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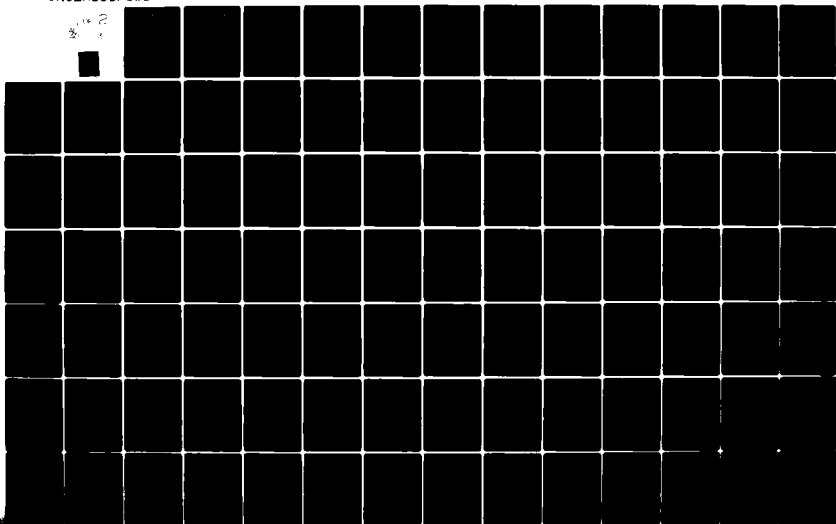
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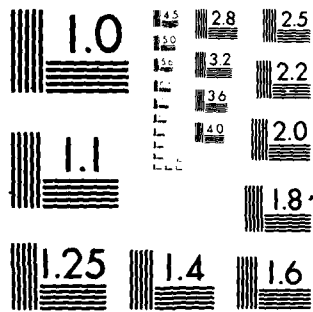
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DEVELOPMENT OF DESIGN REVIEW PROCEDURES FOR ARMY AIR POLLUTION ABATEMENT PROJECTS

Final Report, Vol. II—Appendices

by
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Air pollution control regulations, characterization of emission sources, detailed design of control devices, economic analysis and selection of best control equipment.		
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This report contains appendices to Volume I. It offers more extensive treatment of certain areas of air pollution control. Existing emission control regulations are detailed. Actual mechanisms associated with the control of both particulate and gaseous pollutants are described. Discussion of important factors affecting the performance of various control devices is also provided.		

ACKNOWLEDGEMENT

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APPENDIX A

COMPLIANCE PROGRAM PLANNING

A.1 DEFINITION OF COMPLIANCE PROGRAM OBJECTIVES

The engineer must define the compliance project objectives as they relate to:

1. legal requirements
2. emission assessment
3. expansion and/or cutback plans
4. divisional responsibility.

As these objectives are explored and defined, an awareness of the overall environmental situation will develop and will provide a basis for planning. In determining specific objectives and the tasks to be executed, the engineer must conduct a preliminary assessment of the facility under investigation and identify the emission sources that may require emission control. This assessment will determine the number and complexity of the subsequent steps required to fulfill the compliance plans.

A first step in any program is to determine what processes emit atmospheric pollutants and are subject to a pollution control regulation, or could cause a public nuisance or an adverse health effect. This inventory provides the comprehensive basis for many subsequent planning steps and thus should be as completed as possible.

A comprehensive survey of each process should identify vents and emission parameters. In an initial survey, only individual sources such as boilers, incinerators, and manufacturing processes must be identified. In subsequent, more detailed surveys, all individual vents and stacks serving the process should be identified.

Atmospheric emissions are regulated at local, state, and federal levels. All of these regulations must be researched, and sections applicable to the various plant processes noted. The compliance status of each process must then be determined by comparing actual emissions with allowable emissions.

Enforcement personnel from state or local agencies will contact those facilities thought to be violating emission standards. The facility is then responsible for either proving it is in compliance or implementing control systems to comply with standards.

After preliminary information has been assembled, various functions must be defined more exactly, the format depending on the size and complexity of the emission source and its processes.

The engineer should be responsible for the following activities:

- Process and vent inventories
- Emission assessment
- Compliance plans
- Inspection and maintenance of process and control equipment
- Environmental aspects of process operations.

A.1.1 Process and Vent Inventories

An early step in any environmental program is to inventory all processes that vent to the atmosphere. This information will be useful from an air pollution control standpoint and also in determinations of product loss, heat loss, and building air balance.

A.1.2 Emission Assessment

A critical, potentially time-consuming task is determining the rate of emission from all process vents. These emissions can sometimes be estimated from material balances, equipment design and operating data, or published emission factors. Where the estimated emissions approach or exceed emission regulations, the values should be confirmed by a field measurement program; if the source is obviously in violation, a compliance plan may be based on experience with similar processes. Specific plans for complying with applicable regulations should be developed by the engineering department. Contact with engineering firms specializing in this type of work and with control equipment suppliers is recommended. Some control equipment suppliers may tend to endorse their own hardware even if another control system is better for a specific application. The engineer should also develop equipment operating and maintenance procedures.

A.1.3 Compliance Plans

The engineer usually is responsible for development of control plans and schedules or process modifications for reducing emissions. The magnitude of this task depends on the number of sources not in compliance and the modifications required.

A.1.4 Inspection and Maintenance of Process and Control Equipment

As part of a continuing compliance program, the operation and maintenance of the process and any pollution control equipment must be checked routinely. This effort should be coordinated with the maintenance department. Key items to be observed include leaks in hoods and control device housings, operation of instruments and records of values read, disposal of collected material, visible plume from discharge vents, corrosion, and adherence to a maintenance schedule.

A.1.5 . Environmental Aspects of Process Operations

In addition to the atmospheric emission aspects of environmental planning, the engineer must be aware of other environmental aspects of the processing operation, and should establish communication lines with the appropriate staff members. Other environmental aspects include:

1. Liquid discharge
2. Sludge or solid waste discharge
3. Product use and eventual disposal
4. Accidental spills or emissions
5. Industrial hygiene.

Although some of these do not directly affect atmospheric emissions, many environmental problems are interrelated. For example, resolving an industrial hygiene problem by ventilation of a workroom may create a new emission source, or the installation of a scrubber system to remove atmospheric contaminants may introduce new problems of wastewater discharge or sludge disposal. Potential atmospheric emissions from the use or eventual disposal of a product (such as waste explosives, reactive solvents, and munitions) must also be considered.

Again, the nature of these related environmental responsibilities will vary widely for specific facilities and for specific products. early consideration of potentially related problems could save effort and expense in subsequent control planning.

A.2 EMISSION CONTROL REGULATIONS

A.2.1 History of Air Pollution Control Enforcement

The federal government's involvement in air pollution control began in 1955 with Public Law 159. This law authorized funding for the U.S. Public Health Service to initiate research into the nature and extent of the nation's air pollution problem. With the passage of the Clean Air Act of 1963, grants were authorized to state and local agencies to assist them in their own control programs. The Act also provided some limited authority to the federal government to take action to relieve interstate pollution problems. The basic federal control authority was expanded and strengthened by the Air Quality Act of 1967. One of the more significant measures gave citizens, for the first time, a statutory right to participate in the control process (through public hearings). However, it was not until the Clean Air Act Amendments of 1970 that the regulatory effort had any real bite.

A.2.2 The Clean Air Act Amendments of 1970

The Clean Air Act of 1970 was founded on the concept of attaining specified national ambient air quality standards (NAAQS) to define the quality of air that must be achieved to protect the public health and welfare. Many critical features of the program originated from this foundation, including the basic point that control requirements depend on adequate data and analysis to determine what the air quality actually is, to identify the sources of pollution affecting air quality and the manner in which pollutants are dispersed and interact the ambient air, and to determine what reductions and controls are needed to achieve specified air quality objectives.

EPA promulgated the basic set of current ambient air quality standards in April 1971. These included particulates, sulfur dioxide, photochemical oxidants, hydrocarbons (a precursor to photochemical oxidants), carbon monoxide, and nitrogen oxides. In 1978, EPA promulgated a NAAQS for lead. Following establishment by EPA of the air quality standards, the act directed state agencies to develop and adopt state implementation plans (SIP's) setting forth all of the necessary control efforts to achieve compliance with the standards. The statute set a strict time schedule for both adoption and implementation of the plans.

To provide basic geographic units for the air pollution control program, the country was divided into 247 air quality control regions (AQCR's). Decisions as to the amount of control required in individual AQCR's were based on available air quality. Under a standard rollback approach, the total quantity of pollution in a region was estimated. The quantity of pollution that could be tolerated without exceeding standards was then calculated and, based on the differential, the degree of required reduction was determined. The implementation plan was then drafted to produce a combination of control efforts that would yield an overall reduction sufficient to cover that need.

The act also directed EPA to set new source performance standards (NSPS) for individual industrial categories, requiring new plants to utilize the best system of emission reduction that had been adequately demonstrated. EPA gradually issued a series of these standards, which now covers a number of basic industrial categories. The 1977 Amendments to the Clean Air Act directed EPA to accelerate this program so that within a relatively short period of time standards would be issued for most other significant industrial categories. If an NSPS applied to a particular plant, EPA regulations imposed requirements on the owner to give advance notification to the state before beginning construction, with further notification due before actual start-up of the plant, and finally with a

submission of operating data after start-up. A new plant not yet constructed would also be subject to the NSPS even if such standards had only been proposed for that particular industry.

Section 112 of the Clean Air Act further required that the EPA promulgate national emission standards for hazardous air pollutants (NESHAP's). To date, standards have been promulgated for mercury, asbestos, beryllium, and vinyl chloride. A NESHAP's proposal for benzene is in preparation. Cadmium, arsenic, and copper emissions are also being considered for regulation as hazardous pollutants.

A.2.3 Clean Air Act Amendments--Prevention of Significant Deterioration (PSD)

Of all the federal laws placing environmental controls on industry and in particular new industrial plants, perhaps the most confusing and also the most restrictive are the limits imposed by the Clean Air Act to prevent significant deterioration (PSD) of air quality. These limits apply to those areas of the country already cleaner than required to meet the ambient air quality standards. This regulatory framework evolved out of judicial and administrative action under the 1970 Clean air Act, and subsequently was given full-blown statutory foundation by the 1977 Clean Air Act Amendments.

As enacted in 1970, the Clean Air Act contained no provisions dealing explicitly with protection of air quality in clean air regions. The entire structure of regulatory controls established through the SIP's focused on reducing existing levels of pollution in areas where the air quality standards were being violated. Some people feared, however, that tight controls in the implementation plans would force new industrial growth into areas of the country where little or no previous industrialization had occurred, with a risk of downgrading the existing "better" air quality of such areas.

The situation was challenged in a lawsuit brought by the Sierra Club, ultimately resulting in a decision by the U.S. Supreme Court, which, by a four-to-four tie vote, sustained a lower court decision in favor of the Sierra Club. This required EPA to develop some form of regulatory program to prevent significant deterioration. Accordingly, EPA established an area classification scheme to be applied in all clean air regions. The basic idea was that a moderate amount of industrial development should be routinely permitted in all areas, but that industrialization should not be allowed to degrade air quality to the point that it barely complied with air quality standards. In addition, an opportunity should be provided for states to designate certain areas where pristine air quality was especially valued and any growth generating significant emissions of pollutants should be tightly

curtailed. A system was developed to classify all areas as Class I, Class II, or Class III. The Class I category was to include the pristine areas subject to tightest control. Class II covered areas of moderate growth. Class III was for areas of major industrialization. Under the EPA regulations promulgated in December 1974, all areas were initially classified as Class II. States were authorized to reclassify specified areas to be either Class I or Class III.

The EPA regulations also established another critical concept known as the increment. This was the numerical definition of the amount of additional pollution that may be allowed through the combined effects of all new growth in a particular locality.

EPA also imposed one major additional requirement to assure that the increments would not be used up hastily. It specified that each major new plant must install the best available control technology (BACT) to limit its emissions. This reinforced the same policy underlying the NSPS, and where an NSPS had been promulgated it would control determinations of BACT. Where such standards had not been promulgated, an ad hoc determination was called for in each case.

To implement these controls, EPA required each new source to undergo a reconstruction review. The regulations prohibited a company from commencing construction on a new source until the review procedure, public notice should be given and an opportunity provided for a public hearing on any disputed questions.

A fundamental feature of the PSD regulation adopted by EPA was the limited nature of the program, i.e., increments were only established for particulates and sulfur dioxide. It excluded the automobile pollutants (hydrocarbons, photochemical oxidants, carbon monoxide, and nitrogen oxides) from the program. It also excluded numerous miscellaneous activities that might cause pollution, as well as the construction of new small sources.

When, in 1977, Congress provided the first statutory foundation for PSD, it adopted the basic concepts of the 1974 EPA program. Congress, however, made many changes in critical elements and in virtually every case the effect of those changes was to broaden the program and tighten its requirements. Congress statutorily placed many areas in the pristine air Class I category, and made it quite difficult for states to redesignate areas to Class III. It also tightened some of the increments. Congress significantly expanded the number of industrial plants subject to PSD review and increased the requirements of BACT. It also directed EPA to extend the PSD framework to other pollutants, in addition to sulfur oxides and particulates, and expanded monitoring requirements.

Finally, Congress also expanded the procedures for government review and public scrutiny of PSD applications. The combined effect of all these changes converted the PSD review into a formidable regulatory obstacle course confronting industry and, in particular, new industrial projects.

A.2.3.1 Classification and Increments

In effect, Congress continued the three-class system established by EPA, but with several changes. One change was to direct by statute that certain areas be permanently designated Class I. These included international parks, national wilderness areas and memorial parks exceeding 5,000 acres, and national parks exceeding 6,000 acres. Although the nature of these areas is such that industrial projects would not be located within them, their Class I status could affect projects in neighboring areas where meteorological conditions might result in the transport of emissions into the Class I - designated area. For many projects, particularly in the West, this could be a substantial constraint.

The statute also provided that, except for areas specifically placed in Class I, all other areas in the country subject to PSD be initially designated Class II. States would then have the authorization to redesignate areas either as Class I or as Class III. Before doing so, however, a state would have to hold a public hearing in the affected area and prior to the hearing would have to prepare a detailed analysis, similar in nature to an environmental impact statement, describing the effects of the proposed redesignation.

If the proposal was to redesignate an area as Class III, additional requirements applied. The redesignation had to be specifically approved by the governor of the state after consultation with the state legislature. Also, general purpose units of local government representing a majority of the residents of the area had to enact legislation approving the change.

The 1977 Amendments made various changes in the numerical limitations comprising the increments of pollution increase allowed in Class II and Class III areas. The numbers for Class II were generally loosened slightly, except for the short-term sulfur dioxide limitations, which were tightened. For Class III, the statute established increment limitations, instead of allowing unlimited growth, subject only to compliance with the air quality standards.

A.2.3.2 Sources Subject to PSD

A critical threshold question for any company planning a new project was whether it required reconstruction approval under PSD. It was on this item that congress made its most

profound change to expand the scope of the regulations. First, the 1977 Amendments increased to 28 the number of industrial categories specifically identified in which any new plant (with potential emissions of any regulated pollutant exceeding 100 tons per year) would be covered. In addition, a new plant in any other category was covered if its potential emissions of any regulated pollutant would exceed 250 tons per year. Potential emissions referred to "uncontrolled" emission levels, i.e., measured before application of control devices such as dust collectors, precipitators, and scrubbers, and included fugitive emissions (the definition of potential emissions is currently under revision as a result of Alabama Power Company vs. Costle, 1979). PSD rules also applied if, at the location of the plant, no violations existed or air quality standards for any NAAQS pollutant. For example, since most areas of the country are in compliance with the sulfur dioxide standards (with the notable exception of major industrialized regions), most areas likewise are subject to PSD. A source located outside a PSD area might also become subject to PSD requirements if its emissions could affect a PSD area.

Modifications of existing plants were subject to PSD requirements in the same way as new plants. EPA regulations, however, provided exemption from BACT and impact analysis if the modification that would increase emissions was accompanied by other changes within an overall plant with the net result of zero increase in total emissions. This exemption was referred to as the "bubble" or "no net increase" exemption.

Due to the large number of plants anticipated by EPA to be subject to PSD provisions, the EPA regulations of June 19, 1978, established a two-tier system, in which large plants would be made subject to the full review would include any new source (or major modification) which, after applying its pollution control systems, would have emissions exceeding 50 tons per year, or 1,000 pound per day, or 100 pound per hour. The full review would include a case-by-case determination of the controls required by BACT; an ambient impact analysis to determine whether the source might violate applicable increments or air quality standards; an assessment of effects on visibility, soils, and vegetation, submission of monitoring data; and full public review.

The EPA regulations exempted smaller sources from the major elements of PSD review and, in particular, relieved those sources of the need to comply with BACT (though they still had to comply with any applicable NSPS as well as requirements under the SIP's) and the need to conduct an ambient impact analysis or submit data supporting an ambient air quality analysis. Nonetheless, small sources were not totally exempted from the program. They remained subject to the statutory requirement to apply for and obtain a preconstruction approval, including procedures for public review, and they still might be

required at the request of the EPA to submit data supporting their application. In addition, if emissions from a smaller source would affect a Class I area or if an applicable increment was already being violated, the full PSD requirements for ambient impact analysis would apply.

A.2.4 Clean Air Act Amendments--Nonattainment (NA)

At the risk of oversimplification, the country could be divided into "clean" air areas and "dirty" air areas. PSD established the requirements to be met by new industrial projects in clean areas. A parallel set of requirements was established for new projects in the dirty areas. These were incorporated in the nonattainment provisions of the Clean Air Act and were applicable to those areas of the country failing to attain compliance with ambient air quality standards.

By 1975, it became apparent that air quality standards were not being achieved. With the passing of the initial deadline for attaining these standards, it gradually became clear that continuing violations would be widespread. Accumulating air quality data converted a theoretical concern into a paractical dilemma: was the Clean Air Act intended to stop new industrial construction throughout substantial portions of the country?

After long debate, EPA made its attempt to reconcile the conflicting national concerns for clean air and economic growth. It issued its offsets policy as an Interpretative Ruling in the Federal Register on December 21, 1976. The ruling stated that new plants could be constructed in nonattainment areas, but only if stringent conditions were met. Emissions had to be controlled to the greatest degree possible and more than equivalent offsetting emission reductions had to be obtained from other sources to assure progress toward achievement of the standards.

More specifically, the ruling established the criteria for approval of a new source in a nonattainment area including: (1) the new source had to be equipped with pollution controls to assure the lowest achievable emission rate (LAER), which in no case could be less stringent than any applicable NSPS; (2) all existing sources owned by an applicable implementation plan requirements or under an approved schedule or an enforcement order to achieve such compliance; (3) the applicant had to achieve sufficient "offsets"--reductions in emissions from other existing sources--to more than make up for the emissions to be generated by the new source (after application of LAER); and (4) the emission offsets had to provide a positive net air quality benefit in the affected area.

The formulation of this EPA policy occurred simultaneously with Congressional review of the Clean Air Act, and the

nonattainment problem became one of the chief controversies addressed by Congress in the 1977 Amendments. As in the case of PSD, Congress wrote into the law provisions patterned closely after the approach adopted by EPA in its Interpretative Ruling.

On January 16, 1979, EPA issued new regulations revising the original Interpretative Ruling. These revisions incorporated a number of significant changes prompted by the 1977 Amendments, but preserved the basic framework of the earlier ruling. One change was to convert previous requirements for preconstruction review into a direct permit program. The statute specified, prior to July 1, 1979, each state must amend its implementation plan to require permits for the construction and operation of new or modified major stationary sources in any nonattainment area. The principal conditions for issuance of such a permit, which closely resemble those applied under the original EPA Interpretative Ruling, include:

- New reductions in emissions
- Lowest achievable emission rate
- Other sources in compliance
- Implementation of the applicable SIP.

1. Net Reductions in Emissions

The 1977 Amendments continued the basic principle of the offsets policy, that new plants can be allowed only within a framework that assures a net reduction in total emissions. The statute required "reasonable further progress toward attainment of the air quality standards," including substantial reductions in emissions of the pertinent pollutant in the early years after revision of the SIP. However, the law in effect allowed each state to choose whether or not it would achieve that progress by continuing to apply an offsets approach or by applying a different approach.

2. Lowest Achievable Emission Rate

LAER was deliberately a technology-forcing standard of control. The statute stated that LAER must reflect (a) the most stringent emission limitation contained in the implementation plan of any state for such category of sources, unless the applicant could demonstrate that such limitations were not achievable, or (b) the most stringent emission limitation achievable in practice within the industrial category, whichever is more stringent. In no event could LAER be less stringent than any applicable NSPS. While the statutory language defining BACT directed that "energy, environmental, and economic impacts and other costs" be taken into account, the comparable provision on LAER had instruction that costs be considered.

3. Other Sources in Compliance

Whereas the original EPA Interpretative Ruling required that an applicant certify the compliance status of all other sources owned or operated by it within the same air quality control region, the 1977 Amendments and the revised Interpretative Ruling specified that after July, 1, 1979, the certifications must extend to all sources within the same state.

4. Implementation of the Applicable SIP

This requirement created a special difficulty for applicants, since it raised questions reaching beyond the individual new source. In the early months after July 1, 1979, if the implementation plan had been revised as required by the 1977 Amendments, it probably could be presumed that it was being carried out. However, as time passes, there might be danger that certain milestones of progress contained in the SIP were not being achieved.

As with PSD, nonattainment requirements did not apply to every new source but only to those defined as "major" new sources (or major modifications). Under the revised Interpretative Ruling, the test was whether potential emissions from the new facilities would exceed 100 tons per year of any one of the regulated pollutants.

A.2.5 Area Classification

To determine whether a particular location is classified as attainment (and therefore under PSD) or nonattainment, consult EPA's official listing of designations for all areas of the country, initially published in the Federal Register on March 3, 1978. This listing resulted from an examination of air quality monitoring data and a survey of all areas by the states. The nonattainment rules applied if an area was violating either the primary or secondary ambient air quality standards. If the standards were not violated in the area or if air quality data were insufficient to classify an area, that area was treated as subject to PSD provisions. Complications could arise, however, if subsequent monitoring data found that the status of a specific area should be changed. As part of the permit application under PSD provisions, continuous monitoring data are required. It is conceivable that such data might reveal that an area previously classified as PSD should be reclassified nonattainment and therefore subject to nonattainment requirements.

Another significant complication arises when considering cross-boundary effects. A new source located in a clean air area may generate emissions that could disperse into a nonattainment area. If any such effects would be significant,

the source would have to comply with offsets requirements to assure that it does not aggravate the violation of standards within the nonattainment area. Similarly, a new source located in a nonattainment area might generate emissions that could adversely affect a clean air area. These cross-boundary effects will probably require that many new sources be reviewed under both PSD and nonattainment requirements.

An even more important consideration is that both PSD and nonattainment requirements are applied on the basis of individual pollutants. In many cases, a new plant may be located in an area that is nonattainment for one pollutant, such as photochemical oxidants or particulates, but attainment for other pollutants, such as sulfur dioxide. In that event, the plant must satisfy both the procedural and the substantive requirements under both programs.

Finally, one consequence of a new plant subject to both PSD and nonattainment review requirements is the likelihood that air quality permits will have to be obtained from two different regulatory agencies, state and federal. In most cases, nonattainment review is administered by state agencies, whereas PSD review is generally administered by EPA. The PSD regulations of EPA provide that where dual permits are required, EPA will wait to act until the state proceedings have been completed. Clearly, dual review situations pose substantially greater prospects for administrative delay.

A.2.6 1979 Proposed PSD Revisions

In a suit brought against EPA by the Alabama Power Company (Alabama Power Company vs. Costle, 13 ERC 1225), the U.S. Court of Appeals for the District of Columbia on June 15, 1979, invalidated key provisions of the PSD rules. The EPA, following a court mandate, proposed sweeping changes to the PSD regulations, and also proposed changes to rules affecting nonattainment new source reviews.

Among the significant proposed changes were a substantial reduction in the number of sources that would be closely scrutinized under PSD and nonattainment new source reviews and the exclusion of sources from PSD reviews that were located outside a PSD area, but that adversely affected PSD area in the same state. The principal proposed revisions relate to:

- Definition of major emitting source
- Fugitive emissions
- Geographic applicability
- Modifications
- BACT
- Ambient monitoring
- "De Minimis" cutoffs.

1. Definition of Major Emitting Source

The Clean Air Act mandates preconstruction review and PSD permits for "major emitting sources"--those that emit or have the potential to emit 100 or 250 tons per year, depending on the source category, of any regulated pollutant. EPA determined the annual emission potential without considering emission reductions from air pollution control devices. The new proposed rules would follow the court's dictate by calculating potential emissions after applying air pollution controls. The source under consideration would be considered major if it exceeded the limits (i.e., 100 or 250 tons per year) on any of the regulated pollutants.

2. Fugitive Emissions

EPA previously had included fugitive emissions in calculating total potential emissions from sources. However, the court took issue with the lack of certainty in calculating fugitive emissions and said EPA must make a separate rule to regulate them. Attempting to meet the court's requirements, EPA proposed a list of specific plant types from which fugitive emission could be accurately measured. The rules would apply to both PSD and nonattainment new source reviews.

3. Geographic Applicability

Under the proposed rules and according to court dictates, PSD requirements would apply only to sources located within a clean air area. Unless the source would have an adverse effect on a PSD area in another state. The court invalidated EPA regulations that allowed control of sources outside a PSD area that adversely affected the area. EPA is petitioning the court to reverse this rule or to allow EPA to regulate sources that affect a Class I area or an Indian reservation.

4. Modifications

The proposed regulations would exempt, on a pollutant-by-pollutant basis, major modifications from PSD permit review and controls if the pollutant emissions were "de minimis" or below a significant level. The determinations would consider other emission reductions from the plant. The original provisions invalidated by the Alabama Power case defined a major modification as one that increased plant emissions by 100 or 250 tons per year, depending on the source category, not considering any emission reductions from the plant.

5. BACT

The proposed regulations required that BACT be applied to all pollutants regulated under the Clean Air Act for which major construction would create significant net emission

increases. The previous regulations required BACT only for those pollutants for which the proposed construction would constitute a major emitting source.

6. Ambient Monitoring

The proposed regulations generally call for more extensive ambient monitoring both before and after construction. The proposal would extend the preconstruction requirement of an analysis of the air quality existing at the areas affected by the proposed construction to all pollutants regulated under the act and not just criteria pollutants as the existing PSD regulations require.

The new monitoring requirements would apply to any pollutant regulated under the act without regard to whether such pollutant emissions individually qualify the proposed construction as being "major." Particulates and sulfur dioxide data as required under the proposal would be used to improve modeling predictions of increment availability to future sources.

Regulations governing the adoption of acceptable PSD implementation plans also would be reviewed to indicated with state authorities could accept less than one year's continuous air quality data for a criteria pollutant.

7. "De Minimis" Cutoffs

The proposed regulations would exempt on a pollutant-specific basis major modifications from all permit requirements and new major sources from control technology requirements when emissions of that pollutant were below a specified "de minimis" emission rate.

A.2.7 Research on Applicable Regulations

When the objective is to determine compliance or noncompliance with federal, state, regional, county, or municipal air pollution emission codes, the regulations must be examined thoroughly. The particular regulations that are applicable to the emission source must be defined, the particular pollutants that are regulated must be delineated, and the allowable emission rates must be calculated.

The following procedure is to be used when investigating the allowable emission rates for source:

1. Determine the location of the source: city, county, state, state air quality control region, federal air quality control region (if federal regulations apply).

2. Obtain a judgment as to which authority has jurisdiction in the affected region (the state office will be able to make the judgment) and obtain a copy of the current regulations.
3. Ascertain the status or class of the state air quality control region (the state office will be able to make the judgment) and obtain a copy of the current regulations.
4. Examine the regulations to see if particular regulations are applicable to the source; if not, then general regulations apply. Determine the pollutants that are regulated.
5. For each regulated pollutant, calculate the allowable emission limitation; some limitations are related to operating capacity of the process, others are flat rate or upper concentration limits.

It is most important to be aware of the current statutes or regulations. Section A.2.8 recommends ways to accomplish this.

A.2.8 Maintaining Current Regulations

The U.S. Army Environmental Hygiene Agency (AEHA) has a current file of air pollution regulations applicable to most Army facilities. If the desired regulations are available, a telephone call to the proper agency could confirm whether these regulations are up-to-date.

A list of the names, addresses, and telephone numbers of the federal, state, and local air pollution control authorities is published in the Directory of Governmental Air Pollution Control Agencies. This directory is published annually by the Air Pollution Control Association in cooperation with the Office of Air Quality Planning and Standards, Environmental Protection Agency. It is available free to members through the Air Pollution Control Association, P.O. Box 2861, Pittsburgh, Pennsylvania 15230.

The air pollution regulations of each state are published annually in the Environmental Reporter by the Bureau of National Affairs, Washington, DC 20037. The volume also contains a list of the state air pollution control offices.

Publications of federal regulations are available through the Environmental Reporter, the Federal Register, and the Code of Federal Regulations, Title 40.

A.2.9 Violations

Industrial plants are normally considered in violation of

regulations when a process or control device emits pollutants in excess of the rate cited in the applicable regulation or standard. Excessive emissions could occur because of poor operation and maintenance of a malfunction in the process.

The Federal Register defines malfunctions as follows:

"Malfunctions are sudden and unavoidable failures of control or process equipment, or processes that do not operate in a normal or usual manner. Failures that are caused entirely or in part by poor operation/maintenance or from a malfunction. Technically, a malfunction is considered legitimate, whereas a violation caused by an operation/maintenance problem could result in prosecution."

Most agencies require the reporting of violations in accordance with the SIP's. Some agencies request notification by phone, and others use a more formal reporting system.

Because companies often do not call the regulatory agencies when violations occur, complaints by affected citizens provide a method for detection of violations. Some plants subject to (NSPS) must operate continuous monitors; for such plants, an inspector can readily check the records on the stack monitors to document a violation. For compliance with NSPS, the owner or operator of a plant is required to record any emissions resulting from malfunctions or start-ups that are measured or estimated to be greater than those allowed by NSPS. A report of such emissions must be submitted to the administrator on the 15th day following the end of each calendar quarter.

Notification of Violation

Although procedures for notification and correction of violations vary among state and local agencies, many of them simulate EPA procedures. The procedures discussed in this section are typical; however, each facility should check with the appropriate regulatory agency to determine specifics and deviations.

1. The regulatory agency determines a violation and issues a violation notice.
2. The industry must respond to the notice within a specific period of time.
3. The regulatory agency and the industry confer to discuss the problem and the corrective alternatives that are available.
4. The control agency determines the compliance status of the process or operation for which the application has been filed.

5. If the operation is not in compliance, then a compliance schedule is filed, which is the basis for a consent order.

A compliance schedule is a timetable or milestone chart indicating when certain increments of progress toward correction of the violation will be completed.

A consent order is a formal agreement to complete the engineering indicated in the permit application according to the compliance schedule.

6. When changes have been made to correct the violation, a stack test is performed to indicate whether the plant is in compliance or in violation.
7. If the plant is in compliance, the regulatory agency issues a permit.
8. If compliance is not reached in the first attempt, the process is repeated with a new consent order.

A.2.10 The Direction of Future Air Pollution Regulations

The direction of present governmental air pollution control efforts is toward continued strengthening of the regulatory impact. Such efforts indicated concern for:

1. fine particulate emissions (particles less than 3 microns)
2. hazardous heavy metal emissions
3. Acid rain (from sulfur and nitrogen oxide emissions)
4. volatile organic compounds
5. carcinogenic organic emissions.

Fine particle emission control strategies may include:

1. direct control via fine particle standard. For example, mass emission limitations and/or efficiencies may be specified for specific particle size ranges,
2. indirect control via inhalable particulate regulations and/or visibility restrictions.

The control of hazardous heavy metal emissions might also be related to any fine particle emission standards. Most heavy metal emissions are in the extremely fine particle size range.

The emphasis on carcinogenic emissions is expected to continue as one of the highest priorities at EPA with promulgation of standards anticipated once a satisfactory supporting data base is generated.

Although it is not possible to predict the future, it is possible to prepare for it by monitoring the direction of current research. It is highly recommended that maximum flexibility be designed into the final equipment selected. For example, if the choice is between an electrostatic precipitator or fabric filter for a particular application, selection in favor of the fabric filter may be the wisest choice in view of the fact that fabric filters quite often can more than adequately comply with particulate removal requirements and demonstrate the highest collection efficiencies in the fine particle size range. Assuming the capital costs are comparable, the higher operating costs usually associated with the fabric filter may be worth paying for the greater flexibility. Such trade-offs must be carefully evaluated and incorporated into the overall selection process.

A.3 EMISSION ASSESSMENT

Emissions from any source under investigation by the engineer must be identified and quantified as part of any compliance program throughout each of the major phases:

1. determining initial compliance
2. recommending an emission control approach
3. providing data for design of control system
4. demonstrating compliance after implementation of control approach
5. maintaining continued compliance.

The regulations applicable to the source, as well as the phase of the compliance program, dictate the type of data that must be collected. The emission survey can be developed by applying a combination of techniques:

1. source identification
2. calculation of mass balance
3. application of emission factors and manufacturer's stated collection efficiency of existing control equipment
4. review of existing permit applications
5. fuels analysis
6. source emission tests.

Detailed descriptions of these tests follow.

A.3.1 Source of Emission Data

A.3.1.1 Mass Balance

When the throughputs and composition of raw materials are known, a mass balance usually can be established around each process. The materials balance will indicate the extent of solid, liquid, and gaseous wastes. A materials balance for the

entire facility will also indicate the amount wastes generated, much of which is not airborne.

The basis for the mass balance is obtained by a search of applicable air pollution control regulations. The control regulations state what pollutants are regulated and define each pollutant. The definition of each pollutant determines the conditions under which the pollutant is sampled and its chemical or physical makeup. For instance, because water vapor is not considered an air pollutant, it need not be accurately accounted for in the mass balance. Emissions of sulfur dioxide or organic substances are usually regulated and must be estimated in the materials balance.

A materials balance for gaseous pollutants can be determined by analysis of raw materials, fuels, and products to give the gaseous pollutant potential of many of the compounds liberated during a combustion or chemical process.

A.3.1.2 Emission Factors

Publications listing emission factors provide a range of emissions to be expected from specific processes. These values, which are based on uncontrolled process operations, can be factored with the expected collection efficiency to the facility's air pollution control equipment to yield an estimated pollutant emission rate. For example, where the emission factor for a process is 10 pounds of particulate per ton of product and the process is equipped with a particulate control device that is 90 percent efficient, the emissions would be:

$$10 \text{ lb/ton} \times \frac{100-90}{100} = 1.0 \text{ lb/ton}$$

The Environmental Protection Agency, Office of Air and Waste Management, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina 27711, has made available Publication No. AP-42, "Compilation of Air Pollutant Emission Factors," through its library services. The publication contains emission factors and expected collection efficiencies of control equipment for a large number of processes. The publication is updated periodically with new supplements as data on emission sources become available. In addition, emission factors for selected processes are included in Chapter 1 of this manual.

A.3.1.3 Permit Applications

A completed copy of the facility's current permit application should provide information on equipment, input materials, and potential emissions. Permit applications that are no longer current can be used for background information and reference.

A.3.1.4 Fuel Analysis

Knowledge of fuel composition is especially useful in estimating emission, since many gaseous compounds in the fuel become airborne after combustion (e.g., sulfur in coal or fuel oil exhausts as sulfur dioxide). Other constituents such as ash and volatile matter, directly affect the quantity of particulate emissions.

A.3.1.5 Emission Testing

Emission testing is usually the most accurate method of determining emissions. Specific emission testing procedures are usually prescribed for each pollutant from each process. Emission testing by these prescribed methods, however, is also the most expensive technique of surveying emissions. An emission testing program may include ambient sampling, a series of stack tests over a period of several hours, continuous monitoring, or a combination of these.

Many of the Army facilities have been tested by AEHA or by consultants hired by AEHA or by the Army Corps of Engineers, who will maintain records of all tests on particular sources.

Even if it is determined that emission testing of all sources is required for a comprehensive emission survey, data gathering by the methods described earlier will establish the normal operating conditions for processes and control equipment and will provide a check on values obtained in emission tests. Data from earlier emission tests of a process or a similar process are also helpful.

Testing methods other than those prescribed can provide engineering data in a rapid and inexpensive manner. Examples of this type are a velometer or vane anemometer to determine stack gas velocity and detector tube to determine concentrations for gaseous pollutants.

A.3.1.6 Visible Emissions

State regulations emphasize visible emissions except for water vapor. Training and certification are required for a compliance determination of visible emissions. Most state departments of environmental protection run the required program for certification twice a year. Although an untrained observer cannot make an official determination, he can attempt to estimate the percent obscuration of an object viewed through the stack discharge plume. If no emissions are visible, emissions would be judged to be in compliance with visible emission regulations. The percent of visible opacity is not an accurate indication of total mass emissions, but can indicate trouble areas.

A.3.2 Compliance Testing

Although the EPA has promulgated test procedures, tests prescribed by the state regulatory agencies for criteria pollutants may vary. For example, one state may measure the amount of condensable pollutants, where as another state may count only the "front end" of the sampling train (filterable particulate matter).

Each SIP provides a regulatory scheme for source testing. Some of these schemes require continuous monitoring in addition to periodic testing. It is stressed that each state may have different requirements; no facility should assume that requirements of any specific state are similar to those of its neighboring states or of the federal government. Almost all states specify the test method to be used. All but four states, however, further provide that the source may utilize a nonspecified test method if prior approval is obtained. Most of the SIP's require the use of EPA's Test Method 5 for particulate source tests. A substantial number of states also specify the ASME-PTC27 method, and two jurisdictions (Connecticut and the District of Columbia) also require use of the ASME-PTC21 method for certain sources. Since source tests are expensive, it is important that approval of any proposed test method be obtained from appropriate authorities in advance. In addition, the test must be performed in such a way as to determine compliance. Not only must the facility be operating normally during the test, but a knowledgeable and reliable person must monitor and record the production operations to assure that the extracted sample can be gauged in terms of the emission standard.

Further, the units of various emission regulations may be different, such as the following units for particulate emission:

1. pounds of particulate per hour
2. pounds of particulate per pound of raw material throughput
3. pounds of particulate per pound of final product
4. grains per standard cubic foot of exhaust gas, uncorrected or corrected to 12% CO₂ or 50% excess air
5. pounds of particulate per million Btu heat input
6. pounds of particulate per pound of refuse burned
7. pounds of particulate per thousand pounds of flue gas, corrected to 50% excess air.

Persons monitoring a process during performance of a source test must be cognizant of these units, since they directly affect the monitoring requirements. For example, much more detailed process monitoring and recording are needed to determine compliance with a standard expressed in pounds of particulate per ton of raw material than with a standard

expressed in grains per standard cubic foot.

With regard to obtaining prior approval of a proposed test method, at least 13 states require prenotification of a proposed source test. Failure to comply with this regulation in a timely manner may negate any test data obtained. Since costs of many compliance tests exceed \$5,000, this could be an expensive mistake.

In addition to requiring the source to provide test data, many state agencies are empowered to perform source tests. Although most states do not have the capability to conduct expensive test programs because of the considerable expense, the authority to test is a powerful tool for enforcement of state regulations. As with industry, the state agency can hurt its case through use of improper testing methods. Full cooperation should be given with regard to unit operations during an agency-conducted test.

A.3.3 Process Characterization

Of prime importance when assessing the emissions from a particular source is a definition of the operational characteristics. The emission of pollutants as calculated or as measured will define the rate and/or concentration of pollutants in the stack gases. The next step in the analysis is a determination of how representative this rate or concentration is when the emissions are viewed over a longer period of time. Where the measurement made under maximum load conditions? How often does the process operate at maximum load? Is the start-up/shutdown cycle frequent? How frequent? Does the emission rate change during start-up/shutdown? These are some of the questions that must be asked when characterizing the process. The operating schedule is the key factor during this step of the investigation.

Process descriptions will enable the engineer, consultant, vendor, or regulatory official to categorize the process and to determine the applicability of similar processes. More detailed information is outlined in Chapter 1. However, all that is required in the preliminary assessment is a description of the processing equipment in the flow streams, including existing air pollution control equipment.

A sample form that can be used for process characterization is shown in Table A-1. This is a general form that is applicable to most processes. Since most allowable emission rates that are regulated by the air pollution control agencies are determined by process input rates, process output rates, or fuel consumption rates, these should be fully documented. The plant operations personnel and/or the base engineering staff should be able to supply the engineer with the proper information.

TABLE A-1
PROCESS CHARACTERIZATION

PROCESS: _____

PROCESS CAPACITY: MAXIMUM _____

MINIMUM _____ NORMAL _____

OPERATING SCHEDULE: _____ HRS/DAY _____ DAYS/WK

_____ WKS/YR

BATCH, CONTINUOUS, OR CYCLIC PROCESS: DESCRIBE _____

PERCENT OF OPERATING TIME PROCESS OPERATES AT:

MAXIMUM CAPACITY _____

MINIMUM CAPACITY _____

NORMAL CAPACITY _____

FREQUENCY OF STARTUP/SHUTDOWN: _____

DESCRIPTION OF PROCESSING EQUIPMENT: _____

TYPE OF EXISTING AIR POLLUTION CONTROL EQUIPMENT: _____

UNUSUAL OPERATING CONDITIONS THAT MAY AFFECT EMISSIONS: _____

RAW MATERIALS INPUT: (INCLUDE CAPACITY)

TYPE _____	RATE _____	LB/HR _____
------------	------------	-------------

TYPE _____	RATE _____	LB/HR _____
------------	------------	-------------

TYPE _____	RATE _____	LB/HR _____
------------	------------	-------------

TYPE _____	RATE _____	LB/HR _____
------------	------------	-------------

TABLE A-1 (Cont.)

FUELS INPUT:

TYPE _____ RATE _____

TYPE _____ RATE _____

TYPE _____ RATE _____

EMISSION POINT HEIGHT: ABOVE GROUND _____

ABOVE BUILDING _____

A.3.4 Gas Stream Properties

Knowledge of the properties of the gas stream to be treated is essential to the design of an air pollution control system. Pertinent properties are discussed in this section.

A.3.4.1 Composition

Gas composition is important only as it affects its physical and chemical properties. The chemical properties are important to the extent that there may be chemical reaction between the gas, the contaminant, and the collector. One common example of reaction between gas components and equipment is corrosion of metallic parts of collectors by gases containing sulfur oxides and water vapor. Physical properties of the carrier gas are all important and will be discussed individually.

A.3.4.2 Temperature

The two principal influences of temperature are on the volume of the carrier gas and on the materials of construction of the collector. The former influences the size and cost of the collector and the concentration of the contaminant per unit of volume. Viscosity, density, and other gas properties are temperature dependent.

A.3.4.3 Pressure

In general, a gas pressure high or lower than atmospheric pressure requires that the control device be designed as a pressure vessel. Some types of equipment are much more amenable to being designed into pressure vessels than others. For example, catalytic converters are incorporated into pressure processes for the production of nitric acid and provide an economical process whereby nitrogen oxides are reduced to nitrogen and oxygen before release to the atmosphere.

Pressure of the carrier gas is not of prime importance in particulate collection except for its influence on gas density, velocity, and electrical properties. It may, however, be important in certain special situations, as where the choice is between high efficiency scrubbers and other devices for collection of particulate. In adsorption, high pressure favors removal and may be required in some situations.

A.3.4.4 Viscosity

Viscosity is of importance to collection techniques in two respects.

1. Particulate removal techniques often involve migration of the particles through the gas stream

under the influence of some removal force. Ease of migration decreases with increasing viscosity of the gas stream.

2. Viscosity influences the pressure drop across the collector and thereby becomes a power consideration.

A.3.4.5 Density

Density appears to have no significant effect in most real gas cleaning processes, although the difference between particle density and gas density appears as a factor in the theoretical analysis of all gravitational and centrifugal collection devices.

A.3.4.6 Humidity

Humidity of the carrier gas stream may be important to the selection or performance of control equipment in several different ways.

1. High humidity may contribute to accumulation of solids and lead to the blocking of inertial collectors as well as caking on the filter medium.
2. Humidity can result in cold spot condensation and aggravation of corrosion problems.
3. The presence of water vapor may influence the basic mechanism of removal in electrostatic precipitation and greatly influence resistivity.
4. In catalytic combustion, humidity may be an important consideration in the heat balance that must be maintained.
5. In adsorption, humidity may tend to limit the capacity of the bed if water is preferentially or concurrently adsorbed with the contaminant.
6. In filtration, humidity may influence agglomeration and produce subtle effects.

These considerations are the main limitations to using evaporation cooling for an advantage in gas-moving power requirements. In situations where humidity is a serious problem for one of these reasons, scrubbers or adsorption towers may be particularly appropriate devices.

A.3.4.7 Combustibility

The handling of a carrier gas that is flammable or explosive will require certain precautions, the most important of

which is making sure that the gas is either above the upper explosive limit or below the lower explosive limit for any air mixture that may exist or occur. The use of water scrubbing or adsorption may be an effective means of minimizing the hazards in some instances. Electrostatic precipitators are often impractical, since they tend to spark and may ignite the gas.

A.3.4.8 Reactivity

A reactive gas stream presents special problems. In filtration, for example, the presence of gaseous fluorides may eliminate the possibility of high temperature filtration using glass fiber fabrics. In adsorption, carrier gas must not react preferentially with the adsorption of contaminants when water vapor is present as a component of the carrier gas stream. Also, the magnitude of this problem may be greater when one is dealing with a high temperature process.

A.3.4.9 Toxicity

When the carrier gas is toxic or irritant, special precautions are needed in the construction of the collector, the duct work, and the stack discharge to the atmosphere. The entire system up to the stack should be under negative pressure and the stack must be of tight construction. Since the collector is under suction, special means such as an air lock must be provided for removing the contaminant from the hoppers, if collection is by a dry technique. Special precautions may be required for service and maintenance operations on the equipment.

A.3.4.10 Electric and Sonic Properties

Electrical properties are important to ESP because the rate or ease of ionization will influence removal mechanisms. Generally, intensity of Brownian motion and gas viscosity both increase with gas temperature. These factors are important gas stream characteristics that relate to the sonic properties of the stream. Increases in either property will tend to increase the effectiveness with which sonic energy can be used to produce particle agglomeration.

A.3.5 Flow Characteristics of Gas Stream

A.3.5.1 Flow Rate

The rate of evolution from the process, the temperature of the effluent, and the degree and the means by which it is cooled if cooling is used, fix the rate at which carrier gases must be treated and, therefore, the size of air pollution control equipment. For economic reasons, it is desirable to minimize the size of the control equipment by minimizing the flow rate to be treated by the equipment.

A.3.5.2 Variations in Flow Rate

Rate variations result in velocity changes and thereby influence equipment efficiency and pressure drop. Various control techniques differ in their ability to adjust to flow changes. In situations where rate variations are inescapable, it is necessary to:

1. design for maximum conditions.
2. employ systems that will compensate for flow changes, i.e., modular baghouse units, variable throat venturi scrubbers.

A.3.5.3 Changes in Properties

Variations in flow rates are of two main types:

1. those where merely more or less of the same carrier gas flows
2. those where variations in flow are caused by process changes, which also cause variation in the composition or temperature of the carrier gas.

Variations in contaminant concentration and composition may occur simultaneously. Since many carrier gas properties change when composition and temperature change, equipment selection must recognize these changes.

Carrier gas properties may also change with time. There are processes where flow rate remains reasonably uniform over a process cycle but where gas composition goes through a cyclic variation. The problems are essentially the same as when there is variation of both composition and rate.

A.3.5.4 Control of Air Flow Through System

Control techniques that result in progressively increasing collector pressure loss with time will require that consideration be given to the effect on air mover selection. Fabric filters are perhaps the best illustration of this effect. Accumulation of dust cake during the filtering cycle results in increased resistance to flow. The increase in resistance generally reduces centrifugal fan output. Where the resultant flow variation cannot be tolerated by the process, positive flow displacement blowers or other special precautions as described below must be employed.

Another method to maintain constant flow can be achieved by installing a pressure-controlled damper in the main duct. When the pressure drop across the filter is low, as immediately after cleaning, the damper is in a partially closed position to add pressure drop to the

system. As the pressure drop across the filter increases with dust build up on the fabric, the damper automatically opens enough to maintain the sum of the filter pressure drop and the damper pressure drop constant, thereby maintaining a set flow rate through the duct leading to the collector.

A.3.6 Properties of the Contaminant

Selection and design of an air pollution control system is greatly influenced by the nature of the contaminant. Thorough understanding of the properties of the contaminant is, therefore, very important to deal effectively with an air pollution problem. This section discusses the pertinent properties.

A.3.6.1 Composition

Composition directly affects the use or value of the collected material, which in turn frequently dictates the kind of collection device required. Thus, if the collected material is to be used in process or shipped dry, a dry collector is indicated, and if the collected material is of high intrinsic value, a very efficient collector is indicated.

Just as the carrier gas composition can change throughout a cyclic process, so can the composition of the contaminant. For example, in the secondary smelting of aluminum, the period of evolution of extremely fine $AlCl_3$ fume lasts for only a few minutes of the 8 to 16 hours of the total cycle. Since chemical and physical properties vary with composition, a collector must be able to cope with cyclic composition changes.

A.3.6.2 Loading

Contaminant loading from many processes varies over a wide range for the operating cycle. Ten-to-one variation in loading is not uncommon. One example of such a process is oxygen lancing of the open hearth furnace; another is soot blowing in a steam boiler. Contaminant loading may also vary with gas stream flow rate. A prime example is fly ash in flue gas from a stoker-fired coal furnace. An increase in flue gas flow rate is the result of an increase in upward velocity of air through the coal bed and increased gas velocity in the furnace, both of which increase the carryover from the fuel bed to the gas stream.

A.3.6.3 Phase

The contaminants may be present as gases, particulates, or both. In most air cleaning operations, the con-

contaminant to be removed will not undergo change of phase at temperatures near those normally existing in conventional collection equipment (unless such change of phase is related to the actual removal mechanism, as in absorption, where gaseous pollutants go into solution). However, in some situations, determination of the temperature at which the gas should be cleaned may depend on the relationship between the temperature and phase of the contaminant. For example, aluminum chloride is a by-product in the removal of magnesium from reprocessed aluminum. This aluminum chloride exists as a vapor at temperatures in excess of about 360°F. Since this change of phase takes place at temperatures that commonly exist in many types of control equipment, selection and control of the operating temperature is obviously critical.

A.3.6.4 Solubility

Solubility of contaminant is important to adsorption, absorption, and scrubbing. In absorption, the degree of solubility is one indication of the ease of removal of the contaminant. In adsorption, solubility may be important to the ease with which the adsorbent may be regenerated. In scrubbing to remove particulate, solubility will provide a secondary removal mechanism to aid the basic separating forces.

A.3.6.5 Combustibility

Generally, it is not desirable to use a collection system that permits accumulation of pockets of explosive contaminant. Systems handling such materials must be protected against accumulation of static charges. For example, electrostatic precipitators are not suitable because of their tendency to spark. Wet collection by scrubbing or adsorption methods may be especially appropriate. However, some dusts such as magnesium are pyrophoric in the presence of small amounts of water. In combustion as a control technique (with or without a catalyst), explosive properties must be considered.

A.3.6.6 Reactivity

Certain precautions must be taken in the selection of equipment for the collection of reactive contaminants. In filtration, selection of the filtering media may present a special problem. In adsorption, certain situations require that the adsorbed contaminant react with the adsorbent so that the degree of reactivity will be important.

A.3.6.7 Electrical and Sonic Properties

Sonic properties of the contaminant are significant where sonic agglomeration is employed, such as in certain

types of wet scrubbers. Electrical properties may influence the performance of several collector types.

1. Inertial Collectors

Electrical properties are considered to be a contributing factor influencing the build-up of solids.

2. Electrostatic Precipitators

The electrical properties of the contaminant are of paramount importance in determining collection efficiency and influencing the ease with which it is removed by periodic cleaning.

3. Fabric Filters

Electrostatic phenomena may have direct and observable influence upon the process of cake formation and the subsequent ease of cake removal.

4. Wet Scrubbers

Wet scrubbers are devices in which liquid droplets are formed and contact between these droplets and contaminant particles is required for particle collection. The electrical charge on both particles is an important process variable. The process is most efficient when the charges on the droplet attract rather than repel those on the particle.

A.3.6.8 Toxicity

The degree of contaminant toxicity will influence collector efficiency requirements and may necessitate the use of equipment that will provide ultrahigh efficiency. Toxicity will also affect the means for removal of collected contaminant from the collector and the means of servicing and maintaining the collector. Toxicity of contaminant does not influence the removal mechanisms of any collection technique.

A.3.6.9 Particulate Size, Shape, and Density

Size, shape, and density are the three factors that determine the magnitude of forces resisting movement of a particle through a fluid. These forces are major factors in determining the effectiveness of removal by means of inertial collectors, gravity collectors, venturi scrubbers, and electrostatic precipitators. Even in the case of filters, size and shape of the particles influence both collection efficiency and pressure drop. The only analogous situation in gaseous removal is found in

adsorption where molecular weight relates to the adsorbability of the gas.

It is apparent that the size distribution will largely determine the overall efficiency of a particular piece of control equipment. Generally, the smaller the particulate size to be removed, the greater is the expenditure required for power or equipment or both, as in the examples that follow:

1. Scrubbers

To increase the efficiencies obtainable with scrubbers, it is necessary to expend additional power either to produce high gas stream relative velocities, as in the venturi scrubber, or to produce finely divided spray water.

2. Cyclones

Cyclones will require that a large number of small units be used for higher efficiency in a given situation. Both the power cost (because of the increased pressure drop) and equipment cost (for a multiple unit installation) will increase.

3. Electrostatic Precipitators

Higher efficiencies for electrostatic precipitators will require that the degree of sectionalization be increased because of the approximately inverse logarithmic relationship between outlet concentration and the size of the collection equipment. For example, a precipitator giving 90 percent efficiency may have to be doubled in size to give 99 percent efficiency and tripled in size to give 99.9 percent efficiency.

A.3.6.10 Hygroscopicity

Though hygroscopicity is not related to any removal mechanism, it may be a measure of how readily particulate will cake or tend to accumulate in the equipment if moisture is present. For example, if an accumulation occurs on a fabric filter, it may completely blind it and prevent gas flow.

A.3.6.11 Catalyst Poisons

The presence of traces of materials such as silicones, which on decomposition leave a deposit of silicon (or an oxide of silicon), and metals such as mercury, lead, and zinc may make catalytic combustion

impractical even though effluent stream characteristics are such that it would otherwise be a suitable technique. Other than by mechanical attrition, catalysts are deteriorated by four phenomena associated with stream content or condition:

1. surface coating of the granular structure by particulate contaminants within the gas stream
2. coating by particulate products of oxidation
3. chemical reaction with gaseous components of the stream
4. bed temperature levels that will cause sintering of the catalyst.

These often overlooked considerations must be taken into account when selecting a catalytic oxidation system.

A.3.7 Obtaining a Representative Sample of Contaminant

In order to evaluate any contaminant and predict the ease with which it can be collected, it is necessary to procure a representative sample of the contaminant as it exists in the gas stream. Such an evaluation is seldom possible because the process of collecting the sample, redispersing it for measurement, and measuring the properties of interest involves handling that may change such fundamental properties as effective particle size. For this reason, laboratory investigations and evaluations of a contaminant, while they provide the best available basis for design, are definitely limited in their utility.

Because of this, the preferred way of evaluating the collection ability of a collector type is to pass a portion of the gas stream containing the contaminant into a so-called test unit brought to the plant site. The test unit is a pilot-plant-sized collector employing the same elements and forces on a fraction of the process gas flow as a full-scale unit would apply to the total gas flow. The test unit operates on a sample of the contaminant as it exists in the gas stream. A test unit seldom gives results identical to those from a full-scale unit because scale effects are always a factor in performance. However, test units give more reliable results than laboratory tests using redispersed dust.

Where it is not practical to use a test unit, testing must be done on a collected dust sample. Problems of contaminant collection and redispersion do not exist, of course, if the contaminant is a well-defined gaseous

substance, not reacting with the carrier gas or other contaminants.

A.3.8 Determination of Compliance Status

After development of the emission assessment and the search for applicable emission control regulations, the engineer will compare the actual emission to the allowable emission for each of the regulated pollutants. This is done for the worst case condition, that is, maximum capacity, or during periodic unusual conditions such as soot blowing on a boiler. If the emission rate of a regulated pollutant is marginally out of compliance, then the future plans of that facility should be closely examined; perhaps a cutback in production could change the situation.

If the facility is in noncompliance for any pollutant, then the engineer must explore the avenues of air pollution control even if the source has not been cited by the air pollution control agency.

A.4 ALTERNATIVES TO INSTALLATION OF COLLECTION DEVICES

A.4.1 Modifications of Operations--Introduction

The main thrust of current control technology is directed at hardware, fuels, and materials. These are applied at appropriate points in the operational cycles of processes--from the preparation and charge of the feed (fuel, material, and air) to the discharge of contaminated air and other waste products at the completion of the process cycle. This discussion describes examples of the many modifications that can be made to existing equipment and processes to help reduce emissions.

A.4.2 Change in Fuels or Process Materials

Frequently, it is possible to reduce or eliminate certain contaminants from a particular process simply by substituting another fuel or material having less contaminant emission potential.

The most obvious example is the use of low-sulfur fuels to replace high-sulfur coal or oil, since the emissions of sulfur oxides are proportional to the sulfur content of the fuels used.

According to the Environmental Protection Agency, it is technically feasible to produce or desulfurize fuels to meet the following specifications:

Distillate oil	0.1% sulfur (although generally not available below 0.2% sulfur)
Residual oil	0.3% sulfur
Bituminous coal	0.7% sulfur

Since residual oil is generally obtained from overseas sources, its use is ordinarily restricted to areas accessible to water-borne transportation. There are limited tonnages of 0.7 percent sulfur coal produced in the Western United States. Large reserves of such coal exist but are not currently being mined.

Some examples of process material and/or fuel changes follow:

- 1) In some cases, the sulfur content of coal may be substantially reduced by washing and pulverizing it. As much as 40 percent reduction in sulfur content in some coals may be obtained in this way, but this is not true of most types of coal. Methods for the optimal use of limited supplies of low sulfur fuels include: (a) blending high and low sulfur grades, and

(b) storing low sulfur fuel and issuing it for use as a substitute for a high sulfur fuel when unfavorable weather conditions reduce the natural processes of atmospheric dilution and dispersion.

- 2) To reduce emissions of organic solvents that have a high degree of reactivity in the development of oxidant-type smog, Los Angeles County devised a regulation (Rule 66) limiting the use of such solvents in large-scale operations. The regulation has been largely met by reformulation of industrial and architectural coatings, substituting low-reactivity solvents for high-reactivity solvents.
- 3) In die casting, some molds are coated with mold release compounds containing oils or other volatile material. The heat from the molten metal vaporizes the oils, creating air contaminants. Recently, mold release compounds have been developed that do not contain oils, and this source of air pollution is thereby eliminated.

A.4.3 Process and Facility Changes

In many operations, contaminant emissions can be eliminated or substantially reduced by changes in processes or facilities.

Where closed or covered systems for confining contaminants are impractical, it may be possible to collect the contaminated air or stack gas and to remove the contaminants from it while they are in a relatively concentrated form, before dispersion into the general atmosphere. It has been found possible, and often profitable, to control the loss of volatile materials by condensation and reuse of vapors, as by condensation units on tanks storing volatile petroleum products. For sand-blasting and spraying of materials that produce a dry particulate residue, installation and use of hoods, fans, and fabric filters to enclose the process and prevent the escape of contaminated air may be effective. Hydrogen sulfide and mercaptans generated in petrochemical operations, if discharged through flares, are converted to oxides of sulfur. They may be absorbed from the gas stream and converted to elemental sulfur or sulfuric acid in a sulfur recovery plant.

To reduce or eliminate the pollution potential of a very objectionable operation, it may be advantageous to use an entirely different process to accomplish similar ends. Such changes are likely to require corresponding changes in facilities. As an example, for the disposal of solid waste, an adequate sanitary landfill system can

replace the use of burning dumps or municipal incinerators, both of which may be prolific sources of combustion contaminants.

A.4.4 Improvements in Operational Practices

Even after control techniques have been applied to a process or system, emissions may be greater than necessary if the details of operation are not carefully observed.

The effectiveness of any operational improvement depends upon continuing attention to the procedures necessary to implement them. The change must become part of a continuous procedure of frequent maintenance of process equipment or of control equipment.

Abnormally large emissions to the atmosphere may result from operating production equipment at excessive rates. For example, the output of the rotary sand and stone drier controls the production rate of hot mix asphalt plants. When the hot gas velocity through the drier is increased above the design rate, the quantity of dust emitted increases in greater proportion than the increase in gas flow. In the same industry, machinery progressively declines in effectiveness during the operating season, resulting in cumulative unrepaired damage to dust collectors, exhaust systems, and equipment enclosures. For plants operating in this manner, increased frequency of maintenance measures is required when control performance deteriorates.

As noted previously, washing of coal may substantially reduce the emissions of ash, as well as oxides of sulfur in combustion operations.

APPENDIX B

APPENDIX B. DETAILED DISCUSSION--PARTICULATE CONTROL EQUIPMENT

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APPENDIX B

DETAILED DISCUSSION--PARTICULATE CONTROL EQUIPMENT

B.1 ELECTROSTATIC PRECIPITATORS

B.1.1 Factors Affecting Performance

From a practical as well as a theoretical standpoint, the factors governing precipitator performance are:

1. particle size and concentration of the entering dust
2. electrical conditions within the precipitator (current and voltage)
3. reentrainment of the dust
4. uniformity of the gas flow.

B.1.1.1 Particle Size and Concentration

The particle size of the fly ash produced from electric power boilers varies with the type of boiler and the fuel being burned. The mechanism of formation of fly ash within a boiler is not completely understood. Evidence indicates that individual coal particles are probably fractured during the combustion process and the residual mineral matter agglomerates into spheres of silicates of principally aluminum, iron, and calcium if the temperature in the combustion zone is sufficiently high ($>2,000^{\circ}\text{F}$). Some fly ash is not formed into spheres, but has the appearance of irregularly shaped particles with no evidence of having been fused. This type of fly ash is produced from lignites with high percentages of water at low combustion temperatures ($<1,900^{\circ}\text{F}$). This type of ash is, however, unusual in the United States.

Precipitators used for fly-ash removal are generally installed following the air preheater, at which point the flue gas temperature is typically 300°F . Some precipitators (hot-side) are installed ahead of the air preheater, where the flue gas temperature is 600 to 800°F . If a mechanical collector such as a cyclone is installed ahead of the precipitator, the particle size of the fly ash is altered, since the mechanical collector removes the large-size fraction of the fly ash.

The effect of particle size on collection efficiency can be seen from Figure B-1, which shows the fractional collection efficiency for fly ash of different particle sizes.³⁸ The data are taken from field tests on a full-size cold-side precipitator installed on a pulverized coal boiler. It is apparent that a larger fraction of smaller fly-ash particles would

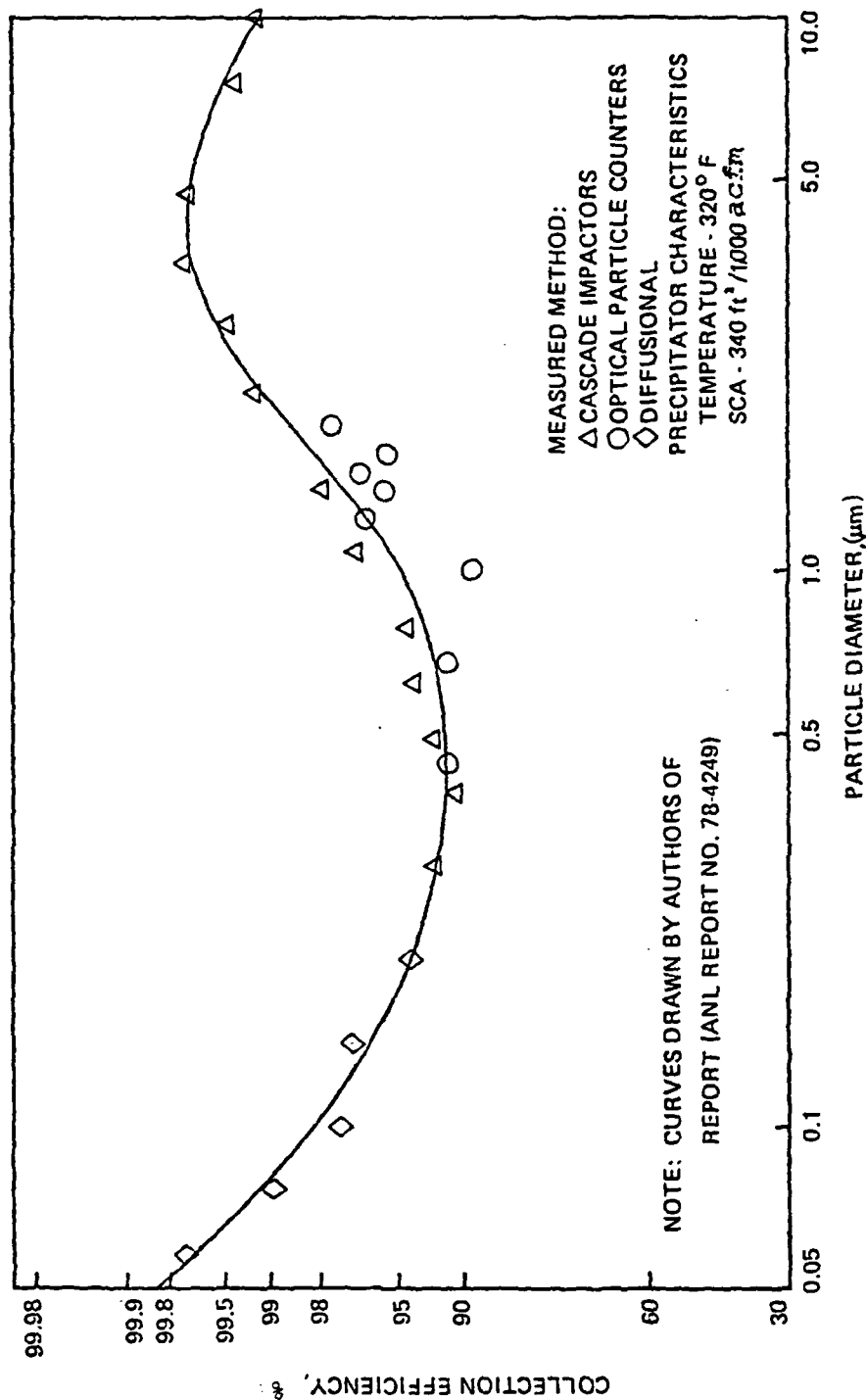


FIGURE B-1

FRACTIONAL EFFICIENCIES FOR A COLD-SIDE
 ELECTROSTATIC PRECIPITATOR WITH THE
 OPERATING PARAMETERS AS INDICATED, INSTALLED
 ON A PULVERIZED COAL BOILER ³⁸

result in a lower overall migration velocity and would give a lower overall efficiency unless a larger collection area is used.

Another effect of particle size on precipitator performance is that, as higher efficiencies are required, a larger percentage of the finer size fraction must be collected. This has the effect of requiring a proportionately larger precipitator size to go from, say, 99 to 99.9 percent than to go from 90 to 99 percent.

B.1.1.2 Electrical Conditions

Electrical characteristics that influence precipitator performance are related to the electrode geometry and the physical and electrical characteristics of the fly ash being collected.

The physical arrangement of the electrodes requires that the corona current pass through the collected dust layer. The voltage drop across this dust layer is determined by the resistivity of the dust, the current density, and the thickness of the dust layer. If the dust resistivity is high ($>5 \times 10^{10}$ ohm-cm) the current will be limited by electrical breakdown within the dust layer. For moderate resistivity dust, the breakdown will result in a spark being propagated across the electrodes.

When the precipitating dust has low electrical resistivity, the current is limited only by electrical breakdown of the gases within the interelectrode region. Current densities of 50 to 60×10^{-6} ampere/ft² or perhaps higher are possible if the electrical resistivity of the dust is low.

If the resistivity of the dust is moderately high (around 5×10^{10} ohm-cm), the electric field within the dust layer can exceed the electrical breakdown condition for currents in the range of 20 to 30×10^{-6} ampere/ft². When breakdown occurs in the dust layer, a spark is propagated to the corona electrode. Precipitator operation is usually limited to spark rates of around 50 to 100 per minute in each electrical section. The maximum current is so related to the dust resistivity that current densities as low as 5×10^{-6} ampere/ft² are found in precipitators when collecting dust with resistivities above about 1×10^{12} ohm-cm.

Voltages in a precipitator are governed principally by the electrode geometry, the particle size and concentration of the dust, the dust resistivity, and the composition and properties of the gas. Large voltage drops across the dust layer can alter the applied voltage, but have little influence on total performance. Fine dust at the inlet can also influence the voltage by a space charge effect.

Fly-ash resistivity is determined principally by the composition of the coal. Combustion of coal containing sulfur results in sulfur oxides, principally sulfur dioxide (SO_2), in the flue gases. Except perhaps for that in the form of metal sulfates, all of the sulfur in the coal appears in the flue gases.

About 1 percent of the SO_2 is oxidized to SO_3 , which combines with the moisture present in the flue gas to form sulfuric acid vapor. At the temperatures at which most precipitators operate (around 300°F or lower), some of the sulfuric acid vapor present is condensed or is adsorbed in the fly-ash surface. The presence of this sulfuric acid on the fly ash reduces the electrical resistivity of the ash in relation to the quantity of sulfuric acid present and the temperature of the flue gases. In general, coals containing sulfur in quantities greater than about 1.5 percent produce fly ash with reasonably low resistivities at temperatures below 300°F . Coals with sulfur in quantities less than 1 percent generally produce ash with moderate to high resistivities. The absolute value of the resistivity of the fly ash can vary, depending on other factors (mainly moisture content of the flue gases and mineral composition of the ash).

The important mineral constituents of fly ash as they influence resistivity are the alkali metals (sodium, lithium, and potassium), iron, and calcium. The alkali metals appear to be the primary charge carriers and these metal ions affect the electrical resistivity in relation to their concentration.

For low-sulfur coals, resistivity is predictable from the composition of the ash. The presence of iron appears to modify the availability or in some instances the species of ion participating in the conduction process. Details of methods for predicting resistivity of ash from low sulfur coals have been published.¹

Calcium appears to affect the resistivity of fly ash as a result of its reaction with the available sulfuric acid, thus requiring a larger quantity of H_2SO_4 to achieve a given reduction in resistivity than for an ash low in calcium.

The mechanism by which sulfuric acid acts to reduce resistivity is not clearly understood. It might chemically attack the fly-ash surface to release additional alkali ions to participate in the conduction process. It might also directly participate in the conduction process. Whatever the mechanism, it is obvious that sulfur in the coal plays an important role in determining fly-ash resistivity and precipitator current density. Shifts from high to low sulfur coals to meet sulfur oxide emission standards have often created high resistivity problems that reduce the effectiveness of electrostatic precipitation.

B.1.1.3 Reentrainment of Dust

A third factor influencing precipitator performance is reentrainment of collected dust, or bypassing of the dust-laden gases around the electrified regions. Reentrainment can take place in a variety of ways: (1) dust being precipitated can strike the dust layer with sufficient velocity to dislodge additional particles; (2) rapping of the plates can propel dust into the gas stream, and falling of dust into the hoppers can result in reentrainment of dust already removed. Gas sneakage from maintaining electrical clearance above and below the electrodes and gas sweepage through the hoppers also influence precipitator performance.

The influence of gas sneakage and reentrainment is reduced considerably by proper baffling and by proper design of rapping gear. Reentrained dust is generally not dispersed as individual particles, so the redispersed dust is more readily collected than would be indicated by the sizes of the discrete particles. Dust reentrained from the first field is readily collected in the subsequent fields. The reentrained dust appearing at a precipitator outlet is principally that resulting from reentrainment of dust collected in the last field.

Recent studies of reentrainment indicate that between 25 and 40 percent of the total emissions from a precipitator is reentrained dust. More complete descriptions of these studies have been published.^{39,40}

B.1.1.4 Gas Flow Uniformity

Nonuniform gas flow is another factor in precipitator performance. The size of the flue gas ducts and space limitations make it difficult to achieve good uniformity of gas flow. As a standard, the Industrial Gas Cleaning Institute has recommended that the gas entering a precipitator should be such that 85 percent of the local velocities should be within 25 percent of the mean and no single point should differ more than +40 percent.⁴¹

B.1.2 Flue Gas Additives

One approach to improving the performance of electrostatic precipitators on existing plants is the use of flue gas additives, which can serve several purposes. One of the most common difficulties with electrostatic precipitators is high resistivity ash resulting from a change in fuel (from high sulfur to low sulfur coal, for example) or from failure to properly assess the resistivity characteristics of the ash in the design phase. Such problems can be overcome through the use of flue gas additives to reduce the ash resistivity or to reduce reentrainment.^{40,42}

A consequence of burning a low sulfur coal to avoid excessive emissions of sulfur dioxide is that the concentration of sulfur trioxide (as well as sulfur dioxide) in the flue gas is lowered, and the problem of excessive ash resistivity is incurred. One solution is to add sulfur trioxide from an external source (vapor from anhydrous sulfur trioxide or sulfuric acid). Alternative sources more frequently used at present are sulfur dioxide (which is vaporized and passed over a catalytic oxidizer in the presence of air) or elemental sulfur (which is burned to sulfur dioxide and then finally converted to sulfur trioxide in a catalytical oxidizer).

Although ammonia is not a naturally occurring component of flue gas, it is sometimes added in place of sulfur trioxide to treat ash from low sulfur coal. The role of ammonia in this connection is not clearly understood. There are theoretical reasons for discounting the value of ammonia for adjusting resistivity, and there is no consistent experimental evidence that the compound has this effect. These statements notwithstanding, there is clear proof that ammonia injection can improve the efficiency of precipitation, but it probably does so through other mechanisms.^{43,44}

B.2 FABRIC FILTERS

B.2.1 Discussion of Filtration and Fabric Types

Two basic types of filtration occur in commercial fabric filters: (1) "media" or fiber filtration and (2) layer or "cake" filtration. In fiber filtration, the dust is retained on the fibers themselves by settling, impaction, interception, and diffusion. In cake filtration, the fiber acts as a support on which a layer of dust is deposited to form a microporous layer capable of removing additional particles by sieving and other basic filtration mechanisms (impaction, interception, diffusion, settling, and electrostatic attraction). In practical industrial cloth filters, both methods occur, but cake filtration is the more important process after the new filter cloth becomes thoroughly impregnated with dust.

A wide variety of woven and felted fabrics are used in fabric filters. Clean felted fabrics are more efficient dust collectors than woven fabrics, but woven materials are capable of giving equal filtration efficiency after a dust layer accumulates on the surface. When a new woven fabric is placed in service, visible penetration of dust may occur until buildup of the cake or dust layer. This normally takes from a few hours to a few days for industrial applications, depending on dust loadings and the nature of the particles. For extremely low grain loadings and especially fine dusts, fabrics are often precoated. Fabrics may be precoated with a coarse dust or similar material to form an artificial filter cake to prevent dust penetration. Another method of reducing dust penetration

in fabrics is based on the use of electrostatics. These forces not only assist filtration by providing an attraction between the dust and fabric, but may also affect particle agglomeration, fabric cleanability, and collection efficiency. Electrostatic charges may be induced in both fabrics and dusts by friction. Agglomeration of some charged dusts may be aided by selection of a fabric with an opposite charge. Thus, for example, a negatively charged dust would agglomerate with a positively charged fabric.

Woven fabrics must be cleaned carefully so as not to completely dislodge the filter cake; otherwise, efficiency will drop. Overcleaning of felted fabrics is generally impossible because they always retain substantial dust deposits within the fabric. Felted fabrics require more thorough cleaning methods than woven materials. For the same cleaning efficiency, felted fabrics are often capable of higher air-to-cloth ratios (i.e., cubic feet per minute per square foot of cloth) than woven fabrics, thereby requiring less filter cloth area, and consequently less space for given air or gas volume. Woven fabrics in conventional baghouses usually have air-to-cloth ratios of 1:1 to 5:1; felted fabrics usually have ratios of 3:1 to 16:1, or ratios several times those of woven fabrics. This is balanced, though, by the higher cost of the felted fabrics and the cleaning method employed. If felted fabrics are used, filter cleaning is limited to the pulse-jet and reverse-jet methods. When woven fabrics are employed, any cleaning technique may be used. Woven fabrics are available in a greater range of temperature and corrosion-resistant materials than are felts and, therefore, cover a wider range of applications.

Textile materials used as filtering media can be woven or felted and made from a large variety of materials. The introduction of synthetic fibers as filter media has produced greater efficiency and durability.

Synthetic fiber yarns are manufactured in three forms:

1. Continuous multifilament yarn consists of several fibers of unlimited length twisted tightly together to produce a smooth yarn. The greater the number of filaments, the bulkier and stronger the yarn.
2. Staplefiber yarn consists of extended continuous fiber that is cut into short lengths. The fiber must then be carded and spun into a yarn in the same manner as natural fibers, such as cotton and wool.
3. Monofilament yarn consists of unbroken lengths of single extruded fibers of relatively large diameter.

Cloth can be produced from any of these basic yarns, either singly or in combination. In conventional fabric dust

collectors, the filtering media is often woven cloth: The permeability is restricted largely to the open pores in the weave; very little air movement can take place through the twisted fibers in the yarn. The weave employed must produce a stable cloth in which the threads cannot be easily pushed about and where the pores between the threads remain relatively constant. Twill or satin weaves are much more stable than plain ones. Cotton satin makes a satisfactory filter media for general purposes and is slightly cheaper than the synthetics, although synthetic materials usually possess advantages over cotton. The advantages of synthetic materials are more apparent when the gas stream is hot, moist, corrosive, abrasive, or sticky or when there is a combination of these difficulties. Wool makes an excellent filter cloth, but it is heavy and expensive. Cloth made with synthetic continuous-multifilament yarn has a completely smooth surface, which results in advantages such as excellent cake release, good moisture resistance, and easy cleaning. The regularity and smoothness of the filament yarn permit the construction of very closely woven lightweight cloth that is capable of retaining the particles. The continuous form of the fiber results in high tensile strength.

Cloth made from staple fiber yarns has a lower tensile strength than that of the continuous filament; because of its greater resilience, however, it has excellent resistance to abrasion and mechanical damage. It cannot be as closely woven as filament cloth, but the hairy nature of the yarns assists fine-particle filtration. Cake release is not as efficient, but this can be improved by surface treatment. Staple fiber may be spun either to the cotton or the wool systems. The former is fine and tightly twisted. Usually, it is necessary to twist yarns together to produce bulk for a filter cloth. In the case of woolen spun yarns, sufficient bulk can be achieved by spinning and twisting a single thread because of the more delicate way in which woolen spinning is effected. Cloth made from monofilament is completely smooth and has good mechanical resistance, but it cannot be produced in close or even moderately close weave; therefore, it is not well suited to dust collection from a gas stream.

A successful filter cloth is based on filament and spun yarn, doubled together in warp and weft. This type of material combines high tensile strength with resilience, good filtering properties, and good cake discharge characteristics.

In contrast to the woven cloth, there are various types of nonwoven materials. Felted wool has been known and used for hundreds of years; its origins are lost in antiquity. One story relates that the inventor was a monk who, on one of his long pilgrimages, eased his sore feet by putting wool into his sandals. When he arrived in the monastery, he found, to his great surprise, that he had made the first woolen felt insole. Heat, moisture, pressure, and the motion of the feet had activated the felting properties of wool. The same factors are used in pressed felt manufacture today.

Wool or hair felt was the first real nonwoven material used for dust collection. No spinning, weaving, or knotting is required because the element of felt is the single fiber, not a manufactured thread or yarn. The fibers are randomly oriented with spaces between them. Felts have a three-dimensional structure.

At present, the most important felts for dust collection are needle felts. The needle felting process produces tough strong fabrics by mechanical interlocking, without recourse to the use of bonding agents. In manufacture, the fiber is laid out on traveling aprons to form a bat, a thick layer of fibers laid in different directions. The bat is then pressed down with boards containing needles with barbs that vibrate through the bat to intermingle the fibers and produce a complex interlocking. The final fabric varies in thickness from 1 to 8 mm. Using an assortment of natural and synthetic fibers, sometimes in blends, a comprehensive range of needle felts can be produced.

All filter media, both woven and nonwoven, should have the right finish. Cotton and wool fabrics should be preshrunk. Sometimes other finishes (such as moisture-proofing or fire-retarding) are desirable, but they should be carefully applied so that the permeability of the filter cloth is not affected.

Synthetic materials should be heat set; to resist axial deformation, they are often silicone-treated for better heat resistance. Some of the synthetic fibers can have a strong static charge, and these should receive antistatic treatment. In applications where the static charge could cause explosions, ground wire strips must be used.

Natural fiber felts are not presently used to any great extent. Needle felts combine the useful properties of both felt and woven fabrics. They have remarkable pore volume and, therefore, good permeability to air; yet, the fine-pore felt achieves an efficient dust separation, even if dusts are of very small particle size. For equal efficiency, felts require a smaller filtration area, as they can be used at higher air velocities. By special calender treatment, the surface of the needle felt can be rendered smoother, thereby providing easier cake release.

The choice of fabric is usually dependent on the following:

1. temperature of the gas stream
2. physical and chemical characteristics of the particles to be collected
3. chemical composition of the carrier gas
4. moisture content of the carrier gas.

Certain filter media are commonly associated with applications in some industries because of temperature considerations and methods of cleaning. For example, a baghouse handling a low-temperature gas stream could use a fabric made of cotton; because of the strength of this type of media, a shaker mechanism could be used to clean the baghouse. On the other hand, for high-temperature applications, it might be necessary to use fiberglass, which are structurally weak. A very gentle cleaning technique would then be required so that the bags would not rupture.

B.2.2 Manufacturer's Guidelines to the Selection of Air/Cloth Ratio for Four Types of Fabric Collectors

B.2.2.1 Shaking Bag Collector

Table B-1 provides the guidelines for determining air-to-cloth ratios for various applications using shaking bag collectors.

B.2.2.2 Glass Cloth Collector

The size of a Dracco glass-cloth dust collector is determined primarily by the volume of gas to be handled and the air-to-cloth ratio. Table B-2 presents air-to-cloth ratios for typical applications. The net cloth area can be calculated by using the following formula:

$$\text{Net cloth area} = \frac{\text{air volume}}{\text{air/cloth ratio}}$$

B.2.2.3 Reverse-Jet Collector

Table B-3 gives the procedure and required chart to determine the air-to-cloth ratio for reverse-jet equipment.

B.2.2.4 Reverse-Pulse Collector

Table B-4 presents the procedure to be followed for the selection of air-to-cloth ratio for reverse pulse equipment.

B.2.3 Factors Affecting Performance of Fabric Filters

Factors that can influence fabric filter performance with fly ash include:

1. fabric structure
2. air-to-cloth ratio
3. maximum pressure drop before cleaning
4. method of cleaning

TABLE B-1
GUIDE TO SHAKING BAG AEROTURN SELECTION

4:1 RATIO			3:1 RATIO			2.5:1 RATIO			2:1 RATIO			1.5:1 RATIO		
MATERIAL	OPERATION		MATERIAL	OPERATION		MATERIAL	OPERATION		MATERIAL	OPERATION		MATERIAL	OPERATION	
Cardboard	1		Asbestos	1, 7, 8		Alumina	2, 3, 4, 5, 6		Ammonium Phosphate	2, 3, 4, 5, 6, 7		Activated Charcoal	2, 4, 5, 6, 7	
Feeds	2, 3, 4, 5, 6, 7		Aluminum Dust	1, 7, 8		Carbon Black	4, 5, 6, 7		Carbon Black	2, 3, 4, 5, 6, 7		Carbon Black	11, 14	
Flour	2, 3, 4, 5, 6, 7		Fibrous Mat'l.	1, 4, 7, 8		Cement	3, 4, 5, 6, 7		Diatomaceous Earth	4, 5, 6, 7		Detergents	2, 4, 5, 6, 7	
Grain	2, 3, 4, 5, 6, 7		Cellulose Mat'l.	1, 4, 7, 8		Coke	2, 3, 5, 6		Dry Petrochem.	2, 3, 4, 5, 6, 7, 14		Metal Fumes, Oxides and other Solid Dispersed Products	10, 11	
Leather Dust	1, 7, 8		Gypsum	1, 3, 5, 6, 7		Ceramic Pigment	4, 5, 6, 7		Dyes	10				
Tobacco	1, 4, 6, 7		Lime (Hydrated)	2, 4, 6, 7		Clay & Brick Dust	2, 4, 6, 12		Fly Ash	2, 3, 4, 5, 6, 7, 14				
Supply Air	13		Perlite	2, 4, 5, 6		Coal	2, 3, 6, 7, 12		Metal Powders	2, 3, 4, 5, 6, 7, 14				
Wood, Dust, Chips	1, 6, 7		Rubber Chem.	4, 5, 6, 7, 8		Kaolin	4, 5, 7		Plastics	2, 3, 4, 5, 6, 7, 14				
			Salt	2, 3, 4, 5, 6, 7		Limestone	2, 3, 4, 5, 6, 7		Resins	2, 3, 4, 5, 6, 7, 14				
			Sand *	4, 5, 6, 7, 9, 15		Rock, Ore Dust	2, 3, 4, 5, 6, 7		Silicates	2, 3, 4, 5, 6, 7, 14				
			Iron Scale	1, 7, 8		Silica	2, 3, 4, 5, 6, 7		Starch	6, 7				
			Soda Ash	4, 6, 7		Sugar	3, 4, 5, 6, 7		Soaps	3, 4, 5, 6, 7				
			Talc	3, 4, 5, 6, 7										
			Machining Operation	1, 8										

CUTTING - 1	MIXING - 4	CONVEYING - 7	FURNACE FUME - 10	INTAKE CLEANING - 13
CRUSHING - 2	SCREENING - 5	GRINDING - 8	REACTION FUME - 11	PROCESS - 14
PULVERIZING - 3	STORAGE - 6	SHAKEOUT - 9	DUMPING - 12	BLASTING - 15

B FINENESS FACTOR

MICRON SIZE	FACTOR
100	1.2
50-100	1.1
10-50 *	1.0
3-10	.9
1-3	.8
1	.7

This information constitutes a guide for commonly encountered situations and should not be considered a "hard-and-fast" rule. Air-to-cloth ratios are dependent on dust loading, size distribution, particle shape and "cohesiveness" of the deposited dust. These conditions must be evaluated for each application. The longer the interval between bag cleaning, the lower the air-to-cloth ratio must be. Finely-divided, uniformly sized particles generally form more dense filter cakes and require lower air-to-cloth ratios than when larger particles are interspersed with the fines. Sticky, oily particles, regardless of shape or size, form dense filter cakes and require lower air-to-cloth ratios.

C DUST LOAD FACTOR

Loading GR. CU. FT.	Factor
1-3	1.2
4-8	1.0
9-17	.95
18-40	.90
> 40	.85

EXAMPLE: Foundry shakeout unit handling 26,000 cfm and collecting 3,500 lb/hr of sand. The particle distribution shows 90% greater than 10 microns. The air is to exhaust to room in winter, to atmosphere in summer.

$$3500 \frac{\text{lb}}{\text{hr}} \div 60 \frac{\text{min}}{\text{hr}} \div 26000 \frac{\text{cu ft}}{\text{min}} \times 7000 \frac{\text{gr}}{\text{lb}} \div 10 = 15.7 \frac{\text{gr}}{\text{cu ft}}$$

*Chart A = 3:1 ratio, Chart B = Factor 1.0, Chart C = .95, 3 x 1 x .95 = 2.9 air to cloth ratio. 26,000 ÷ 2.9 = 9,000 sq. ft. Use size 1-600 Shaking Bag Aeroturn with 9,420 sq. ft. of filter area.

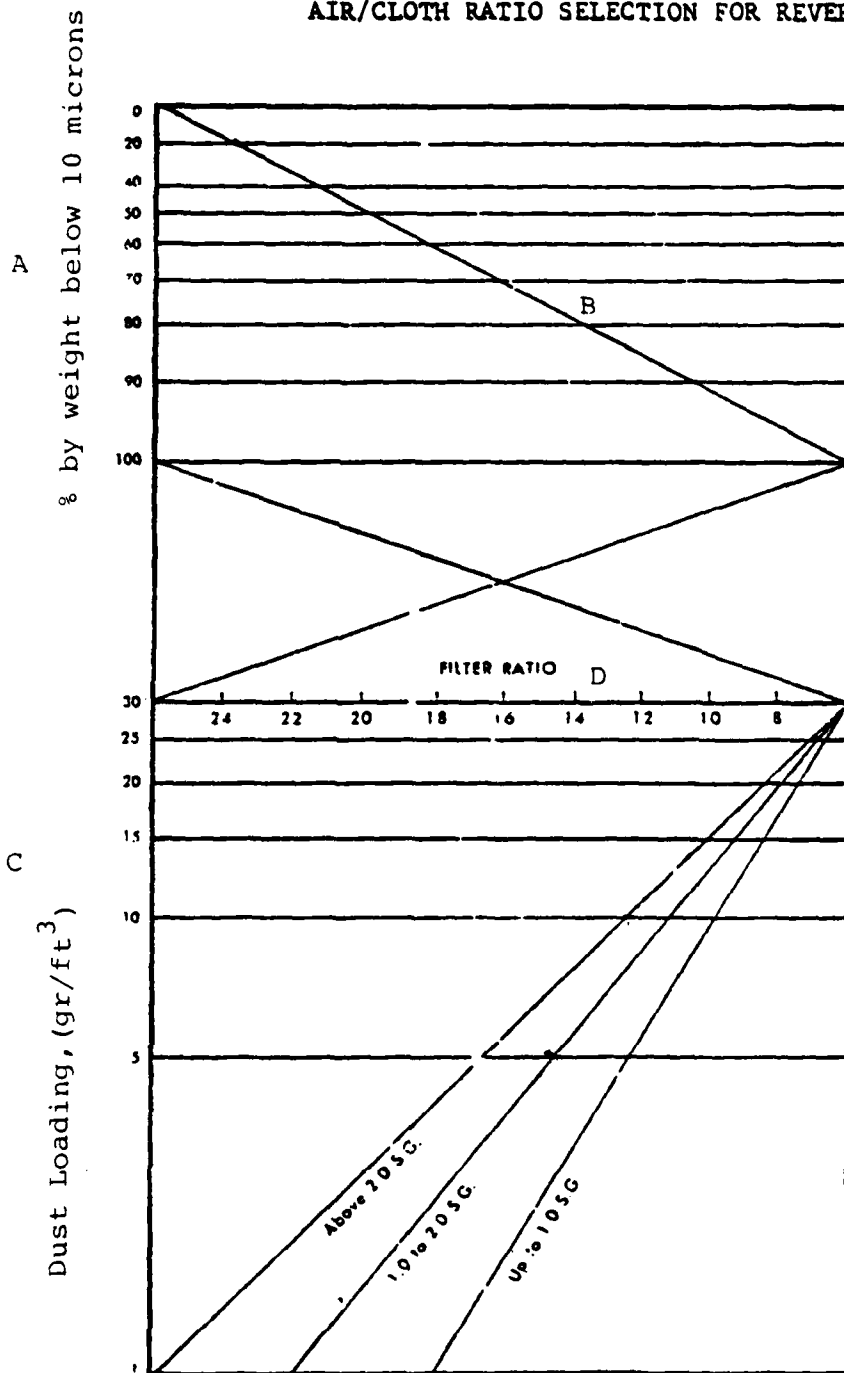
TABLE B-2

AIR/CLOTH RATIO FOR DRACCO GLASS-CLOTH COLLECTOR^a

<u>Application</u>	<u>Ratio</u>
1. Carbon black generator furnace and and channel black	1:1 - 1:3:1
2. Electric furnace and ferro alloy furnace, most mettallurgical fume	1.5:1 - 1.8:1
3. Cement and lime kilns, wet and dry process; open hearth furnaces and smelters	1.8:1 - 2:1
4. Clinker coolers, refractory kilns and furnaces; coal-fired boilers (power plant)	2:1 - 2.3:1
5. Special application only	2.3:1 - 2.5:1

^aFrom Fuller Company Bulletin DCB-1B.

TABLE B-3

AIR/CLOTH RATIO SELECTION FOR REVERSE JET EQUIPMENT^a

HOW TO USE

In order to select Filter Ratio, three conditions pertaining to your specific dust collection job are needed. They are:

- The approximate percentage, by weight, of dust particles 10 microns or smaller.
- Dust content of the air entering the Aeroturn Collector expressed in terms of grains (7000 per lb.) per cubic foot. Use average or normal values for both dust and air quantities.
- Specific gravity of the material to be collected.

- From appropriate point on vertical scale A draw horizontal line intersecting sloping line B.
- From appropriate point on vertical scale C draw horizontal line intersecting the sloping line which represents the proper specific gravity range for the material to be collected.
- Now, draw a straight line between points selected in steps 1 and 2 above. The intersection of this line with horizontal scale D gives the Filter Ratio.

^a From Buffalo Forge Co. Bulletin AP650.

TABLE B-4

AIR/CLOTH RATIO SELECTION FOR REVERSE PULSE EQUIPMENT^a

"...The application of this Guide is to high performance, high filter rate (or velocity) collectors which usually use a felt media combined with frequent and thorough cleaning. Examples are pulse jet types and blow ring (i.e., reverse jet) style units.....The Guide consists of five factors which are multiplied together to arrive at a filter rate."

TABLE A

Multiplier A	15°	12	10	9.0	6.0**
M	Cake Mix	Asbestos	Alumina	Ammonium	Activated Carbon
	Cardboard Dust	Buffing Dust	Aspirin	Phosphate-	Carbon Black
	Cocoa	Fibrous &	Carbon Black	Fertilizer	(Molecular)
A	Feeds	Cellulosic	(Finished)	Coke	Detergents
	Flour	Material	Cement	Diatomaceous	Fumes and other
T	Grain	Foundry Shakeout	Ceramic Pigments	Earth	dispersed
	Leather Dust	Gypsum	Clay & Brick Dusts	Dry Petro-	products direct
	Sawdust	Lime (Hydrated)	Coal	chemicals	from reactions
E	Tobacco	Perlite	Flourspar	Dyes	Powdered Milk
		Rubber Chemicals	Gum, Natural	Fly Ash	Soaps
R		Salt	Kaolin	Metal Powder	
		Sand	Limestone	Metal Oxides	
I		Sandblast Dust	Perchlorates	Pigments,	
		Soda Ash	Rock Dust, Ores	Metallic and	
A		Talc	and Minerals	Synthetic	
			Silica	Plastics	
L			Sorbic Acid	Resins	
			Sugar	Silicates	
S				Starch	
				Stearates	
				Tannic Acid	

*In general physically and chemically stable materials.

**Also includes those solids that are unstable in their physical or chemical state due to hygroscopic nature, sublimation and/or polymerization.

TABLE B

APPLICATION	FACTOR B
NUISANCE VENTING	1.0
Relief of transfer points, conveyors, packing stations, etc.	
PRODUCT COLLECTION	0.9
Air conveying-venting mills flash driers classifiers, etc.	
PROCESS GAS FILTERATION	0.8
Spray driers, kilns, reactors, etc.	

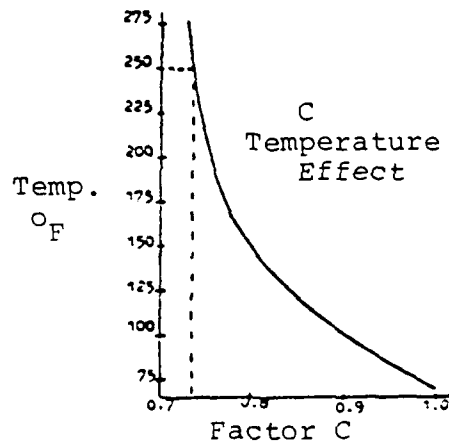


TABLE C shows temperature effect as related to amount of cloth fabric required.

^a From R. F. Frey and T. V. Reinauer, Pulverizing Machinery Co., "New Filter Rate Guide," Air Engineering, 30 (April 1964).

TABLE B-4 (Cont.)

TABLE D

FINENESS	FACTOR D
Over 100 micron	1.2
50 to 100 micron	1.1
10 to 50 micron	1.0
3 to 10 micron	0.9
Under 3 micron	0.8

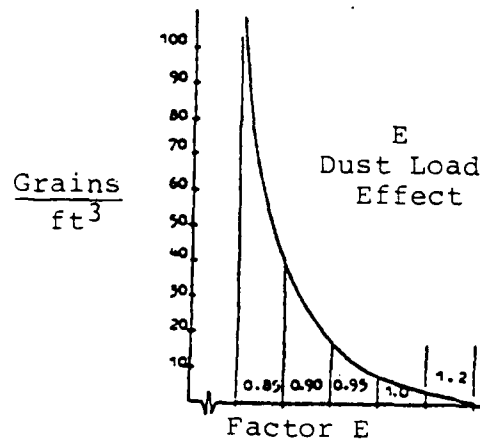


TABLE E shows dust load effect, and shows typical performance curve of a pulse jet or blow ring collector.

A. This factor is obtained from Table A. It is a function of the material itself, combining many of the items that effect filtration. Laboratory test can determine this factor, but field experience on a given material is far superior since longer operating periods are sometimes necessary to arrive at true equilibrium. The normal datum used is operation at ambient temperature with average 10-50 micron dust and approximately 10 grains/cu. ft. load from a nuisance class application.

B. An application factor. Obviously, process operation with attendant upsets must be treated differently than simple venting. This factor attempts to classify common applications.

C. The temperature effect. Experience has shown more cloth is required with increased temperature approximately as shown on Curve "C". The explanation is probably a gas viscosity increase with temperature. This is eventually counteracted by reduced density, hence the curve is asymptotic to a value of approximately 0.7 at 250° or more.

D. The fineness factor. This obvious factor needs little explanation. It is sometimes difficult to divorce fineness from the character of the material. Fume in general has a low "A" factor because of fineness.

E. The dust load curve. This curve is the typical performance curve of a pulse jet or blow ring collector plotted at a constant differential pressure. It usually becomes asymptotic to a given cfm/Sq. Ft. which means that above a certain loading, normally in excess of 100 grains/Cu. Ft., a given collector can handle more material without lowering cfm/Sq. Ft. The probable reason for this is the fact that the air becomes saturated with dust, much as it can become saturated with water and simply cannot hold more, thus the bag surfaces receive a saturation-limited rate of accumulation per unit time.

EXAMPLE:

Given: 36000 acfm effluent from a spray drier
Plastic Resin Dust 20 to 30 μ average size (fines present to 0.5 μ) 1500 lbs/Hr.

Required: Filter Rate

$$\text{Grains/Ft.}^3 = \frac{1500}{60} \times \frac{7000}{36000} =$$

4.9

Solution: A = 9.0
B = 0.8
C = 0.78
D = 1.0
E = 1.0

Filter Rate = $9.0 \times 0.8 \times 0.78 \times 1.0 \times 1.0 = 5.6 \text{ cfm/Sq. ft.}$
Approximately 6500 Sq. Ft. MIKRO-PULSAIRE required.

5. cleaning frequency
6. intensity of cleaning
7. flue gas temperature and humidity.

These factors can be divided into two categories: factors that are basic to the design of a fabric filter system for optimum performance and factors that relate to the behavior of the system as installed. During the design of a baghouse, questions of fabric, method of cleaning, air-to-cloth ratio, operating temperature, and humidity need to be considered. Once the baghouse is operating, cleaning rate, duration and intensity of cleaning, and other variables related to the operation of the collector are adjusted to keep pressure drop before the cleaning below the maximum allowable.

B.2.3.1 Upset Operating Conditions

Other occurrences can influence the collection efficiency of the baghouse. Bags can be blinded, or clogged, during boiler start-up. Temperature excursions through acid dew points may corrode the baghouse structure and adversely affect the life and performance of the bags. Another potential problem is air preheater failure, which can drive temperature above safe operating limits for the bags.

Fabric filter performance is not influenced by some of the factors that are considered critical in electrostatic precipitator and scrubber operation. Woven fabric filters are relatively insensitive to inlet dust loading. Also, fly-ash resistivity is of little consequence for fabric collectors since collection does not depend on electrostatic attraction. In contrast to the operation of a scrubber, fabric filter collection efficiency is not a function of particle wettability or pressure drop.

B.2.3.2 Dust Loading

The insensitivity of fabric filters to inlet dust loading is well known. Laboratory studies have shown for a specified dust/fabric combination and a fixed operating mode for the collector that the average mass emission and its related size properties may be nearly independent of the concentration and size of the inlet dust. These results led the authors to conclude that no simple relationship exists between typical outlet and inlet concentrations for most fabric filters. The insensitivity of outlet emission rate to inlet dust concentration is understandable if considerable penetration arises from leakage. If so, emissions consist primarily of previously collected dust deposited within the fabric.

B.2.3.3 Electrostatic Effects

Electrostatic effects in fabric filters may not be entirely negligible, since it has been observed that collection of dust by a fabric filter is enhanced if it has a static charge, especially in the presence of an electric field. On the other hand, fabric filters are obviously quite efficient in fly-ash collection when no attempt at static electrification is made.

B.2.3.4 Pressure Drop

An operating pressure drop of 3 to 4 inches of water is typical for fly-ash collection, but some industrial baghouses operate substantially above 10 inches of water. Pressure figures such as these are values averaged over the filtering cycle. When filtration begins, the pressure drop increases nonlinearly until a filter cake is built and linearly thereafter.

B.2.3.5 Filter Cake Porosity

Fabric filter performance is degraded by the presence of pinhole inclusions in the filter cake. These pinholes can be seen on the surface of a fabric upon which dust is collected, and occur with both woven and felted fabrics. In one test, the number density of such holes on a woven fabric was 250 per square meter. Calculations that consider the size and number density of these pinholes indicate that 8 percent of the total gas flow through the fabric is through these pinholes. It has been conjectured that the increase in penetration in the 2- to 5- μ m range of particle sizes is mainly the result of pinhole leaks, which allow relatively more coarse particles to pass through. The number of pinholes increases as the air-to-cloth ratio increases.

There is some agreement, then, that emissions from fabric filters are the result of indirect fault processes, such as seepage or pinhole leaks or both, rather than the result of a failure to collect these particles in the first place. If so, the following penetration characteristics can be explained:

1. Increased penetration due to increased face velocity can be understood to result from the increased prevalence of pinholes at high velocity, and from increased pressure drop, which may lead to increased seepage.
2. Constant penetration as the dust cake thickens can be understood because of the inability of an established pinhole to seal, once formed. The high gas velocity through the pinhole may preclude effective hole blocking, except by very large particles.

3. Continuously decreasing penetration as the dust cake thickens can be understood if the fabric and dust do not interact to form pinholes.
4. Constant penetration for particles of all sizes is explained if particles get through pinholes. A hole has no size fractionating capability.
5. The insensitivity of outlet emission rate to inlet concentration is explained if considerable penetration arises from seepage. In this case, emissions are primarily of previously collected dust deposited within the fabric, and dust that is currently collecting may not have a major influence.

B.2.4 Particulate Preconditioning Equipment

The prefilter particulate treatment process, if any, may be designed for (a) the enhancement of particulate agglomeration, thereby precipitating out of the gas flow, some material prior to deposition on the fabric and/or improving the resistance properties of the dust cake, (b) the preseparation of coarse particles by gravity sedimentation or inertial techniques, or (c) the injection of additives to produce a dust cake sufficiently dense to provide high efficiency collection of low concentrations of fine material, or alternatively additives to produce a more porous dust cake with lower resistance.

Use of any of the above techniques may require reappraisal of preliminary cost estimates for the fabric filter system for the following reasons:

1. change of deposit permeability, and hence cycle time, due to alteration of particle size distribution
2. change of inlet loading
3. change of cake removability or residual permeability
4. change in properties of the collected material such as bulk density and total volume
5. changes in gas stream properties.

One must balance the economic advantages of changes in dust properties against the costs of installing and operating the preconditioning equipment. Of course, if the treatment process is used to elevate collection efficiency to levels satisfying pollution control regulations, the equipment costs become a necessary investment.

B.2.5 Gas Preconditioning Equipment

Hot process effluents are usually partly cooled before filtering to reduce the flow volume, which in turn decreases the filter fabric area requirement. Lowering the gas temperature toward the dew point often extends fabric life and may permit the use of less expensive or more durable materials. Prior to entering the collector, the process effluent may also be altered through combustion, absorption, chemical reaction, or humidification, any of which may influence the design of other fabric filter system components. Temperature conditioning, a common treatment, is usually accomplished by the methods described²⁸ in Table B-5. In other situations, it may prove more economical to filter the gas essentially at process effluent temperature, or even at increased temperature, provided that the temperatures do not exceed the upper limit for the fabric.

Somewhat related to the three cooling methods outlined in Table B-5 are the special systems for emergency protection of the equipment. These include CO₂ devices that automatically release high-pressure gases to cool the effluent, should its temperature exceed a critical preset limit; fail-safe dampers held in position by set-point melting links; burst-out panels to prevent duct or collector rupture due to pressure or vacuum excursions; and various types of alarm systems. Such equipment can be reliable and relatively inexpensive compared to the cost of replacing a collector system. Rapid-cool equipment can also shorten the time required to take equipment out of service. Heating equipment may facilitate start-ups by preventing condensation.

TABLE B-5

METHODS OF TEMPERATURE CONDITIONING²⁸

Radiation-Convection Cooling (long, uninsulated inlet ducts)

- Advantages: Lowest flow volume of the three methods
Smoothing or damping flow, temperature, pressure, or other surges or peaks in the process effluent stream
Saving of heat (building space heating)
- Disadvantages: Cost of extensive ducting
Space requirements of ducting
Possibility of duct plugging by sedimentation

Evaporation (by water injection well ahead of the filter)

- Advantages: Low installation cost, even with automatic controls
Capability of close and rapid control of temperature
Capability of partial dust removal and/or gas control via scrubbing
- Disadvantages: Danger of incomplete evaporation and consequent wetting of the filter or chemical attack of the fabric or filter
Increased danger of exceeding the dewpoint and increased possibility of chemical attack
Increased steam plume visibility, a hazard near highway
Possible increase in volume filtered

Dilution (by adding ambient air to the process effluent stream)

- Advantages: Lowest installation cost, especially at very high initial temperatures
- Disadvantages: Substantial increase in total filtering volume
Automatic control of both temperature and filtering velocity is not possible
Uncontrollable intake of ambient moisture, dust, without prior conditioning of the dilution air

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APPENDIX C

DETAILED DISCUSSION-GASEOUS CONTROL EQUIPMENT

C.1 CONTROL BY ABSORPTION

C.1.1 Introduction

Gas absorption as applied to the control of air pollution is concerned with the removal of one or more pollutants from a contaminated gas stream by treatment with a liquid. The necessary condition is the solubility of these pollutants in the absorbing liquid. The rate of transfer of the soluble constituents from the gas to the liquid phase is determined by diffusional processes occurring on each side of the gas-liquid interface. Consider, for example, the process taking place when a mixture of air and sulfur dioxide is brought into contact with water. The SO_2 is soluble in water, and those molecules that come into contact with the water surface dissolve immediately. However, the SO_2 molecules are initially dispersed throughout the gas phase, and they can only reach the water surface by diffusing through the air, which is substantially insoluble in water. When the SO_2 at the water surface has dissolved, it is distributed throughout the water phase by a second diffusional process. Consequently, the rate of absorption is determined by the rates of diffusion in both the gas and the liquid phases. This phenomenon is discussed in Section C.1.2.

Equilibrium is another extremely important factor to be considered in controlling the operation of absorption systems. The rate at which the pollutant will diffuse into an absorbent liquid will depend on the departure of the system from equilibrium. The rate at which equilibrium is established is then essentially dependent on the rate of diffusion of the pollutant through the nonabsorbed gas and through the absorbing liquid. Equilibrium concepts and relationships are considered in Section C.1.3.

The rate at which the pollutant mass is transferred from one phase to another depends also on a mass transfer, or rate coefficient, which equates the quantity of mass being transferred with the driving force. As can be expected, this transfer process would cease upon the attainment of equilibrium. Individual and overall mass transfer coefficients are discussed in Section C.1.4 as they relate to both the gas and liquid phases.

C.1.2 Diffusion-Introduction

Gas absorption is essentially a mass transfer, or diffusional operation, characterized by a transfer of one substance through another, usually on a molecular scale. The mass transfer process may be considered as the result of a concentration difference driving force, the diffusing substance moving from a place of relatively high concentration to one of relatively low concentration. The rate at which this mass is transferred depends, to a great extent, on the diffusional characteristics of both the diffusing substance and the medium.

Diffusion may be defined as the movement, under the influence of physical stimulus, of an individual component through a mixture. The most common cause of diffusion is a concentration gradient of the diffusing component. A concentration gradient tends to move the component in such a direction as to equalize concentrations and destroy the gradient. Diffusion may result from molecular action only or from a combination of molecular and turbulent action.

Assuming essentially uniform concentrations within the bulk liquid and bulk gas at any instant of time, the diffusional rate-governing step in the transfer of solute gas between vapor and liquid is taken to exist directly at the gas-liquid interface. In order to explain observed phenomena in terms of a physically conceivable model, it was proposed that at the interface there may exist a thin film of gas and a thin film of liquid within which the principal resistances, or rate-determining diffusional transfer mechanisms, are concentrated. Precisely at the interface, these two films are in equilibrium. This two-film concept is illustrated³² in Figure C-1. The liquid concentrations and partial pressures of the absorbed gas, component A, at a given instant in time, are represented by the curves between c_{AL} and c_{AI} and between P_{AG} and P_{AI} , respectively. With the passage of time in a nonflowing closed system, these two curves would become straight horizontal lines as the bulk gas concentration and the bulk liquid concentration attain equilibrium. In a flowing system, Figure C-1 represents conditions at some counter-current flow point (for example, at a particular height in an absorption column) where, as the gas and liquid pass each other, the bulk materials do not have sufficient time of contact to attain equilibrium. However, at the exact interface of contact, the gas and liquid do attain equilibrium instantaneously, and the driving force potential with which molecules of solute gas are transferred across the interface during this instant is dependent on the concentration gradient in the films.

The dependence of diffusional flow on concentration gradient is defined by Fick's Law,

$$dn = DA (dc/dz)dt$$

namely, dn , the quantity of material diffusing in direction z through an area A , is proportional to the time interval dt , the area, and the concentration gradient in the direction of diffusion (dc/dz). The proportionality factor, D , is the diffusivity, or diffusion coefficient, of the solute material through the bulk fluid. Fick's Law is the fundamental equation of diffusion. It was developed from the kinetic theory of gases, and its agreement with experiment is one of the evidences substantiating kinetic theory.

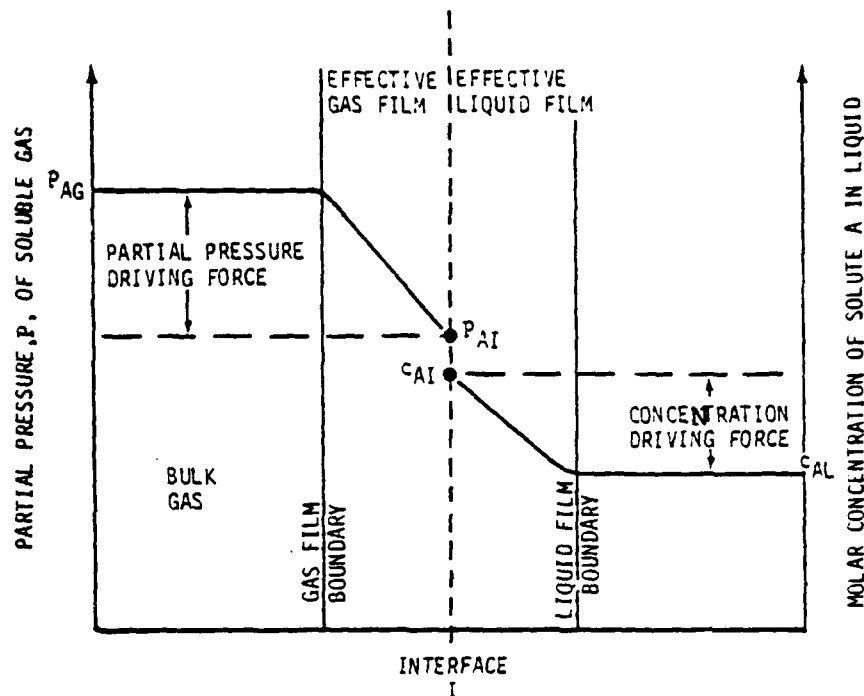


FIGURE C-1

CONCENTRATION PROFILE FOR ABSORBED COMPONENT
A TO ILLUSTRATE THE TWO-FILM CONCEPT³²

Unlike the rate of transfer, the amount of material transferred across the interface is not dependent on the concentration gradient, but rather on the equilibrium relationship. Although a very large concentration gradient may exist, for example, across the interface, this does not necessarily mean a great amount of material will likewise be transferred. Equilibrium conditions will establish the maximum amount of material that can be transferred, while the concentration gradient driving force will determine how fast.

C.1.2.1 Diffusion in Gases

Molecular gas diffusion results from the linear motions of the molecules. At any instant, the individual molecules in a gas are moving in random directions at speeds varying from zero to very large values. The molecules move at random and suffer frequent collisions with one another. Because of the frequent collisions, the molecular velocities are being continually changed in both direction and magnitude. Diffusion is more rapid at higher

temperatures because of the greater molecular velocities. It is similarly more rapid at low pressures because the average distance between the molecules is greater and the collisions are less frequent. Small molecules diffuse rapidly, primarily due to their greater molecular speeds, and also because the chance for collisions is not so great as for large molecules. Thus, in general, diffusion increases with an increase in molecular weight and the size of the individual molecule.

C.1.2.2 Diffusion in Liquids

Investigations on diffusion in liquids are not as advanced as those on diffusion in gases, and experimental data are not as available. The rate of diffusion in liquids is much slower than in gases, and mixtures of liquids may take a long time to reach equilibrium unless agitated. This is, in part, explained by a much closer spacing of the molecules; as a result, molecular attractions are more important. Diffusivities in liquids are, therefore, smaller than in gases.

In the absence of an adequate theory for diffusion in liquids, it is usually assumed that Fick's Law is obeyed and that the equations developed in the previous section for diffusion in gases can be applied also to diffusion in liquids, i.e.,

$$dn = D_L A (dc/dz) dt$$

where D_L = liquid diffusivity.

This treatment is necessarily approximate since it has been found that the diffusivity in liquids depends to some extent on the concentrations of the solution, especially where large concentrations are concerned and when the behavior of a solution deviates from the ideal solution laws.

C.1.3 Equilibrium Relationships

Systems undergoing changes spontaneously do so in a definite direction. If left to themselves, they eventually attain a state where no further action apparently takes place. Such a state is called an equilibrium state. When a hot slab, for example, is placed in contact with a cold slab, the temperature of the cold surface rises and that of the hot one falls until an equilibrium point is reached, when both surfaces are at the same temperature. For gas absorption in a liquid, the equilibrium state is considered as that composition of the gas phase and that composition of the liquid phase that would be established if the gas and liquid phases were in mutual contact for an infinitely long period of time. The expression for the equilibrium condition may take many forms. For the equilibrium between a pure liquid and its vapor, the vapor-pressure curve is familiar. The curve expresses in pressure units the vapor concentration that is in equilibrium with the pure liquid when both are at a specified temperature. In the case of a liquid mixture, equilibrium must exist between the liquid and vapor phase in regard to each constituent present.

For a binary mixture, the equilibrium relation is a relatively simple one describing the concentration or partial pressure of each constituent in the vapor phase that is in equilibrium with a liquid of one particular composition at the specified temperature. The vapor, of course, will be of different liquid mixtures.

For all such combinations not at equilibrium, the difference in concentration of some property (for example, mass or energy) between that in the existing condition and that which would exist at the equilibrium condition is a driving force tending to alter the system toward the equilibrium condition. The rate at which a gaseous constituent of a mixture will dissolve, or diffuse, in an absorbent liquid, therefore, will depend on the departure from equilibrium that is maintained. Thus, if SO_2 gas, whether or not mixed with inert gas, is brought into contact with water at room temperature, the SO_2 will continue to dissolve in the water until its concentration there is approximately 60 times that in the gaseous phase. This state represents equilibrium, and no further solution of the gas will occur unless this equilibrium is disturbed. If water containing dissolved SO_2 is contacted with a gas containing less than $1/60$ as much SO_2 per unit volume as the water, SO_2 will escape from the water and pass into the gas until the ratio of the concentrations in the two phases has attained the specified equilibrium value. Therefore, if one desires to remove SO_2 from a gaseous mixture using water as the scrubbing medium, it is obvious that equilibrium sets the absolute lower limit on the amount of water necessary for this removal.

Equilibrium is established at a rate that is essentially dependent on the rate of diffusion of the solute gas through the nonabsorbed gas and through the absorbing liquid. A limit to mass transfer is reached if the two phases come to equilibrium. The net transfer of material then ceases. In industrial processes requiring high production rates, a significant deviation from equilibrium must be maintained, as the rate of mass transfer at any point is proportional to the driving force, which is the departure from equilibrium at that point. To evaluate these driving forces, a knowledge of equilibrium between phases is of basic importance. In gas absorption analysis, these phase equilibria data will be used to determine the quantity of liquid necessary to absorb the required amount of the soluble component (pollutant) from the gas stream and also to determine the height required for a given separation.

It is often possible, and frequently the case, when considering the removal of a gaseous pollutant by absorption, to assume that only the pollutant is transferred between phases. Usually both the solubility of the nondiffusing, (inert) gas in the liquid and the presence of vapor from the liquid in the gas are neglected. The important variables to be considered then are the pressure, temperature, and the concentrations of the pollutant in the liquid and the gas phase. The temperature and pressure may be fixed. The concentrations of the pollutant in the various phases are

defined from phase equilibria relationships. Equations relating the equilibrium concentrations in the two phases have been developed and are available in most thermodynamics textbooks.

Example

To determine the overall mass transfer coefficient, K_G , for the absorption of ammonia in water, special laboratory tests were performed using a 1-ft ID column packed with 5.5 ft of 1-inch Raschig rings. A mixture of ammonia and air was supplied to the bottom of the column, and the gas stream entering and leaving the column was analyzed by drawing off gas samples, absorbing the ammonia in standard acid solution, and titrating the excess acid. Water was fed to the top of the column at a measured rate, and effluent liquor from the bottom of the column was also analyzed. One of the trial runs at an air flow rate (excluding the ammonia) of 62.16 and a water rate of 100 gph resulted in the following ammonia concentrations:

- a. NH_3 gas entering column = 0.00309 lb/ft^3
- b. NH_3 gas leaving column = 0.000139 lb/ft^3
- c. NH_3 solution leaving column = 0.867 lb/ft^3

The partial pressure of NH_3 in equilibrium with the solution leaving the column was found to be 8.36 mm Hg. The average temperature was 20°C .

Calculate the overall mass transfer coefficient, K_G , in $\text{lb}_m/\text{hr-ft}^2\text{-atm}$.

Solution:

$$\text{Air} = 0.0765 \text{ lb/ft}^3$$

$$\begin{aligned} \text{Air rate in} &= 62.16 \text{ acfm} (0.0765 \text{ lb/ft}^3) (60 \text{ min/hr}) \\ &= 285 \text{ lb/hr} = 9.84 \text{ lb}_m/\text{hr} \end{aligned}$$

$$\begin{aligned} \text{or } (9.84 \text{ lb}_m/\text{hr}) (62.16) \text{ acfm} (60 \text{ min/hr}) \\ &= 0.00264 \text{ lb}_m/\text{ft}^3 \end{aligned}$$

$$\text{NH}_3 \text{ inlet: } 0.00309 \text{ lb/ft}^3 (\text{lb}_m/17 \text{ lb}) = 0.000182 \text{ lb}_m/\text{ft}^3$$

$$\text{Volume fraction} = 0.000182 / (0.00264 + 0.000182) = 0.0645$$

$$\text{NH}_3 \text{ outlet: } 0.000139 \frac{\text{lb}}{\text{ft}^3} (\text{lb}_m/17 \text{ lb}) = 0.0000081 \text{ lb}_m/\text{ft}^3$$

$$\text{Volume fraction} = 0.0000081 / (0.00264 + 0.0000081) = 0.003$$

Thus,

$$\begin{aligned} \text{Volumetric flow rate of total gas stream entering column} \\ &= (62.16 \text{ acfm}) / 0.936 = 66.44 \text{ acfm} \end{aligned}$$

$$\begin{aligned} \text{Volumetric flow rate of total gas stream leaving column} \\ &= (62.16 \text{ acfm}) / 0.997 = 62.35 \text{ acfm} \end{aligned}$$

$$\text{NH}_3 \text{ entering column} = 66.4 (0.00309) = 0.205 \text{ lb/min}$$

$$\text{NH}_3 \text{ leaving column} = 62.35 (0.000139) = 0.00867 \text{ lb/min}$$

$$\text{Net NH}_3 \text{ absorbed} = (0.205 - 0.00867) = 0.1963 \text{ lb/min}$$

Driving Force:

$$\begin{aligned}
 P_{\text{NH}_3} \text{ in gas at bottom of column} &= 0.0645(1) = 0.0645 \text{ atm} \\
 P_{\text{NH}_3} \text{ in equilibrium with exiting solution} &= \frac{8.36 \text{ mm Hg}}{760 \text{ mm Hg/atm}} \\
 &= 0.011 \text{ atm} \\
 \Delta p_1 &= 0.0535 \text{ atm} \\
 P_{\text{NH}_3} \text{ in gas at top of column} &= 0.003(1) = 0.003 \text{ atm} \\
 P_{\text{NH}_3} \text{ in equilibrium with solution entering} &= 0 \\
 \Delta p_2 &= 0.003 \text{ atm}
 \end{aligned}$$

At these low concentrations, it can be assumed that both the equilibrium and operating curves are straight lines, and the log mean partial pressure difference may be used.

$$\begin{aligned}
 &\Delta p_1 - \Delta p_2 \\
 p_m &= \frac{\Delta p_1 - \Delta p_2}{\ln(\Delta p_1/\Delta p_2)} = 0.0175 \text{ atm}
 \end{aligned}$$

$$\text{Column cross-sectional area} = 0.785 d_T^2 = 0.785 (1 \text{ ft})^2 = 0.785 \text{ ft}^2$$

$$\text{Specific area of packing} = 58 \text{ ft}^2/\text{ft}^3 \text{ (Table C-3)}$$

$$\text{Area of packing in 5.5 ft height} = (0.785) (58 \text{ ft}^2/\text{ft}^3) (5.5 \text{ ft}) = 250 \text{ ft}^2$$

$$\text{Ammonia absorbed} = \frac{(0.1963 \text{ lb/min}) (69 \text{ min/hr})}{(17 \text{ lb/lb}_m)}$$

$$= 0.693 \text{ lb}_m/\text{hr}$$

$$K_G = \frac{0.693 \text{ lb}_m \text{ NH}_3 \text{ absorbed/hr}}{(250 \text{ ft}^2) (0.0175 \text{ atm})}$$

$$= 0.1584 \text{ lb}_m/\text{hr-ft}^2\text{-atm}$$

Note: This assumes all the packing is wetted by solvent and is able to provide surface for mass transfer.

C.1.4 Experimental Mass Transfer Coefficients

In many instances, investigators have found that their data correlate quite well on the basis of some empirical relationship quite distinct from the foregoing formalized treatment and that these relationships are useful in design work for the particular system studied. Examples of such relationships are shown³² in Table C-1.

Often experimental data are correlated in terms of dimensionless numbers such as the Schmidt number ($N_{Sc} = \mu/\rho D_{AB}$) and the Reynold's number ($N_{Re} = \bar{L} v \rho/\mu$). Figure C-2^C shows³² the effect of packing diameter on mass transfer coefficient. In the absence of experimental mass transfer data, many correlations are available to estimate the mass transfer coefficient for the system being studied. In practice, when choosing a correlation, one should make every effort to match as closely as possible the system conditions under which the correlation was formulated. They, in general, apply to absorption columns loaded with various types of packings. The various types of absorption columns and the different packings utilized will be discussed in Section C.1.5.

TABLE C-1
MASS TRANSFER DATA FOR SOME SYSTEMS INVESTIGATED³²

Solute	Solvent	Packing	Size (in.)	Column diameter (in.)	Gas rate, G' (lb./hr.) (ft. ²)	Liquid rate, L' (lb./hr.) (ft. ²)	Mass transfer coefficients
Ammonia	Water	Rings	1/2	12	100 1,000	160 1,100	$k_{G,a} = 0.065 G'^{0.75} L'^{-0.35}$ $\dagger 0.311 \times 10^{-4} m$
Ammonia	Water	Rings	1	12	100 1,000	160 1,100	$k_{G,a} = 0.036 G'^{0.75} L'^{-0.35}$ $\dagger 0.1031 \times 10^{-4} m$
Ammonia	Water	Rings	1 1/2	12	100 1,000	160 1,100	$k_{G,a} = 0.014 G'^{0.75} L'^{-0.35}$ $\dagger 0.0931 \times 10^{-4} m$
Ammonia	Water	Rings	1	10	55 530	440 2,050	$k_{G,a} = 0.046 G'^{0.75} L'^{-0.4}$
Ammonia	Water	Rings	1	15	100 1,100	1,800 18,000	$k_{G,a} = 0.027 G'^{0.75} L'^{-0.35}$
Ammonia	Water	Saddles	1	15	100 1,100	1,800 18,000	$k_{G,a} = 0.013 G'^{0.75} L'^{-0.45}$
Ammonia	Water	Saddles	1	18	700	1,500	23
Ammonia	Water	Saddles	1	18	700	1,500	$k_{G,a} = (\text{constant})(G')^{0.7}(L')^{0.3}$
Ammonia	Water	Rings	3	16	20 200	500	$k_{G,a} = 0.122 G'^{0.75}$
Ammonia	Water	Spiral (partition)	4	16	20 200	500	$k_{G,a} = 0.135 G'^{0.75}$
Acetone	Water	Rings	3/8	6	203 525	470 1,150	$k_{G,a} = 0.000183 G'^{0.6} L'^{-0.74}$ $\dagger 0.0281 \times 10^{-4} m$
Acetone	Water	Rings	1/2	6	203 525	470 1,150	$k_{G,a} = 0.000118 G'^{0.6} L'^{-0.61}$ $\dagger 0.0281 \times 10^{-4} m$
Acetone	Water	Rings	3/4	10	203 525	470 1,150	$k_{G,a} = 0.000035 G'^{0.6} L'^{-0.51}$ $\dagger 0.0281 \times 10^{-4} m$
Acetone	Water	Rings	1 1/4	10	203 525	470 1,150	$k_{G,a} = 0.00139 G'^{0.6} L'^{-0.596}$ $\dagger 0.0281 \times 10^{-4} m$
Acetone	Water	Rings	1	8	65 850	900 12,000	$k_{G,a} = 0.034 L'^{-0.43}$ $\dagger 0.103 \times 10^{-4}$
Sulfur dioxide	Water	Rings	1	10	100 600	100 2,000	$k_{G,a}(50^\circ) = 0.038 L'^{-0.43}$ $\dagger 0.140$ $k_{G,a}(60^\circ) = 0.090$ $k_{G,a}(70^\circ) = 0.048 L'^{-0.35}$ $\dagger 0.028 G'^{0.6} L'^{-0.43}$ $k_{G,a}(80^\circ) = 0.05 G'^{0.6} L'^{-0.43}$ $\dagger 0.076$ $k_{G,a}(90^\circ) = 0.033 G'^{0.6}$ $\dagger 0.0435 L'^{-0.43}$

TABLE C-1 (cont.)

Solute	Solvent	Packing	Size (in.)	Column diameter (in.)	Gas rate, G' (lb/hr) (ft ²)	Liquid rate, L' (lb/hr) (ft ²)	Mass transfer coefficients	$\frac{1}{K_G} = \frac{1}{K_G^a} + \frac{1}{5000 K_L}$
Acetone, methyl ethyl ketone, methyl isobutyl ketone, and methyl n-amyl ketones	Water	Rings	0.394	4	100-700	150-3,000	$K_G^a = 0.307 D_G^{0.54} G'^{0.8}$	
Carbon dioxide	Water	Rings	3/8	2.05	58	1,500-11,000	$K_G^a = 0.523 D_G^{0.54} G'^{0.8}$	
Carbon dioxide	Water	Rings	1	10	57-314	770-9,120	$K_G^a = 0.021 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Rings	1/2	20	100	400-10,000	$K_G^a = 0.296 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Rings	1	20	100	400-10,000	$K_G^a = 0.191 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Rings	1 1/2	20	230	400-10,000	$K_G^a = 0.0958 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Rings	2	20	230	400-10,000	$K_G^a = 0.0789 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Saddles	1/2	20	100	400-30,000	$K_G^a = 0.277 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Saddles	1	20	230	400-30,000	$K_G^a = 0.195 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Saddles	1 1/2	20	230	400-30,000	$K_G^a = 0.185 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Rings	1	15	570	3,000-32,000	$K_G^a = 0.120 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Saddles	1	15	570	3,000-32,000	$K_G^a = 0.201 D_G^{0.54} G'^{0.8}$	
Oxygen	Water	Rings	1	4, 14	40-650	1,000-28,000	$K_G^a = 0.124 D_G^{0.54} G'^{0.8}$	
Water	Phosphoric Acid	Rings	1	10	128-566	210-820	$K_G^a = 0.01 G'^{0.8}$	
Benzene	Kerosene	Saddles	1	12	0-80	1,000-3,000	$K_G^a = 0.0084 G'^{0.55}$	
Trichloroethylene	Kerosene	Saddles	1	12	0-80	1,000-3,000	$K_G^a = 0.0087 G'^{0.55}$	
Chloroform	Kerosene	Saddles	1	12	0-80	1,000-3,000	$K_G^a = 0.0073 G'^{0.55}$	
Carbon tetrachloride	Kerosene	Rings	1	12	39-217	800-1,600	$K_G^a = 0.0107 G'^{0.55}$	

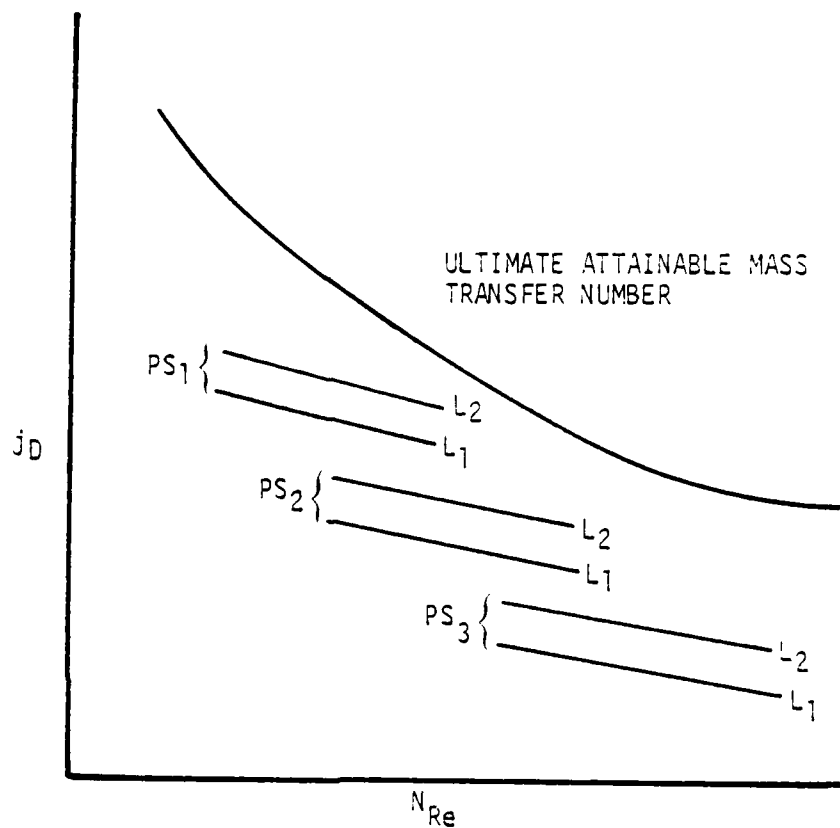


FIGURE C-2

EFFECT OF PACKING DIAMETER AND LIQUID RATE
ON GAS-FILM MASS TRANSFER COEFFICIENT ³²

(PS_1 , PS_2 , PS_3 indicate increasing packing
size; L_1 , L_2 indicate increasing liquid
flow rate)

C.1.5 Design Principles for Absorption Control Equipment

C.1.5.1 Introduction

The engineering design of gas absorption equipment must be based on the sound application of the principles of diffusion, equilibrium, and mass transfer. The main requirement in equipment design is to bring the gas into intimate contact with the liquid; that is, to provide a large interfacial area and a high intensity of interface renewal. The final choice rests with the various criteria that must be met. For example, if minimum pressure drop is a requirement, a packed column would be preferable to a plate-type column.

In most processes involving the absorption of a gaseous pollutant from an effluent gas stream, its inlet conditions (flow rate, composition, and temperature) are usually known. The temperature and composition of the inlet liquid and the composition of the outlet gas are usually specified. The main objectives, then, in the design of an absorption column are the determination of the solvent flow rate and the calculation of the principal dimensions of the equipment (column diameter and height to accomplish the operation). These objectives can be attained by evaluating, for a selected solvent at a given flow rate, the number of theoretical separation units (stages or plates) and converting them into practical units of column height or number of actual plates by means of existing correlations.

The general design procedure consists of a number of steps that have to be taken into consideration (details follow shortly):

1. solvent selection
2. equilibrium data evaluation
3. estimation of operating data (usually consisting of a mass and energy balance, where the energy balance decides whether the absorption process can be considered as isothermal or adiabatic)
4. column selection (should the column selection not be obvious or specified, calculations must be carried out for the different types of columns and the final selection based on economic consideration)
5. calculations of column diameter (for packed columns, this is usually based on flooding conditions, and for plate columns on the optimum gas velocity or the liquid-handling capacity of the plate).
6. estimation of column height or the number of plates (for packed columns, the column height is obtained by multiplying the number of transfer units, obtained from a knowledge of equilibrium and operating data, by the height of a transfer unit; for plate columns, the number of theoretical plates determined from the plot of equilibrium and operating lines is divided by the estimated overall plate efficiency to give the number of actual plates, which in turn allows the column height to be estimated from the plate spacing)

7. determination of pressure drop through the column (for packed columns, correlations dependent on packing type, column operation data, and physical properties of the constituents involved are available to estimate the pressure drop through the packing; for plate columns, the pressure drop per plate is obtained and multiplied by the number of plates).

This section considers estimation of the operating data and the important physical dimensions required for equipment design specifications.

C.1.5.2 Overall and Componential Mass and Energy Balances

The operating data to be determined or estimated are the flow rates, terminal concentrations, and terminal temperatures of the phases. The flow rates and terminal concentrations fix the operating line, while the terminal temperatures indicate to what extent the operation can be considered isothermal, that is, whether the equilibrium needs to be corrected for changes in liquid temperature. The operating line is obtained by a mass balance and the outlet liquid temperature is evaluated from an energy balance on the column.

A material balance around the column shown³² in Figure C-3 is given by:

$$(\text{total moles in}) = (\text{total moles out})$$

$$G_{m1} + L_{m2} = G_{m2} + L_{m1} \quad (\text{C.1})$$

For component A, the mass balance becomes

$$G_{m1}Y_{A1} + L_{m2}x_{A2} = G_{m2}Y_{A2} + L_{m1}x_{A1} \quad (\text{C.2})$$

or, assuming $G_{m1} = G_{m2}$ and $L_{m1} = L_{m2}$ (reasonable for most air pollution control applications where contaminant concentrations are usually extremely small), then

$$G_m Y_{A1} + L_m x_{A2} = G_m Y_{A2} + L_m x_{A1} \quad (\text{C.3})$$

and rearranging

$$\frac{L_m}{G_m} = \frac{Y_{A1} - Y_{A2}}{x_{A1} - x_{A2}} \quad (\text{C.4})$$

Equation C.4 is the equation of a straight line known as the operating line, on x, y coordinates, of slope L_m/G_m , which passes through the points (x_{A1}, y_{A1}) and (x_{A2}, y_{A2}) as indicated³² in Figure C-4.

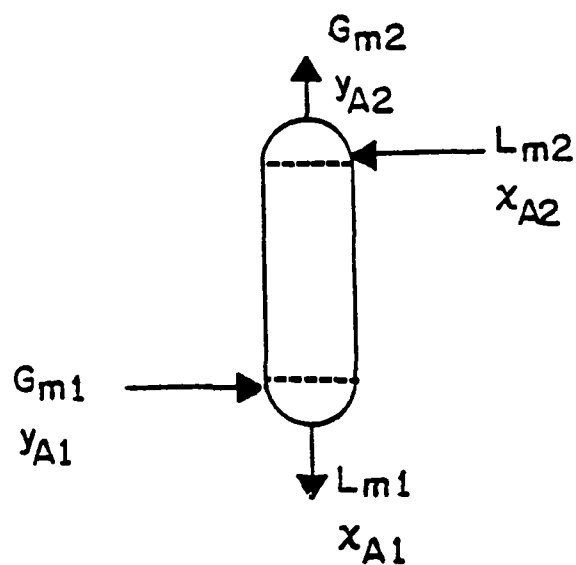


FIGURE C-3

MATERIAL BALANCE FOR ABSORPTION OF
COMPONENT A IN AN ABSORPTION COLUMN³²

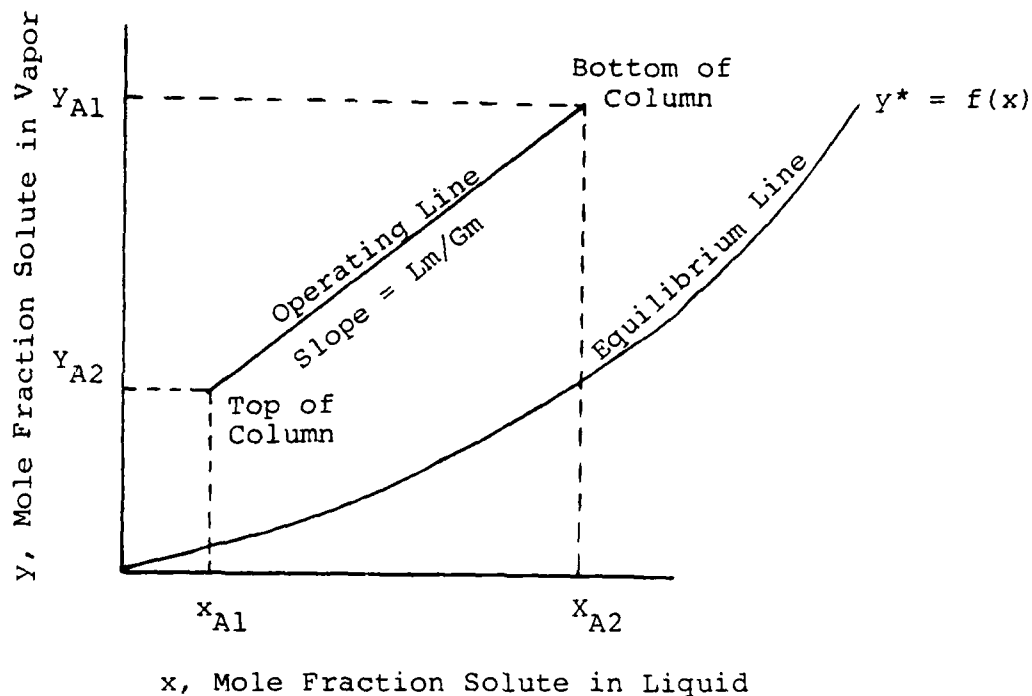


FIGURE C-4
OPERATING LINE USING MOLE FRACTION UNITS
UNDER DILUTE CONDITIONS³²

C.1.5.3 Choosing Operating Lines

In the design of most absorption columns, the quantity of gas to be treated (G_m), the terminal concentrations (y_{A1} and y_{A2}), and the composition of the entering liquid (x_{A2}) are ordinarily fixed by process requirements; however, the quantity of liquid solvent to be used is subject to some choice. Should this quantity already be specified, the operating line in Figure C-4 is fixed. If the quantity of solvent is unknown, the operating line is consequently unknown. This can be resolved by considering the minimum liquid-gas ratio.

With reference to Figure C-5(a), the operating line must pass through point A and must terminate at the ordinate y_{A1} ³². If such a quantity of liquid is used to give operating line AB, the existing liquid will have the composition x_{A1} . If less liquid is used, the exit-liquid composition will clearly be greater, as at point C, but since the driving forces for mass transfer are less,

the absorption is more difficult. The time of contact between gas and liquid must then be greater, and the absorber must be correspondingly taller. The minimum liquid that may be used corresponds to the operating line AD, which has the greatest slope for any line touching the equilibrium curve and is tangent to the curve at E. At point E, the diffusional driving force is zero, the required contact time for the concentration change desired is infinite, and an infinitely tall column results. This then represents the limiting liquid-gas ratio.

Frequently, the equilibrium curve takes the shape of that shown in Figure C-5(b)³². In this case, the minimum liquid-gas ratio corresponds to an exit-liquid concentration in equilibrium with the entering gas.

The importance of the minimum liquid-gas ratio lies in the fact that column operation is frequently specified as some factor of the minimum liquid-gas ratio. For example, a typical situation frequently encountered is that the actual operating line, $(L_m/G_m)_{act}$, is 1.5 times the minimum, $(L_m/G_m)_{min}$.

C.1.5.4 Solvent Selection

In gas absorption operations, the choice of a particular solvent is most important. Water is frequently used as it is very inexpensive and plentiful, but the following properties must also be considered:

1. gas solubility (A high gas solubility is desired since it increases the absorption rate and minimizes the quantity of solvent necessary. Generally, solvents chemically similar to the solute to be absorbed will provide good solubility.)
2. volatility (A low solvent vapor pressure is desired since the gas leaving an absorption unit is ordinarily saturated with the solvent and much may be lost if the solvent is highly volatile.)
3. corrosiveness
4. cost
5. viscosity (Low viscosity is preferred for reasons of rapid absorption rates, improved flooding characteristics, lower pressure drops, and good heat transfer characteristics.)
6. chemical stability (The solvent should be chemically stable and, if possible, nonflammable.)
7. toxicity
8. low freezing point (If possible, a low freezing point is favored since any solidification of the solvent in the column could prove disastrous.)

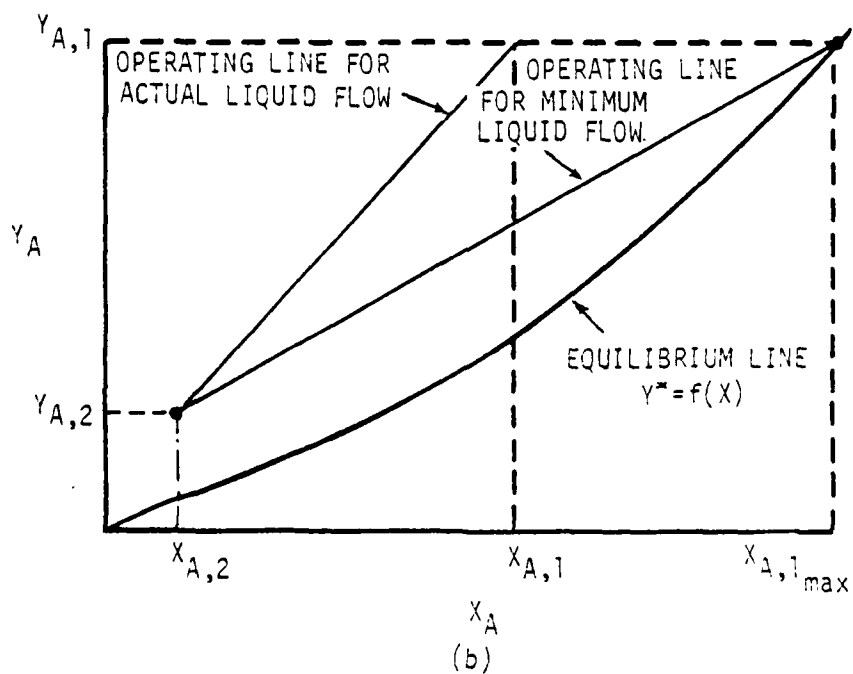
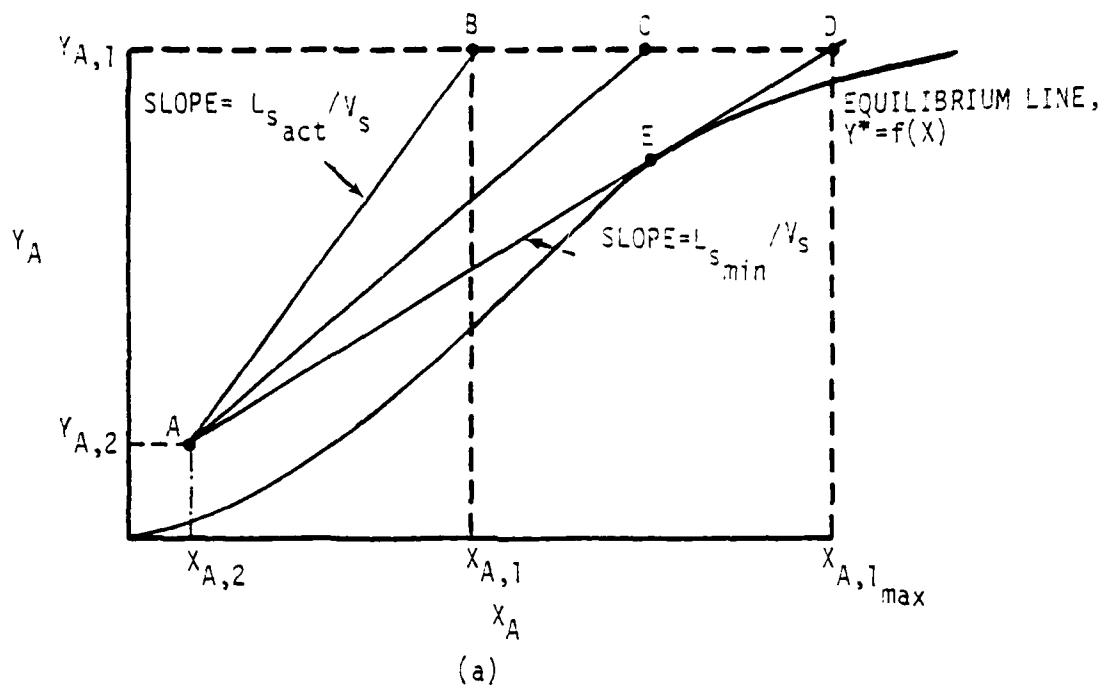


FIGURE C-5
MINIMUM LIQUID-GAS RATIO DETERMINATION³²

Once the solvent is specified, the choice and design of an absorption system may be determined.

C.1.6 Packed Columns

For the case of continuous-contact operation, the phases flow through the equipment in a continuous manner with intimate contact throughout. Equilibrium between two phases at any position in the equipment is never established.

Packed columns, used for this continuous contact of liquid and gas, are usually vertical columns filled with packing of large surface area. The liquid is distributed over and trickles down through the packed bed, thus exposing a large surface area to contact the gas. The countercurrent packed column (see Figure C-6)³² is the most common type of unit encountered in gaseous pollutant control for the removal of the undesirable gas, vapor, or odor. The gas stream (containing the pollutant) moves upwards through the packed bed against an absorbing or reacting liquor (solvent-scrubbing solution) that is injected at the top of the packing, thus resulting in the highest possible efficiency. Since the solute concentration in the gas stream decreases as it rises through the column, there is constantly fresher solvent available for contact. This provides the maximum average driving force for the diffusion process throughout the packed bed.

Occasionally, co-current flow may be used, where the gas stream and solvent both enter the top of the column. Initially, there is a very high rate of absorption that constantly decreases until, with an infinitely tall column, the gas and liquid would leave in equilibrium. In this case, high gas and liquid rates are possible since the pressure drop tends to be rather low. However, these columns are efficient only when large driving forces are available, for example, with very soluble gases or acid scrubbing in caustic media. The design for this case utilizes minimum column diameters because of the low pressure drop and nonflooding characteristics. In general, co-current flow is not often used except in the case of a very tall column built in two sections: both sections are located on the ground as shown in Figure C-7, with the second section operating in co-current flow merely as an economy measure to save on the large diameter gas pipe connecting the two.³² For an operation requiring an exceptionally high solvent flow rate, however, co-current flow might be used to prevent flooding that could occur in countercurrent operation.

Packed columns may also operate in cross flow (see Figure C-8)³² where the air stream moves horizontally through the packed bed and is irrigated by the scrubbing liquid that flows vertically down through the packing. Cross-flow designs are characterized by low solvent consumption and fairly high air flow capacity at low pressure drop. Where highly soluble gases are to be removed, the cross-flow packed scrubber has several advantages over the countercurrent scrubber. Using the same liquid and gas mass flow rates, a cross-flow scrubber has lower pressure drop. Besides reducing solvent consumption drastically, the cross-flow principle also

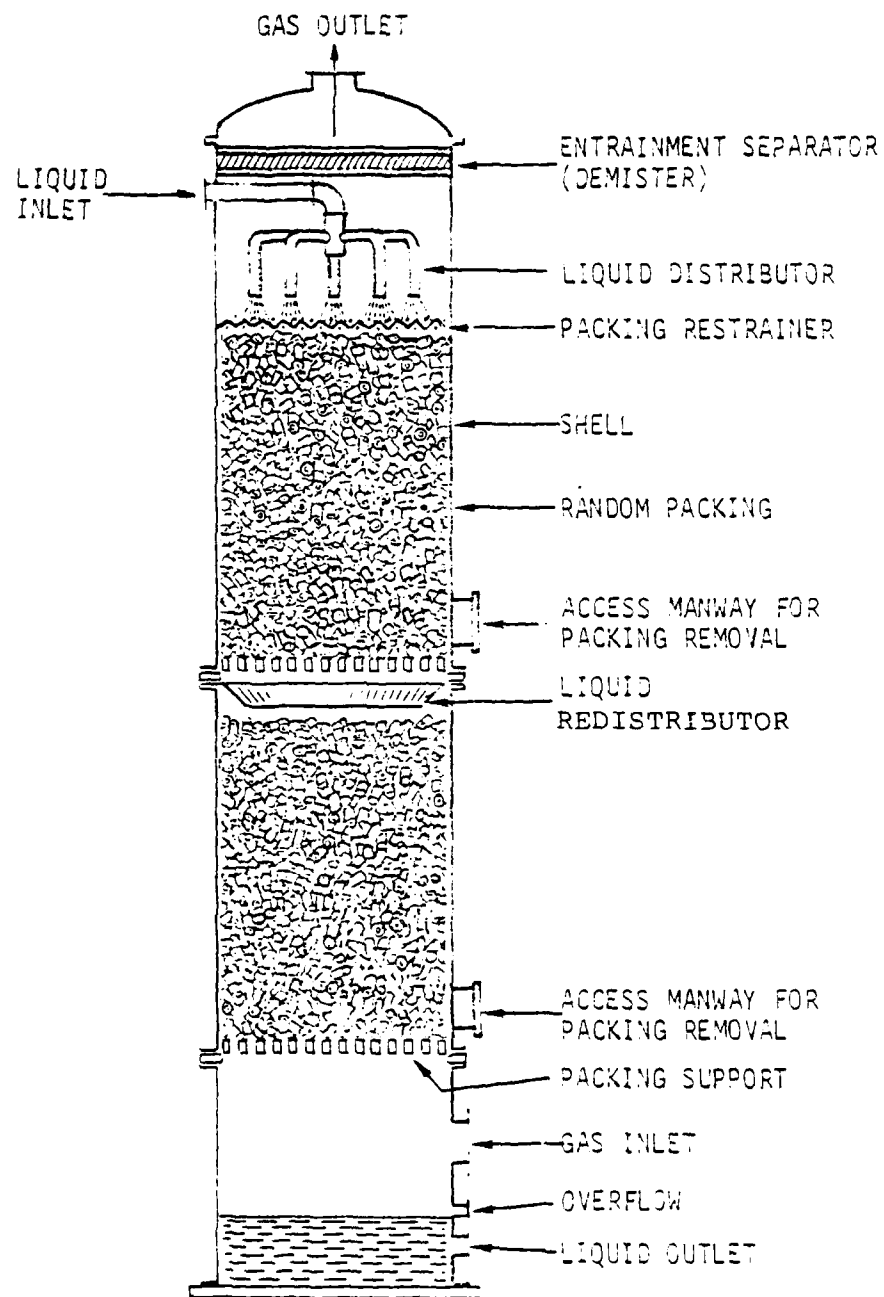


FIGURE C-6
TYPICAL COUNTERCURRENT PACKED COLUMN³²

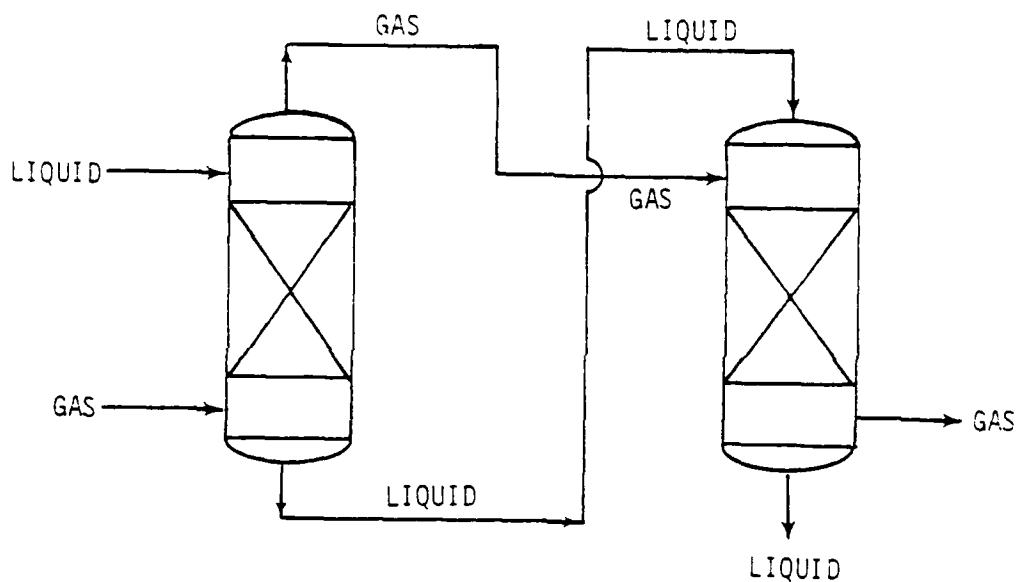


FIGURE C-7
COUNTERCURRENT-CO-CURRENT ARRANGEMENT FOR VERY TALL COLUMNS³²

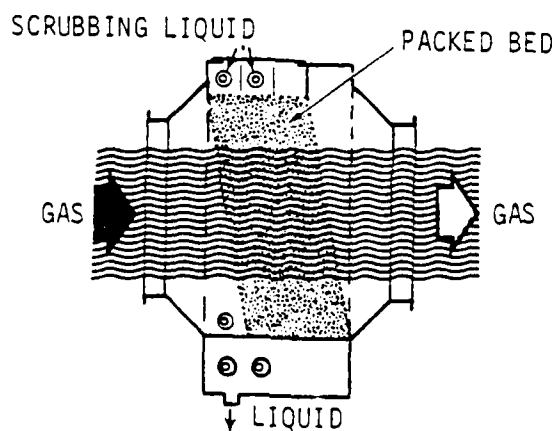


FIGURE C-8
CROSS FLOW OPERATION IN A PACKED COLUMN³²

reduces pump and fan motor sizes. Other advantages include less plugging from solids dropout at the packing support plate and the possible use of higher gas and liquid rates because of extremely low pressure drop. On the other hand, liquid entrainment from these systems is rather high and mist eliminators are usually required downstream.

Packed columns are characterized by a number of features to which their widespread popularity may be attributed:

1. minimum structure (The packed column usually needs only a packing support and liquid distributor about every 10 feet along its height.)
2. versatility (The packing material can be changed by simply dumping it and replacing it with a type giving better efficiency, lower pressure drop, or higher capacity. The depth of packing can also be easily changed if efficiency turns out to be less than anticipated or if feed or product specifications change.)
3. corrosive-fluids handling (Ceramic packing is common and often preferable to metal or plastic because of its corrosion resistance. When packing does deteriorate, it is quickly and easily replaced.)
4. low pressure drop (Unless operated at very high liquid rates, where the liquid becomes the continuous phase as its films thicken and merge, the pressure drop per linear foot of packed height is relatively low.)
5. range of operation (Although efficiency varies with gas and liquid feed rates, the range of operation is relatively broad.)
6. low investment (When plastic packings are satisfactory or when the columns are less than about 3 to 4 feet in diameter, cost is relatively low.)

C.1.6.1 Packing

The packing is the heart of the performance of this type of equipment. Its proper selection entails an understanding of packing operational characteristics and the effect on performance of the significant physical differences between the various types. The main points to be considered in choosing the column packing include:

1. durability and corrosion resistance (The packing should be chemically inert to the fluid being processed.)
2. free space per cubic foot of packed space (The free space controls the liquor holdup in the column, as well as the pressure drop across it.) Ordinarily, the frac-

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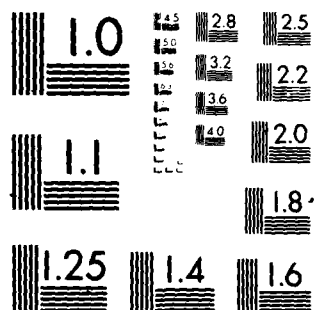
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tional void volume, or fraction of free space, in the packed bed should be large.

3. wetted surface area per unit volume of packed space (This area is very important since it determines the interfacial surface between liquid and gas. It is rarely equal to the actual geometric surface since the packing is usually not completely wetted by the fluid.)
4. frictional resistance to the flow of gas (This affects the pressure drop over the column.)
5. packing stability and structural strength to permit easy handling and installation
6. weight per cubic foot of packed space
7. cost per square foot of effective surface.

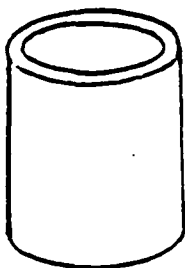
Table C-2 illustrates some of the various types of packings with their associated application features.

TABLE C-2
SOME TYPICAL PACKINGS AND APPLICATIONS³²

Packing

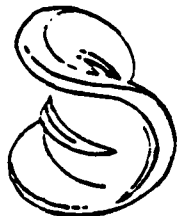
Application Features

Raschig rings



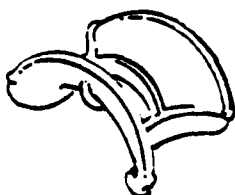
Most popular type; usually cheaper per unit cost but sometimes less efficient than others. Available in widest variety of materials to fit service. Very sound structurally. Usually packs by dumping wet or dry, with larger 4-to 6-in. sizes sometimes hand stacked. Wall thickness varies between manufacturers, also some dimensions; available surface changes with wall thickness. Produce considerable side thrust on tower. Usually has more internal liquid to walls of column.

Berl Saddles



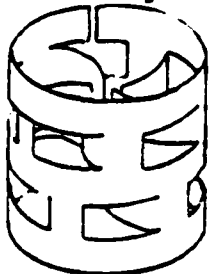
More efficient than Raschig rings in most applications, but more costly. Packing nests together and creates "tight" spots in bed, which promotes channeling but not as much as Raschig rings. Do not produce much side thrust and have lower unit pressure drops with higher flooding point than Raschig rings. Easier to break in bed than Raschig rings.

Intalox Saddles



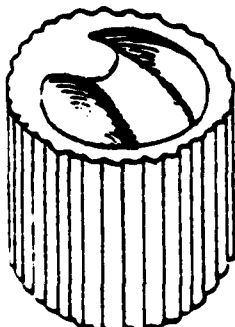
One of the most efficient packings, but more costly. Very little tendency or ability to nest and block areas of bed. Gives fairly uniform bed. Higher flooding limits and lower pressure drop than Raschig rings or Berl saddles. Easier to break in bed than Raschig rings.

Pull rings



Lower pressure drop (less than half) than Raschig rings; higher flooding limit. Good liquid distribution, high capacity. Considerable side thrust on column wall. Available in metal, plastic, and ceramic.

Spiral rings



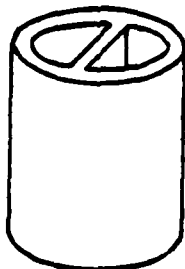
Usually installed as stacked, taking advantage of internal whirl of gas-liquid and offering extra contact surface over Raschig rings, Lessing rings, or cross-partition rings. Available in single, double, and triple internal spiral designs. Higher pressure drop. Wide variety of performance data not available.

TABLE C-2 (Cont.)

Packing

Application Features

Lessing rings



Not many performance data available, but in general slightly better than Raschig rings; pressure drop slightly higher. High side wall thrust.

Ceramic balls



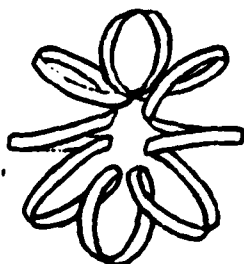
Tend to fluidize in certain operating ranges; self-cleaning, uniform bed structure, higher pressure drop, and better contact efficiency than Raschig rings. High side thrust. Not

Goodlow packing and wire mesh packing



Available in metal only, used in large and small columns for distillation, absorption, scrubbing, liquid extraction. High efficiency, low pressure drop.

Teller rosette (Tellerette)



Available in plastic; lower pressure drops, higher flooding limits than Raschig rings or Berl saddles. Very low unit weight, low side thrust. Relatively expensive.

Cross-partition rings



Usually used stacked, and as first layers on support grids for smaller packing above. Pressure drop relatively low, channeling reduced for comparative stacked packings. No side wall thrust.

Table C-3 provides some important characteristics of each.³² The difference between random and stacked packings should also be emphasized. Random packings are those simply dumped into the column during installation and allowed to fall at random; it is the most common method of packing installation. During installation prior to pouring the packing into the column, the column is first filled with water, which prevents breakage of the more fragile packing by reducing the velocity of the fall. The fall should be as gentle as possible since broken packing tightens the bed and increases pressure drop. Stacked packing, on the other hand, is specially laid out and stacked by hand, making it a tedious operation and rather costly. It is avoided where possible except for the initial layers on supports. Liquid distributed in this way usually flows straight down through the packing immediately adjacent to the point of contact.

Tables C-4 and C-5 provide the values of constants required to determine the heights of transfer units for different types of packing. Diffusion coefficients of several vapors and gases are given in Tables C-6 and C-7.

C.1.6.2 Liquid Distribution

Liquid distribution plays an important role in the efficient operation of a packed column. A good packing from the process viewpoint can be reduced in effectiveness by poor liquid distribution across the top of its upper surface. Poor distribution reduces the effective wetted packing area and promotes liquid channeling (see Figure C-9).³² The final selection of the mechanism of distributing the liquid across the packing depends on the size of the column, type of packing, tendency of packing to divert liquid to column walls, and materials of construction for distribution. For stacked packing, the liquid usually has little tendency to cross-distribute and thus moves down the column in the cross-sectional area that it enters. In the dumped condition, most packings follow a conical distribution down the column, with the apex of the cone at the liquid impingement point. For uniform liquid flow and reduced channeling of gas and liquid with as efficient use of the packed bed as possible, the impingement of the liquid onto the bed must be as uniform as possible. The liquid coming down through the packing and on the wall of the column should be redistributed after a bed depth of approximately three column diameters for Raschig rings and five to ten column diameters for saddle packings. As a guide, Raschig rings usually have a maximum 10 to 15 feet of packing per section, while saddle packing can use a maximum 12 to 20 feet. As a general rule of thumb, however, the liquid should be redistributed every 10 feet of packed height. The redistribution brings the liquid off the wall and outer portions of the column and directs it toward the center area of the column for a new start at distribution and contact in the next lower section. Redistribution is usually not necessary for stacked bed packings, as the liquid flows essentially in vertical streams.

TABLE C-3
CHARACTERISTICS OF SOME TYPICAL PACKINGS (NET & DUMP PACKED) 32

Type of packing	Material	Nominal packing size (in.)									
		1/4	3/8	1/2	5/8	3/4	1	1-1/4	1-1/2	2	3-1/2
Intalox saddles	Ceramic	F: 600	330	200	—	145	98	—	52	40	22
		e: 0.75	—	0.78	—	0.77	0.775	—	0.81	0.79	—
Raschig rings	Ceramic	a: 300	—	190	—	102	78	—	59.5	36	—
		F: 1,600 ^{a,c}	1,000 ^{a,c}	640 ^d	380 ^d	255 ^d	160 ^e	125 ^{a,f}	95 ^f	65 ^e	37 ^{a,h}
Bert saddles	Ceramic	e: 0.73	0.68	0.63	0.68	0.73	0.73	0.74	0.71	0.74	0.78
		a: 240	155	111	100	80	58	45	38	28	19
Pall rings	Plastic	F: 900 ^a	—	240 ^a	—	170 ⁱ	110 ⁱ	—	65 ⁱ	45 ^a	—
		e: 0.60	—	0.63	—	0.66	0.69	—	0.75	0.72	—
Pall rings	Metal	a: 274	—	142	—	82	76	—	44	32	—
		F: —	—	—	97	—	52	—	32	25	16
Pall rings	Metal	e: —	—	—	0.88	—	0.90	—	0.905	0.91	—
		a: —	—	—	110	—	63	—	39	31	23.4
Raschig rings 1/32-in. wall	Metal	F: —	—	—	70	—	48	—	28	20	16
		e: —	—	—	0.902	—	0.938	—	0.953	0.964	—
Raschig rings 1/16-in. wall	Metal	a: —	—	—	131.2	—	66.3	—	48.1	36.6	—
		F: 700 ^a	390 ^a	300 ^a	258	185 ^a	115 ^a	—	—	—	—
Raschig rings 1/16-in. wall	Metal	e: 0.69	—	0.84	—	0.88	0.92	—	—	—	—
		a: 236	—	128	—	83.5	62.7	—	—	—	—
Raschig rings 1/16-in. wall	Metal	F: —	—	410	290	230	137	110 ^a	83	57	32 ^a
		e: —	—	0.73	—	0.78	0.85	0.87	0.90	0.92	0.95
		a: —	—	118	—	71.8	56.7	49.3	41.2	31.4	20.6

F = Packing factor; e = Fractional void volume, ft³ voids/ft³ packed volume; a = Specific packing surface, ft²/ft³ packed volume

^a Extrapolated
^b 1/32-in. wall
^c 1/16-in. wall
^d 3/32-in. wall
^e 1/8-in. wall
^f 3/16-in. wall
^g 1/4-in. wall
^h 3/8-in. wall
ⁱ Data by Leva

TABLE C-4

CONSTANTS FOR USE IN DETERMINING GAS
FILM'S HEIGHT OF TRANSFER UNITS³²

Raschig rings	α	β	δ	Range of G^*	Range of L^*
3/8 in.	2.32	0.45	0.47	200 to 500	500 to 1,500
1 in.	7.00 6.41	0.39 0.32	0.58 0.51	200 to 800 200 to 600	400 to 500 500 to 4,500
1.5 in.	17.30 2.58	0.38 0.38	0.66 0.40	200 to 700 200 to 700	500 to 1,500 1,500 to 4,500
2 in.	3.82	0.41	0.45	200 to 800	500 to 4,500
Berl saddles					
0.5 in.	32.40 0.81	0.30 0.30	0.74 0.24	200 to 700 200 to 700	500 to 1,500 1,500 to 4,500
1 in.	1.97	0.36	0.40	200 to 800	400 to 4,500
1.5 in.	5.05	0.32	0.45	200 to 1000	400 to 4,500
3-in. partition rings	650	0.58	1.06	150 to 900	3,000 to 10,000
Spiral rings (stacked staggered)					
3-in. single spiral	2.38	0.35	0.29	130 to 700	3,000 to 10,000
3-in. triple spiral	15.60	0.38	0.60	200 to 1000	500 to 3,000
Drip-point grids					
No. 6146	3.91	0.37	0.39	130 to 1000	3,000 to 6,500
No. 6295	4.56	0.17	0.27	100 to 1000	2,000 to 11,500

* G and L are gas and liquid flow rates, respectively, lb/hr-ft²

* G and L are gas and liquid flow rates

TABLE C-5

CONSTANTS FOR USE IN DETERMINING
LIQUID FILM'S HEIGHT OF TRANSFER UNITS ³²

<u>Packing</u>	<u>ϕ</u>	<u>η</u>	<u>Range of L^*, lb/hr ft²</u>
Raschig rings			
3/8 in.	0.00182	0.46	400 to 15,000
0.5 in.	0.00357	0.35	400 to 15,000
1 in.	0.0100	0.22	400 to 15,000
1.5 in.	0.0111	0.22	400 to 15,000
2 in.	0.0125	0.22	400 to 15,000
Berl saddles			
0.5 in.	0.00666	0.28	400 to 15,000
1 in.	0.00588	0.28	400 to 15,000
1.5 in.	0.00625	0.28	400 to 15,000
3-in. partition rings	0.0625	0.09	3,000 to 14,000
Spiral rings (stacked staggered)			
3-in. single spiral	0.00909	0.28	400 to 15,000
3-in. triple spiral	0.0116	0.28	3,000 to 14,000
Drip-point grids			
No. 6146	0.0154	0.23	3,500 to 30,000
No. 6295	0.00725	0.31	2,500 to 22,000

* L is the liquid flow rate.

TABLE C-6

DIFFUSION COEFFICIENTS OF GASES AND VAPORS IN AIR AT
25°C AND 1 ATMOSPHERE³²

<u>Substance</u>	<u>D(cm²/sec)</u>	<u>$\frac{\mu}{\rho D}$</u>
Ammonia	0.236	0.66
Carbon dioxide	0.164	0.94
Hydrogen	0.410	0.22
Oxygen	0.206	0.75
Water	0.256	0.60
Carbon disulfide	0.107	1.45
Ethyl ether	0.093	1.66
Methanol	0.159	0.97
Ethyl alcohol	0.119	1.30
Propyl alcohol	0.100	1.55
Butyl alcohol	0.090	1.72
Amyl alcohol	0.070	2.21
Hexyl alcohol	0.059	2.60
Formic acid	0.159	0.97
Acetic acid	0.133	1.16
Propionic acid	0.099	1.56
i-Butyric acid	0.081	1.91
Valeric acid	0.067	2.31
i-Caproic acid	0.060	2.58
Diethyl amine	0.105	1.47
Butyl amine	0.101	1.53
Aniline	0.072	2.14
Chloro benzene	0.073	2.12
Chloro toluene	0.065	1.38
Propyl bromide	0.105	1.47
Propyl iodide	0.096	1.61
Benzene	0.088	1.76
Toluene	0.084	1.84
Ethyl benzene	0.077	2.01
Propyl benzene	0.059	2.62
Diphenyl	0.068	2.28
n-Octane	0.060	2.58
Mesitylene	0.067	2.31

TABLE C-7

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DIFFUSION COEFFICIENTS IN LIQUIDS AT 20°C

Solute ^a	$D \times 10^5$	$\frac{\mu}{\rho D}$
	(cm ² /sec) $\times 10^5$	
O ₂	1.80	558
CO ₂	1.50	570
N ₂ O	1.51	665
Cl ₂	1.76	570
Br ₂	1.22	824
H ₂	5.13	196
N ₂	1.64	613
HCl	2.64	381
H ₂ S	1.41	712
H ₂ SO ₄	1.73	580
HNO ₃	2.60	390
Acetylene	1.56	645
Acetic acid	0.88	1,140
Methanol	1.28	785
Ethanol	1.00	1,005
Propanol	0.87	1,150
Butanol	0.77	1,310
Allyl alcohol	0.93	1,080
Phenol	0.84	1,200
Glycerol	0.72	1,400
Pyrogallol	0.70	1,440
Hydroquinone	0.77	1,300
Urea	1.06	946
Resorcinol	0.80	1,260
Urethane	0.92	1,090
Lactose	0.43	2,340
Maltose	0.43	2,340
Glucose	0.60	---
Mannitol	0.58	1,730
Raffinose	0.37	2,720
Sucrose	0.45	2,230
Sodium chloride	1.35	745
Sodium hydroxide	1.51	665
CO ₂ ^b	3.40	445
Phenol ^b	0.80	1,900
Chloroform ^b	1.23	1,230
Phenol ^c	1.54	479
Chloroform ^c	2.11	350
Acetic acid ^c	1.92	384
Ethylene dichloride ^c	2.45	301

^a Solvent is water except where indicated.^b Solvent is ethanol.^c Solvent is benzene.

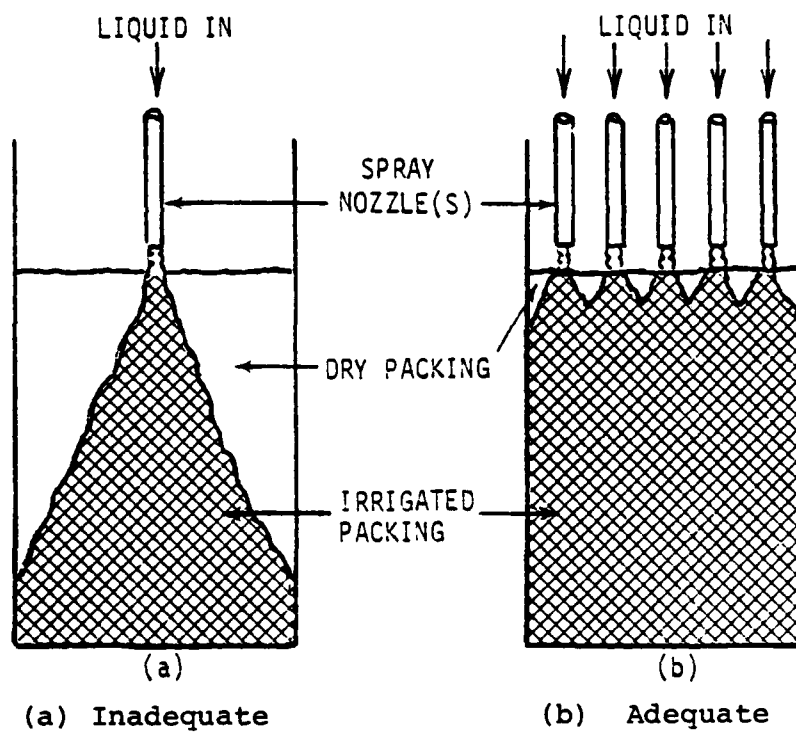


FIGURE C-9
LIQUID DISTRIBUTION AND PACKING IRRIGATION³²

C.1.7 Plate Columns

Plate columns are essentially vertical cylinders in which the liquid and gas are contacted in stepwise fashion (staged operation) on plates or trays, in a manner shown schematically for one type³² in Figure C-10. The liquid enters at the top and flows downward by gravity. On the way, it flows across each plate and through a downspout to the plate below. The gas passes upward through openings of some sort in the plate, then bubbles through the liquid to form a froth, disengages from the froth, and passes on to the next plate above. The overall effect is a multiple countercurrent contact of gas and liquid. Each plate of the column is a stage, since on the plate the fluids are brought into intimate contact, interphase diffusion occurs, and the fluids are separated. The number of theoretical plates (or stages) is dependent on the difficulty of the separation to be carried out and is determined solely from material balances and equilibrium considerations. The diameter of the column, on the other hand, depends on the quantities of liquid and gas flowing through the column per unit time. The actual number of plates required for a given separation is greater than the theoretical number due to plate inefficiency. To achieve high plate efficiencies, the contact time between gas and liquid on each plate should be long, so as to permit the diffusion to occur, the interfacial surface between phases must be as large as possible, and a relatively high degree of turbulence is required to obtain high mass transfer coefficients. In order to increase contact time, the liquid pool on each plate should be deep so that the gas bubbles will require a relatively long time to rise through the liquid. Relatively high gas velocities are also preferred for high plate efficiencies. This results in the gas being very thoroughly dispersed into the liquid and causes froth formation, which provides large interfacial surface areas. On the other hand, great depths of liquid on the plates, although leading to high plate efficiencies, result in higher pressure drop per plate. High gas velocities, although providing good vapor-liquid contact, may lead to excessive entrainment accompanied by high pressure drop. Hence, the various arrangements and dimensions chosen for the design of plate columns are usually those which experience has proven to be reasonably good compromises.

The particular plate selection and its design can substantially affect the performance of a given absorption operation. Each plate should be designed so as to give as efficient a contact between the vapor and liquid as possible, within reasonable economic limits. The principal types of plates encountered are bubble-cap plates and perforated plates.

C.1.7.1 Bubble-Cap Plates

In bubble-cap plates, the vapor rises up through "risers" into the bubble-cap, out through the slots as bubbles, and into the surrounding liquid on the plate. Figure C-11 demonstrates vapor-liquid action for a bubble-cap plate.³²

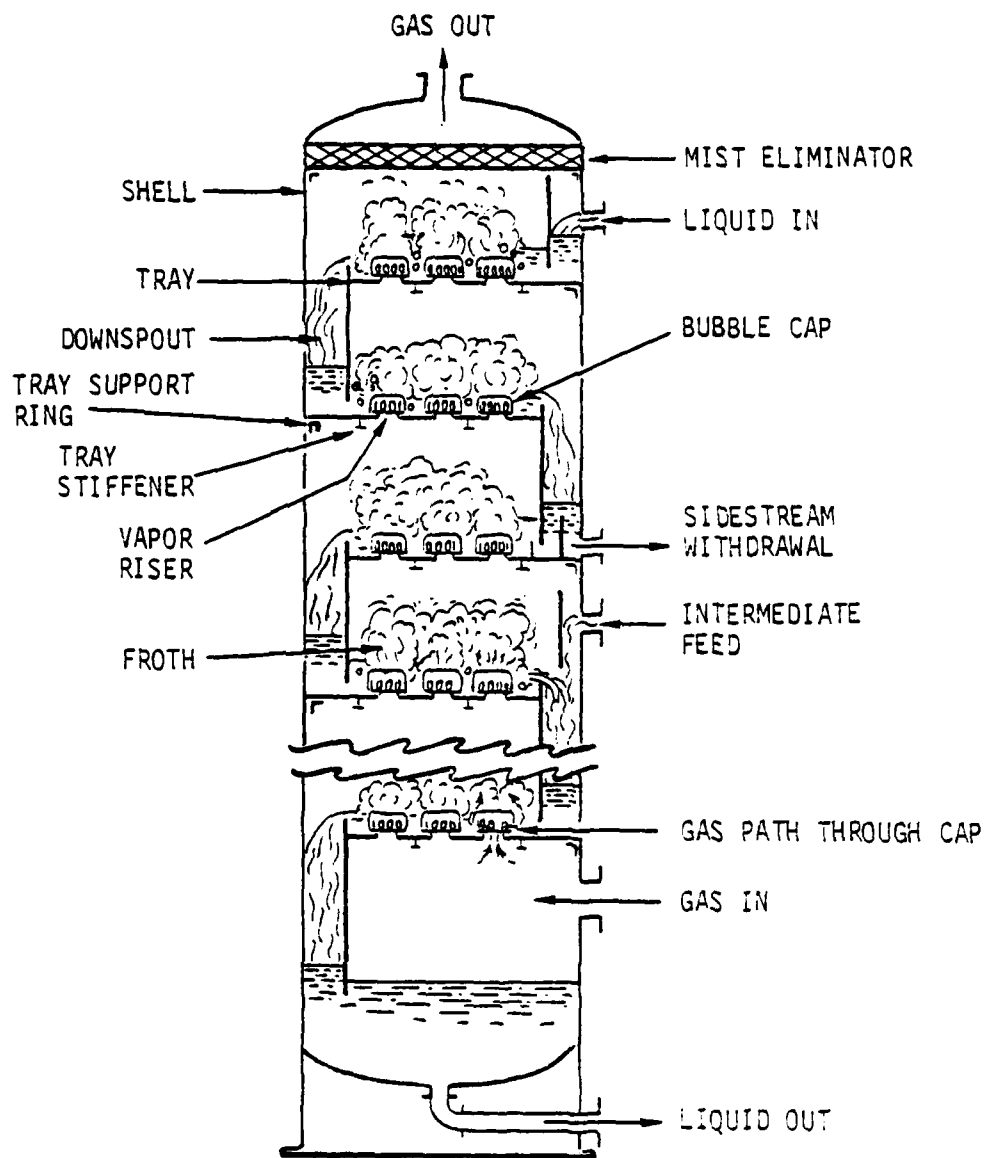


FIGURE C-10
TYPICAL BUBBLE-CAP PLATE COLUMN³²

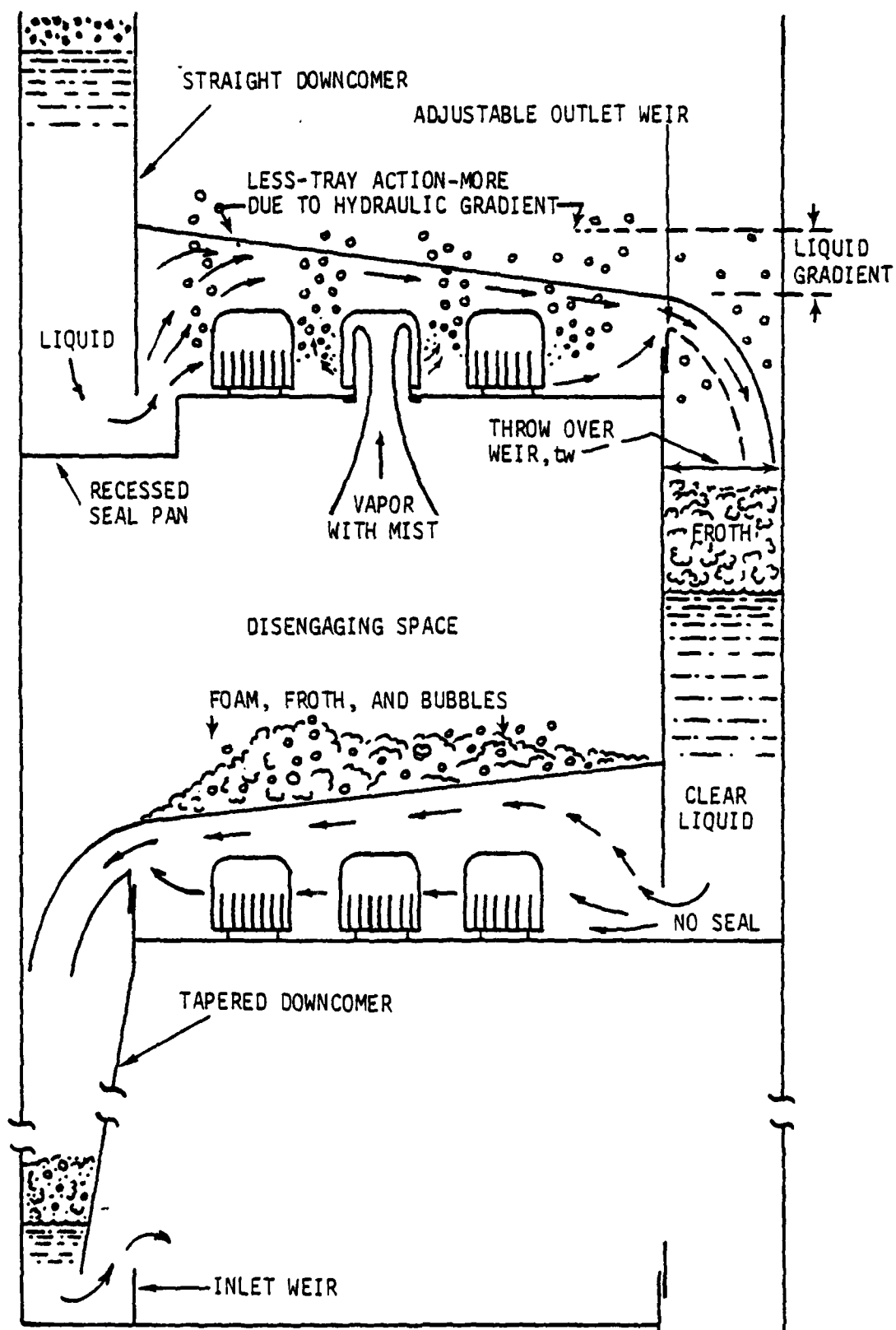


FIGURE C-11
 BUBBLE-CAP PLATE-SCHEMATIC DYNAMIC OPERATION³²
 C-35

The bubble-cap plate design is the most flexible of plate designs for varying vapor and liquid rates. On the average, plates are usually spaced approximately 18 inches apart.

C.1.7.2 Perforated or Sieve Plates

In perforated or sieve plates, the vapor rises through small holes (usually 1/8 to 1 inch in diameter) in the plate floor and bubbles through the liquid in a fairly uniform manner. The perforated plate is made with or without the downcomer. With the downcomer, the liquid flows across the plate floor and over a weir (if used), then through the downcomer to the plate below. Figure C-12 shows the operation schematically.³² The downcomers are not generally suitable for columns operating under variable load.

When the downcomers are used, plate spacing usually averages about 15 inches. In perforated plates without the downcomer, at the same time that the vapor rises through the holes, the liquid head forces liquid countercurrent through these holes and onto the plate below. In this case, 12 inches is the usual average plate spacing. In general, perforated plates are used in systems where high capacity near-design rates are to be maintained. Since they have only about one-third the entrainment of bubble-cap plates, perforated plates can be spaced closer together.

C.1.7.3 Plate Layout

The simplest plate arrangement considering fluid flow and mechanical details³² is the cross-flow shown in Figure C-13, which fits the majority of designs. When liquid flows become small with respect to vapor flows, the reverse plate is recommended; when liquid load is high with respect to vapor, the double-pass plate is suggested, as the path is cut in half and the liquid gradient reduced; and for the extremely high liquid loads, the double-pass cascade is recommended. These latter two arrangements are usually encountered only in large-diameter columns. Table C-8 may be used as a guide for tentative selection of plate type for a given capacity.³²

C.1.7.4 Constant C_F for Various Plate Types

(1) Bubble-cap plates

$$C_F = \left[-a \log \left(\frac{\bar{L}}{\bar{V}} \sqrt{\frac{\rho_G}{\rho_L}} \right) + b \right] \left[\frac{\sigma}{20} \right]^{0.2}$$

where L = superficial liquid mass velocity, lb/hr-ft²

$\bar{V}$ = superficial gas mass velocity, lb/hr-ft²

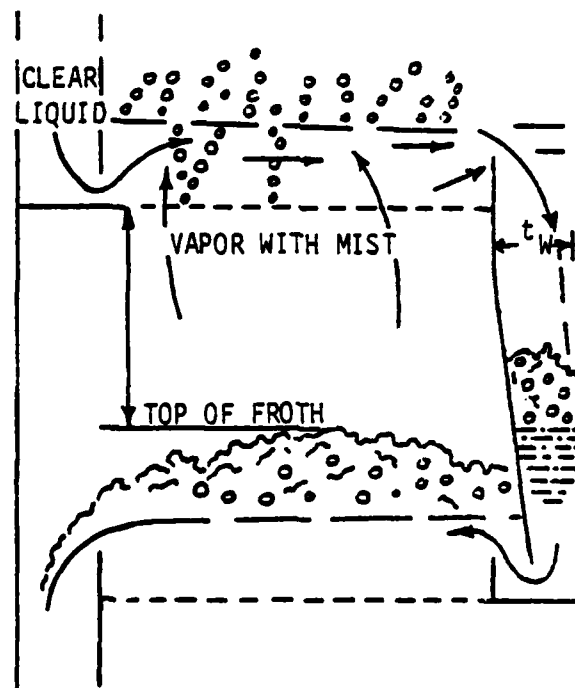
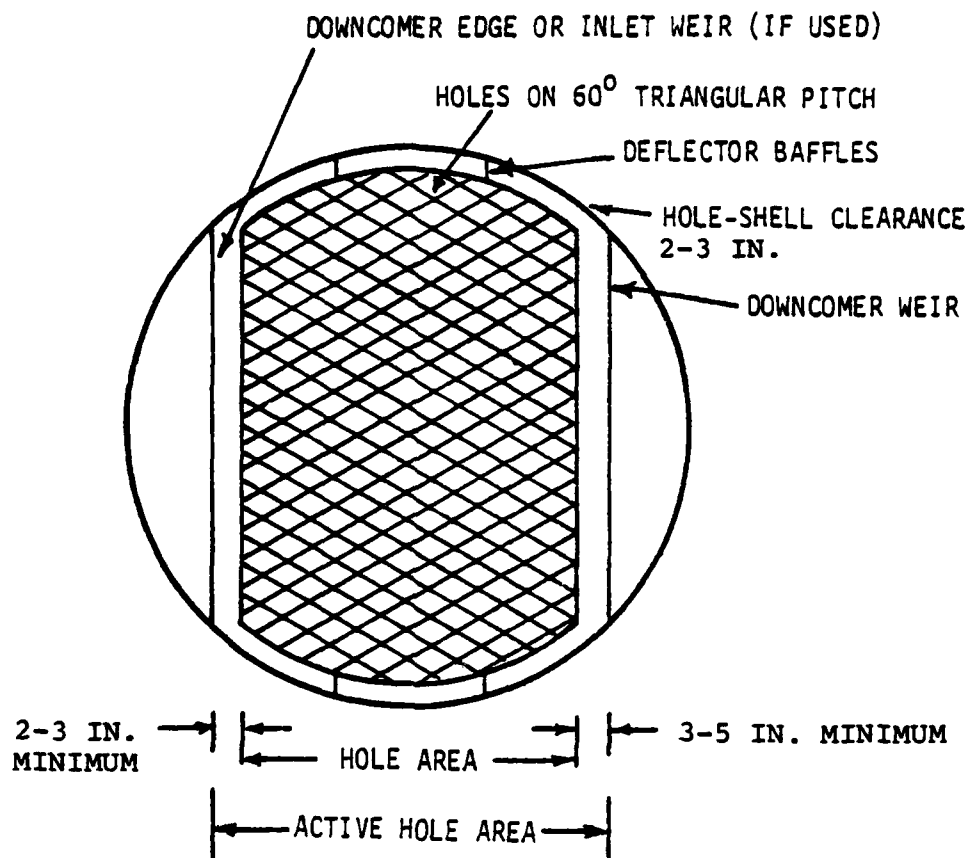


FIGURE C-12
SIEVE OR PERFORATED PLATE WITH DOWNCOMER³²

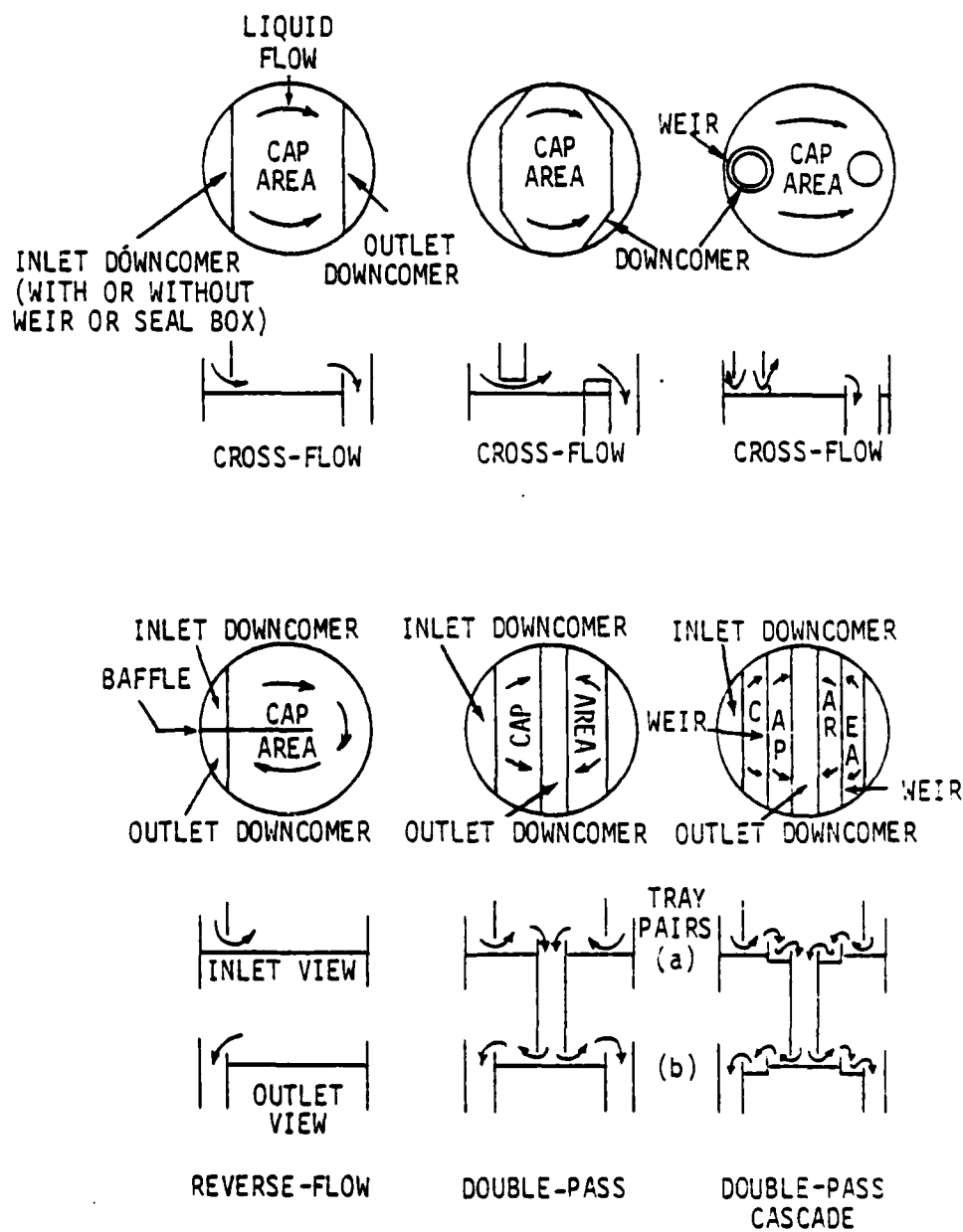


FIGURE C-13
 PLATE TYPES BY LIQUID PATHS³²

TABLE C-8
GUIDE FOR TENTATIVE SELECTION OF PLATE TYPE³²

Estimated Tower Diameter (ft)	Range of Liquid Capacity			
	Reverse Flow	Cross Flow	Double Pass	Cascade Double Pass
3	0-30	30-200	-	-
4	0-40	40-300	-	-
6	0-50	50-400	400-700	-
8	0-50	50-500	500-800	-
10	0-50	50-500	500-900	900-1,400
12	0-50	50-500	500-1,000	1,000-1,600
15	0-50	50-500	500-1,100	1,100-1,800
20	0-50	50-500	500-1,100	1,100-2,000

ρ_G = gas density, lb/ft³

ρ_L = liquid density, lb/ft³

σ = surface tension, dynes/cm

a, b = constants given in Table C-9.³²

(2) Perforated sieve plates

$$C_F = \left[-a \log \left(\frac{\bar{L}}{\bar{V}} \sqrt{\frac{\rho_G}{\rho_L}} \right) + b \right] \left[\frac{\sigma}{20} \right]^{0.2} \left[5 \frac{A_h}{A_a} + 0.5 \right]$$

where A_a = active area of the plate (taken to be that between inlet downcomer and the outlet weir on a cross flow plate)

A_h = hole area per plate.

C.1.8 Miscellaneous

There are many different types of mass transfer gas absorption equipment available in addition to the plate or packed columns mentioned previously.

C.1.8.1 Gas-sparged Vessels

The simplest method of dispersing a gas in a liquid for absorption is the injection of the gas through a perforated pipe or sparger of some type into a vessel filled with the liquid. Unless the sparger has minute perforations, the gas bubbles formed tend to be too large, resulting in a relatively small interfacial surface for the absorption operation. On the other hand, if the sparger is designed to create the necessary small bubbles, power requirements to force the gas through the small openings will be high. To increase dispersion, the gas is sometimes injected just below a rotating propeller, where the shearing action of the blade tends to break apart the larger bubbles. A mechanical agitator (Figure C-16) may also be used to increase the degree of dispersion.

In a single vessel, the advantage of true countercurrent flow cannot be fully realized since the concentration of absorbed gas in the liquid is uniform throughout the vessel, assuming that there is good agitation. Hence, absorption equivalent to only one theoretical plate (or equilibrium stage) can be achieved per vessel. Continuous operation may be obtained using multiple vessels in series where the gas and liquid travel from vessel to vessel in opposite directions.

TABLE C-9
RECOMMENDED CONDITIONS AND DIMENSIONS FOR PLATE COLUMNS³²

General

1. Plate spacing (TS):

Column diameter, D_T , ft.	TS, in.
-	6-in. minimum
4 or less	18-20
4-10	24
10-12	30
12-24	36

2. Liquid flow:

- (a) Not over 0.165 ft³/(sec) (ft diam) for
singlepass cross-flow plates
(b) Not over 0.35 ft³/(sec) (ft weir length)
for others

3. Downcomer holdup (total vol. of downspout,
ft³/ft liquid per sec): 8 sec minimum (superficial)

4. Downcomer seal: 0.5 in. minimum at no liquid flow

5. Weir length: Straight, rectangular weirs of
cross-flow plates, 0.6-0.8 D_T

6. Liquid gradient: 0.5 in. (1.25 in. maximum)

7. Pressure drop per plate:

Pressure	Pressure drop
35 mm Hg abs	3mm Hg or less
1 atm	0.07-0.12 psi
300 psi	0.15 psi

Bubble-cap Plates

1. Liquid seal:

Pressure	Seal, in.
vacuum	0.5-1.5
1 atm	1.0-2.0
50-100 psi	1.5-3.0
200-300 psi	2.0-4.0

2. Skirt clearance: 0.5 in. minimum, 1.5 in. for
dirty liquids

3. Flooding constant C_F - sections 3.2.4.2 and C-1.7.4

Range of $\left(\frac{L'}{G}\right) \left(\frac{G}{L}\right)$	a	b
0.01-0.03 (use values at 0.03)		
0.03-0.2	0.0041 TS + 0.0135	0.0047 TS + 0.068
0.20-1.0	0.0068 TS + 0.049	0.0028 TS + 0.044

Perforated Plates

1. Flooding constant C_F - sections 3.2.4.2 and C-1.7.4

Range of $\left(\frac{L'}{G}\right) \left(\frac{G}{L}\right)$	a	b
0.01-0.1 (use values at 0.1)		
0.1-1.0	0.0062 TS + 0.0385	0.00253 + 0.05

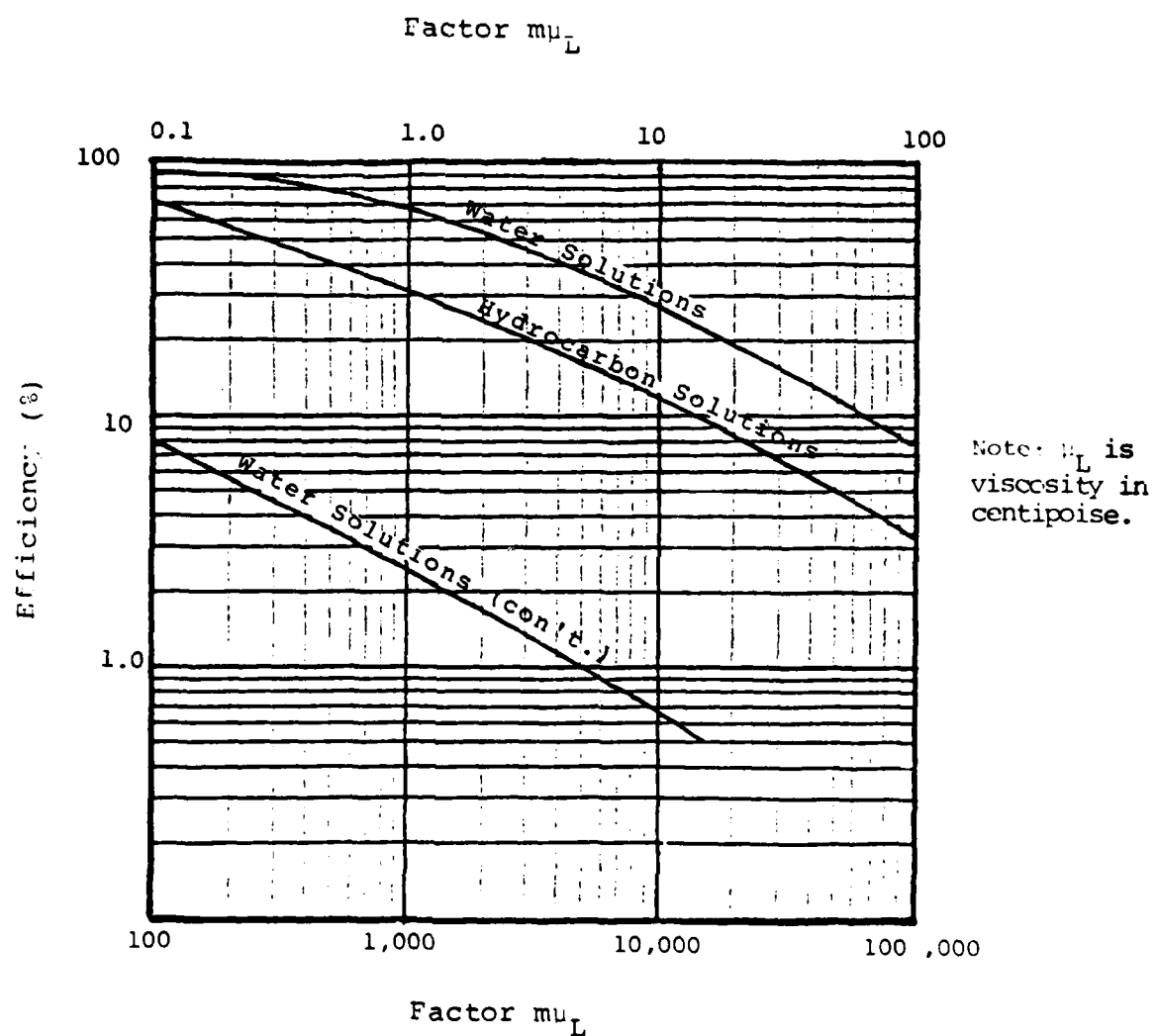


FIGURE C-14

CORRELATION OF PLATE EFFICIENCIES OF GAS ABSORBERS WITH GAS SOLUBILITY AND LIQUID VISCOSITY ACCORDING TO METHOD OF O'CONNELL³²

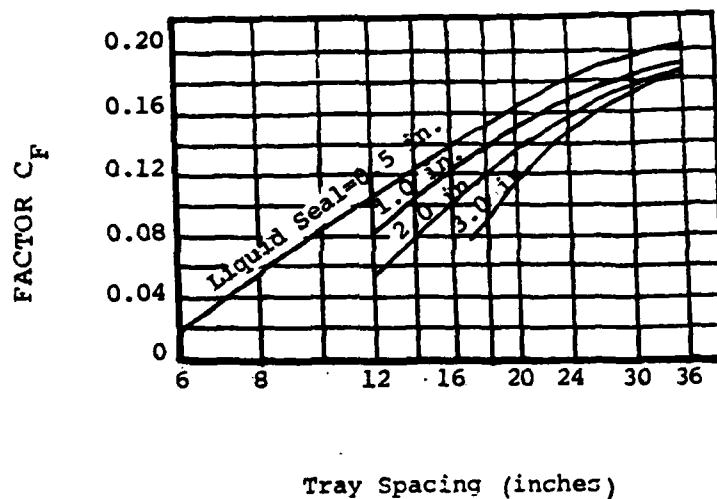


FIGURE C-15
 TRAY-SPACING CONSTANTS TO ESTIMATE
 BUBBLE-CAP TRAY TOWER'S SUPERFICIAL
 VAPOR VELOCITY³²

Gas-sparged vessels, for example, have been used to remove highly odorous gaseous products from the reaction of sulphur and sperm oil in the manufacture of specialty lubricants. Here the effluent gases, containing a considerable amount of hydrogen sulfide, are forced by their own pressure from the closed reactor, through a vent pipe fitted with a sparger, into a tank filled with caustic soda. This arrangement, without auxiliary mechanical agitation of the liquid, reduces the odor of the effluent gas to an innocuous level. Control, however, is affected primarily by chemical reaction rather than by true absorption. Another application for this type of vessel is the elimination of visible emissions from vents of hydrochloric acid storage tanks during tank loading. In this case, water or caustic soda is usually used as the liquid. In the absence of any control equipment, these hydrogen chloride emissions tend to be quite dense. The opacity can be reduced to a negligible amount by bubbling the displaced tank vapors through a simple perforated pipe into the water or caustic soda.

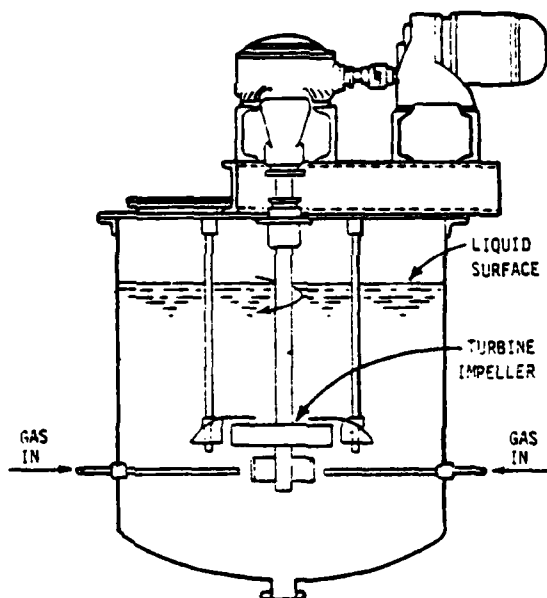


FIGURE C-16

GAS-SPARGED ABSORBER WITH MECHANICAL AGITATION³²

C.1.8.2 Spray Columns

In a simple countercurrent spray column,³² as shown in Figure C-17, the gas enters at a point near the chamber bottom and passes through the liquid introduced at the top of the chamber by means of single or multiple nozzles. In order to provide a large liquid surface for contact, relatively fine droplets are required. Hence, high pressure drops across the spray nozzles are usually encountered. There is also the danger of liquid entrainment at all except very low gas velocities. Higher gas velocities without excessive entrainment can be obtained with a centrifugal-type spray chamber,³² as illustrated in Figure C-18, where the spray droplets are forced to the chamber walls by the centrifugal action of the tangentially entering gas stream before they can be carried out through the top of the chamber. In addition to countercurrent spray columns, co-current spray columns (see Figure C-19)³² are sometimes used where the gases enter and pass down with the liquid and are withdrawn from a side connection near the vessel bottom.

In general, the performance of these units is rather poor because the droplets tend to coalesce after they have fallen through a few feet, and the interfacial area is thereby seriously reduced. Although there is considerable turbulence in the gas phase, there is little circulation of the liquid within the drops, and the resistance of the equivalent liquid film tends to be high. Spray columns are, therefore, useful only where the main resistance to mass transfer lies within the gas phase (very soluble gases).

C.1.8.3 Cascade Columns

The cascade column, shown in Figure C-20, is provided with either horizontal or conical metal sheets over which the liquid is sprayed vigorously.³² Both the surface of the liquid film and the surfaces of the streamlets and drops provide the active surface. The advantage of these columns lies in the relatively low pressure drop for the gas flow and the small influence of contaminants.

C.1.8.4 Venturi Scrubbers

The venturi scrubber, though primarily used for the removal of particulates from gas streams, also finds application in the removal of gaseous pollutants. It essentially acts as a single stage contact device and is only considered when the gas is highly soluble in the liquid solvent. The necessary interphase contact (co-current) is obtained by difference between the velocity of the gas and liquid and by turbulence created in the venturi throat. Dispersion in venturi scrubbers is achieved primarily in one of two ways--the first by injecting the liquid into the gas stream as it passes through the venturi (as shown in Figure C-21),³² and the second by admitting the gas to the liquid stream as it passes through the venturi (as shown in Figure C-22).³² Note that with both types, a gas-liquid separation chamber is necessary to prevent entrainment.

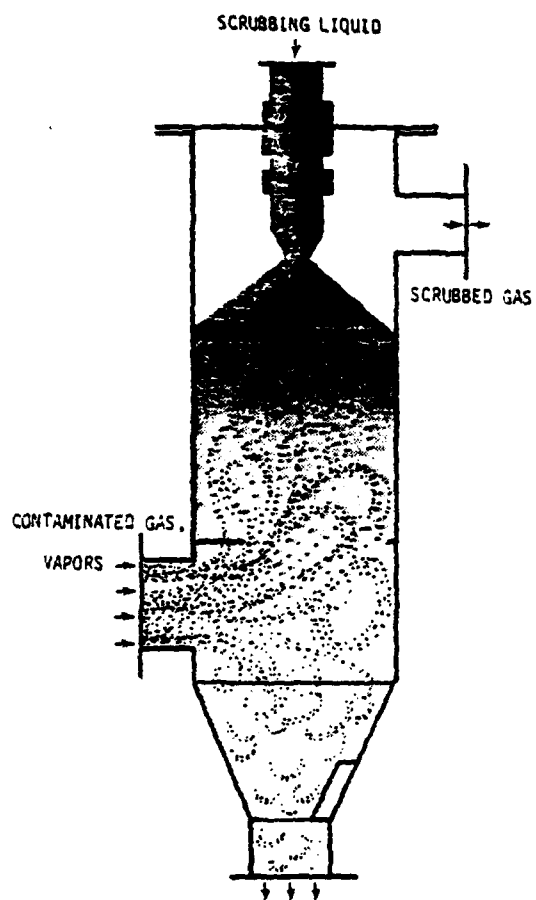


FIGURE C-17
COUNTERCURRENT SPRAY COLUMN³²

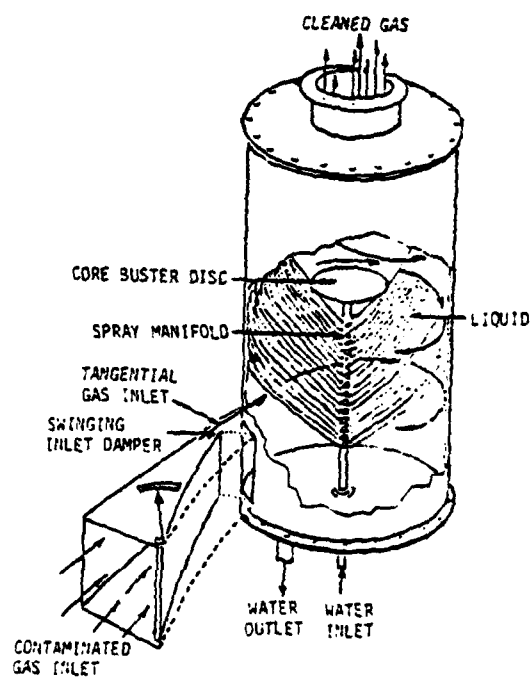


FIGURE C-18
CYCLONE SCRUBBER³²

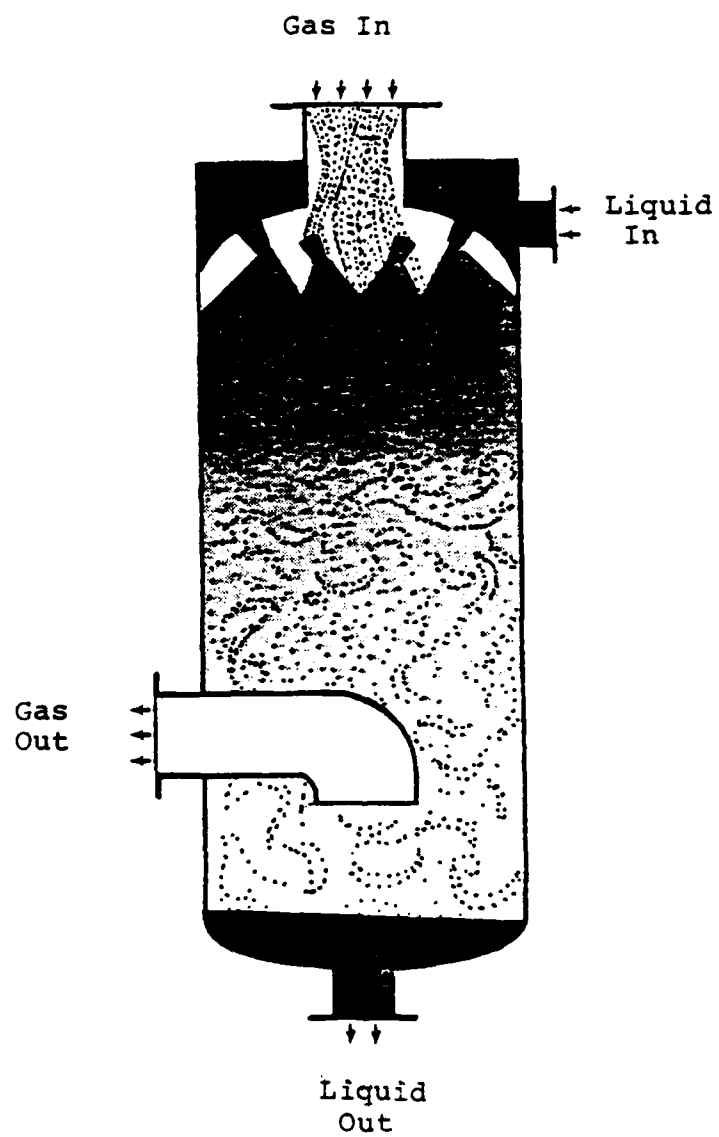


FIGURE C-19
CO-CURRENT SPRAY COLUMN³²

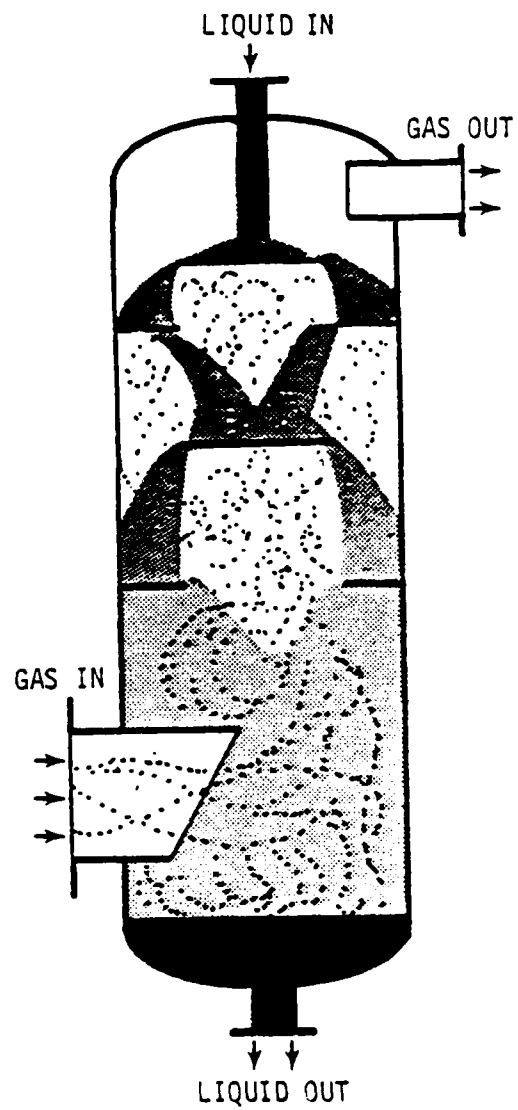
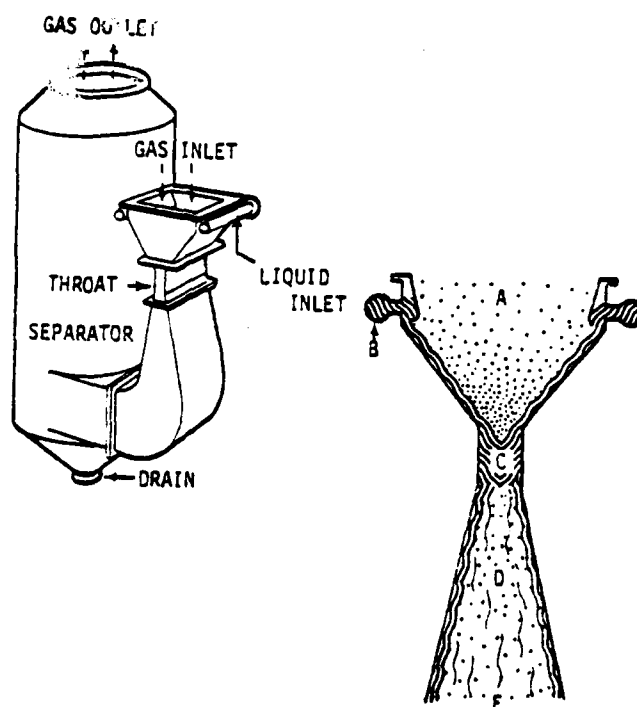


FIGURE C-20
CASCADE SCRUBBER³²



- A - The contaminated gas enters the venturi and is accelerated in the converging section.
- B - The scrubbing liquid is introduced, uniformly, at the top of the converging section and cascades by gravity and velocity pressures towards the throat.
- C - The contaminated gas and the scrubbing liquid enter the venturi throat where they are mixed at high energy and extreme turbulence.
- D - The scrubbed gas and entrained droplets (with contaminants entrapped) enter the diverging section where further collisions and agglomeration take place, creating larger drops.
- E - The gases then proceed to the separator where liquid drops are easily removed from the gas stream and are collected.

FIGURE C-21

VENTURI SCRUBBER-DISPERSION BY LIQUID INJECTION
 INTO THE GAS STREAM AS IT PASSES THROUGH THE VENTURI³²

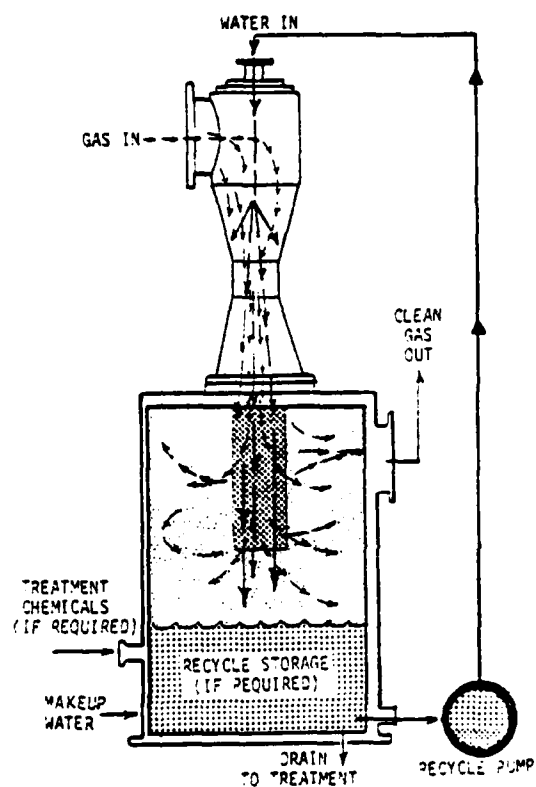


FIGURE C-22

VENTURI SCRUBBER WITH LIQUID RECYCLE-- DISPERSION BY
 ADMITTING GAS TO THE LIQUID STREAM AS IT PASSES THROUGH
 THE VENTURI³²

C.2 CONTROL BY ADSORPTION

C.2.1 Introduction

Study of adsorption of various gases (or vapors) on solid surfaces has revealed that the forces operative in adsorption are not the same in all cases. Two types of adsorption are generally recognized--physical or van der Waals adsorption and chemical or activated adsorption. Treybal³¹ offers a thorough discussion of the subject.

Physical adsorption is the result of the intermolecular forces of attraction between molecules of the solid and the substance adsorbed. When, for example, the intermolecular attractive forces between a solid and a gas (or vapor) are greater than those existing between molecules of the gas itself, the gas will condense upon the surface of the solid even though its pressure may be lower than the vapor pressure corresponding to the prevailing temperature. The adsorbed substance does not penetrate the crystal lattice of the solid and does not dissolve in it, but remains entirely upon the surface. If, however, the solid is highly porous, containing many fine capillaries, the adsorbed substance will penetrate these interstices if it wets the solid. At equilibrium, the partial pressure of the adsorbed substance equals the pressure of the contacting gas phase. By raising the temperature, the adsorbed gas is readily removed or desorbed in unchanged form.³² Physical adsorption is characterized by low heats of adsorption (on the order of 40 Btu or less per mole of adsorbate) and by the fact that the adsorption equilibrium is reversible and is established rapidly.

Chemisorption, or activated adsorption, is the result of chemical interaction between the solid and the adsorbed substance.³² Chemisorption is also accompanied by much higher heat changes (varying from 80 to as high as 400 Btu). Chemisorption is of particular importance in catalysis, but will not be considered here.

C.2.2 Nature of Adsorbents

Although it is probable that all solids adsorb gases (or vapors) to some extent, adsorption as a rule is not very pronounced unless an adsorbent possesses a large surface for a given mass. For this reason, such adsorbents as silica gel, charcoals, and molecular sieves are particularly effective as adsorbing agents. These substances have a very porous structure and, with their large exposed surfaces, can take up appreciable volumes of various gases. The extent of adsorption can be increased further by activating the adsorbent in various ways. Wood charcoal can be activated by heating between 350° to 1,000°C in a vacuum or in air, steam, and certain other gases to a point where the adsorption of carbon tetrachloride, for example, at 24°C can be increased from 0.011 to 1.48 grams per gram of charcoal. The activation apparently involves distilling out hydrocarbon impurities from charcoal, which leads to exposure of a larger surface free for possible adsorption.

The amount of gas (or vapor) adsorbed by a solid depends on the natures of the adsorbent and the gas being adsorbed, the surface area of the adsorbent, the temperature, and the pressure of the gas. As may be expected, an increase in the surface area of adsorbent increases the total amount of gas adsorbed. Since this adsorbent surface area cannot always be readily determined, common practice is to employ the adsorbent mass as a measure of the surface available and to express the amount of adsorption per unit mass of adsorbing agent used.

A concept that becomes especially important in determining adsorbent capacity is that of "available" surface, that is, surface area accessible to the adsorbate molecule. It is apparent from pore size distribution data that the major contribution to surface area is pores of molecular dimensions. It seems logical to assume that a molecule, because of steric effects, will not readily penetrate into a pore smaller than a certain minimum diameter--hence, the concept that molecules are "screened out." This minimum diameter is the so-called critical diameter and is characteristic of the adsorbate and is related to molecular size. The critical diameters of some common molecules are given in Table C-10. Thus, for any molecule, the effective surface area for adsorption can exist only in pores that the molecule can enter.

Because of the irregular shape of both pores and molecules, and also because of constant molecular motion, the fine pores are not blocked by the large molecules but are open for entry by small molecules. Also, the greater mobility of the smaller molecule should permit it to diffuse ahead of the larger molecule and penetrate the fine pores first.

C.2.3 Adsorption - Desorption Cycle

Figure C-23 presents a schematic diagram of an adsorption bed with regeneration facility.

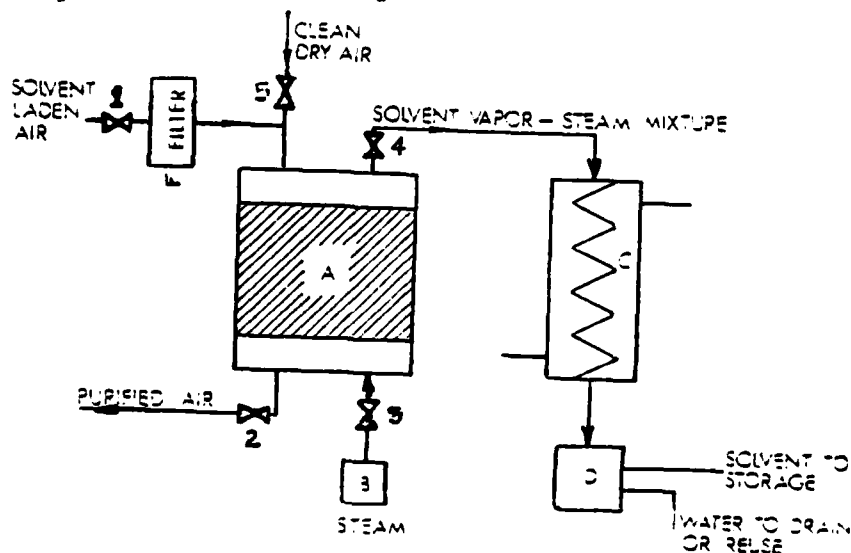


FIGURE C-23

ADSORPTION BED WITH REGENERATION FACILITY

TABLE C-10
CRITICAL DIMENSIONS OF SOME MOLECULES³²

<u>Molecule</u>	<u>Critical Diameter (Å)</u>
Helium	2.0
Hydrogen	2.4
Acetylene	2.4
Oxygen	2.8
Carbon monoxide	2.8
Carbon dioxide	2.8
Nitrogen	3.0
Water	3.15
Ammonia	3.8
Argon	3.84
Methane	4.0
Ethylene	4.25
Ethylene oxide	4.2
Ethane	4.2
Methanol	4.4
Ethanol	4.4
Cyclopropane	4.75
Propane	4.89
n-Butane to n-C ₂₂ H ₄₆	4.9
Propylene	5.0
Butene-1	5.1
Butene-2 Trans.	5.1
1,3-Butadiene	5.2
Chlorodifluoromethane (R-22)	5.3
Thiophene	5.3
i-Butane to i-C ₂₂ H ₄₆	5.58
Dichlorofluoromethane (R-12)	5.93
Cyclohexane	6.1
Toluene	6.7
p-Xylene	6.7
Benzene	6.8
Carbon tetrachloride	6.9
Chloroform	6.9
Neopentane	6.9
m-Xylene	7.1
o-Xylene	7.4
Triethylamine	8.4

TABLE C-11
BASIC TYPES OF LINDS MOLECULAR SIEVES¹²

Nominal Diameter (A)	Available Form	Bulk Density (lb/ft ³)	Heat of Adsorption (max) (Btu/lb H ₂ O)	Equilibrium H ₂ O Capacity (wt %)	Molecules Adsorbed	Molecules Excluded	Applications
3	Powder 1/16-in. Pellets 1/8 in. Pellets	30 47 47	1,800	23 20 20	Molecules with an effective diameter <1 A, including H ₂ O and NH ₃	Molecules with an effective diameter >3 A, e.g., ethane	The preferred molecular sieve adsorbent for the commercial dehydration of unsaturated hydrocarbon streams such as cracked gas, propylene, butadiene, and acetylene. It is also used for drying polar liquids such as methanol and ethanol.
4	Powder 1/16-in. Pellets 1/8-in. Pellets 8 x 12 Beads 4 x 8 Beads 14 x 10 Mesh	30 45 45 45 45 44	1,800	28.5 22 22 22 22 22	Molecules with an effective diameter <4 A, including ethanol, H ₂ S, CO, SO ₂ , C ₂ H ₄ , C ₂ H ₆ , and C ₃ H ₆	Molecules with an effective diameter >4 A, e.g., propane	The preferred molecular sieve adsorbent for static dehydration in a closed gas or liquid system. It is used as static desiccant in household refrigeration systems, in packaging of drugs, electronic components, and perishable chemicals, and as a water scavenger in paint and plastic systems. Also used commercially in drying saturated hydrocarbon streams.
5	Powder 1/16-in. Pellets 1/8 in. Pellets	30 43 43	1,800	28 21.5 21.5	Molecules with an effective diameter <5 A, including n-C ₄ H ₁₀ , n-C ₄ H ₈ , C ₃ H ₈ to C ₂₂ H ₄₄ , N ₂	Molecules with an effective diameter >5 A, e.g., also compounds and all 4 carbon rings	Separates normal paraffin from branched-chain and cyclic hydrocarbons through a selective adsorption process.
8	Powder 1/16-in. Pellets 1/8 in. Pellets	30 36 36	1,800	36 28 28	Low paraffins and olefins, C ₂ H ₆ , molecules with an effective diameter <8 A	High-n-butylamine and larger	Aromatic hydrocarbon separation.
10	Powder 1/16-in. Pellets 1/8 in. Pellets	30 38 38	1,800	36 28.5 28.5	Molecules with an effective diameter <10 A	Molecules with an effective diameter >10 A, e.g., (C ₁ F ₉) ₃ N	Used commercially for general gas drying, air plant feed purification (simultaneous removal of H ₂ O and CO ₂), and liquid hydrocarbon and natural gas sweetening (H ₂ S and mercaptan removal).

TABLE C-12
EFFICIENCY OF CARBON ADSORPTION AND LELS FOR
COMMON POLLUTANTS

<u>Pollutant</u>	<u>Lower Explosive Limit (percent by volume in air</u>	<u>Carbon Adsorp- tion Efficiency (percent)</u>
Acetone	2.15	8
Benzene	1.4	6
n-Butyl acetate	1.7	8
n-Butyl alcohol	1.7	8
Carbon tetrachloride	n	10
Chloroform	n	10
Cyclohexane	1.31	6
Ethyl acetate	2.2	8
Ethyl alcohol	3.3	8
Heptane	1	6
Hexane	1.3	6
Isobutyl alcohol	1.68	8
Isopropyl acetate	2.18	8
Isopropyl alcohol	2.5	8
Methyl acetate	4.1	7
Methyl alcohol	6.0	7
Methylene chloride	n	10
Methyl ethyl ketone	1.81	8
Methyl isobutyl ketone	1.4	7
Perchloroethylene	n	20
Toluene	1.27	7
Trichlorethylene	n	15
Trichloro trifluoroethane	n	8
V M & P Naptha	0.81	7
Xylene	1.0	10

Efficiencies are based on 200 cfm of 100°F solvent-laden air, with no other impurities per hundred pounds of carbon per hour. Solvent recovery is 90-95%. Concentrations of solvent will alter efficiencies somewhat, but for estimating purposes those figures are satisfactory for 25 ppm and greater. See Section for the use of this table. Source: Hoyt Manufacturing.

The steps of an adsorption-desorption cycle are discussed below.

Adsorption. Valves 1 and 2 are open. Valves 3, 4, and 5 are closed. Air containing vapor is passed through "F", prefiltration system for removal of solid particles, then through activated charcoal bed "A" for adsorption of the solvent vapors. The purified air is then exhausted or returned for reuse.

Desorption. After the activated charcoal has become saturated, Valves 1 and 2 are closed and Valves 3 and 4 are opened. Steam from boiler B heats the activated charcoal bed and strips the solvent vapor. The solvent vapor-steam mixture is passed through Condenser C. The condensate then drains into the decanter D for separation (immiscible solvent).

Drying. Valves 1, 3, and 4 are closed and Valves 2 and 5 are opened. Clean, dry air is passed over the activated charcoal bed to remove excess moisture. The entire cycle is then repeated.

C.2.4 Types of Adsorbents

C.2.4.1 Activated Carbon

Charcoal, an inefficient form of activated carbon, is obtained by the carbonization of wood. Various raw materials have been used in the preparation of adsorbent chars, resulting in the development of active carbon, a much more adsorbent form of charcoal. Industrial manufacture of activated carbon currently is largely based on nut shells or coal, which are subjected to heat treatment in the absence of air; in the case of coal, heat treatment is followed by steam activation at high temperatures. Other substances of a carbonaceous nature, also used in the manufacture of active carbons, include wood, coconut shells, peat, and fruit pits.

Some approximate properties of typical granular gas (or vapor) adsorbent carbons include:

Bulk density	22-34 lb/ft ³
Heat capacity	0.27-0.36 Btu/lb-°F
Pore volume	0.56-1.20 cm ³ /g
Surface area	600-1,600 m ² /g
Average pore diameter	15-25 Å
Regeneration temperature (steaming)	100°-140°C
Maximum allowable temperature	150°C

Gas (or vapor) adsorbent carbons find primary application in solvent recovery (hydrocarbon vapor emissions), odor elimination, and gas purification.

C.2.4.2 Activated Alumina

Activated alumina (hydrated aluminum oxide) is produced by special heat treatment of precipitated or native aluminas or bauxite. It is available in either granular or pellet form with the following typical properties:

Density in bulk:	granules	38-42 lb/ft ³
	pellets	54-58 lb/ft ³
Specific heat		0.21-0.25 Btu/lb-°F
Pore volume		0.29-0.37 cm ³ /g
Surface area		210-360 m ² /g
Average pore diameter		18-48°A
Regeneration temperature		200°-250°C
Stable up to		500°C

Activated alumina is mainly used for the drying of gases, particularly under pressure.

C.2.4.3 Silica Gel

The manufacture of silica gel consists of the neutralization of sodium silicate by mixing with dilute mineral acid, washing the gel then formed free of salts produced during the neutralization reaction, followed by drying, roasting, and grading processes. The name gel arises from the jellylike form of the material during one stage of its production. It is generally used in granular form, although bead forms are available. The material has the following typical physical properties:

Bulk density	44-46 lb/ft ³
Heat capacity	0.22-0.26 Byu/lb-°F
Pore volume	0.37 cm ³ /g
Surface area	750 m ² /g
Average pore diameter	22°A
Regeneration temperature	120°-250°C
Stable up to	400°C

Silica gel also finds primary use in gas drying, although it also finds application in gas desulfurization and purification.

C.2.4.4 Molecular Sieves

Unlike the amorphous adsorbents--activated carbon, activated alumina, and silica gel--molecular sieves are crystalline, being essentially dehydrated zeolites, i.e., alumino-silicates in which atoms are arranged in a definite pattern. The complex structural units of molecular sieves have cavities at their centers to which access is by pores or windows. For certain types of crystalline zeolites, these pores are precisely uniform in diameter. Due to the crystalline porous structure and precise uniformity of the small pores, adsorption phenomenon only takes place with molecules small enough and of suitable shape to enter the cavities through the pores.

The sieves are manufactured by hydrothermal crystal growth from aluminosilicate gels followed by specific heat treatment to effect dehydration; they have the following typical properties:

	<u>Anhydrous Sodium Alumino- silicate</u>	<u>Anhydrous Calcium Alumino- silicate</u>	<u>Anhydrous Alumino- silicate</u>
<u>Type</u>	4 A	5 A	13 X
Density in bulk (lb/ft ³)	44	44	38
Specific heat (Btu/lb °F)	0.19	0.19	-
Effective diameter of pores (°A)	4	5	13
Regeneration temperature	200°-300°C	200°-300°C	200°-300°C
Stable up to (short period)	600°C	600°C	600°C

Some of the other basic types and properties of molecular sieves are presented in Table C-11 along with their applications.³²

C.2.5 The Adsorption Process

The adsorption process involves three necessary steps. The fluid must first come in contact with the adsorbent, at which time the adsorbate is preferentially, or selectively, adsorbed on the adsorbent. Next, the unadsorbed fluid must be separated from the adsorbent-adsorbate; finally, the adsorbent must be regenerated by removing the adsorbate or discarding used adsorbent and replacing it with fresh material. Regeneration is performed in a variety of ways, depending on the nature of the adsorbate. Gases

or vapors are usually desorbed by either raising the temperature (thermal cycle) or reducing the pressure (pressure cycle) of the adsorbent-adsorbate. The more popular thermal cycle is accomplished by passing hot gas through the adsorption bed in the opposite direction to the flow during the adsorption cycle. This procedure ensures that the gas passing through the unit during the adsorption cycle always meets the most active adsorbent last and that the adsorbate concentration in the adsorbent at the outlet end of the unit is always maintained at a minimum.

C.2.6 Design Principles

C.2.6.1 Selection of Adsorbent

Industrial adsorbents are usually capable of adsorbing both organic and inorganic gases or vapors. However, their preferential adsorption characteristics and other physical properties make each one more or less specific for a particular application. General experience has shown that for the adsorption of vapors of an organic nature, activated carbon has superior properties, having hydrocarbon selective properties and high adsorption capacity for such materials. Inorganic adsorbents, such as activated alumina or silica gel, can also be used to adsorb organic materials, but difficulties can arise during regeneration. Activated alumina, silica gel, and molecular sieves will also adsorb any water vapor preferentially to the organic contaminant. At times, this may be a considerable drawback in the application of these adsorbents for organic contaminant removal.

The normal method of regeneration of adsorbents is by use of steam, hot air, nitrogen, or other gas streams; this method can cause, in the majority of cases, at least slight decomposition of the organic compound on the adsorbent. Two difficulties therefore arise: first, the incomplete recovery of the adsorbate, although this may be unimportant; second, the adsorbent progressively deteriorates in capacity as the number of cycles increases due to blocking of the pores from carbon formed by hydrocarbon decomposition. With activated carbon, a steaming process is used and the difficulties of regeneration are thereby overcome. This is not feasible with silica gel or activated alumina because of the risk of breakdown of these materials when in contact with water.

Adsorption takes place at the interphase boundary; therefore, the adsorbent surface area is an important factor. Generally, the higher the adsorbent surface area, the greater its adsorption capacity. However, the surface area has to be available in a particular pore size within the adsorbent. At low partial pressure (or concentration), the surface area in the smallest pores in which the adsorbate can enter is the most efficient. At higher pressures, the large pores become more important, while at very high concentrations, capillary condensation will take place within the pores, and the total micropore volume is the limiting factor. The action of molecular sieves is slightly different from that of other adsorbents because selectivity is determined more by pore size limitations

of the molecular sieve. In selecting molecular sieves, it is important that the contaminant molecule to be removed be smaller than the available pore size. Hence, the particular adsorbent should not only have an affinity for the contaminant in question, but also have sufficient surface available for adsorption.

C.2.6.2 Design Data

Having chosen the adsorbent, the next step will be to calculate the quantity of adsorbent required, and eventually consider other factors such as temperature rise of the gas stream due to adsorption and what the useful life of the adsorbent might be under operating conditions. The sizing and overall design of the adsorption system depend on the properties and characteristics of both the feed gas to be treated and the adsorbent. The following information is required for design purposes.

A. Gas Stream

1. Adsorbate concentration
2. Temperature
3. Temperature rise during adsorption
4. Pressure
5. Flow rate
6. Presence of adsorbent contaminant material
7. Gas density at operating temperature and pressure
8. Gas viscosity at operating temperature and pressure

B. Adsorbent

1. Adsorption capacity as used on-stream
2. Temperature rise during adsorption
3. Isothermal or adiabatic operation
4. Life, if presence of contaminant material is unavoidable
5. Possibility of catalytic effects causing adverse chemical reaction in the gas stream or formation of solid polymerizates on the adsorbent bed, with consequent deterioration
6. Bulk density
7. Particle size (usually reported as a mean equivalent particle diameter). The dimensions and shape of particles affect both the pressure drop through the adsorbent bed and the diffusion rate into the particles. All things being equal, adsorbent beds consisting of smaller particles will cause a higher pressure drop and will be more efficient.
8. Pore data. They may permit elimination from consideration of adsorbents whose pore diameter will not admit the desired adsorbate molecule.

9. Hardness. It indicates the care that must be taken in handling adsorbents to prevent the formation of undesirable fines.

10. Regeneration information.

The adsorbent is generally used in a fixed bed through which the contaminated air is passed. Depending on the concentration and market value, the contaminant is either recovered or discarded when the loading of the adsorbent requires regeneration. It is now necessary to evaluate the dynamic capacity of an adsorbent bed in a little more detail. Consider Figure C-24 for a binary solution containing a strongly absorbed solute (gaseous) pollutant at concentration C_0 . The gas stream containing the pollutant is to be passed continuously down through a relatively deep bed of adsorbent that is initially free of adsorbate. The top layer of adsorbent, in contact with the entering contaminated gas, adsorbs the pollutant rapidly and effectively, and the remaining pollutant is almost entirely removed by the layers of adsorbent in the lower part of the bed. Now the effluent from the bottom of the bed is practically pollutant-free as at C_1 . The top layer of the bed is practically saturated, and the bulk of the adsorption takes place over a relatively narrow adsorption zone in which there is a rapid change in concentration. The saturated bed length is L_{st} . As the gas stream continues to flow, the adsorption zone of length L_z travels downward, similar to a wave, at a rate usually much less than the linear velocity of the gas stream through the bed. At some later time, roughly half of the bed is saturated with the pollutant, but the effluent concentration C_2 is still practically zero. Finally at C_3 , the lower portion of the adsorption zone reaches the bottom of the bed, and the concentration of pollutant in the effluent suddenly rises to an appreciable value for the first time. The system is said to have reached the breakpoint. The pollutant concentration in the effluent gas stream now rises rapidly as the adsorption zone passes through the bottom of the bed, and at C_4 just about reaches the initial value C_0 . At this point the bed is just about fully saturated with pollutant. The portion of the curve between C_3 and C_4 is termed the breakthrough curve. If the gas stream continues to flow, little additional adsorption takes place since the bed is, for all practical purposes, entirely in equilibrium with the gas stream. Theoretically, zero concentration is attained only at infinite bed length, but for practical purposes, concentration of $0.01 C_0$ to $0.001 C_0$ are considered essentially zero; hence, the finite bed lengths.

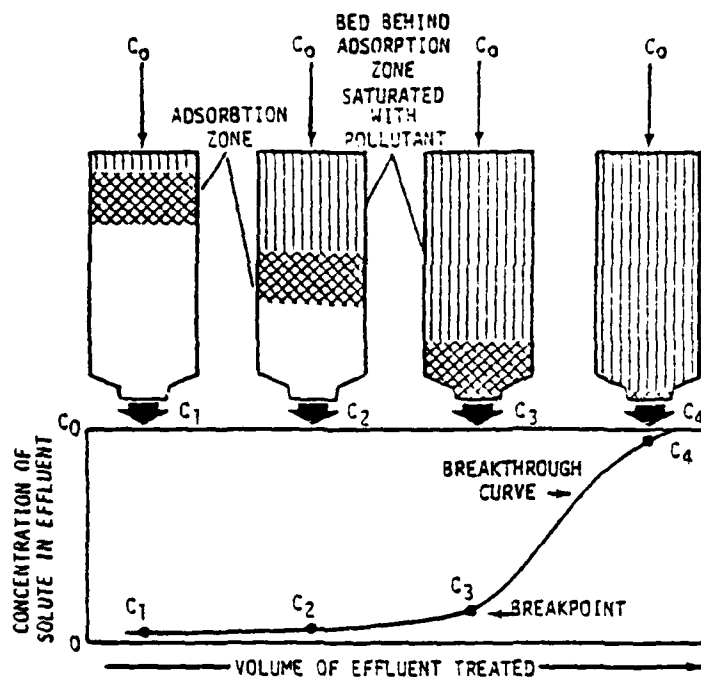


FIGURE C-24

ADSORPTION WAVE FRONT ³²

The time at which the breakthrough curve appears and its shape greatly influence the method of operating a fixed-bed adsorber. The curves usually have an S shape, but they may be steep or relatively flat and in some cases may be considerably distorted. The actual rate and mechanism of the adsorption process, the nature of the adsorption equilibrium, the fluid velocity, the pollutant concentration in the entering gas, and the adsorber bed length all contribute to the shape of the curve produced for any system. The breakpoint is very sharply defined in some cases, while in others it is not. Generally, the breakpoint time decreases bed height, increased adsorbent particle size, increased gas flow rate through the bed, and increased initial pollutant concentration in the entering gas stream.

In addition to the type of adsorbent, the following factors also play an important role:

- a. the particle size of an adsorbent (may depend on maximum allowable pressure drop)
- b. the depth of the adsorbent bed
- c. the gas velocity
- d. the temperatures of the gas stream and the adsorbent
- e. the concentrations of the contaminants not to be removed, including moisture

- f. the removal efficiency required
- g. possible decomposition or polymerization of contaminants on the adsorbent
- h. intermittent operation of the adsorber
- i. regeneration conditions
- j. the pressure of the system.

a. Adsorbent Particle Size

The dimensions and shape of particles affect both the pressure drop through the adsorbent bed and the diffusion rate into particles. The pressure drop is lowest when the adsorbent particles are spherical and uniform in size. However, the external mass transfer increases inversely with the $d^{3/2}$ and the internal adsorption rate inversely as d^2 . The pressure drop will vary with the Reynolds number, being roughly proportional to velocity and inversely proportional to particle diameter. Adsorbent beds consisting of smaller particles, although causing a higher pressure drop, will be more efficient. Therefore, the sharper and smaller mass transfer zone will be obtained.

b. Depth of the Adsorbent Bed

The effect of bed depth on adsorption mass transfer is twofold. First, it is important that the bed is deeper than the length of the transfer zone, which is unsaturated. Second, any multiple of the minimum bed depth gives more than proportional increased capacity. In general, it is advantageous to size an adsorbent bed to the maximum length allowed by pressure drop considerations. The determination of the depth of the mass transfer zone (MTZ) or unsaturated depth may be determined by experiment.

$$MTZ = \frac{\text{Total bed depth}}{t_{St} / (t_{St} - t_B) - X}$$

t_B = time required to reach breakpoint

t_{St} = time required to saturation

X = the degree of saturation in the MTZ.

c. Gas Velocity

The velocity of the gas stream through adsorbent beds is limited by the adsorbent crushing velocity, which varies with different types of adsorbents.

The length of the MTZ is directly proportional to the velocity. Thus, at high velocities, the unsaturated zone is elongated.

d. Temperature

As discussed previously, adsorption decreases with increasing temperature. Because the equilibrium capacity of adsorbents is lower at higher temperatures, the dynamic or breakthrough capacity will also be lower and the MTZ will proportionally change with temperature.

The adsorption process is exothermic. As the adsorption front moves through the bed, a temperature front also proceeds in the same direction, and some of the heat is imparted to the gas stream.

e. The Presence and Concentration of Other Contaminants

It is important to stress the fact that some portion of all gases present will be adsorbed on the adsorbent surface. Because these gases compete for the available surface area and/or pore volume, the effect of their presence will be to lower the adsorption capacity for the particular adsorbate to be removed. Although activated carbon is less sensitive to moisture than silica gel or alumina at high gas moisture content, its adsorption capacity can be considerably lower than in a dry air stream. It is preferable to adsorb organic contaminants from the lowest relative humidity gas stream when using unimpregnated adsorbents. The reverse is true for most impregnated adsorbents, where the moisture enhances the reaction between the gaseous contaminants and the impregnating agent.

f. The Removal Efficiency of the System

At times, it is sufficient to lower the adsorbate concentration to only a small amount, while in other cases, total removal is required. Naturally, deeper adsorbent beds are required to achieve a 99.99 percent single pass removal than for a partial 60 to 80 percent removal efficiency.

g. Decomposition and Polymerization of the Adsorbate

Some solvents or compounds may decompose, react, or polymerize when in contact with adsorbents. The decomposed product may be adsorbed at a lower capacity than the original substance, or may have different corrosion properties, etc. As an example, in an air stream, NO is converted to NO₂ when in contact with activated carbon. Polymerization on the adsorbent surface will significantly lower its adsorption capacity and render it nonregenerable by conventional methods. Such an example is the adsorption of acetylene on activated carbon at higher temperatures. Decomposition may also take place in regenerative systems during direct stream stripping of the adsorbent bed.

h. Intermittent Operation of the Adsorber

Very often, the adsorbers are operated periodically, and the concentration of the contaminant greatly varies depending on the periodic discharge of contaminants. The performance of the adsorption system is impaired under these conditions. This is caused by the variation of adsorbate concentrations with bed height.

i. Regeneration Conditions

Economical consideration is the most important factor in choosing between the in-place regeneration and the replacement of the entire adsorbent charge.

C.3 CONTROL BY COMBUSTION

The factors influencing completeness of combustion are evaluated in detail below.

1. Temperature

Every combustible substance has a minimum ignition temperature, which must be attained, or exceeded, in the presence of oxygen if combustion is to ensue under the given conditions. Since the reaction rate increases with temperature, temperatures considerably above the ignition temperatures of the combustible may be necessary to accomplish complete combustion in a reasonable amount of time.

2. Oxygen

Oxygen is necessary for combustion to occur. The end products of combustion depend on the supply of oxygen. When methane, for instance, is burned with too little oxygen, solid carbon results.

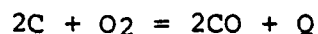


The solid carbon agglomerates, forming particles of soot and smoke. If enough oxygen is supplied, the carbon is burned to carbon dioxide.

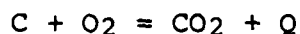


Here it is completely burned, no solid is set free, and hence, there is no smoke.

When carbon is burned with an insufficient supply of oxygen, carbon monoxide results:



If enough oxygen is available, then carbon dioxide results:



To achieve complete combustion of a combustible compound with air, a stoichiometric (theoretical) quantity of oxygen must be available. The quantities of air that must be furnished to obtain theoretical complete combustion for many combustible compounds are shown in Table C-13.

It is necessary, however, to use more than the theoretical air required to assure sufficient oxygen for complete combustion. Excess air would not be required if it were possible to have every oxygen molecule combine with the combustibles. The amount of

excess air added to insure complete combustion must be held at a practical minimum to reduce the stack heat losses. Realistic values of excess air necessary to burn various fuels are given in Table C-14.

TABLE C-13

COMBUSTION CONSTANTS^a

Substance	Heat of Combustion (Btu per lb)		For 100% Total Air, Moles of Air Per Mole of Combustible
	Gross (High)	Net (Low)	
Carbon	14,093	14,093	4.76
Hydrogen	61,100	51,623	2.38
Carbon monoxide	4,347	4,347	2.38
Paraffin Series			
Methane	23,879	21,520	9.53
Ethane	22,320	20,432	16.68
Propane	21,661	19,944	23.82
n-Butane	21,308	19,680	30.97
Isobutane	21,257	19,629	30.97
n-Pentane	21,091	19,517	38.11
Isopentane	21,052	19,478	38.11
n-Hexane	20,940	19,403	45.26
Olefin Series			
Ethylene	21,644	20,295	14.29
Propylene	21,041	19,691	21.44
n-Butene	20,840	19,496	28.59
Isobutene	20,730	19,382	28.59
n-Pentene	20,712	19,363	35.73
Aromatic Series			
Benzene	18,210	17,480	35.73
Toluene	18,440	17,620	42.88
Xylene	18,650	17,700	50.02
Miscellaneous Gases			
Acetylene	21,500	20,776	11.91
Naphthalene	17,298	16,708	57.17
Methyl alcohol	10,259	9,078	7.15
Ethyl alcohol	13,161	11,929	14.29
Ammonia	9,668	8,001	3.57
Sulfur	3,932	3,983	4.76
Hydrogen sulfide	7,100	6,545	7.15

^a From "Fuel Flue Gases," American Gas Association.

TABLE C-14

USUAL AMOUNT EXCESS AIR SUPPLIED TO FUEL-BURNING EQUIPMENT

	<u>Type of Furnace or Burners</u>	<u>Excess Ai (% by wt)</u>
Pulverized coal	Completely water-cooled furnace for slag-tap or dry-ash removal	15-20
	Partially water-cooled furnace for dry-ash removal	15-40
Crushed coal	Cyclone furnace-pressure or suction	10-15
Coal	Stoker-fired, forced-draft, B&W chain grate	15-20
	Stoker-fired, forced-draft, underfeed	20-50
	Stoker-fired, natural-draft	50-65
Fuel-oil	Oil-burners, register-type	5-10
	Multifuel burners and flat-frame	10-20
Acid sludge	Cone and flat flame burners, steam-automated	10-15
Natural, coke oven, and refinery gas	Register-type burners	5-10
	Multifuel burners	7-12
Blast-furnace gas	Intertube nozzle-type burners	15-18
Wood	Dutch-oven (10-23% through grates) and Hoffft-type	20-25
Bagasse	All furnaces	23-35
Black liquor	Recovery furnaces for kraft and soda-pulping processes	5-7

3. Time

A fundamental factor in the design and performance of combustion equipment is the time required for combustion of a particle in relation to the residence time in the equipment at combustion conditions. The residence time (at conditions conducive to complete combustion) should be greater than the time required for combustion of a particle.

The time of residence depends primarily on aerodynamic factors, including size, which are arbitrarily set in the design of the unit. The time of combustion is controlled by the temperature and aerodynamic factors. The time of residence, then, becomes a question of economy namely, size versus temperature. The smaller the unit, the higher the temperature must be to oxidize the material at the time of contact.

4. Turbulence

Not only must the oxygen be supplied, but it must be intimately mixed with the material being burned so that it is available to the combustible substance at all times.

5. Heat of Combustion

The rapid oxidation of combustible compounds results in the exothermic reaction (evolution of heat). The heat evolved (Q) is known as the "heat of reaction," or more specifically the "heat of combustion."

C.3.1 Types of Combustion

C.3.1.1 Flame Combustion

a. Yellow Flame

A luminous (yellow) flame results when air and fuel flowing through separate ports are ignited at the burner nozzle. Combustion occurs over an extended area in the combustion chamber, producing a highly radiant flame. The expansion of the gases as the flame progresses provides the necessary turbulence, while a large combustion chamber assures the necessary time at the combustion temperature to complete the reaction.

b. Blue Flame

A burner arranged to mix the air and fuel prior to delivery to the burner nozzle will produce a short, intense, blue flame, permitting complete oxidation within a confined space.

In any fuel-fired burner, whether it is of the luminous (yellow flame) or premixed (blue flame) type, sustained combustion depends upon maintaining

the air-gas supply to the burner within the flammable range.

C.3.1.2 Flare Combustion

All process plants that handle hydrocarbons, hydrogen, ammonia, hydrogen cyanide, or other toxic or dangerous gases are subject to emergency conditions, which occasionally require immediate release of large volumes of such gases for protection of plant and personnel. In any petrochemical process, hydrocarbons present with inert gases, such as nitrogen and carbon dioxide, must be continuously released in variable volume and concentration. Where these gases are released at energy concentrations constantly within or above the flammable range, their disposal can be handled most economically and safely by application of flares. However, smokeless burning of huge quantities of gases by flares presents some serious design problems. First, the flare must be sufficiently elevated above ground level for heat and flame protection of adjacent buildings and personnel. Flame must also be sustained at varying rates, exceeding by many times the operating range of industrial burners. These physical demands prevent the employment of combustion chambers.

Flare combustion is often characterized by a luminous (yellow) flame. The luminous flame results when oxygen in the air surrounding the flame comes in contact with the hydrocarbons by diffusion only. The luminous color is from incandescent carbons, which result from the cracking of the hydrocarbon molecules.

Blue-flame flare combustion can be accomplished by adding water vapor, under proper temperature conditions, as the gas is burned. A water-gas reaction is set up, generating carbon monoxide and hydrogen which assist in the production of blue-flame burning by removing the unburned carbon. Combustion of carbon monoxide and hydrogen results in carbon dioxide and water.

C.3.1.3 Thermal Combustion

Gases vented from industrial processes are generally exhausted at concentrations far below the lower flammable limit. At these concentrations of gases, combustion in an enclosed chamber is necessary.

Thermal combustion is commonly called thermal incineration. A separately fired burner is normally employed to sustain rapid oxidation. The flame per se has no influence on the reaction except that it

provides the time-temperature-turbulence factors. Since "the three T's" allow considerable latitude in design, numerous combinations of the "three T's" will result in complete combustion. Generally, however, furnace construction costs require a practical limit on holding time of less than 0.5 to 0.75 seconds. Residence temperature may vary from 950°F for naphtha vapors to 1,600°F for methane and somewhat higher for some aromatic hydrocarbons. Higher percentages of inert gases in the gas stream act as oxidation depressants and will demand higher temperatures.

C.3.1.4 Catalytic Combustion

Catalytic combustion is the lowest-temperature method of rapidly oxidizing combustible gases and vapors. Many substances exhibit catalytic properties, but metals in the platinum family are recognized for their ability to produce the lowest catalytic ignition temperatures.

Since catalytic oxidation is a surface reaction, relatively small amounts of platinum are used in a way that exposes the maximum surface area to the gas stream. This is accomplished by coating a high surface area substance with the catalyst and arranging the catalyst-coated substances in catalyst beds.

Sufficient surface area must be supplied to permit the oxidation reaction to be completed within the bed, since "the three T's" still apply if "exposed catalyst surface" is substituted for "time." Turbulence is achieved in the passage of the contaminated gases through the bed. Catalyst temperature results from the oxidation reaction itself, plus burner or electric preheating where necessary. With platinum alloy catalysts, oxidation of hydrogen will be initiated at ambient temperature, naphtha at 450°F, and methane at 750°F.

The temperatures required to catalytically oxidize many organic compounds are given in Table C-15.

Catalytic combustion is generally applicable when: (1) the gas stream to be handled contains vaporized or gaseous combustible materials and (2) there is no large amount of dust, fly ash, or other solid inorganic material in the gas stream.

Catalytic systems are designed to prevent condensate formation in exhaust equipment. The exhaust fan in a catalytic system is located on the hot side of the system so that all vapors passing through it are above the condensation temperature.

TABLE C-15

INDUSTRIAL APPLICATIONS OF CATALYTIC COMBUSTION

Industrial Process	Contaminating Agents in Waste Gases	Approximate Temperature Required for Catalytic Oxidation
Asphalt oxidizing	Aldehydes, anthracenes, oil vapors, hydrocarbons	600°-700°F
Carbon black mfg.	H ₂ , CO, CH ₄ , carbon	^a 1,200°F-1,800°F
Catalytic cracking units	CO, hydrocarbons	650°-800°F
Core ovens	Wax, oil vapors	600°-700°F
Formaldehyde mfg.	H ₂ , CH ₄ , CO, HCHO	650°F
HNO ₃ mfg.	NO, NO ₂	^b 500°-1,200°F
Metal lithography ovens	Solvents, resins	500°-750°F
Octyl-phenol mfg.	C ₆ H ₅ OH	600°-800°F
Phthalic anhydride mfg.	Maleic acid, phthalic acid, naphthaquinones, carbon monoxide, formaldehyde	500°-650°F
Polyethylene mfg.	Hydrocarbons	500°-1,200°F
Printing presses	Solvents	600°F
Carnish cooking	Hydrocarbon vapors	600°-700°F
Wire coating and enameling ovens	Solvents, varnish	600°-700°F

^a Temperature in excess of 1,200°F required to oxidize carbon.

^b Reducing atmosphere required.

C.3.2 Combustion Terminology

C.3.2.1 Heat of Combustion

The heat released by the complete combustion of a specific quantity of fuel with molecular oxygen. Heats of combustion are normally reported in Btu per cubic foot or Btu per pound of fuel.

C.3.2.2 Gross Heating Value

The total heat obtained from the complete combustion of a fuel that is at 60°F when combustion starts, and the combustion products of which are cooled to 60°F before the quantity of heat released is measured. Constant pressure, normally 1 atmosphere (29.92 in. Hg), is maintained throughout the entire combustion process. Gross heating values are also referred to as total or higher heating values.

C.3.2.3 Net Heating Value

The gross heating value minus the latent heat of vaporization of the water formed by the combustion of the hydrogen in the fuel. For a fuel containing no hydrogen, the net and gross heating values are the same.

C.3.2.4 Latent Heat of Vaporization

Heat given off by a vapor condensing to a liquid or gained by a liquid evaporating to a vapor, without a change in temperature. The latent heat of vaporization of water at 212°F is 970.3 Btu per pound.

C.3.2.5 Sensible Heat

Heat, the addition or removal of which results in a change in temperature without phase change, as opposed to latent heat of vaporization.

C.3.2.6 Available Heat

The gross quantity of heat released within a combustion chamber minus (1) the sensible heat carried away by the dry flue gases and (2) the latent heat and sensible heat carried away in water vapor contained in the flue gases. The available heat represents the net quantity of heat remaining for useful heating.

C.3.2.7 Heat Content

The sum total of the latent and sensible heat present in a substance (gas, liquid, or solid) minus that contained at an arbitrary set of conditions chosen as the reference or zero point. Heat content is usually expressed in units of Btu per pound. For gases, the heat content may be expressed in Btu per cubic foot if the conditions of pressure and temperature under which these volumes are measured, are specified.

C.3.3 Types of Equipment

Combustion control equipment can be divided into three types: flares, thermal incinerators, and catalytic reactors.

C.3.3.1 Flares

The flare system is used primarily as a safe method for disposing excess waste gases. However, the flare system itself can present additional safety problems, including the explosion potential of a flare, thermal radiation hazards from the flame, and the problem of toxic asphyxiation during flame-out. Aside from safety, there are several other problems that must be dealt with during the design and operation of a flare system. These problems fall into the general area of emissions from flares and include the formation of smoke, the luminosity of the flame, noise during flaring, and the possible emission of air pollutants during flaring.

The volume of the waste stream to be disposed is also an important factor. With very large volumes of gas, direct flame combustion by incineration or a flame afterburner device becomes impractical due to the size of equipment needed. However, capacity for an elevated flare can be increased easily by increasing the diameter of the stack. A typical small flare with a 4-inch diameter stack has a capacity of 30,000 scfh. A normal refinery flare with a capacity of 5,000,000 scfh would need only a 36-inch diameter flare stack.

The heat content of a waste gas falls into two classes. The gases can either maintain their own combustion or they cannot maintain their own combustion. In general, a waste gas with a heating value greater than 200 Btu/ft³ can be flared successfully. The

heating value is based on the lower heating value of the waste gas at the flare. Below 200 Btu/ft³, enriching the waste gas by injecting a gas having a high heating value may be necessary. The addition of such a rich gas is called endothermic flaring. Gases with a heating value as low as 60 Btu/ft³ have been flared but at a significant fuel demand. It is usually not feasible to flare a gas with a heating value below 100 Btu/ft³. If the flow of low Btu gas is continuous, incineration can be used to dispose the gas. For intermittent flows, endothermic flaring is the only possibility.

Flares are mostly used for the disposal of hydrocarbons. Waste gases composed of natural gas, propane, ethylene, propylene, butadiene, and butane probably constitute over 95 percent of the material flared.

In recent years, gases whose combustion products may cause problems, such as those containing hydrogen sulfide or chlorinated hydrocarbons, have not been recommended for flaring.

In general, there are three types of flare systems in use today, the elevated, ground, and forced-draft flare. This section will describe the equipment available for flaring waste gases by these systems and will also present relative cost data for the different systems.

a. Elevated Flares

The modern elevated flare system is made up of several components including the flare tip, some type of gas trap directly below the tip, a pilot and ignition system at the top of the flare tip, and the stack and its support. When smokeless burning is required, a steam injection system must also be provided at the top of the flare. Water seals and knockout drums are also usually required for safety reasons.

(1) Flare Tips

A flare tip must be capable of operating over a wide range of turndown ratios. To achieve this, the flare must have excellent flameholding ability and mixing characteristics. Flameholding is ensured by providing multiple, continuous pilots around the combustion tip and by providing a flame stabilization ring on the

combustion tip. Figure C-25 shows the standard flare tips available.³² The flare tip is usually made of stainless steel or some other high temperature and corrosion-resistant alloy.

Smokeless burning can be achieved with special flare tips that inject water, natural gas, or steam into the flame, increasing air-gas mixing to ensure complete combustion. Water injection has many disadvantages including the formation of ice in the winter and mist in the summer, the tremendous pressure head needed for an elevated flare, and a turndown ratio much less than steam, making control very difficult with the possibility of quenching the flame. Natural gas has also been injected into the flame for smokeless burning but only in the case where the gas itself has no value since it is also burned during flaring. For these reasons, steam injection is most commonly used for smokeless burning.

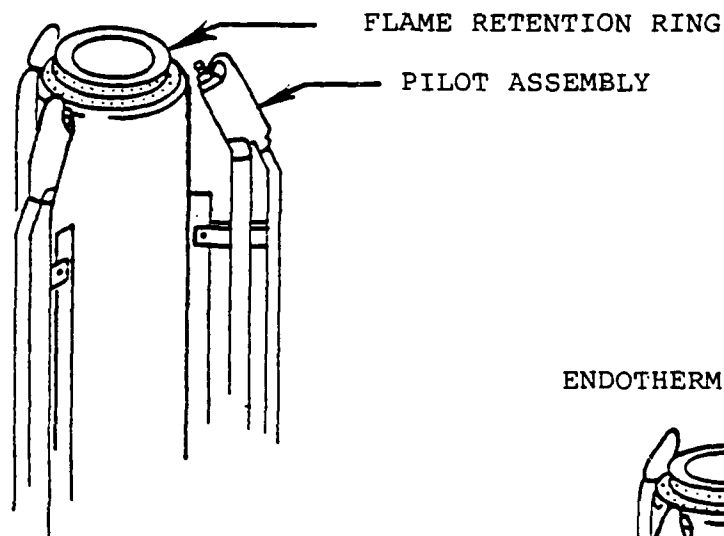
There are two basic steam injection techniques used in elevated flares. In one method, steam is injected from nozzles on an external ring around the top of the tip. In the second method, the steam is injected by a single nozzle located concentrically within the burner tip. Manufacturers use various types of nozzles to create a circular, swirl, fan, or jet effect.

(2) Pilot and Ignition System

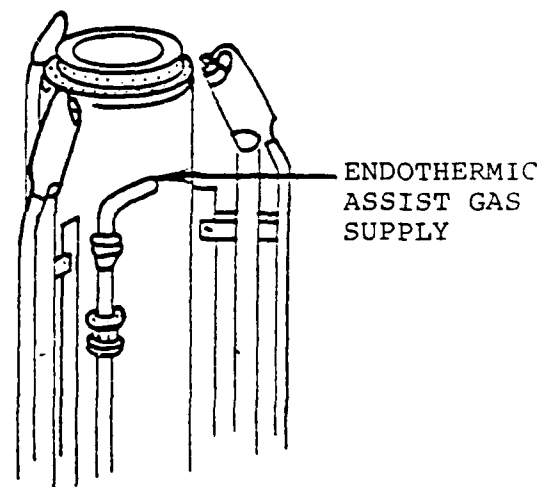
The ignition system for a flare installation usually consists of the pilot burners and the pilot burner igniters. The pilot burners serve to ignite the outflowing gases and to keep the gas burning. These pilots must provide a stable flame to ignite the flare gases, and in many cases, to keep them burning. To accomplish this, more than one, and usually three or four, pilot burners are always used.

A separate system must be provided for the ignition of the pilot burner to safeguard against flare failure. The usual method is spark ignition of a gas/air mixture in an ignition chamber. The flame front travels through an igniter tube to the pilot burner at the top of the flare. This system

UTILITY FIELD FLARE TIP



ENDOTHERMIC FIELD FLARE TIP



SMOKELESS FIELD FLARE TIP

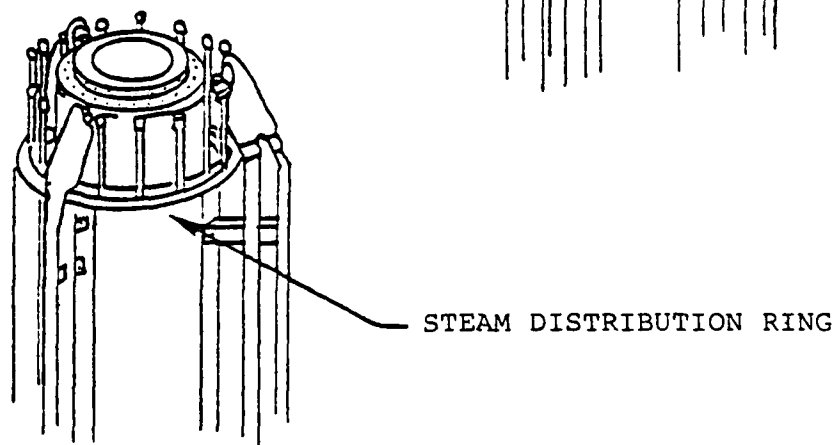


FIGURE C-25
FLARE TIPS 32

permits the igniter to be set up at a safe distance from the flare, up to 100 feet, and still ignite the pilots satisfactorily. On elevated flares, the pilot flame is usually not visible and an alarm system to indicate pilot flame failure is desirable. This is usually done by a thermocouple in the pilot burner flame. In the event of flame failure, the temperature drops and an alarm sounds.

(3) The Stack and Its Support

The stack must be provided with a ladder with a cage, and a landing on top for repair and maintenance purposes. Towers for refineries can range from 200 to 400 feet high. Flare towers with a proportion of length-to-diameter ratio less than 30 are usually constructed as self-supporting stacks; towers with a proportion $30 < L/D < 100$ are supported with a set of guys, and with the proportion $L/D > 100$, the towers are made with two or more sets of guys. Self-supporting stacks are usually not built over 50 feet high because of the large and expensive foundation required.

The guys need a large area for high stacks; thus, it is often preferable to build steel supports to which the stack is fastened. These supports are usually steel framework with a square cross section widened at the base. A triangular cross section, adopted from the modern television antennas, is more economical and has been used in several refineries. The flare stack will expand because of the hot gas flow, and the supporting structure must be able to accommodate this expansion.

(4) Water Seals, Flame Arrestors, and Knockout Drums

Water seals and flame arrestors are used to prevent a flame front from entering the flare system. Flame arrestors have a tendency to plug and obstruct flow and are not capable of stopping a flame front in mixtures of air with hydrogen, acetylene, ethylene oxide, and carbon disulfide.

Water seals are used to prevent a flame front and air from entering the flare gas collection system. The weight of the water seal causes it to be located at or near grade, and therefore the seal cannot be used to prevent air from entering the stack.

Knockout drums are located at or near the base of elevated flares to separate liquid from gases being burned. If the large liquid droplets are not removed, they could burn all the way to the ground. Designed for gases, flare lines can contain liquids from liquid expansion reliefs, liquid carried over from gas reliefs, and condensed vapors. The knockout drum is used to remove these liquids before the gases are flared.

b. Ground Flares

A ground flare consists of a burner and auxiliaries, such as a seal, pilot burner, and igniter. One type of ground flare consists of conventional burners discharging horizontally with no enclosures. This flare must be installed in a large, open area for safe operation and fire protection. If the ignition system fails, this flare is not as capable of dispersing the gases as an elevated flare. Thus, it has found only limited applications.

Ground flares may also consist of multiple burners enclosed within a refractory shell as in the recently developed "low-level" flares. The essential purpose of a low-level flare is complete concealment of the flare flame as well as smokeless burning at a low noise level.

The size of the enclosure depends upon the capacity of the flare, but can become quite large. An enclosed ground flare with a capacity of 25,000 lb/hr has an enclosure 100 feet high and 20 feet in diameter. This same capacity could be handled by a 8-inch-diameter elevated flare.

The initial costs of an enclosed ground flare usually limit their capacity to just a portion of a plant's emergency dump rates.

c. Forced-Draft Flares

The forced-draft flare uses air provided by a blower to supply primary air and turbulence necessary to provide smokeless burning of relief gases without the use of steam.

However, this flare also has a high initial cost. The cost can run two to three times the cost of a conventional flare, mainly since two stacks are necessary to keep the air and gas separated until they are mixed and ignited at the top. A blower flare should have an automatic air turndown device to prevent excess air from quenching the flame and creating smoke if the flare gas rate is reduced. Variable speed blowers or baffles coupled to flow sensing devices have been used on these flares to extend their turndown ratio. Because of costs and turndown ratio limitations, this flare has been used mostly in special applications.

C.3.3.2 Thermal Incinerators

Thermal incinerators or afterburners can be used with a range of organic vapor concentrations, substantially below the lower flammable level (lower explosive limit). As a rule, a factor of four is employed for safety precautions. Reactions are conducted at elevated temperatures in order to insure high chemical reaction rates for the organics. To achieve this temperature, it is necessary to preheat the feed stream with auxiliary energy. Along with the contaminant-laden gas stream, air and fuel are continuously delivered to the reactor (see Figure C-26³²) where the fuel is combusted with air in a firing unit (burner). The burner may use the air in the process waste stream as the combustion air for the auxiliary fuel or it may use a separate source of outside air for this purpose. The products of combustion and the unreacted feed stream are intensely mixed and enter the reaction zone of the unit. The pollutants in the process gas stream are then reacted at the elevated temperature. A diagram of a typical industrial unit is given in Figure C-25. The unit requires operating temperatures in the 1,200° to 1,500°F range for combustion of most pollutants. A residence time of 0.2 to 1.0 second is recommended in the literature, but this factor is primarily dictated by kinetic considerations. A length-to-diameter ratio of 2.0 to 3.0 is usually employed. The end products are continuously discharged at the outlet of the reactor.

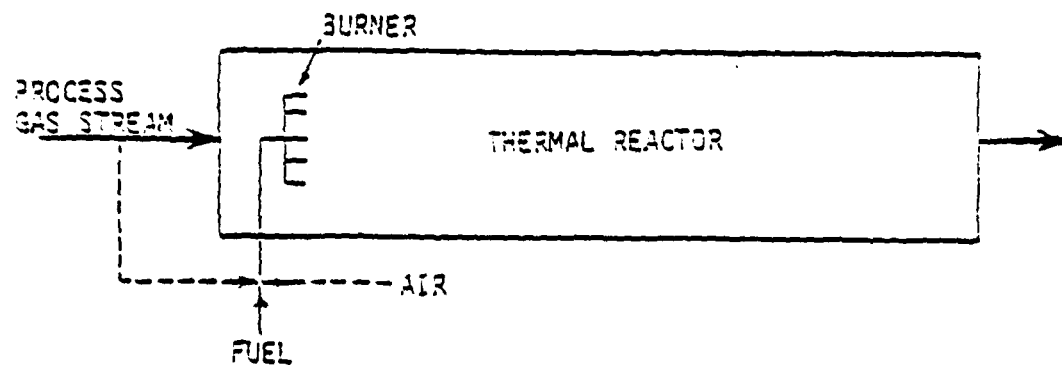


FIGURE C-26
THERMAL COMBUSTION DEVICE³²

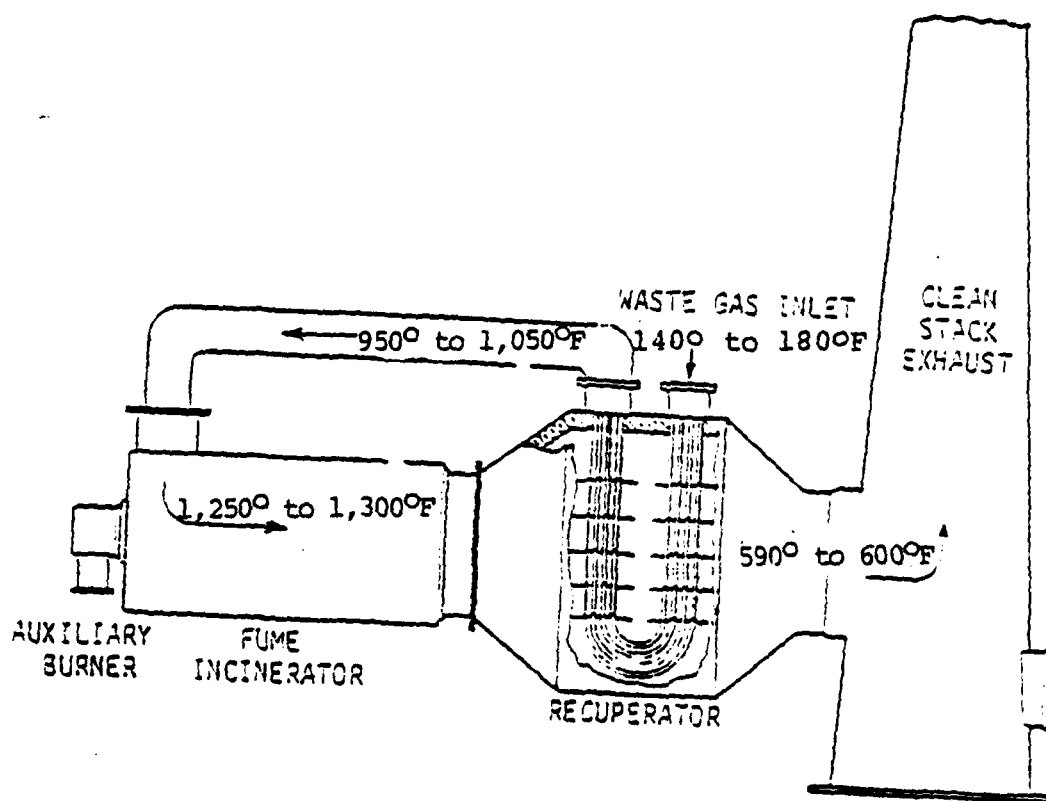


FIGURE C-27
THERMAL COMBUSTION WITH ENERGY (HEAT) RECOVERY³²

The average gas velocity can range from as low as 10 ft/sec to as high as 50 ft/sec. (The velocity increases from inlet to outlet due to the increase in the number of moles of the reacting fluid and the increase in temperature due to reaction.) These high velocities are required to prevent settling of particulates (if present) and to minimize the dangers of flashback and fire hazards.

The fuel is usually natural gas. The energy liberated by reaction may be directly recovered in the process or indirectly recovered by suitable external heat exchange (see Figure C-27³²). Heat recovery should definitely be included in a design analysis since the energy is the only commodity of value that is usually derived from the combustion process.

Due to the high operating temperatures, the unit must be constructed of metals capable of withstanding high temperatures. Combustion devices are usually constructed with an outer steel shell that is lined with refractory material. However, refractory material is heavy, with densities ranging from 50 lb/ft³ for lightweight insulating firebrick to 175 lb/ft³ for castable refractories. Refractory wall thickness is in the 3-inch to 9-inch range. This weight adds considerably to the cost. Because of its light weight, fiberbrick wall construction is being used in some units. These combustion reactors also vary in shape from tanks to tubular pipes. Tubular pipes are usually used because the high surface-to-volume ratio is advantageous for energy recovery and suitable for continuous operation.

Miscellaneous Design Parameters for Thermal Incineration

1. Oxidize combustible material by raising the temperature of the material above its auto-ignition temperature and holding it there for a brief period of time to complete oxidation.
2. Most OSHA regulations insist that the mixture be below 25 percent LEL (lower explosive limit) with 50 percent LEL usually considered absolute maximum. Dilution may be required to attain this.

3. Required temperature should be several hundred degrees above the auto-ignition temperature of the solvent vapor to be destroyed.

4. It is good engineering practice to design for 1,200° to 1,500°F to meet air pollution codes. A design temperature of 1,400°F⁺ is recommended to operate at whatever temperature is required under existing codes; this permits compliance with any later change in regulations merely by changing the setting on the temperature controller.

These temperatures are normally adequate for the complete destruction of pollutants if the stream is held for 0.1 to 0.3 seconds after the required temperature has been attained.

C.3.3.3 Catalytic Reactors

A typical catalytic reactor for the combustion of organic vapors is presented in Figure C-28³². The gas stream is delivered to the reactor continuously by a fan at a velocity in the range of 10 to 30 ft/sec, but at a lower temperature--usually in the 650° to 800°F range--than the thermal unit. A length-to-diameter ratio less than 0.5 is usually employed. The gases, which may or may not be preheated, pass through the catalyst bed where the reaction occurs. The combustion products, which are again made up of water vapor, carbon dioxide, inerts, and unreacted vapors, are continuously discharged from the outlet at a higher temperature.

Metals in the platinum family are recognized for their ability to promote combustion at low temperatures. Other catalysts include various oxides of copper, chromium, vanadium, nickel, and cobalt.

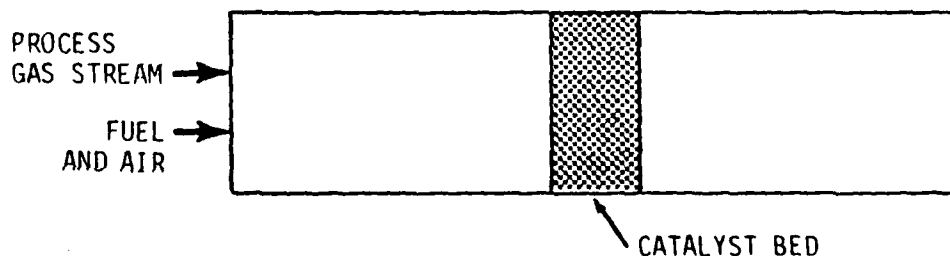


FIGURE C-28³²
CATALYTIC COMBUSTION REACTOR

These catalysts are subject to poisoning, particularly from halogens, halogen and sulfur compounds, zinc, arsenic, lead, mercury, and particulates. High temperatures can reduce catalyst activity. It is, therefore, important that catalyst surfaces be clean and active to insure optimum performance. Catalysts can usually be regenerated with superheated steam.

Catalysts may be porous pellets, usually cylindrical or spherical in shape, ranging from 1/16 to 1/2 inch in diameter. Small sizes are recommended, but these cause an increase in the pressure drop through the reactor. Other shapes include honeycombs, ribbons and wire mesh. Since catalysis is a surface phenomenon, an important physical property of these particles is that the internal pore surface is much greater than the outside surface.

The following sequence of steps is involved in the catalytic conversion of reactants to products:

1. transfer of reactants to and products from the outer catalyst surface
2. diffusion of reactants and products within the pore of the catalyst
3. activated adsorption of reactants and the desorption of the products on the active centers of the catalyst
4. reaction(s) on active centers on the catalyst surface

At the same time, energy effects arising due to chemical reaction can result in the following:

1. heat transfer to or from active centers to catalyst particle surface
2. heat transfer to and from reactants and products within the catalyst particle
3. heat transfer to and from moving streams in the reactor
4. heat transfer from one catalyst particle to another within the reactor
5. heat transfer to or from the walls of the reactor

C.4 CONTROL BY CONDENSATION

C.4.1 Phase Equilibrium Constant

Although the phase equilibrium constant is primarily used in distillation calculations, it is also employed in both chemical reaction (combustion) operations and organic removal condensation calculations. The phase equilibrium constant for a component i , k_i , is defined by

$$k_i = y_i/x_i \quad (1)$$

where y_i = mole fraction of i in the vapor phase

x_i = mole fraction of i in the liquid phase.

If the vapor phase behaves as an ideal gas and the liquid phase is assumed to be an ideal solution, then

$$k_i = p_i/p \quad (2)$$

where p_i = vapor pressure of i

p = total pressure of the system.

The equilibrium constant is, therefore, a strong function of temperature and pressure.

The phase equilibrium principles will now be applied to a typical condenser (refer to Figure C-29). An overall material balance on the condenser is simply given by:

$$F = L + V \quad (3)$$

where F = moles of feed
 L = moles of liquid
 V = moles of vapor.

A material balance for component i gives

$$Fz_i = Lx_i + Vy_i \quad (4)$$

where z_i = mole fraction of i in feed.

Since

$$k_i = y_i/x_i \quad (1)$$

some modest manipulation of Equations 1 and 4 yields

$$y_i = Fz_i / ((L/K_i) + V) \quad (5)$$

Summing this equation results in

$$\sum_{i=1}^n y_i = 1.0 = \sum_{i=1}^n Fz_i / (L/K_i) + V \quad (6)$$

where n is the number of components in the system. This method of analysis assumes that the liquid (L) and vapor (V) are at equilibrium, which may be questionable for certain condensers. Nevertheless, it will be assumed satisfactory for estimation purposes.

These equations must usually be solved by trial and error. For example, if the percentage of the vapor to be removed by condensation is specified, an outlet temperature must be assumed. The phase equilibrium constant can then be determined for each component at the operating pressure. The summation of the individual mole fractions in either liquid or vapor phases must equal unity if the correct equilibrium temperature is used. Should the correct temperature not have been chosen, another temperature is assumed. This procedure is repeated until Equation 6 is satisfied.

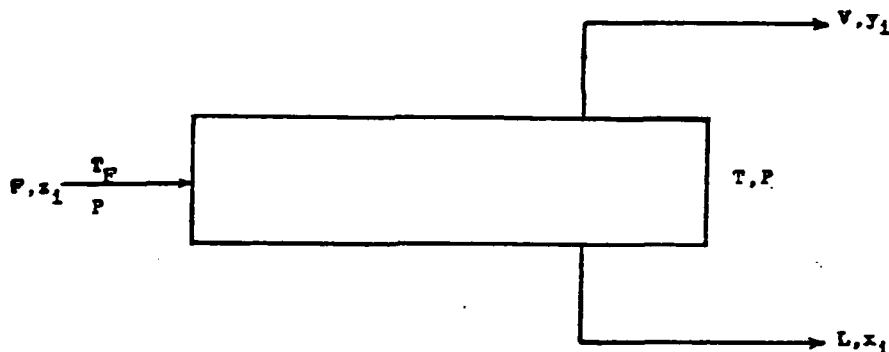


FIGURE C-29

MATERIAL BALANCE ON THE CONDENSER

C.4.2 Contact Condensers

Spray condensers, jet condensers, and barometric condensers (see Figure C-30³²) all use water or some other liquid in direct contact with the vapor to be condensed. The temperature approach between the liquid and the vapor is very small so the efficiency of the condenser is high, but large volumes of the liquid are necessary. If the vapor is soluble in the liquid, then the system is essentially an absorptive one. If the vapor is not soluble, then it is a true condenser--the temperature of the vapor must be below the dewpoint. Direct contact condensers are seldom used for the removal of organic solvent vapors because the condensate then contains an organic-water mixture that must be separated or treated before disposal. However, contact condensers are the most effective means of removing heat from hot gas streams when the recovery of organics is not a consideration.

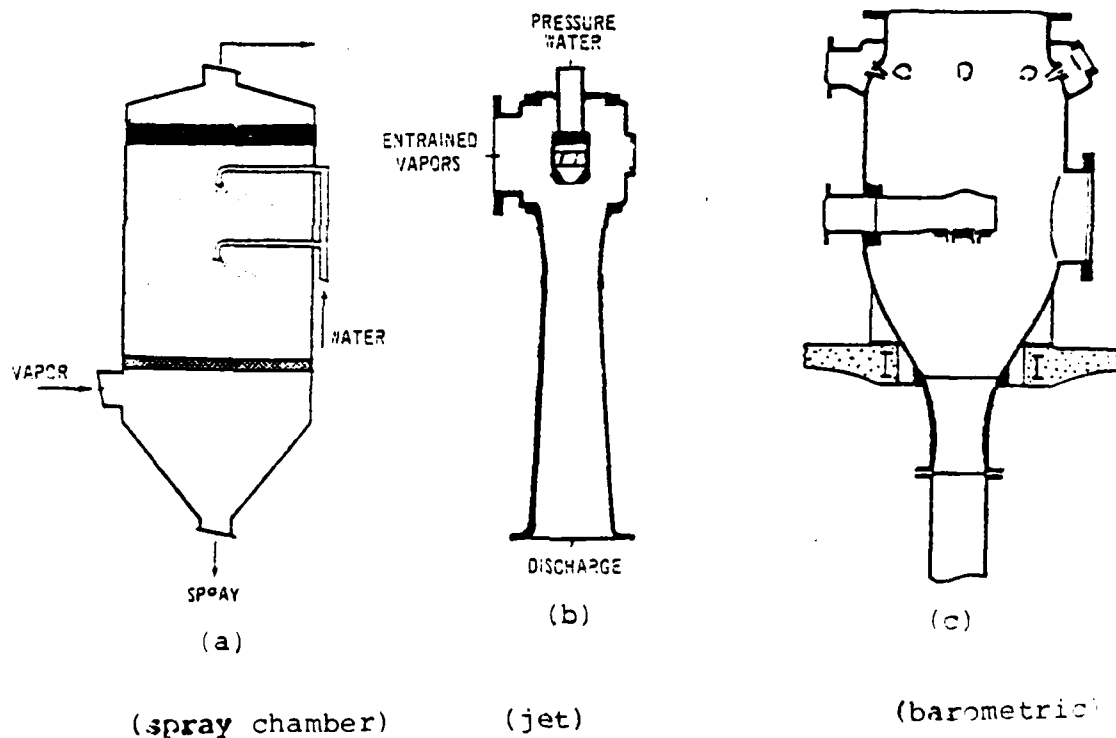


FIGURE C-30³²

DIRECT CONTACT CONDENSERS

Direct contact condensers involve the simultaneous transfer of heat and mass. Design procedures available for absorption, humidification, cooling towers, etc., may be applied with some modifications. However, detailed analysis of this material is beyond the scope of this manual. In practice, very crude empirical correlations--not available in the literature--are usually employed in designing and predicting performance of this type of unit.

C.4.3 Water-cooled Surface Condensers

In a surface condenser, a heat transfer surface separates the coolant from the vapor stream. The advantage of this type of condenser is that it produces a much smaller quantity of condensate, which results in reduced sewage treatment costs. Surface condensers also have lower operating costs than contact condensers since the coolant can be recycled.

The most commonly used surface condensers are shell-and-tube condensers with water as the coolant, and extended surface condensers with ambient air as the cooling medium. A surface condenser designed to provide sub-cooling of the condensate will reduce odor emissions. In one case, a surface condenser that sub-cooled the condensate to 80°F reduced the odor emissions by approximately 50 percent. Although the 50 percent reduction was based on measured odor concentrations, the flow rate from the condenser was estimated because of its low velocity. This reduction is usually impractical because cooling-tower water cannot be cooled low enough to cool condensate to 80°F at usual wet-bulb temperatures. In addition, odor concentrations increase across a surface condenser, as indicated in Table C-16. These facts necessitate the venting of noncondensable gases to additional control equipment.

TABLE C-16

ODOR REMOVAL EFFICIENCIES

<u>Inlet Conc. (o.u./min)^a</u>	<u>Condenser Type</u>	<u>Condensate Temp. (°F)</u>	<u>Outlet Conc. (o.u./min)</u>	<u>Odor Removal Efficiency (%)</u>
25,000,000	Surface	80	12,500,000	50
25,000,000	Direct contact	80	250,000	99

^a Odor emission rates are defined in ASTM Method D1391.
o.u. means odor units

C.4.4 Air-cooled Surface Condensers

Air-cooled surface condensers are used extensively when heat rejection from a process is possible by using ambient air as the coolant. Air-cooled condensers are usually constructed with either fin tubes or some other form of extended surface to increase the heat transfer area.

Condensing steam has a large heat-transfer coefficient, and air has a very small one. Therefore, air is placed on the fin side to take advantage of the large heat-transfer area. Condensation occurs inside the tubes.

Air-cooled condensers offer an advantage over water-cooled units in that they require no water connections, cooling towers, or cooling-water treatment and are simpler to install. Operating costs for an air-cooled condenser may be higher than for an equivalent water-cooled condenser, however, because of the larger power consumption of the fan.

Air-cooled condensers are usually provided with multiple fan units, one of which has a two-speed motor. As the ambient air temperature decreases, a temperature probe in the condensate line senses the corresponding decrease in water temperature and either shuts off fan motors or switches the two-speed fan motor to a lower speed. This conserves power and prevents condenser freeze-up during the winter months.

The emission reduction associated with the use of a surface condenser was discussed previously. If a condenser could be designed to provide cooling of the condensate to 80°F, the odor emissions would be decreased by about 50 percent. Most air-cooled condensers, however, are not designed to provide cooling of the condensate below 140°F, and their main function is to condensate water vapor.

C.4.5 Condenser-Incinerator Systems

Condenser-incinerator combinations are usually more practical and more efficient than incinerators, especially for controlling cooker streams. When a condenser is used to remove steam from cooker streams before incineration, the volume of the stream is reduced as much as 20 times, and a considerable portion of bad odor is removed with the condensate. Other reduction streams that contain from 15 to 40 percent moisture may also warrant the use of a condenser. Factors such as volumes, exit temperatures, fuel costs, water availability, and equipment cost determine condenser feasibility for these streams.

Figure C-31 shows a typical condenser-incinerator system.³² The entrainment separator prevents animal matter that may escape the cooker from entering the condenser and incinerator. The use of a water-cooled surface condenser indicates that the system is probably designed to handle a large volume of cooker gases. Notice that the low-moisture streams are added downstream from the condenser.

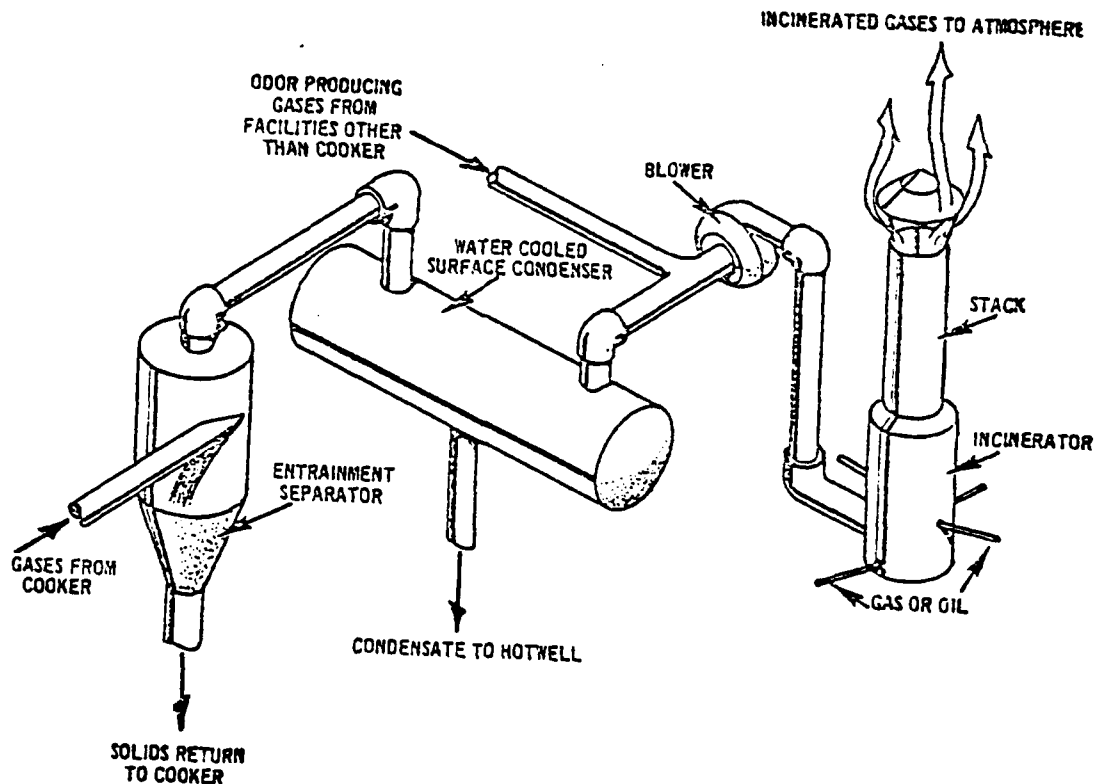


FIGURE C-31

ODOR CONTROL SYSTEM WITH ENTRAINMENT SEPARATOR,
SURFACE CONDENSER, AND INCINERATOR³²

APPENDIX D

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APPENDIX D

CONVERSION EQUATIONS AND CONVERSION TABLES

D.1 CONVERSION EQUATIONS

This section presents equations for temperature conversion. There are four important temperature scales:

1. Centigrade scale ($^{\circ}\text{C}$)
2. Fahrenheit scale ($^{\circ}\text{F}$)
3. Kelvin scale ($^{\circ}\text{K}$)
4. Rankine scale ($^{\circ}\text{R}$)

Kelvin and Rankine are known as absolute scales. Conversion of temperature from one scale to the other can be accomplished by using the following equations:

1. $T(^{\circ}\text{C}) = \frac{5}{9} [T(^{\circ}\text{F}) - 32]$
2. $T(^{\circ}\text{K}) = T(^{\circ}\text{C}) + 273.16$
3. $T(^{\circ}\text{F}) = \frac{9}{5} T(^{\circ}\text{C}) + 32$
4. $T(^{\circ}\text{R}) = T(^{\circ}\text{F}) + 459.67$

D.2 CONVERSION TABLES

Tables D-1 through D-9 provide conversion factors for several useful quantities.

TABLE D-1
CONVERSION FACTORS FOR COMMON GASEOUS AIR POLLUTION
MEASUREMENTS

<u>To convert from</u>	<u>To</u>	<u>Multiply by</u>
milligrams/m ³	micrograms/m ³	1,000
	micrograms/liter	1.0
	ppm by volume (20°C)	(24.04/M)
	ppm by weight	0.8347
	lb/ft ³	62.43 x 10 ⁻⁹
micrograms/m ³	milligrams/m ³	0.001
	micrograms/liter	0.001
	ppm by volume (20°C)	(0.02404/M)
	ppm by weight	834.7 x 10 ⁻⁶
	lb/ft ³	62.43 x 10 ⁻¹²
micrograms/liter	milligrams/m ³	1.0
	micrograms/liter	1,000
	ppm by volume (20°C)	(24.04/M)
	ppm by weight	0.8347
	lb/ft ³	62.43 x 10 ⁻⁹
ppm by volume (20°C)	milligrams/m ³	(M/24.04)
	micrograms/m ³	(M/0.02404)
	micrograms/liter	(M/24.04)
	ppm by weight	(M/28.8)
	lb/ft ³	(M/385.1 x 10 ⁶)
ppm by weight	milligrams/m ³	1.198
	micrograms/m ³	1.198 x 10 ⁻³
	micrograms/liter	1.198
	ppm by volume (20°C)	(28.8/M)
	lb/ft ³	7.48 x 10 ⁻⁶
lb/ft ³	milligrams/m ³	16.018 x 10 ⁶
	micrograms/m ³	16.018 x 10 ⁹
	micrograms/liter	16.018 x 10 ⁶
	ppm by volume (20°C)	(385.1 x 10 ⁶ /M)
	ppm by weight	133.7 x 10 ³

Note: cm = 0.0328 ft
gal (US) = 0.1337 ft³
liter = 0.03532 ft³ = 0.001 m³
microgram = 0.000001 g
micron = 0.0000394 in. = 0.001 mm
milligram = 0.001 g
lb = 7,000 grains = 453.6 g
M = Molecular weight

TABLE D-2

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS

<u>To convert from</u>	<u>To</u>	<u>Multiply by</u>
mg/m ³	g/ft ³	283.2 x 10 ⁻⁶
	g/m ³	0.001
	g/m ³	1000.00
	g/ft ³	28.32
	lb/1,000 ft ³	62.43 x 10 ⁻⁶
g/ft ³	mg/m ³	35.3145 x 10 ³
	g/m ³	35.314
	g/m ³	35.314 x 10 ⁶
	g/ft ³	1.0 x 10 ⁶
	lb/1,000 ft ³	2.2046
g/m ³	mg/m ³	1000.0
	g/ft ²	0.02832
	g/m ³	1.0 x 10 ⁶
	g/ft ³	28.317 x 10 ³
	lb/1,000 ft ³	0.06243
g/m ³	mg/m ³	0.001
	g/ft ³	28.317 x 10 ⁻⁹
	g/m ³	1.0 x 10 ⁻⁶
	g/ft ³	0.02832
	lb/1,000 ft ³	62.43 x 10 ⁻⁹
g/ft ³	mg/m ³	35.314 x 10 ⁻³
	g/ft ³	1.0 x 10 ⁻⁶
	g/m ³	35.314 x 10 ⁻⁶
	g/m ³	35.314
	lb/1,000 ft ³	2.2046 x 10 ⁻⁶
lb/1,000 ft ³	mg/m ³	16.018 x 10 ³
	g/ft ³	0.35314
	g/m ³	16.018 x 10 ⁶
	g/m ³	16.018
	g/ft ³	353.14 x 10 ³
no. of particles/ft ³	no./m ³	35.314
	no./l	35.314 x 10 ⁻³
	no./cm ³	35.314 x 10 ⁻⁶
ton/mi ²	lb/acre	3.125
	lb/1,000 ft ²	0.07174
	g/m ²	0.3503
	kg/km ²	350.3
	mg/m ²	350.3
	mg/cm ²	0.03503
	g/ft ²	0.03254
lb	gr	7,000
m	in.	3.937 x 10 ⁻⁵
	mm	1.0 x 10 ⁻³

TABLE D-3

CONVERSION FACTORS -- EMISSION RATE

DESIRED UNITS

GIVEN UNITS	GRAMS				KG				POUNDS				POUNDS				TONS			
	PER SEC	PER MIN	PER HOUR	PER DAY	PER MIN	PER HOUR	PER DAY	PER DAY	PER MIN	PER HOUR	PER DAY	PER DAY	PER MIN	PER HOUR	PER DAY	PER DAY	PER HOUR	PER HOUR	PER DAY	PER DAY
GRAMS PER SEC	1.0000 E 00	6.0000 E 01	3.6000 E 00	8.6400 E 01	1.3228 E-01	7.9366 E 00	1.9048 E 02	3.9683 E-03	9.2240 E-02											
GRAMS PER MIN	1.6667 E-02	1.0000 E 00	6.0000 E-02	1.4400 E 00	2.2046 E-03	1.3228 E-01	3.1747 E 00	6.6139 E-05	1.5873 E-03											
KG PER HOUR	2.7778 E-01	1.6667 E 01	1.0000 E 00	2.4000 E 01	3.6744 E-02	2.2046 E 00	5.2911 E 01	1.1023 E-03	2.4455 E-02											
KG PER DAY	1.1574 E-02	6.9444 E-01	4.1667 E-02	1.0000 E 00	1.5310 E-03	9.1859 E-02	2.2046 E 00	4.5930 E-05	1.1023 E-03											
POUNDS PER MIN	7.5599 E 00	4.5359 E 02	2.7216 E 01	6.5317 E 02	1.0000 E 00	6.0000 E 01	1.4400 E 03	3.0000 E-02	7.2000 E-01											
POUNDS PER HOUR	1.2600 E-01	7.5599 E 00	4.5359 E-01	1.0886 E 01	1.6667 E-02	1.0000 E 00	2.4000 E 01	5.0000 E-04	1.2000 E-02											
POUNDS PER DAY	5.2499 E-03	3.1499 E-01	1.8900 E-02	4.5359 E-01	6.9444 E-04	4.1667 E-02	1.0000 E 00	2.0833 E-05	5.0000 E-04											
TONS PER HOUR	2.5200 E 02	1.5120 E 04	9.0718 E 02	2.1772 E 04	3.3333 E 01	2.0000 E 03	4.8000 E 04	1.0000 E 00	2.4000 E 01											
TONS PER DAY	1.0500 E 01	6.2999 E 02	3.7799 E 01	9.0718 E 02	1.3889 E 00	8.3333 E 01	2.0000 E 03	4.1667 E-02	1.0000 E 00											

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

TABLE D-4

CONVERSION FACTORS -- AREA
DESIRER UNITS

GIVEN UNITS	CONVERSION FACTORS -- AREA							
	SQ METER	SQ KM	SQ CM	SQ INCH	SQ FOOT	SQ YARD	ACRE	SQ STAT MILE
SQ METER	1.0000 E 00	1.0000 E-06	1.0000 E 04	1.5500 E 03	1.0764 E 01	1.1960 E 00	2.4710 E-04	3.8610 E-07
SQ KM	1.0000 E 06	1.0000 E 00	1.0000 E 10	1.5500 E 09	1.0764 E 07	1.1960 E 06	2.4710 E 02	3.8610 E-01
SQ CM	1.0000 E-04	1.0000 E-10	1.0000 E 00	1.5500 E-01	1.0764 E-03	1.1960 E-04	2.4710 E-08	3.8610 E-11
SQ INCH	6.4516 E-04	6.4516 E-10	6.4516 E 00	1.0000 E 00	6.9444 E-03	7.7160 E-04	1.5942 E-07	2.4910 E-10
SQ FOOT	9.2903 E-02	9.2903 E-08	9.2903 E 02	1.4400 E 02	1.0000 E 00	1.1111 E-01	2.2957 E-05	3.5870 E-08
SQ YARD	8.3613 E-01	8.3613 E-07	8.3613 E 03	1.2960 E 03	9.0000 E 00	1.0000 E 00	2.0661 E-04	3.2283 E-07
ACRE	4.0469 E 03	4.0469 E-03	4.0469 E 07	6.2726 E 06	4.3560 E 04	4.8400 E 03	1.0000 E 00	1.5625 E-03
SQ STAT MILE	2.5900 E 06	2.5900 E 00	2.5900 E 10	4.0145 E 09	2.7878 E 07	3.0976 E 06	6.4000 E 02	1.0000 E 00
SQ NAUT MILE	3.4345 E 06	3.4345 E 00	3.4345 E 10	5.3235 E 09	3.6969 E 07	4.1076 E 06	8.4869 E 02	1.3261 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEFATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

TABLE D-5

CONVERSION FACTORS-- MASS

		DESIRED UNITS								
		GRAM	MICROGRAM	KILOGRAM	METRIC TON	SHORT TON	LONG TON	GRAIN	OUNCE (AVDP)	POUNDS (AVDP)
GIVEN UNITS										
GRAM	1.0000 E 00	1.0000 E 06	1.0000 E 03	1.0000 E 06	1.1023 E 06	9.8421 E 07	1.5432 E 01	3.5274 E 02	2.2046 E 03	
MICROGRAM	1.0000 E 06	1.0000 E 00	1.0000 E 09	1.0000 E 12	1.1023 E 12	9.8421 E 13	1.5432 E 05	3.5274 E 08	2.2046 E 09	
KILOGRAM	1.0000 E 03	1.0000 E 09	1.0000 E 00	1.0000 E 03	1.1023 E 03	9.8421 E 04	1.5432 E 04	3.5274 E 01	2.2046 E 00	
METRIC TON	1.0000 E 06	1.0000 E 12	1.0000 E 03	1.0000 E 00	1.1023 E 00	9.8421 E 01	1.5432 E 07	3.5274 E 04	2.2046 E 03	
SHORT TON	9.0718 E 05	9.0718 E 11	9.0718 E 02	9.0718 E 01	1.0000 E 00	8.9286 E 01	1.4000 E 07	3.2000 E 04	2.0000 E 03	
LONG TON	1.0160 E 06	1.0160 E 12	1.0160 E 03	1.0160 E 00	1.1200 E 00	1.0000 E 00	1.5680 E 07	3.9840 E 04	2.2400 E 03	
GRAIN	6.4799 E 02	6.4799 E 04	6.4799 E 05	6.4799 E 08	7.1428 E 08	6.3775 E 08	1.0000 E 00	2.2857 E 03	1.4286 E 04	
OUNCE (AVDP)	2.8349 E 01	2.8349 E 07	2.8349 E 02	2.8349 E 05	3.1250 E 05	2.7902 E 05	4.3750 E 02	1.0000 E 00	6.4500 E 02	
POUND (AVDP)	4.5359 E 02	4.5359 E 08	4.5359 E 01	4.5359 E 04	5.0000 E 04	4.4643 E 04	7.0000 E 03	1.6000 E 01	1.0000 E 00	

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

TABLE D-6

CONVERSION FACTORS -- CONCENTRATION, DENSITY

DESIRED UNITS

<u>GIVEN UNITS</u>	<u>DESIRED UNITS</u>				<u>DESIRED UNITS</u>				<u>DESIRED UNITS</u>				<u>DESIRED UNITS</u>			
	GRAM PER CU METER	MG PER CU METER	MICROGRAM PER CU M	MICROGRAM PER LITER	GRAIN PER CU FT	OUNCE PER CU FT	LB PER CU FT	GRAM PER CU FT	LB PER CU METER							
GRAM PER CU METER	1.0000 E 00	1.0000 E 03	1.0000 E 06	1.0000 E 03	4.3700 E-01	9.9885 E-04	6.2428 E-03	2.8317 E-02	2.2046 E-03							
MG PER CU METER	1.0000 E-03	1.0000 E 00	1.0000 E 03	1.0000 E 00	4.3700 E-04	9.9885 E-07	6.2428 E-06	2.8317 E-05	2.2046 E-06							
MICROGRAM PER CU M	1.0000 E-06	1.0000 E-03	1.0000 E 00	1.0000 E-03	4.3700 E-07	9.9885 E-10	6.2428 E-11	2.8317 E-08	2.2046 E-09							
MICROGRAM PER LITER	9.9997 E-04	9.9997 E-01	9.9997 E 02	1.0000 E 00	4.3699 E-04	9.9883 E-07	6.2427 E-06	2.8316 E-05	2.2046 E-06							
GRAIN PER CU FT	2.2883 E 00	2.2883 E 03	2.2883 E 06	2.2883 E 03	1.0000 E 00	2.2857 E-03	1.4286 E-04	6.4799 E-02	5.0449 E-03							
OUNCE PER CU FT	1.0011 E 03	1.0011 E 06	1.0011 E 09	1.0012 E 06	4.3750 E 02	1.0000 E 00	6.2500 E-02	4.8349 E 01	2.2072 E 00							
LB PER CU FT	1.6018 E 04	1.6018 E 07	1.6018 E 10	1.6019 E 07	7.0000 E 03	1.6000 E 01	1.0000 E 00	4.5359 E 02	3.5314 E 01							
GRAM PER CU FT	3.5314 E 01	3.5314 E 04	3.5314 E 07	3.5315 E 04	1.5432 E 01	3.5274 E-02	2.2046 E-03	1.0000 E 00	7.7855 E-02							
LB PER CU METER	4.5359 E 02	4.5359 E 05	4.5359 E 08	4.5360 E 05	1.9822 E 02	4.5307 E-01	2.8317 E-02	1.2844 E 01	1.0000 E 00							

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

TABLE D-7

CONVERSION FACTORS-- PRESSURE

DESIRED UNITS

<u>GIVEN UNITS</u>	<u>DESIRED UNITS</u>					
	<u>MILLIBAR</u>	<u>BAR</u>	<u>ATMOSPHERE</u> DYNES PER SQ CM	<u>KG</u> PER SQ CM	<u>LB</u> PER SQ CM	<u>MM MERCURY</u> IN. MERCURY
MILLIBAR	1.0000 E 00	1.0000 E-03	9.8692 E-04	1.0000 E 03	1.4504 E-02	7.5006 E-01
BAR	1.0000 E 03	1.0000 E 00	9.8692 E-01	1.0000 E 06	1.4504 E 01	7.5006 E 02
ATMOSPHERE	1.0133 E 03	1.0133 E 00	1.0000 E 00	1.0133 E 06	1.4696 E 01	7.6000 E 02
DYNES PER SQ CM	1.0000 E-03	1.0000 E-06	9.8692 E-07	1.0000 E 00	1.4504 E-05	7.5006 E-05
KG PER SQ CM	9.8066 E 02	9.8066 E-01	9.8066 E-01	1.0000 E 05	1.4223 E 01	7.3556 E 02
LB PER SQ IN.	6.8947 E 01	6.8947 E-02	6.8046 E-02	7.0307 E-02	1.0000 E 00	5.1715 E 01
MM MERCURY	1.3332 E 00	1.3332 E-03	1.3158 E-03	1.3332 E 03	1.9387 E-02	1.0000 E 00
IN. MERCURY	3.3864 E 01	3.3864 E-02	3.3421 E-02	3.3864 E 04	4.9115 E-01	2.5400 E 01

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS -- POWER

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENFATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

TABLE D-9
CONVERSION FACTORS -- ENERGY PER UNIT AREA
DESIRED UNITS

GIVEN UNITS	DESIRED UNITS				
	LANGLEY	CAL (15) PER SQ CM	BTU PER SQ CM	INT KW-HR PER SQ M	ABS JOULES PER SQ CM
LANGLEY	1.0000 E 00	1.0000 E 00	3.6855 E 00	1.1624 E-02	4.1855 E 00
CAL (15) PER SQ CM	1.0000 E 00	1.0000 E 00	3.6855 E 00	1.1624 E-02	4.1855 E 00
BTU PER SQ FT	2.7133 E-01	2.7133 E-01	1.0000 E 00	3.1540 E-03	1.1357 E 00
INT KW-HR PER SQ M	8.6029 E 01	8.6029 E 01	3.1706 E 02	1.0000 E 00	3.6007 E 02
ABS JOULES PER SQ CM	2.3892 E-01	2.3892 E-01	8.8054 E-01	2.7772 E-03	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

D.3 GASEOUS EMISSIONS CALCULATIONS

General Equations

A. Parts Per Million (ppm) by Volume Dry:

$$\text{ppm} = \frac{(48.15)(\text{mg}_{\text{comp}})(T_m + 460)}{(\text{MW})(V_m)(P_m)}$$

$$\text{ppm @ } \underline{X} \% \text{ EA} = \text{ppm measured} \times \frac{(\text{Total Air @ meas'd. EA})}{(\text{Total Air @ } \underline{X} \% \text{ EA})}$$

where Total Air = 100 + EA (for O₂, equivalent Excess Air Used)

B. Pounds Per Hour (Lb/Hr.):

$$\text{Lb/Hr.} = \frac{(7.467 \times 10^{-6})(\text{mg}_{\text{comp}})(Q_s)(T_m + 460)}{(V_m)(P_m)}$$

where: mg_{comp} = weight of component sampled (mg)
 T_m = Temperature of meter (°F)
 MW = Molecular weight of component
 V_m = Metered gas volume (ACF)
 P_m = Metered pressure (in. Hg absolute)
 Q_s = Stack gas flow (SCFMD)

Specific Equations

SO₂, Sulfur Dioxide (MW = 64.1)

$$\text{ppm} = \frac{(0.7512)(\text{mg SO}_2)(T_m + 460)}{(P_m)(V_m)}$$

F⁻, Fluoride (MW = 19.0)

$$\text{ppm} = \frac{(2.534)(\text{mg F}^-)(T_m + 460)}{(P_m)(V_m)}$$

SO₃, Sulfur Trioxide (MW = 80.1)

$$\text{ppm} = \frac{(0.6011)(\text{mg SO}_3)(T_m + 460)}{(P_m)(V_m)}$$

Cl⁻, Chloride (MW = 35.5)

$$\text{ppm} = \frac{(1.356)(\text{mg Cl}^-)(T_m + 460)}{(P_m)(V_m)}$$

Hg, Mercury (MW = 200.6)

$$\text{ppm} = \frac{(0.2400)(\text{mg Hg})(T_m + 460)}{(P_m)(V_m)}$$

HCl, Hydrogen Chloride (MW = 36.5)

$$\text{ppm} = \frac{(1.319)(\text{mg HCl})(T_m + 460)}{(P_m)(V_m)}$$

NO_x, Oxides of Nitrogen as NO₂ (MW = 46.0)

$$\text{ppm} = \frac{(1.047)(\text{mg NO}_2)(T_F + 460)}{(P_i - P_f)(V_F, CF)}$$

F denotes flask
 i denotes initial
 f denotes final
 V_F, CF = liters/28.32

D.4 TGV ULTIMATE LIQUID/SOLID CALCULATIONS

HF	= Heat content of fuel as fired (Btu/Lb)
Pb	= Barometric pressure (in.Hg)
Ps	= Static pressure (in.Hg)
RF	= Fuel firing rate (lb/hr)
Ts	= Flue gas temperature (^o F)
%C	= Percent carbon in fuel by weight
%CO	= Percent carbon monoxide in flue gas
%CO ₂	= Percent carbon dioxide in flue gas
%H	= Percent hydrogen in fuel by weight
%H ₂ O _A	= Percent water in ambient air
%H ₂ O _F	= Percent water from fuel analysis
%N ₂	= Percent nitrogen in flue gas
%O	= Percent oxygen in fuel by weight
%O ₂	= Percent oxygen in flue gas
%S	= Percent sulfur in fuel by weight

1. Heat Input (MM Btu/hr)

$$HI = \frac{RF \times HF}{1,000,000}$$

2. Theoretical volume of air required for combustion (SCFD/lb fuel)

$$VT = (\%C \times 1.514 + \%H \times 4.54 + \%S \times 0.568 - \%O \times .568) \times 530/520$$

3. Volume of dry combustion products (SCFD/lb fuel)

$$Vc = (\%C \times 1.505 + \%H \times 3.57 + \%S \times 0.557 + \%N \times 0.135 - \%O \times 0.488) \times 530/520$$

4. Volume of water produced from combustion (SCF/lb fuel)

$$Vw = (\%H \times 1.89 + \%H_2O_F \times .21) \times 530/520$$

5. Total volume of combustion products (SCF/lb fuel)

$$V_{Total} = Vc + Vw$$

6. Volume of carbon dioxide produced (SCFD/lb fuel)

$$VCO_2 = \%C \times 0.315 \times 530/520$$

7. Ultimate percent carbon dioxide

$$UCO_2 = 100 \times VCO_2/Vc$$

8. Theoretical dry gas flow rate (SCFMD)

$$RT = \frac{Vc \times RF}{60}$$

9. Percent excess air as measured based on %CO₂

$$\%ECO_2 = \frac{100}{VT} \times 100 \times \left[\frac{VCO_2}{\%CO_2} - Vc \right]$$

10. Percent excess air as measured using O₂

$$\%EO_2 = 100 \times \left[\frac{\%O_2 - 0.5 \times \%CO}{.264 \times \%N_2 - (\%O_2 - .5 \times \%CO)} \right]$$

11. Total volume of air required based on %CO₂ (SCFD/lb fuel)

$$VTCO_2 = (1 - \frac{\%ECO_2}{100}) \times VT$$

12. Total volume of air required based on %O₂ (SCFD/lb fuel)

$$VTO_2 = (1 - \frac{\%EO_2}{100}) \times VT$$

13. Volume of excess air as measured based on %CO₂ (SCFD/lb fuel)

$$VECO_2 = (\%ECO_2/100) \times VT$$

14. Volume of excess air as measured based on %O₂ (SCFD/lb fuel)

$$VEO_2 = (\%EO_2/100) \times VT$$

15. Calculated flue gas moisture based on %CO₂ (% Volume)

$$\%H_2OCO_2 = \frac{(\frac{\%H_2OA}{100} \times VTCO_2 + Vw) \times 100}{V_{Total} + VECO_2 + \frac{\%H_2OA}{100} \times VTCO_2}$$

16. Calculated flue gas moisture based on %O₂ (% volume)

$$\%H_2OO_2 = \frac{\left[\frac{\%H_2OA}{100} \times VTO_2 + Vw \right] \times 100}{V_{Total} + VEO_2 + \frac{\%H_2OA}{100} \times VTO_2}$$

17. Combustion air plus leakage based on %CO₂ (SCFMDX)

$$VLCO_2 = (1 - \%ECO_2/100) \times VT \times RF/60$$

18. Combustion air plus leakage based on %O₂ (SCFM DX)

$$VLO_2 = (1 + \%EO_2/100) \times VT \times RF/60$$

19. Standard gas flow rate dry based on %CO₂ (SCFM DX)

$$RGWCO_2 = (RT + \%ECO_2 \times VT \times RF)/6000$$

20. Standard gas flow rate dry based on %O₂ (SCFM DX)

$$RGWO_2 = (RT + \%EO_2 \times VT \times RF)/6000$$

21. Standard gas flow rate wet based on %CO₂ (SCFM WX)

$$RGOCO_2 = RGWCO_2 / (1 - \%H_2OCO_2/100)$$

22. Standard gas flow rate wet based on %O₂ (SCFM WX)

$$RGDO_2 = RGWO_2 / (1 - \%H_2OO_2/100)$$

23. Stack gas flow rate wet based on %CO₂ (ACFM WX)

$$RACO_2 = RGWCO_2 \times \frac{(Ts + 460)}{530} \times \frac{29.92}{(Pb + Ps/13.6)}$$

24. Stack gas flow rate wet based on %O₂ (ACFM WX)

$$RAO_2 = RGWO_2 \times \frac{(Ts + 460)}{530} \times \frac{29.92}{(Pb + Ps/13.6)}$$

OPTION TWO

25. Percent oxygen in flue gas as calculated from carbon dioxide input

$$O_2 = 100 \frac{[2095 \times \frac{\%ECO_2}{100} \times VT]}{[V_c + \frac{\%ECO_2}{100} \times VT]}$$

26. Percent nitrogen in flue gas as calculated from oxygen and carbon dioxide in flue gas.

$$N_2 = 100 - CO_2 - O_2$$

OPTION THREE

27. Carbon dioxide in the flue gas as calculated from excess air.

$$CO_2 = 100 \frac{(VCO_2 + 0.0003 \times \%EO_2 \times VT)}{[V_c + \frac{\%EO_2}{100} \times VT]}$$

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