majority of nozzles used in wet scrubbers produce sprays in the 200 to 800 micrometer range.[27,28]

TABLE 2-2. PREDICTED EFFECT OF SURFACE TENSION (σ) ON THE PENETRATION THROUGH A VENTURI SCRUBBER[26]

Droplet Diameter		Penetration	
σ = 72 dynes/cm	σ = 30 dynes/cm	σ = 72 dynes/cm	σ = 30 dynes/cm
205	144	0.020	0.011
144	102	0.020	0.013
51	36	0.020	0.021

The effect of improved particle coalescence into a droplet is difficult to estimate. Presumably this would benefit sources with marginally wettable particulate matter.

Liquor surface tension will vary according to the quantities of materials absorbed from the gas stream, the quantities of surfactant added, and the rates of the purge and makeup streams. Chemicals added to the liquor to improve the rate of settling of solids in the scrubber clarifier and recirculation tank can have an impact opposite to that for the surfactant. The influence of foaming suppressants on the surface tension of the liquor is not known. Due to the potential variability of the surface tension and the moderate effect this may have on scrubber performance, the quantities of all surfactants, flocculants, and anti-foam agents should be recorded during each stack test and during subsequent evaluation periods.

If it is necessary to quantify the surface tension, ASTM Method D 1590-60 can be used.[29] This technique is based on the ring method of measurement and has a precision of 0.3 dyne per centimeter.[29] Most commercial laboratories have the necessary equipment for this test procedure.

2.7 CONDENSATION AND EVAPORATION EFFECTS ON PERFORMANCE

Impaction can be enhanced by the condensation of water vapor on the surfaces of particles and, to a lesser degree, by the condensation of water vapor on existing water droplets. Evaporation of water vapor from existing droplets has an adverse effect on scrubber performance.

The beneficial effect of condensation is primarily due to the increased mass present on a particle. The increased inertia of the particle yields higher impaction efficiency. A secondary benefit results from the mass gradiant which exists whenever condensation is occurring. The imbalance in the momentum imparted by the water vapor molecules on each side of the particle results in a modest movement toward the surface of the condensation site.[30] This phenomenon is termed diffusiophoresis. The negative effect of evaporation is the opposite of that described above.

The quantity of water available for the inadvertent condensation is usually quite limited. This can be estimated by use of psychrometric chart (actual physical conditions are dependent on the prevailing gas pressures). It is usually in the range of 0.01 to 0.15 pound of water per pound of dry air.

Calvert and Jhaveri have presented information indicating that the quantities necessary to achieve substantial improvement in scrubber performance are in the range of 0.2 to 1.0 pound of water per pound of dry air.[31] This is illustrated in Figure 2-26.

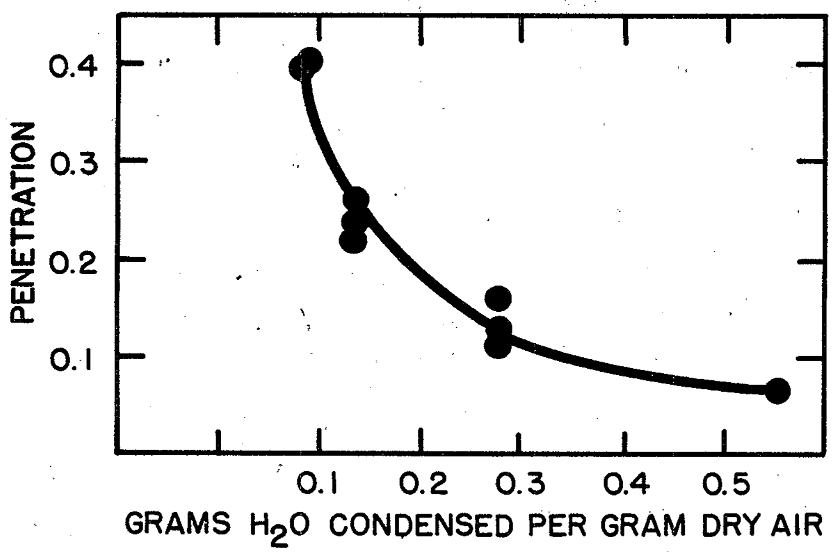


Figure 2-26. Beneficial effect of condensation.[31]

There are few commercially operating scrubbers which have a quantity of water vapor condensing that is this large. In order to induce this phenomenon, it is possible to evaporate a large quantity of water in a high temperature zone of the process duct work or to inject large quantities of low pressure steam. Cooling of the inlet liquor stream would also favor condensation. Lemon has presented operating data on a novel scrubber system which used artificial means to induce condensation.[32] This system was also able to achieve compliance with all applicable requirements at a pressure drop of only 20 inches w.c., while the earlier scrubber on this source required a pressure drop of 40 inches w.c. for a similar penetration rate.

At the moderate water vapor levels present in most effluent streams, the presence of condensation would have little effect. The plume appearance would provide an initial indication of a dramatic change in the water vapor content of the effluent stream. Other parameters which would be useful indicators include the gas stream inlet temperature and the liquor stream inlet temperature.

3.0 FACTORS AFFECTING SCRUBBER SYSTEM RELIABILITY

The performance of a scrubber system is dependent on the operating characteristics discussed in Section 2.0 and on the integrity of the scrubber internals. The latter is addressed in this section. Failure of these components can lead to extended downtime of the system or operation in temporary noncompliance. Both the operator and the regulatory agency inspector have an interest in minimizing these problems by identifying the emergence of factors which threaten scrubber components and ultimately degrade scrubber performance.

3.1 CORROSION AND EROSION OF SCRUBBER SHELL

The susceptibility of a scrubber to erosion is a direct function of the gas velocities within the entry ductwork and the scrubber shell. The venturi scrubber throat is most prone to these problems due to the extreme gas velocities of 20,000 to 40,000 feet per minute at this point. Other areas of common erosion failure are illustrated in Figure 3-1.

Regulatory agency inspectors usually do not have the opportunity or safety equipment to perform internal inspections of control equipment, therefore, they must use the less direct, external symptoms of erosion. This includes the obvious holes worn through the shell at critical high velocity points or points of gas stream turning. In extreme cases, these holes can lead to severe inleakage of ambient air and a reduction of the quantity of gas pulled from the process. The extent of the air infiltration can be quantified using pitot tubes before and after the collector (and accounting for absorption and condensation/evaporation within the scrubber).

A valuable sign of potential erosion problems is the quantity of suspended solids in the liquor. The potential for erosion is directly related to the percent suspended solids. The performance of the clarifier and/or the settling pond can also have an impact on the susceptibility to erosion in that the large, abrasive particles should settle out. The greater the recirculation flow rate relative to the make-up and purge flows, the greater the potential for build-up of high suspended solids.

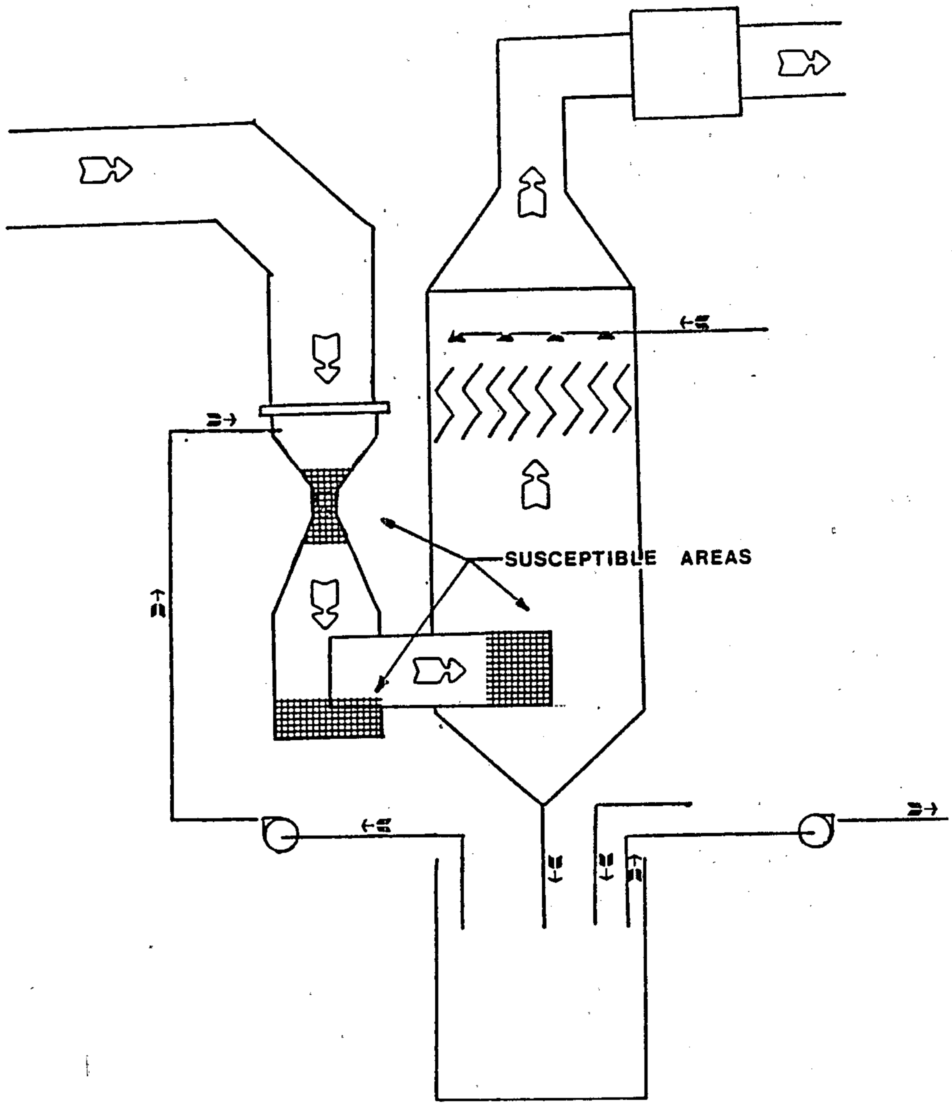


Figure 3-1. Areas of a venturi scrubber vulnerable to erosion.

Also, systems which purge only once per day or once per week can develop high suspended solids levels late in the operating period. A rough check on the quantity and character of the suspended solids can be made by obtaining a sample of the liquor leaving the scrubber sump and observing the initial turbidity and the rate of settling.

Due to the absorption of corrosive materials such as sulfur dioxide, sulfur trioxide, hydrogen chloride, and hydrogen fluoride, corrosion of the scrubber shell and ancillary equipment is a common problem. It is important to maintain the pH of the liquor well above the levels at which carbon steel (the most common material used in scrubber construction) is attacked. A pH of 6 or greater is usually satisfactory. An appropriate pH is usually maintained using alkaline additives such as soda ash, lime or limestone. The performance of the alkaline additive delivery system and the process control instrumentation are very important in minimizing short term low pH excursions. The operation of the pH monitor used to control the rate of additive injection should be checked on at least a daily basis unless long term operating experience justifies less frequent inspection. A portable pH meter or pH paper can be used for this check. The sample should be collected at the sump of the scrubber since this is often the point of minimum pH.

The recirculation rate is an important factor in determining the extent to which halogenated compounds are building up in the scrubbing liquor. Relatively small levels of chlorides and fluorides can attack many types of materials, especially the 300 series stainless steels.

One convenient means to monitor potential corrosion problems is to prepare small coupons (small circular samples) of the various materials used throughout the scrubber system. These are placed in racks which can be mounted at various locations in the scrubber. During every outage these are visually inspected for pitting and cracking and are weighed for material loss. This information provides an early indication of developing corrosion problems.

3.2 EROSION AND PLUGGAGE OF SPRAY NOZZLES

Spray nozzles are extremely susceptible to erosion and pluggage problems due to the high velocities of the liquid stream and due to the suspended solids within the stream. The most common types of nozzles in use include the hollow cone and the full cone. The latter is particularly prone to pluggage due to the presence of an internal spinner vane. The vane is installed to achieve the full cone spray pattern which is necessary for distribution of liquor on a packed bed.

Damage to the nozzles can sometimes be determined by observing the spray angle while the nozzles are operating at normal line pressures.

(This can usually be done safely while the system is down and only the pumps are operating.) If the spray angle is considerably greater than previously, then it is very possible that the nozzle orifice has been enlarged by erosion. If the spray angle has decreased or if a distinct spray pattern is no longer achieved, it is likely that the nozzle is partially or completely plugged. Both conditions lead to severe gas-liquid maldistribution.

Erosion problems on the tangential inlet to the entrainment separator are common to many types of scrubbers because of the concentration of large, abrasive particulates in the outer part of the inlet duct. The venturi-rod type scrubber is also prone to erosion of the rods within the throat, hence these must be checked on a routine basis.

Venturi scrubbers in which the throat is oriented vertically may have erosion/abrasion failure at the bottom of the divergent section as the gas stream turns 90° to enter the entrainment separator. One means of minimizing this problem is to include, below the venturi throat, a flooded elbow containing 6" to 9" of trapped liquor.

Erosion can best be identified during a routine internal inspection of the scrubber shell, entrainment separator, entry ductwork, and other such components. The erosion of corrosion protective linings such as rubber or synthetic coatings is particularly important since gaps and crevices in the lining can lead to rapid corrosion underneath the lining. The entire lining can be defeated by erosion of a small area in an erosion prone zone of the scrubber.

The visual check of spray angle usually cannot be done by a regulatory agency inspector or an operator while the entire system is operating. Some indirect indications of the nozzle condition can be used in lieu of these observations. If a nozzle has plugged significantly, the pipe leading to that nozzle in the scrubber begins to cool. Comparision of the skin temperature of one pipe against that of the pipes leading to other nozzles is a reasonably reliable indicator of pluggage. It is common to find a skin temperature 5 to 10 degrees below that of adjacent pipes. Pluggage of a nozzle will also be indicated by an increase in the line pressure near the nozzle. Erosion of the nozzle orifice yields the opposite conditions. Unfortunately, line pressure is difficult to interpret since it is strongly dependent on the liquid flow rate. The relationship between pressure and flow rate (for a nozzle in original condition) is presented in Equation 4-1.[28]

$$\frac{L_1}{L_2} = \frac{\sqrt{P_1}}{\sqrt{P_2}} \qquad \text{Equation 3-1}$$

where:

L_1 = liquid flow rate at pressure 1
L_2 = liquid flow rate at pressure 2
P_1 = pressure 1
P_2 = pressure 2

During a routine inspection it is difficult to determine whether a change in line pressure is due to a change in the internal condition of the nozzle or simply due to a change in the liquid flow rate.

If possible, all nozzles for venturi scrubbers should have external rod-out capability. This is usually not feasible for spray tower scrubbers and the nozzles used to clean demisters. In these cases, an automatic flush system may be of benefit. If a pond is used for settling, it is advisible that it have several zones separated by weirs and the pick-up for the pump be near the water's surface to prevent entrainment of silt.

3.3 FANS

Fans can either be installed before or after the scrubber. Only radial blade designs are used ahead of the scrubber due to the large quantities of suspended particulate in the gas stream and the fact that other fan wheel designs are prone to fan wheel particulate buildup. Fans installed following the scrubber should be the radial blade type.

The principal problems of fans on wet scrubber systems include fan wheel erosion, fan wheel buildup, and bearing failure.[33] Corrosion is also a common problem. Both fan wheel erosion and fan wheel buildup will eventually result in increased vibration which is usually audibly and visually detectable. For systems prone to this problem, vibration sensors are advisable, enabling a source to have the fan automatically tripped if the vibration reaches undesirable levels. If during a routine inspection of a scrubber system, excessive fan vibration is noticed, extreme caution and immediate action is necessary. Disintegrating fans can fling metal parts over a wide area.

Fan bearings should be inspected on a frequent basis for oil level, oil color, oil temperature, and vibration. Bearings found to be inadequately lubricated may require a greater frequency of lubrication or the installation of a forced lubrication system. Excessive bearing wear may be caused by a higher than originally specified fan operating temperature or by misalignment of the bearing mountings.

Fan belts should be checked periodically for wear. At the time of installation, belts should be checked for proper tension. Loose belts can cause the entire dust collector system to malfunction. Out-of-line sheaves will destroy belts; uneven wear on grooves of sheaves and the surfaces of the belts indicates misalignment.

Fan vibration can sometimes be caused by air flow factors and, in these cases, can be eliminated by adjusting the inlet or outlet dampers, modifying the inlet or outlet dampers, modifying the inlet and/or outlet ductwork, or changing the sheaves. The latter will have a direct affect on the gas flow rate and will result in a change in the tip speed (which should never exceed the manufacturer's recommended rate).

Operating problems experienced by fans downstream of scrubbers are generally only symptoms of more fundamental problems with the particle capture and/or entrainment separation.

3.4 PUMPS

The two types of pumps in service on wet scrubber systems are the centrifugal and positive displacement pumps. The centrifugal pump is the most common.

Accelerated wear of the pump impeller occurs at high suspended solids levels. As is the case with spray nozzles, the best way to minimize scrubber downtime due to pump malfunctions, is to minimize the total quantity of suspended solids and especially the larger suspended particles (greater than 25 micrometers). A strainer ahead of the pump will improve the quality of liquor passing through and thereby minimize wear.

Another common problem with pumps is leakage through the packing glands; pumps must be repacked whenever necessary. This can be minimized through the use of double seals with a clean water, pressurizing line. All bearings on the pumps and the pump couplings should be lubricated periodically in accordance with the manufacturer's instructions.

3.5 PIPING AND VALVES

All piping is subject to erosion, especially at elbows. The rate of erosion is a function of the flow velocity, the quantity of suspended solids, the particle size distribution of the suspended solids, and the presence of corrosive agents. The proper materials of construction must be selected in order to minimize this problem.

Valves are also subject to erosion. Those which are operated in either a fully open or closed position are affected much less than those used in a partially open mode for flow throttling purposes.

In order to reduce pluggage of lines during outages, the piping should be completely drained. This requires that each line have a modest slope so that a pocket of liquid cannot remain after draining. The drain should be at the lowest point of each piping system. Draining is also necessary to prevent the freezing of lines during outages.

During routine inspections, one should be aware of the piping design with regard to drainage capability. If it appears inadequate, and the systems runs in a cyclic nature, occasional pluggage and/or freezing problems should be anticipated. Periods of noncompliance can occur initially after start-up of the system and prior to the rectification of a piping freezing/pluggage problem. In such cases, the pump discharge pressure will be high, the nozzle pressure will be low, and the gas exit temperature from the scrubber will be high. The gas phase pressure drop across the scrubber will be low due to the lack of typical liquor flow rates.

3.6 DUCTS

The most common problems with the ducts leading to a scrubber include dust buildup, erosion/abrasion, flex failure, and failure of expansion joints. The last three of these conditions result in air infiltration and consequently, a reduction in the quantity of gas pulled from the process equipment. The extent of air infiltration can be quantified by preparing an oxygen profile at various points along the duct from the source to the scrubber.

Dust buildup occurs in low gas velocity zones of the duct work. This can occur wherever the duct work is oversize for the effluent gas flow rate and during periods of operation at reduced process rates. Clean out ports should be located at convenient locations along the ductwork to facilitate occassional removal of accumulated material. Without this cleaning the duct work can collapse (unless the supports have been designed to take the combined weight of the duct and the deposits).

4.0 SCRUBBER INSPECTION AND PERFORMANCE EVALUATION

The purpose of a wet scrubber performance evaluation is to determine whether the penetration has increased or decreased since the previous evaluation and to identify any conditions which threaten the proper operation of the scrubber system. The performance evaluation must incorporate the operating variables and factors presented earlier in Sections 2.0 and 3.0. A brief summary of these are presented below in Table 4-1.

TABLE 4-1. PERFORMANCE EVALUATION PARAMETERS

Penetration Variables
Inlet and Outlet Static Pressure
Demister Pressure Drop
Bypass Duct Pressure Drop
Gas Inlet and Outlet Temperatures
Liquid Inlet and Outlet Temperatures
Gas Inlet O_2 Levels
Gas Inlet CO_2 Levels
Liquid Suspended Solids and Dissolved Solids
Liquid Surface Tension
Bypass Duct Temperature Profile
Rate of Liquor Evaporation and Condensation
Condensible Vapor Levels in Inlet Gas
Particle Size Distribution
Absolute Humidity of Inlet Gas
Operating Factors
Liquor pH
Liquor Suspended and Dissolved Solids
Liquor Supply Line Pressure
Nozzle Spray Pattern
Fan Vibration
Integrity of Ductwork

The list of variables is long and some of them cannot be measured or observed directly. The performance evaluation approach must include some indirect means to consider these difficult-to-measure factors.

The routine performance evaluation is structured to aquire only the minimum data necessary to detect a change in wet scrubber performance. When abnormal conditions are found, the remainder of the measurements and other inspection procedures are performed to determine the nature of the specific problem.

4.1 BASELINE PERFORMANCE EVALUATION TECHNIQUE

The routine evaluation of wet scrubbers must be done in a logical sequence in order to obtain all the necessary information and to minimize the time requirements. The technique recommended is the Baseline Inspection Technique.[34] This approach is based on the assumption that the operating characteristics and performance of each control system is unique. The approach is designed to control for the myriad of process variables and control device design factors, any one of which can singly or collectively influence performance.

To ensure the accuracy of the performance evaluation, the Baseline Inspection Technique utilizes a comparison of present operating conditions with historical baseline levels for the unit. Each variable which has shifted significantly is considered a "symptom" of possible operating problems. While compiling the operating data, the general condition of the wet scrubber is observed to identify problems which could affect future reliability of the system. The baseline data are compiled during periods when the wet scrubber is operating well, preferably during a compliance or acceptable stack test.

The evaluation is accomplished by proceeding in a counterflow manner through the entire system; the stack and plume opacities are observed first, and then the scrubber system is inspected component by component proceeding backwards through the system in the direction opposite to the flow of the gas stream. This is illustrated in Figure 4-1.

The time consuming inspection of process equipment and operating conditions is done by the agency inspector only when deemed necessary based on data collected during inspection of the scrubber and observation of the stack opacity. The advantages of this approach include the following: (1) potentially confidential process information is obtained only when absolutely necessary, (2) the inconveniecnce to the operator is minimized, and (3) on-site time is minimized. Since the inspection data are organized in a coherent manner as the inspection proceeds, the effort can gradually be focused on only the problems of direct interest. In other words, the intensity of the evaluation can be minimized and many of the measurements can be avoided. This is a particularly important point considering the extensive list of operating variables and reliability factors presented earlier. The typical order of inspection for a routine evaluation is presented in Table 4-2.

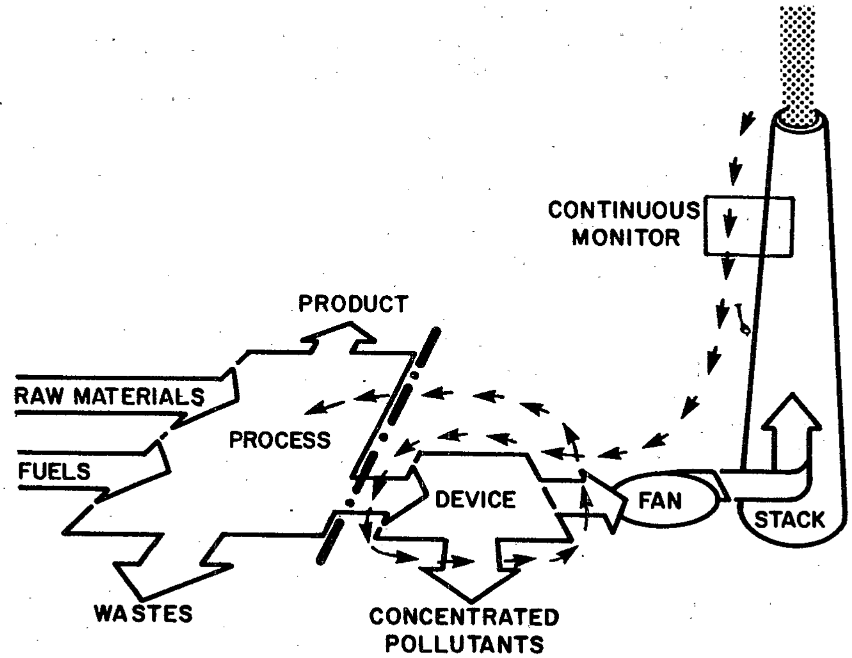


Figure 4-1. Counterflow inspection sequence.

TABLE 4-2. ROUTINE INSPECTION POINTS

1.	Stack Discharge	Plume Opacity at the Stack Discharge Presence or Absence of Entrainment Presence or Absence of Condensed Water Presence or Absence of "Mud" Lip
2.	Fan	Vibration (Qualitative Check)
3.	Demister	Pressure Drop
4.	Scrubber	Pressure Drop pH Liquor Line Skin Temperatures Turbidity Continuous or Intermittant Purge Use of Anti-Foaming Agents and Surfactants
5.	Bypass Duct	Damper Position
6.	Ductwork	Holes and Leaks Integrity of Expansion Joints
7.	Process	Hood Capture Effectiveness (Qualitative)

Depending on the size of the scrubber system and the convenience of the measurement ports, the routine inspection should take between 1 and 4 hours. This is a reasonable time commitment considering that this type of evaluation can aid in the early identification of operating problems that might ultimately result in extended periods of noncompliance and expensive repairs.

4.1.1 File Review

Prior to inspecting a scrubber system, an agency inspector should review the agency files to familiarize himself with all pertinent information on the particular scrubber, types of emissions, and operating history. The following items should be checked:

1. Pending compliance schedules and variances
2. Construction and/or operating permits pertaining to source processes
3. Past conditions of noncompliance
4. Malfunctions reports
5. History of abnormal operations

The inspector should know what regulations are applicable to the facility; and if he has any questions, he should consult the agency administration or legal staff prior to conducting the inspection. It is important to know what data are useful in confirming compliance and what evidence is necessary to document possible violations of each of the applicable regulations.

The inspector should also refer to plant layout drawings to familiarize himself with emission point locations, to draw flow diagrams, and to prepare the inspection report. If available in the files, the inspector should note the facility's personal safety equipment requirments.

Based on his review of agency files, the inspector should schedule an inspection time when plant processes will be operating at representative conditions. The scheduling of a time to visit plants having batch operations or other irregular operating schedules (e.g., seasonal) is especially important. The files should always be reviewed briefly before entry to the plant so that important plant characteristics will be more easily remembered.

4.1.2 Evaluation of Plume Opacity

The initial step in any scrubber inspection is to observe the visible emissions exiting the stack under representative operating conditions and under weather conditions which permit opacity observations. The visible emission observation, while more difficult than on other control devices because of steam plume interferences, can provide a good indication of the scrubber's performance.

In order to compare the opacity against baseline levels, the opacity must be observed at the point of stack discharge where the pathlength is fixed. Very often this is not possible due to the presence of light scattering condensed water droplets. If this is the case, the opacity of the residual plume should be observed after the point of water droplet dissipation. The latter provides only a very rough check on the overall performance of the scrubber.

Experienced observers are able to distinguish between a plume obscured by water droplets and a plume free of water droplets. Particulate matter in a plume usually has a bluish-white or brownish-white color. Water vapor, on the other hand, is usually a brilliant white color. A plume containing water droplets also appears to have more texture and is more wispy in nature than a plume free of water droplets. To confirm the difference between the plume being observed and a water droplet plume, it is usually possible to simultaneously note the behavior of a nearby steam vent plume.

After the plume observation is completed, the discharge from any bypass stacks (if separate) should be observed. A general check should also be made for fugitive emissions from process sources.

During these initial observations, a check should be made for any entrained droplet fallout from the plume. The presence of dried spots on adjacent equipment and in the surrounding area is an indication of demister or entrainment separator problems. When the entrainment of solids is severe, a lip of mud forms around the stack mouth and the stack is discoloured several feet down from the opening.

4.1.3 Fan Evaluation

The location of the fan relative to the scrubber system should be ascertained. If the fan is ahead of the scrubber, then the remainder of the scrubber system and ductwork is under positive pressure. Leaks in the gas handling system or an open measurement port will allow the gas to escape into the areas immediately around the scrubber. Personnel conducting the performance evaluation should avoid any partially confined areas where leaking gas could result in high concentrations of toxic agents.

If the fan is located downstream of the scrubber, then the shell and the inlet ductwork is under negative pressure. In this case, any leaks or open measurement ports will result in inleakage of ambient air. This presents less of a personnel exposure problem, however, it should not be assumed that pockets of toxic contaminants are not present in some partially confined areas. Fans on the downstream side are vulnerable to buildup of material on the fan wheel. This can lead to imbalance of the wheel, particularly if the fan tip speed is high. If this remains uncorrected, severe vibration and eventual disintegration of the fan is possible. Personnel evaluating scrubber operation should leave the vicinity of a severly vibrating fan immediately; operators of such systems should take immediate action to take the fan off line.

The inspector should ask about the recent operating history of the fan with respect to particulate buildup, vibration, bearing failure, or corrosion. These are indications of potential carryover from the demister.

4.1.4 Demister Pressure Drop

If there is entrained solids fallout from the plume or vibration of the induced draft fan, the operation of the demister should be checked. The upstream and downstream static pressures should be measured and compared against baseline levels. A significant increase in the pressure drop usually means partial pluggage of the demister, while pressure drop values much lower than baseline values can signal that there are openings through the demister beds.

It is generally advisable to have several static pressure ports around the scrubber shell both before and after the demister. In this way the upstream and downstream static pressures can be averaged.

The measurements may first be made using a portable slack tube type manometer or a Minihelic® differential pressure gauge. Due to the low pressure drops involved, however, it may be necessary to repeat the measurements using an inclined manometer or, at least, a low range Magnahelic® gauge. The Magnahelic® and Minihelic® gauges should be calibrated regularly.[35]

The presence or absence of a demister flush system should be noted. This often consists of an array of spray nozzles above and/or below the demister. Use of the sprays on a once per shift and a once per day basis substantially reduces the potential for demister pluggage. The agency inspector should inquire about the cleaning system operating schedule.

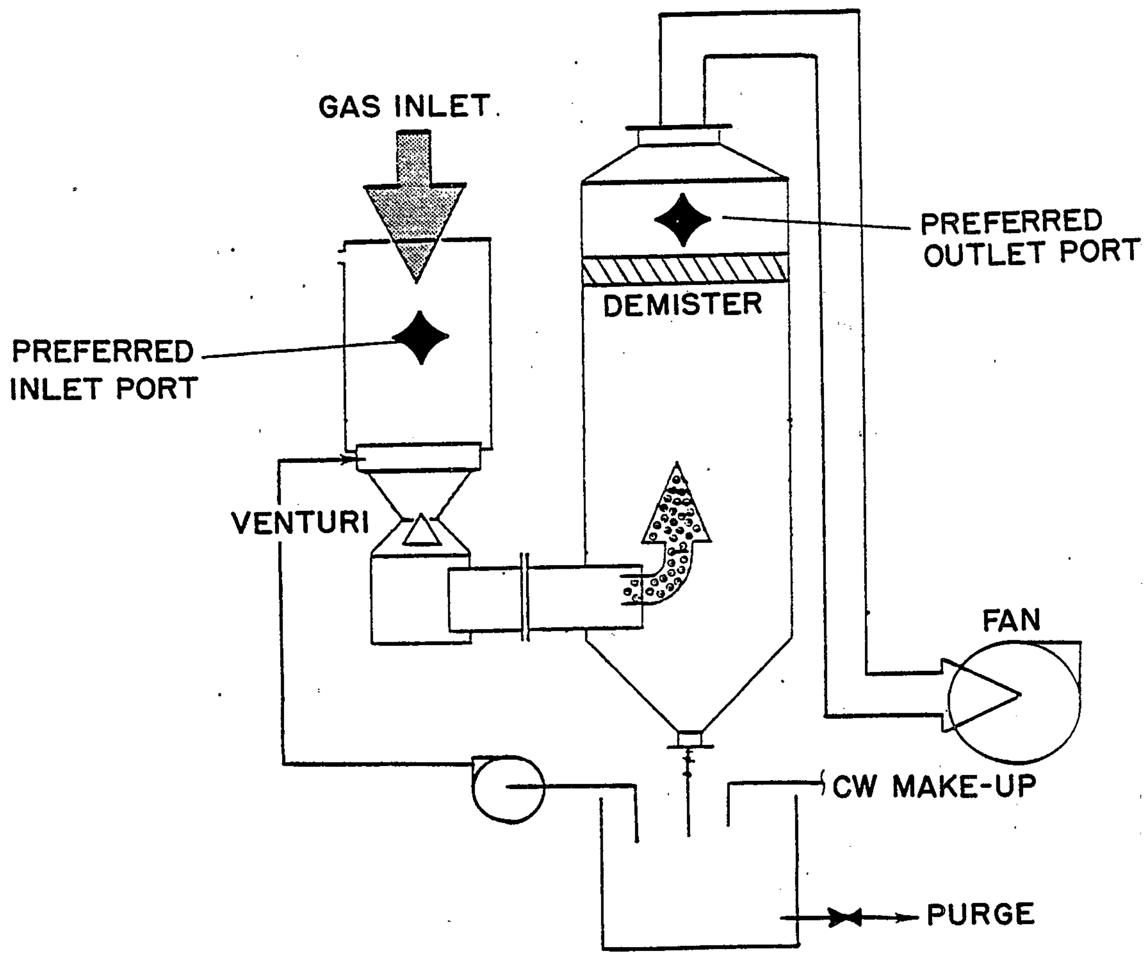
If an inspector is being conducted when the scrubber is down, it may be possible to visually check for buildup on the demister. (Care is necessary to avoid exposure to toxic gases which may be trapped within the scrubber vessel.)

4.1.5 Scrubber Pressure Drop

4.1.5.1 Measurement of Pressure Drop. The penetration of particulate matter through the scrubber is partially a function of the pressure drop. Thus, measurement of the pressure drop is an essential step in the routine performance evaluation. Unfortunately, the permanent on-site monitors are not always reliable because of the potential for line pluggage. For this reason, it is usually advisable to measure the pressure drop using portable gauges.

Locating proper measurement ports is the first step in measuring the pressure drop. The fundamental rule in locating and using measurement ports is only those that are safely accessible should be used. Access to ports in some scrubber systems may involve close contact with hot ducts, unsafe climbing, and/or exposures to fugitive gas leaks. Heroic efforts should not be taken to reach ports which have been incorrectly located. A second rule is ports must be in a location relatively free of interference from sludge and entrained water droplets. Recommended locations for ports in tray-type scrubber and venturi scrubber systems are shown in Figure 4-2.

It is important that the fan and the fan dampers not be included in the system between the two measurement ports. Inclusion of the demister (or cyclonic entrainment separator in venturi scrubbers) is also not ideal; however, it must often be included because the region between the venturi throat and the demister has a high flow rate with high concentrations of entrained water droplets and other materials, making measurements of static pressure difficult. Inclusion of the demister usually adds only 0.5 to 2 inches of pressure drop (if there are no deposits), only a small fraction of the venturi throat pressure drop.



Figue 4-2. Preferred static pressure measurement locations.

Once the appropriate measurement ports have been located, the measurement work can begin. However, before opening the port, the operating pressure within the duct or scrubber shell should be considered; it can either be roughly estimated or previous records and measurements can be reviewed. If the system operates under positive pressure, the opening of the port can result in the unintentional fumigation of the area, in which case everyone present should be prepared with the necessary personal protective equipment. If the system operates under negative pressure, then it is necessary to be aware of the possibility that air infiltration through the port can result in measurement errors by the aspiration effect. This is illustrated in Figure 4-3.

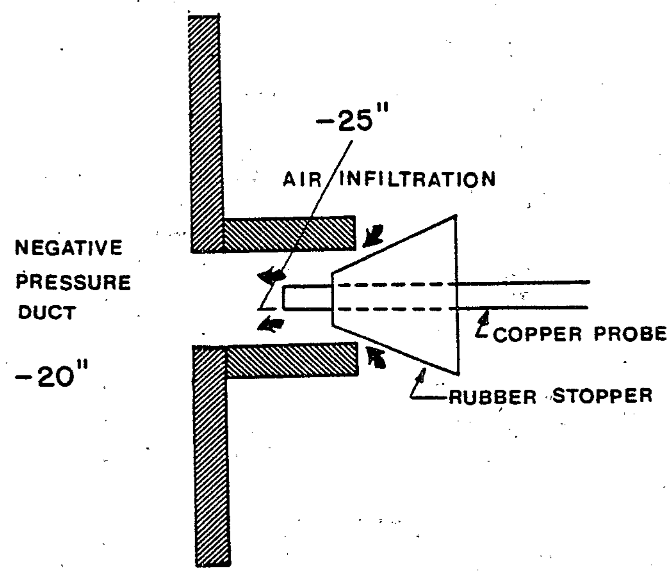


Figure 4-3. Aspiration effect error in static pressure measurement.

Suction induced by air infiltration around the probe leads to measured static pressures which are less (more negative) than actual. The magnitude of the error can be as great as 10 to 15 inches w.c. for some venturi scrubbers. Even tray-type units operating in the 6 to 12 inch pressure drop range, can have aspiration errors of 1 to 2 inches. One way to minimize the aspiration effect in the measurement of static pressure is to use a probe inserted well into the duct or scrubber shell. This is illustrated in Figures 4-4a and b.

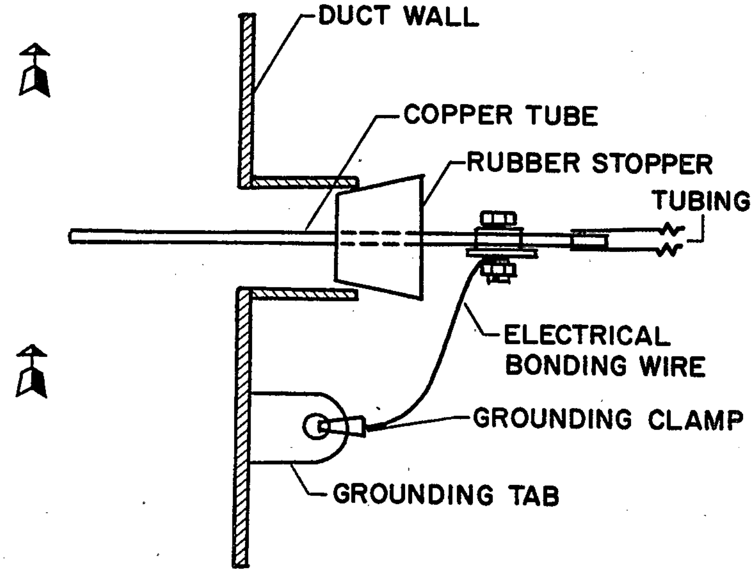


Figure 4-4a. Measurement of static pressure using a copper tube.

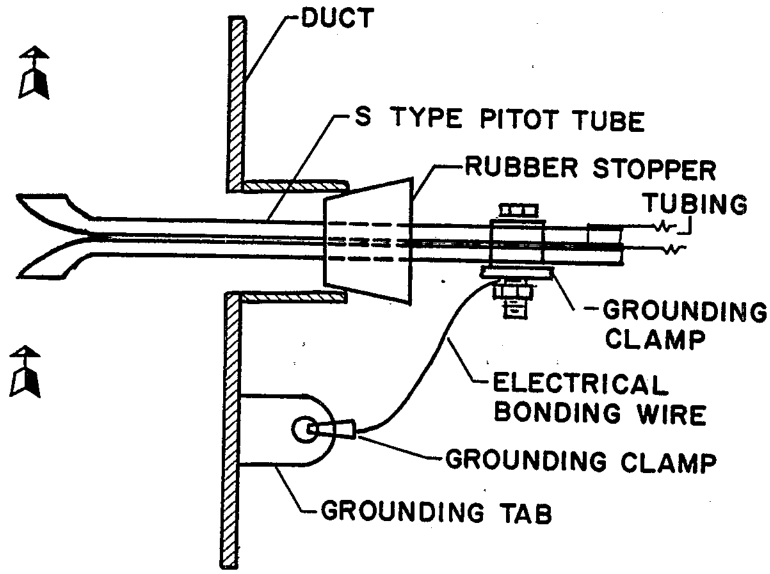


Figure 4-4b. Measurement of static pressure using a pitot tube.

Figure 4-4a illustrates the use of a 1/4" O.D. copper tube, while Figure 4-4b illustrates use of the pitot tube. Both approaches are very effective in avoiding problems with aspiration; however, both involve the risk of water droplet and solids impaction on the probe. The measurement port must usually be at least 3/4" in diameter to use the S-type pitot tube.

The higher the negative static pressure is at a given location, the smaller the measurement port should be in order to ensure that the port can be effectively sealed during measurement. If it is necessary to use an oversized port, care must be taken to insure a good seal. The use of gloves is not recommended since they can be sucked into the gas stream. On the same account, sampling probes can also be lost.

One quite useful assembly for oversized ports is illustrated in Figure 4-5. This consists of a 1/4" O.D. copper tube which is inserted through a #4 rubber stopper and then a commercial sanding disk (with a 1/4" O.D. hole). The sanding disk serves as an effective flange to prevent air infiltration and the rubber stopper holds the copper tube. This assembly has been used with no difficulties on measurement ports serving ducts at up to 100" negative pressure. The sanding disk should be at least 1" greater in diameter than the port on which it is used.

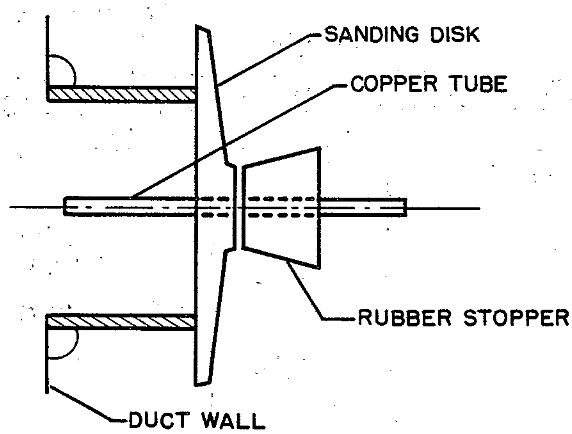


Figure 4-5. Measurement port seal.

In measuring the static pressure drop across a scrubber, it is good practice to measure the upstream and downstream static pressures one at a time. First of all, this guarantees that errors will not occur due to pluggage of one of the ports. In the case of wet scrubbers, it is possible (and even likely) that a port will plug minutes after it has been rodded-out. Therefore, hooking up two separate lines to one gauge as shown in Figure 4-6a is not recommended. It is preferable to make the measurements one at a time as illustrated in Figure 4-6b. In this case, a zero reading clearly indicates a port which was not originally cleaned out or which has become blocked again. Furthermore, less tubing is necessary when making the measurements one at a time. Since most of the ports are some distance apart, the connecting tubing necessary to measure pressure drop directly could represent a safety hazard; it could also pass next to a hot gas duct which would cause it to collapse or burn.

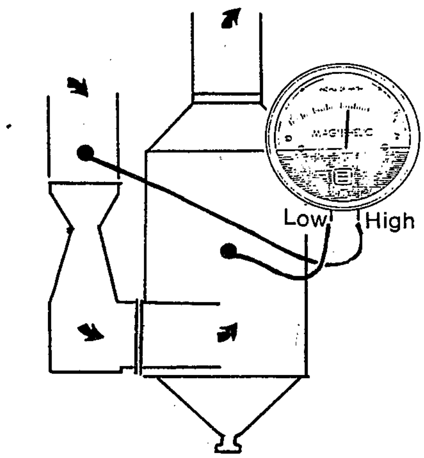


Figure 4-6a. Poor approach for measuring pressure drop across a venturi scrubber.

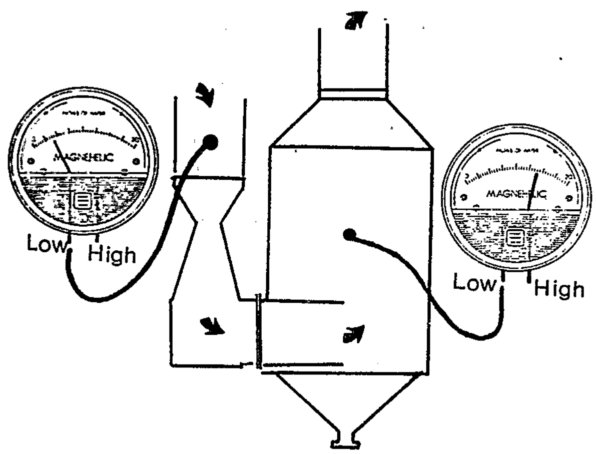


Figure 4-6b. Preferred approach for measuring pressure drop across a venturi scrubber.

Before opening any static pressure port, it is important to confirm that the port is not connected to any type of electrical transducer. In some systems, transducers are an integral part of the overall process control system; the opening of the port can result in a low pressure signal which will trigger the tripping off-line of the fan and process equipment. If there is any doubt about the existence of a transducer somewhere along the static pressure line, it should be assumed that one exists. Preferably there should be separate, isolated static pressure ports installed strictly for the purposes of routine evaluaton using portable gauges.

When recording the static pressure data, the location of each measurement should be carefully noted. The data has no meaning whatsoever without the accompanying data concerning measurement location. A sketch of the system, showing the ports, the scrubber, the demister, dampers, bypass ducts, and fan(s) should be included in the notes. As discussed in the next section, the temperature of the gas stream should be measured at the same points.

The pressure drop measurements should be conducted over a moderate time period at each location to determine if there are any short term temporal variations. These can be caused by cyclic process operating conditions or by "seeking" type adjustable throat mechanisms (for venturi scrubbers).

4.1.5.2 Measurement of Temperature. Immediately after measuring the static pressure at the inlet and outlet ports, the gas stream temperature should be recorded at the same points. These values can then be used to convert the static pressures back to a standard gas density. (See Section 2.3 for a discussion of the relationship between pressure drop, gas density, and energy consumption.) In making these temperature measurements, caution must be exercised to avoid (1) air infiltration at the port which causes cooling of the measurement probe and (2) water droplet impaction on the probe which also causes cooling.

The temperature at the scrubber inlet can also be used as an indication of potential operating problems. If it is greater than 300° F and the gas stream contains a high concentration of condensible metallic or organic vapors, then submicrometer particles can condense after the gas has passed through the zone of optimal inertial impaction. If it is over

300° F in combination with a high solids content liquor, then "regeneration" can result from the droplets evaporating to dryness.

4.1.5.3 Analysis of Pressure Drop. Low static pressure drop across a wet scrubber, coupled with a high stack or residual opacity suggests that the penetration rate has increased relative to the baseline level. The logical starting point when confronted with these conditions is to carefully inspect the entire liquid pumping and distribution system. The reason for this is that pressure drop is a direct function of the liquid-to-gas ratio at any specific gas velocity.

The most common reason for low liquid flowrate is nozzle or pipe pluggage. This may be indicated by an increase in the pump discharge pressure (from the baseline levels). Other problem symptoms include low pipe skin temperatures and high suspended solids in the recirculation line. If possible, the operator should rod out each nozzle and determine if there is a change in the pressure drop and in the pump discharge pressure.

A second reason for the low static pressure drop may be a decrease in the gas velocity through the system. In the case of adjustable throat venturis, the movement of the throat mechanism (damper, vanes, plump bob) can change the throat velocity by a factor of 3. The relationship between the gas velocity and throat velocity is linear, therefore, the pressure drop can also vary by a factor of 3. In some designs, it is possible to check for relative movement of the throat mechanism. If the wet scrubber is a tray-type, spray tower, or simple venturi, then throat velocity adjustments cannot be made independently of the gas flow rate. In these cases, it may be advisable to measure the inlet gas flow rate to determine if the wet scrubber system is operating at less than design flow rates; most scrubbers are less efficient under these conditions since particle impaction is less effective.

The recommended technique for the measurement of gas flow rate upstream of a wet scrubber is the Pitot tube (EPA Reference Method 2). Due to the large quantities of suspended material upstream of the scrubber, it is generally necessary to use the S-type probe which is less prone to pluggage. It should be noted that wet scrubbers are often used on sources which intermittantly or continuously generate effluent gases in the explosive range. Accordingly, any probes inserted upstream of the scrubber should be carefully grounded. A less accurate, but safer approach is to measure the gas flow rate downstream of the scrubber. The decreased accuracy results from evaporation of some of the liquor, and condensation in the scrubber. Nevertheless, the downstream value is generally close to the upstream value (after correction for gas density differences).

Another indication of the gas flow rate can be obtained indirectly by using the fan motor current. A decrease in the corrected fan motor current usually accompanies a decrease in the gas flow rate. Correction of the motor current to standard conditions can be accomplished by multiplying the fan current at actual conditions by the appropriate factor presented in Table 4-3. The data in Table 4-3 is accurate only when the fan inlet static pressure is not less than -20 inches w.c.

Other problems which can lead to low pressure drop all involve the pump and the liquid distribution system. Pump impeller wear and pump seal leakage can both contribute to a decrease in the liquid flow rate. At the earliest opportunity, the operator should inspect the pump packing, the pump impeller, and strainers mounted before the pump. The position of any flow control valves should also be checked.

TABLE 4-3. FAN DATA TEMPERATURE CORRECTION[a]

Temp °F	Factor	Temp °F	Factor
20	0.91	320	1.47
40	0.94	340	1.51
60	0.98	360	1.55
80	1.92	380	1.59
100	1.06	400	1.62
120	1.09	420	1.66
140	1.13	440	1.70
160	1.17	460	1.74
180	1.21	480	1.77
200	1.25	500	1.81
220	1.28	520	1.85
240	1.32	540	1.89
260	1.36	560	1.92
280	1.40	580	1.96
300	1.43	600	2.00

[a]From "Basic Energy/Environment Analysis", NAPA information series 67, by C. Heath, August 1978.

4.1.6 Liquid-Gas Distribution

Liquid-gas distribution is, unfortunately, a difficult factor to consider during a routine evaluation. Usually, the only conclusive evidence of poor distribution (also called liquor maldistribution) is the observation of severe scaling and deposits inside the unit. In extreme cases, there may be a decrease in the pressure drop across the scrubber or across an individual tray, at a constant gas flow rate.

Wet scrubber systems with moderate to high suspended solids levels should be checked to the extent possible for maldistribution problems. Partially or completely plugged nozzles are a major cause of poor gas-liquid distribution which is particularly disruptive in venturi scrubbers. One external check for plugged nozzles which can be made is to compare the skin temperatures of the various liquor supply lines going to the scrubber. If one of these lines is plugged, the flow of hot recirculated liquor through it will be substantially reduced and its skin temperature will begin to fall. A difference of 5 to 10 degrees F between two supply lines often indicates a plugged line. (The temperature difference is not as great as might be expected since conduction of heat along the pipe continues despite the plug.) Supply line pressure can also provide evidence of pluggage.

4.1.7 Liquor Quality

4.1.7.1 pH Measurement and Evaluation. The pH of the recirculated liquor should be measured during each routine evaluation. This can be done using color indicating pH paper or a portable pH meter. The pH paper is adequate assuming it is not necessary to have highly accurate data and the scrubber liquor will not attack the paper. Highly colored liquor, liquor with high levels of foam, liquor with high levels of colloidal matter, and oxidizing liquor all preclude the use of the pH paper.

The liquor sample should be drawn from a region of the system where its pH is at the lowest value. This is commonly at the scrubber sump effluent point, prior to the discharge into the recirculation tank. Another sampling point of interest is the collected liquor entrainment at the region of the demister. This sample can be acquired using the probe developed and discussed by Schifftner.[36]

A battery powered portable pH meter is ideal for pH evaluation of wet scrubber systems. These normally have an accuracy of ± 0.2 pH units and should be standardized using at least two buffers.

4.1.7.2 Solids Content. The liquor turbidity should be qualitatively analyzed. If the turbidity is high, nozzle erosion and/or line pluggage could occur in the system. The rate by which the material settles to the bottom of the sampling flask should also be considered, since it is an indirect indication of the particle size. Larger particulate material is more abrasive.

If the turbidity appears high, the inspector should evaluate the purge rates. A reduction in this purge rate can lead to an increase in the total solids content. The settling pond (if any) should also be inspected to ensure there is minimum total solids at the pump intake.

The presence of a persistent, high opacity plume at apparently adequate pressure drop levels can be due to evaporative regeneration of particulate in the presaturator or the quench tower. Samples of the liquor fed to the chamber should be obtained over a representative period of time; these should be analyzed for both suspended solids and dissolved solids. Similar samples should be obtained of liquor drained from the chamber which did not evaporate. The difference in the total solids content of the feed and discharge streams will give a rough indication of the loss of particulate to the gas stream. This is only approximate since some of the solids are lost as entrained water droplets from the chamber, and it is possible that some particulate from the inlet gas stream is captured in the chamber discharge stream.

4.1.7.3 Surface Tension. If the opacity of the discharge has increased without any other apparent changes, then one possible cause is a change in the surface tension. This change could affect both the droplet size distribution and the effectiveness of impaction. The surface tension can be measured using ASTM Method D-150. The quantity of antifoaming agents, surfactants and flocculants should be recorded, if known.

4.1.8 Nozzle Pluggage

Nozzle pluggage should be suspected when there is increased opacity and one or more liquor feed lines with lowered skin temperatures. If it is impossible to rod the nozzles out during operation, then it must be done during the next outage. At this time, each nozzle should be visually inspected for erosion and pluggage; if damaged, the nozzles should be replaced. In some cases, it will be possible to open an access hatch and observe the operation of the nozzles (with no gas flowing through the system). If a nozzle is partially plugged, the spray angle and pattern will be severely distorted. If it is completely plugged, at best, only a trickle of liquor will be observed. A high powered light (explosion proof) is useful for inspection of the nozzles from the access hatch.

4.1.9 Bypass Duct Damper

The damper position of the bypass duct should be checked. If there is any indication of substantial leakage across the duct, follow up testing is necessary.

4.1.10 Presaturator and Ductwork

Presaturator (or quench) water quality is particularly important; a sample of this liquor should be obtained and checked. Turbidity of this liquor should be very low, in fact, it should resemble drinking water quality.

The general physical condition of the ductwork leading from the process to the scrubber should be briefly checked. Fugitive leaks from positive pressure systems are a direct bypass of the scrubber system. Leaks into negative systems can reduce the quantity of gas pulled from the source and thereby affect capture and result in fugitive emissions at the process. The locations of any obvious holes or gaps/tears in expansion joints should be noted on a sketch.

Air infiltration along the inlet duct can be evaluated by determining the O_2 levels (combustion sources only) at various points along the duct. An increase in the O_2 levels between two measurement points provides clear indication of the location of the leakage. A material balance can be used to estimate the quantity.

Air infiltration along the ductwork can also be detected by comparison of the gas inlet temperature to the baseline value. A substantial decrease is indicative of air infiltration.

4.1.11 Process Conditions

As discussed earlier, the process operating conditions and raw material characteristics can have a major impact on scrubber operating conditions including, but not limited to: the particle size distribution, the gas flow rate, the particle surface characteristics, and the concentration of condensible vapors. Nonetheless, it is easier to identify the emergence of problems by observing the stack and performing a routine evaluation of the scrubber, than by first evaluating the process equipment. Thus, the evaluation of process conditions should be used primarily as a follow-up to problems identified by inspection of the air pollution control equipment.

On a routine basis, the evaluation should be limited to ascertaining the overall process operating rate and determining the adequacy of hood capture (if applicable). The hood capture can usually be evaluated visually from a safe vantage point; an alternative method is to use the hood static pressure as a qualitative means to estimate the hood gas flow rate. Comparison of the present hood static pressure against the baseline period hood static pressure provides an estimate of any shifts in hood capture efficiency.

An increase in the vapor concentration (material which may condense in the scrubber to form particulate matter) of the gas stream can be indicated by an increase in the stack opacity as compared to baseline values and perhaps by a change in the process operating conditions. The presence of vaporous material can be confirmed by an extractive stack test using a front filter (unheated) and a set of impingers immersed in ice. Note that this does not yield a quantitative measurement, only an indication of the pretense of vaporous material.

4.2 APPLICATION OF BASELINE PERFORMANCE EVALUATION TECHNIQUE TO SPECIFIC TYPES OF SCRUBBERS

There is substantial diversity in the design of particulate wet scrubbers. The various types of scrubbers serve different applications, are vulnerable to different operating problems, have different maintenance requirements, and have different particulate removal capabilities. To a certain extent, the means of evaluating performance is also different. Some of the unique factors which must be considered while evaluating performance for common types of scrubbers are described in this section. It is by no means an exhaustive summary of inspection techniques, rather it is intended to illustrate use of the evaluation approach presented earlier.

Six major categories of particulate wet scrubbers are presented in Table 4-4. These are listed in the approximate order of both increasing effectiveness and increasing operating cost. The preformed spray scrubbers range from simple "homemade" units for small scale material transfer applications to very large, sophisticated systems used in flue gas desulfurization systems. Packed tower scrubbers are generally used for combination particulate and gaseous contaminant removal. They are rarely used solely for particulate control since there are more economical and simple approaches of equal or greater effectiveness. Moving bed scrubbers were developed as an alternative to packed beds for applications where the gas stream contains sticky particulate which could clog a packed bed. This is a comparatively new approach, having been only introduced during the last 20 years. There are numerous tray-type scrubbers almost all of which offer

TABLE 4-4. MAJOR TYPES OF WET SCRUBBERS[a,b]

Category	Common Application	Specific Type
Preformed Spray	Material Handling Asphalt	Spray Towers Cyclonic Spray Towers Vane-type Cyclonic Towers Multiple-tube Cyclones
Packed Bed	Phosphate Fertilizer	Standard Packed Bed Fiber-bed Cross-flow Grid-packed
Moving Bed	Primary Aluminum Coal-fired Boilers	Turbulent Contact Absorbers
Tray-type Impingement Plate	Municipal Incinerators	Perforated Plate
Mechanically Aided	Material Handling	Wet Fans
Gas-atomized	Foundries Coal-fired boilers Asphalt Steel Mills Sewage Sludge Incinerators	Standard Venturis Variable Throat Venturis Orifice Scrubbers

a List not intended to be all inclusive.
b Adapted from a similar table presented in Reference 37.

moderate to high removal efficiencies at low pressure drops. They are currently used in a very wide set of applications. The principal category of scrubber for high efficiency collection of submicron particulate is the gas-atomized type, the most common of which is the venturi scrubber.

4.2.1 Preformed Spray Scrubbers

The preformed spray scrubber is the simplest type of wet scrubber and it has the lowest overall particulate collection capability. It usually consists of a vertical contact chamber with an array of spray nozzles as shown in Figure 4-7. The particulate laden gas stream enters near the bottom and passes upward past the spray headers. The nozzles may consist of sophisticated liquid atomizing nozzles or may simply be small holes drilled into the spray header.

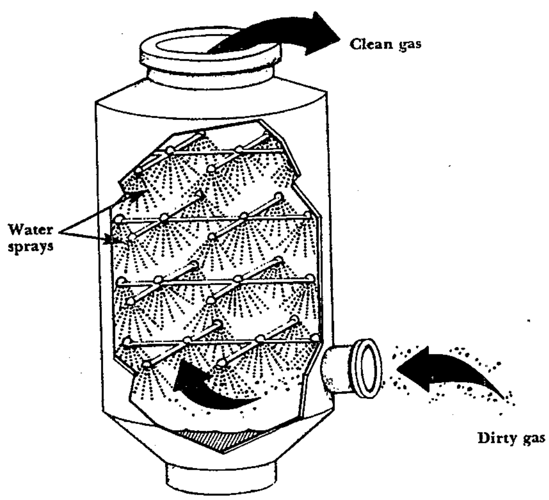


Figure 4-7. Typical preformed spray scrubber.

(Courtesy of EPA's Air Pollution Training Institute.)

This type of scrubbing system is often difficult to evaluate due to the lack of instrumentation and accessibility. Rarely do preformed spray scrubbers include continuous recording pH meters and recirculation liquor flow meters. There is usually a pump discharge pressure gauge but rarely pressure gauges on the individual pipes leading to the nozzle.

The types of data which are useful for evaluating the performance are listed in Table 4-5. Emphasis is given to analyses of the recirculation liquor quality since nozzle erosion and pluggage can be major problems for preformed spray scrubbers. Both problems have a direct and significant impact on the particulate collection efficiency by changing the spray coverage and average droplet sizes. During a routine inspection, the turbidity of the recirculation should be observed (classified as "light", "moderate", and heavy"). If the turbidity is moderate or heavy, the condition of the spray nozzles should be evaluated to the extent possible. Pluggage of some of the nozzles will be indicated by an increase in the supply pipe pressure. Erosion of the nozzle will yield the opposite effect on the supply pipe pressure gauge.

Many of these systems operate on an intermittent basis. The condition of the nozzles can be checked while the scrubber is off-line by operating the recirculation pump for a short period of time and observing each nozzle with a high powered flashlight (explosion proof). Pluggage or erosion of the nozzle will result in a distorted spray angle. This check should only be done if there is an appropriate access hatch and if the scrubber vessel is purged of any toxic gaseous and particulate.

If there is any indication of liquor solids related operating problems, the condition of the pond (if any) should be checked. The pond should have sufficient capacity to allow suspended materials to settle; multiple zones separated by weirs will permit maximum settling. The pump intake line should be located well above the elevation in the pond where silt and collected solids can be entrained in the liquor.

TABLE 4-5. PREFORMED SCRUBBER EVALUATION DATA

Data	Baseline	Routine
Recirculation Liquor Turbidity (Light, Moderate Heavy)	x	x
Recirculation Liquor Total Solids	x	
Recirculation Liquor Suspended Solids	x	
Recirculation Liquor pH	x	x
Spray Nozzle Operating Pressure	x	x
Physical Condition of Shell	x	x
Scrubber Inlet O_2 or CO_2 Levels (Combustion Sources Only)	x	
Quantity of Surfactants Used	x	x
Quantity of Anti-Foaming Agents Used	x	x
Liquor Flow Rate	x	x

It is important to measure the pH of spray tower scrubbers since many of these are constructed of carbon steel. If the pH of the recirculation liquor falls below 6, corrosion is probable. If the pH increases above 10, precipitation of calcium and magnesium compounds can result in scaling of the scrubber and pluggage of the pipes and nozzles.

The liquor flow rate to the scrubber is an important operating variable. The on-site monitor should be checked. If one is not available, the flow rate should be estimated at the point where the liquor returns to the pond or the recirculation tank. One parameter which is not of interest is the pressure drop across the scrubber. This is not directly related to the effectiveness of the particle capture and the magnitudes of the pressure drops are small.

4.2.2 Packed Bed Scrubbers

Packed bed scrubbers (also called packed tower scrubbers) have primarily been used for gas absorption or for gas cooling. Both functions are facilitated by the large liquid surface exposed to the gas stream as the liquid flows downward over the packing material. A typical packed bed scrubber is illustrated in Figure 4-8. Another common type of packed bed system is a cross flow scrubber. It is particularly advantageous when a liquid mist is being collected since this facilitates drainage of the accumulated material from the bed.

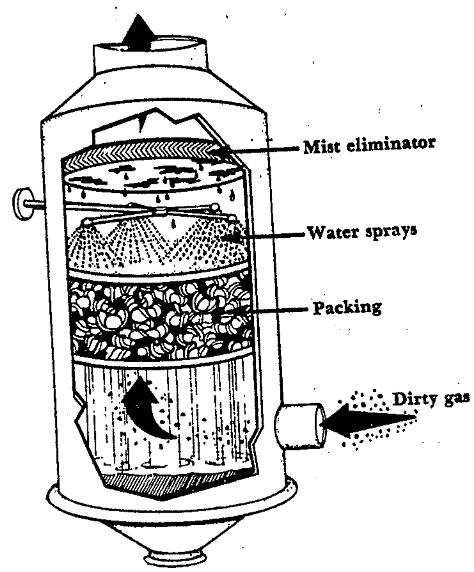


Figure 4-8. Typical packed bed scrubber.

(Courtesy of EPA's Air Pollution Training Institute.)

The packing materials used in packed beds can consist of crushed granite, raschig rings, pall rings tellerettes, and intalox saddles. These are illustrated in Figure 4-9 (with the exception of the gravel). All of the packing materials are usually the size range of 0.5 to 3 inches (1.25-7.5 centimeters), and the packing is usually randomly oriented in the bed. Some commercial units utilize several beds in series, each with a separate liquor supply and distribution system.

The types of data most useful for the evaluation of packed bed scrubbers (particulate removal only) are listed in Table 4-6. As in the case with the preformed scrubbers, the primary emphasis is the liquor quality. One of the major operating problems of packed bed scrubbers is pluggage of the bed due to deposition and/or precipitation of solids.[38] The flow rate of liquor is often insufficient to remove the accumulated material. These solids can cause increased static pressure drop across the unit, reduced gas flow through the control system, and channeling of the gas stream through only a part of the bed.

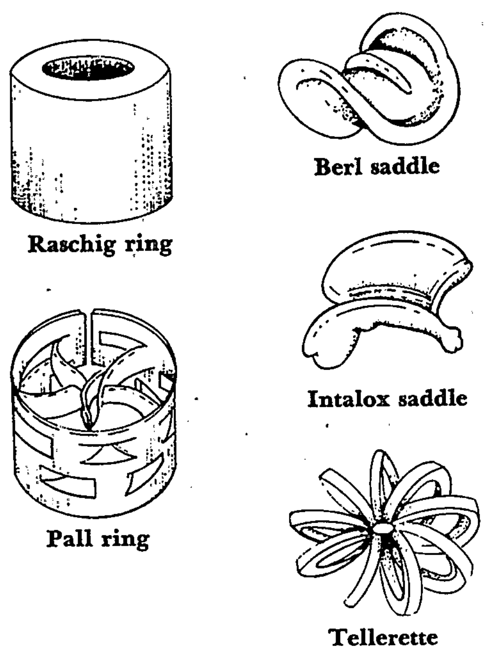


Figure 4-9. Typical packing materials.

(Courtesy of EPA's Air Pollution Training Institute.)

TABLE 4-6. PACKED BED SCRUBBER EVALUATION DATA

Data	Baseline	Routine
Recirculation Turbidity (Light, Moderate, Heavy)	x	x
Recirculation Liquor Total Solids	x	x
Recirculation Liquor pH	x	x
Recirculation Liquor Nozzle Pressures	x	x
Recirculation Liquor Flow Rate	x	x
Inlet and Outlet Gas Temperatures	x	
Apparent Shell Corrosion and Erosion	x	x

The turbidity of the recirculation liquor should be low. The condition of the packing should be checked if the turbidity is moderate to heavy. This can usually be done by opening the access hatches above and below each bed (the scrubber must be off-line).

Typical liquid-to-gas ratios for packed bed scrubbers are 1 to 6 gallons per 1000 ACF (0.1 to 0.5 liters per AM^3).[39] A decrease in the liquor flow rate relative to the baseline period may indicate a reduction in the particulate removal rate and a major decrease in the gaseous removal efficiency. The pH is measured primarily to ensure that corrosion is not occurring.

4.2.3 Moving Bed Scrubbers

Moving bed scrubbers were developed primarily as an alternative to packed bed scrubbers in applications having very sticky particulate material and/or high levels of gaseous contaminants. The turbulent motion of the lightweight packing material allows self cleaning of the deposited material without sacrificing the good gas transfer capability common to packed bed scrubbers. Principal applications of this type of scrubber include primary aluminum Soderberg potlines and coal-fired boilers (for flue gas desulfurization). A simple schematic of a moving bed scrubber is shown in Figure 4-10. The trade name commonly used is Turbulent Contact Absorber (TCA).

As shown in Figure 4-10, the gas enters at the lower side of the unit after passing through a presaturator chamber (optional). The pollutant laden gas stream passes upward through a series of beds each of which is 10% to 25% full of the lightweight packing. The liquor is introduced at

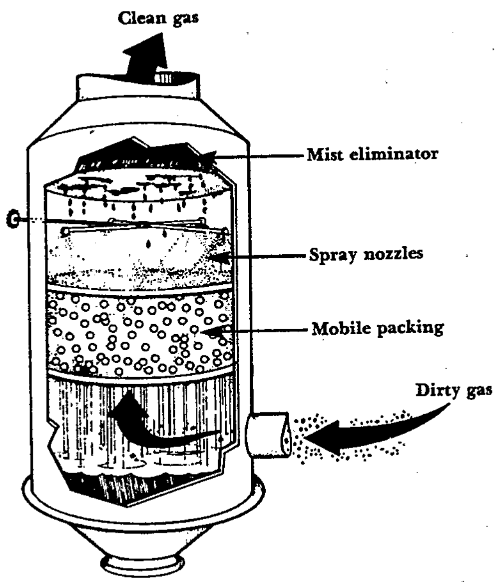


Figure 4-10. Typical moving bed scrubber.

(Courtesy of EPA's Air Pollution Training Institute.)

the top through a set of nozzles and passes through the beds counter-current to the gas flow. The bed is fluidized by the moving gas stream and this results in the formation of liquid droplets and sheets in the turbulent zone of the bed. Often one or more beds of packing are operated dry (above the point of liquid injection) in order to serve as an initial demister. A chevron demister or equivalent serves as the main entrainment separator.

Evaluation data for moving bed scrubbers are presented in Table 4-7. Unlike the previous types of scrubbers discussed, the liquor turbidity is not critical to the performance of the scrubber. Therefore, an increase or decrease in the liquor turbidity would not be cause for major concern, this would, however, eventually degrade the liquor distribution nozzles at the top of the scrubber.

TABLE 4-7. TURBULENT CONTACT ABSORBER EVALUATION DATA

Data	Baseline	Routine
Static Pressure Drops Across Each Stage	x	x
Recirculation Liquor pH	x	x
Recirculation Liquor Flow Rate	x	
Spray Nozzle Header Pressure	x	x
Physical Condition of Shell	x	x

The pressure drop the entire scrubber would be measured by measuring the static pressure at the scrubber inlet, and the pressure drop prior to the demister. The procedures for measuring static pressure discussed earlier should be used. Typical pressure drops are 4 to 20 inches of water. The pressure drop is proportional to the gas velocity, the rate of liquor addition, and to the number of beds in series.

The recirculation liquor flow rate needs to be confirmed only if there has been a decrease in the pressure drops or an increase in the plume residual opacity.

4.2.4 Tray-type Scrubbers

A tray-type tower consists of a vertical shell with one or more plates or stages mounted horizontally. The liquor is introduced at the top through a simple delivery pipe and flows onto the top stage. The height of liquor on this stage is maintained at 0.5 to 3 inches (1.3 to 7.6 centimeters) by a downcomer on the side opposite the inlet pipe. While the liquor is passing across the stage it is exposed to a relatively high velocity gas stream which passes up through numerous holes in the stage. A sketch of a tray-type scrubber is shown in Figure 4-11. Two common stage designs are illustrated in Figure 4-12.

Penetration of particles greater than 1 μmA is low in most tray type scrubbers. The degree of control for submicron particles is partially dependent on the number of stages, the type of stage, the size of the holes in the stage, and the design gas velocities through the holes. The static pressure drop is several inches of water per stage.[40,41]

As with almost all types of particulate wet scrubbers, tray-type units are vulnerable to corrosion and pluggage. Both corrosion and pluggage have an impact on the particulate collection efficiency in addition to their obvious effect on the scrubber's useful life.

The static pressure drop across the scrubber is directly related to the particulate removal effectiveness, therefore, this should be measured during each inspection. Measurement posts should be located before the first tray, between each tray, and after the last tray before the gas stream enters the demister section. The liquor quality is important,

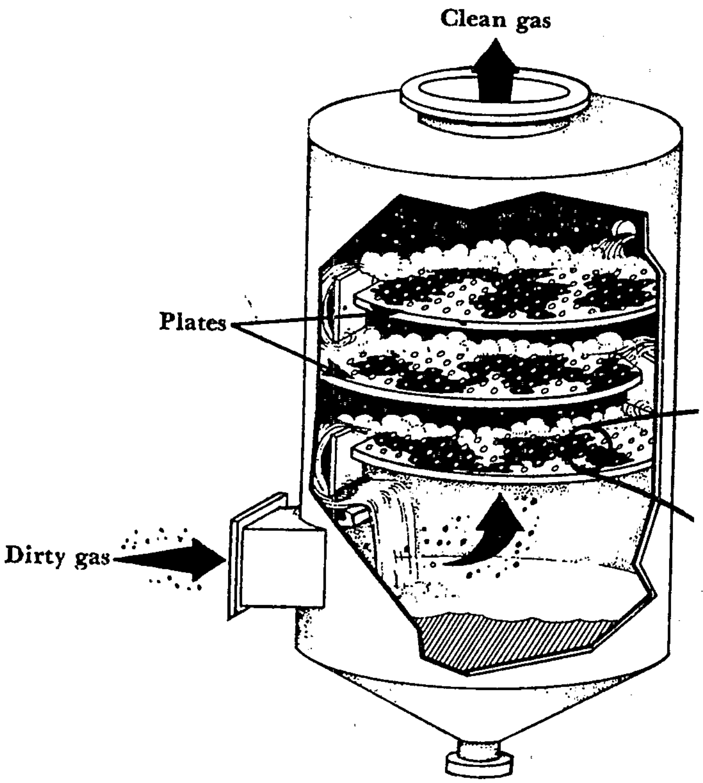


Figure 4-11. Tray-type scrubber.

(Courtesy of EPA's Air Pollution Training Institute.)

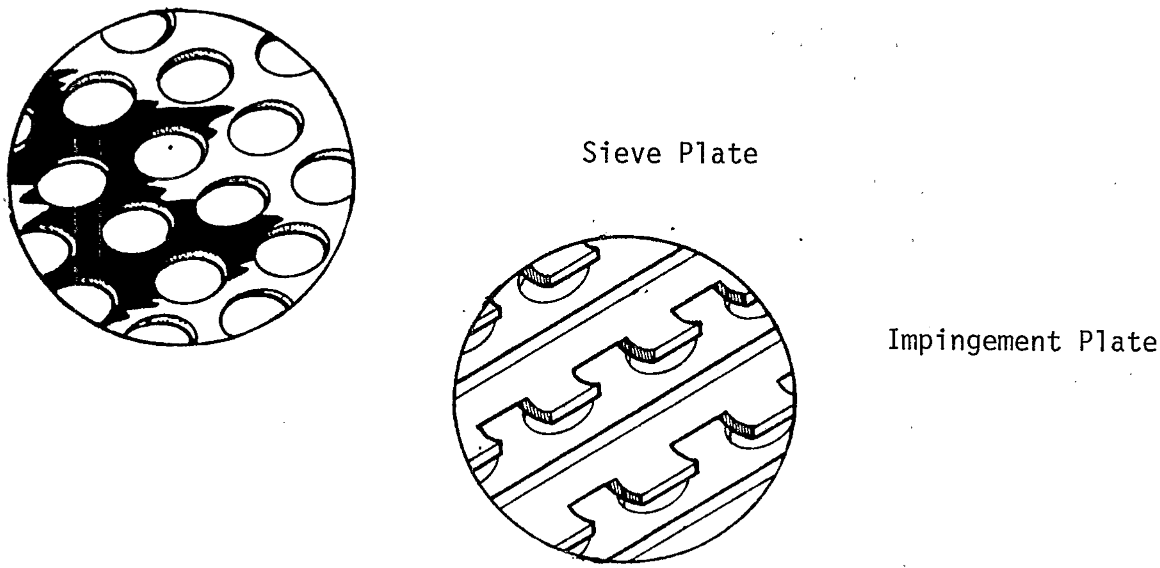


Figure 4-12. Types of stages.

(Courtesy of EPA's Air Pollution Training Institute.)

especially for the impingement tray type scrubbers. Due to the extremely small holes in the tray (approximately 3/16ths of an inch), suspended solids concentrations of more than 1% by weight can lead to rapid pluggage. Obviously, the turbidity of the recirculation liquor should be very low.

If the opacity of the unit has increased, it may be necessary to evaluate the condition of the trays. This can be done by opening access hatches above and below each of the trays. A build-up of materials in part of the tray can lead to the channeling problem. Partial pluggage of the holes leads to an increased pressure drop. Evaluation data for tray-type scrubbers are presented in Table 4-8.

TABLE 4-8. TRAY-TYPE SCRUBBER EVALUATION DATA

Data	Baseline	Routine
Pressure Drop Across Each Stage/Tray	x	x
Recirculation Liquor Turbidity (Light, Moderate, Heavy)	x	x
Recirculation Liquor Suspended Solids	x	
Recirculation Liquor pH	x	x
Physical Condition of Shell	x	x
Physical Condition of Trays	x	

4.2.5 Gas-atomized Scrubbers

Gas-atomized scrubbers are the most energy intensive and efficient type of particulate wet scrubber now in large scale commercial utilization. Regardless of the specific design, they all operate by accelerating the gas stream to high velocities, usually in the range of 10,000 to 40,000 feet per minute (3,050 to 12,2000 meters per minute). The design differences are found in the method of injecting the scrubber liquid into the gas stream at the converging section of the scrubber. Here, during the period before the atomized liquid reaches the same velocity as the accelerated gas stream, the droplets serve as inertial impaction targets for the entrained particles.

4.2.5.1 Orifice scrubbers. The common denominator in orifice scrubber design is that the constricted area which serves as the "throat" is partially flooded by a stationary pool of liquor. Atomization and acceleration of the liquor occurs as the gas stream passes through the constricted area with typical liquid-to-gas ratios up to 20 gallons per 1000 ACFM. Evaluation data requirements are provided in Table 4-9.

TABLE 4-9. ORIFICE SCRUBBER EVALUATION DATA

Data	Baseline	Routine
Pressure Drop	x	x
Liquor pH	x	x
Liquor Level	x	x
Physical Condition of Shell and Internal Components	x	x

One commercial type of orifice scrubber, a Western Precipitation Tubulaire Gas Scrubber, is illustrated in Figure 4-13. The particulate laden gas stream passes down through the central delivery tube and then makes a 180 degree turn after it passes around the central cone. The baffle to the left of the inlet tube serves as a demister. It is very difficult to evaluate the liquid-to-gas ratio with this kind of device, since the liquor flows by gravity back to the main sump without the need for a recirculation pump and piping (some systems have recycle pumps); nevertheless, the liquor level control is very important for the proper operation of the scrubber.

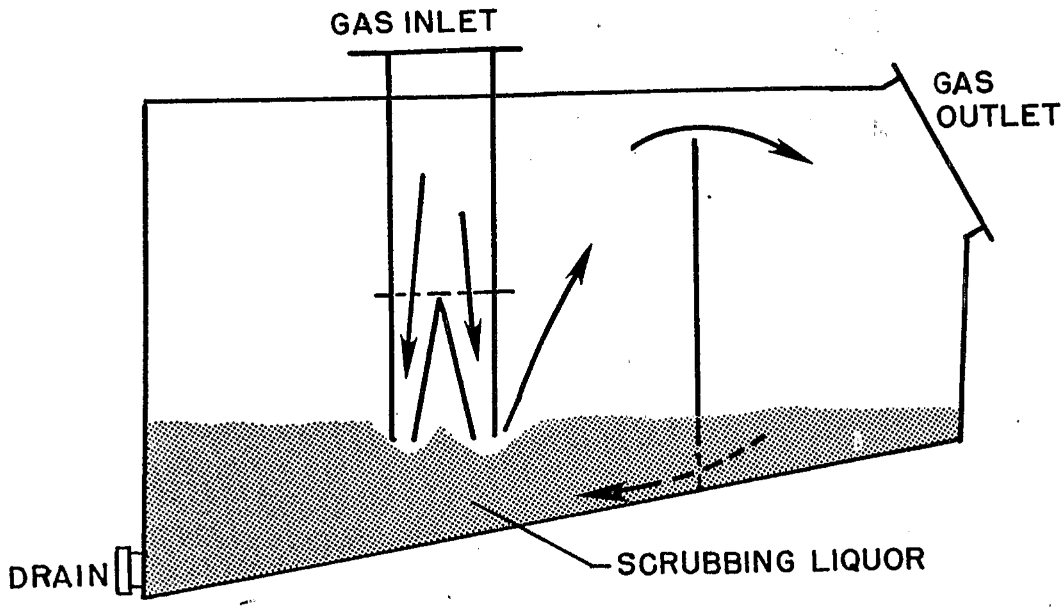


Figure 4-13. Typical orifice type gas-atomized scrubber.[42]

A second common type of orifice scrubber is illustrated in Figure 4-14. The contaminated gas stream enters from the top of the collector and flows down the rectangular inlet channel. The gas turns near the bottom and enters a set of venturi nozzles inclined slightly upward. The liquid level is controlled to a height that ensures that the desirable amount of liquid is entrained and atomized. There are a number of venturi nozzles arranged in parallel; particulate impaction on the droplets occurs primarily in the throat of these nozzles due to their high relative velocites in this region. The entrained droplets are later removed in the series of stationary baffles located downstream of the nozzles.

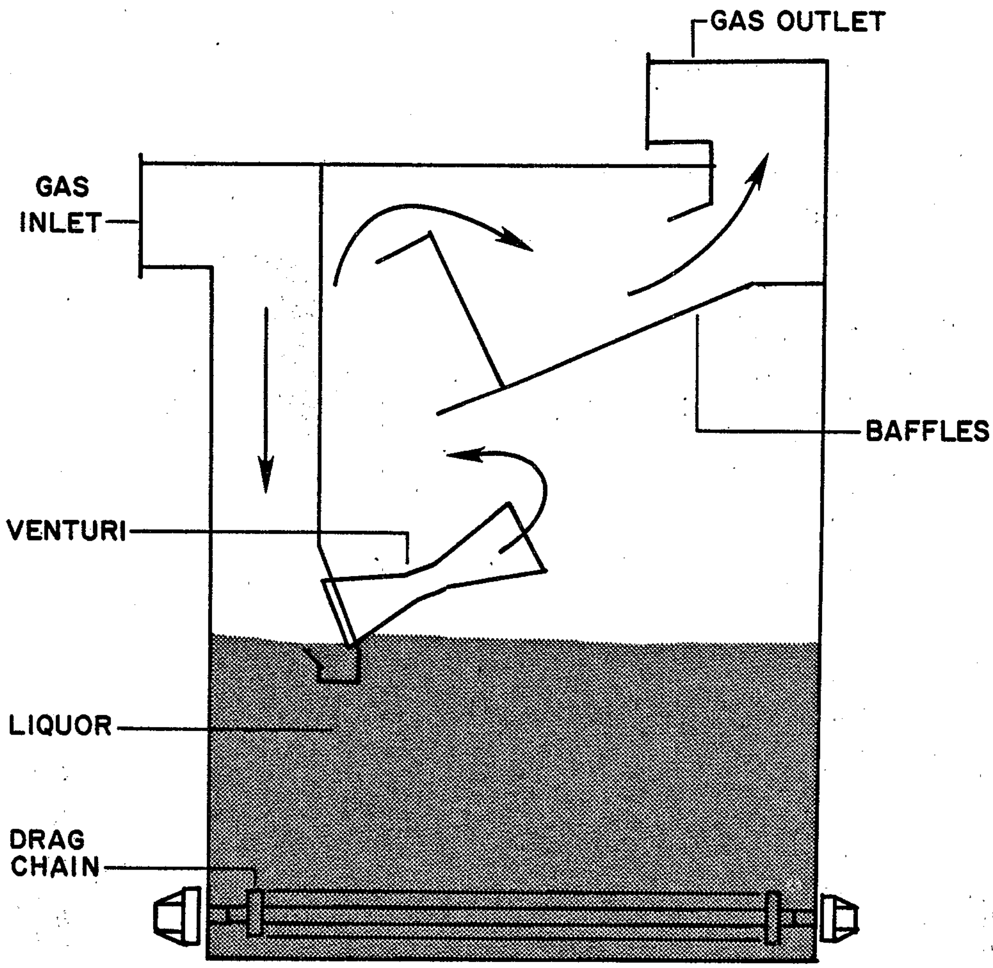


Figure 4-14. Typical orifice type gas-atomized scrubber.[43]

As shown in Figure 4-14, a drag conveyor at the bottom of the sump removes the accumulated solids. As with the previously mentioned type of orifice scrubber, there is no recirculation line and pump since the liquor is retained inside the collector. For this reason, it is difficult to independently evaluate the liquid-to-gas ratio.

Since the fan is often mounted directly above the collector, care must be taken in the measurement of the pressure drop across the unit. The inlet static pressure may be taken on the inlet duct or anywhere along the inlet chamber portion of the scrubber. The outlet pressure must be taken before the gas enters the inlet to the fan. For this reason, the static pressure port must be located along the collector wall in the general vicinity of that illustrated in Figure 4-14. Location of the port below the first baffle is not recommended due to the high quantity of sludge and liquor which impacts on the wall and could cause pluggage.

One of the principal problems of orifice scrubbers is maintaining proper liquid levels. Sufficient make-up water must be added to allow for evaporation, carry-over of droplets, and loss of liquid in the sludge. Corrosion and erosion of the constricted area or venturi nozzles are also common problems and can lead to substantially reduced collection efficiency. Accordingly, these nozzles often are simply bolted in to facilitate replacement.[44]

4.2.5.2 Venturi scrubbers. This type of gas-atomized scrubber is generally used in applications requiring large scale systems. There are numerous varieties available with the principal differences being in:

1. Methods for varying the throat area to adjust for changes in gas flow rate.

2. Methods for injecting the liquor ahead of the throat.

3. Presence or absence of a diverging section.

4. Design of the entrained liquor droplet separator following the throat.

A standard fixed throat venturi scrubber is illustrated in Figure 4-15. The particulate laden gas stream enters the converging section of the venturi which usually has an angle of approximately 25°. The liquor is injected in the converging section and is atomized near the inlet to the throat. Immediately following the converging section, the gas stream enters a diverging section (the throat having a negligible length in this case). In the diverging section of the throat of the unit shown in Figure 4-15 the angle is less than 15°; here the gas is gradually decelerated prior to entry to the cyclonic chamber. As shown in the plan view sketch, the gas stream enters the entrainment separator tangentially. Some commercial units incorporate an additional demister tray to further remove the entrained droplets.

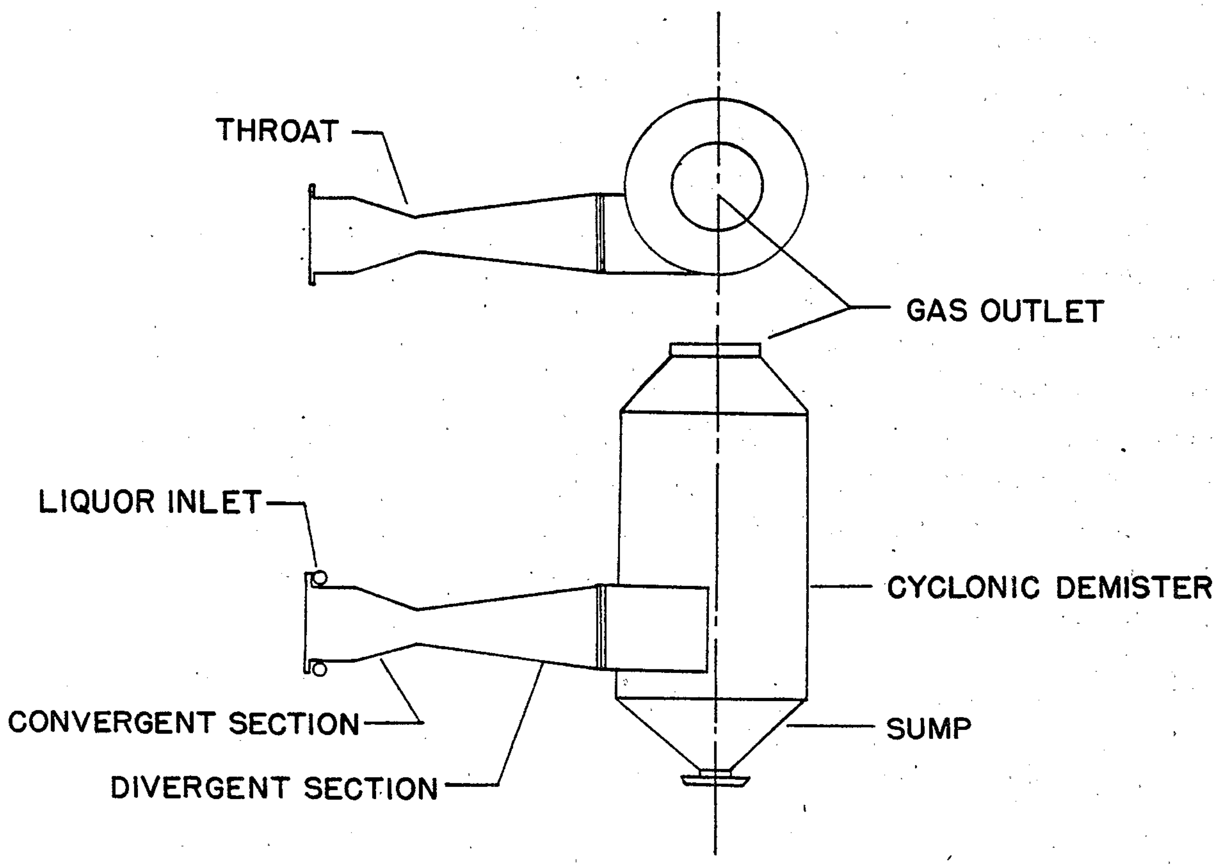


Figure 4-15. Venturi scrubber with long divergent section.

Data necessary for the evaluation of venturi scrubbers is presented in Table 4-10. The pressure drop is particularly important since this is related to the impaction effectiveness. As described earlier, the pressures must be converted back to a standard gas density, if the inlet and outlet gas densities have changed substantially since the baseline period.

TABLE 4-10. EVALUATION DATA FOR VENTURI SCRUBBERS

Data	Baseline	Routine
Pressure Drop	x	x
Recirculation Liquor Flow Rate	x	x
Recirculation Liquor Total Solids	x	x
Recirculation Line Skin Temperatures	x	x
Presaturator Total Solids	x	
Presaturator Turbidity (Light, Moderate, Heavy)	x	x
Inlet and Outlet Gas Temperatures	x	x
Physical Condition of Shell	x	x
Quantity of Surfactants Used	x	
Quantity of Flocculants Used	x	
Quantity of Anti-Foaming Agents Used	x	
Recirculation Liquor pH	x	x

Due to the gradual slope of the divergent section in this unit, the kinetic energy of the gas/liquor stream is partially converted back to potential energy. As a result, the gas stream static pressure will increase moderately as the gas passes through the divergent section. The pressure drop of direct interest to the inertial impaction phenomenon is the pressure drop between points 1 and 2 in Figure 4-15. The actual pressure drop measured in many commercial systems is representative of the pressure drop between points 1 and 3. The latter value will be lower according to the extent of static pressure recovery.

A variation of the classical fixed throat design is the annular ring throat. The flange separating the converging and diverging sections has a small extension lip which supports a ring insert. The area of the opening in this insert determines the maximum throat velocity at a given gas flow rate, and thereby controls the collection efficiency. This insert can be changed and will vary the collection efficiency.[45] On some commercial units it is difficult to determine if such a change has been made or even that the scrubber has an insert. Erosion of an insert over the time can lead to a reduction in gas velocities and a corresponding reduction in the particulate control efficiency. Erosion of the insert or installation of a different insert can often be detected by comparing the present pressure drop at a given gas flow rate and liquor flow rate with baseline data. One generally accepted relationship for the pressure drop is shown in Equation 5-1.

$$\Delta P = 0.001\ V_t^2\ (L/G) \qquad \text{Equation 5-1}$$

where:

ΔP = pressure drop, centimeters of water

V_t^2 = throat velocity, cm/sec

L/G = liquid-to-gas ratio, $(m^3/g)/(m^3/g)$

In a common type of adjustable venturi, a hand cranked assembly moves a center cone up or down to change the annular throat area. The length of the throat also varies slightly as the cone moves. The liquor is injected from a set of four tangential pipes (no nozzles) and from a center deluge pipe oriented directly above the center cone. A flooded elbow (a depression of 6" to 9" filled with liquid) is used at the bottom of the venturi section to absorb the impact of the turning gas stream. This reduces erosion of the elbow.

Another variation of the annular area variable throat venturi is the flooded disc scrubber. As shown in Figure 4-16, the center assembly includes a large flat disc mounted horizontally at a point just upstream of the constricted area. The liquor passes up through the center column and out over the disc. As the gas stream is accelerated around the edges of the disc, the liquor is entrained and atomized. Particulate impaction on the atomized liquor occurs directly downstream of the disc. The gas velocity can be controlled by slight adjustments in the elevation of the flooded disc with relation to the constricted area.[46] There is no divergent section per se, therefore, no substantial pressure recovery would be expected downstream of this type of collector.

One variable throat design common to many commercial units is depicted in Figure 4-17. In this design, two damper blades are used to vary the open area in the rectangular throat and thus control the gas velocity through the throat. The position of the damper blades are controlled either manually or by a differential pressure sensor and controller. The liquor can be injected by a number of methods including the deluge nozzles with deflectors shown in Figure 4-17. Other designs have a single variable damper on the throat with a side mounted controller. In these units, the liquor spray is directed towards the section opposite the damper.

The dampers are in the high velocity zone, therefore, erosion can be a problem. The scrubber may gradually lose the capability to achieve the baseline pressure drops. To diagnose this problem an internal inspection may be necessary when the scrubber is off-line and purged out (agency inspectors should <u>not</u> enter equipment).

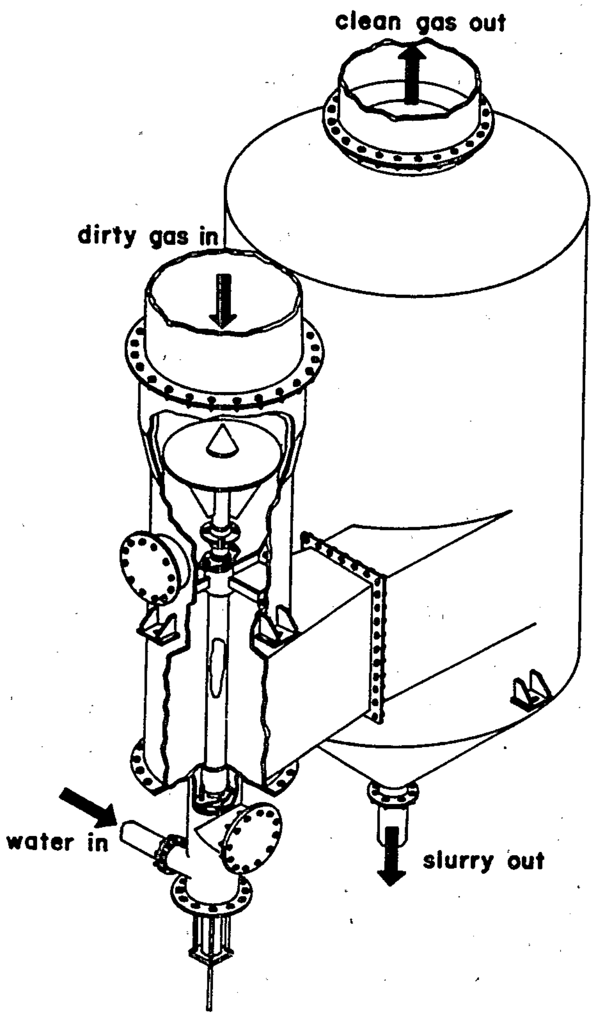


Figure 4-16. Flooded disc type venturi scrubber.

(Courtesy of Research Cottrell.)

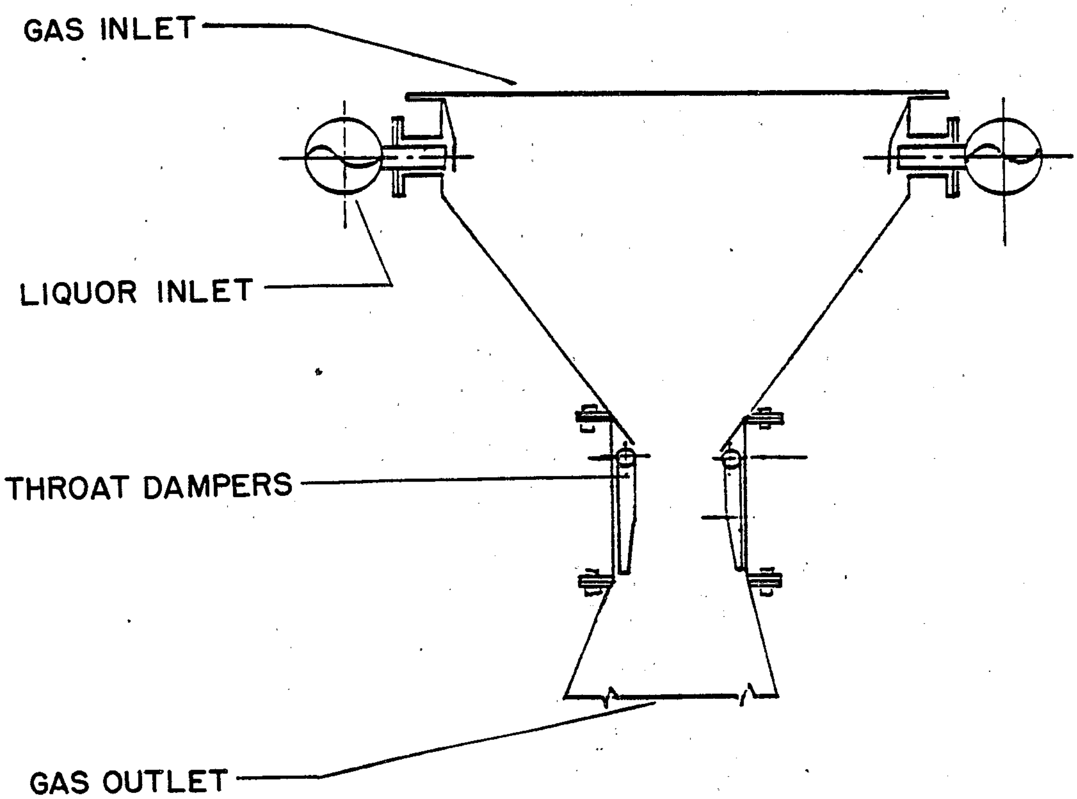


Figure 4-17. Adjustable venturi throat mechanism.

A variable rod-type, adjustable venturi scrubber is illustrated in Figure 4-18. In this design, the throat is comprised of the multiple slots between the rows of horizontal rods. The gas velocity can be modified by changing the diameter of the rods, the spacing of the rods, and the spacing between adjacent layers of the rods.[47] This type of scrubber is conceptually similar to the annular ring type discussed earlier, except that changes in the throat area can be made while the unit is on-line. However, it is difficult for regulatory agency personnel to independently determine that the rod arrangement has been changed. Erosion and corrosion of the rods are potential problems. The pressure drop can provide a good indication of these conditions.

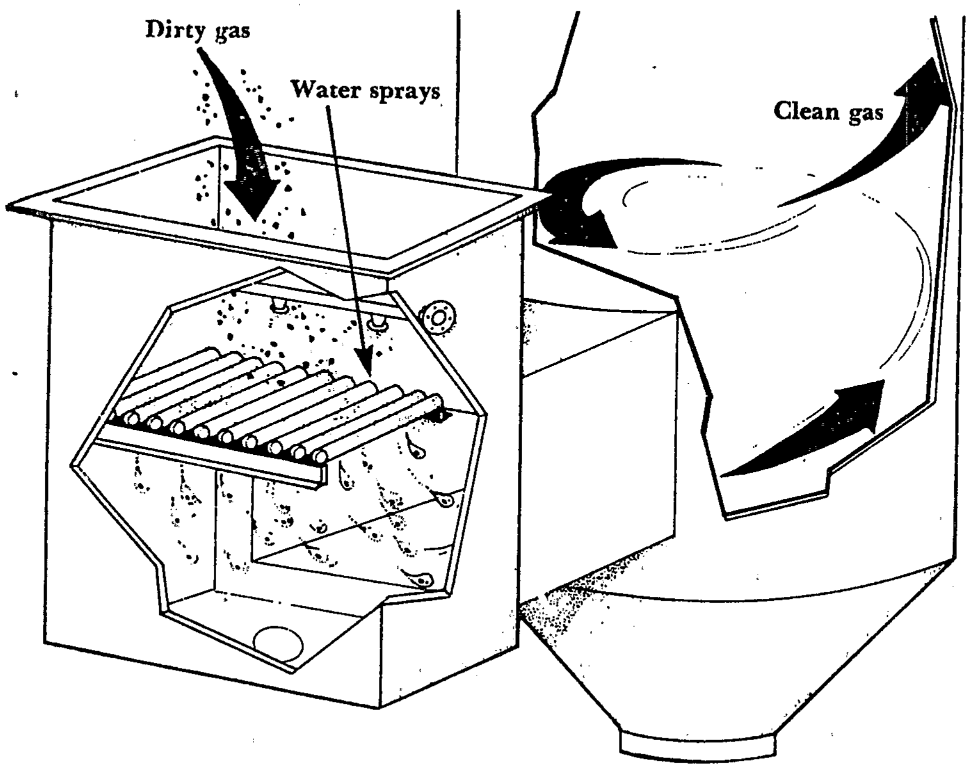


Figure 4-18. Variable rod venturi scrubber.

4.3 APPLICATION OF BASELINE PERFORMANCE EVALUATION TECHNIQUE TO SPECIFIC INDUSTRIES

This section describes a number of wet scrubbers applications and the problems unique to each application to a specific source category. It is not an exhaustive summary of all applications of the various types of wet scrubbers. However, each application has been included because it illustrates conditions and potential problems that must be considered when evaluating the performance of the wet scrubbers on many different processes.

4.3.1 Sludge Lime Kilns at Kraft Pulp Mills

Calcination of the sludge produced in the kraft pulping process is necessary to reuse the lime. The sludge, which is normally 55% to 65% solids, is fed to a rotary kiln which is usually fired by either oil or natural gas.[48,49,50] Typically rotary kilns are 8 to 13 feet in diameter and 100 to 400 feet long,[49] and have exit temperatures in the range of 300° to 500° F.[48] A venturi scrubber having either a fixed or variable throat is the most common type of air pollution control device used on rotary kilns. Some plants have previously used impingement plate scrubbers, but the venturis have gradually gained the major share of the market because of their lower capital cost and higher efficiency.[49]

Typical static pressure drops for the venturi scrubbers range from 10 to 30 inches of water; however, the large majority of the systems operate in the much narrower range of 15 to 20 inches of water.[48] The liquid-to-gas ratios vary somewhat depending on the design of the equipment, but a representative ratio would fall in the range of 10 to 25 gallons per 1000 ACF.[49] Due to the alkaline nature of the entrained dust, the pH of the recirculating liquor is high, often above 11. Consequently, scaling has been a problem in some units

The mass loadings of the inlet gas stream from the rotary kiln are relatively high at 3 to 20 grains per ACF.[48,49] The large majority of these particles are calcium oxide dust particles which have a fairly large geometric mean size. However, the gas stream may also contain a small small quantity of sodium oxide material which evolves as a very small diameter fume.[50,51] During the periods when substantial quantities of submicron sodium oxide particulate are present, the mass emissions can be higher than the baseline period even though the pressure drop has not changed. This illustrates an important point: A wet scrubber cannot be evaluated independent of basic process operational checks. In this case, the amount of sodium material evolved is strongly dependent on the quantity of sodium in the limestone mud feed, which varies from 0.1% to 2.5% by weight. The inspector should evaluate the operation of the mud washers if there is any question concerning the emissions from the scrubber system.

Compared with other applications of wet scrubbers, the quantity of suspended solids in the recirculation liquor of lime kiln scrubbers can be high. The solids usually range from 10% to 30% by weight,[49] and pluggage of the inlet lines to the venturi scrubber is a frequent problem.

Venturi scrubbers on lime kilns are rarely equipped with presaturation chambers, thus, the inlet gas temperatures to the throat are usually greater than 300°F, causing some liquor evaporation. This can have an adverse effect on particle collection and will increase the gas volume handled by the induced draft fan.

The typical operating characteristics of particulate wet scrubbers used on rotary lime kilns are summarized in Table 4-11.

TABLE 4-11. TYPICAL OPERATING CHARACTERISTICS OF SCRUBBERS ON ROTARY LIME KILNS AT KRAFT PULP MILLS[50,51]

Parameter	Scrubber Type	
	Impingement	Venturi
Liquid-To-Gas Ratio, Gals/1000 ACF	4-5	10-25
Liquor Solids Content, % by weight	1-2	10-30
Pressure Drop, Inches H_2O	5-7	10-30

The principal problem of the impingement plate scrubber as applied to rotary line kilns, is the pluggage of the very small holes in the plates. For this reason, the solids content of the recirculation liquor must be maintained at less than 2% by weight. The venturi scrubber on the other hand, is less expensive to purchase and can be operated at a higher solids level, therefore, use of the venturi facilitates the overall plant-wide water and lime balances. The venturi operates at a higher pressure drop and achieves greater particulate removal efficiencies at these pressure drops. The venturi scrubber is the type used on systems installed in the last 10 years.

4.3.2 Asphalt Batch Plants

There are several major processes used to make asphalt concrete, the two most common being the hot mix batch plants and the newer drum mix plants. There are substantial differences in the characteristics of the particulate matter from these two processes. In both cases, subtle process changes change the particle size distribution substantially and may even alter the wettability of the materials.

In the conventional hot mix plant, the various grades of aggregate necessary to produce the types of asphalt are stored in open piles or bins near the dryer. These are fed from the bins at a controlled rate using weigh belt feeders. The accumulated material passes into the top of the dryer where it is exposed to high temperature flue gas. The aggregate is dried as it passes through the dryer countercurrent to the gas stream. A single burner, usually fired by either gas or oil, is used to provide the necessary heat.

The dried aggregate is then transferred to the top of the tower where it is mixed with heated asphalt purchased from local refineries. The aggregate and asphalt are mixed in the pug mill and discharged to delivery trucks. The flue gas from this process passes through a cyclone for removal of the potentially useful aggregate dust, and then goes to the scrubber. Most newer plants, being subject to the Standards of Performance for New Sources, use a venturi type scrubber; however, numerous older stationary plants use either a simple spray tower or a cenrifugal washer. In some cases, the spray tower scrubbers in use have either been designed or extensively modified by the operators.

In the drum mix process, the aggregate drying and mixing with asphalt are both accomplished in the rotary drum. The asphalt is injected at a point midway down the dryer where the gas temperature should be sufficiently low to prevent significant volatilization of the asphalt components. However, the injection point should not be too far removed from the firing end, or the gas temperature will be too low to permit proper coating of the aggregate and the resulting product will not meet customer specifications.

The particulate matter emitted from drum mix plants is significantly different from that of conventional hot mix plants. Emissions from drum mix plants, especially if the injection point is too close to the flame zone, will include a portion of condensed hydrocarbon particles. These can be significantly smaller in size than the entrained aggregate itself and the material may be less wettable due to the organic nature of the emissions. A similar problem can result when a drum mix plant is used for the recycling of asphalt. In this case, the old road bed material is ground and added through a chute near the middle of the drum. Volatilization of the asphalt materials can lead to a very difficult to control, partially organic particulate matter.[52]

When there is partial volatilization of the asphalt binder, the wet scrubber baseline data may be misleading. Due to the large number of very small particles, the emissions may be substantially higher than during the baseline period even though there has been no significant change in the observed pressure drop or the liquid to gas ratio. If the plume residual opacity is high and there has been no significant change in the scrubber operating parameters, the inspector should inquire about changes in the asphalt binder injection.

Typical operating conditions for the wet scrubbers used in asphalt plants are listed in the following Table 4-12. The range of pressure drops is quite large. This is partially due to the variable quantities of organic material volatilized (drum mix plants) and the variable particle size distribution resulting from the drying of the aggregate itself (drum mix and hot mix batch). The latter is due to variations in the friability of the aggregate which can breakdown in certain plants to form a high concentration of fines and the presence of clay fines in certain aggregates. Both act to substantially increase the amount of small diameter dusts entering the scrubber. The process and raw material variables discussed

TABLE 4-12. TYPICAL OPERATING CHACTERISTICS OF ASPHALT PLANT PARTICULATE WET SCRUBBERS[53,54,55]

Parameter	Hot Mix		Drum Mix
	Spray Tower Scrubbers and Centrifugal Scrubbers	Venturi Scrubbers	Venturi Scrubbers
Liquid-to-Gas Ratio, Gals/1000 ACF	3-10	5-10	5-10
Pressure Drop, Inches H_2O	2-6	15-25	15-30*
Inlet Gas Temperature, °F	325-425	325-425	225-350

*Asphalt Concrete NSPS Background Document (EPA) recommends a venturi scrubber with a pressure drop of at least 20 inches of water.

above underscore the importance of evaluating each system on a site-specific basis using the baseline data. The data presented in Table 4-12 is not intended to be applied as performance criteria for a specific asphalt concrete scrubber.

Regardless of the type of asphalt plant, the size of the facility is usually quite small. The range of gas volumes is 15,000 to 50,000 SCFM,[54,55] well below that for wet scrubbers in other applications. Due to the size of the plants and the intermittent operating schedules, there is rarely an engineering staff available to assist the operator in diagnosing operating problems. Furthermore, many of the wet scrubber systems at these plants have no instrumentation for determining pressures, liquid flow rates, and gas temperatures. Another problem common to asphalt concrete plants is reentrainment.

Many of the plants construct a make-shift pond for settling of the solids collected. In some cases, inadequate ponds or inadequate pump intake designs result in excessive solids pick-up. This can lead to pluggage and erosion in the scrubber. Ponds should be separated by several overflows in order to improve settling. General design criteria for settling ponds are listed below.

Number of zones	= 3
Volume	= 1/2 day circulating pump capacity
Depth	= 6 feet (minimum)
Width	= twice the length

Additional design criteria are discussed in reference 56.

Scrubbers used on hot mix plants burning natural gas have few problems with corrosion; however, those burning oil with a high sulfur content can have low pH problems, especially if the recirculation rate is high. Corrosion of the scrubber can also be caused by mildly acidic ground waters in certain locations and by acidic components in the aggregates being dried. It is important to check the liquor pH frequently and neutralize with hydrated lime or caustic soda, if necessary.

4.3.3 Grey Iron Foundries

A grey iron foundry cupola is a firebrick, refractory lined cylindrical furnace used for the melting of scrap to produce grey iron. The cupola is alternately charged with coke, limestone and soda ash, and scrap. The effluent gases pass through the top of the cupola and exit at temperatures as high as 1800 °F. The entrained particulate matter is partially composed of incompletely combusted coke and entrained charge materials. Because of the high temperatures involved, there is a substantial quantity of submicron fume and condensed organic particles. The gas stream also contains very high concentrations of carbon monoxide (CO). The concentration of CO can vary from as low as several percent to as high as 25% depending on the iron to coke ratio charged and the degree of maldistribution of the material across the cross section of the cupola.[57] The extremely high negative static pressures present near the I.D. fan, can cause severe air inleakage. If this inleakage results in inadequate exhaust of the cupola, then some discharge may be evident from the cupola top. Fugitive leaks of exhaust gases during periods of positive pressure operation can pose a risk to inspection personnel because of the high concentrations of CO and particulate matter present in the gas stream.

Due to the batch type operation of cupolas, their effluent conditions are not constant. Thus, stack test data taken at one point in time may not be representative of other stages of a heat. Significant differences in the particle size distribution, the carbon dioxide/carbon monoxide ratio, and the gas temperature may occur making it very difficult to prepare a baseline data set. The cupola conditions must be well documented in order to make the baseline data reasonable.

Venturi scrubbers are the most frequently used for control of cupola emissions. These are necessary due to the small particle sizes involved. Often the pressure drop of the scrubber must exceed 40 inches w.c. in order to achieve an adequate removal efficiency. In some cases the required pressure drop exceeds 120 inches of water. At the typical pressure drops of cupola venturi scrubbers, the outlet static pressures (between the scrubber and the fan) are in the range of -25 inches to -125 inches.

Care must be taken to avoid very large errors in the measurement of the pressure drop due to the aspiration effect discussed earlier.

As shown in Figure 4-19 the effluent concentration from the scrubber can be a function of the scrap quality. The increased emissions with oily scrap is probably due to increased concentrations of organic vapor which condense in the scrubber to form a very small, difficult to wet particulate material. Therefore, pressure drop is not acceptable as a single indicator of performance. As in other scrubber applications, the process operation and material characteristics must be taken into account.

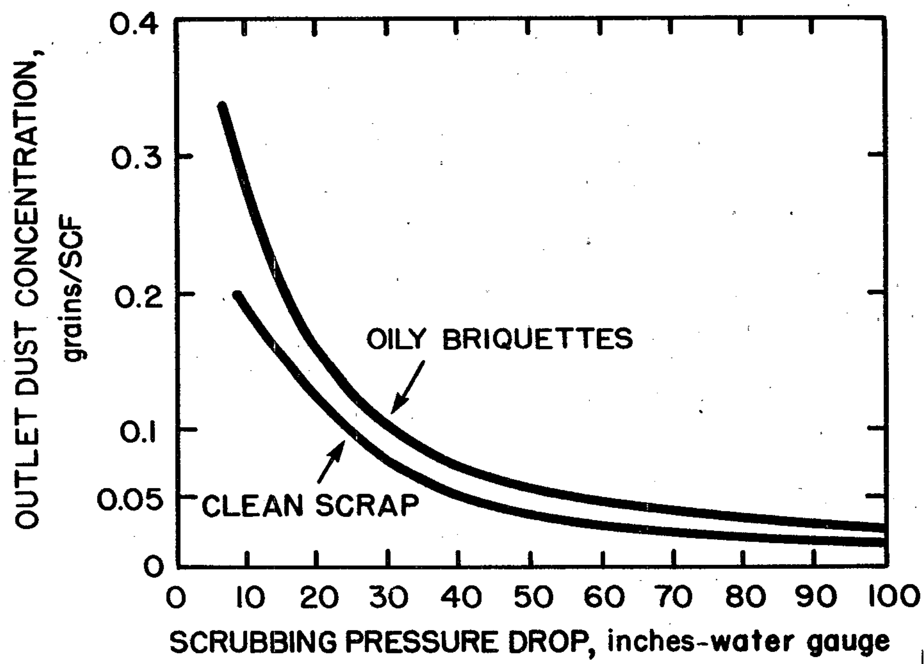


Figure 4-19. Pressure drop collection efficiency relationship.

Typical operating conditions for the wet scrubber used on cupolas are listed in Table 4-13. It appears that basic cupola design characteristics do not have a significant effect on emissions or specific melting rates. The use of briquettes increases emissions. The blast rate also has a significant effect causing greater emissions and smaller particle sizes as the blast rate increases.

TABLE 4-13. TYPICAL OPERATING CHARACTERISTICS OF PARTICULATE WET SCRUBBERS ON GREY IRON CUPOLAS[58]

Parameter	Values
Liquid-to-Gas Ratio, Gals/1000 ACF	10-25
Pressure Drop, Inches H_2O	25-45
Gas Inlet Temperature, °F	160-200
Liquor Solids Content, % by weight	1-10

4.3.4 Coal-fired Boilers

Particulate wet scrubbers used on coal-fired boilers are generally found in conjunction with SO_2 absorption systems. The most common types of particulate scrubbers in this application include variable throat venturis (e.g. plumb bob, venturi rod) and moving bed scrubbers. This type of installation is large, with gas flows exceeding 10^6 ACFM; typical operating conditions are presented in Table 4-14. In most cases, there are several scrubbing trains in series so that changes in boiler load can be accommodated. Due to the high cost of such systems, there is almost always reasonable instrumentation including pH monitors, static pressure gauges, and liquor flow rate meters.

TABLE 4-14. TYPICAL OPERATING CHARACTERISTICS OF PARTICULATE WET SCRUBBERS ON COAL-FIRED BOILERS[59,60]

Parameter	Venturi (all types)	Moving Bed
Liquid-to-Gas Ratio, Gals/1000 ACF	16-30	50
Pressure Drop, Inches H_2O	3-20	10-15
Gas Inlet Temperture, °F	280-450	280-350
Liquor pH	6-8	6-8

The particle size distribution and mass loadings from a given boiler are a function of the fuel quality and the boiler firing conditions (such as excess air rates). Compared with other types of sources, the gas quantities and the particle size characteristics are relatively stable. Thus, scrubbers at pulverized coal-fired boilers are suitable candidates for the development of relatively simple baseline performance curves.

Two of the principal problems reported from these types of scrubbers are corrosion and scaling, both of which are partially dependent on the pH of the recirculation liquor. Operation of the particulate scrubber at pH levels below 6 can lead to severe corrosion of carbon steel components. Scaling results from precipitation of calcium and magnesium compounds which normally happens at pH levels of 9 and above. One factor of importance in this phenomenon seems to be the degree of oxidation of sulfite to sulfate in the liquor.

Recent water quality requirements have resulted in greater recirculation rates than previously would have been considered. This, in turn, has increased (1) the risk of corrosion due to the concentration of chlorides and other corrosive agents, (2) the risk of erosion due to the higher solids levels, and (3) the risk of pluggage.

High opacity conditions have been observed at a number of wet scrubbers which appear to be operating satisfactorily. The light scattering aerosol formation is not well understood, however, it may be due to condensation of vaporous material formed in the boiler. The most likely compound is sulfuric acid vapor.[61]

4.3.5 Municipal Incinerators

During the last ten years, the number of municipal incinerators in operation has been gradually decreasing due to the increased use of landfills. Nevertheless, a number of wet scrubber systems are used for particulate control on the incinerators still in operation. The types of scrubbers commonly found in this application include impingement plate scrubbers and various types of venturis. Typical operating characteristics for these venturi systems are presented in Table 4-15.

One of the major problems of wet scrubber operation as applied to municipal incinerators is control of the condensible, partially oxidized organic matter which forms when the incinerator operating temperature is too low. This material condenses while passing through the scrubber. The final particle sizes are too small for effective impaction in the scrubber, and therefore, collection efficiency is low. Few scrubbers have been able to achieve the NSPS limits because of this problem. The residual plume from these units is generally a bluish white. Due to the high chloride content of the material charged, corrosion of the scrubbing systems applied to incinerators can be severe.

TABLE 4-15. TYPICAL OPERATING CHARACTERISTICS OF MUNICIPAL INCINERATOR VENTURI SCRUBBERS[62,63,64]

Parameter	Venturi Scrubber
Liquid-to-Gas Ratio, Gals/1000	4 - 8
Pressure Drop, Inches H_2O	15 - 60
Inlet Gas Temperature, °F	300 - 500
Liquor Solids Content, % by weight	1 - 10

As with other applications of scrubbers, some process operational data must be evaluated to determine if there has been a significant shift in the baseline conditions. The incinerator operating temperature and the charging rate should be checked at a minimum. It may also be necessary to determine if there has been a change in the types of materials charged to the incinerator.

4.3.6 Basic Oxygen Furnaces

Venturi scrubbers have commonly been used to control the fine particulate emissions from basic oxygen furnaces (BOF's). This application is of interest due to the very high static pressure drops involved and the cyclic nature of the gas flow rate over the 30 to 45 minute operating cycle; the latter raises a question concerning the definition of pressure drop.

The basic oxygen furnace is a batch reactor in which up to 350 tons of pig iron and scrap are converted to steel by the oxidation of the carbon, phosphorus, silicon, and magnesium impurities. The materials charged include a minimum of 70% molten iron, 10% to 30% scrap, and limited quantities of flux materials such as lime and fluorspar.[65] The offgas from the BOF consists of 75% to 90% carbon monoxide and the gas temperature is approximately 3000°F before dilution .

The gas evolution rate varies substantially during the oxygen blow period. An example gas flow rate versus time curve is presented in Figure 4-20. Since the pressure drop across a venturi scrubber is a function of the gas flow rate, the pressure drop will also have major variations during the production cycle. To be explicit, the time must be specified along with pressure drop value. The typical operating conditions of venturi scrubbers and quenchers serving BOF's are presented in Table 4-16.

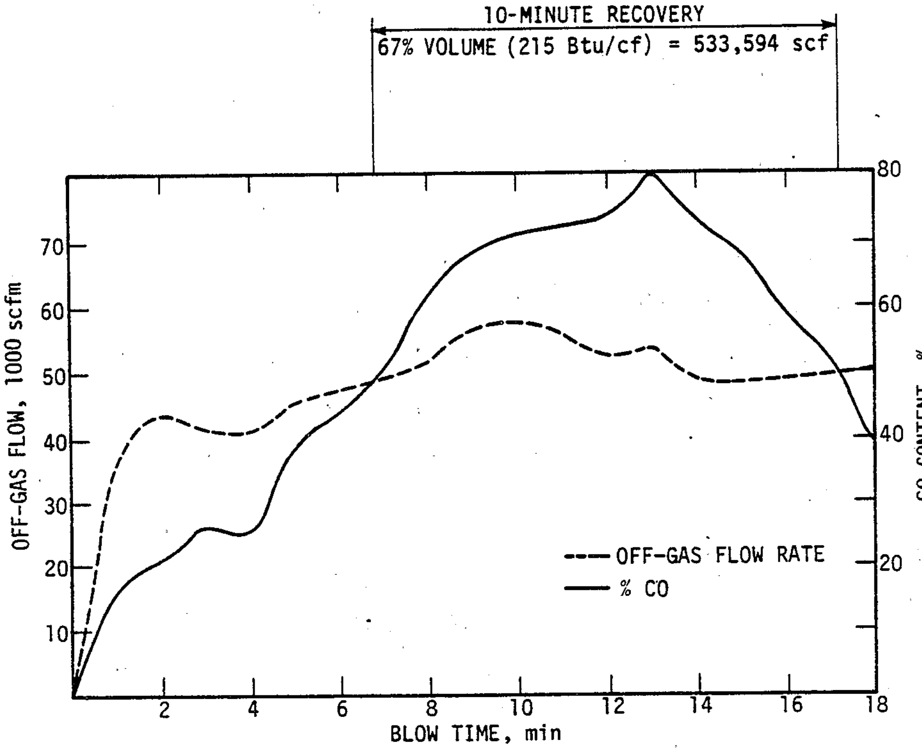


Figure 4-20. Gas flow rate and CO content during a blow.[22]

The particulate matter entrained in the gas stream is very fine with 85% to 95% of the mass smaller than 1 micrometer in diameter and as much as 20% of the mass less than 0.5 micrometers.[66] The venturi scrubbers are operated at very high pressure drops to achieve reasonable control efficiencies. The typical range is 40 to 70 inches of water.[22,65] Due to these high negative static pressures, pressure drop measurements must be made carefully. The particle size distribution generated by the process and consequently the pressure drop necessary, is a function of the raw material charge characteristics, the rate of oxygen blow, the type and quantity of ladle additions, and the condition of the refractory.

A quencher is used to decrease the gas temperature prior to entry to the venturi scrubber. As much as 80% of the particulate matter is removed in the quencher, therefore, the pressure drop across this collector is also of interest.

TABLE 4-16. TYPICAL OPERATING CONDITIONS OF VENTURI SCRUBBERS SERVING BASIC OXYGEN FURNACES[22,65,66]

Parameter	Venturi Scrubber	Quencher
Liquid to Gas Ratio, Gallons/1000 ACF	25-50	Variable
Pressure Drop, Inches H_2O	50-70	5-10
Gas Inlet Temperature, °F	120-150	3000

5.0 EVALUATION OF OPERATION AND MAINTENANCE PROCEDURES

This section addresses basic operation and maintenance procedures for wet scrubber systems. Since there is considerable diversity in the design of scrubber systems and in applications, there is no one set of operation and maintenance procedures which is adequate in every case. Instead, it is necessary to tailor the procedures to the specific site involved; this is an evolutionary process in which the initial procedures are modified in response to the specific operating problems experienced at the site.

The procedures presented in this section represent a skeleton of the initial operation and maintenance requirements for a wet scrubber system. For some systems, these procedures include steps which are unnecessary and for some systems, important maintenance items may not be included. Therefore, regulatory agency personnel should not conclude that the following procedures necessarily constitute a complete description of good operating practice.

5.1 STARTUP AND SHUTDOWN PROCEDURES

Proper startup and shutdown procedures are important in preventing (1) damage to the corrosion and abrasion resistant lining in the scrubber (if used), (2) overheating of the fan motor, and (3) damage to the pump impeller and motor. Each scrubber manufacturer provides instructions for proper startup and shutdown of its system which should be strictly followed. To illustrate the major elements, a condensed version of these procedures is provided in the two lists that follow.

<u>Routine Startup</u>

- o Inspect piping and valves and open or close valves to permit proper flow of fluid from the system to recycle tank, pumps, and return lines.
- o Inspect ductwork system to assure that all ductwork leading to the scrubber is intact and that damper blades move with damper control activation. Flow of exhaust gas to scrubber should not be initialed until liquid circuit has been fully started. Inspect and test instruments to be sure they are operating properly.
- o Make sure that the unit is level (especially important for tray-type scrubbers).
- o Turn on all electrical switches for controls and instruments.

- Fill system with scrubbing liquid by opening plant water lines to recycle tank, allow it to fill to proper level, and then start recycle pump.
- Open liquid line to quench/presaturator sections and adjust to proper flow.
- Open damper to direct exhaust gas flow to venturi scrubber and start the fan.

Prior to the startup of a wet scrubber, a complete internal inspection should be conducted. A partial list of the items to inspect include: the condition of the spray nozzles; the condition of the supply lines to the scrubber; presence of internal deposits; presence of worn or eroded linings; presence of partially plugged or warped demisters; and presence of corrosion on the interior trays, downcomers, and other components. For some types of scrubbers, it may be advisable to visually confirm that the inlet liquor flow is sufficient to completely wet the venturi convergent section to avoid any wet-dry interface problems.

During startup, the bypass duct (if any) should be gradually closed as the inlet damper is gradually opened. If the fan inlet damper is opened too quickly, it is possible to overload the fan motor.

After operating conditions have stabilized, a complete set of readings should be taken and compared against the baseline operating levels. It is advisable to conduct a routine evaluation, as discussed earlier, to confirm that the system is operating properly.

It may become necessary to adjust the liquid flow rates to maintain the recycle tank level. This requires balancing the water make-up rate, the purge rate, the sludge removal rate, and the recycle rate.

<u>Routine shutdown</u>

- Turn off the fan and close the inlet or outlet damper. Open the bypass damper to ensure that the scrubber is isolated from any process gas flow.
- Continue pump operation and all internal water sprays until the scrubber system has cooled.
- If the system will be exposed to cold weather conditions, or if an extended shutdown is anticipated, all pipes should be drained.

- o An internal inspection should be conducted to determine if there are eroded or plugged nozzles, worn (corrosion or abrasion resistant) liners, damaged demisters, or other problems which warrant maintenance attention prior to startup.
- o All deposits which could accelerate corrosion of the scrubber should be washed out.

During shutdown, it is particularly important not to expose the scrubber system to any high temperature excursions. For this reason the pumps and internal sprays should be operated until well after the scrubber has been isolated from the process. It is also important to continue the alkali additions to the system long enough to prevent low pH excursions after shutdown.

5.2 ROUTINE MAINTENANCE

This section presents general information concerning the operation and maintenance of wet scrubber components; specific maintenance requirements vary substantially depending on the design of the scrubber and its application.

5.2.1 Fans

The types of operating problems experienced with fans depend on whether the fan unit is before or after the scrubber. If the fan is in the upstream position where the particulate mass concentration is high, erosion of the fan wheel is of concern. Due to the high gas temperatures prior to a scrubber, it may also be necessary to cool the fan bearings. If the fan is in the downstream position, it is vulnerable to the buildup of solids and corrosion.

Regardless of location, all fan wheels should be visually inspected on a regular basis. A typical frequency is monthly, although in some applications weekly inspection is warranted. If the fan vibration increases noticeably, the fan wheel should be inspected as soon as possible.

Fan bearings require frequent inspection; they should be checked for oil level, oil color, and operating temperature. Bearing wear can cause vibration problems. The bearing housing and mountings should also be checked on a weekly basis.

On belt-driven fans, the belt tension should be checked on a weekly basis. Loose belts are prone to a distinctive squealing which suggests an unintentional reduction of several hundred R.P.M. and a decrease in the gas flow delivered by the fan. The rotational speed of the fan can be checked using a manual tachometer, a phototachometer, or a strobo-tachometer. Use of these instruments is discussed in the paper by Richards and Segall.[35] Fans should never be operated at tip speeds greater than those recommended by the fan manufacturer.

5.2.2 Pumps

The most common pump related problems include erosion of the impellers, erosion and chipping of the liner, and leakage of the pump glands. All pump bearings should be lubricated regularly and inspected on a frequent basis. The actual schedule depends somewhat on the severity of the application, with more frequent attention required if the total solids content of the liquor is high and/or the pH is low. High wear pump parts should be kept on hand since delivery times are sometimes long. If possible a spare pump should be available.

5.2.3 Valves

The operational status of all control valves should be checked on at least a weekly basis. They are vulnerable to sticking, pluggage, and erosion. Air activated valves are also subject to freezing if the compressed air supply is not properly dried.

5.2.4 Nozzles

The frequency of nozzle inspection varies with the type of scrubber and the quantity of suspended solids in the recirculation liquor. If the suspended solids level is greater than several percent, erosion and/or pluggage are probable. As an initial check, the nozzle operating pressures should be recorded on a daily basis. An increase or decrease in the operating pressure without a corresponding change in the liquor flow rate strongly suggests that the nozzle condition has deteoriated. If pluggage is suspected due to an increase in the nozzle pressure, the nozzles should be rodded out (if possible) and then the presssure rechecked.

When the scrubber is down, nozzle conditions can be evaluated by an internal inspection or by observing the spray angle while the liquor recirculation system is operating. A high intensity (explosion proof) flashlight is useful for checking the individual spray nozzles. It is generally advisable to keep a set of replacement nozzles when they are used in severe applications.

5.2.5 Recirculation Tank

The gradual accumulation of sludge at the bottom of the recirculation tank is undesirable. Whenever the system is down for maintenance, the quantity of the deposits should be checked either by draining the system or simply by the use of a rod. Draining the tank is preferable since it is possible to check for corrosion and erosion when the tank is empty.

If a mixer is used in the recirculation system, the condition of the impeller should be checked on at least a monthly basis.

5.2.6 Dampers

It is advisable to exercise all dampers at least once a month to confirm that they have not "frozen" in the open position. The damper drive mechanism and bearings should be lubricated in accordance with the manufacturers specifications.

If a purge air blower is necessary to keep the damper seating surfaces clean, this should be checked on a daily basis to ensure that the blower is operating.

5.2.7 Instruments

Instrumentation systems are particularly prone to operating problems and therefore should be checked on a daily basis. The status of a pH control system can be checked using either a portable pH meter or pH paper. It is important to take these measurements at approximately the same location as the pH probe of the instrumentation system, since pH can vary substantially throughout a wet scrubber system. Deviations from the baseline level and/or a difference in the two readings suggest either a problem with the installed pH meter or failure of the alkaline additive delivery system. The most common pH meter problems are scaling scaling of the probe and breakage of the probe.

5.2.8 Motors

The motor bearings and the motor starting switches should be lubricated on a routine basis. The manufacturers' guidelines should be followed. All contacts, cooling fans, and other components should be inspected at least once per year.

5.2.9 Demisters

All chevron and mesh pad type demisters should be inspected on at least a weekly basis to prevent excessive solids buildup. Gradual scaling of the demister will lead to an increase in local gas velocities through the open areas and this in turn will result in entrainment. Presence of solids on the demister can be determined by using a high intensity (explosion proof) flashlight. The condition of the demister flush nozzles should be evaluated at the same time. Any deposits should be removed as soon as possible using either the existing spray system or an external hose.

5.3 ELEMENTS OF MODEL RECORD AND REPORT SYSTEM

A comprehensive recordkeeping system addressing the operation, maintenance, and performance of the wet scrubbers at a particular source can be of valuable assistance to both the control agency inspector and the plant manager. The information contained in such a system can provide the inspector with a preliminary indication of the overall condition and performance of the control equipment. It can also direct the inspector's attention to specific problem areas that may require special attention during the inspection.

The records will allow the operator to ascertain the effectiveness of his operation and maintenance program, as well as determine the extent of deterioration of control system components. The latter benefit can, in a well-maintained recordkeeping system, minimize the time that the process and control equipment is out of service due to repairs. In addition, significant cost savings can be realized by diagnosing and repairing major equipment failures before they occur.

For either the inspector or the plant manager to benefit from a recordkeeping and report program, there are several important aspects of the use of the program that should be realized. For the program to be effective, recordkeeping should routinely executed on a daily basis. Some advance warning is usually given prior to equipment failure; however, the time between the initial indication of a problem and the resultant failure can be very short. The earlier a problem is discovered and rectified, the greater the reduction in repair time and cost.

A recordkeeping program should never be considered an entirely independent system on which decisions are based. The data contained in the records can, for many reasons, be inaccurate or misleading. The major cause of such problems is that the data are obtained from faulty instruments. Thus, agency inspectors and plant operators should always conduct a physical inspection of the equipment to verify the accuracy of instrument data. Quality assurance is another important part of such a program, particularly in ensuring that the data are that useful.

The recommended recordkeeping practices that follow are intended to provide an overview example of elements of a model record and report program. The items that are discussed are not for a particular scrubber, but rather encompass many different scrubber types and applications. Each recordkeeping system should be tailored for the specific scrubber configuration and the process to which it is applied. In tailoring a recordkeeping system, applicable elements from this model program should be included, as well as any others which may apply to the specific situation.

5.3.1 Scrubber Operation Record Elements

There are certain data common to all scrubber types which should be included in any scrubber recordkeeping system. These data elements are listed in Table 5-1. These routinely measured parameter values, compared to the baseline values obtained during a compliance test (or the initial performance evaluation test), can provide a very good indication of the performance of a scrubber. In addition, examination of these parameters over time can aid in the detection of component deterioration in the scrubber system.

It is recommended that whenever possible, the scrubber operation data be obtained using portable instruments. Each tap hole through which a measurement is made should be cleaned prior to every measurement. Because the plugging of tap holes occurs so frequently, cleaning of the holes is

TABLE 5-1. SCRUBBER OPERATION DATA

Inlet Gas Temperature
Outlet Gas Temperature
Total Static Pressure Drop
Static Pressure Drop of Mist Eliminator
Liquor Feed Rate
Liquor pH
Water Makeup Rate
Fan Current
Fan RPM
Fan Gas Inlet Temperature
Nozzle Pressure
Pump Discharge Pressure
Recycle Bleed Rate
Chemical Addition Rate
Liquor Solids Concentration

important to ensure that a partially or completely plugged hole does not result in an erroneous measurement. This, in fact, is one of the reasons that portable instruments should be used rather than fixed gauges. Too often a reading from a fixed gauge will be recorded without checks to see that the gauge's tap hole is not plugged. Regardless of whether the instruments are fixed or portable, each must be calibrated at intervals which are at least as frequent as the manufacturers' specifications.

The measurement of the inlet and outlet gas temperatures can provide an indication of problems in the heat exchange mechanics of the scrubber. For instance, abnormally high outlet gas temperatures suggest that the scrubber liquor flow is below normal or the gas flow rate is well above design value. In either case, the liquor-gas contact within the scrubber is less than optimum, which results in a lower particulate removal efficiency. A low outlet gas temperature can indicate a low gas flow rate through the scrubber or an inleakage of ambient air.

Pressure drop measurements can confirm problem areas identified by the temperature measurements. They can also indicate other potential problems. Low pressure drops across the scrubber are indicative of little or no liquor flow to the scrubber and low gas flow rates through the scrubber. In venturi scrubbers, a low pressure drop can be caused by the venturi throat being out of adjustment, while the cause in a tray-type scrubber may be the collapse of the impingement tray. A high pressure drop on a packed bed scrubber is usually the result of the bed becoming plugged. Pressure drop increases are associated with unexpected increases in gas or liquor flow rate.

A determination of the gas flow rate through the scrubber can be made using information collected from fan measurements. It is very important to know if the scrubber is operating in the flow rate range for which it was designed. If the necessary baseline data were collected during a previous performance test, the fan current can be used to estimate the present flow rate.

The measurement of the scrubbing liquor pH can provide insight into operational problems, as well as indicate potential damage to the scrubber structure. A low pH reading usually indicates loss of additive feed or low liquor flow rates. Since these rate measurements are included in the routinely collected scrubber data, the cause of the problem can be easily determined. Low pH measurements should serve as a warning that corrosion damage to the scrubber shell may have occurred, and thus, a visual, internal inspection of the scrubber should be conducted.

Low nozzle operating pressure is usually a result of low liquor flow rate or erosion of the nozzles. If nozzle erosion has occurred, the droplet size emitted by the nozzles will be larger than the design size. Also, low liquor flow will produce altered droplet size distributions. Either situation will result in decreased collection efficiency. Since the liquor flow rate is a routinely measured parameter, an increase in the flow reading should prompt a visual inspection of the nozzles for erosion; at this time, the valves should also be examined for erosion. A decrease in the flow can indicate pump impeller wear or liquor line pluggage. The recycle bleed rate measurements can show bleed line pluggage when the flow is reduced and valve wear when the flow increases.

The various combinations of pump motor current and discharge pressure can be used to identify several probable problems. For instance, a decrease in both water pressure and amperage draw can mean that there are nozzles missing, significant pump wear, or suction line plugging. Other combinations suggest nozzle or spray bar plugging and manifold or spray bar leakage due to holes. The pump motor current can also be used to determine if a decrease in scrubber liquid flow is caused by an equipment maintenance problem such as a plugged line, by a worn pump impeller, or in fact, may only be a result of an improperly calibrated flow meter.

The remaining scrubber operation data which should be monitored are liquor solids concentration and chemical addition rates. Monitoring the solids concentration can ensure that the desired collection efficiency is maintained and scaling is minimized. It also helps reduce abrasion in the liquor contact points throughout the piping and scrubber system. In scrubbers which use chemical additives to control the liquor pH or the concentration of dissolved solids, measurement of the rate of addition is important in reducing the problems created by corrosion and scaling.

5.3.2 Process Record Elements

In addition to the scrubber data, there are certain process data that should also be routinely recorded. These data are shown in Table 5-2. Since baseline scrubber data are used as standards on which to judge subsequently measured scrubber parameters, it is equally important to know how the daily process data compare to the baseline values. Process variations in feed types and rates can effect the collection efficiency of scrubbers by altering the character of the inlet particulate gas stream. Of particular importance in this regard is the particle size distribution at the inlet, a parameter on which greatly affects scrubber performance.

TABLE 5-2. PROCESS CONDITION DATA

Process Feed Rate
Percent Load Capacity
Process Feed Descriptor

The ancillary equipment in a scrubber system is also often responsible for many of the operational problems. This equipment includes the fans, pumps, motors, ductwork, piping, valves, clarifiers, and instrumentation. Failure of any of these components can be disastrous not only to the performance, but also to the longevity of the entire scrubber system.

In order to facilitate the recording of the scrubber parameters previously discussed, a suggested record format is presented in Table 5-3.

The daily, monthly, and semi-annual performance logs for the scrubber's ancillary equipment are provided in Tables 5-4, 5-5, and 5-6, respectively. As with any other operation and maintenance record system, space is provided to explain any corrective actions which were initiated to resolve any abnormal observed values. It is highly recommended that all data be collected on a routine basis and compiled in a notebook used only for recordkeeping purposes.

TABLE 5-3. DAILY SCRUBBER OPERATION DATA LOG

PLANT NAME__________ UNIT NO.______ DATE______ SHIFT______

Operation Parameter	Baseline Value	Observed Value	Corrective Action
Inlet Gas Temperature			
Outlet Gas Temperature			
Total Static Pressure Drop			
Scrubber Pressure Drop			
Static Pressure Drop/Mist Eliminator			
Liquor Recirculation Rate			
Liquor pH			
Makeup Rate			
Nozzle Pressure			
Purge Rate			
Chemical Addition Rate			
Anti-foaming Agent			
Flocculant			
Surfactant			
Liquor Turbidity			

TABLE 5-4. WEEKLY SCRUBBER ANCILLARY EQUIPMENT PERFORMANCE LOG

PLANT NAME__________ UNIT NO. __________ DATE__________ SHIFT__________

Operation Parameter or Condition	Normal	Abnormal	Corrective Action
FANS AND FAN BEARINGS			
Vibration			
Oil Level			
Oil Color			
Oil Temperature			
Fan Motor Bearings			
Lubrication			
PUMP BEARINGS			
Oil Levels			
Seal Leaks			
Vibration			
PUMP MOTOR BEARINGS			
Lubrication			
DAMPER AIR PURGE SYSTEM			
Ease of Operation			

TABLE 5-5. MONTHLY SCRUBBER ANCILLARY EQUIPMENT PERFORMANCE LOG

PLANT NAME__________ UNIT NO.______ DATE______ SHIFT______

Operation Parameter or Condition	Normal	Abnormal	Corrective Action
FAN BEARINGS			
Leaks, Cracks, Loose Fittings			
DRAG CHAIN DRIVE MECHANISM			
Temperature Rise			
Sprocket Wear			
Chain Tension			
Oil Level			
Sprocket Alignment			
MOTOR BEARINGS			
Leaks, Cracks, Loose Fittings			
DUCT WORK			
Leakage			
Excessive Flexing			
DAMPERS			
Ease of Operation			
Leakage			

(Continued)

TABLE 5-5. MONTHLY SCRUBBER ANCILLARY EQUIPMENT PERFORMANCE LOG (Continued)

PLANT NAME__________ UNIT NO.______ DATE______ SHIFT______

Operation Parameter or Condition	Normal	Abnormal	Corrective Action
CLARIFIER PIPLINE			
Plugging			
SPRAY BARS			
Nozzle Plugging			
Nozzle Wear			
PIPES AND MANIFOLDS			
Plugging			
Leaking			
PRESSURE GAUGES			
Accuracy			
MAIN BODY OF SCRUBBER			
Material Feed Buildup			
Abrasion			
Corrosion			

TABLE 5-6. SEMI-ANNUAL SCRUBBER ANCILLARY EQUIPMENT PERFORMANCE LOG

PLANT NAME__________ UNIT NO.______ DATE______ SHIFT______

Operation Parameter or Condition	Normal	Abnormal	Corrective Action
FAN BEARINGS			
Clearances			
Wear, Pitting, Scoring			
PUMP BEARINGS			
Leaks, Cracks, Loose Fittings			
Clearances			
Wear, Pitting, Scoring			
DRAG CHAIN BEARINGS & GEAR REDUCERS			
Lubrication			
Wear, Pitting, Scoring			
Clearances			
Leaks, Cracks, Loose Fittings			
MOTOR BEARINGS			
Clearances			
Wear, Pitting, Scoring			
DAMPER SEALS			
Wear			

(Continued)

TABLE 5-6. SEMI-ANNUAL SCRUBBER ANCILLARY EQUIPMENT PERFORMANCE LOG (Continued)

PLANT NAME__________ UNIT NO.______ DATE______ SHIFT______

Operation Parameter or Condition	Normal	Abnormal	Corrective Action
DAMPER DRIVE MECHANISM			
Operation			
Alignment			
DAMPER BEARINGS, BLADES, BLOWERS			
Wear			
Leakage			
FLOW METERS			
Accuracy			

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APPENDIX A
PENETRATION

Throughout this report the term "penetration" is used frequently. This is a convenient means to express the quantity of emissions leaving a scrubber. Penetration is related to the collection efficiency of the scrubber as shown in Equation A-1.

$$X = 1 - E/100 \qquad \text{Equation A-1}$$

Where: X = penetration, dimensionless
E = collection efficiency (percent), dimensionless

Penetration is also related to the number of transfer units as shown in Equation A-2.

$$N_t = Ln(1/X) \qquad \text{Equation A-2}$$

Conversion charts for converting from one to the other of these terms are provided. The concept of penetration is illustrated in Figure A-1, below.

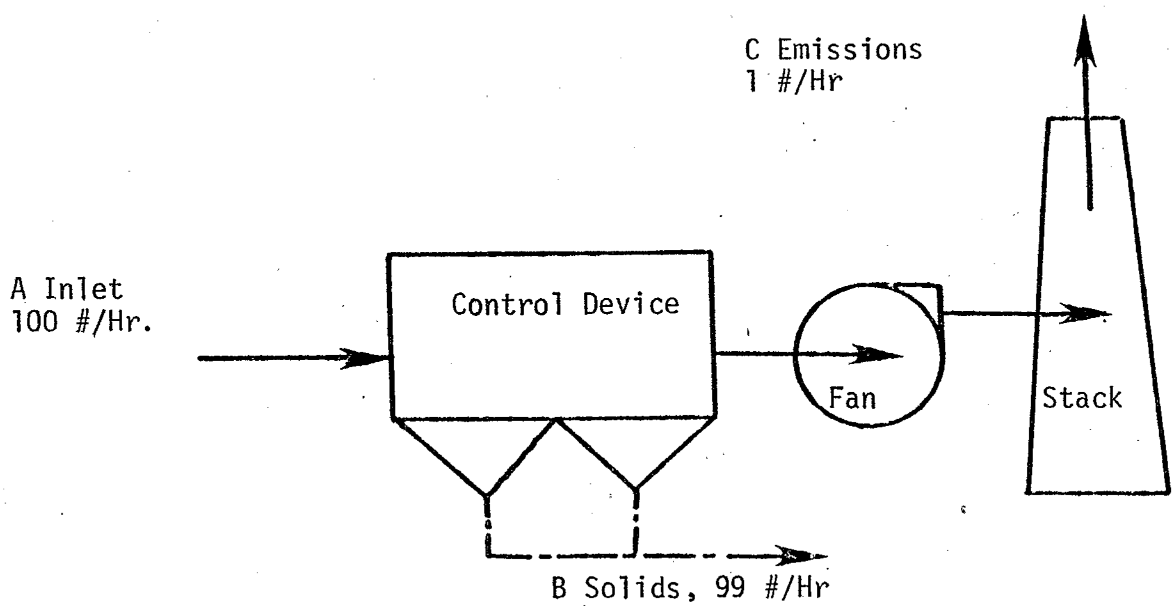

Figure A-1. Penetration as related to control device inlet concentration, solids collection, and resulting emissions; in this case, the penetration equals 0.01.

The penetration is simply the particulate emissions divided by the inlet loading of particulate (C/A) or 0.01, while the efficiency is the inlet loading minus the particulate emissions divided by one hundred [(A-C)/100] or 0.99. The penetration is a more descriptive parameter at the high efficiencies typical of present scrubber systems and is a much more convenient expression to use when referring to multiple sets of control systems, since the penetration of a system of control devices is related to the individual penetration values (see equations A-3 and A-4 below).

Parallel Collectors

$$X_t = X_1 + S_2 + \ldots + X_n \qquad \text{Equation A-3}$$

Series of Collectors

$$X_t = (X_1)(X_2) \ldots (X_n) \qquad \text{Equation A-4}$$

Where: X_t = total penetration of the system

X_1 = penetration of Unit 1

X_2 = penetration of Unit 2

X_n = penetration of Unit n

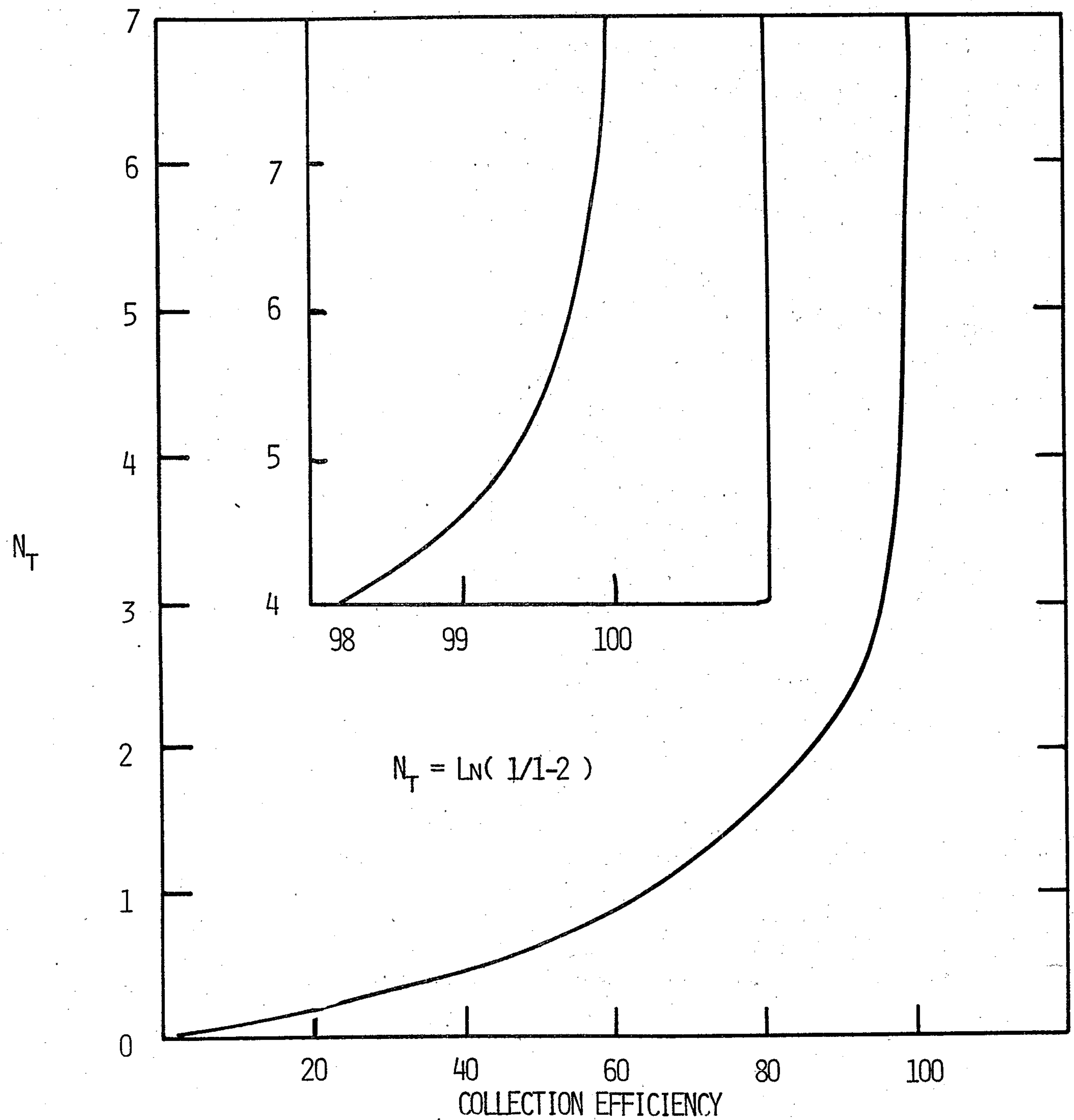

Figure A-2. Conversion from collection efficiency to transfer units.

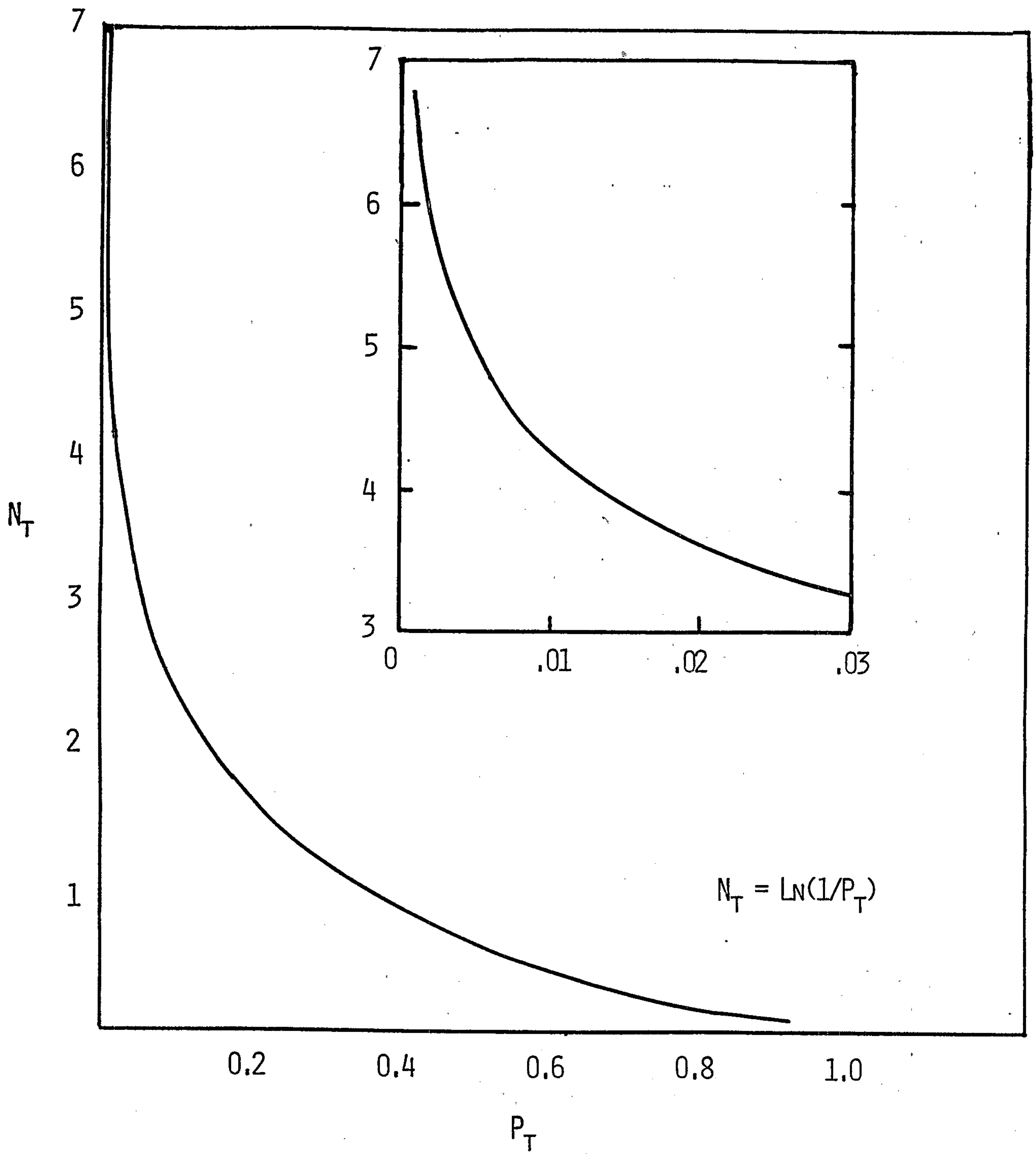

Figure A-3. Conversion from penetration to transfer units.

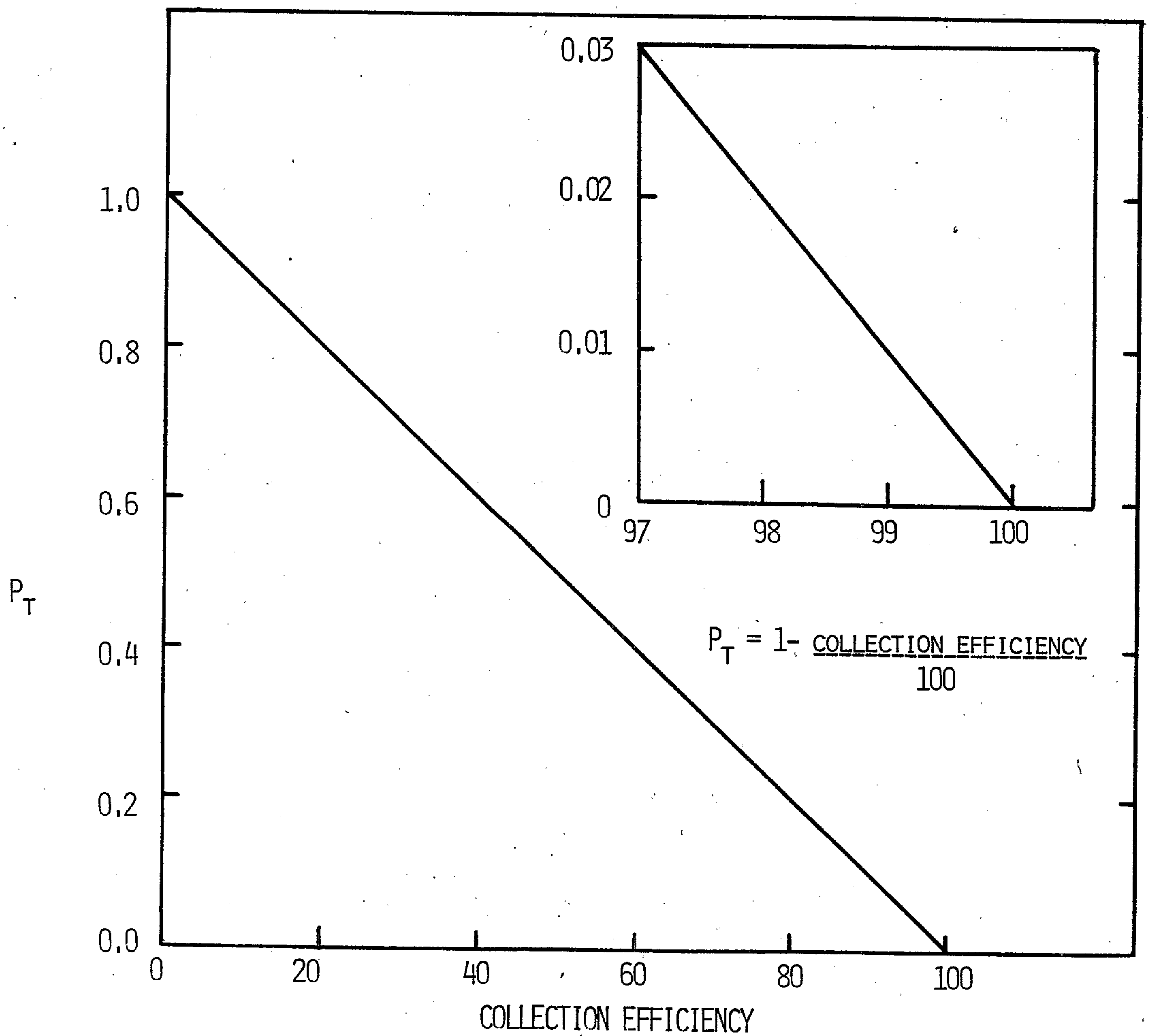

Figure A-4. Conversion from collection efficiency to penetration.

APPENDIX B
BASIC STATISTICAL METHODS

1. Plotting Emission Correlation Lines

   a. Step 1 - Plot Data in any one of the following forms:

      (1) linear
      (2) semi-log
      (3) log-log

      Select the curve with linear characteristics.

   b. Compute statistical parameters using table below.

Point	x	x^2	y	y^2	xy
1					
2					
3					
4					
5					
.					
.					
.					
n					
	$\Sigma x=$	$\Sigma x^2=$	$\Sigma y=$	$\Sigma y^2=$	$\Sigma xy=$

$$m = \Sigma(x-\bar{x})^2 = \Sigma x^2 - \frac{(\Sigma x)^2}{n}$$

$$p = \Sigma(x-\bar{x})\ (y-\bar{y}) = \Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}$$

$$k = \Sigma(y-\bar{y})^2 = \Sigma y^2 - \frac{(\Sigma y)^2}{n}$$

$$\bar{x} = \Sigma x/n$$

$$\bar{y} = \Sigma y/n$$

   c. Calculate equation for linear regression line using form:

$$y = \bar{y} + \frac{p}{m}(x-\bar{x})$$

   d. Calculate correlation coefficient:

$$r = \frac{p}{\sqrt{(m)\ (k)}}$$

e. Calculate confidence interval for linear regression line.

(1) Calculate sum of squares of deviations of y from regression line:

$$z = k - \frac{p^2}{m}$$

(2) Calculate residual mean square:

$$S_o^2 = \frac{z}{n-2}$$

$$S_o = \sqrt{\frac{z}{n-2}}$$

(3) Select confidence interval level desired, then look up value for t using the following table.

	t			
n-2	90%	95%	98%	99%
1	6.31	12.71	31.82	63.66
2	2.92	4.30	6.97	9.93
3	2.35	3.18	4.54	5.84
4	2.13	2.78	3.75	4.60
5	2.02	2.57	3.37	4.63
6	1.94	2.45	3.14	3.71
7	1.89	2.37	3.00	3.50
8	1.86	2.31	2.89	3.36
9	1.83	2.26	2.82	3.25
10	1.81	2.23	2.76	3.17
11	1.80	2.20	2.72	3.11
12	1.78	2.18	2.68	3.06
13	1.77	2.16	2.65	3.01
14	1.76	2.15	2.62	2.98
15	1.75	2.13	2.60	2.95
16	1.74	2.12	2.58	2.92
17	1.74	2.11	2.57	2.90
18	1.73	2.10	2.55	2.88
19	1.73	2.09	2.51	2.86
20	1.72	2.09	2.53	2.83

(4) Calculate interval values using the equations below.

$$y_{upper} = y_o + (t)(s) \sqrt{\left\{\frac{1}{n} + \frac{(x_o - \bar{x})^2}{m}\right\}}$$

$$y_{lower} = y_o - (t)(s) \sqrt{\left\{\frac{1}{n} + \frac{(x_o - \bar{x})^2}{m}\right\}}$$

APPENDIX C
DATA TABLES

TABLE C-1. VISCOSITIES OF AIR AT 1 ATM PRESSURE

Temp °F	Centipoise	lb/ft-sec
120	0.0192	1.29×10^{-5}
140	0.0195	1.31×10^{-5}
160	0.0198	1.33×10^{-5}
180	0.0201	1.35×10^{-5}
200	0.0206	1.38×10^{-5}
250	0.0218	1.46×10^{-5}
300	0.0229	1.54×10^{-5}
350	0.0238	1.60×10^{-5}
400	0.0250	1.68×10^{-5}
450	0.0260	1.75×10^{-5}
500	0.0270	1.81×10^{-5}
600	0.0285	1.92×10^{-5}
700	0.0305	2.05×10^{-5}
800	0.0320	2.15×10^{-5}

Source: Chemical Engineers Handbook, page 3-211.

TABLE C-2. GAS DENSITY AT SATURATED TEMPERATURE AND PRESSURE

	Pressure, inches w.c.				
Degrees, F	-0"	-20"	-40"	-60"	-80"
120	0.0655	0.0621	0.0587	0.0554	0.0520
130	0.0634	0.0601	0.0568	0.0535	0.0502
140	0.0613	0.0580	0.0547	0.0515	0.0482
150		0.0556	0.0524	0.0492	0.0461
160		0.0531	0.0499	0.0468	0.0436
170		0.0502	0.0471	0.0440	0.0409
180		0.0470	0.0439	0.0409	0.0378
190		0.0434	0.0404	0.0374	0.0344

Source: Environmental Elements, Psychrometric Tables for Wet Scrubber System Design Information, Series DIS-10-003, June 1979.

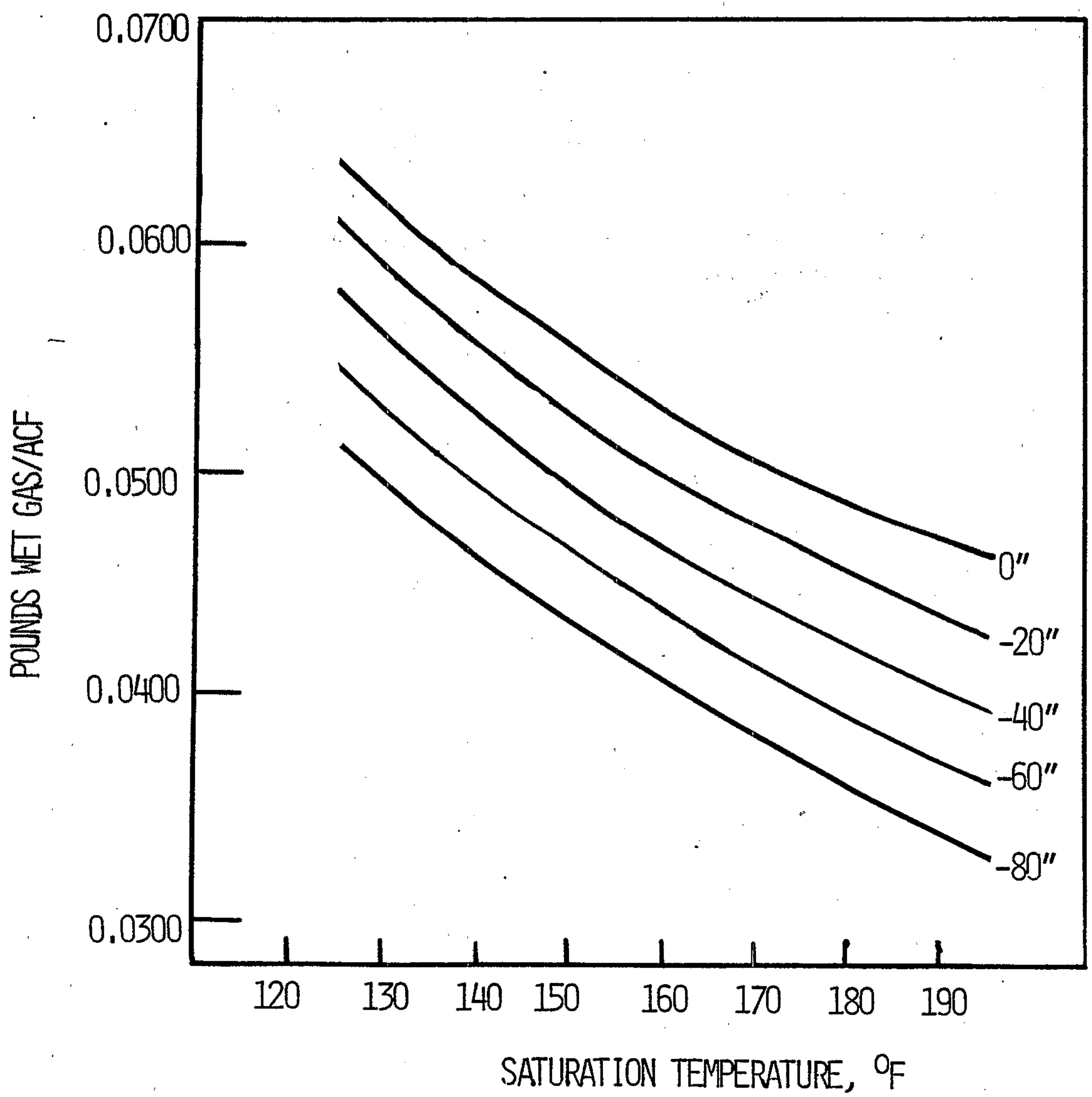

Figure C-1. Gas densities as a function of temperature and pressure.

APPENDIX D
TROUBLESHOOTING CHARTS

TABLE D-1. TROUBLESHOOTING CHART BASED ON PARAMETER MEASUREMENTS[56,67]

Symptom	Cause	Action
High exit-gas temperature	a. Very low venturi-liquid flowrate	a. Check pump output; look for plugged piping, nozzles, etc. incorrectly opened valves, overthrottled pump-discharge valves.
	b. High cooling-water inlet temperature.	b. Check heat-exchanger operation and adjust cooling-water flowrate and temperature.
	c. High scrubber-inlet temperature or excess gas flow.	c. Check upstream equipment operation.
Low pressure drop (scrubber section)	a. Low airflow rate	a. Check blower
	b. Low liquid flow rate	b. Check pump/nozzles
	c. Eroded cleaning section	c. Inspect
	d. Meters plugged	d. Clean lines
High pressure drop	a. High airflow rate	a. Check blower
	b. Plugging in ducts or scrubber	b. Inspect
Low pressure drop (mist eliminator)	a. Low airflow rate	a. Check blower
	b. Low liquid flow rate	b. Check pump/nozzles
	c. Media dislocated	c. Inspect
High pressure drop	a. High airflow rate	a. Check blower
	b. High liquid flowrate	b. Check pump/nozzles
	c. Clogging	c. Inspect/clean
	d. Flooding	d. Inspect/drain

Cont'd.

TABLE D-1. TROUBLESHOOTING CHART BASED ON PARAMETER MEASUREMENTS[56,67]

Symptom	Cause	Action
Pump leaks	a. Packing or seals	a. Replace
Pump pressure increase	b Nozzle plugging	b. Reduce nozzles
	c. Valves closed	c. Open valves
Pump flowrate/ pressure diminished	a. Impeller wear	a. Replace
	b. Nozzle abraded	b. Replace
	c. Speed too low	c. Check motor
	d. Defective packing	d. Replace
	e. Obstruction in piping	e. Check pipes, strainer, and impeller
	MEASUREMENTS	
Recycle flowrate increase	a. Valve and/or nozzle erosion	a. Check and replace damaged parts
Bleed flow reduction	a. Line pluggage	a. Inspect and clean bleed line
Bleed flow increase	a. Valve worn	a. Check and replace bleed valve
Inlet and outlet gas temperatures equal	a. No liquor flow because of plugged nozzles	a. Check and clean or replace nozzles
	b. No liquor flow because of inoperative pumps	b. Check and repair or replace pump
Low nozzle pressure	a. Low liquor flow	a. Check pump output, look for plugged nozzles, and pipes, incorrectly opened valves, overthrottled pump discharge valve.

cont'd.

TABLE D-1. TROUBLESHOOTING CHART BASED ON PARAMETER MEASUREMENTS[56,67]

Symptom	Cause	Action
	MEASUREMENTS (Cont'd.)	
High exit water Temperature	a. Low liquor flow	a. See above
	b. High gas flowrate	b. Check fan-damper setting, venturi throat setting fan operation vs. fan curve
Low pH of recirculation liquor	a. Low liquor flow	a. See above
	b. Insufficient chemical treatment	b. Adjust chemical addition rate

TABLE D-2. TROUBLESHOOTING CHART BASED ON SCRUBBER CONDITION AND PERFORMANCE[56,67]

Symptom	Cause	Action
Poor cleaning performance	a. Low scrubbing-liquor flowrate	a. Check pump output. Look for plugged piping and nozzles, incorrectly opened valves, overthrottled pump-discharge valve.
	b. Low pressure-drop across venturi	b. Check for low scrubbing-liquor flowrate; low gas flowrate; inoperative or uncalibrated variable-throat controller; damaged variable-throat blade/disk.
	c. Inlet dust loading or size distribution beyond scrubber design capability	c. If operating modifications fail to correct the problem, analyze particle size and quantity.
	d. Excessive gas flow	d. Check fan-damper setting venturi-throat setting, system fan operation vs. fan curve.
	e. Partially blocked entrainment separator	e. Check washdown sprays if installed. Check composition of spray liquor. If scaling occurs, investigate use of low-pH flushing liquor.
Exhaust-gas liquor entrainment	a. Moisture eliminator drain plugged (tangential vane eliminators only)	a. Shut down and snake out the eliminator drain. If problem recurs, add flushing water to continuously irrigate drain pipe.
	b. Excessive water frothing (possibly due to foaming agent in liquor)	b. Sparge a liquor sample. If liquor froth does not disappear quickly, foaming may be choking downcomers and drains. Analyze liquor for foaming agents.

cont'd.

TABLE D-2. TROUBLESHOOTING CHART BASED ON SCRUBBER CONDITION AND PERFORMANCE[56,67]

Symptom	Cause	Action
	c. Plugging of chevron-type eliminator	c. Check flushing-spray conditions and pattern. Use more flushing periods per hour. Poor gas-cleaning performance will accelerate buildup. Check liquor chemistry for scaling agents.
	d. Excessive gas flow	d. Check fan damper position. Check variable venturi-throat opening.
Fan motor overload	a. Low scrubber-pressure-drop due to excessive throat opening	a. Normally, the fan damper will provide enough "choke" to prevent overload, so fan damper must be checked with variable throat opening. Check throat operator and liquor flow.
Plugged spray nozzles	a. Nozzle openings too small	a. Modify strainer/nozzle-opening ratio so that nozzle holes are at least twice the diameter of strainer openings.
	b. Solids concentration too high in spray liquor	b. Check separation equipment. Check for excessive dust load in gas stream. Check for purge-line malfunctioning.
	c. Pipe scale or debris entering liquid stream beyond strainer	c. Remove spray heads and flush spray piping and nozzles. Replace piping if corrosion is apparent.

cont'd.

TABLE D-2. TROUBLESHOOTING CHART BASED ON SCRUBBER CONDITION AND PERFORMANCE[56,67]

Symptom	Cause	Action
Excessive nozzle wear	a. Solids concentration too high in spray liquor	a. Check separation equipment. Check for excessive dust load in gas stream and for purge-line malfunctioning.
	b. Abrasives in spray liquor	b. Remove abrasives from liquor stream or install abrasion-resistant linings in wear zone.
	c. Low pH in combination with abrasives, causing erosion/corrosion	c. Check separation equipment. Check for excessive dust load in gas stream and for purge-line malfunctioning. Remove abrasives from liquor stream or install abrasion-resistant linings in wear zones. Add alkali for pH modification.
Excessive throat wear	a. High solids recirculation	a. Check solids-separation equipment. Check for excessive dust load in gas stream and for purge-line malfunctioning.
	b. Corrosion/erosion	b. Check separation equipment. Check for excessive dust load in gas stream and for purge-line malfunctioning. Add alkai for pH modification. Install abrasion-resistant liners in high-wear zones if liquor modifications are not practical.
	c. Excessive gas velocity	c. Check throat pressure-drop and reduce to design point.

cont'd.

TABLE D-2. TROUBLESHOOTING CHART BASED ON SCRUBBER CONDITION AND PERFORMANCE[56,67]

Symptom	Cause	Action
Erratic automatic-throat operation	a. Prime-mover malfunction	a. Remove from service, repair or replace. Most throats can be held in a fixed position close to design pressure-drop by mechanical means during this procedure.
	b. Sensor signal incorrect	b. Check sensor taps on vessel for solids buildup. Check transmission tubing for liquid buildup or air leaks. Clean or repair sensor.
	c. Transmitted signal incorrect	c. Clean or repair sensor. Check instrument air-supply pressure and filters. Check tubing for leaks. Check positioner filter and connections. (Clean instrument air is critical here.) Thoroughly clean positioner internals and check freeness of operation.
	d. Damaged damper disk-mechanism	d. First make external inspection of drive train. If damaged area is not observed, shut unit down and make internal inspection using a throat-actuator manual override. Check for packing damage and excessively tight packing gland.

cont'd.

TABLE D-2. TROUBLESHOOTING CHART BASED ON SCRUBBER CONDITION AND PERFORMANCE[56,67]

Symptom	Cause	Action
Corrosion	a. Inadequate neutralization	a. Check pH control
	b. Protective lining deterioration	b. Replace liners
Erosion	a. Incompatible materials	a. Replace materials
	b. High recycled solids content	b. Wastewater system
Scaling	a. Improper chemical treatment	a. Change treatment
Pipe plugging	a. High solids content	a. Cleaning
	b. Abrupt expansion/contraction/ bends	b. Change pipe fittings
Pump noise/heat	a. Misalignment	a. Check
	b. Bearing damage	b. Replace
	c. Cavitation	c. Check
Fan vibration	a. Material buildup on blades	a. Clean fan blades
Excessive abrasion on scrubber body	a. Large particle size distribution	a. Check operation of quench chamber
No liquor flow	a. Nozzles and/or pipes plugges	a. Clean or replace
	b. Pumps inoperative	b. Repair or replace

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16. ABSTRACT

This report concerns the inspection and evaluation of performance of particulate wet scrubbers installed at stationary sources to identify and rectify operating conditions contributing to excessive emissions. It includes discussions of gas-atomized scrubbers, plate-type scrubbers, packed tower scrubbers, and spray tower scrubbers. The evaluation approach proposed utilizes comparisons of present performance parameters and conditions with site-specific performance established previously under a controlled set of conditions.

17. KEY WORDS AND DOCUMENT ANALYSIS

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