

Waste Management

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List of Abbreviations

Abbreviation	Definition	Abbreviation	Definition
3P	Pollution prevention pays	MACT	Maximum achievable control technology
ABS	Alkyl benzene sulfonate	MSDA	Material safety data sheets
ACC	Annualized capital costs	MSW	Municipal solid waste
BACT	Best available control technology	MWC	Municipal waste combustors
BAT	Best available technology	MWI	Medical waste incinerators
BCOD	Biodegradable chemical oxygen demand	NBOD	Nitrogenous biochemical oxygen demand
BCT	Best conventional technology	NIMBY	Not in my back yard
BOD	Biochemical oxygen demand	NPDES	National pollutant discharge elimination system
BSRT	Biomass solids retention time	NSPS	New source performance standards
BTEX	Benzene, toluene, xylene	PCB	Polychlorinated biphenyl
CAA	Clean Air Act	PIES	Pollution prevention information exchange systems
CAAA	Clean Air Act Amended	PM	Particulate matter
CCP	Comprehensive costing procedures	POTW	Publicly owned treatment work
CFR	Code of federal regulations	PPIC	Pollution prevention information clearinghouse
COD	Chemical oxygen demand	PSD	Prevention of significant deterioration
CPI	Chemical process industries	RCRA	Resource Conservation and Recovery Act
CRF	Capital recovery factor	RDF	Refuse-derived fuel
CTDMPLUS	Complex terrain dispersion model plus algorithms for unstable situations	SARA	Superfund Amendments and Reauthorization Act
CWRT	Center for Waste Reduction Technologies	SCR	Selective catalytic reduction
DCF	Direct installation cost factor	SCS	Stationary-container systems
DO	Dissolved oxygen	SE	Strength of the treated waste
DRE	Destruction and removal efficiency	SMART	Save money and reduce toxics
EBCT	Empty bed contact time	SO	Strength of the untreated waste
EPA	Environmental Protection Agency	SS	Suspended solids
FML	Flexible membrane liner	TCC	Total capital cost
GAX	Granular activated carbon	TCP	Traditional costing procedures
HAPS	Hazardous air pollutants	TGNMO	Total gas nonmethane organics
HAZWOPER	Hazardous waste operators	TOC	Total organic carbon
HCS	Hauled-container systems	TSA	Total systems approach
HRT	Reactor hydraulic retention time	TSCA	Toxic Substances Control Act
HSWA	Hazardous and Solid Waste Act	TSD	Treatment, storage, and disposal
I-TEF	International toxic equivalency factor	UASB	Upflow anaerobic sludge blanket
ICF	Indirect installation cost factor	VOC	Volatile organic compound
ISO	International Organization for Standardization	VOST	Volatile organic sampling train
LCA	Life cycle assessment	VSS	Volatile suspended solids
LCC	Life cycle costing	WRAP	Waste reduction always pays
LOX	Liquid oxygen	WTE	Waste-to-energy (systems)

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INTRODUCTION TO WASTE MANAGEMENT

In this section, a number of references are made to laws and procedures that have been formulated in the United States with respect to waste management. An engineer handling waste-management problems in another country would well be advised to know the specific laws and regulations of that country. Nevertheless, the treatment given here is believed to be useful as a general guide.

Multimedia Approach to Environmental Regulations in the United States Among the most complex problems to be faced by industry during the 1990s is the proper control and use of the natural environment. In the 1970s the engineering profession became acutely aware of its responsibility to society, particularly for the protection of public health and welfare. The decade saw the formation and rapid growth of the U.S. Environmental Protection Agency (EPA) and the passage of federal and state laws governing virtually every aspect of the environment. The end of the decade, however, brought a realization that only the more simplistic problems had been addressed. A limited number of large sources had removed substantial percentages of a few readily definable air pollutants from their emissions. The incremental costs to improve the removal percentages would be significant and would involve increasing numbers of smaller sources, and the health hazards of a host of additional toxic pollutants remained to be quantified and control techniques developed.

Moreover, in the 1970s, air, water, and waste were treated as separate problem areas to be governed by their own statutes and regulations. Toward the latter part of the decade, however, it became obvious that environmental problems were closely interwoven and should be treated in concert. The traditional type of regulation—command and control—had severely restricted compliance options.

The 1980s began with EPA efforts redirected to take advantage of the case-specific knowledge, technical expertise, and imagination of those being regulated. Providing plant engineers with an incentive to find more efficient ways of abating pollution would greatly stimulate innovation in control technology. This is a principal objective, for

example, of EPA's "controlled trading" air pollution program, established in the Offsets Policy Interpretative Ruling issued by the EPA in 1976, with statutory foundation given by the Clean Air Act Amendments of 1977. The Clean Air Act Amendments of 1990 expanded the program even more to the control of sulfur oxides under Title IV. In effect, a commodities market on "clean air" was developed.

The rapidly expanding body of federal regulation presents an awesome challenge to traditional practices of corporate decision-making, management, and long-range planning. Those responsible for new plants must take stock of the emerging requirements and construct a fresh approach.

The full impact of the Clean Air Act Amendments of 1990, the Clean Water Act, the Safe Drinking Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Responsibility, Compensation and Liability (Superfund) Act, and the Toxic Substances Control Act is still not generally appreciated. The combination of all these requirements, sometimes imposing conflicting demands or establishing differing time schedules, makes the task of obtaining all regulatory approvals extremely complex.

One of the dominant impacts of environmental regulations is that the lead time required for the planning and construction of new plants is substantially increased. When new plants generate major environmental complexities, the implications can be profound. Of course, the exact extent of additions to lead time will vary widely from one case to another, depending on which permit requirements apply and on what difficulties are encountered. For major expansions in any field of heavy industry, however, the delay resulting from federal requirements could conceivably add 2 to 3 years to total lead time. Moreover, there is always the possibility that regulatory approval will be denied. So, contingency plans for fulfilling production needs must be developed.

Any company planning a major expansion must concentrate on environmental factors from the outset. Since many environmental approvals require a public hearing, the views of local elected officials and the com-

munity at large are extremely important. To an unprecedented degree, the political acceptability of a project can now be crucial.

Plant Strategies At the plant level, a number of things can be done to minimize the impact of environmental quality requirements. These include:

1. Maintaining an accurate source-emission inventory
2. Continually evaluating process operations to identify potential modifications that might reduce or eliminate environmental impacts
3. Ensuring that good housekeeping and strong preventive-maintenance programs exist and are followed
4. Investigating available and emerging pollution-control technologies
5. Keeping well informed of the regulations and the directions in which they are moving
6. Working closely with the appropriate regulatory agencies and maintaining open communications to discuss the effects that new regulations may have
7. Keeping the public informed through a good public-relations program.

It is unrealistic to expect that at any point in the foreseeable future Congress will reverse direction, reduce the effect of regulatory controls, or reestablish the preexisting legal situation in which private companies are free to construct major industrial facilities with little or no restraint by federal regulation.

Corporate Strategic Planning Contingency planning represents an essential component of sound environmental planning for a new plant. The environmental uncertainties surrounding a large capital project should be specified and related to other contingencies (such as marketing, competitive reactions, politics, foreign trade, etc.) and mapped out in the overall corporate strategy.

Environmental factors should also be incorporated into a company's technical or research and development program. Since the planning horizons for new projects may now extend to 5 to 10 years, R&D programs can be designed for specific projects. These may include new process modifications or end-of-pipe control technologies.

Another clear need is to integrate environmental factors into financial planning for major projects. It must be recognized that strategic environmental planning is as important to the long-range goal of the corporation as is financial planning. Trade-off decisions regarding financing may have to change as the project goes through successive stages of environmental planning and permit negotiations. For example, requirements for the use of more expensive pollution control technology may significantly increase total project costs; or a change from end-of-pipe to process modification technology may preclude the use of industrial revenue bond financing under Internal Revenue Service (IRS) rules. Regulatory delays can affect assumptions as to both the rate of expenditure and inflation factors. Investment, production, environmental, and legal factors are all interrelated and can have a major impact on corporate cash flow.

Most companies must learn to deal more creatively with local officials and public opinion. The social responsibility of companies can become an extremely important issue. Companies should apply thoughtfulness and skill to the timing and conduct of public hearings. Management must recognize that local officials have views and constituencies that go beyond attracting new jobs.

From all these factors, it is clear that the approval and construction of major new industrial plants or expansions is a far more complicated operation than it has been in the past, even the recent past. Stringent environmental restrictions are likely to preclude construction of certain facilities at locations where they otherwise might have been built. In other cases, acquisition of required approvals may generate a heated technical and political debate that can drag out the regulatory process for several years.

In many instances, new requirements may be imposed while a company is seeking approval for a proposed new plant. Thus, companies intending to expand their basic production facilities should anticipate their needs far in advance, begin preparation to meet the regulatory challenge they will eventually confront, and select sites with careful consideration of environmental attributes. It is the objective of this section to assist the engineer in meeting this environmental regulatory challenge.

UNITED STATES AIR QUALITY LEGISLATION AND REGULATIONS

Although considerable federal legislation dealing with air pollution has been enacted since the 1950s, the basic statutory framework now in effect was established by the Clean Air Act of 1970; amended in 1974 to deal with energy-related issues; amended in 1977, when a number of amendments containing particularly important provisions associated with the approval of new industrial plants were adopted; and amended in 1990 to address toxic air pollutants and ozone non-attainment areas.

Clean Air Act of 1970 The Clean Air Act of 1970 was founded on the concept of attaining National Ambient Air Quality Standards (NAAQS). Data were accumulated and analyzed to establish the quality of the air, identify sources of pollution, determine how pollutants disperse and interact in the ambient air, and define reductions and controls necessary to achieve air-quality objectives.

EPA promulgated the basic set of current ambient air-quality standards in April 1971. The specific regulated pollutants were particulates, sulfur dioxide, photochemical oxidants, hydrocarbons, carbon monoxide, and nitrogen oxides. In 1978, lead was added. Table 25-1 enumerates the present standards.

To provide basic geographic units for the air-pollution control program, the United States was divided into 247 air quality control regions (AQCRs). By 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 the degree of reduction called for was determined. States were required by EPA to develop state implementation plans (SIPs) to achieve compliance.

The act also directed EPA to set new source performance standards (NSPS) for specific industrial categories. New plants were required to use the best system of emission reduction available. EPA gradually issued these standards, which now cover a number of basic industrial categories (as listed in Table 25-2). The 1977 amendments to the Clean Air Act directed EPA to accelerate the NSPS program and included a regulatory program to prevent significant deterioration in those areas of the country where the NAAQS were being attained.

Finally, Sec. 112 of the Clean Air Act required that EPA promulgate National Emission Standards for Hazardous Air Pollutants (NESHAPs). Between 1970 and 1989, standards were promulgated for asbestos, beryllium, mercury, vinyl chloride, benzene, arsenic, radionuclides, and coke-oven emissions.

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

EPA established an area classification scheme to be applied in all such regions. The basic idea was to allow a moderate amount of industrial development but not enough to degrade air quality to a point at which it barely complied with standards. In addition, states were to designate certain areas where pristine air quality was especially desirable. All air-quality areas were categorized as Class I, Class II, or Class III. Class I areas were pristine areas subject to the tightest control. Permanently designated Class I areas included international parks, national wilderness areas, memorial parks exceeding 5000 acres, and national parks exceeding 6000 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 them. Class II areas were areas of moderate industrial growth. Class III areas were areas of major industrialization. Under EPA regulations promulgated in December 1974, all areas were initially categorized as Class II. States were authorized to reclassify specified areas as Class I or Class III.

The EPA regulations also established another critical concept

TABLE 25-1 National Primary and Secondary Ambient Air Quality Standards

Pollutant	Averaging time	Primary standards	Secondary standards
Sulfur oxides	Annual arithmetic mean 24 h 3 h	80 µg/m ³ (0.03 ppm) 365 µg/m ³ (0.14 ppm)	
Particulate matter (PM ₁₀ , particulates with aerodynamic diameter less than or equal to 10 microns)	Annual geometric mean 24 h	75 µg/m ³ 260 µg/m ³	1,300 µg/m ³ (0.5 ppm) 60 µg/m ³ 150 µg/m ³
Ozone	1 h	240 µg/m ³ (0.12 ppm)	Same as primary standard
Carbon monoxide	8 h 1 h	10 mg/m ³ 40 mg/m ³ (35 ppm)	Same as primary standard
Nitrogen oxides	Annual arithmetic mean	100 µg/m ³ (0.05 ppm)	Same as primary standard
Lead	3 months	1.5 µg/m ³	Same as primary standard

NOTE: National standards, other than those based on annual arithmetic means or annual geometric means, are not to be exceeded more than once a year.

TABLE 25-2 Source Categories for Which New Source Performance Standards Have Been Set as of 1991

Fossil-Fuel-Fired Steam Generators for Which Construction Commenced after August 17, 1971	Primary Lead Smelters	Pressure-Sensitive Tape and Label Surface Coating Operations
Electric Utility Steam Generating Units for Which Construction Commenced after September 18, 1978	Primary Aluminum Reduction Plants	Metal Coil Surface Coating
Industrial-Commercial-Institutional Steam Generating Units	Phosphate Fertilizer Industry: Wet-Process Phosphoric Acid Plants	Asphalt Processing and Asphalt Roofing Manufacture
Incinerators	Phosphate Fertilizer Industry: Superphosphoric Acid Plants	Equipment Leaks of VOC in the Synthetic Organic Chemicals Manufacturing Industry
Portland Cement Plants	Phosphate Fertilizer Industry: Diammonium Phosphate Plants	Beverage Can Surface Coating Industry
Nitric Acid Plants	Phosphate Fertilizer Industry: Triple Superphosphate Plants	Bulk Gasoline Terminals
Sulfuric Acid Plants	Phosphate Fertilizer Industry: Granular Triple Superphosphate Storage Facilities	New Residential Wood Heaters
Asphalt Concrete Plants	Coal Preparation Plants	Rubber Tire Manufacturing Industry
Petroleum Refineries	Ferroalloy Production Facilities	Flexible Vinyl and Urethane Coating and Printing
Storage Vessels for Petroleum Liquids for Which Construction, Reconstruction, or Modification Commenced after June 11, 1973, and Prior to May 19, 1978	Steel Plants: Electric Arc Furnaces Constructed after October 21, 1974, and on or before August 17, 1983	Equipment Leaks of VOC in Petroleum Refineries
Storage Vessels for Petroleum Liquids for Which Construction, Reconstruction, or Modification Commenced after May 18, 1978, and Prior to July 23, 1984	Steel Plants: Electric Arc Furnaces and Argon-Oxygen Decarburization Vessels Constructed after August 7, 1983	Synthetic Fiber Production Facilities
Volatile Organic Liquid Storage Vessels (Including Petroleum Liquid Storage Vessels) for Which Construction, Reconstruction, or Modification Commenced after July 23, 1984	Kraft Pulp Mills	Petroleum Dry Cleaners
Secondary Lead Smelters	Glass Manufacturing Plants	Equipment Leaks of VOC from Onshore Natural Gas Processing Plants
Secondary Brass and Bronze Production Plants	Grain Elevators	Onshore Natural Gas Processing; SO ₂ Emissions
Primary Emissions from Basic Oxygen Process Furnaces for Which Construction Commenced after June 11, 1973	Surface Coating of Metal Furniture	Nonmetallic Mineral Processing Plants
Secondary Emissions from Basic Oxygen Process Steelmaking Facilities for Which Construction Commenced after January 20, 1983	Stationary Gas Turbines	Wool Fiberglass Insulation Manufacturing Plants
Sewage Treatment Plants	Lime Manufacturing Plants	VOC Emissions from Petroleum Refinery Wastewater Systems
Primary Copper Smelters	Lead-Acid Battery Manufacturing Plants	Magnetic Tape Coating Facilities
Primary Zinc Smelters	Metallic Mineral Processing Plants	Industrial Surface Coating; Surface Coating of Plastic Parts for Business Machines
	Automobile and Light-Duty Truck Surface Coating Operations	Volatile Organic Compound Emissions from Synthetic Organic Chemical Manufacturing Industry (SOCMI) Air Oxidation Unit Processes
	Phosphate Rock Plants	Volatile Organic Compound Emissions from Synthetic Organic Chemical Manufacturing Industry Distillation Operations
	Ammonium Sulfate Manufacture	Polymeric Coating of Supporting Substrates Facilities
	Graphic Arts Industry: Publication Rotogravure Printing	

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 (see Table 25-3). To assure that the increments would not be used up hastily, EPA specified that each major new plant must install best available control technology (BACT) to limit 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 requires that every new source undergo preconstruction review. The regulations prohibited a company from commencing construction on a new source until the review had been completed and provided that, as part of the review procedure, public notice should be given and an opportunity provided for a public hearing on any disputed questions.

Sources Subject to Prevention of Significant Deterioration (PSD) Sources subject to PSD regulations (40 CFR, Sec. 52.21, Aug. 7, 1980) are major stationary sources and major modifications located in attainment areas and unclassified areas. A major stationary source was defined as any source listed in Table 25-4 with the potential to emit 100 tons per year or more of any pollutant regulated under the Clean Air Act (CAA) or any other source with the potential to emit 250 tons per year or more of any CAA pollutant. The “potential to emit” is defined as the maximum capacity to emit the pollutant under applicable emission standards and permit conditions (after application of any air pollution control equipment) excluding secondary emissions. A “major modification” is defined as any physical or operational change of a major stationary source producing a “significant net emissions increase” of any CAA pollutant (see Table 25-5).

Ambient monitoring is required of all CAA pollutants with emissions greater than or equal to Table 25-5 values for which there are

TABLE 25-3 Prevention of Significant Deterioration (PSD) Air-Quality Increments

	Maximum allowable increase over baseline air quality, $\mu\text{g}/\text{m}^3$			Primary ambient air-quality standard, $\mu\text{g}/\text{m}^3$
	Class I	Class II	Class III	
Particulate matter				
Annual geometric mean	5	19	37	75
24-h maximum	10	37	75	260
SO ₂				
Annual arithmetic mean	2	20	40	80
24-h maximum	5	91	182	365
3-h maximum	25	512	700	1300*

*Secondary standard rather than primary standard.

TABLE 25-4 Sources Subject to PSD Regulation if Their Potential to Emit Equals or Exceeds 100 Tons per Year

Fossil-fuel-fired steam electric plants of more than 250 million Btu/h heat input
Coal-cleaning plants (with thermal dryers)
Kraft-pulp mills
Portland-cement plants
Primary zinc smelters
Iron and steel mill plants
Primary aluminum-ore-reduction plants
Primary copper smelters
Municipal incinerators capable of charging more than 250 tons of refuse per day
Hydrofluoric, sulfuric, and nitric acid plants
Petroleum refineries
Lime plants
Phosphate-rock-processing plants
Coke-oven batteries
Sulfur-recovery plants
Carbon-black plants (furnace process)
Primary lead smelters
Fuel-conversion plants
Sintering plants
Secondary metal-production plants
Chemical-process plants
Fossil-fuel boilers (or combinations thereof) totaling more than 250 million Btu/h heat input
Petroleum-storage and -transfer units with total storage capacity exceeding 300,000 bbl
Taconite-ore-processing plants
Glass-fiber-processing plants
Charcoal-production plants

TABLE 25-5 Significant Net Emissions Increase

Pollutant	Tons/year
CO	100
NO _x (as NO ₂)	40
SO ₂	40
Particulate matter	25
Ozone	40 of volatile organic compounds
Lead	0.6
Asbestos	0.007
Beryllium	0.0004
Mercury	0.1
Vinyl chloride	1
Fluorides	3
Sulfuric acid mist	7
Hydrogen sulfide	10
Total reduced sulfur	10
Reduced-sulfur compounds	10
Other CAA pollutants	>0

NAAQS. Continuous monitoring is also required for other CAA pollutants for which the EPA or the state determines that monitoring is necessary. The EPA or the state may exempt any CAA pollutant from these monitoring requirements if the maximum air-quality impact of the emissions increase is less than the values in Table 25-6 or if present concentrations of the pollutant in the area that the new source would affect are less than the Table 25-6 values. The EPA or the state

may accept representative existing monitoring data collected within 3 years of the permit application to satisfy monitoring requirements.

EPA regulations provide exemption from BACT and ambient air-impact analysis if the modification that would increase emissions is accompanied by other changes within the plant that would net a zero increase in total emissions. This exemption is referred to as the "bubble" or "no net increase" exemption.

A full PSD review would include a case-by-case determination of the controls required by BACT, an ambient air-impact analysis to determine whether the source might violate applicable increments or air-quality standards; an assessment of the effect on visibility, soils, and vegetation; submission of monitoring data; and full public review.

EPA regulations exempted smaller sources from the major elements of PSD review and, in particular, relieved those sources from compliance with BACT (though they still had to comply with applicable NSPS as well as with requirements under the SIP program). Smaller sources were also exempted from conducting ambient air-impact analysis and submitting data supporting an ambient air-quality analysis. Smaller sources, however, were not exempted from the program altogether. They remained subject to the statutory requirements to obtain preconstruction approval, including procedures for public review, and they still might be required, at EPA request, to submit data supporting their applications. Also, if emissions from a smaller source would affect a Class I area or if an applicable increment were already being violated, the full PSD requirements for ambient air-impact analysis would apply.

Nonattainment (NA) Those areas of the United States failing to attain compliance with ambient air-quality standards were considered nonattainment areas. New plants could be constructed in nonattainment areas 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 ambient air-quality standards. Specifically, (1) the new source must be equipped with pollution controls to assure lowest achievable emission rate (LAER), which in no case can be less stringent than any applicable NSPS; (2) all existing sources owned by an applicant in the same region must be in compliance with applicable state implementation plan requirements or be under an approved schedule or an enforcement order to achieve such compliance; (3) the applicant must have sufficient offsets to more than

TABLE 25-6 Concentration Impacts below Which Ambient Monitoring May Not Be Required

	$\mu\text{g}/\text{m}^3$	Average time
CO	575	8-h maximum
NO ₂	14	24-h maximum
TSP	10	24-h maximum
SO ₂	13	24-h maximum
Lead	0.1	24-h maximum
Mercury	0.25	24-h maximum
Beryllium	0.0005	24-h maximum
Fluorides	0.25	24-h maximum
Vinyl chloride	15	24-h maximum
Total reduced sulfur	10	1-h maximum
H ₂ S	0.04	1-h maximum
Reduced-sulfur compounds	10	1-h maximum

make up for the emissions to be generated by the new source (after application of LAER); and (4) the emission offsets must provide "a positive net air quality benefit in the affected area."

LAER was deliberately a technology-forcing standard of control. The statute stated that LAER must reflect (1) the most stringent emission limitation contained in the implementation plan of any state for such category of sources unless the applicant can demonstrate that such a limitation is not achievable, or (2) the most stringent 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 provided no instruction that economics be considered.

For existing sources emitting pollutants for which the area is nonattainment, reasonable available control technology (RACT) would be required. EPA defines RACT by industrial category.

Controlled-Trading Program The legislation enacted under the Clean Air Act Amendments of 1977 provided the foundation for EPA's controlled-trading program, the essential elements of which include:

- Bubble policy (or bubble exemption under PSD)
- Offsets policy (under nonattainment)
- Banking and brokerage (under nonattainment)

While these different policies vary broadly in form, their objective is essentially the same: to substitute flexible economic-incentive systems for the current rigid, technology-based regulations that specify exactly how companies must comply. These market mechanisms have made regulating easier for EPA and less burdensome and costly for industry.

Bubble Policy The bubble concept introduced under PSD provisions of the Clean Air Act Amendments of 1977 was formally proposed as EPA policy on Jan. 18, 1979, the final policy statement being issued on Dec. 11, 1979. The bubble policy allows a company to find the most efficient way to control a plant's emissions as a whole rather than by meeting individual point-source requirements. If it is found less expensive to tighten control of a pollutant at one point and relax controls at another, this would be possible as long as the total pollution from the plant would not exceed the sum of the current limits on individual point sources of pollution in the plant. Properly applied, this approach would promote greater economic efficiency and increased technological innovation.

There are some restrictions, however, in applying the bubble concept:

1. The bubble may be only used for pollutants in an area where the state implementation plan has an approved schedule to meet air-quality standards for that pollutant.
2. The alternatives used must ensure that air-quality standards will be met.
3. Emissions must be quantifiable, and trades among them must be even. Each emission point must have a specific emission limit, and that limit must be tied to enforceable testing techniques.
4. Only pollutants of the same type may be traded; that is, particulates for particulates, hydrocarbons for hydrocarbons, etc.
5. Control of hazardous pollutants cannot be relaxed through trades with less toxic pollutants.
6. Development of the bubble plan cannot delay enforcement of federal and state requirements.

Some additional considerations must be noted:

1. The bubble may cover more than one plant within the same area.
2. In some circumstances, states may consider trading open dust emissions for particulates (although EPA warns that this type of trading will be difficult).
3. EPA may approve compliance date extensions in special cases. For example, a source may obtain a delay in a compliance schedule to install a scrubber if such a delay would have been permissible without the bubble.

EPA will closely examine particulate size distribution in particulate emission trades because finer particulates disperse more widely, remain in the air longer, and frequently are associated with more adverse health effects.

It will be the responsibility of industry to suggest alternative control approaches and demonstrate satisfactorily that the proposal is equivalent in pollution reduction, enforceability, and environmental impact to existing individual process standards.

Offsets Policy Offsets were EPA's first application of the concept that one source could meet its environmental protection obligations by getting another source to assume additional control actions. In nonattainment areas, pollution from a proposed new source, even one that controls its emissions to the lowest possible level, would aggravate existing violations of ambient air-quality standards and trigger the statutory prohibition. The offsets policy provided these new sources with an alternative. The source could proceed with construction plans, provided that:

1. The source would control emissions to the lowest achievable level.
2. Other sources owned by the applicant were in compliance or on an approved compliance schedule.
3. Existing sources were persuaded to reduce emissions by an amount at least equal to the pollution that the new source would add.

Banking and Brokerage Policy EPA's banking policy is aimed at providing companies with incentives to find more offsets. Under the original offset policy, a firm shutting down or modifying a facility could apply the reduction in emissions to new construction elsewhere in the region only if the changes were made simultaneously. However, with banking a company can "deposit" the reduction for later use or sale. Such a policy will clearly establish that clean air (or the right to use it) has direct economic value.

Clean Air Act of 1990 In November, 1990, Congress adopted the Clean Air Act Amendments of 1990, providing substantial changes to many aspects of the existing CAAA. The concepts of NAAQS, NSPS, and PSD remain virtually unchanged. However, significant changes have occurred in several areas that directly affect industrial facilities and electric utilities and air-pollution control at these facilities. These include changes and additions in the following major areas:

- Title I Nonattainment areas
- Title III Hazardous air pollutants
- Title IV Acid deposition control
- Title V Operating permits

Title I: Nonattainment Areas The existing regulations for nonattainment areas have been made more stringent in several areas. The CAAA of 1990 requires the development of comprehensive emission inventory-tracking for all nonattainment areas and establishes a classification scheme that defines nonattainment areas into levels of severity. For example, ozone nonattainment areas are designated as marginal, moderate, serious, severe (two levels), and extreme, with compliance deadlines of 3, 6, 9, 15-17, and 20 years, respectively, with each classification having more stringent requirements regarding strategies for compliance (see Table 25-7). Volatile organic compound (VOC) emissions reductions of 15 percent are required in moderate areas by 1996 and 3 percent a year thereafter for severe or extreme areas until compliance is achieved. In addition, the definition of a major source of ozone precursors (previously 100 tons per year of NO_x, CO, or VOC emissions) was redefined to as little as 10 tons per year in the extreme classification, with increased offset requirements of 1.5 to 1 for new and modified sources. These requirements place major constraints on affected industries in these nonattainment areas. A similar approach is being taken in PM₁₀ and CO nonattainment areas.

Title III: Hazardous Air Pollutants The Title III provisions on hazardous air pollutants (HAPs) represent a major departure from the previous approach of developing NESHAPs. While only eight HAPs were designated in the 20 years since enactment of the CAAA of 1970, the new CAAA of 1990 designated 189 pollutants as HAPs requiring regulation. These are summarized in Table VIII and will affect over 300 major source categories. Major sources are defined as any source (new or existing) that emits (after control) 10 tons a year or more of any regulated HAP or 25 tons a year or more of any combination of HAPs. The deadlines for promulgation of the source categories and appropriate emission standards are as follows:

- First 40 source categories November 15, 1992
- Coke oven batteries December 31, 1992
- 25% of all listed categories November 15, 1994

TABLE 25-7 Ozone Nonattainment Area Classifications and Associated Requirements

Nonattainment area classification	One-hour ozone concentration design value, ppm	Attainment date	Major source threshold level, tons VOCs/yr	Offset ratio for new/modified sources
Marginal	0.121–0.138	Nov. 15, 1993	100	1.1 to 1
Moderate	0.138–0.160	Nov. 15, 1996	100	1.15 to 1
Serious	0.160–0.180	Nov. 15, 1999	50	1.2 to 1
Severe	0.180–0.190	Nov. 15, 2005	25	1.3 to 1
	0.190–0.280	Nov. 15, 2007	25	1.3 to 1
Extreme	0.280 and up	Nov. 15, 2010	10	1.5 to 1

Publicly owned treatment works November 15, 1995
 50% of all listed categories November 15, 1997
 100% of all categories November 15, 2000

Each source will be required to meet maximum achievement control technology (MACT) requirements. For existing sources, MACT is defined as a stringency equivalent to the average of the best 12 percent of the sources in the category. For new sources, MACT is defined as the best controlled system. New sources are required to meet MACT immediately, while existing sources have three years from the date of promulgation of the appropriate MACT standard. As an early incentive, existing sources that undergo at least a 90 percent reduction in emissions of a HAP (or 95 percent for a hazardous particulate) prior to the promulgation of the MACT standard will be issued a six-year extension on the deadline for final compliance.

Title IV: Acid Deposition Control The Acid Deposition Control Program is designed to reduce emissions of SO₂ in the United States by 10 million tons per year, resulting in a net yearly emission of 8.9 million tons by the year 2000. Phase I of the program requires 111 existing uncontrolled coal-fired power plants (≥100 MW) to reduce emissions to 2.5 pounds of SO₂ per 10⁶ Btu by 1995 (1997 if scrubbers are used to reduce emissions by at least 90 percent). The reduction is to be accomplished by issuing all affected units emission “allowances” equivalent to what their annual average SO₂ emissions would have been in the years 1985–1987 based on 2.5 pounds SO₂ per 10⁶ Btu coal. The regulations represent a significant departure from previous regulations where specified SO₂ removal efficiencies were mandated; rather, the utilities will be allowed the flexibility of choosing which strategies will be used (e.g., coal washing, low-sulfur coal, flue gas desulfurization, etc.) and which units will be controlled, as long as the overall “allowances” are not exceeded. Any excess reduction in SO₂ by a utility will create “banked” emissions that can be sold or used at another unit.

Phase II of Title IV limits the majority of plants ≥20 MW and all plants ≥75 MW to maximum emissions of 1.2 pounds of SO₂ per 10⁶ Btu after the year 2000. In general, new plants would have to acquire banked emission allowances in order to be built. Emission allowances will be traded through a combination of sell/purchase with other utilities, EPA auctions and direct sales.

Control of NO_x under the CAAA of 1990 will be accomplished through the issuance of a revised NSPS in 1994, with the objective of reducing emissions by 2 million tons a year from 1980 emission levels. The technology being considered is the use of low-NO_x burners (LNBs). The new emission standards will not apply to cyclone and wet bottom boilers, unless alternative technologies are found, as these cannot be retrofitted with existing LNB technologies.

Title V: Operating Permits Title V of the 1990 Clean Air Act Amendments established a new operating permit program to be administered by state agencies in accordance with federal guidelines. An approved state program will basically require a source to obtain a permit that covers each and every requirement applicable to the source under the Clean Air Act. A major impact of the Title V program is that sources are required to implement measures to demonstrate routinely that they are operating in compliance with permit terms. This represents a dramatic shift from previous practices where, to bring an enforcement action, regulatory authorities were required to demonstrate that a source was in noncompliance.

Initially, all “major” sources of air pollution are required to obtain an operating permit. However, any state permitting authority may extend the applicability of the operating permit to minor sources as

well. Once a source is subject to the permit program as a major source for any one pollutant, emissions of every regulated air pollutant must be addressed in the permit application.

The operating permit must outline specifically how and when a source will be allowed to operate over the five-year term of the permit. The permit the state develops from an application becomes the principal mechanism for enforcement of all air-quality regulations. As such, it is critically important to submit an application that allows maximum operating flexibility.

Sources must also include in their permit applications monitoring protocols sufficient to document compliance with each permit term and condition.

The Title V operating permit requires the submission of at least five types of reports:

1. The initial compliance report
2. The annual compliance certification
3. Monitoring reports submitted at least every six months
4. Progress reports for sources not in compliance when the application is submitted
5. Prompt reports on any deviations from the permit terms

Permit fees are a mandatory element of the Title V program. In most cases, fees will be assessed for emissions on a dollars-per-ton-emitted basis.

Regulatory Direction The current direction of regulations and air-pollution control efforts is clearly toward significantly reducing the emissions to the environment of a broad range of compounds, including:

1. Volatile organic compounds and other ozone precursors (CO and NO_x)
2. Hazardous air pollutants, including carcinogenic organic emissions and heavy metal emissions
3. Acid rain precursors, including SO_x and NO_x

In addition, the PM₁₀ NAAQS will continue to place emphasis on quantifying and reducing particulate emissions in the less than 10-μm particle-size range. Particle size-specific emission factors have been developed for many sources, and size-specific emission standards have been developed in a number of states. These standards are addressing concerns related to HAP emissions of heavy metals, which are generally associated with the submicron particles.

Although it is not possible to predict the future, it is possible to prepare for it and influence it. It is highly recommended that maximum flexibility be designed into new air-pollution control systems to allow for increasingly more stringent emission standards for both particulates and gases. Further, it is everyone’s responsibility to provide a thorough review of existing and proposed new processes and to make every attempt to identify economical process modifications and/or material substitutions that reduce or, in some cases, eliminate both the emissions to the environment and the overdependency on retrofitted or new end-of-pipe control systems.

UNITED STATES WATER QUALITY LEGISLATION AND REGULATIONS

Federal Water Pollution Control Act In 1948, the original Federal Water Pollution Control Act (FWPCA) was passed. This act and its various amendments are often referred to as the Clean Water Act (CWA). It provided loans for treatment plant construction and temporary authority for federal control of interstate water pollution. The enforcement powers were so heavily dependent on the states as

to make the act almost unworkable. In 1956, several amendments to the FWPCA were passed that made federal enforcement procedures less cumbersome. The provision for state consent was removed by amendments passed in 1961, which also extended federal authority to include navigable waters in the United States.

In 1965 the Water Quality Act established a new trend in water pollution control. It provided that the states set water quality standards in accordance with federal guidelines. If the states failed to do so, the standards would be set by the federal government subject to a review hearing. In 1966, the Clean Water Restoration Act transferred the Federal Water Pollution Control Administration from the Department of Health, Education and Welfare to the Department of the Interior. It also gave the Interior Department the responsibility for the Oil Pollution Act.

After the creation of EPA in 1970, the EPA was given the responsibility previously held by the Department of the Interior with respect to water pollution control. In subsequent amendments to the FWPCA in 1973, 1974, 1975, 1976, and 1977, additional Federal programs were established. The goals of these programs were to make waterways of the United States fishable and swimmable by 1983 and to achieve zero discharge of pollutants by 1985. The National Pollutant Discharge Elimination System (NPDES) was established as the basic regulatory mechanism for water pollution control. Under this program, the states were given the authority to issue permits to "point-source" dischargers provided the dischargers gave assurance that the following standards would be met:

1. Source-specific effluent limitations (including New Source Performance Standards)
2. Toxic pollutant regulations (for specific substances regardless of source)

3. Regulations applicable to oil and hazardous substance liability

In order to achieve that stated water-quality goal of fishable and swimmable waters by 1983, each state was required by EPA to adopt water-quality standards that met or exceeded the Federal water quality criteria. After each state submitted its own water-quality standards, which were subsequently approved by EPA, the Federal criteria were removed from the Code of Federal Regulations. The state water-quality standards are used as the basis for establishing both point-source-based effluent limitations and toxic pollutant limitations used in issuing NPDES permits to point-source discharges.

Source-Based Effluent Limitations Under the FWPCA, EPA was responsible for establishing point-source effluent limitations for municipal dischargers, industrial dischargers, industrial users of municipal treatment works, and effluent limitations for toxic substances (applicable to all dischargers).

Standards promulgated or proposed by EPA under 40 CFR, Parts 402 through 699, prescribe effluent limitation guidelines for existing sources, standards of performance for new sources, and pretreatment standards for new and existing sources. Effluent limitations and new source performance standards apply to discharges made directly into receiving bodies of water. The new standards require best available technology (BAT) and are to be used by the states when issuing NPDES permits for all sources 18 months after they are made final by EPA. Pretreatment standards apply to waste streams from industrial sources that are sent to publicly owned treatment works (POTW) for final treatment. These regulations are meant to protect the POTW from any materials that would either harm the treatment facility or pass through untreated. They are to be enforced primarily by the local POTW. These standards are applicable to particular classes of point-sources and pertain to discharges into navigable waters without regard to the quality of the receiving water. Standards are specific for numerous subcategories under each point-source category.

Limitations based upon application of the best practicable control technology currently available (BPT) apply to existing point-sources and should have been achieved by July 1, 1977. Limitations based upon application of the BATEA (Best Available Technology Economically Achievable) that will result in reasonable further progress toward elimination of discharges had to be achieved by July 1, 1984.

Clean Water Act of 1977 The 1977 Clean Water Act directed EPA to review all BAT guidelines for conventional pollutants in those industries not already covered.

On August 23, 1978 (43 FR 37570), the EPA proposed a new approach to the control of conventional pollutants by effluent guideline limitations. The new guidelines were known as best conventional pollutants control technology (BCT). These guidelines replaced the existing BAT limitations, which were determined to be unreasonable for certain categories of pollutants.

In order to determine if BCT limitations would be necessary, the cost effectiveness of conventional pollutant reduction to BAT levels beyond BPT levels had to be determined and compared to the cost of removal of this same amount of pollutant by a publicly owned treatment works of similar capacity. If it was equally cost-effective for the industry to achieve the reduction required for meeting the BAT limitations as the POTW, then the BCT limit was made equal to the BAT level. When this test was applied, the BAT limitation set for certain categories were found to be unreasonable. In these subcategories EPA proposed to remove the BAT limitations and revert to the BPT limitations until BCT control levels could be formulated.

Control of Toxic Pollutants Since the early 1980s, EPA's water-quality standards guidance placed increasing importance on toxic pollutant control. The Agency urged states to adopt criteria into their standards for the priority toxic pollutants, particularly those for which EPA had published criteria guidance. EPA also provided guidance to help and support state adoption of toxic pollutant standards with the *Water Quality Standards Handbook* (1983) and the *Technical Support Document for Water Quality Toxics Control* (1985 and 1991).

Despite EPA's urging and guidance, state response was disappointing. A few states adopted large numbers of numeric toxic pollutant criteria, primarily for the protection of aquatic life. Most other states adopted few or no water-quality criteria for priority toxic pollutants. Some relied on "free from toxicity" criteria and so-called "action levels" for toxic pollutants or occasionally calculated site-specific criteria. Few states addressed the protection of human health by adopting numeric human health criteria.

State development of case-by-case effluent limits using procedures that did not rely on the statewide adoption of numeric criteria for the priority toxic pollutants frustrated Congress. Congress perceived that states were failing to aggressively address toxics and that EPA was not using its oversight role to push the states to move more quickly and comprehensively. Many in Congress believed that these delays undermined the effectiveness of the Act's framework.

1987 CWA Amendments In 1987, Congress, unwilling to tolerate further delays, added Section 303 (c) (2) (B) to the CWA. The Section provided that, whenever a state reviews water-quality standards or revises or adopts new standards, the state had to adopt criteria for all toxic pollutants listed pursuant to Section 307 (a) (1) of the Act for which criteria have been published under Section 304 (a), the discharge or presence of which in the affected waters could reasonably be expected to interfere with those designated uses adopted by the state, as necessary to support such designated uses. Such criteria had to be specific numerical criteria for such toxic pollutants. When such numerical criteria are not available, wherever a state reviews water-quality standards, or revises or adopts new standards, the state has to adopt criteria based on biological monitoring or assessment methods consistent with information published pursuant to Section 304 (a) (8). Nothing in this Section was to be construed to limit or delay the use of effluent limitations or other permit conditions based on or involving biological monitoring or assessment methods or previously adopted numerical criteria.

In response to this new Congressional mandate, EPA redoubled its efforts to promote and assist state adoption of numerical water-quality standards for priority toxic pollutants. EPA's efforts included the development and issuance of guidance to the states on acceptable implementation procedures. EPA attempted to provide the maximum flexibility in its options that complied not only with the express statutory language but also with the implied congressional objective: prompt adoption of numeric toxic pollutant criteria. The Agency believed that flexibility was important so that each state could comply with Section 303 (c) (2) (B) within its resource constraints. EPA distributed final guidance on December 12, 1988. This guidance was similar to earlier drafts available for review by the states. The availability of the guidance was published in the *Federal Register* on January 5, 1989 (54 FR 346).

The structure of Section 303 (c) is to require states to review their water-quality standards at least once each three-year period. Section 303 (c) (2) (B) instructs states to include reviews for toxics criteria whenever they initiate a triennial review. EPA initially looked at February 4, 1990, the 3-year anniversary of the 1987 CWA amendments, as a convenient point to index state compliance. The April 17, 1990 *Federal Register* Notice (55 FR 14350) used this index point for the preliminary assessment of state compliance. However, some states were very nearly completing their state administrative processes for ongoing reviews when the 1987 amendments were enacted and could not legally amend those proceedings to address additional toxics criteria. Therefore, in the interest of fairness, and to provide such states a full 3-year review period, EPA's FY 1990 Agency Operating Guidance provided that states should complete adoption of the numeric criteria to meet Section 303 (c) (2) (B) by September 30, 1990.

Section 303 (c) does not provide penalties for states that do not complete timely water-quality standard reviews. In no previous case had an EPA Administrator found that state failure to complete a review within three years jeopardized the public health or welfare to such an extent that promulgation of Federal standards pursuant to Section 303 (c) (4) (B) was justified. However, the pre-1987 CWA never mandated state adoption of priority toxic pollutants or other specific criteria. EPA relied on its water-quality standards regulation (40 CFR 131.11) and its criteria and program guidance to the states on appropriate parametric coverage in state water quality standards, including toxic pollutants. With Congressional concern exhibited in the legislative history for the 1987 Amendments regarding undue delays by states and EPA, and because states have been explicitly required to adopt numeric criteria for appropriate priority toxic pollutants since 1983, the Agency is proceeding to promulgate Federal standards pursuant to Section 303 (c) (4) (B) of the CWA and 40 CFR 131.22 (b).

States have made substantial recent progress in the adoption, and EPA approval, of toxic pollutant water-quality standards. Furthermore, virtually all states have at least proposed new toxics criteria for priority toxic pollutants since Section 303 (c) (2) (B) was added to the CWA in February of 1987. Unfortunately, not all such state proposals address, in a comprehensive manner, the requirements of Section 303 (c) (2) (B). For example, some states have proposed to adopt criteria to protect aquatic life, but not human health; other states have proposed human health criteria that do not address major exposure pathways (such as the combination of both fish consumption and drinking water). In addition, in some cases final adoption of proposed state toxics criteria that would be approved by EPA has been substantially delayed due to controversial and difficult issues associated with the toxic pollutant criteria adoption process.

Biological Criteria While the overall mandate of the Clean Water Act may now be more clearly stated and understood, the tools needed are still under development, and their full application is being worked out. The direction is towards a more comprehensive approach to water quality protection, which might be more appropriately termed "water resource protection" to encompass the living resources and their habitat along with the water itself.

In 1991, EPA directed states to adopt biological criteria into their water-quality standards by September 30, 1993. To assist the states, EPA issued its "Policy on the Use of Biological Assessments and Criteria in the Water-Quality Program," which sets forth the key policy directions governing the shift to the use of biological criteria:

- "Biological surveys shall be fully integrated with toxicity and chemical-specific assessment methods in state water-quality programs."
- "Biological surveys should be used together with whole-effluent and ambient toxicity testing, and chemical-specific analyses to assess the attainment/nonattainment of designated aquatic life uses in state water-quality standards."
- "If any one of the three assessment methods demonstrate that water-quality standards are not attained, it is EPA's policy that appropriate action should be taken to achieve attainment, including use of regulatory authority" (the independent applicability policy).
- "States should designate aquatic life uses that appropriately address biological integrity and adopt biological criteria necessary to protect those uses."

These policy statements are founded on the existing language and authorities in Clean Water Act Sections 303 (c) (2) (A) and (B). EPA defined biological criteria as "numerical values or narrative expressions used to describe the expected structure and function of the aquatic community."

Most states currently conduct biological surveys. These consist of the collection and analysis of resident aquatic-community data and a subsequent determination of the aquatic community's structure and function. A limiting factor in the number of surveys conducted is simply the funding to support field sampling. Most states also take their survey data through the next level of analysis, which is a biological assessment, in which the biological condition of the water body is evaluated. A state needs to conduct a biological assessment to justify designated waters as having uses less than the Clean Water Act goal of "fishable/swimmable" [Sec. 101 (a) (2)].

Implementing biological criteria requires that the state establish what the expected condition of a biological community should be. This expected condition (or reference condition) is based on measurements at either unimpacted sites or sites that are minimally impacted by human activities. A key element of developing and adopting biological criteria is developing a set of metrics (biological measurements) and indices (summations of those metrics) that are sensitive to reflecting the community changes that occur as a result of human perturbation. Metrics may include measures of species richness, percentages of species of a particular feeding type, and measures of species abundance and condition. The development of metrics and indices have been major technical advances that have effectively brought the field to the point of implementing biological integrity measures.

Aside from the need for additional monitoring and data as a basis for biological criteria, the largest impediment is currently related to the question of how or whether biological criteria should be translated directly into NPDES permit requirements. A strict reading of the NPDES regulations leads some individuals to conclude that every water-quality standard potentially affected by a discharge must have a specific effluent limit. In the case of biological criteria, the direct translation isn't always possible. The preferred approach is to use biological criteria as a primary means to identify impaired waters that will then need additional study. Appropriate discharge controls can then be applied.

The other area of contention in adopting biocriteria is the EPA policy of "independent applicability." This policy recognizes that chemical-specific criteria, toxicity testing (WET tests), and biological criteria each have unique as well as overlapping attributes, limitations, and program applications. No single approach is superior to another; rather, the approaches are complementary. When any one of these approaches indicates that water quality is impaired, appropriate regulatory action is needed. Critics of this approach most frequently cite biological criteria as the superior, or determining, measure and would use it to override an exceedance of chemical-specific criteria.

EPA and many states are now moving towards a watershed or basin management approach to water management. This is a holistic approach that looks at the multiple stresses and activities that affect a basin and evaluates these effects in the context of the survival of ecological systems. Biological criteria are recognized by states as a necessary tool for detecting impacts to important aquatic resources that would otherwise be missed, particularly those caused by nonpoint source activities, and for defining the desired endpoint of environmental restoration activities.

To assist states, EPA has issued programmatic guidance (*Biological Criteria: National Program Guidance for Surface Waters*, April 1990; *Procedures for Initiating Narrative Biological Criteria*, October 1992). In addition, EPA will be issuing over the next couple of years technical guidance specific to developing biological criteria for streams and small rivers, lakes and reservoirs, estuaries, and wetlands.

Metal Bioavailability and Toxicity Another area of policy and regulatory change that bears directly on questions of biological integrity is the application of toxic-metal water-quality criteria. EPA is in the midst of reconsidering its approach to implementing toxic metals criteria. This was prompted in part by the difficulty that some dischargers are having in meeting the state ambient water-quality criteria

for metals, which generally are expressed as total recoverable metals (a measurement that includes the metal dissolved in water plus metal that becomes dissolved when the sample is treated with acid). At issue is whether the criteria can be expressed in a form that more accurately addresses the toxicity of the metal to aquatic life, thereby providing the desired level of aquatic life protection, while allowing more leeway in the total amount of metal discharged. This is a technically complex issue that will require long-term research even if short-term solutions are implemented.

The bioavailability, and hence the toxicity, of metal depends on the physical and chemical form of the metal, which in turn depends on the chemical characteristics of the surrounding water. The dissolved form of the metal is generally viewed as more bioavailable and therefore more toxic than the particulate form. Particulate matter and dissolved organic matter can bind the metal, making it less bioavailable. What is not well known or documented is the various chemical transformations that occur both within the effluent stream and when the effluent reaches and mixes with the receiving water. Metal that is not bioavailable in the effluent may become bioavailable under ambient chemical conditions.

The NPDES regulations (40 CFR 122.45) require effluent limits to be expressed as total recoverable metal. This requirement makes sense as a means to monitor and regulate both the total metal loading and also the effectiveness of wastewater treatment that involves chemical precipitation of the metal.

From the perspective of ecological integrity called for in the Clean Water Act, any adjustment to the implementation of toxic metals criteria needs to be integrated with both sediment criteria and biological criteria to provide ecosystem protection envisioned by the Act.

Regulatory Direction EPA and states are directed by the Clean Water Act to develop programs to meet the Act's stated objective: "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" [Sec. 101 (a)]. Efforts to date have emphasized "clean water" quite literally, by focusing on the chemical makeup of discharges and their compliance with chemical water-quality standards established for surface water bodies. These programs have successfully addressed many water-pollution problems, but they are not sufficient to identify and address all of them. A large gap in the current regulatory scheme is the absence of a direct measure of the condition of the biological resources that we are intending to protect (the biological integrity of the water body). Without such a measure it will be difficult to determine whether our water-management approaches are successful in meeting the intent of the Act. Taken together, chemical, physical, and biological integrity are equivalent to the "ecological integrity" of a water body. It is highly likely the future will see interpretation of biological integrity and ecological integrity, and the management of ecological systems, assuming a much more prominent role in water-quality management.

UNITED STATES SOLID WASTE LEGISLATION AND REGULATIONS

Much of the current activity in the field of solid waste management, especially with respect to hazardous wastes and resources recovery, is a direct consequence of recent legislation. Therefore, it is important to review the principal legislation that has affected the entire field of solid-waste management.

What follows is a brief review of existing legislation that affects the management of solid wastes. The actual legislation must be consulted for specific detail. Implementation of the legislation is accomplished through regulations adopted by federal, states, and local agencies. Because these regulations are revised continuously, they must be monitored continuously, especially when design and construction work is to be undertaken.

Rivers and Harbors Act, 1899 Passed in 1899, the Rivers and Harbor Act directed the U.S. Army Corps of Engineers to regulate the dumping of debris in navigable waters and adjacent lands.

Solid Waste Disposal Act, 1965 Modern solid-waste legislation dates from 1965, when the Solid Waste Disposal Act, Title II of Public Law 88-272, was enacted by Congress. The principal intent of this act was to promote the demonstration, construction, and application

of solid waste management and resource-recovery systems that preserve and enhance the quality of air, water, and land resources.

National Environmental Policy Act, 1969 The National Environmental Policy Act (NEPA) of 1969 was the first federal act that required coordination of federal projects and their impacts with the nation's resources. The act specified the creation of Council on Environmental Quality in the Executive Office of the President. This body has the authority to force every federal agency to submit to the council an environmental impact statement on every activity or project which it may sponsor or over which it has jurisdiction.

Resource Recovery Act, 1970 The Solid Waste Disposal Act of 1965 was amended by Public Law 95-512, the Resources Recovery Act of 1970. This act directed that the emphasis of the national solid-waste-management program should be shifted from disposal as its primary objective to that of recycling and reuse of recoverable materials in solid wastes or the conversion of wastes to energy.

Resource Conservation and Recovery Act, 1976 RCRA is the primary statute governing the regulation of solid and hazardous waste. It completely replaced the Solid Waste Disposal Act of 1965 and supplemented the Resource Recovery Act of 1970; RCRA itself was substantially amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA). The principal objectives of RCRA as amended are to:

- Promote the protection of human health and the environment from potential adverse effects of improper solid and hazardous waste management
- Conserve material and energy resources through waste recycling and recovery
- Reduce or eliminate the generation of hazardous waste as expeditiously as possible

To achieve these objectives, RCRA authorized EPA to regulate the generation, treatment, storage, transportation, and disposal of hazardous wastes. The structure of the national hazardous waste regulatory program envisioned by Congress is laid out in Subtitle C of RCRA (Sections 3001 through 3019), which authorized EPA to:

- Promulgate standards governing hazardous waste generation and management
- Promulgate standards for permitting hazardous waste treatment, storage, and disposal facilities
- Inspect hazardous waste management facilities
- Enforce RCRA standards
- Authorize states to manage the RCRA Subtitle C program, in whole or in part, within their respective borders, subject to EPA oversight

Federal RCRA hazardous waste regulations are set forth in 40 CFR Parts 260 through 272. The core of the RCRA regulations establishes the "cradle to grave" hazardous waste regulatory program through seven major sets of regulations:

- Identification and listing of regulated hazardous wastes (Part 261)
- Standards for generators of hazardous waste (Part 262)
- Standards for transporters of hazardous waste (Part 263)
- Standards for owners/operators of hazardous waste treatment, storage, and disposal facilities (Parts 264, 265, and 267)
- Standards for the management of specific hazardous wastes and specific types of hazardous waste management facilities (Part 266)
- Land disposal restriction standards (Part 268)
- Requirements for the issuance of permits to hazardous waste facilities (Part 270)
- Standards and procedures for authorizing state hazardous waste programs to be operated in lieu of the federal program (Part 271)

EPA, under Section 3006 of RCRA, may authorize a state to administer and enforce a state hazardous waste program in lieu of the federal Subtitle C program. To receive authorization, a state program must:

- Be equivalent to the federal Subtitle C program
- Be consistent with, and no less stringent than, the federal program and other authorized state programs
- Provide adequate enforcement of compliance with Subtitle C requirements

Toxic Substances Control Act, 1976 The two major goals of the Toxic Substances Control Act (TSCA), passed by Congress in

1976, are (1) the acquisition of sufficient information to identify and evaluate potential hazards from chemical substances and (2) the regulation of the manufacture, processing, distribution, use, and disposal of any substance that presents an unreasonable risk of injury to health of the environment.

Under TSCA, the EPA has issued a ban on the manufacture, processing, and distribution of products containing PCBs. Exporting of PCB has also been banned. TSCA also required that PCB mixtures containing more than 50 ppm PCBs must be disposed of in an acceptable incinerator or chemical waste landfill. All PCB containers or products containing PCBs had to be clearly marked and records maintained by the operator of each facility handling at least 45 kilograms of

PCB. These records include PCBs in use in transformers and capacitors, PCBs in transformers and capacitors removed from service, PCBs stored for disposal, and a report on the ultimate disposal of the PCBs.

TSCA also placed restrictions on the use of chlorofluorocarbons, asbestos, and fully halogenated chlorofluoroalkanes such as aerosol propellants.

Regulatory Direction There is no doubt that pollution prevention continues to be the regulatory direction. The development of new and more efficient processes and waste minimization technologies will be essential to support this effort.

POLLUTION PREVENTION

This subsection is drawn in part from "Pollution Prevention Overview," prepared by B. Wainwright and L. Theodore, copyrighted, 1993.

FURTHER READING: American Society of Testing and Materials, *Standard Guide for Industrial Source Reduction*, draft copy dated June 16, 1992. American Society of Testing and Materials, *Pollution Prevention, Reuse, Recycling and Environmental Efficiency*, June, 1992. California Department of Health Services, *Economic Implications of Waste Reduction, Recycling, Treatment, and Disposal of Hazardous Wastes: The Fourth Biennial Report*, California, 1988. Citizen's Clearinghouse for Hazardous Waste, *Reduction of Hazardous Waste: The Only Serious Management Option*, Falls Church, CCHW, 1986. Congress of the United States. Office of Technology Assessment, *Serious Reduction of Hazardous Waste: For Pollution Prevention and Industrial Efficiency*, Washington, D.C., GPO, 1986. Friedlander, S., "Pollution Prevention—Implications for Engineering Design, Research, and Education," *Environment*, May 1989, p. 10. Theodore, L. and Y. McGuinn, *Pollution Prevention*, New York, Van Nostrand Reinhold, 1992. Theodore, L. and R. Allen, *Pollution Prevention: An ETS Theodore Tutorial*, Roanoke, VA, ETS International, Inc., 1994. Theodore, L., *A Citizen's Guide to Pollution Prevention*, East Williston, NY, 1993. United States EPA, *Facility Pollution Prevention Guide*. (EPA/600/R-92/088), Washington, D.C., May 1992. United States EPA, "Pollution Prevention Fact Sheets," Washington, D.C., GPO, 1991. United States EPA, 1987 *National Biennial RCRA Hazardous Waste Report—Executive Summary*, Washington, D.C., GPO, 1991. United States EPA, Office of Pollution Prevention, *Report on the U.S. Environmental Protection Agency's Pollution Prevention Program*, Washington, D.C., GPO, 1991. World Wildlife Fund, *Getting at the Source—Executive Summary*, 1991.

INTRODUCTION

The amount of waste generated in the United States has reached staggering proportions; according to the United States Environmental Protection Agency (EPA), 250 million tons of solid waste alone are generated annually. Although both the Resource Conservation and Recovery Act (RCRA) and the Hazardous and Solid Waste Act (HSWA) encourage businesses to minimize the wastes they generate, the majority of the environmental protection efforts are still centered around treatment and pollution clean-up.

The passage of the Pollution Prevention Act of 1990 has redirected industry's approach to environmental management; pollution prevention has now become the environmental option of this decade and the 21st century. Whereas typical waste-management strategies concentrate on "end-of-pipe" pollution control, pollution prevention attempts to handle waste at the source (i.e., source reduction). As waste handling and disposal costs increase, the application of pollution prevention measures is becoming more attractive than ever before. Industry is currently exploring the advantages of multimedia waste reduction and developing agendas to *strengthen* environmental design while *lessening* production costs.

There are profound opportunities for both industry and the individual to prevent the generation of waste; indeed, pollution prevention is today primarily stimulated by economics, legislation, liability concerns, and the enhanced environmental benefit of managing waste at the source. The Pollution Prevention Act of 1990 has established pollution prevention as a national policy, declaring that "waste should be prevented or reduced at the source wherever feasible, while pollu-

tion that cannot be prevented should be recycled in an environmentally safe manner" (Ref. 1). The EPA's policy establishes the following hierarchy of waste management:

1. Source reduction
2. Recycling/reuse
3. Treatment
4. Ultimate disposal

The hierarchy's categories are prioritized so as to promote the examination of each individual alternative prior to the investigation of subsequent options (i.e., the most preferable alternative should be thoroughly evaluated before consideration is given to a less accepted option). Practices that decrease, avoid, or eliminate the generation of waste are considered source reduction and can include the implementation of procedures as simple and economical as good house-keeping. Recycling is the use, reuse, or reclamation of wastes and/or materials that may involve the incorporation of waste recovery techniques (e.g., distillation, filtration). Recycling can be performed at the facility (i.e., on-site) or at an off-site reclamation facility. Treatment involves the destruction or detoxification of wastes into nontoxic or less toxic materials by chemical, biological, or physical methods, or any combination of these control methods. Disposal has been included in the hierarchy because it is recognized that residual wastes will exist; the EPA's so-called "ultimate disposal" options include land-filling, land farming, ocean dumping, and deep-well injection. However, the term *ultimate disposal* is a misnomer, but is included here because of its adaptation by the EPA.

Table 25-8 provides a rough timetable demonstrating the United States' approach to waste management. Note how waste management has begun to shift from pollution *control*-driven activities to pollution *prevention* activities.

The application of waste-management practices in the United States has recently moved toward securing a new pollution prevention ethic. The performance of pollution prevention assessments and their subsequent implementation will encourage increased activity into methods that will further aid in the reduction of hazardous wastes. One of the most important and propitious consequences of the pollution-prevention movement will be the development of life-cycle design and standardized life-cycle cost-accounting procedures. These two consequences are briefly discussed in the two paragraphs that follow. Additional information is provided in a later subsection.

TABLE 25-8 Waste Management Timetable

Prior to 1945	No control
1945–1960	Little control
1960–1970	Some control
1970–1975	Greater control (EPA is founded)
1975–1980	More sophisticated control
1980–1985	Beginning of waste-reduction management
1985–1990	Waste-reduction management
1990–1995	Formal pollution prevention programs (Pollution Prevention Act)
1995–2000	Widespread acceptance of pollution prevention
After 2000	???

The key element of life-cycle design is Life-Cycle Assessment (LCA). LCA is generally envisioned as a process to evaluate the environmental burdens associated with the cradle-to-grave life cycle of a product, process, or activity. A product's life cycle can be roughly described in terms of the following stages:

1. Raw material
2. Bulk material processing
3. Production
4. Manufacturing and assembly
5. Use and service
6. Retirement
7. Disposal

Maintaining an objective process while spanning this life cycle can be difficult given the varying perspective of groups affected by different parts of that cycle. LCA typically does not include any direct or indirect monetary costs or impacts to individual companies or consumers.

Another fundamental goal of life-cycle design is to promote sustainable development at the global, regional, and local levels. There is significant evidence that suggests that current patterns of human and industrial activity on a global scale are not following a sustainable path. Changes to achieve a more sustainable system will require that environmental issues be more effectively addressed in the future. Principles for achieving sustainable development should include (Ref. 2):

1. *Sustainable resource use (conserving resources, minimizing depletion of nonrenewable resources, using sustainable practices for managing renewable resources).* There can be no product development or economic activity of any kind without available resources. Except for solar energy, the supply of resources is finite. Efficient designs conserve resources while also reducing impacts caused by material extraction and related activities. Depletion of nonrenewable resources and overuse of otherwise renewable resources limits their availability to future generations.

2. *Maintenance of ecosystem structure and function.* This is a principal element of sustainability. Because it is difficult to imagine how human health can be maintained in a degraded, unhealthy natural world, the issue of ecosystem health should be a more fundamental concern. Sustainability requires that the health of all diverse species as well as their interrelated ecological functions be maintained. As only one species in a complex web of ecological interactions, humans cannot separate their success from that of the total system.

3. *Environmental justice.* The issue of environmental justice has come to mean different things to different people. Theodore (Ref. 3) has indicated that the subject of environmental justice contains four key elements that are interrelated: environmental racism, environmental health, environmental equity, and environmental politics. (Unlike many environmentalists, Theodore has contended that only the last issue, politics, is a factor in environmental justice.) A major challenge in sustainable development is achieving both intergenerational and intersocietal environmental justice. Overconsuming resources and polluting the planet in such a way that it enjoins future generations from access to reasonable comforts irresponsibly transfer problems to the future in exchange for short-term gain. Beyond this intergenerational conflict, enormous inequities in the distribution of resources continue to exist between developed and less developed countries. Inequities also occur within national boundaries.

Life cycle is a perspective that considers the true costs of product production and/or services provided and utilized by analyzing the price associated with potential environmental degradation and energy consumption, as well as more customary costs like capital expenditure and operating expenses. Unfortunately, a host of economic and economic-related terms have appeared in the literature. Some of these include total cost assessment, life-cycle costing, and full-cost accounting. Unfortunately, these terms have come to mean different things to different people at different times. In an attempt to remove this ambiguity, the following three economic terms are defined below. The reader is also referred to Fig. 25-1 for additional details.

1. *Traditional costing procedure (TCP).* This accounting procedure *only* takes into account capital and operating (including environmental) costs.

2. *Comprehensive costing procedure (CCP).* The economic procedure includes not only the traditional capital and operating costs but

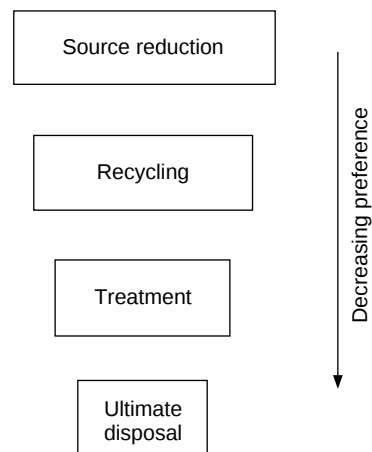


FIG. 25-1 Pollution prevention hierarchy.

also peripheral costs such as liability, regulatory related expensive, borrowing power, and social considerations.

3. *Life-cycle costing (LCC).* This type of analysis requires that all the traditional costs of project or product system, from raw-material acquisition to end-result product disposal, be considered.

The TCP approach is relatively simple and can be easily applied to studies involving comparisons of different equipments, different processes, or even parts of processes. CCP has now emerged as the most realistic approach that can be employed in economic project analyses. It is the recommended procedure for pollution-prevention studies. The LCC approach is usually applied to the life-cycle analysis (LCA) of a product or service. It has found occasional application in project analysis.

The remainder of this subsection on pollution prevention will be concerned with providing the reader with the necessary background to understand the meaning of pollution prevention and its useful implementation. Assessment procedures and the economic benefits derived from managing pollution at the source are discussed along with methods of cost accounting for pollution prevention. Additionally, regulatory and nonregulatory methods to promote pollution prevention and overcome barriers are examined, and ethical considerations are presented. By eliminating waste at the source, all can participate in the protection of the environment by reducing the amount of waste material that would otherwise need to be treated or ultimately disposed; accordingly, attention is also given to pollution prevention in both the domestic and business office environments.

POLLUTION-PREVENTION HIERARCHY

As discussed in the introduction, the hierarchy set forth by the USEPA in the Pollution Prevention Act establishes an order to which waste-management activities should be employed to reduce the quantity of waste generated. The preferred method is source reduction, as indicated in Fig. 25-1. This approach actually precedes traditional waste management by addressing the source of the problem prior to its occurrence.

Although the EPA's policy does not consider recycling or treatment as actual pollution prevention methods per se, these methods present an opportunity to reduce the amount of waste that might otherwise be discharged into the environment. Clearly, the definition of pollution prevention and its synonyms (e.g., waste minimization) must be understood to fully appreciate and apply these techniques.

Waste minimization generally considers all of the methods in the EPA hierarchy (except for disposal) appropriate to reduce the volume or quantity of waste requiring disposal (i.e., source reduction). The definition of *source reduction* as applied in the Pollution Prevention Act, however, is "any practice that reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream

or otherwise released into the environment . . . prior to recycling, treatment or disposal" (Ref. 1). Source reduction reduces the amount of waste generated; it is therefore considered true pollution prevention and has the highest priority in the EPA hierarchy.

Recycling (or reuse) refers to the use (or reuse) of materials that would otherwise be disposed of or treated as a waste product. A good example is a rechargeable battery. Wastes that cannot be directly reused may often be recovered on-site through methods such as distillation. When on-site recovery or reuse is not feasible due to quality specifications or the inability to perform recovery on-site, off-site recovery at a permitted commercial recovery facility is often a possibility. Such management techniques are considered secondary to source reduction and should only be used when pollution cannot be prevented.

The treatment of waste is the third element of the hierarchy and should be utilized only in the absence of feasible source reduction or recycling opportunities. Waste treatment involves the use of chemical, biological, or physical processes to reduce or eliminate waste material. The incineration of wastes is included in this category and is considered "preferable to other treatment methods (i.e., chemical, biological, and physical) because incineration can permanently destroy the hazardous components in waste materials" (Ref. 4). It can also be employed to reduce the volume of waste to be treated.

Of course, several of these pollution-prevention elements are used by industry in combination to achieve the greatest waste reduction. Residual wastes that cannot be prevented or otherwise managed are then disposed of only as a last resort.

Figure 25-2 provides a more detailed schematic representation of the two preferred pollution prevention techniques (i.e., source reduction and recycling).

MULTIMEDIA ANALYSIS AND LIFE-CYCLE ANALYSIS

Multimedia Analysis In order to properly design and then implement a pollution prevention program, sources of all wastes must be fully understood and evaluated. A multimedia analysis involves a multifaceted approach. It must not only consider one waste stream but all potentially contaminant media (e.g., air, water, land). Past

waste-management practices have been concerned primarily with treatment. All too often, such methods solve one waste problem by transferring a contaminant from one medium to another (e.g., air stripping); such waste shifting is *not* pollution prevention or waste reduction.

Pollution prevention techniques must be evaluated through a thorough consideration of all media, hence the term multimedia. This approach is a clear departure from previous pollution treatment or control techniques where it was acceptable to transfer a pollutant from one source to another in order to solve a waste problem. Such strategies merely provide short-term solutions to an ever increasing problem. As an example, air pollution control equipment prevents or reduces the discharge of waste into the air but at the same time can produce a solid (hazardous) waste problem.

Life-Cycle Analysis The aforementioned multimedia approach to evaluating a product's waste stream(s) aims to ensure that the treatment of one waste stream does not result in the generation or increase in an additional waste output. Clearly, impacts resulting during the production of a product or service must be evaluated over its entire history or life cycle. This life-cycle analysis or total systems approach (Ref. 3) is crucial to identifying opportunities for improvement. As described earlier, this type of evaluation identifies "energy use, material inputs, and wastes generated during a product's life: from extraction and processing of raw materials to manufacture and transport of a product to the marketplace and finally to use and dispose of the product" (Ref. 5).

During a forum convened by the World Wildlife Fund and the Conservation Foundation in May 1990, various steering committees recommended that a three-part life-cycle model be adopted. This model consists of the following:

1. An inventory of materials and energy used, and environmental releases from all stages in the life of a product or process
2. An analysis of potential environmental effects related to energy use and material resources and environmental releases
3. An analysis of the changes needed to bring about environmental improvements for the product or process under evaluation

Traditional cost analysis often fails to include factors relevant to future damage claims resulting from litigation, the depletion of nat-

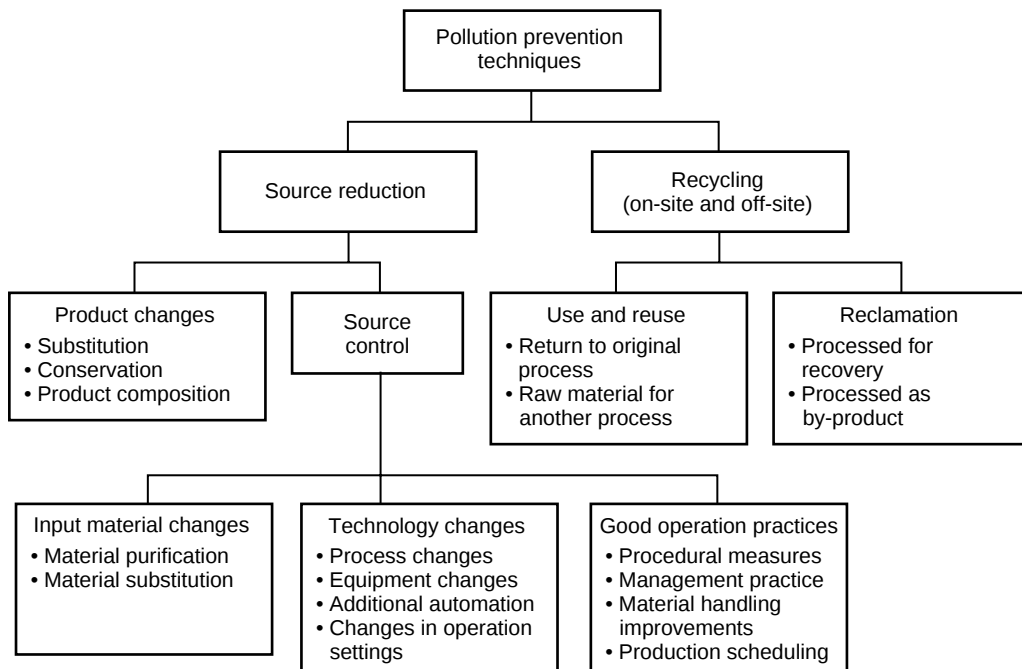


FIG. 25-2 Pollution prevention techniques.

ural resources, the effects of energy use, and the like. As such, waste-management options such as treatment and disposal may appear preferential if an overall life-cycle cost analysis is not performed. It is evident that environmental costs from cradle to grave have to be evaluated together with more conventional production costs to accurately ascertain genuine production costs. In the future, a total systems approach will most likely involve a more careful evaluation of pollution, energy, and safety issues. For example, if one was to compare the benefits of coal versus oil as a fuel source for an electric power plant, the use of coal might be considered economically favorable. In addition to the cost issues, however, one must be concerned with the environmental effects of coal mining (e.g., transportation and storage prior to use as a fuel). Society often has a tendency to overlook the fact that there are serious health and safety matters (e.g., miner exposure) that must be considered along with the effects of fugitive emissions. When these effects are weighed alongside standard economic factors, the full cost benefits of coal usage may be eclipsed by environmental costs. Thus, many of the economic benefits associated with pollution prevention are often unrecognized due to inappropriate cost-accounting methods. For this reason, economic considerations are detailed later.

POLLUTION-PREVENTION ASSESSMENT PROCEDURES

The first step in establishing a pollution prevention program is the obtainment of management commitment. This is necessary given the inherent need for project structure and control. Management will determine the amount of funding allotted for the program as well as specific program goals. The data collected during the actual evaluation is then used to develop options for reducing the types and amounts of waste generated. Figure 25-3 depicts a systematic approach that can be

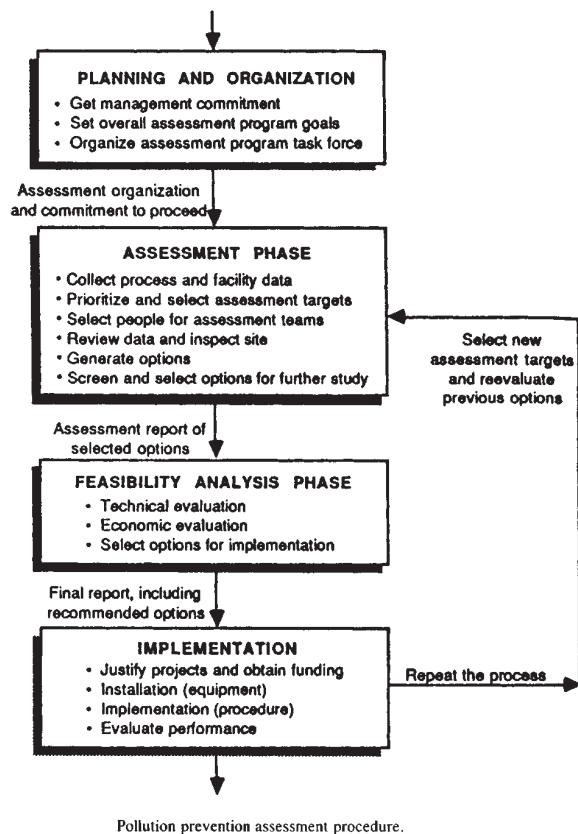


FIG. 25-3 Pollution prevention assessment procedure.

used during the procedure. After a particular waste stream or area of concern is identified, feasibility studies are performed involving both economic and technical considerations. Finally, preferred alternatives are implemented. The four phases of the assessment (i.e., planning and organization, assessment, feasibility, and implementation) are introduced in the following subsections. Sources of additional information as well as information on industrial programs is also provided in this section.

Planning and Organization The purpose of this phase is to obtain management commitment, define and develop program goals, and assemble a project team. Proper planning and organization are crucial to the successful performance of the pollution-prevention assessment. Both managers and facility staff play important roles in the assessment procedure by providing the necessary commitment and familiarity with the facility, its processes, and current waste-management operations. It is the benefits of the program, including economic advantages, liability reduction, regulatory compliance, and improved public image that often leads to management support.

Once management has made a commitment to the program and goals have been set, a program task force is established. The selection of a team leader will be dependent upon many factors including their ability to effectively interface with both the assessment team and management staff.

The task force must be capable of identifying pollution reduction alternatives as well as be cognizant of inherent obstacles to the process. Barriers frequently arise from the anxiety associated with the belief that the program will negatively affect product quality or result in production losses. According to an EPA survey, 30 percent of industry comments responded that they were concerned that product quality would decline if waste minimization techniques were implemented (Ref. 6). As such, the assessment team, and the team leader in particular, must be ready to react to these and other concerns (Ref. 2).

Assessment Phase The assessment phase aims to collect data needed to identify and analyze pollution-prevention opportunities. Assessment of the facility's waste-reduction needs includes the examination of hazardous waste streams, process operations, and the identification of techniques that often promise the reduction of waste generation. Information is often derived from observations made during a facility walk-through, interviews with employees (e.g., operators, line workers), and review of site or regulatory records. One professional organization suggests the following information sources be reviewed, as available (Ref. 7):

1. Product design criteria
2. Process flow diagrams for all solid waste, wastewater, and air emissions sources
3. Site maps showing the location of all pertinent units (e.g., pollution-control devices, points of discharge)
4. Environmental documentation, including: Material Safety Data Sheets (MSDS), military specification data, permits (e.g., NPDES, POTW, RCRA), SARA Title III reports, waste manifests, and any pending permits or application information
5. Economic data, including: cost of raw material management; cost of air, wastewater, and hazardous waste treatment; waste management operating and maintenance costs; and waste disposal costs
6. Managerial information: environmental policies and procedures; prioritization of waste-management concerns; automated or computerized waste-management systems; inventory and distribution procedures; maintenance scheduling practices; planned modifications or revisions to existing operations that would impact waste-generation activities; and the basis of source reduction decisions and policies

The use of process flow diagrams and material balances are worthwhile methods to quantify losses or emissions and provide essential data to estimate the size and cost of additional equipment, other data to evaluate economic performance, and a baseline for tracking the progress of minimization efforts (Ref. 3). Material balances should be applied to individual waste streams or processes and then utilized to construct an overall balance for the facility. Details on these calculations are available in the literature (Ref. 8). In addition, an introduction to this subject is provided in the next section.

The data collected is then used to prioritize waste streams and operations for assessment. Each waste stream is assigned a priority

based on corporate pollution-prevention goals and objectives. Once waste origins are identified and ranked, and potential methods to reduce the waste stream are evaluated. The identification of alternatives is generally based on discussions with the facility staff; review of technical literature; and contacts with suppliers, trade organizations, and regulatory agencies.

Alternatives identified during this phase of the assessment are evaluated using screening procedures so as to reduce the number of alternatives requiring further exploration during the feasibility analysis phase. The criteria used during this screening procedure include: cost-effectiveness; implementation time; economic, compliance, safety and liability concerns; waste-reduction potential; and whether the technology is proven (Refs. 4, 8). Options that meet established criteria are then examined further during the feasibility analysis.

Feasibility Analysis The selection procedure is performed by an evaluation of technical and economic considerations. The technical evaluation determines whether a given option will work as planned. Some typical considerations follow:

1. Safety concerns
2. Product quality impacts or production delays during implementation
3. Labor and/or training requirements
4. Creation of new environmental concerns
5. Waste reduction potential
6. Utility and budget requirements
7. Space and compatibility concerns

If an option proves to be technically ineffective or inappropriate, it is deleted from the list of potential alternatives. Either following or concurrent with the technical evaluation, an economic study is performed, weighing standard measures of profitability such as payback period, investment returns, and net present value. Many of these costs (or, more appropriately, cost savings) may be substantial yet are difficult to quantify. (Refer to *Economic Considerations Associated with Pollution Prevention*.)

Implementation The findings of the overall assessment are used to demonstrate the technical and economic worthiness of program implementation. Once appropriate funding is obtained, the program is implemented not unlike any other project requiring new procedures or equipment. When preferred waste-pollution-prevention techniques are identified, they are implemented and should become part of the facility's day-to-day management and operation. Subsequent to the program's execution, its performance should be evaluated in order to demonstrate effectiveness, generate data to further refine and augment waste-reduction procedures, and maintain management support.

It should be noted that waste reduction, energy conservation, and safety issues are interrelated and often complementary to each other. For example, the reduction in the amount of energy a facility consumes usually results in reduced emissions associated with the generation of power. Energy expenditures associated with the treatment and transport of waste are similarly reduced when the amount of waste generated is lessened; at the same time, worker safety is elevated due to reduced exposure to hazardous materials. However, this is not always the case. Addition of air-pollution control systems at power plants decreases net power output due to the power consumed by the equipment. This in turn requires more fuel to be combusted for the same power exported to the grid. This additional fuel increases pollution from coal mining, transport, ash disposal, and the like. In extreme cases, very high recovery efficiencies for some pollutants can raise, not lower, total emissions. Seventy percent removal might produce a 2 percent loss in power output; 90 percent recovery could lead to a 3 percent loss; 95 percent, a 5 percent loss; 99 percent, a 10 percent loss, and so on. The point to be made is that pollution control is generally not a "free lunch."

Sources of Information The successful development and implementation of any pollution prevention program is not only dependent on a thorough understanding of the facility's operations but also requires an intimate knowledge of current opportunities and advances in the field. In fact, 32 percent of industry respondents to an EPA survey identified the lack of technical information as a major factor delaying or preventing the implementation of a waste-

minimization program (Ref. 6). One of EPA's positive contributions has been the development of a national Pollution Prevention Information Clearinghouse (PPIC) and the Pollution Prevention Information Exchange System (PIES) to facilitate the exchange of information needed to promote pollution prevention through efficient information transfer (Ref. 2).

PPIC is operated by the EPA's Office of Research and Development and the Office of Pollution Prevention. The clearinghouse is comprised of four elements:

1. Repository, including a hard copy reference library and collection center and an on-line information retrieval and ordering system.
2. PIES, a computerized conduit to databases and document ordering, accessible via modem and personal computer: (703) 506-1025.
3. PPIC uses the RCRA/Superfund and Small Business Ombudsman Hotlines as well as a PPIC technical assistance line to answer pollution-prevention questions, access information in the PPIC, and assist in document ordering and searches. To access PPIC by telephone, call:

RCRA/Superfund Hotline, (800) 242-9346

Small Business Ombudsman Hotline, (800) 368-5888

PPIC Technical Assistance, (703) 821-4800

4. PPIC compiles and disseminates information packets and bulletins and initiates networking efforts with other national and international organizations.

Additionally, the EPA publishes a newsletter entitled *Pollution Prevention News* that contains information including EPA news, technologies, program updates, and case studies. The EPA's Risk Reduction Engineering Laboratory and the Center for Environmental Research Information has published several guidance documents, developed in cooperation with the California Department of Health Services. The manuals supplement generic waste reduction information presented in the EPA's *Waste Minimization Opportunity Assessment Manual* (Ref. 9).

Pollution prevention or waste minimization programs have been established at the State level and as such are good sources of information. Both Federal and State agencies are working with universities and research centers and may also provide assistance. For example, the American Institute of Chemical Engineers has established the Center for Waste Reduction Technologies (CWRT), a program based on targeted research, technology transfer, and enhanced education.

Industry Programs A significant pollution-prevention resource may very well be found with the "competition." Several large companies have established well-known programs that have successfully incorporated pollution-prevention practices into their manufacturing processes. These include, but are not limited to: 3M—Pollution Prevention Pays (3P); Dow Chemical—Waste Reduction Always Pays (WRAP); Chevron—Save Money and Reduce Toxics (SMART); and, the General Dynamics Zero Discharge Program.

Smaller companies can benefit by the assistance offered by these larger corporations. It is clear that access to information is of major importance when implementing efficient pollution-prevention programs. By adopting such programs, industry is affirming pollution prevention's application as a good business practice and not simply a "noble" effort.

ASSESSMENT PHASE MATERIAL BALANCE CALCULATIONS

(The reader is directed to Refs. 4 and 10 for further information.)

One of the key elements of the assessment phase of a pollution prevention program involves mass balance equations. These calculations are often referred to as material balances; the calculations are performed via the conservation law for mass. The details of this often-used law are described below.

The conservation law for mass can be applied to any process or system. The general form of the law follows:

$$\text{mass in} - \text{mass out} + \text{mass generated} = \text{mass accumulated}$$

This equation can be applied to the total mass involved in a process or to a particular species, on either a mole or mass basis. The conserva-

tion law for mass can be applied to steady-state or unsteady-state processes and to batch or continuous systems. A steady-state system is one in which there is no change in conditions (e.g., temperature, pressure) or rates of flow with time at any given point in the system; the accumulation term then becomes zero. If there is no chemical reaction, the generation term is zero. All other processes are classified as unsteady state.

To isolate a system for study, the system is separated from the surroundings by a boundary or envelope that may either be real (e.g., a reactor vessel) or imaginary. Mass crossing the boundary and entering the system is part of the mass-in term. The equation may be used for any compound whose quantity does not change by chemical reaction or for any chemical element, regardless of whether it has participated in a chemical reaction. Furthermore, it may be written for one piece of equipment, several pieces of equipment, or around an entire process (i.e., a total material balance).

The conservation of mass law finds a major application during the performance of pollution-prevention assessments. As described earlier, a pollution-prevention assessment is a systematic, planned procedure with the objective of identifying methods to reduce or eliminate waste. The assessment process should characterize the selected waste streams and processes (Ref. 11)—a necessary ingredient if a material balance is to be performed. Some of the data required for the material balance calculation may be collected during the first review of site-specific data; however, in some instances, the information may not be collected until an actual site walk-through is performed.

Simplified mass balances should be developed for each of the important waste-generating operations to identify sources and gain a better understanding of the origins of each waste stream. Since a mass balance is essentially a check to make sure that what goes into a process (i.e., the total mass of all raw materials), what leaves the process (i.e., the total mass of the products and by-products), the material balance should be made individually for all components that enter and leave the process. When chemical reactions take place in a system, there is an advantage to doing "elemental balances" for specific chemical elements in a system. Material balances can assist in determining concentrations of waste constituents where analytical test data are limited. They are particularly useful when there are points in the production process where it is difficult or uneconomical to collect analytical data.

Mass-balance calculations are particularly useful for quantifying fugitive emissions such as evaporative losses. Waste stream data and mass balances will enable one to track flow and characteristics of the waste streams over time. Since in most cases the accumulation equals zero (steady-state operation), it can then be assumed that any buildup is actually leaving the process through fugitive emissions or other means. This will be useful in identifying trends in waste/pollutant generation and will also be critical in the task of measuring the performance of implemented pollution prevention options. The result of these activities is a catalog of waste streams that provides a description of each waste, including quantities, frequency of discharge, composition, and other important information useful for material balance. Of course, some assumptions or educated estimates will be needed when it is impossible to obtain specific information.

By performing a material balance in conjunction with a pollution prevention assessment, the amount of waste generated becomes known. The success of the pollution prevention program can therefore be measured by using this information on baseline generation rates (i.e., that rate at which waste is generated without pollution prevention considerations).

BARRIERS AND INCENTIVES TO POLLUTION PREVENTION

As discussed previously, industry is beginning to realize that there are profound benefits associated with pollution prevention including cost effectiveness, reduced liability, enhanced public image, and regulatory compliance. Nevertheless, there are barriers or disincentives identified with pollution prevention. This section will briefly outline both barriers and incentives that may need to be confronted or considered during the evaluation of a pollution prevention program.

Barriers to Pollution Prevention ("The Dirty Dozen") There are numerous reasons why more businesses are not reducing the wastes they generate. The following "dirty dozen" are common disincentives:

1. *Technical limitations.* Given the complexity of present manufacturing processes, waste streams exist that cannot be reduced with current technology. The need for continued research and development is evident.

2. *Lack of information.* In some instances, the information needed to make a pollution-prevention decision may be confidential or is difficult to obtain. In addition, many decision makers are simply unaware of the potential opportunities available regarding information to aid in the implementation of a pollution-prevention program.

3. *Consumer preference obstacles.* Consumer preference strongly affects the manner in which a product is produced, packaged, and marketed. If the implementation of a pollution-prevention program results in the increase in the cost of a product or decreased convenience or availability, consumers might be reluctant to use it.

4. *Concern over product quality decline.* The use of a less hazardous material in a product's manufacturing process may result in decreased life, durability, or competitiveness.

5. *Economic concerns.* Many companies are unaware of the economic advantages associated with pollution prevention. Legitimate concerns may include decreased profit margins or the lack of funds required for the initial capital investment.

6. *Resistance to change.* The unwillingness of many businesses to change is rooted in their reluctance to try technologies that may be unproven or based on a combination of the barriers discussed in this section.

7. *Regulatory barriers.* Existing regulations that have created incentives for the control and containment of wastes are at the same time discouraging the exploration of pollution-prevention alternatives. Moreover, since regulatory enforcement is often intermittent, current legislation can weaken waste-reduction incentives.

8. *Lack of markets.* The implementation of pollution-prevention processes and the production of environmentally friendly products will be of no avail if markets do not exist for such goods. As an example, the recycling of newspaper in the United States has resulted in an overabundance of waste paper without markets prepared to take advantage of this raw material.

9. *Management apathy.* Many managers capable of making decisions to begin pollution-prevention activities, do not realize the potential benefits of pollution prevention.

10. *Institutional barriers.* In an organization without a strong infrastructure to support pollution-prevention plans, waste-reduction programs will be difficult to implement. Similarly, if there is no mechanism in place to hold individuals accountable for their actions, the successful implementation of a pollution-prevention program will be limited.

11. *Lack of awareness of pollution prevention advantages.* As mentioned in reason no. 5, decision makers may merely be uninformed of the benefits associated with pollution reduction.

12. *Concern over the dissemination of confidential product information.* If a pollution-prevention assessment reveals confidential data pertinent to a company's product, fear may exist that the organization will lose a competitive edge with other businesses in the industry.

Pollution-Prevention Incentives ("A Baker's Dozen") Various means exist to encourage pollution prevention through regulatory measures, economic incentives, and technical assistance programs. Since the benefits of pollution prevention can surpass prevention barriers, a "baker's dozen" incentives is presented below:

1. *Economic benefits.* The most obvious economic benefits associated with pollution prevention are the savings that result from the elimination of waste storage, treatment, handling, transport, and disposal. Additionally, less tangible economic benefits are realized in terms of decreased liability, regulatory compliance costs (e.g., permits), legal and insurance costs, and improved process efficiency. Pollution prevention almost always pays for itself, particularly when the time required to comply with regulatory standards is considered. Several of these economic benefits are discussed separately below.

2. *Regulatory compliance.* Quite simply, when wastes are not generated, compliance issues are not a concern. Waste-management costs associated with record keeping, reporting, and laboratory analysis are reduced or eliminated. Pollution prevention's proactive approach to waste management will better prepare industry for the future regulation of many hazardous substances and wastes that are currently unregulated. Regulations have, and will continue to be, a moving target.

3. *Liability reduction.* Facilities are responsible for their wastes from "cradle-to-grave." By eliminating or reducing waste generation, future liabilities can also be decreased. Additionally, the need for expensive pollution liability insurance requirements may be abated.

4. *Enhanced public image.* Consumers are interested in purchasing goods that are safer for the environment, and this demand, depending on how they respond, can mean success or failure for many companies. Business should therefore be sensitive to consumer demands and use pollution-prevention efforts to their utmost advantage by producing goods that are environmentally friendly.

5. *Federal and state grants.* Federal and state grant programs have been developed to strengthen pollution-prevention programs initiated by states and private entities. The EPA's "Pollution Prevention by and for Small Business" grant program awards grants to small businesses to assist their development and demonstration of new pollution-prevention technologies.

6. *Market incentives.* Public demand for environmentally preferred products has generated a market for recycled goods and related products; products can be designed with these environmental characteristics in mind, offering a competitive advantage. In addition, many private and public agencies are beginning to stimulate the market for recycled goods by writing contracts and specifications that call for the use of recycled materials.

7. *Reduced waste-treatment costs.* As discussed in reason no. 5 of the dirty dozen, the increasing costs of traditional end-of-pipe waste-management practices are avoided or reduced through the implementation of pollution-prevention programs.

8. *Potential tax incentives.* In an effort to promote pollution prevention, taxes may eventually need to be levied to encourage waste generators to consider reduction programs. Conversely, tax breaks could be developed for corporations that utilize pollution-prevention methods to foster pollution prevention.

9. *Decreased worker exposure.* By reducing or eliminating chemical exposures, businesses benefit by lessening the potential for chronic workplace exposure and serious accidents and emergencies. The burden of medical monitoring programs, personal exposure monitoring, and potential damage claims are also reduced.

10. *Decreased energy consumption.* As mentioned previously, methods of energy conservation are often interrelated and complementary to each other. Energy expenditures associated with the treatment and transport of waste are usually but not always reduced when the amount of waste generated is lessened, while at the same time the pollution associated with energy consumed by these activities is abated.

11. *Increased operating efficiencies.* A potential beneficial side effect of pollution-prevention activities is a concurrent increase in operating efficiency. Through a pollution-prevention assessment, the assessment team can identify sources of waste that result in hazardous waste generation and loss in process performance. The implementation of a reduction program will often rectify such problems through modernization, innovation, and the implementation of good operating practices.

12. *Competitive advantages.* By taking advantage of the many benefits associated with pollution prevention, businesses can gain a competitive edge.

13. *Reduced negative environmental impacts.* Through an evaluation of pollution-prevention alternatives, which consider a total systems approach, consideration is given to the negative impact of environmental damage to natural resources and species that occur during raw-material procurement and waste disposal. The performance of pollution-prevention endeavors will therefore result in enhanced environmental protection.

ECONOMIC CONSIDERATIONS ASSOCIATED WITH POLLUTION-PREVENTION PROGRAMS

The purpose of this subsection is to outline the basic elements of a pollution-prevention cost-accounting system that incorporates both traditional and less tangible economic variables. The intent is not to present a detailed discussion of economic analysis but to help identify the more important elements that must be considered to properly quantify pollution-prevention options.

The greatest driving force behind any pollution-prevention plan is the promise of economic opportunities and cost savings over the long term. Pollution prevention is now recognized as one of the lowest-cost options for waste/pollutant management. Hence, an understanding of the economics involved in pollution prevention programs/options is quite important in making decisions at both the engineering and management levels. Every engineer should be able to execute an economic evaluation of a proposed project. If the project cannot be justified economically after all factors—and these will be discussed in more detail below—have been taken into account, it should obviously not be pursued. The earlier such a project is identified, the fewer resources will be wasted.

Before the true cost or profit of a pollution-prevention program can be evaluated, the factors contributing to the economics must be recognized. There are two traditional contributing factors (capital costs and operating costs), but there are also other important costs and benefits associated with pollution prevention that need to be quantified if a meaningful economic analysis is going to be performed. Table 25-9 demonstrates the evolution of various cost-accounting methods. Although Tables 25-8 (see introduction) and 25-9 are not directly related, the reader is left with the option of comparing some of the similarities between the two.

The Total Systems Approach (TSA) referenced in Table 25-9 aims to quantify not only the economic aspects of pollution prevention but also the social costs associated with the production of a product or service from cradle to grave (i.e., life cycle). The TSA attempts to quantify less tangible benefits such as the reduced risk derived from not using a hazardous substance. The future is certain to see more emphasis placed on the TSA approach in any pollution-prevention program. As described earlier, a utility considering the option of converting from a gas-fired boiler to coal-firing is usually not concerned with the environmental effects and implications associated with such activities as mining, transporting, and storing the coal prior to its usage as an energy feedstock. Pollution-prevention approaches in the mid-to-late 1990s will become more aware of this need.

The economic evaluation referred to above is usually carried out using standard measures of profitability. Each company and organization has its own economic criteria for selecting projects for implementation. (For example, a project can be judged on its payback period. For some companies, if the payback period is more than 3 years, it is a dead issue.) In performing an economic evaluation, various costs and savings must be considered. The economic analysis presented in this subsection represents a preliminary, rather than a detailed, analysis. For smaller facilities with only a few (and perhaps simple) processes, the entire pollution-prevention assessment procedure will tend to be much less formal. In this situation, several obvious pollution-prevention options such as the installation of flow controls and good operating practices may be implemented with little

TABLE 25-9 Economic Analysis Timetable

Prior to 1945	Capital costs only
1945–1960	Capital and some operating costs
1960–1970	Capital and operating costs
1970–1975	Capital, operating, and some environmental control costs
1975–1980	Capital, operating, and environmental control costs
1980–1985	Capital, operating, and more sophisticated environmental control costs
1985–1990	Capital, operating, and environmental controls, and some life-cycle analysis (Total Systems Approach)
1990–1995	Capital, operating, and environmental control costs and life-cycle analysis (Total Systems Approach)
1995–2000	Widespread acceptance of Total Systems Approach
After 2000	???

or no economic evaluation. In these instances, no complicated analyses are necessary to demonstrate the advantages of adopting the selected pollution-prevention option. A proper perspective must also be maintained between the magnitude of savings that a potential option may offer and the amount of manpower required to do the technical and economic feasibility analyses. A short description of the various economic factors—including capital and operating costs and other considerations—follows.

Once identified, the costs and/or savings are placed into their appropriate categories and quantified for subsequent analysis. Equipment cost is a function of many variables, one of the most significant of which is capacity. Other important variables include operating temperature and/or pressure conditions, and degree of equipment sophistication. Preliminary estimates are often made using simple cost-capacity relationships that are valid when the other variables are confined to a narrow range of values.

The usual technique for determining the capital costs (i.e., total capital costs, which include equipment design, purchase, and installation) for the facility is based on the factored method of establishing direct and indirect installation costs as a function of the known equipment costs. This is basically a modified Lang method, whereby cost factors are applied to known equipment costs (Refs. 13 and 14). The first step is to obtain from vendors the purchase prices of the primary and auxiliary equipment. The total base price, designated by X , which should include instrumentation, control, taxes, freight costs, and so on, serves as the basis for estimating the direct and indirect installation costs. These costs are obtained by multiplying X by the cost factors, which are available in the literature (see Refs. 13–20).

The second step is to estimate the direct installation costs by summing all the cost factors involved in the direct installation costs, which include piping, insulation, foundation and supports, and so on. The sum of these factors is designated as the DCF (direct installation cost factor). The direct installation costs are then the product of the DCF and X . The third step consists of estimating the indirect installation costs; that is, all the cost factors for the indirect installation costs (engineering and supervision, startup, construction fees, and so on) are added; the sum is designated by ICF (indirect installation cost factor). The indirect installation costs are then the product of ICF and X . Once the direct and indirect installation costs have been calculated, the total capital cost (TCC) may be evaluated as follows:

$$TCC = X + (DCF)(X) + (ICF)(X)$$

This is then converted to annualized capital costs (ACC) with the use of the capital recovery factor (CRF), which can be calculated from the following equation:

$$CRF = \frac{(i)(1+i)^n}{(1+i)^n - 1}$$

where n = projected lifetime of the project, years
 i = annual interest rate, expressed as a fraction

The annualized capital cost (ACC) is the product of the CRF and TCC and represents the total installed equipment cost distributed over the lifetime of the project. The ACC reflects the cost associated with the initial capital outlay over the depreciable life of the system. Although investment and operating costs can be accounted for in other ways such as present-worth analysis, the capital recovery method is preferred because of its simplicity and versatility. This is especially true when comparing somewhat similar systems having different depreciable lives. In such decisions, there are usually other considerations besides economic, but if all other factors are equal, the alternative with the lowest total annualized cost should be the most viable.

Operating costs can vary from site to site since these costs reflect local conditions (e.g., staffing practices, labor, utility costs). Operating costs, like capital costs, may be separated into two categories: direct and indirect costs. Direct costs are those that cover material and labor and are directly involved in operating the facility. These include labor, materials, maintenance and maintenance supplies, replacement parts, wastes, disposal fees, utilities, and laboratory costs. Indirect costs are those operating costs associated with, but not directly involved in, operating the facility; costs such as overhead (e.g., building/land lease-

ing and office supplies), administrative fees, property taxes, and insurance fees) fall into this category. However, the major direct operating costs are usually those associated with labor and materials.

The main problem with the traditional type of economic analysis is that it is difficult—nay, in some cases impossible—to quantify some of the not-so-obvious economic merits of a pollution-prevention program. Several considerations have just recently surfaced as factors that need to be taken into account in any meaningful economic analysis of a pollution-prevention effort. What follows is a summary listing of these considerations, most which have been detailed earlier.

1. Decreased long-term liabilities
2. Regulatory compliance
3. Regulatory recordkeeping
4. Dealings with the EPA
5. Dealings with state and local regulatory bodies
6. Elimination or reduction of fines and penalties
7. Potential tax benefits
8. Customer relations
9. Stockholder support (corporate image)
10. Improved public image
11. Reduced technical support
12. Potential insurance costs and claims
13. Effect on borrowing power
14. Improved mental and physical well-being of employees
15. Reduced health-maintenance costs
16. Employee morale
17. Other process benefits
18. Improved worker safety
19. Avoidance of rising costs of waste treatment and/or disposal
20. Reduced training costs
22. Reduced emergency response planning

Many proposed pollution-prevention programs have been squelched in their early stages because a comprehensive economic analysis was not performed. Until the effects described above are included, the true merits of a pollution-prevention program may be clouded by incorrect and/or incomplete economic data. Can something be done by industry to remedy this problem? One approach is to use a modified version of the standard Delphi panel. In order to estimate these other economic benefits of pollution prevention, several knowledgeable individuals within and perhaps outside the organization are asked to independently provide estimates, with explanatory details, on these economic benefits. Each individual in the panel is then allowed to independently review all responses. The cycle is then repeated until the group's responses approach convergence.

Finally, pollution-prevention measures can provide a company with the opportunity of looking their neighbors in the eye and truthfully saying that all that can reasonably be done to prevent pollution is being done. In effect, the company is doing right by the environment. Is there an economic advantage to this? It is not only a difficult question to answer quantitatively but also a difficult one to answer qualitatively. The reader is left to ponder the answer to this question.

POLLUTION PREVENTION AT THE DOMESTIC AND OFFICE LEVELS

Concurrent with the United States' growth as an international economic superpower during the years following World War II, a new paradigm was established whereby society became accustomed to the convenience and ease with which goods could be discarded after a relatively short useful life. Individuals have come to expect these everyday comforts with what may be considered an unconscious ignorance towards the ultimate effect of the throwaway lifestyle. In fact, many, while fearful of environmental degradation, are not aware of the ill effect these actions have on the world as a whole. Many individuals who abide by the "not in my back yard" (NIMBY) mind-set also feel pollution prevention does not have to occur "in my house."

The past two decades have seen an increased social awareness of the impact of modern-day lifestyles on the environment. Public environmental concerns include issues such as waste disposal; hazardous-material regulations; depletion of natural resources; and air, water, and land pollution. Nevertheless, roughly one-half of the total quan-

tity of waste generated each year can be attributed to domestic sources!

More recently, concern about the environment has begun to stimulate environmentally correct behavior. After all, the choices made today affect the environment of tomorrow. Simple decisions can be made at work and at home that conserve natural resources and lessen the burden placed on a waste-management system. By eliminating waste at the source, society is participating in the protection of the environment by reducing the amount of waste that would otherwise need to be treated or ultimately disposed.

There are numerous areas of environmental concern that can be directly influenced by the consumer's actions. The first issue, which is described above, is that of waste generation. Second, energy conservation has significantly affected Americans and has resulted in cost-saving measures that have directly reduced pollution. As mentioned previously, energy conservation is directly related to pollution prevention since a reduction in energy use usually corresponds to less energy production and, consequently, less pollution output. A third area of concern is that of accident and emergency planning. Relatively recent accidents like Chernobyl and Bhopal have increased public awareness and helped stimulate regulatory policies concerned with emergency planning. Specifically, Title III of the Superfund Amendments and Reauthorization Act (SARA) of 1986 established the Emergency Planning and Community Right-to-Know Act and forever changed the concept of environmental management. This law attempts to avert potential emergencies through careful planning and the development of contingency plans. Planning for emergency situations can help protect human health and the environment (Ref. 21).

Based on the above three areas of potential concern, a plethora of waste reduction activities can be performed at home or in an office environment. One can easily note the similarities between these activities and those pollution-prevention activities performed in industry. The following few examples are identified by category according to this notation (Ref. 21):

- Waste reduction
- ★ Accidents, health, and safety
- Energy conservation

At home

- Purchase products with the least amount of packaging
- Borrow items used infrequently
- ★ Handle materials to avoid spills (and slips, trips)
- ★ Keep hazardous materials out-of-reach of children
- Use energy-efficient lighting (e.g., florescent)
- Install water-flow restriction devices on sink faucets and showerheads

At the office

- Pass on verbal memos when written correspondence isn't required
- Reuse paper before recycling it
- ★ Know building evacuation procedures
- ★ Adhere to company medical policies (e.g., annual physicals)
- Don't waste utilities simply because you are not paying for them
- Take public transportation to the office

The use of pollution-prevention principles on the home front clearly does not involve the use of high-technology equipment or major lifestyle changes; success is only dependent upon active and willing public participation. All can help to make a difference.

Before pollution prevention becomes a fully accepted way of life, considerable effort still needs to be expended to change the way one looks at waste management. A desire to use "green" products and services will be of no avail in a market where these goods are not available. Participation in pollution-prevention programs will increase through continued education, community efforts, and lobbying for change. Market incentives can be created and strengthened by tax policies, price preferences, and packaging regulations created at the federal, state, and local levels. Each individual should take part by communicating with industry and expressing concerns. For example,

citizens should feel free to write letters to decision makers at both business organizations and government institutions regarding specific products or legislation. Letters can be positive, demonstrating personal endorsement of a green product, or disapproving, expressing discontent and reluctance to use a particular product because of its negative environmental effect (Ref. 21).

By starting now, society will learn through experience to better manage its waste while providing a safer and cleaner environment for future generations.

ETHICAL CONSIDERATIONS

Given the evolutionary nature of pollution prevention, it is evident that as technology changes and continued progress is achieved, society's opinion of both what is possible and desirable will also change. Government officials, scientists, and engineers will face new challenges to fulfill society's needs while concurrently meeting the requirements of changing environmental regulations. It is now apparent that attention should also be given to ethical considerations and their application to pollution prevention policy. How one makes decisions on the basis of ethical beliefs is clearly a personal issue but one that should be addressed. In order to examine this issue, the meaning of ethics must be known, although the intent here is not to provide a detailed discussion regarding the philosophy of ethics or morality.

Ethics can simply be defined as the analysis of the rightness and wrongness of an act or actions. According to Dr. Andrew Varga, director of the Philosophical Resources Program at Fordham University, in order to discern the morality of an act, it is customary to look at the act on the basis of four separate elements: its object, motive, circumstances, and consequences (Ref. 22). Rooted in this analysis is the belief that if one part of the act is bad, then the overall act itself cannot be considered good. Of course, there are instances where the good effects outweigh the bad, and therefore there may be a reason to permit the evil. The application of this principle is not cut and dry and requires decisions to be made on a case-by-case basis. Each must make well-judged decisions rooted in an understanding of the interaction between technology and the environment. After all, the decisions made today will have an impact not only on this generation but on many generations to come. If one chooses today not to implement a waste-reduction program in order to meet a short-term goal of increased productivity, this might be considered a good decision since it benefits the company and its employees. However, should a major release occur that results in the contamination of a local sole-source of drinking water, what is the good?

As an additional example, toxicological studies have indicated that test animals exposed to small quantities of toxic chemicals had better health than control groups that were not exposed. A theory has been developed that says that a low-level exposure to the toxic chemical results in a challenge to the animal to maintain homeostasis; this challenge increases the animal's vigor and, correspondingly, its health. However, larger doses seem to cause an inability to adjust, resulting in negative health effects. Based on this theory, some individuals would believe that absolute pollution reduction might not be necessary.

FUTURE TRENDS

The reader should keep an open mind when dealing with the types of issues discussed above and facing challenges perhaps not yet imagined. Clearly, there is no simple solution or answer to many of the questions. The EPA is currently *attempting* to develop a partnership with government, industry, and educators to produce and distribute pollution-prevention educational materials. Given EPA's past history and performance, there are understandable doubts as to whether this program will succeed (Ref. 23).

Finally, no discussion on pollution prevention would be complete without reference to the activities of the 49-year-old International Organization for Standardization (ISO). ISO recently created Technical Committee 207 (TC 207) to begin work on new standards for environmental management systems (EMS). The ramifications, especially to the chemical industry, which has become heavily involved in the development of these standards, will be great. TC 207's activities are

being scrutinized closely and will continue to be into 1997 when the first environmental standards are expected to be published. This new environmental management set of standards will be entitled ISO 14000. Once this new standard is in place, it is expected that customers will require their product suppliers to be certified by ISO 14000. In addition, some service suppliers who have an impact on the environment will also probably be expected to obtain an ISO 14000 certification. Certification will imply to the customer that, when the product or service was prepared, the environment was not significantly damaged in the process. This will effectively require that the life-cycle design mentality discussed earlier be applied to all processes. Implementing the life-cycle design framework will require significant organizational and operational changes in business. To effectively promote the goals of sustainable development, life-cycle designs will have to successfully address cost, performance, and cultural and legal factors.

The impact of all of the above on both the industry and the con-

sumer will be significant. All have heard the expression "I've met the enemy . . . and we're it." After all, it is the consumer who can and will ultimately have the final say. Once the consumer refuses to buy and/or accept products and/or services that damage the environment, that industry is either out of business or must change its operations to environmentally acceptable alternatives. With the new standards, customers (in addition to other organizations) of certified organizations will be assured that the products or services they purchase have been produced in accordance with universally accepted standards of environmental management. Organizational claims, which today can be misleading or erroneous, will, under the standards, be backed up by comprehensive and detailed environmental management systems that must withstand the scrutiny of intense audits.

Can all of the above be achieved in the near future? If it can, then society need only key its environmental efforts on educating the consumer.

AIR-POLLUTION MANAGEMENT OF STATIONARY SOURCES

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INTRODUCTION

Air pollutants may be classified into two broad categories: (1) natural and (2) human-made. Natural sources of air pollutants include:

- Windblown dust
- Volcanic ash and gases
- Ozone from lightning and the ozone layer
- Esters and terpenes from vegetation
- Smoke, gases, and fly ash from forest fires
- Pollens and other aeroallergens
- Gases and odors from biologic activities
- Natural radioactivity

Such sources constitute background pollution and that portion of the pollution problem over which control activities can have little, if any, effect.

Human-made sources cover a wide spectrum of chemical and physical activities and are the major contributors to urban air pollution. Air pollutants in the United States pour out from over 10 million vehicles, the refuse of over 250 million people, the generation of billions of kilowatts of electricity, and the production of innumerable products demanded by everyday living. Hundreds of millions of tons of air pollutants are generated annually in the United States alone. The five main classes of pollutants are particulates, sulfur dioxide, nitrogen oxides, volatile organic compounds, and carbon monoxide. Total emissions in the United States are summarized by source category for the year 1993 in Table 25-10.

Air pollutants may also be classified as to the origin and state of matter:

1. Origin
 - a. Primary. Emitted to the atmosphere from a process
 - b. Secondary. Formed in the atmosphere as a result of a chemical reaction
2. State of matter
 - a. Gaseous. True gases such as sulfur dioxide, nitrogen oxide, ozone, carbon monoxide, etc.; vapors such as gasoline, paint solvent, dry cleaning agents, etc.
 - b. Particulate. Finely divided solids or liquids; solids such as dust, fumes, and smokes; and liquids such as droplets, mists, fogs, and aerosols

Gaseous Pollutants Gaseous pollutants may be classified as inorganic or organic. Inorganic pollutants consist of:

1. *Sulfur gases.* Sulfur dioxide, sulfur trioxide, hydrogen sulfide
2. *Oxides of carbon.* Carbon monoxide, carbon dioxide
3. *Nitrogen gases.* Nitrous oxide, nitric oxide, nitrogen dioxide, other nitrous oxides
4. *Halogens, halides.* Hydrogen fluoride, hydrogen chloride, chlorine, fluorine, silicon tetrafluoride
5. *Photochemical products.* Ozone, oxidants
6. *Cyanides.* Hydrogen cyanide
7. *Ammonium compounds.* Ammonia
8. *Chlorofluorocarbons.* 1,1,1-trichloro-2,2,2-trifluoroethane; trichlorofluoromethane, dichlorodifluoromethane; chlorodifluoromethane; 1,2-dichloro-1,1,2,2-tetrafluoroethane; chloropentafluoroethane

Organic pollutants consist of:

1. *Hydrocarbons*
 - a. Paraffins. Methane, ethane, octane
 - b. Acetylene
 - c. Olefins. Ethylene, butadiene
 - d. Aromatics. Benzene, toluene, benzpyrene, xylene, styrene
2. *Aliphatic oxygenated compounds*
 - a. Aldehydes. Formaldehyde
 - b. Ketones. Acetone, methylethylketone

TABLE 25-10 1993 National Emissions by Source Category in short tons ×1000

Source category	Particulate (PM-10)	Sulfur dioxide	Nitrogen oxides	Volatile organic compounds	Carbon monoxide
Fuel combustion					
Electric utility	270	15836	7782	36	322
Industrial	219	2830	3176	271	667
Other	723	600	732	341	4444
Chemical and allied product manufacturing	75	450	414	1811	1998
Metals processing	141	580	82	74	2091
Petroleum and related industries	26	409	95	720	398
Other industrial processes	311	413	314	486	732
Solvent utilization	2	1	3	6249	2
Storage and transport	55	5	3	1861	56
Waste disposal and recycling	248	37	84	2271	1732
Highway vehicles	197	438	7437	6094	59989
Off-highway	395	278	2986	2207	15272
Natural sources—wind erosion	628				
Miscellaneous	42200	11	296	893	9506
Fugitive dust	41801				
Nonfugitive dust	399				
Total	45490	21888	23404	23314	97209

SOURCE: EPA-454/R-94-027, National Air Pollutant Emission Trends, 1900–1993.

- c. Organic acids
- d. Alcohols. Methanol, ethanol, isopropanol
- e. Organic halides. Cyanogen chloride bromobenzyl cyanide
- f. Organic sulfides. Dimethyl sulfide
- g. Organic hydroperoxides. Peroxyacetyl nitrite or nitrate (PAN)

The most common gaseous pollutants and their major sources and significance are presented in Table 25-11.

Particulate Pollutants Particulates may be defined as solid or liquid matter whose effective diameter is larger than a molecule but smaller than approximately 100 μm . Particulates dispersed in a gaseous medium are collectively termed an *aerosol*. The terms *smoke*, *fog*, *haze*, and *dust* are commonly used to describe particular types of aerosols, depending on the size, shape, and characteristic behavior of the dispersed particles. Aerosols are rather difficult to classify on a scientific basis in terms of their fundamental properties such as settling rate under the influence of external forces, optical activity, ability to absorb an electrical charge, particle size and structure, surface-to-volume ratio, reaction activity, physiological action, and so on. In general, particle size and settling rate have been the most characteristic properties for many purposes. On the other hand, particles on the order of 1 μm or less settle so slowly that, for all practical purposes, they are regarded as permanent suspensions. Despite possible advantages of scientific classification schemes, the use of popular descriptive terms such as smoke, dust, and mist, which are essentially based on the mode of formation, appears to be a satisfactory and convenient method of classification. In addition, this approach is so well established and understood that it undoubtedly would be difficult to change.

Dust is typically formed by the pulverization or mechanical disintegration of solid matter into particles of smaller size by processes such as grinding, crushing, and drilling. Particle sizes of dust range from a lower limit of about 1 μm up to about 100 or 200 μm and larger. Dust particles are usually irregular in shape, and particle size refers to some average dimension for any given particle. Common examples include fly ash, rock dusts, and ordinary flour. *Smoke* implies a certain degree of optical density and is typically derived from the burning of organic materials such as wood, coal, and tobacco. Smoke particles are very fine, ranging in size from less than 0.01 μm up to 1 μm . They are usually spherical in shape if of liquid or tarry composition and irregular in shape if of solid composition. Owing to their very fine particle size, smokes can remain in suspension for long periods of time and exhibit lively brownian motion.

Fumes are typically formed by processes such as sublimation, condensation, or combustion, generally at relatively high temperatures. They range in particle size from less than 0.1 μm to 1 μm . Similar to smokes, they settle very slowly and exhibit strong brownian motion.

Mists or fogs are typically formed either by the condensation of water or other vapors on suitable nuclei, giving a suspension of small

liquid droplets, or by the atomization of liquids. Particle sizes of natural fogs and mists lie between 2 and 200 μm . Droplets larger than 200 μm are more properly classified as drizzle or rain. Many of the important properties of aerosols that depend on particle size are presented in Sec. 17, Fig. 17-34.

When a liquid or solid substance is emitted to the air as particulate matter, its properties and effects may be changed. As a substance is broken up into smaller and smaller particles, more of its surface area is exposed to the air. Under these circumstances, the substance, whatever its chemical composition, tends to combine physically or chemically with other particles or gases in the atmosphere. The resulting combinations are frequently unpredictable. Very small aerosol particles (from 0.001 to 0.1 μm) can act as condensation nuclei to facilitate the condensation of water vapor, thus promoting the formation of fog and ground mist. Particles less than 2 or 3 μm in size (about half by weight of the particles suspended in urban air) can penetrate the mucous membrane and attract and convey harmful chemicals such as sulfur dioxide. In order to address the special concerns related to the effects of very fine, inhalable particulates, EPA replaced its ambient air standards for total suspended particulates (TSP) with standards for particulate matter less than 10 μm in size (PM_{10}).

By virtue of the increased surface area of the small aerosol particles and as a result of the adsorption of gas molecules or other such properties that are able to facilitate chemical reactions, aerosols tend to exhibit greatly enhanced surface activity. Many substances that oxidize slowly in their massive state will oxidize extremely fast or possibly even explode when dispersed as fine particles in the air. Dust explosions, for example, are often caused by the unstable burning or oxidation of combustible particles, brought about by their relatively large specific surfaces. Adsorption and catalytic phenomena can also be extremely important in analyzing and understanding the problems of particulate pollution. The conversion of sulfur dioxide to corrosive sulfuric acid assisted by the catalytic action of iron oxide particles, for example, demonstrates the catalytic nature of certain types of particles in the atmosphere. Finally, aerosols can absorb radiant energy and rapidly conduct heat to the surrounding gases of the atmosphere. These are gases that ordinarily would be incapable of absorbing radiant energy by themselves. As a result, the air in contact with the aerosols can become much warmer.

Estimating Emissions from Sources Knowledge of the types and rates of emissions is fundamental to evaluation of any air pollution problem. A comprehensive material balance on the process can often assist in this assessment. Estimates of the rates at which pollutants are discharged from various processes can also be obtained by utilizing published emission factors. See *Compilation of Air Pollution Emission Factors (AP-42)*, 4th ed., U.S. EPA, Research Triangle Park, North Carolina, September, 1985, with all succeeding supplements and the EPA Technology Transfer Network's CHIEF. The emission factor is a statistical average of the rate at which pollutants are emitted from the

TABLE 25-11 Typical Gaseous Pollutants and Their Principal Sources and Significance

Air pollutants	From manufacturing sources such as these	In typical industries	Cause these damaging effects
Alcohols	Used as a solvent in coatings	Surface coatings, printing	Sensory and respiratory irritation
Aldehydes	Results from thermal decomposition of fats, oil, or glycerol; used in some glues and binders	Food processing, light process, wood furniture, chip board	An irritating odor, suffocating, pungent, choking; not immediately dangerous to life; can become intolerable in a very short time
Ammonia	Used in refrigeration, chemical processes such as dye making, explosives, lacquer, fertilizer	Textiles, chemicals	Corrosive to copper, brass, aluminum, and zinc; high concentration producing chemical burns on wet skin
Aromatics	Used as a solvent in coatings	Surface coatings, printing	Irritation of mucous membranes, narcotic effects; some are carcinogens
Arsine	Any soldering, pickling, etching, or plating process involving metals or acids containing arsenic	Chemical processing, smelting	Breakdown of red cells in blood
Carbon dioxide	Fuel combustion; calcining	Industrial boilers, cement and lime production	Greenhouse gas
Carbon monoxide	Fuming of metallic oxides, gas-operated fork trucks	Primary metals; steel and aluminum	Reduction in oxygen-carrying capacity of blood
Chlorine	Manufactured by electrolysis, bleaching cotton and flour; by-product of organic chemicals	Textiles, chemicals	Attacks entire respiratory tract and mucous membrane of eye
Chlorofluorocarbons	Used in refrigeration and production of porous foams; degreasing agent	Refrigeration, plastic foam production, metal fabricating	Attacks stratospheric ozone layer; greenhouse gas
Hydrochloric acid	Combustion of coal or wastes containing chlorinated plastics	Coal-fired boilers, incinerators	Irritant to eyes and respiratory system
Hydrogen cyanide	From metal plating, blast furnaces, dyestuff works	Metal fabricating, primary metals, textiles	Capable of affecting nerve cells
Hydrogen fluoride	Catalyst in some petroleum refining, etching glass, silicate extraction; by-product in electrolytic production of aluminum	Petroleum, primary metals, aluminum	Strong irritant and corrosive action on all body tissue; damage to citrus plants, effect on teeth and bones of cattle from eating plants
Hydrogen sulfide	Refinery gases, crude oil, sulfur recovery, various chemical industries using sulfur compounds	Petroleum and chemicals; Kraft pulping process	Foul odor of rotten eggs; irritating to eyes and respiratory tract; darkening exterior paint
Ketones	Used as a solvent in coatings	Surface coatings, printing	Sensory and respiratory irritation
Lead	Incineration, smelting and casting, transportation.	Copper and lead smelting, MSWs	Neurological impairments; kidney, liver, and heart damage.
Nitrogen oxides	High-temperature combustion: metal cleaning, fertilizer, explosives, nitric acid; carbon-arc combustion; manufacture of H ₂ SO ₄	Metal fabrication, heavy chemicals	Irritating gas affecting lungs; vegetation damage
Odors	Slaughtering and rendering animals, tanning animal hides, canning, smoking meats, roasting coffee, brewing beer, processing toiletries	Food processing, allied industries	Objectionable odors
Ozone	Reaction product of VOC and nitrogen oxides	Not produced directly	Irritant to eyes and respiratory system
Phosgenes	Thermal decomposition of chlorinated hydrocarbons, degreasing, manufacture of dyestuffs, pharmaceuticals, organic chemicals	Metal fabrication, heavy chemicals	Damage capable of leading to pulmonary edema, often delayed
Sulfur dioxide	Fuel combustion (coal, oil), smelting and casting, manufacture of paper by sulfite process	Primary metals (ferrous and nonferrous); pulp and paper	Sensory and respiratory irritation, vegetation damage, corrosion, possible adverse effect on health

burning or processing of a given quantity of material or on the basis of some other meaningful parameter. Emission factors are affected by the techniques employed in the processing, handling, or burning operations, by the quality of the material used, and by the efficiency of the air-pollution control. Since the combination of these factors tends to be unique to a source, emission factors appropriate for one source may not be satisfactory for another source. Hence, care and good judgment must be exercised in identifying appropriate emission factors. If appropriate emission factors cannot be found or if air-pollution control equipment is to be designed, specific source sampling should be conducted. The major industrial sources of pollutants, the air con-

taminants emitted, and typical control techniques are summarized in Table 25-12.

Effects of Air Pollutants

Materials The damage that air pollutants can do to some materials is well known: ozone in photochemical smog cracks rubber, weakens fabrics, and fades dyes; hydrogen sulfide tarnishes silver; smoke dirties laundry; acid aerosols ruin nylon hose. Among the most important effects are discoloration, corrosion, the soiling of goods, and impairment of visibility.

TABLE 25-12 Control Techniques Applicable to Unit Processes at Important Emission Sources

Industry	Process of operation	Air contaminants emitted	Control techniques
Aluminum reduction plants	Materials handling: Buckets and belt Conveyor or pneumatic conveyor	Particulates (dust)	Exhaust systems and baghouse
	Anode and cathode electrode preparation: Cathode (baking) Anode (grinding and blending)	Hydrocarbon emissions from binder Particulates (dust) Particulates (dust), CO, SO ₂ , hydrocarbons, and fluorides	Exhaust systems and mechanical collectors
	Baking		High-efficiency cyclone, electrostatic precipitators, scrubbers, catalytic combustion or incinerators, flares, baghouse
	Pot charging	Particulates (dust), CO, HF, SO ₂ , CF ₄ , and hydrocarbons	High-efficiency cyclone, baghouse, spray towers, floating-bed scrubber, electrostatic precipitators, chemisorption, wet electrostatic precipitators
Asphalt plants	Metal casting	Cl ₂ , HCl, CO, and particulates (dust)	Exhaust systems and scrubbers
	Materials handling, storage and classifiers: elevators, chutes, vibrating screens	Particulates (dust)	Wetting; exhaust systems with a scrubber or baghouse
	Drying: rotary oil- or gas-fired	Particulates, SO ₂ , NO _x , VOC, CO, and smoke	Proper combustion controls, fuel-oil preheating where required; local exhaust system, cyclone and a scrubber or baghouse
	Truck traffic	Dust	Paving, wetting down truck routes
Cement plants	Quarrying: primary crusher, secondary crusher, conveying, storage	Particulates (dust)	Wetting; exhaust systems with fabric filters
	Dry processes: materials handling, air separator (hot-air furnace)	Particulates (dust)	Local exhaust system with mechanical collectors and baghouse
	Grinding	Particulates (dust)	Local exhaust system with cyclones and baghouse
	Pneumatic, conveying and storage	Particulates (dust)	
	Wet process: materials handling, grinding, storage	Wet materials, no dust	
	Kiln operations: rotary kiln	Particulates (dust), CO, SO ₂ , NO _x , hydrocarbons, aldehydes, ketones	Electrostatic precipitators, acoustic horns and baghouses, scrubber
Coal-preparation plants	Clinker cooling: materials handling	Particulates (dust)	Local exhaust system and electrostatic precipitators or fabric filters
	Grinding and packing, air separator, grinding, pneumatic conveying, materials handling, packaging	Particulates (dust)	Local exhaust system and fabric filters
	Materials handling: conveyors, elevators, chutes	Particulates (dust)	Local exhaust system and cyclones
	Sizing: crushing, screening, classifying	Particulates (dust)	Local exhaust system and cyclones
Coke plants	Dedusting	Particulates (dust)	Local exhaust system, cyclone precleaners, and baghouse
	Storing coal in piles	Blowing particulates (dust)	Wetting, plastic-spray covering
	Refuse piles	H ₂ S, particulates, and smoke from burning storage piles	Digging out fire, pumping water onto fire area, blanketing with incombustible material
	Coal drying: rotary, screen, suspension, fluid-bed, cascade	Dust, smoke, particulates, sulfur oxides, H ₂ S	Exhaust systems with cyclones and fabric filters
Fertilizer industry (chemical)	By-product-ovens charging	Smoke, particulates (dust)	Pipe-line charging, careful charging techniques, portable hooding and scrubber or baghouses
	Pushing	Smoke, particulates (dust), SO ₂	Minimizing green-coke pushing, scrubbers and baghouses
	Quenching	Smoke, particulates (dust and mists), phenols, and ammonia	Baffles and spray tower
	By-product processing	CO, H ₂ S, methane, ammonia, H ₂ , phenols, hydrogen cyanide, N ₂ , benzene, xylene, etc.	Electrostatic precipitator, scrubber, flaring
	Material storage (coal and coke)	Particulates (dust)	Wetting, plastic spray, fire-prevention techniques
Fertilizer industry (chemical)	Phosphate fertilizers: crushing, grinding, and calcining	Particulates (dust)	Exhaust system, scrubber, cyclone, baghouse
	Hydrolysis of P ₂ O ₅	PH ₃ , P ₂ O ₅ /PO ₄ mist	Scrubbers, flare
	Acidulation and curing	HF, SiF ₄	Scrubbers
	Granulation	Particulates (dust)/(product recovery)	Exhaust system, scrubber, or baghouse
	Ammoniation	NH ₃ , NH ₄ Cl, SiF ₄ , HF	Cyclone, electrostatic precipitator, baghouse, high-energy scrubber
	Nitric acid acidulation	NO _x , gaseous fluoride compounds	Scrubber, addition of urea
	Superphosphate storage and shipping	Particulates (dust)	Exhaust system, cyclone or baghouse
	Ammonium nitrate reactor	NH ₃ , NO _x	Scrubber
Fertilizer industry (chemical)	Prilling tower	NH ₄ , NO ₃	Proper operation control, scrubbers

TABLE 25-12 Control Techniques Applicable to Unit Processes at Important Emission Sources (Continued)

Industry	Process of operation	Air contaminants emitted	Control techniques
Foundries: Iron	Melting (cupola): Charging Melting Pouring Bottom drop	Smoke and particulates Smoke and particulates, fume Oil, mist, CO Smoke and particulates	Closed top with exhaust system, CO afterburner, gas-cooling device and scrubbers, baghouse or electrostatic precipitator, wetting to extinguish fire
Brass and bronze	Melting: Charging Melting Pouring	Smoke particulates, oil mist Zinc oxide fume, particulates, smoke Zinc oxide fume, lead oxide fume	Low-zinc-content red brass: use of good combustion controls and slag cover; high-zinc-content brass: use of good combustion controls, local exhaust system, and baghouse or scrubber
Aluminum	Melting: charging, melting, pouring	Smoke and particulates	Charging clean material (no paint or grease); proper operation required; no air-pollution-control equipment if no fluxes are used and degassing is not required; dirty charge requiring exhaust system with scrubbers and baghouses
Zinc	Melting: Charging Melting Pouring Sand-handling shakeout Magnetic pulley, conveyors, and elevators, rotary cooler, screening, crusher-mixer Coke-making ovens	Smoke and particulates Zinc oxide fume Oil mist and hydrocarbons from diecasting machines Particulates (dust), smoke, organic vapors Particulates (dust) Organic acids, aldehydes, smoke, hydrocarbons	Exhaust system with cyclone and baghouse, charging clean material (no paint or grease) Careful skimming of dross Use of low-smoking die-casting lubricants Exhaust system, cyclone, and baghouse Use of binders that will allow ovens to operate at less than 204°C (400°F) or exhaust systems and afterburners
Galvanizing operations	Hot-dip-galvanizing-tank kettle: dipping material into the molten zinc; dusting flux onto the surface of the molten zinc	Fumes, particulates (liquid), vapors: NH ₄ Cl, ZnO, ZnCl ₂ , Zn, NH ₃ , oil, and carbon	Close-fitting hoods with high in-draft velocities (in some cases, the hood may not be able to be close to the kettle, so the in-draft velocity must be very high), baghouses, electrostatic precipitators
Kraft pulp mills	Digesters: batch and continuous Multiple-effect evaporators Recovery furnace Weak and strong black-liquor oxidation Smelt tanks Lime kiln	Mercaptans, methanol (odors) H ₂ S, other odors H ₂ S, mercaptans, organic sulfides, and disulfides H ₂ S Particulates (mist or dust) Particulates (dust), H ₂ S	Condensers and use of lime kiln, boiler, or furnaces as afterburners Caustic scrubbing and thermal oxidation of noncondensables Proper combustion controls for fluctuating load and unrestricted primary and secondary air flow to furnace and dry-bottom electrostatic precipitator; noncontact evaporator Packed tower and cyclone Demisters, venturi, packed tower, or impingement-type scrubbers Venturi scrubbers
Municipal and industrial incinerators	Single-chamber incinerators Multiple-chamber incinerators (retort, inline): Flue-fed Wood waste Municipal incinerators (50 tons and up per day):	Particulates, smoke, volatiles, CO, SO _x , ammonia, organic acids, aldehydes, NO _x , dioxins hydrocarbons, odors, HCl, furans Particulates, smoke, and combustion contaminants Particulates, smoke, and combustion contaminants Particulates, smoke, and combustion contaminants Particulates, smoke, volatiles, CO, ammonia, organic acids, aldehydes, NO _x , furans, hydrocarbons, SO _x , hydrogen chloride, dioxins and odors	Afterburner, combustion controls Operating at rated capacity, using auxiliary fuel as specified, and good maintenance, including timely cleanout of ash Use of charging gates and automatic controls for draft; afterburner Continuous-feed systems; operation at design load and excess air; cyclones Preparation of materials, including weighing, grinding, shredding; control of tipping area, furnace design with proper automatic controls; proper start-up techniques; maintenance of design operating temperatures; use of electrostatic precipitators, scrubbers, and baghouses; proper ash cleanout

TABLE 25-12 Control Techniques Applicable to Unit Processes at Important Emission Sources (Continued)

Industry	Process of operation	Air contaminants emitted	Control techniques
Municipal and industrial incinerators	Pathological incinerators	Odors, hydrocarbons, HCl, dioxins, furans	Proper charging, acid gas scrubber, baghouse
	Industrial waste	Particulates, smoke, and combustion contaminants	Modified fuel feed, auxiliary fuel and dryer systems, cyclones, scrubbers
Nonferrous smelters, primary: Copper	Roasting	SO ₂ , particulates, fume	Exhaust system, settling chambers, cyclones or scrubbers and electrostatic precipitators for dust and fumes and sulfuric acid plant for SO ₂
	Reverberatory furnace	Smoke, particulates, metal oxide fumes, SO ₂	Exhaust system, settling chambers, cyclones or scrubbers and electrostatic precipitators for dust and fumes and sulfuric acid plant for SO ₂
	Converters: charging, slag skim, pouring, air or oxygen blow	Smoke, fume, SO ₂	Exhaust system, settling chambers, cyclones or scrubbers and electrostatic precipitators for dust and fumes and sulfuric acid plant for SO ₂
Lead	Sintering	SO ₂ , particulates, smoke	Exhaust system, cyclones and baghouse or precipitators for dust and fumes, sulfuric acid plant for SO ₂
	Blast furnace	SO ₂ , CO, particulates, lead oxide, zinc oxide	Exhaust system, settling chambers, afterburner and cooling device, cyclone, and baghouse
	Dross reverberatory furnace	SO ₂ , particulates, fume	Exhaust system, settling chambers, cyclone and cooling device, baghouse
	Refining kettles	SO ₂ , particulates	Local exhaust system, cooling device, baghouse or precipitator
Cadmium	Roasters, slag, fuming furnaces, deleading kilns	Particulates	Local exhaust system, baghouse or precipitator
Zinc	Roasting	Particulates (dust) and SO ₂	Exhaust system, humidifier, cyclone, scrubber, electrostatic precipitator, and acid plant
	Sintering	Particulates (dust) and SO ₂	Exhaust system, humidifier, electrostatic precipitator, and acid plant
	Calcining	Zinc oxide fume, particulates, SO ₂ , CO	Exhaust system, baghouse, scrubber or acid plant
	Retorts: electric arc		
Nonferrous smelters, secondary	Blast furnaces and cupolas-recovery of metal from scrap and slag	Dust, fumes, particulates, oil vapor, smoke, CO	Exhaust systems, cooling devices, CO burners and baghouses or precipitators
	Reverberatory furnaces	Dust, fumes, particulates, smoke, gaseous fluxing materials	Exhaust systems, and baghouses or precipitators, or venturi scrubbers
	Sweat furnaces	Smoke, particulates, fumes	Precleaning metal and exhaust systems with afterburner and baghouse
	Wire reclamation and autobody burning	Smoke, particulates	Scrubbers and afterburners
Paint and varnish manufacturing	Resin manufacturing: closed reaction vessel	Acrolein, other aldehydes and fatty acids (odors), phthalic anhydride (sublimed)	Exhaust systems with scrubbers and fume burners
	Varnish: cooking-open or closed vessels	Ketones, fatty acids, formic acids, acetic acid, glycerine, acrolein, other aldehydes, phenols and terpenes; from tall oils, hydrogen sulfide, alkyl sulfide, butyl mercaptan, and thiofen (odors)	Exhaust system with scrubbers and fume burners; close-fitting hoods required for open kettles
	Solvent thinning	Olefins, branched-chain aromatics and ketones (odors), solvents	Exhaust system with fume burners
Rendering plants	Feedstock storage and housekeeping	Odors	Quick processing, washdown of all concrete surfaces, paving of dirt roads, proper sewer maintenance, enclosure, packed towers
	Cookers and percolators	SO ₂ , mercaptans, ammonia, odors	Exhaust system, condenser, scrubber, or incinerator
	Grinding	Particulates (dust)	Exhaust system and scrubber
Roofing plants (asphalt saturators)	Felt or paper saturators: spray section, asphalt tank, wet looper	Asphalt vapors and particulates (liquid)	Exhaust system with high inlet velocity at hoods (3658 m/s [>200 ft/min]) with either scrubbers, baghouses, or two-stage low-voltage electrostatic precipitators
	Crushed rock or other minerals handling	Particulates (dust)	Local exhaust system, cyclone or multiple cyclones

TABLE 25-12 Control Techniques Applicable to Unit Processes at Important Emission Sources (Concluded)

Industry	Process of operation	Air contaminants emitted	Control techniques
Steel mills	Blast furnaces: charging, pouring	CO, fumes, smoke, particulates (dust)	Good maintenance, seal leaks; use of higher ratio of pelletized or sintered ore; CO burned in waste-heat boilers, stoves, or coke ovens; cyclone, scrubber, and baghouse
	Electric steel furnaces: charging, pouring, oxygen blow	Fumes, smoke, particulates (dust), CO	Segregating dirty scrap; proper hooding, baghouses or electrostatic precipitator
	Open-hearth furnaces: oxygen blow, pouring	Fumes, smoke, SO _x , particulates (dust), CO, NO _x	Proper hooding, settling chambers, waste-heat boiler, baghouse, electrostatic precipitator, and wet scrubber
	Basic oxygen furnaces: oxygen blowing	Fumes, smoke, CO, particulates (dust)	Proper hooding (capturing of emissions and dilute CO), scrubbers, or electrostatic precipitator
	Raw material storage Pelletizing Sintering	Particulates (dust) Particulates (dust) Smoke, particulates (dust), SO ₂ , NO _x	Wetting or application of plastic spray Proper hooding, cyclone, baghouse Proper hooding, cyclones, wet scrubbers, baghouse, or precipitator

1. *Discoloration.* Many air pollutants accumulate on and discolor buildings. Not only does sooty material blacken buildings, but it can accumulate and become encrusted. This can hide lines and decorations and thereby disfigure structures and reduce their aesthetic appeal. Another common effect is the discoloration of paint by certain acid gases. A good example is the blackening of white paint with a lead base by hydrogen sulfide.

2. *Corrosion.* A more serious effect and one of great economic importance is the corrosive action of acid gases on building materials. Such acids can cause stone surfaces to blister and peel; mortar can be reduced to powder. Metals are also damaged by the corrosive action of some pollutants. Another common effect is the deterioration of tires and other rubber goods. Cracking and apparent “drying” occur when these goods are exposed to ozone and other oxidants.

3. *Soiling of goods.* Clothes, real estate, automobiles, and household goods can easily be soiled by air contaminants, and the more frequent cleaning thus required can become expensive. Also, more frequent cleaning often leads to a shorter life span for materials and to the need to purchase goods more often.

4. *Impairment of visibility.* The impairment of atmospheric visibility (i.e., decreased visual range through a polluted atmosphere) is caused by the scattering of sunlight by particles suspended in the air. It is not a result of sunlight being obscured by materials in the air. Since light scattering, and not obscuration, is the main cause of the reduction in visibility, reduced visibility due to the presence of air pollutants occurs primarily on bright days. On cloudy days or at night there may be no noticeable effect, although the same particulate concentration may exist at these times as on sunny days. Reduction in visibility creates several problems. The most significant are the adverse effects on aircraft, highway, and harbor operations. Reduced visibility can reduce quality of life and also cause adverse aesthetic impressions that can seriously affect tourism and restrict the growth and development of any area. Extreme conditions such as dust storms or sandstorms can actually cause physical damage by themselves.

Vegetation Vegetation is more sensitive than animals to many air contaminants, and methods have been developed that use plant response to measure and identify contaminants. The effects of air pollution on vegetation can appear as death, stunted growth, reduced crop yield, and degradation of color. It is interesting to note that in some cases of color damage such as the silvering of leafy vegetables by oxidants, the plant may still be used as food without any danger to the consumer; however, the consumer usually will not buy such vegetables on aesthetic grounds, so the grower still sustains a loss. Among the pollutants that can harm plants are sulfur dioxide, hydrogen fluoride, and ethylene. Plant damage caused by constituents of photochemical smog has been studied extensively. Damage has been attributed to ozone and peroxyacetyl nitrites, higher aldehydes, and products of the reaction of ozone with olefins. However, none of the cases precisely duplicates all features of the damage observed in the field, and the question remains open to some debate and further study.

Animals Considerable work continues to be performed on the effects of pollutants on animals, including, for a few species, experiments involving mixed pollutants and mixed gas-aerosol systems. In general, such work has shown that mixed pollutants may act in several different ways. They may produce an effect that is additive, amounting to the sum of the effects of each contaminant acting alone; they may produce an effect that is greater than the simply additive (synergistic) or less than the simply additive (antagonistic); or they may produce an effect that differs in some other way from the simply additive.

The mechanism by which an animal can become poisoned in many instances is completely different from that by which humans are affected. As in humans, inhalation is an important route of entry in acute air-pollution exposures such as the Meuse Valley and Donora incidents (see the paragraph on **humans** below). However, probably the most common exposure for herbivorous animals grazing within a zone of pollution will be the ingestion of feed contaminated by air pollutants. In this case, inhalation is of secondary importance.

Air pollutants that present a hazard to livestock, therefore, are those that are taken up by vegetation or deposited on the plants. Only a few pollutants have been observed to cause harm to animals. These include arsenic, fluorides, lead, mercury, and molybdenum.

Humans There seems to be little question that, during many of the more serious episodes, air pollution can have a significant effect on health, especially upon the young, elderly, or people already in ill health. Hundreds of excess deaths have been attributed to incidents in London in 1952, 1956, 1957, and 1962; in Donora, Pennsylvania, in 1948; in New York City in 1953, 1963, and 1966; and Bhopal, India in 1989. Many of the people affected were in failing health, and they were generally suffering from lung conditions. In addition, hundreds of thousands of persons have suffered from serious discomfort and inconvenience, including eye irritation and chest pains, during these and other such incidents. Such acute problems are actually the lesser of the health problems. There is considerable evidence of a chronic threat to human health from air pollution. This evidence ranges from the rapid rise of emphysema as a major health problem, through identification of carcinogenic compounds in smog, to statistical evidence that people exposed to polluted atmospheres over extended periods of time suffer from a number of ailments and a reduction in their life span. There may even be a significant indirect exposure to air pollution. As noted above, air pollutants may be deposited onto vegetation or into bodies of water, where they enter the food chain. The impact of such indirect exposures is still under review.

Sufficient evidence is available to indicate that atmospheric pollution in varying degrees does affect health adversely. [Amdur, Melvin, and Drinker, “Effect of Inhalation of Sulfur Dioxide by Man,” *Lancet*, **2**, 758 (1953); Barton, Corn, Gee, Vassallo, and Thomas, “Response of Healthy Men to Inhaled Low Concentrations of Gas-Aerosol Mixtures,” *Arch. Environ. Health*, **18**, 681 (1969); Bates, Bell, Burnham, Hazucha, and Mantha, “Problems in Studies of Human Exposure to Air Pollutants,” *Can. Med. Assoc. J.*, **103**, 833 (1970); Ciocco and

Thompson, "A Follow-Up of Donora Ten Years After: Methodology and Findings," *Am. J. Public Health*, **51**, 155 (1961); Daly, "Air Pollution and Causes of Death," *Br. J. Soc. Med.*, **13**, 14 (1959); Jaffe, "The Biological Effect of Photochemical Air Pollutants on Man and Animals," *Am. J. Public Health*, New York, **57**, 1269 (1967); New York Academy of Medicine, Committee on Public Health, "Air Pollution and Health," *Bull. N.Y. Acad. Med.*, **42**, 588 (1966); Pemberton and Goldberg, "Air Pollution and Bronchitis," *Br. Med. J.*, London, **2**, 567 (1954); Snell and Luchsinger, "Effect of Sulfur Dioxide on Expiratory Flowrates and Total Respiratory Resistance in Normal Human Subjects," *Arch. Environ. Health*, Chicago, **18**, 693 (1969); Speizer and Frank, "A Comparison of Changes in Pulmonary Flow Resistance in Healthy Volunteers Acutely Exposed to SO₂ by Mouth and by Nose," *J. Ind. Med.*, **23** 75 (1966); Stocks, "Cancer and Bronchitis Mortality in Relation to Atmospheric Deposit and Smoke," *Br. Med. J. London*, **1**, 74 (1959); Toyama, "Air Pollution and Its Health Effects in Japan," *Arch. Environ. Health*, Chicago, **8**, 153 (1963); U.K. Ministry of Health, "Mortality and Morbidity During London Fog of December 1952," Report on Public Health and Medical Subjects No. 95, London, 1954; U.S. Public Health Service, "Air Pollution in Donora, Pa.: Preliminary Report," Public Health Bull. 306.] It contributes to excesses of death, increased morbidity, and earlier onset of chronic respiratory diseases. There is evidence of a relationship between the intensity of the pollution and the severity of attributable health effects and a consistency of the relationship between these environmental stresses and diseases of the target organs. Air pollutants can both initiate and aggravate a variety of respiratory diseases including asthma. In fact, the clinical presentation of asthma may be considered an air pollution host-defense disorder brought on by specific airborne irritants: pollens, infectious agents, and gaseous and particulate chemicals. The bronchopulmonary response to these foreign irritants is bronchospasm and hypersecretion; the airways are intermittently and reversibly obstructed.

Air-pollutant effects on neural and sensory functions in humans vary widely. Odorous pollutants cause only minor annoyance; yet, if persistent, they can lead to irritation, emotional upset, anorexia, and mental depression. Carbon monoxide can cause death secondary to the depression of the respiratory centers of the central nervous system. Short of death, repeated and prolonged exposure to carbon monoxide can alter sensory protection, temporal perception, and higher mental functions. Lipid-soluble aerosols can enter the body and be absorbed in the lipids of the central nervous system. Once there, their effects may persist long after the initial contact has been removed. Examples of agents of long-term chronic effects are organic phosphate pesticides and aerosols carrying the metals lead, mercury, and cadmium.

The acute toxicological effects of most air contaminants are reasonably well understood, but the effects of exposure to heterogeneous mixtures of gases and particulates at very low concentrations are only beginning to be comprehended. Two general approaches can be used to study the effects of air contaminants on humans: epidemiology, which attempts to associate the effect in large populations with the cause, and laboratory research, which begins with the cause and attempts to determine the effects. Ideally, the two methods should complement each other.

Epidemiology, the more costly of the two, requires great care in planning and often suffers from incomplete data and lack of controls. One great advantage, however, is that moral barriers do not limit its application to humans as they do with some kinds of laboratory research. The method is therefore highly useful and has produced considerable information. Laboratory research is less costly than epidemiology, and its results can be checked against controls and verified by experimental repetition.

A SOURCE-CONTROL-PROBLEM STRATEGY

Strategy Control technology is self-defeating if it creates undesirable side effects in meeting objectives. Air pollution control must be considered in terms of regulatory requirements, total technological systems (equipment and processes), and ecological consequences, such as the problems of treatment and disposal of collected pollutants.

It should be noted that the 1990 Clean Air Act Amendments (CAAA) have impacted on the control approach in a significant manner. In particular, the CAAA have placed an increased emphasis on control technology by requiring Best Available Control Technology (BACT) on new major sources and modifications, and by requiring Maximum Achievable Control Technology (MACT) on new and *existing* major sources of Hazardous Air Pollutants (HAPs).

The control strategy for environmental-impact assessment often focuses on five alternatives whose purpose would be the reduction and/or elimination of pollutant emissions:

1. Elimination of the operation entirely or in part
2. Modification of the operation
3. Relocation of the operation
4. Application of appropriate control technology
5. Combinations thereof

In light of the relatively high costs often associated with pollution-control systems, engineers are directing considerable effort toward process modification to eliminate as much of the pollution problem as possible at the source. This includes evaluating alternative manufacturing and production techniques, substituting raw materials, and improving process-control methods. Unfortunately, if there is no alternative, the application of the correct pollution-control equipment is essential. The equipment must be designed to comply with regulatory emission limitations on a continual basis, interruptions being subject to severe penalty depending upon the circumstances. The requirement for design performance on a continual basis places very heavy emphasis on operation and maintenance practices. The escalating costs of energy, labor, and materials can make operation and maintenance considerations even more important than the original capital cost.

Factors in Control-Equipment Selection In order to solve an air-pollution problem, the problem must be defined in detail. A number of factors must be considered prior to selecting a particular piece of air-pollution-control equipment. In general, these factors can be grouped into three categories: environmental, engineering, and economic.

Environmental Factors These include (1) equipment location, (2) available space, (3) ambient conditions, (4) availability of adequate utilities (i.e., power, water, etc.) and ancillary-system facilities (i.e., waste treatment and disposal, etc.), (5) maximum allowable emission (air pollution codes), (6) aesthetic considerations (i.e., visible steam or water-vapor plume, etc.), (7) contributions of the air-pollution-control system to wastewater and land pollution, and (8) contribution of the air-pollution-control system to plant noise levels.

Engineering Factors These include:

1. Contaminant characteristics (e.g., physical and chemical properties, concentration, particulate shape and size distribution [in the case of particulates], chemical reactivity, corrosivity, abrasiveness, and toxicity)
2. Gas-stream characteristics (e.g., volume flow rate, temperature, pressure, humidity, composition, viscosity, density, reactivity, combustibility, corrosivity, and toxicity)
3. Design and performance characteristics of the particular control system (i.e., size and weight, fractional efficiency curves [in the case of particulates]), mass-transfer and/or contaminant-destruction capability (in the case of gases or vapors), pressure drop, reliability, turndown capability, power requirements, utility requirements, temperature limitations, maintenance requirements, operating cycles (including startup and shutdown) and flexibility toward complying with more stringent air-pollution codes.

Economic Factors These include capital cost (equipment, installation, engineering, etc.), operating cost (utilities, maintenance, etc.), emissions fees, and life-cycle cost over the expected equipment lifetime.

Comparing Control-Equipment Alternatives The final choice in equipment selection is usually dictated by the equipment capable of achieving compliance with regulatory codes at the lowest uniform annual cost (amortized capital investment plus operation and maintenance costs). To compare specific control-equipment alternatives, knowledge of the particular application and site is essential. A preliminary screening, however, may be performed by reviewing the advantages and disadvantages of each type of air-pollution-control

equipment. General advantages and disadvantages of the most popular types of air-pollution equipment for gases and particulates are presented in Tables 25-13 through 25-25. Other activities that must be accomplished before final compliance is achieved are presented in Table 25-26.

In addition to using annualized cost comparisons in evaluating an air-pollution-control (APC) equipment installation, the impact of the 1990 Clean Air Act Amendments (CAAA) and resulting regulations also must be included in the evaluation. The CAAA prescribes specific pollution-control requirements for particular industries and locations. As an example, the CAAA requires that any major stationary source or

TABLE 25-13 Advantages and Disadvantages of Cyclone Collectors

Advantages
1. Low cost of construction
2. Relatively simple equipment with few maintenance problems
3. Relatively low operating pressure drops (for degree of particulate removal obtained) in the range of approximately 2- to 6-in water column
4. Temperature and pressure limitations imposed only by the materials of construction used
5. Collected material recovered dry for subsequent processing or disposal
6. Relatively small space requirements
Disadvantages
1. Relatively low overall particulate collection efficiencies, especially on particulates below 10 µm in size
2. Inability to handle tacky materials

TABLE 25-14 Advantages and Disadvantages of Wet Scrubbers

Advantages
1. No secondary dust sources
2. Relatively small space requirements
3. Ability to collect gases as well as particulates (especially "sticky" ones)
4. Ability to handle high-temperature, high-humidity gas streams
5. Capital cost low (if wastewater treatment system not required)
6. For some processes, gas stream already at high pressures (so pressure-drop considerations may not be significant)
7. Ability to achieve high collection efficiencies on fine particulates (however, at the expense of pressure drop)
8. Ability to handle gas streams containing flammable or explosive materials
Disadvantages
1. Possible creation of water-disposal problem
2. Product collected wet
3. Corrosion problems more severe than with dry systems
4. Steam plume opacity and/or droplet entrainment possibly objectionable
5. Pressure-drop and horsepower requirements possibly high
6. Solids buildup at the wet-dry interface possibly a problem
7. Relatively high maintenance costs
8. Must be protected from freezing
9. Low exit gas temperature reduces exhaust plume dispersion
10. Moist exhaust gas precludes use of most additional controls

TABLE 25-15 Advantages and Disadvantages of Dry Scrubbers

Advantages
1. No wet sludge to dispose of
2. Relatively small space requirements
3. Ability to collect acid gases at high efficiencies
4. Ability to handle high-temperature gas streams
5. Dry exhaust allows addition of fabric filter to control particulate
Disadvantages
1. Acid gas control efficiency not as high as with wet scrubber
2. No particulate collection—dry scrubber generates particulate
3. Corrosion problems more severe than with dry systems
4. Solids buildup at the wet-dry interface possibly a problem
5. Relatively high maintenance costs
6. Must be protected from freezing
7. Low exit gas temperature reduces exhaust plume dispersion

TABLE 25-16 Advantages and Disadvantages of Electrostatic Precipitators

Advantages
1. Extremely high particulate (coarse and fine) collection efficiencies attainable (at a relatively low expenditure of energy)
2. Collected material recovered dry for subsequent processing or disposal
3. Low pressure drop
4. Designed for continuous operation with minimum maintenance requirements
5. Relatively low operating costs
6. Capable of operation under high pressure (to 150 lbf/in ²) or vacuum conditions
7. Capable of operation at high temperatures [to 704°C(1300°F)]
8. Relatively large gas flow rates capable of effective handling
Disadvantages
1. High capital cost
2. Very sensitive to fluctuations in gas-stream conditions (in particular, flows, temperature, particulate and gas composition, and particulate loadings)
3. Certain particulates difficult to collect owing to extremely high- or low-resistivity characteristics
4. Relatively large space requirements required for installation
5. Explosion hazard when treating combustible gases and/or collecting combustible particulates
6. Special precautions required to safeguard personnel from the high voltage
7. Ozone produced by the negatively charged discharge electrode during gas ionization
8. Relatively sophisticated maintenance personnel required
9. Gas ionization may cause dissociation of gas stream constituents and result in creation of toxic byproducts
10. Sticky particulates may be difficult to remove from plates
11. Not effective in capturing some contaminants that exist as vapors at high temperatures (e.g., heavy metals, dioxins)

TABLE 25-17 Advantages and Disadvantages of Fabric-Filter Systems

Advantages
1. Extremely high collection efficiency on both coarse and fine (sub-micrometer) particles
2. Relatively insensitive to gas-stream fluctuation; efficiency and pressure drop relatively unaffected by large changes in inlet dust loadings for continuously cleaned filters
3. Filter outlet air capable of being recirculated within the plant in many cases (for energy conservation)
4. Collected material recovered dry for subsequent processing or disposal
5. No problems with liquid-waste disposal, water pollution, or liquid freezing
6. Corrosion and rusting of components usually not problems
7. No hazard of high voltage, simplifying maintenance and repair and permitting collection of flammable dusts
8. Use of selected fibrous or granular filter aids (precoating), permitting the high-efficiency collection of submicrometer smokes and gaseous contaminants
9. Filter collectors available in a large number of configurations, resulting in a range of dimensions and inlet and outlet flange locations to suit installment requirements
10. Relatively simple operation
Disadvantages
1. Temperatures much in excess of 288°C (550°F) requiring special refractory mineral or metallic fabrics that are still in the developmental stage and can be very expensive
2. Certain dusts possibly requiring fabric treatments to reduce dust seeping or, in other cases, assist in the removal of the collected dust
3. Concentrations of some dusts in the collector (~50 g/m ³) forming a possible fire or explosion hazard if a spark or flame is admitted by accident; possibility of fabrics burning if readily oxidizable dust is being collected
4. Relatively high maintenance requirements (bag replacement, etc.)
5. Fabric life possibly shortened at elevated temperatures and in the presence of acid or alkaline particulate or gas constituents
6. Hygroscopic materials, condensation of moisture, or tarry adhesive components possibly causing crusty caking or plugging of the fabric or requiring special additives
7. Replacement of fabric, possibly requiring respiratory protection for maintenance personnel
8. Medium pressure-drop requirements, typically in the range 4- to 10-in water column

TABLE 25-18 Advantages and Disadvantages of Absorption Systems (Packed and Plate Columns)*Advantages*

1. Relatively low pressure drop
2. Standardization in fiberglass-reinforced plastic (FRP) construction permitting operation in highly corrosive atmospheres
3. Capable of achieving relatively high mass-transfer efficiencies
4. Increasing the height and/or type of packing or number of plates capable of improving mass transfer without purchasing a new piece of equipment
5. Relatively low capital cost
6. Relatively small space requirements
7. Ability to collect particulates as well as gases
8. Collected substances may be recovered by distillation

Disadvantages

1. Possibility of creating water (or liquid) disposal problem
2. Product collected wet
3. Particulates deposition possibly causing plugging of the bed or plates
4. When FRP construction is used, sensitive to temperature
5. Relatively high maintenance costs
6. Must be protected from freezing

TABLE 25-19 Comparison of Plate and Packed Columns*Packed column*

1. Lower pressure drop
2. Simpler and cheaper to construct
3. Preferable for liquids with high-foaming tendencies

Plate column

1. Less susceptible to plugging
2. Less weight
3. Less of a problem with channeling
4. Temperature surge resulting in less damage

TABLE 25-20 Advantages and Disadvantages of Adsorption Systems*Advantages*

1. Possibility of product recovery
2. Excellent control and response to process changes
3. No chemical-disposal problem when pollutant (product) recovered and returned to process
4. Capability of systems for fully automatic, unattended operation
5. Capability to remove gaseous or vapor contaminants from process streams to extremely low levels

Disadvantages

1. Product recovery possibly requiring an exotic, expensive distillation (or extraction) scheme
2. Adsorbent progressively deteriorating in capacity as the number of cycles increases
3. Adsorbent regeneration requiring a steam or vacuum source
4. Relatively high capital cost
5. Prefiltering of gas stream possibly required to remove any particulate capable of plugging the adsorbent bed
6. Cooling of gas stream possibly required to get to the usual range of operation (less than 49°C [120°F])
7. Relatively high steam requirements to desorb high-molecular-weight hydrocarbons
8. Spent adsorbent may be considered a hazardous waste
9. Some contaminants may undergo a violent exothermic reaction with the adsorbent

major modification plan that is subject to Prevention of Significant Deterioration (PSD) requirements must under go a Best Available Control Technology (BACT) analysis. The BACT analysis is done on a case-by-case basis. The process involves evaluating the possible types of air-pollution-control equipment that could be used for technology and energy and in terms of the environment and economy. The analysis uses a top-down approach that lists all available control technologies in descending order of effectiveness. The most stringent technology is chosen unless it can be demonstrated that, due to tech-

TABLE 25-21 Advantages and Disadvantages of Combustion Systems*Advantages*

1. Simplicity of operation
2. Capability of steam generation or heat recovery in other forms
3. Capability for virtually complete destruction of organic contaminants

Disadvantages

1. Relatively high operating costs (particularly associated with fuel requirements)
2. Potential for flashback and subsequent explosion hazard
3. Catalyst poisoning (in the case of catalytic incineration)
4. Incomplete combustion, possibly creating potentially worse pollution problems
5. Even complete combustion may produce SO₂, NO_x, and CO₂
6. High temperature components and exhaust may be hazardous to maintenance personnel and birds
7. High maintenance requirements—especially if operation is cyclic

TABLE 25-22 Advantages and Disadvantages of Condensers*Advantages*

1. Pure product recovery (in the case of indirect-contact condensers)
2. Water used as the coolant in an indirect-contact condenser (i.e., shell-and-tube heat exchanger), not in contact with contaminated gas stream, and is reusable after cooling
3. May be used to produce vacuum to remove contaminants from process

Disadvantages

1. Relatively low removal efficiency for gaseous contaminants (at concentrations typical of pollution-control applications)
2. Coolant requirements possibly extremely expensive
3. Direct-contact condenser may produce water discharge problems

TABLE 25-23 Advantages and Disadvantages of Biofiltration*Advantages*

1. Uses natural biological processes and materials
2. Relatively simple and economical
3. High destruction efficiencies for oxygen-rich, low-contaminant concentration gas streams
4. Waste products are CO₂ and water

Disadvantages

1. Raw gas must not be lethal to microorganisms
2. Gas stream must be maintained at proper temperature and humidity
3. Heavy particulate loadings can damage pore structure of filter bed

TABLE 25-24 Advantages and Disadvantages of Membrane Filtration*Advantages*

1. Low energy utilization
2. Modular design
3. Low capital costs
4. Low maintenance
5. Superior separation ability

Disadvantages

1. Potential particulate fouling problems if not properly designed

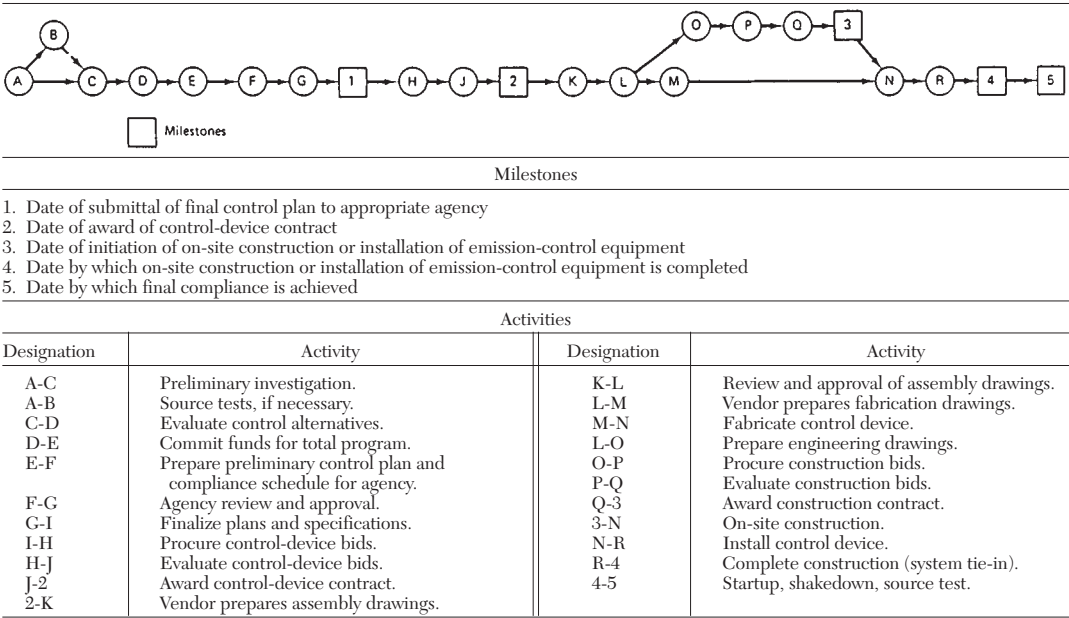
TABLE 25-25 Advantages and Disadvantages of Selective Catalytic Reduction of Nitrogen Oxides*Advantages*

1. Capable of 90% NO_x removal
2. Uses readily available urea reagent
3. Exhaust products are N₂ and water

Disadvantages

1. Spent catalyst may be considered hazardous waste
2. Gas stream must be maintained at proper temperature and humidity
3. Heavy particulate loadings can damage pore structure of filter bed

TABLE 25-26 Compliance Activity and Schedule Chart



nical, energy, environmental, or economic considerations, this type of APC technology is not feasible.

The 1990 CAAA introduced a new level of control for hazardous (toxic) air pollutants (HAPs). As a result, EPA has identified 189 HAPs for regulation. Rather than rely upon ambient air quality standards to set acceptable exposures to HAPs, the CAAA requires that EPA promulgate through the end of the decade Maximum Achievable Control Technology (MACT) standards for controlling HAPs emitted from specified industries. These standards are based on the level of control established by the best performing 12 percent of industries in each of the categories identified by EPA.

DISPERSION FROM STACKS

Stacks discharging to the atmosphere have long been the most common industrial method of disposing of waste gases. The concentrations to which humans, plants, animals, and structures are exposed at ground level can be reduced significantly by emitting the waste gases from a process at great heights. Although tall stacks may be effective in lowering the ground-level concentration of pollutants, they do not in themselves reduce the amount of pollutants released into the atmosphere. However, in certain situations, their use can be the most practical and economical way of dealing with an air-pollution problem.

Preliminary Design Considerations To determine the acceptability of a stack as a means of disposing of waste gases, the acceptable ground-level concentration (GLC) of the pollutant or pollutants must be determined. The topography of the area must also be considered so that the stack can be properly located with respect to buildings and hills that might introduce a factor of air turbulence into the operation of the stack. Awareness of the meteorological conditions prevalent in the area, such as the prevailing winds, humidity, and rainfall, is also essential. Finally, an accurate knowledge of the constituents of the waste gas and their physical and chemical properties is paramount.

Wind Direction and Speed Wind direction is measured at the height at which the pollutant is released, and the mean direction will indicate the direction of travel of the pollutants. In meteorology, it is conventional to consider the wind direction as the direction from which the wind blows; therefore, a northwest wind will move pollutants to the southeast of the source.

The effect of wind speed is twofold: (1) Wind speed will determine the travel time from a source to a given receptor; and (2) wind speed

will affect dilution in the downwind direction. Generally, the concentration of air pollutants downwind from a source is inversely proportional to wind speed.

Wind speed has velocity components in all directions so that there are vertical motions as well as horizontal ones. These random motions of widely different scales and periods are essentially responsible for the movement and diffusion of pollutants about the mean downwind path. These motions can be considered atmospheric turbulence. If the scale of a turbulent motion (i.e., the size of an eddy) is larger than the size of the pollutant plume in its vicinity, the eddy will move that portion of the plume. If an eddy is smaller than the plume, its effect will be to diffuse or spread out the plume. This diffusion caused by eddy motion is widely variable in the atmosphere, but even when the effect of this diffusion is least, it is in the vicinity of three orders of magnitude greater than diffusion by molecular action alone.

Mechanical turbulence is the induced-eddy structure of the atmosphere due to the roughness of the surface over which the air is passing. Therefore, the existence of trees, shrubs, buildings, and terrain features will cause mechanical turbulence. The height and spacing of the elements causing the roughness will affect the turbulence. In general, the higher the roughness elements, the greater the mechanical turbulence. In addition, mechanical turbulence increases as wind speed increases.

Thermal turbulence is turbulence induced by the stability of the atmosphere. When the Earth's surface is heated by the sun's radiation, the lower layer of the atmosphere tends to rise and thermal turbulence becomes greater, especially under conditions of light wind. On clear nights with wind, heat is radiated from the Earth's surface, resulting in the cooling of the ground and the air adjacent to it. This results in extreme stability of the atmosphere near the Earth's surface. Under these conditions, turbulence is at a minimum. Attempts to relate different measures of turbulence of the wind (or stability of the atmosphere) to atmospheric diffusion have been made for some time. The measurement of atmospheric stability by temperature-difference measurements on a tower is frequently utilized as an indirect measure of turbulence, particularly when climatological estimates of turbulence are desired.

Lapse Rate and Atmospheric Stability Apart from mechanical interference with the steady flow of air caused by buildings and other obstacles, the most important factor that influences the degree of turbulence and hence the speed of diffusion in the lower air is the varia-

tion of temperature with height above the ground, referred to as the "lapse rate." The dry-adiabatic lapse rate (DALR) is the temperature change for a rising parcel of dry air. The dry-adiabatic lapse rate can be approximated as -1°C per 100 m, or $dT/dz = -10^{-2}^\circ\text{C/m}$ or $-5.4^\circ\text{F}/1000\text{ ft}$. If the rising air contains water vapor, the cooling due to adiabatic expansion will result in the relative humidity being increased, and saturation may be reached. Further ascent would then lead to condensation of water vapor, and the latent heat thus released would reduce the rate of cooling of the rising air. The buoyancy force on a warm-air parcel is caused by the difference between its density and that of the surrounding air. The perfect-gas law shows that, at a fixed pressure (altitude), the temperature and density of an air parcel are inversely related; temperature is normally used to determine buoyancy because it is easier to measure than density. If the temperature gradient (lapse rate) of the atmosphere is the same as the adiabatic lapse rate, a parcel of air displaced from its original position will expand or contract in such a manner that its density and temperature remain the same as its surroundings. In this case there will be no buoyancy forces on the displaced parcel, and the atmosphere is termed "neutrally stable."

If the atmospheric temperature decreases faster with increasing altitude than the adiabatic lapse rate (superadiabatic), a parcel of air displaced upward will have a higher temperature than the surrounding air. Its density will be lower, giving it a net upward buoyancy force. The opposite situation exists if the parcel of air is displaced downward, and the parcel experiences a downward buoyancy force. Once a parcel of air has started moving up or down, it will continue to do so, causing unstable atmospheric conditions. If the temperature decreases more slowly with increasing altitude than the adiabatic lapse rate, a displaced parcel of air experiences a net restoring force. The buoyancy forces then cause stable atmospheric conditions (see Fig. 25-4).

Strongly stable lapse rates are commonly referred to as *inversions*. The strong stability inhibits mixing across the inversion layer. Normally these conditions of strong stability extend for only several hundred meters vertically. The vertical extent of the inversion is referred to as the *inversion depth*. Two distinct types are observed: the ground-level inversion, caused by radiative cooling of the ground at night, and inversions aloft, occurring between 500 and several thousand meters above the ground (see Fig. 25-5). Some of the more common lapse-rate profiles with the corresponding effect on stackplumes are presented in Fig. 25-6.

From the viewpoint of air pollution, both stable surface layers and low-level inversions are undesirable because they minimize the rate of dilution of contaminants in the atmosphere. Even though the surface layer may be unstable, a low-level inversion will act as a barrier to vertical mixing, and contaminants will accumulate in the surface layer below the inversion. Stable atmospheric conditions tend to be more frequent and longest in persistence in the autumn, but inversions and stable lapse rates are prevalent at all seasons of the year.

Design Calculations For a given stack height, the calculational sequence begins by first estimating the effective height of the emission, employing an applicable plume-rise equation. The maximum GLC may then be determined by using an appropriate atmospheric-diffusion equation. A simple comparison of the calculated GLC for the particular pollutant with the maximum GLC permitted by the local air-pollution codes dictates whether the stack is operating satisfactorily.

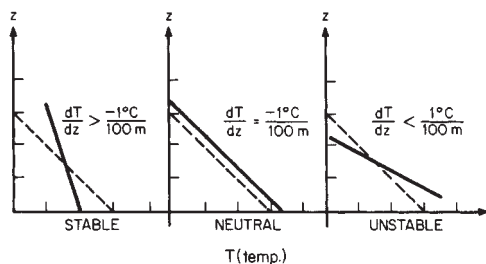


FIG. 25-4 Stability criteria with measured lapse rate.

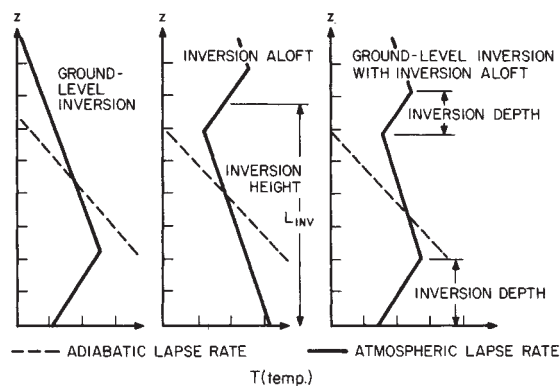


FIG. 25-5 Characteristic lapse rates under inversion conditions.

Conversely, with knowledge of the maximum acceptable GLC standards, a stack that will satisfy these standards can be properly designed.

Effective Height of an Emission The effective height of an emission rarely corresponds to the physical height of the stack. If the plume is caught in the turbulent wake of the stack or of buildings in the vicinity of the stack, the effluent will be mixed rapidly downward toward the ground. If the plume is emitted free of these turbulent zones, a number of source emission characteristics and meteorological factors influence the rise of the plume. The source emission characteristics include the gas flow rate and the temperature of the effluent at the top of the stack and the diameter of the stack opening. The meteorological factors influencing plume rise include wind speed, air temperature, shear of the wind speed with height, and atmospheric stability. No theory on plume rise presently takes into account all of these variables. Most of the equations that have been formulated for computing the effective height of an emission are semi-empirical. When considering any of these plume-rise equations, it is important to evaluate each in terms of the assumptions made and the circumstances existing at the time that the particular correlation was formulated. The formulas generally are not applicable to tall stacks (above 305 m [1000 ft] effective height).

The effective stack height (equivalent to the effective height of the emission) is the sum of the actual stack height, the plume rise due to the exhaust velocity (momentum) of the issuing gases, and the buoyancy rise, which is a function of the temperature of the gases being emitted and the atmospheric conditions.

Some of the more common plume-rise equations have been summarized by Buonicore and Theodore (*Industrial Control Equipment for Gaseous Pollutants*, vol. 2, CRC Press, Boca Raton, Florida, 1975) and include:

- ASME, *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, ASME, New York, 1968.
- Bosanquet-Carey-Halton, *Proc. Inst. Mech. Eng. (London)*, **162**, 355 (1950).
- Briggs, *Plume Rise*, AEC Critical Review ser., U.S. Atomic Energy Commission, Div. Tech. Inf.
- Brummage et al., *The Calculation of Atmospheric Dispersion from a Stack*, CONCAWE, The Hague, 1966.
- Carson and Moses, *J. Air Pollut. Control Assoc.*, **18**, 454 (1968) and **19**, 862 (1969).
- Csanady, *Int. J. Air Water Pollut.*, **4**, 47 (1961).
- Davison-Bryant, *Trans. Conf. Ind. Wastes*, 14th Ann. Meet. Ind. Hyg. Found. Am., **39**, 1949.
- Holland, *Workbook of Atmospheric Dispersion Estimates*, U.S. EPA Publ. AP-26, 1970.
- Lucas, Moore, and Spurr, *Int. J. Air Water Pollut.*, **7**, 473 (1963).
- Montgomery et al., *J. Air Pollut. Control Assoc.*, **22**(10), 779, TVA (1972).
- Stone and Clarke, *British Experience with Tall Stacks for Air Pollution Control on Large Fossil-Fueled Power Plants*, American Power Conference, Chicago, 1967.

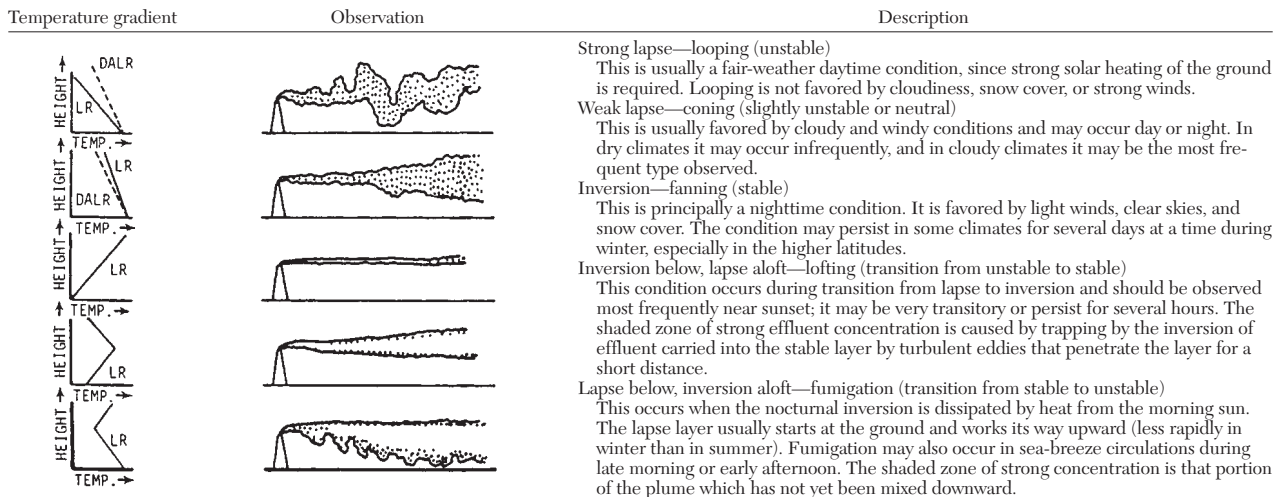


FIG. 25-6 Lapse-rate characteristics of atmospheric-diffusion transport of stack emissions.

- Stumke, Staub, **23**, 549 (1963).

See also:

- Briggs, G. A., *Plume Rise Predictions: Lectures on Air Pollution and Environmental Impact Analyses*, Workshop Proceedings, American Meteorological Society, Boston, Massachusetts, 1975, pp. 59–111.
- Randerson, Darryl (ed.), *Plume Rise and Buoyancy Effects*, Atmospheric Science and Power Production, DOE Report DOE/TIC-27601, 1981.

Maximum Ground-Level Concentrations The effective height of an emission having been determined, the next step is to study its path downward by using the appropriate atmospheric-dispersion formula. Some of the more popular atmospheric-dispersion calculational procedures have been summarized by Buonicore and Theodore (op. cit.) and include:

- Bosanquet-Pearson model [Pasquill, *Meteorol. Mag.*, **90**, 33, 1063 (1961), and Gifford, *Nucl. Saf.*, **2**, 4, 47 (1961).]
- Sutton model [Q.J.R. *Meteorol. Soc.*, **73**, 257 (1947).]
- TVA Model [Carpenter et al., *J. Air Pollut. Control Assoc.*, **21**(8), (1971), and Montgomery et al., *J. Air Pollut. Control Assoc.*, **23**(5), 388 (1973).]

See also:

- Bornstein et al., *Simulation of Urban Barrier Effects on Polluted Urban Boundary Layers Using the Three-Dimensional URBMET\TVM Model with Urban Topography*, Air Pollution Proceedings, 1993.
- EPA, *Guidance on the Application of Refined Dispersion Models for Air Toxins Releases*, EPA-450/4-91-007.
- Zannetti, Paolo, *Air Pollution Modeling: Theories, Computational Methods, and Available Software*, Van Nostrand, Reinhold, New York, 1990.
- Zannetti, Paolo, *Numerical Simulation Modeling of Air Pollution: An Overview*, Ecological Physical Chemistry, 2d International Workshop, May 1992.

Miscellaneous Effects

Evaporative Cooling When effluent gases are washed to absorb certain constituents prior to emission, the gases are cooled and become saturated with water vapor. Upon release of the gases, further cooling due to contact with cold surfaces of ductwork or stack is likely. This cooling causes water droplets to condense in the gas stream. Upon release of the gases from the stack, the water droplets evaporate, withdrawing the latent heat of vaporization from the air and cooling the plume. The resulting negative buoyancy reduces the effective stack height. The result may be a plume (with a greater density than that of the ambient atmosphere) that will fall to the ground. If any pol-

lutant remains after scrubbing, its full effect will be felt on the ground in the vicinity of the stack.

Aerodynamic Downwash Should the stack exit velocity be too low as compared with the speed of the crosswind, some of the effluent can be pulled downward by the low pressure on the lee side of the stack. This phenomenon, known as “stack-tip downwash,” can be minimized by keeping the exit velocity greater than the mean wind speed (i.e., typically twice the mean wind speed). Another way to minimize stack-tip downwash is to fit the top of the stack with a flat disc that extends for at least one stack diameter outward from the stack.

If it becomes necessary to increase the stack-gas exit velocity to avoid downwash, it may be necessary to remodel the stack exit. A venturi-nozzle design has been found to be the most effective. This design also keeps pressure losses to a minimum.

Building Downwash A review must be conducted for each stack to determine if building downwash effects need to be considered. Atmospheric flow is disrupted by aerodynamic forces in the immediate vicinity of structures or terrain obstacles. The disrupted flow near either building structures or terrain obstacles can both enhance the vertical dispersion of emissions from the source and reduce the effective height of the emissions from the source, resulting in an increase in the maximum GLC.

EPA Air Dispersion Models EPA addresses modeling techniques in the “Guideline on Air Quality Models” (GAQM-Revised, EPA-450-2/78-027R, July 1986). Several computational models are available for performing air quality analyses. However, there is no one model capable of properly addressing all conceivable modeling situations. The EPA recommends a case-by-case approach to selection of appropriate models. All models incorporate assumptions that are designed to predict conservative results. Since the general intention of modeling is to determine if the maximum GLC is below regulatory limits, modeling is performed beginning with the simpler models with the most conservative assumptions and proceeding to more complex models with more sophisticated input data. Input data includes source characteristics, topography, and meteorological factors.

The air quality modeling procedures can be categorized into four generic classes: Gaussian, numerical, statistical, and physical. Gaussian models are the most widely used techniques for estimating the impact from nonreactive pollutants. Numerical models are more appropriate for urban applications involving reactive pollutants. In cases where the scientific understanding of the physical or chemical processes involved is lacking, a statistical modeling approach may be necessary. Statistical modeling involves the collection of a large number of site-specific measurements that are evaluated to develop a predictive modeling tool that is limited to use at that site. Physical modeling is performed using a wind tunnel or other fluid modeling

facility. Physical modeling may be useful for complex flow situations, such as building, terrain, or stack downwash conditions, plume impact on elevated terrain, diffusion in an urban environment, or diffusion in complex terrain. It is generally limited to use within a few square kilometers surrounding the source.

Most modeling can be performed using Gaussian models. The simplest Gaussian model is the EPA SCREEN2 model. This is an interactive computational model that incorporates algorithms for calculating maximum GLC in simple terrain (below stack top) or complex terrain (above stack top) considering downwash and cavity effects. The SCREEN2 model is designed for single source modeling. A set of conservative meteorological conditions is contained within the model.

The Industrial Source Complex (ISC2) model allows for modeling to be performed in simple terrain for multiple sources and allows for use of real meteorological data. Complex I is a screening level model commonly used in complex terrain modeling. This model may use real meteorological data and allows for modeling multiple sources. The Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS) is a refined point source Gaussian air quality model for use in all stability conditions for complex terrain applications. Its use of meteorological and terrain data is different from other EPA models. CTDMPLUS requires the parameterization of individual hill shapes using a terrain preprocessor. CTSCREEN is a screening version of CTDMPLUS. It contains the same algorithms but is run with synthetic meteorological data.

SOURCE CONTROL OF GASEOUS EMISSIONS

There are four chemical-engineering unit operations commonly used for the control of gaseous emissions:

1. *Absorption.* See Sec. 4, "Thermodynamics"; and Sec. 18, "Liquid Gas Systems." For plate columns, see Sec. 18, "Gas-Liquid Contacting: Plate Columns." For packed columns, see Sec. 18, "Gas-Liquid Contacting: Packed Columns."

2. *Adsorption.* See Sec. 16, "Adsorption and Ion Exchange."

3. *Combustion.* See Sec. 9, "Heat Generation" and "Fired Process Equipment." For incinerators, see material under these subsections.

4. *Condensation.* See Sec. 10, "Heat Transmission"; Sec. 11, "Heat-Transfer Equipment"; and Sec. 12, "Evaporative Cooling." For direct-contact condensers, see Sec. 11, "Evaporator Accessories"; and Sec. 12, "Evaporative Cooling." For indirect-contact condensers, see Sec. 10, "Heat Transfer with Change of Phase" and "Thermal Design of Heat-Transfer Equipment"; and Sec. 11, "Shell and Tube Heat Exchangers" and "Other Heat Exchangers for Liquids and Gases."

These operations, which are routine chemical engineering operations, have been treated extensively in other sections of this handbook.

There are three additional chemical engineering unit operations that are increasing in use in recent years. They are:

1. *Biofiltration*

2. *Membrane filtration*

3. *Selective catalytic reduction*

and are discussed further in this section.

Absorption The engineering design of gas absorption equipment must be based on a sound application of the principles of diffusion, equilibrium, and mass transfer as developed in Secs. 5 and 14 of the handbook. 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 and to minimize resistance and maximize driving force. This contacting of the phases can be achieved in many different types of equipment, the most important being packed and plate columns. The final choice between them rests with the various criteria that must be met. For example, if the pressure drop through the column is large enough that compression costs become significant, a packed column may be preferable to a plate-type column because of the lower pressure drop.

In most processes involving the absorption of a gaseous pollutant from an effluent gas stream, the gas stream is the processed fluid; hence, its inlet condition (flow rate, composition, and temperature) are usually known. The temperature and composition of the inlet liq-

uid and the composition of the outlet gas are usually specified. The main objectives in the design of an absorption column, then, 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 obtained by evaluating, for a selected solvent at a given flow rate, the number of theoretical separation units (stage or plates) and converting them into practical units column heights or number of actual plates by means of existing correlations.

The general design procedure consists of a number of steps to be taken into consideration. These include:

1. Solvent selection

2. Equilibrium-data evaluation

3. Estimation of operating data (usually consisting of a mass and energy in which the energy balance decides whether the absorption balance can be considered 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 based on economic considerations)

5. Calculation 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 number of plates (for packed columns, 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 of packing type, column-operating 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)

Solvent Selection The choice of a particular solvent is most important. Frequently, water is 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 this increases the absorption rate and minimizes the quantity of solvent necessary. Generally, solvents of a chemical nature similar to that of the solute to be absorbed will provide good solubility.

2. *Volatility.* A low solvent vapor pressure is desired, since the gas leaving the absorption unit is ordinarily saturated with the solvent, and much may thereby be lost.

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 makes the column inoperable.

Equipment The principal types of gas-absorption equipment may be classified as follows:

1. Packed columns (continuous operation)

2. Plate columns (staged operations)

3. Miscellaneous

Of the three categories, the packed column is by far the most commonly used for the absorption of gaseous pollutants. Miscellaneous gas-absorption equipment could include acid gas scrubbers that are commonly classified as either "wet" or "dry." In wet scrubber systems, the absorption tower uses a lime-based sorbent liquor that reacts with the acid gases to form a wet/solid by-product. Dry scrubbers can be grouped into three categories: (1) spray dryers; (2) circulating spray dryers; and (3) dry injection. Each of these systems yields a dry product that can be captured with a fabric filter baghouse downstream and

thus avoids costly wastewater treatment systems. The baghouse is highly efficient in capturing the particulate emissions, and a portion of the overall acid gas removal has been found to occur within the baghouse. Additional information may be found by referring to the appropriate sections in this *handbook* and the many excellent texts available, such as McCabe and Smith, *Unit Operations of Chemical Engineering*, 3d ed., McGraw-Hill, New York, 1976; Sherwood and Pigford, *Absorption and Extraction*, 2d ed., McGraw-Hill, New York, 1952; Smith, *Design of Equilibrium Stage Processes*, McGraw-Hill, New York, 1963; Treybal, *Mass Transfer Operations*, 3d ed., McGraw-Hill, New York, 1980; McKenna, Mycock, and Theodore, *Handbook of Air Pollution Control Engineering and Technology*, CRC Press, Boca Raton, Florida, 1995; Theodore and Allen, *Air Pollution Control Equipment*, ETSI Prof. Training Inst., Roanoke, Virginia, 1993.

Absorption The design of gas-adsorption equipment is in many ways analogous to the design of gas-absorption equipment, with a solid adsorbent replacing the liquid solvent (see Secs. 16 and 19). Similarity is evident in the material- and energy-balance equations as well as in the methods employed to determine the column height. The final choice, as one would expect, rests with the overall process economics.

Selection of Adsorbent Industrial adsorbents are usually capable of adsorbing both organic and inorganic gases and vapors. However, their preferential adsorption characteristics and other physical properties make each of them 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 preferentially adsorb any water vapor with 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, inert gas (i.e., nitrogen), or other gas streams, and in the majority of cases this can cause at least slight decomposition of the organic compound on the adsorbent. Two difficulties arise: (1) incomplete recovery of the adsorbate, although this may be unimportant; and (2) progressive deterioration in capacity of the adsorbent as the number of cycles increases owing 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 liquid water.

In some cases, none of the adsorbents has sufficient retaining capacity for a particular contaminant. In these applications, a large-surface-area adsorbent can be impregnated with an inorganic compound or, in rare cases, with a high-molecular-weight organic compound that can react chemically with the particular contaminant. For example, iodine-impregnated carbons are used for removal of mercury vapor and bromine-impregnated carbons for ethylene or propylene removal. The action of these impregnants is either catalytic conversion or reaction to a nonobjectionable compound or to a more easily adsorbed compound. For this case, general adsorption theory no longer applies to the overall effects of the process. For example, mercury removal by an iodine-impregnated carbon proceeds faster at a higher temperature, and a better overall efficiency can be obtained than in a low-temperature system.

Since adsorption takes place at the interphase boundary, the adsorption surface area becomes an important consideration. Generally, the higher the adsorption 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) a surface area in the smallest pores in which the adsorbate can enter is the most efficient. At higher pressures the larger pores become more important; at very high concentrations, capillary condensation will take place within the pores, and the total micropore volume becomes the limiting factor.

The action of molecular sieves is slightly different from that of other adsorbents in that selectivity is determined more by the pore-size lim-

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

Design Data The adsorbent having been selected, the next step is to calculate the quantity of adsorbent required and eventually consider other factors such as the temperature rise of the gas stream due to adsorption and the useful life of the adsorbent 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 should be known or available for design purposes:

1. Gas stream
 - a. Adsorbate concentration.
 - b. Temperature.
 - c. Temperature rise during adsorption.
 - d. Pressure.
 - e. Flow rate.
 - f. Presence of adsorbent contaminant material.
2. Adsorbent
 - a. Adsorption capacity as used on stream.
 - b. Temperature rise during adsorption.
 - c. Isothermal or adiabatic operation.
 - d. Life, if presence of contaminant material is unavoidable.
 - e. Possibility of catalytic effects causing an adverse chemical reaction in the gas stream or the formation of solid polymerizates on the adsorbent bed, with consequent deterioration.
 - f. Bulk density.
 - g. Particle size, usually reported as a mean equivalent particle diameter. The dimensions and shape of particles affect both the pressure drops through the adsorbent bed and the diffusion rate into the particles. All things being equal, adsorbent beds consisting of smaller particles, although causing a higher pressure drop, will be more efficient.
 - h. Pore data, which are important because they may permit elimination from consideration of adsorbents whose pore diameter will not admit the desired adsorbate molecule.
 - i. Hardness, which indicates the care that must be taken in handling adsorbents to prevent the formation of undesirable fines.
 - j. Regeneration information.

The design techniques used include both stagewise and continuous-contacting methods and can be applied to batch, continuous, and semi-continuous operations.

Adsorption Phenomena 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 fluid must be separated from the adsorbent-adsorbate, and, finally, the adsorbent must be regenerated by removing the adsorbate or by 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). The more popular thermal cycle is accomplished by passing hot gas through the adsorption bed in the direction opposite to the flow during the adsorption cycle. This 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.

In the first step, in which the molecules of the fluid come in contact with the adsorbent, an equilibrium is established between the adsorbed fluid and the fluid remaining in the fluid phase. Figures 25-7 through 25-9 show several experimental equilibrium adsorption isotherms for a number of components adsorbed on various adsorbents. Consider Fig. 25-7, in which the concentration of adsorbed gas on the solid is plotted against the equilibrium partial pressure p^0 of the vapor or gas at constant temperature. At 40°C, for example, pure propane vapor at a pressure of 550 mm Hg is in equilibrium with an adsorbate concentration at point P of 0.04 lb adsorbed propane per pound of silica gel. Increasing the pressure of the propane will cause

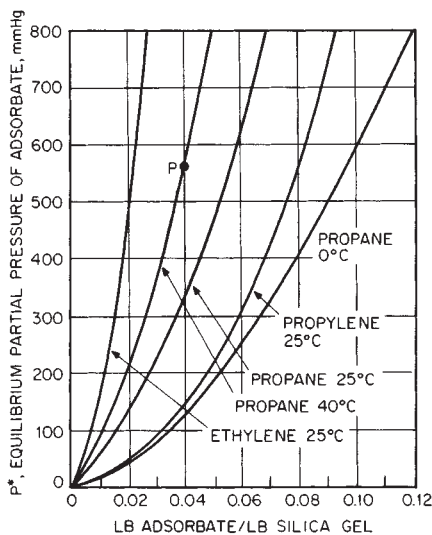


FIG. 25-7 Equilibrium partial pressures for certain organics on silica gel.

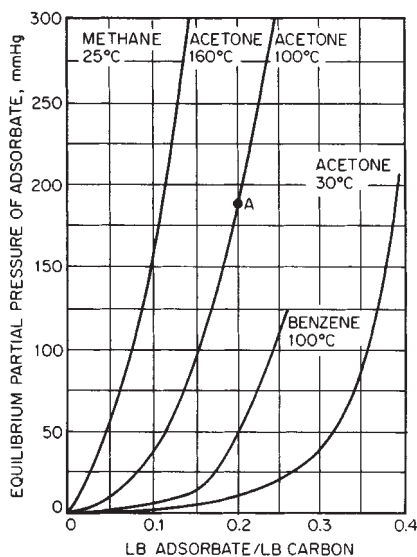


FIG. 25-8 Equilibrium partial pressures for certain organics on carbon.

more propane to be adsorbed, while decreasing the pressure of the system at P will cause propane to be desorbed from the carbon.

The adsorptive capacity of activated carbon for some common solvent vapors is shown in Table 25-27.

Adsorption-Control Equipment If a gas stream must be treated for a short period, usually only one adsorption unit is necessary, provided, of course, that a sufficient time interval is available between adsorption cycles to permit regeneration. However, this is usually not the case. Since an uninterrupted flow of treated gas is often required, it is necessary to employ one or more units capable of operating in this fashion. The units are designed to handle gas flows without interruption and are characterized by their mode of contact, either staged or continuous. By far the most common type of adsorption system used to remove an objectionable pollutant from a gas stream consists of a number of fixed-bed units operating in such a sequence that the gas flow remains uninterrupted. A two- or three-bed system is usually

employed, with one or two beds bypassed for regeneration while one is adsorbing. A typical two-bed system is shown in Fig. 25-10, while a typical three-bed system is shown in Fig. 25-11. The type of system best suited for a particular job is determined from several factors, including the amount and rate of material being adsorbed, the time between cycles, the time required for regeneration, and the cooling time, if required.

Typical of continuous-contact operation for gaseous-pollutant adsorption is the use of a fluidized bed. During steady-state staged-contact operation, the gas flows up through a series of successive fluidized-bed stages, permitting maximum gas-solid contact on each stage. A typical arrangement of this type is shown in Fig. 25-12 for multistage countercurrent adsorption with regeneration. In the upper part of the tower, the particles are contacted countercurrently on perforated trays in relatively shallow beds with the gas stream containing the pollutant, the adsorbent solids moving from tray to tray through downspouts. In the lower part of the tower, the adsorbent is regenerated by similar contact with hot gas, which desorbs and carries off the pollutant. The regenerated adsorbent is then recirculated by an airlift to the top of the tower.

Although the continuous-countercurrent type of operation has found limited application in the removal of gaseous pollutants from process streams (for example, the removal of carbon dioxide and sulfur compounds such as hydrogen sulfide and carbonyl sulfide), by far the most common type of operation presently in use is the fixed-bed adsorber. The relatively high cost of continuously transporting solid particles as required in steady-state operations makes fixed-bed adsorption an attractive, economical alternative. If intermittent or batch operation is practical, a simple one-bed system, cycling alternately between the adsorption and regeneration phases, will suffice.

Additional information may be found by referring to the appropriate sections of this *handbook*. A comprehensive treatment of adsorber design principles is given in Buonicore and Theodore, *Industrial Control Equipment for Gaseous Pollutants*, vol. 1, 2d ed., CRC press, Boca Raton, Florida, 1992.

Combustion Many organic compounds released from manufacturing operations can be converted to innocuous carbon dioxide and water by rapid oxidation (chemical reaction): combustion. However, combustion of gases containing halides may require the addition of acid gas treatment to the combustor exhaust.

Three rapid oxidation methods are typically used to destroy combustible contaminants: (1) flares (direct-flame-combustion), (2) thermal combustors, and (3) catalytic combustors. The thermal and flare methods are characterized by the presence of a flame during combustion. The combustion process is also commonly referred to as "after-burning" or "incineration."

To achieve complete combustion (i.e., the combination of the combustible elements and compounds of a fuel with all the oxygen that they can utilize), sufficient space, time, and turbulence and a temperature high enough to ignite the constituents must be provided.

The three T 's of combustion—time, temperature, and turbulence—govern the speed and completeness of the combustion reaction. For complete combustion, the oxygen must come into intimate contact with the combustible molecule at sufficient temperature and for a sufficient length of time for the reaction to be completed. Incomplete reactions may result in the generation of aldehydes, organic acids, carbon, and carbon monoxide.

Combustion-Control Equipment Combustion-control equipment can be divided into three types: (1) flares, (2) thermal incinerators, (3) catalytic incinerators.

Flares In many industrial operations and particularly in chemical plants and petroleum refineries, large volumes of combustible waste gases are produced. These gases result from undetected leaks in the operating equipment, from upset conditions in the normal operation of a plant in which gases must be vented to avoid dangerously high pressures in operating equipment, from plant startups, and from emergency shutdowns. Large quantities of gases may also result from off-specification product or from excess product that cannot be sold. Flows are typically intermittent, with flow rates during major upsets of up to several million cubic feet per hour.

The preferred control method for excess gases and vapors is to

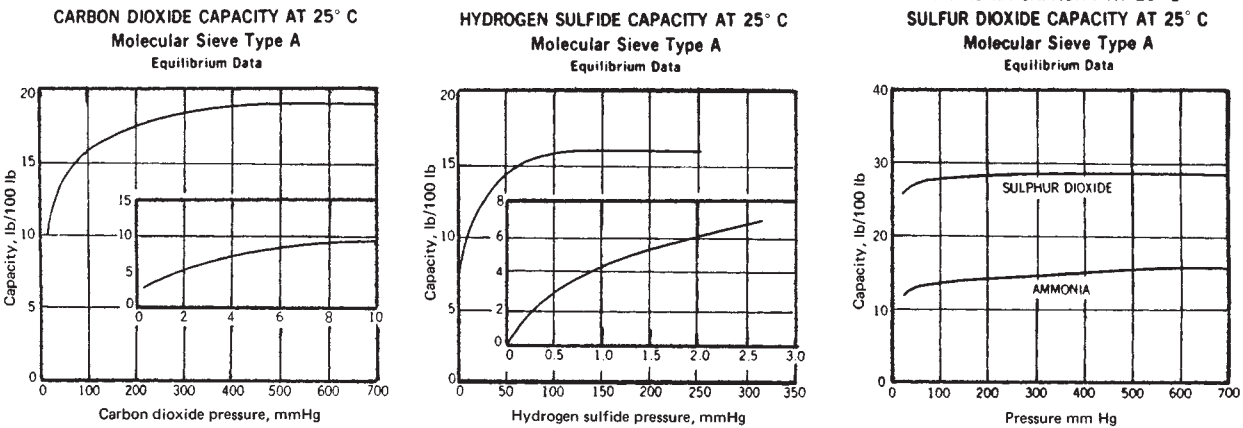


FIG. 25-9 Equilibrium partial pressures for certain gases on molecular sieves. (A. J. Buonicore and L. Theodore, Industrial Control Equipment for Gaseous Pollutants, vol. I, CRC Press, Boca Raton, Fla., 1975.)

recover them in a blowdown recovery system. However, large quantities of gas, especially those during upset and emergency conditions, are difficult to contain and reprocess. In the past all waste gases were vented directly to the atmosphere. However, widespread venting caused safety and environmental problems, and, in practice, it is now customary to collect such gases in a closed flare system and to burn them as they are discharged.

Although flares can be used to dispose of excess waste gases, such systems can present additional safety problems. These include the explosion potential, thermal-radiation hazards from the flame, and the problem of toxic asphyxiation during flameout. Aside from these safety aspects, there are several other problems associated with flaring that must be dealt with during the design and operation of a flare system. These problems include the formation of smoke, the luminosity of the flame, noise during flame, and the possible emission of by-product air pollutants during flaring.

The heat content of the waste stream to be disposed is another important consideration. The heat content of the waste gas falls into two classes. The gases can either support their own combustion or not. In general, a waste gas with a heating value greater than 7443 kJ/m³ (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 7443 kJ/m³, enriching the waste gas by injecting another gas with a higher heating value may be necessary. The addition of such a rich gas is called "endothermic flaring." Gases with a heating value as low as 2233 kJ/m³ (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 3721 kJ/m³ (100 Btu/ft³). If the flow of low-Btu gas is continuous, thermal or catalytic incineration can be used to dispose of the gas. For intermittent flows, however, endothermic flaring may be the only possibility.

TABLE 25-27 Adsorptive Capacity of Common Solvents on Activated Carbons*

Solvent	Carbon bed weight, %†
Acetone	8
Heptane	6
Isopropyl alcohol	8
Methylene chloride	10
Perchloroethylene	20
Stoddard solvent	2-7
1,1,1-Trichloroethane	12
Trichloroethylene	15
Trichlorotrifluoroethane	8
VM&P naphtha	7

*Assuming steam desorption at 5 to 10 psig.
†For example, 8 lb of acetone adsorbed on 100 lb of activated carbon.

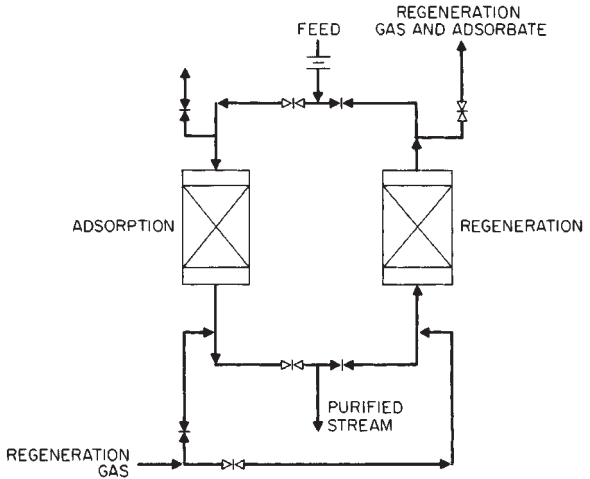


FIG. 25-10 Typical two-bed adsorption system.

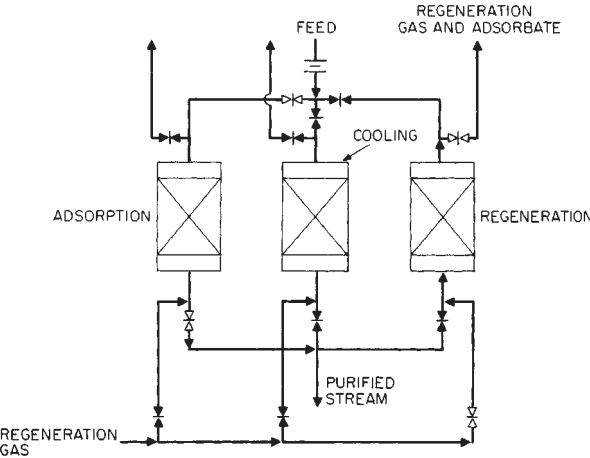


FIG. 25-11 Typical three-bed adsorption system.

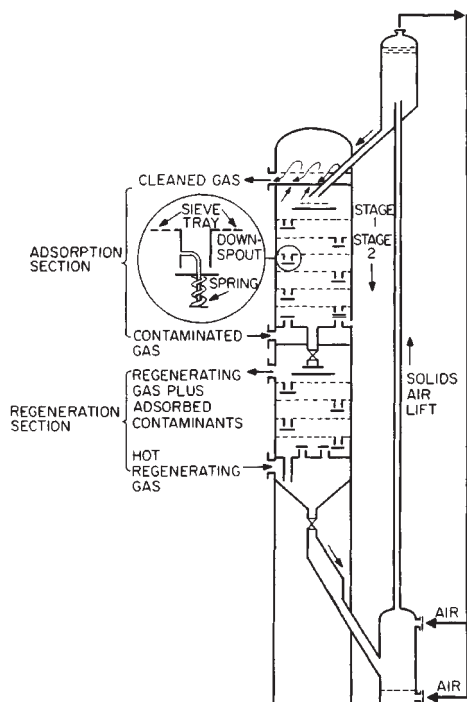


FIG. 25-12 Multistage countercurrent adsorption with regeneration.

Although most flares are used to dispose of intermittent waste gases, some continuous flares are in use, but generally only for relatively small volumes of gases. The heating value of large-volume continuous-flow waste gases is usually too valuable to lose in a flare. Vapor recovery or the use of the vapor as a fuel in a process heater is preferred over flaring. Since auxiliary fuel must be added to the gas in order to flare, large continuous flows of a low-heating-value gas are usually more efficient to burn in a thermal incinerator than in the flame of a flare.

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. Flares have been used successfully to control malodorous gases such as mercaptans and amines, but care must be taken when flaring these gases. Unless the flare is very efficient and gives good combustion, obnoxious fumes can escape unburned and cause a nuisance.

Flaring of hydrogen sulfide should be avoided because of its toxicity and low odor threshold. In addition, burning relatively small amounts of hydrogen sulfide can create enough sulfur dioxide to cause crop damage or a local nuisance. For gases whose combustion products may cause problems, such as those containing hydrogen sulfide or chlorinated hydrocarbons, flaring is not recommended.

Thermal Incinerators Thermal incinerators or afterburners can be used over a fairly wide but low range of organic vapor concentration. The concentration of the organics in air must be 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 to ensure high chemical-reaction rates for the organics. To achieve this temperature, it is necessary to preheat the feed stream using auxiliary energy. Along with the contaminant-laden gas stream, air and fuel are continuously delivered to the incinerator (see Fig. 25-13). The fuel and contaminants are combusted with air in a firing unit (burner). The burner may utilize 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. The products of combustion and the unreacted feed stream are intensely mixed and

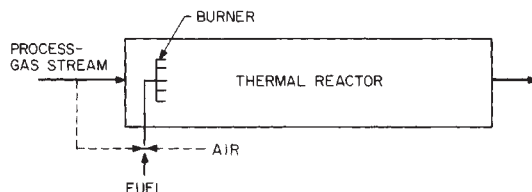


FIG. 25-13 Thermal-combustion device.

enter the reaction zone of the unit. The pollutants in the process-gas stream are then reacted at the elevated temperature. Thermal incinerators generally require operating temperatures in the range of 650 to 980° C (1200 to 1800° F) for combustion of most organic pollutants (see Table 25-28). A residence time of 0.2 to 1.0 is often recommended, but this factor is dictated primarily by complex kinetic considerations. The kinetics of hydrocarbon (HC) combustion in the presence of excess oxygen can be simplified into the following first-order rate equation:

$$\frac{d(\text{HCl})}{dt} = -k[\text{HCl}] \quad (25-1)$$

where k = pseudo-first-order rate constant (s^{-1}). If the initial concentration is $C_{A,0}$, the solution of Eq. (25-1) is:

$$\ln\left(\frac{C_A}{C_{A,0}}\right) = -kt \quad (25-2)$$

Equation (25-2) is frequently used for a kinetic modeling of a burner using mole fractions in the range of 0.15 and 0.001 for oxygen and HC, respectively. The rate constant is generally of the following Arrhenius form:

$$k = Ae^{-E/RT} \quad (25-3)$$

where: A = pre-exponential factor, s^{-1} (see Table 2, *Air Pollution Engineering Manual*, Van Nostrand Reinhold, New York, 1992, p. 62)

E = activation energy, cal/gmol (see Table 2, *Air Pollution Engineering Manual*, Van Nostrand Reinhold, New York, 1992, p. 62)

R = universal gas constant, 1.987 cal/gmol °K

T = absolute temperature, °K

The referenced table for A and E is a summary of first-order HC combustion reactions.

TABLE 25-28 Thermal Afterburners: Conditions Required for Satisfactory Performance in Various Abatement Applications

Abatement category	Afterburner residence time, s	Temperature, °F
Hydrocarbon emissions: 90 + % destruction of HC	0.3–0.5	1100–1250°
Hydrocarbons + CO: 90 + % destruction of HC + CO	0.3–0.5	1250–1500
Odor		
50–90% destruction	0.3–0.5	1000–1200
90–99% destruction	0.3–0.5	1100–1300
99 + % destruction	0.3–0.5	1200–1500
Smokes and plumes		
White smoke (liquid mist)	0.3–0.5	800–1000†
Plume abatement	0.3–0.5	1250–1500
90 + % destruction of HC + CO	0.3–0.5	
Black smoke (soot and combustible particulates)	0.7–1.0	1400–2000

†Temperatures of 1400 to 1500°F (760 to 816°C) may be required if the hydrocarbon has a significant content of any of the following: methane, cellulose, and substituted aromatics (e.g., toluene and xylenes).

†Operation for plume abatement only is not recommended, since this merely converts a visible hydrocarbon emission into an invisible one and frequently creates a new odor problem because of partial oxidation in the afterburner.

The end combustion products are continuously emitted at the outlet of the reactor. The average gas velocity can range from as low as 3 m/s (10 ft/s) to as high as 15 m/s (50 ft/s). These high velocities are required to prevent settling of particulates (if present) and to minimize the dangers of flashback and fire hazards. Space velocity calculations are given in the "Incinerator Design and Performance Equation" section.

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 Fig. 25-14).

Because of the high operating temperatures, the unit must be constructed of metals capable of withstanding this condition. Combustion devices are usually constructed with an outer steel shell that is lined with refractory material. Refractory-wall thickness is usually in the 0.05- to 0.23-m (2- to 9-in) range, depending upon temperature considerations.

Some of the advantages of the thermal incinerators are:

1. Removal of organic gases
2. Removal of submicrometer organic particles
3. Simplicity of construction
4. Small space requirements

Some of the disadvantages are:

1. High operating costs
2. Fire hazards
3. Flashback possibilities

Catalytic Incinerators Catalytic incinerators are an alternative to thermal incinerators. For simple reactions, the effect of the presence of a catalyst is to (1) increase the rate of the reaction, (2) permit the reaction to occur at a lower temperature, and (3) reduce the reactor volume.

In a typical catalytic incinerator for the combustion of organic vapors, the gas stream is delivered to the reactor continuously by a fan at a velocity in the range of 3 to 15 m/s (10 to 30 ft/s), but at a lower temperature, usually in the range of 350 to 425° C (650 to 800° F), than the thermal unit. (Design and performance equations used for calculating space velocities are given in the next section). The gases, which may or may not be preheated, pass through the catalyst bed, where the combustion reaction occurs. The combustion products, which again are made up of water vapor, carbon dioxide, inerts and unreacted vapors, are continuously discharged from the outlet at a higher temperature. Energy savings can again be effected by heat recovery from the exit stream.

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. These catalysts are subject to poisoning, particularly from halogens, halogen and sulfur compounds, zinc, arsenic, lead, mercury, and particulates. It is therefore important that catalyst surfaces be clean and active to ensure optimum performance.

Catalysts may be porous pellets, usually cylindrical or spherical in shape, ranging from 0.16 to 1.27 cm ($\frac{1}{16}$ to $\frac{1}{2}$ in) in diameter. Small

sizes are recommended, but the pressure drop through the reactor increases. Among other shapes are honeycombs, ribbons, and wire mesh. Since catalysis is a surface phenomenon, a physical property of these particles is that the internal pore surface is nearly infinitely 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 pores of the catalyst
 3. Activated adsorption of reactants and the desorption of the products on the active centers of the catalyst
 4. Reaction or reactions on active centers on the catalyst surface
- At the same time, energy effects arising from chemical reaction can result in the following:

1. Heat transfer to or from active centers to the 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

Some of the advantages of catalytic incinerators are:

1. Lower fuel requirements as compared with thermal incinerators
2. Lower operating temperatures
3. Minimum insulation requirements
4. Reduced fire hazards
5. Reduced flashback problems

The disadvantages include:

1. Higher initial cost than thermal incinerators
2. Catalyst poisoning
3. Necessity of first removing large particulates
4. Catalyst-regeneration problems
5. Catalyst disposal

Incinerator Design and Performance Equations The key incinerator design and performance calculations are the required fuel usage and physical dimensions of the unit. The following is a general calculation procedure to use in solving for these two parameters, assuming that the process gas stream flow, inlet temperature, combustion temperature, and required residence time are known. The combustion temperature and residence time for thermal incinerators can be estimated using Table 25-28 and Eqs. (25-1) through (25-3).

1. The heat load needed to heat the inlet process gas stream to the incinerator operating temperature is:

$$Q = \Delta H \quad (25-4)$$

2. Correct the heat load for radiant heat losses, RL :

$$Q = (1 + RL) (\Delta H); RL = \text{fractional basis} \quad (25-5)$$

3. Assuming that natural gas is used to fire the burner with a known heating value of HV_G , calculate the available heat at the operating temperature. A shortcut method usually used for most engineering purposes is:

$$HA_T = (HV_G) \left(\frac{HA_T}{HV_G} \right)_{\text{ref}} \quad (25-6)$$

where the subscript "ref" refers to a reference fuel. For natural gas with a reference HV_G of 1059 Btu/scf, the heat from the combustion using no excess air would be given by:

$$(HA_T)_{\text{ref}} = -0.237(t) + 981; T = F \quad (25-7)$$

4. The amount of natural gas needed as fuel (NG) is given by:

$$NG = \frac{Q}{HA}; \text{ consistent units} \quad (25-8)$$

5. The resulting volumetric flow rate is the sum of the combustion of the natural gas q and the process gas stream p at the operating temperature:

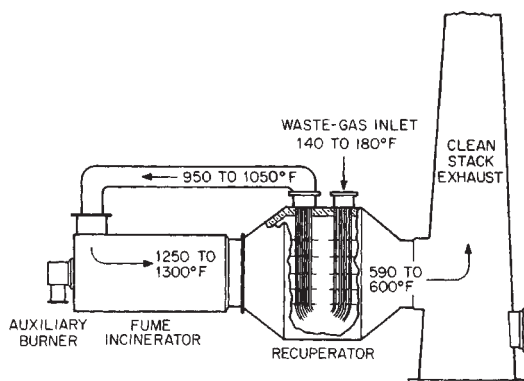


FIG. 25-14 Thermal combustion with energy (heat) recovery.

$$q_T = q_p + q_c \quad (25-9)$$

A good estimate for q_c is:

$$q_c = (11.5)(NG) \quad (25-10)$$

6. The diameter of the combustion device is given by:

$$S = \frac{q_T}{v_i} \quad (25-11)$$

where v_i is defined as the velocity of the gas stream at the incinerator operating temperature.

Condensation Frequently in air-pollution-control practice, it becomes necessary to treat an effluent stream consisting of a condensable pollutant vapor and a noncondensable gas. One control method to remove such pollutants from process-gas streams that is often overlooked is condensation. Condensers can be used to collect condensable emissions discharged to the atmosphere, particularly when the vapor concentration is high. This is usually accomplished by lowering the temperature of the gaseous stream, although an increase in pressure will produce the same result. The former approach is usually employed by industry, since pressure changes (even small ones) on large volumetric gas-flow rates are often economically prohibitive.

Condensation Equipment There are two basic types of condensers used for control: contact and surface. In contact condensers, the gaseous stream is brought into direct contact with a cooling medium so that the vapors condense and mix with the coolant (see Fig. 25-15). The more widely used system, however, is the surface condenser (or heat exchanger), in which the vapor and the cooling medium are separated by a wall (see Fig. 25-16). Since high removal efficiencies cannot be obtained with low-condensable vapor concentrations, condensers are typically used for pretreatment prior to some other more efficient control device such as an incinerator, absorber, or adsorber.

Contact Condensers Spray condensers, jet condensers, and barometric condensers all utilize 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, the system is essentially an absorptive one. If the vapor is not soluble, the system is a true condenser, in which case the temperature of the vapor must be below the dew point. Direct-contact condensers are seldom used for the removal of organic solvent vapors because the condensate will contain an organic-water mixture that must be separated or treated before disposal. They are, however, the most effective method of removing heat from hot gas streams when the recovery of organics is not a consideration.

In a direct-contact condenser, a stream of water or other cooling liquid is brought into direct contact with the vapor to be condensed. The liquid stream leaving the chamber contains the original cooling liquid plus the condensed substances. The gaseous stream leaving the chamber contains the noncondensable gases and such condensable vapor as did not condense; it is reasonable to assume that the vapors in the exit gas stream are saturated. It is then the temperature of the exit gas stream that determines the collection efficiency of the condenser.

The advantages of contact condensers are that (1) they can be used to produce a vacuum, thereby creating a draft to remove odorous vapors and also reduce boiling points in cookers and vats; (2) they usually are simpler and less expensive than the surface type; and (3) they usually have considerable odor-removing capacity because of the greater condensate dilution (13 lb of 60° F water is required to condense 1 lb of steam at 212° F and cool the condensate to 140° F). The principal disadvantage is the large water requirement. Depending on the nature of the condensate, odor in the wastewater can be offset by using treatment chemicals.

Direct-contact condensers involve the simultaneous transfer of heat and mass. Design procedures available for absorption, humidification, cooling towers, and the like may be applied with some modifications.

Surface Condensers Surface condensers (indirect-contact condensers) are used extensively in the chemical-process industry. They are employed in the air-pollution-equipment industry for recovery, control, and/or removal of trace impurities or contaminants. In the surface type, coolant does not contact the vapor condensate. There are various types of surface condensers including the shell-and-tube, fin-fan, finned-hairpin, finned-tube-section, and tubular. The use of surface condensers has several advantages. Salable condensate can be recovered. If water is used for coolant, it can be reused, or the condenser may be air-cooled when water is not available. Also, surface condensers require less water and produce 10 to 20 times less condensate. Their disadvantage is that they are usually more expensive and require more maintenance than the contact type.

Biofilters Biofilters are an APC technology that uses microorganisms, generally bacteria, to treat odorous off-gas emissions in an environmentally safe and economic manner. The biofilters consist of a porous filter media through which a waste gas stream is distributed. Microorganisms that feed on the waste gas are attached to this porous substrate. The biofiltration process is related to conventional activated sludge treatment in that, in both instances, the microorganisms are used to completely oxidize organic compounds into CO₂ and water. Biofilters are used to control the off-gas emissions from composting operations, rendering plants, food and tobacco processing, chemical manufacturing, iron and steel foundries, and other industrial facilities. Biofilters are in widespread use in Europe and Japan and are slowly becoming more acceptable as an APC technology in the United States.

General Process Description Biofilters are fixed film bioreactors that use microorganisms attached to substrate materials such as compost, peat, bark, soil, or inert materials to convert organic and inorganic waste products into CO₂ and water. The substrate provides structural support and elemental nutrients for the microbes. Its porous structure should provide adequate surface area at a reasonably low gas pressure drop. As waste gases are passed through the reactor, the target pollutants diffuse into the biofilm. The pollutants are then decomposed through the natural aerobic biodegradation process.

Biofilters are most economic when applied to low-concentration gas streams (<1000 ppm) that are also oxygen rich. Greater than 90 percent destruction efficiencies can be obtained for water-soluble organics such as alcohols, aldehydes, and amines. Water-soluble inor-

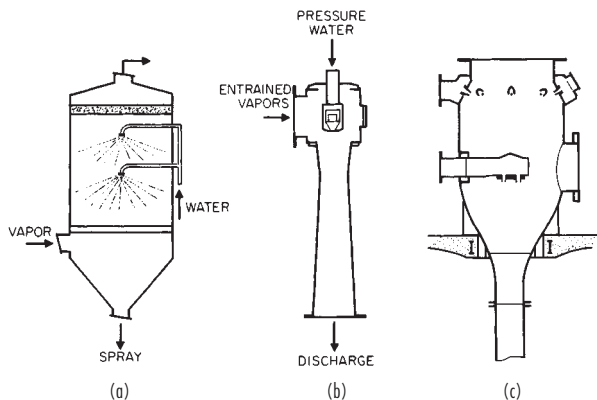


FIG. 25-15 Typical direct-contact condensers. (a) Spray chamber. (b) Jet. (c) Barometric.

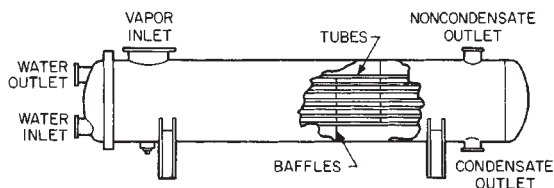


FIG. 25-16 Typical surface condenser (shell-and-tube).

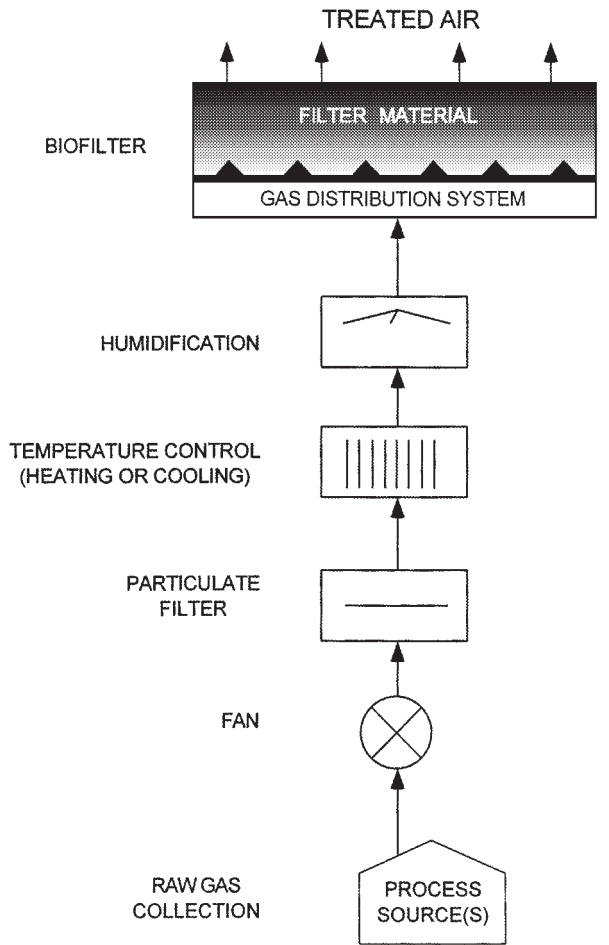


FIG. 25-17 Schematic flowsheet illustrating the individual elements of an open, single-layer biofilter system. Particulate filtration and/or temperature adjustment is often combined with the equipment to adjust gas humidity content.

ganics, such as H₂S and NH₃, can also readily undergo aerobic decomposition. The basic biofilter process steps involved are shown in Fig. 25-17 and are as follows:

1. Collection and transportation of raw waste gases from the processing/manufacturing area to a gas pretreatment area via ductwork and blowers.
2. Pretreatment of the raw waste gas to remove particulates, adjust temperature and humidify to saturation.
3. The pretreated gas is evenly distributed throughout the biofilter.

Microorganisms The naturally occurring microorganisms that are commonly used in biofilters are the same bacteria and fungi that are currently used in activated-sludge wastewater treatment and landfills. Genetically engineered microbes have been created to digest manmade chemical species, such as the organic aromatics xylene and styrene. On-going genetic engineering research is expected to increase the number of chemical species that can be biodegraded. This will also contribute to lowering the cost and size of current filter beds by decreasing the required digestion time. The more commonly used microorganisms are listed in Table 25-29.

Design and Construction The capacity and efficiency of biofilter operation are a direct function of active surface area, filter void

TABLE 25-29 Microorganisms Frequently Identified in Biofilters

Bacteria	Fungi
<i>Actinomyces globisporus</i> <i>Micrococcus albus</i> <i>Micromonospora vulgaris</i> <i>Bacillus cereus</i> <i>Streptomyces</i> spp.	<i>Penicillium</i> spp. <i>Cephalosporium</i> spp. <i>Mucor</i> spp. <i>Circinella</i> spp. <i>Cephalotecium</i> spp. <i>Ovularia</i> spp. <i>Stemphilium</i> spp.

SOURCE: Data compiled from Ottengraf, S. P. P., "Biological Systems for Waste Gas Elimination," 1987, Table 3.

space, target removal efficiency, gas species, and gas loading. Proper design of the main biofilter components is very important to ensure a feasible, cost-effective operation.

Raw Gas Composition The suitability of the raw gas stream must first be determined. The raw gas stream must contain the following in order to ensure both reasonable removal efficiencies and microorganism life expectancy:

1. An oxygen concentration equal to ambient level.
2. Gas concentrations below lethal levels for microorganisms used.
3. Lethal gas species must be absent from the raw gas stream.

Raw Gas Transport The gas is collected from the processing area and is transported by ductwork and ID fans to the preconditioning equipment.

Raw Gas Preconditioning In order to ensure the required destruction efficiency and continued biofilter life, the raw gas stream must be adjusted to a preselected range of particulate loading, temperature, and humidification before the gas can be safely introduced into the biofilter.

Preconditioning for Particulates Heavy particulate loading of the inlet gas with dust, grease, oils, or other aerosols can be very damaging to the pore structure of the filter bed, resulting in an eventual pressure-drop increase. Oils and heavy metals that are deposited on the filter bed can be poisonous to the microorganisms that live within the biofilm. Particulate APC equipment such as fabric filters and venturi scrubbers are generally adequate for this level of particulate removal.

Temperature The operating temperature of a biofilter is primarily controlled by the inlet gas temperature. The recommended operating temperature range for high destruction efficiency is between 20° to 40° C, with an optimum temperature of 37° C (98° F). At lower temperatures, the bacteria growth will be limited, and at extremely low temperatures the bacteria could possibly be destroyed. At temperatures above the recommended range, the bacteria's activity is also impaired. Extremely high temperatures will destroy the bacteria within the filter bed.

In terms of an economic determination, gas temperature adjustment is often the most important cost factor in determining whether to use a biofilter or a more conventional system. If the process gas stream is at an extremely high temperature (+100° C), the cost of cooling the inlet gas stream might favor more conventional methods for odor control such as thermal oxidation.

Humidification The microorganisms that digest the target pollutants live in a thin water layer called the biofilm that surrounds the filter substrate. Without the biofilm, the microorganisms would die; therefore, maintaining a wetted surface within the filter bed is crucial. Insufficient moisture can also lead to shrinking and cracking of the filter media, resulting in reduced active surface area and gas by-passing.

Humidification of the gas stream is the preferred method of keeping the filter bed moist. Gas moisture is usually added to the incoming gas stream downstream of the particulate removal APC equipment by either water sprays or steam. Adding moisture directly to the top of the bed in order to maintain filter media moisture is not recommended since this can result in: (1) localized drying of the substrate, and (2) cold water addition will reduce the activity of the microorganisms until the water becomes warmed to the steady-state filter-bed temperature.

Gas Distribution System The function of the gas distribution

system is to ensure even flow of the preconditioned gas stream to all areas of the filter bed. In upflow biofilter designs, the gas distribution system also provides the following:

1. A means of drainage, collection, and transportation of excess water within the filter bed
2. Prevents the potential contamination of surrounding soil by leaking filter leachate
3. A structural base for the filter bed media

The gas distribution system can be composed of a network of perforated pipe, slotted or vented concrete block, or metal grating. When there are no space limitations, single-level filters are used. In regions where footprint space is limited, like Japan, multiple-deck filter beds have become commonplace. If inorganic compounds are being treated, corrosion-resistant materials of construction are used due to the acidic by-products of the bioreaction.

Filter Matrix The most common filter substrates in use today are soils or compost produced from leaves, bark, wood chips, activated sludge, paper, or other organic materials. In selecting a proper filter substrate for a specific use, the following should be considered:

1. The particle size and porosity of the filter media, since operating efficiency is directly related to the available biofilm surface area.
2. The filter media must be a source of inorganic nutrients for the microbes. In cases of long-term operation, inorganic nutrients can be periodically added to the bed.
3. Compaction of the filter bed over time will result in gas channeling and pressure-drop increases. This can be avoided by adding large, rigid particles such as plastic spheres, ceramics, or wood/bark chips to provide additional support to the filter substrate.
4. Good bed drainage characteristics are necessary to ensure that reaction products are easily transported out of the filter media. The leachate is generally recycled through the humidification process to reduce the wastewater stream.
5. The filter media should have buffering capacity in order to maintain a pH of at least 3. This is especially a concern when inorganic compounds are targeted for reduction by the biofilter.
6. The filter media should be composed of materials that have a nonobjectional odor.

Kinetics The capacity and efficiency of biofilter operation is a function of active surface area, filter void space, target removal efficiency, gas species, gas concentration, and gas flow rate. A simplified theoretical model described by S.P.P. Ottengraf et al. is schematically represented by in Fig. 25-18. The mass balance made around the liquid-phase biolayer can be described as follows:

$$D \times \left(\frac{d^2 C_1}{dx^2} \right) - R = 0 \quad (25-12)$$

where: D = the mass-transfer coefficient, L^2/T

C_1 = liquid phase concentration, M/L^3

x = distance through biolayer, L

R = substrate utilization rate, $M/L^3/T$ (biodegradation rate)

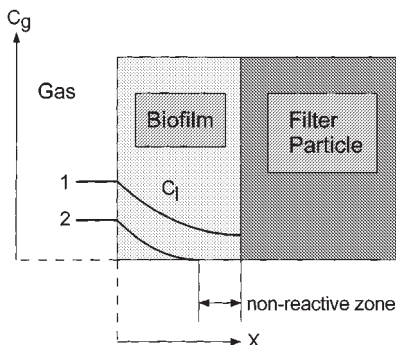


FIG. 25-18 Biophysical model for the biolayer. C_g is the concentration in the gas phase. The two concentration profiles shown in the biolayer (C_1) refer to (1) elimination reaction rate limited, and (2) diffusion limited. (SOURCE: Redrawn from Ref. 26.)

The Ottengraf biolayer mass balance assumes the following:

1. Monod kinetic model applies.
2. Biodegradation occurs in the biofilm liquid phase.
3. The biofilm thickness is small compared to the diameter of the substrate; therefore, the biofilm can be regarded as a flat surface.
4. Plug flow of the gas through the filter media.
5. Gas and liquid phase concentrations follow Henry's law.
6. Ideal gas law applies; i.e., no gas species interactions.
7. Steady state.

The biodegradation rate R is characterized by the Monod (or Michaelis-Menten) following relationship:

$$R = R_{\max} \times \frac{C_1}{(C_1 + K_m)} \quad (25-13)$$

where: K_m = the Monod (Michaelis-Menten) constant, M/L^3
 $R_{\max}$ = the maximum substrate utilization rate, $M/L^3/T$

$R_{\max}$ is a function of the active microorganism concentration in the biofilm and is defined as:

$$R_{\max} = X \times \frac{\mu_m}{y_i} \quad (25-14)$$

where: X = cell concentration of the active microbes, M/L^3 ;
 μ_m = the maximum growth rate of microbe species, $1/T$;
 y_i = cell yield coefficient of microbe species, dimensionless

Two rate-limiting cases exist with the above mass balance:

1. **Reaction rate limited (zero-order kinetics).** In this case, the biofilm concentration has no effect on reaction rate, and the biodegradation breakthrough curve is linear.

2. **Diffusion rate limited (first-order kinetics).** In this case, the reaction rate is controlled by the rate of diffusion of the pollutant species into the biofilm.

The concentration profiles that result from the above two rate-controlling mechanisms are shown in Fig. 25-18.

One of the listed assumptions for Ottengraf's kinetic model was that no gas-phase interactions occur between different chemical species (the ideal-gas assumption). Under actual operating conditions, gas-phase interactions can either have a negative or positive impact on biofilter operation. These interactions include:

1. Cometabolism, which increases the biodegradation rate of the multiple targeted compounds.
2. Cross-inhibition, which decreases the biodegradation rate of the multiple targeted compounds.
3. Vertical stratification, where the most easily degraded compounds are metabolized first upon entering the filter bed. The more difficult-to-metabolize compounds pass through the lower region of the bed and are metabolized in the upper levels.

Based upon the above-mentioned species interactions, pilot-scale testing is generally recommended to accurately size a biofilter bed for a multicomponent waste gas stream.

Membrane Filtration Membrane systems have been used for several decades to separate colloidal and molecular slurries by the chemical process industries (CPI). Membrane filtration was not viewed as a commercially viable pollution control technology until recently. This conventional wisdom was due to fouling problems exhibited when handling process streams with high solid content. This changed with the advent of membranes composed of high-flux cellulose acetate. In Europe and Asia, membrane filtration systems have been used for several years, primarily for ethanol dewatering for synthetic fuel plants. Membrane systems were selected in these cases for their (1) low energy utilization; (2) modular design; (3) low capital costs; (4) low maintenance; and (5) superior separations. In the United States, as EPA regulations become increasingly stringent, a renewed interest in advanced membrane filtration systems has occurred. In this case, the driving factors are the membrane system's ability to operate in a pollution-free, closed-loop manner with minimum wastewater output. Low capital and maintenance costs also result from the small amount of moving parts within the membrane systems.

Process Descriptions Selectively permeable membranes have an increasingly wide range of uses and configurations as the need for

more advanced pollution control systems are required. There are four major types of membrane systems: (1) pervaporation; (2) reverse osmosis (RO); (3) gas absorption; and (4) gas adsorption. Only membrane pervaporation is currently commercialized.

Membrane Pervaporation Since 1987, membrane pervaporation has become widely accepted in the CPI as an effective means of separation and recovery of liquid-phase process streams. It is most commonly used to dehydrate liquid hydrocarbons to yield a high-purity ethanol, isopropanol, and ethylene glycol product. The method basically consists of a selectively-permeable membrane layer separating a liquid feed stream and a gas phase permeate stream as shown in Fig. 25-19. The permeation rate and selectivity is governed by the physicochemical composition of the membrane. Pervaporation differs from reverse osmosis systems in that the permeate rate is not a function of osmotic pressure, since the permeate is maintained at saturation pressure (Ref. 24).

Three general process groups are commonly used when describing pervaporation: (1) water removal from organics; (2) organic removal from water (solvent recovery); and (3) organic/organic separation. Organic/organic separations are very uncommon and therefore will not be discussed further.

Ethanol Dehydration The membrane-pervaporation process for dehydrating ethanol was first developed by GFT in West Germany in the mid 1970s, with the first commercial units being installed in Brazil and the Philippines. At both sites, the pervaporation unit was coupled to a continuous sugarcane fermentation process that produced ethanol at concentrations up to 96 percent after vacuum pervaporation. The key advantages of the GFT process are (1) no additive chemicals are required; (2) the process is skid-mounted (low capital costs and small footprint); (3) and there is a low energy demand. The low energy requirement is achieved because only a small fraction of the water is actually vaporized and that the required permeation driving force is provided by only a small vacuum pump. The basic ethanol dehydration process schematic is shown in Fig. 25-20. A key advantage of all pervaporation processes is that vapor-liquid equilibria and possible resulting azeotropic effects are irrelevant (see Fig. 25-21 and Ref. 24).

Solvent Recovery The largest current industrial use of pervaporation is the treatment of mixed organic process streams that have become contaminated with small (10 percent) quantities of water. Pervaporation becomes very attractive when dehydrating streams down to less than 1 percent water. The advantages result from the small operating costs relative to distillation and adsorption. Also, distillation is often impossible, since azeotropes commonly form in multicomponent organic/water mixtures.

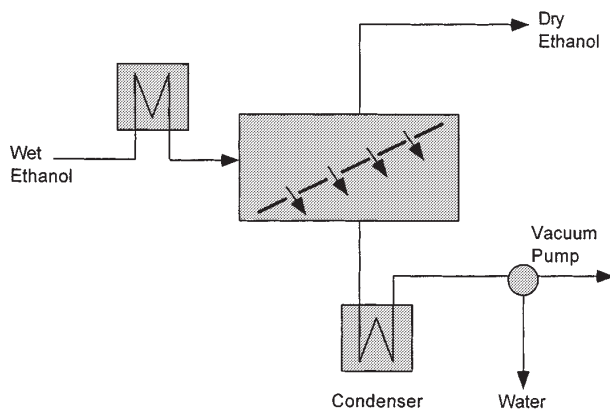


FIG. 25-20 Ethanol dehydration using pervaporation membrane. (SOURCE: Redrawn from Ref. 24.)

Pervaporation occurs in three basic steps:

1. Preferential sorption of chemical species
2. Diffusion of chemical species through the membrane
3. Desorption of chemical species from the membrane

Steps 1 and 2 are controlled by the specific polymer chemistry and its designed interaction with the liquid phase. The last step, consisting of evaporation of the chemical species, is considered to be a fast, nonselective process. Step 2 is the rate-limiting step. The development by the membrane manufacturers of highly selective, highly permeable composite membranes that resist fouling from solids has subsequently been the key to commercialization of pervaporation systems. The membrane composition and structure are designed in layers, with each layer fulfilling a specific requirement. Using membrane dehydration as an example, a membrane filter would be composed of a support layer of nonwoven porous polyester below a layer of polyacrylonitrile (PAN) or polysulfone ultrafiltration membrane and a layer of 0.1- μm -thick crosslinked polyacrylate, polyvinyl alcohol (PVA). Other separations membranes generally use the same two sublayers. The top layer is interchanged according to the selectivity desired.

Emerging Membrane Control Technologies The recent improvements in membrane technology have spawned several potentially commercial membrane filtration uses.

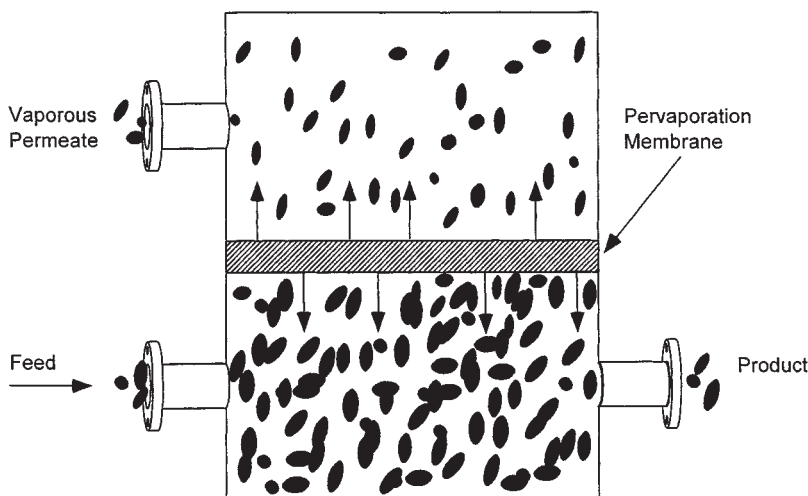


FIG. 25-19 Pervaporation of gas from liquid feed across membrane to vaporous permeate. (SOURCE: Redrawn from Ref. 24.)

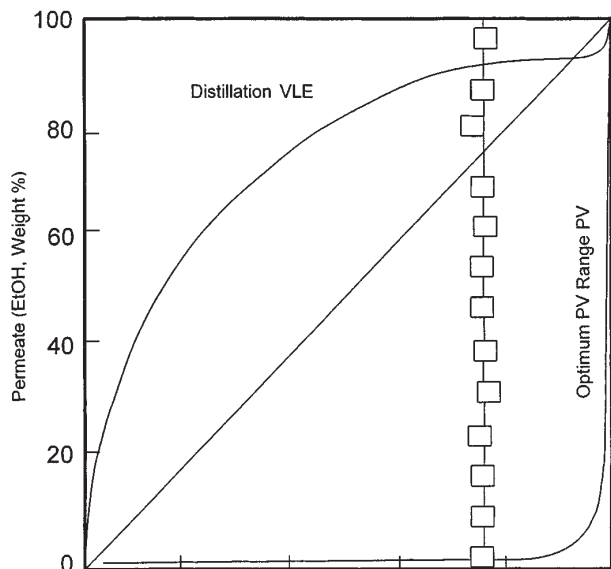


FIG. 25-21 Comparison of two types of pervaporation membranes to distillation of ethanol-water mixtures. (SOURCE: Redrawn from Ref. 24.)

Reverse Osmosis (RO) Membranes A type of membrane system for treating oily wastewater is currently undergoing commercialization by Bend Research, Inc. The system uses a tube-side feed module that yields high fluxes while being able to handle high-solids-content waste streams (Ref. 25). Another type of reverse osmosis technique is being designed to yield ultrapurified HF recovered from

spent etching solutions. It is estimated that 20,000 tons of spent solution is annually generated in the United States and that using membrane RO could save 1 million bbl/yr of oil.

In Situ Filter Membranes In situ membranes are being fitted into incinerator flue-gas stacks in an attempt to reduce hydrocarbon emissions. Two types of commercially available gas separation membranes are being studied: (1) flat cellulose acetate sheets; and (2) hollow-tube fiber modules made of polyamides.

Vibratory Shear-Enhanced Membranes The vibratory shear-enhancing process (VSEP) is just starting commercialization by Logic International, Emeryville, CA. It employs the use of intense sinusoidal shear waves to ensure that the membrane surfaces remain active and clean of solid matter. The application of this technology would be in the purification of wastewater (Ref. 2).

Vapor Permeation Vapor permeation is similar to vapor pervaporation except that the feed stream for permeation is a gas. The future commercial viability of this process is based upon energy and capital costs savings derived from the feed already being in the vapor-phase, as in fractional distillation, so no additional heat input would be required. Its foreseen application areas would be the organics recovery from solvent-laden vapors and pollution treatment. One commercial unit was installed in Germany in 1989 (Ref. 26).

Selective Catalytic Reduction of Nitrogen Oxides The traditional approach to reducing ambient ozone concentrations has been to reduce VOC emissions, an ozone precursor. In many areas, it has now been recognized that elimination of persistent exceedances of the National Ambient Air Quality Standard for ozone may require more attention to reductions in the other ingredients in ozone formation, nitrogen oxides (NO_x). In such areas, ozone concentrations are controlled by NO_x rather than VOC emissions.

Selective catalytic reduction (SCR) has been used to control NO_x emissions from utility boilers in Europe and Japan for over a decade. Applications of SCR to control process NO_x emissions in the chemical industry are becoming increasingly common. A typical SCR system is shown in Fig. 25-22.

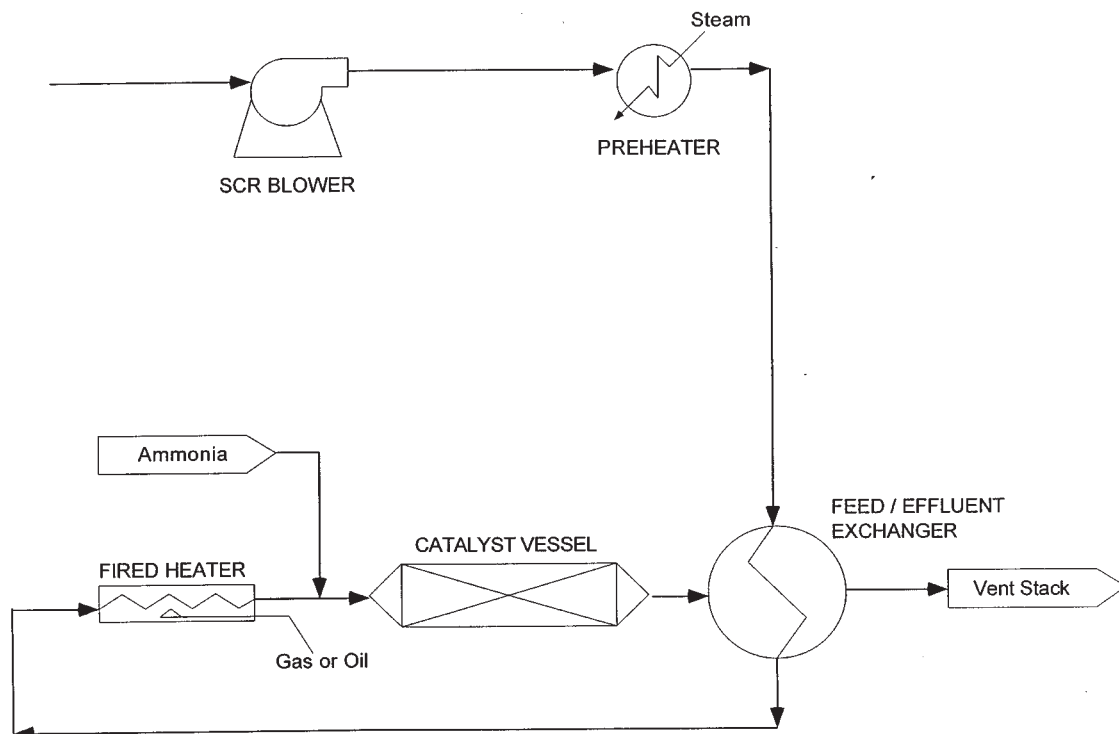
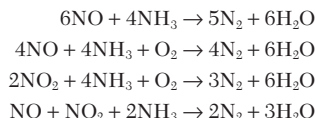


FIG. 25-22 Selective catalytic reduction of nitrogen oxides.

NO_x -laden fumes are preheated by effluent from the catalyst vessel in the feed/effluent heat exchanger and then heated by a gas- or oil-fired heater to over 600° F. A controlled quantity of ammonia is injected into the gas stream before it is passed through a metal oxide, zeolite, or promoted zeolite catalyst bed. The NO_x is reduced to nitrogen and water in the presence of ammonia in accordance with the following exothermic reactions:



NO_x analyzers at the preheater inlet and catalyst vessel outlet monitor NO_x concentrations and control the ammonia feed rate. The effluent gives up much of its heat to the incoming gas in the feed/effluent exchanger. The vent gas is discharged at about 350° F.

SOURCE CONTROL OF PARTICULATE EMISSIONS

There are four conventional types of equipment used for the control of particulate emissions:

1. Mechanical collectors
2. Wet scrubbers
3. Electrostatic precipitators
4. Fabric filters

Each is discussed in Sec. 17 of this handbook under "Gas-Solids Separations." The effectiveness of conventional air-pollution-control equipment for particulate removal is compared in Fig. 25-23. These fractional efficiency curves indicate that the equipment is least efficient in removing particulates in the 0.1- to 1.0- μm range. For wet

scrubbers and fabric filters, the very small particulates (0.1 μm) can be efficiently removed by brownian diffusion. The smaller the particulates, the more intense their brownian motion and the easier their collection by diffusion forces. Larger particulates (>1 μm) are collected principally by impaction, and removal efficiency increases with particulate size. The minimum in the fractional efficiency curve for scrubbers and filters occurs in the transition range between removal by brownian diffusion and removal by impaction.

A somewhat similar situation exists for electrostatic precipitators. Particulates larger than about 1 μm have high mobilities because they are highly charged. Those smaller than a few tenths of a micrometer can achieve moderate mobilities with even a small charge because of aerodynamic slip. A minimum in collection efficiency usually occurs in the transition range between 0.1 and 1.0 μm . The situation is further complicated because not all particulates smaller than about 0.1 μm acquire charges in an ion field. Hence, the efficiency of removal of very small particulates decreases after reaching a maximum in the submicrometer range.

The selection of the optimum type of particulate collection device (i.e., ESP or fabric filter baghouse) is often not obvious without conducting a site-specific economic evaluation. This situation has been brought about by both the recent reductions in the allowable emissions levels and advancements with fabric filter and ESP technologies. Such technoeconomic evaluations can result in application and even site-specific differences in the final optimum choice (see *Precip Newsletter*, 220, June, 1994 and *Fabric Filter Newsletter*, 223, June, 1994).

Improvements in existing control technology for fine particulates and the development of advanced techniques are top-priority research goals. Conventional control devices have certain limitations. Precipitators, for example, are limited by the magnitude of charge on the particulate, the electric field, and dust reentrainment. Also, the resistivity of the particulate material may adversely affect both charge and electric field. Advances are needed to overcome resistivity and extend the performance of precipitators not limited by resistivity (see Buonicore and Theodore, "Control Technology for Fine Particulate Emissions," DOE Rep. ANL/ECT-5, Argonne National Laboratory, Argonne, Illinois, October 1978). Recent design developments with the potential to improve precipitator performance include pulse energization, electron beam ionization, wide plate spacing, and pre-charged units [Balakrishnan et al., "Emerging Technologies for Air Pollution Control," *Pollut. Eng.*, **11**, 28-32 (Nov. 1979); "Pulse Energization," *Environ. Sci. Technol.* **13**(9), 1044 (1974); and Midkaff, "Change in Precipitator Design Expected to Help Plants Meet Clean Air Laws," *Power*, **126**(10), 79 (1979)].

Fabric filters are limited by physical size and bag-life considerations. Some sacrifices in efficiency might be tolerated if higher air-cloth ratios could be achieved without reducing bag life (improved pulse-jet systems). Improvements in fabric filtration may also be possible by enhancing electrostatic effects that may contribute to rapid formation of a filter cake after cleaning.

Scrubber technology is limited by scaling and fouling, overall reliability, and energy consumption. The use of supplementary forces acting on particulates to cause them to grow or otherwise be more easily collected at lower pressure drops is being closely investigated. The development of electrostatic and flux-force-condensation scrubbers is a step in this direction.

The electrostatic effect can be incorporated into wet scrubbing by charging the particulates and/or the scrubbing-liquor droplets. Electrostatic scrubbers may be capable of achieving the same efficiency for fine-particulate removal as is achieved by high-energy scrubbers, but at substantially lower power input. The major drawbacks are increased maintenance of electrical equipment and higher capital cost.

Flux-force-condensation scrubbers combine the effects of flux force (diffusiophoresis and thermophoresis) and water-vapor condensation. These scrubbers contact hot, humid gas with subcooled liquid, and/or they inject steam into saturated gas, and they have demonstrated that a number of these novel devices can remove fine particulates (see Fig. 25-24). Although limited in terms of commercialization, these systems may find application in many industries.

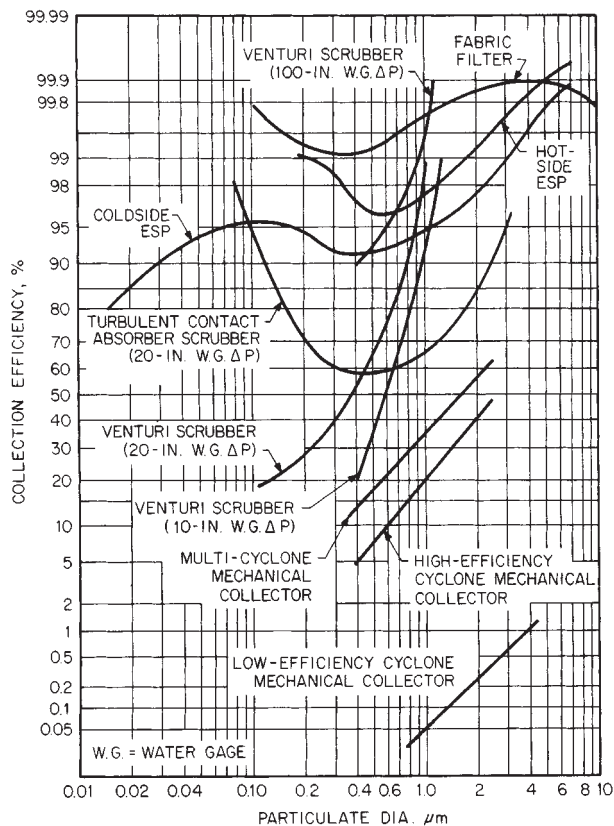


FIG. 25-23 Fractional efficiency curves for conventional air-pollution-control devices. [Chem. Eng., 87(13), 83 (June 30, 1980).]

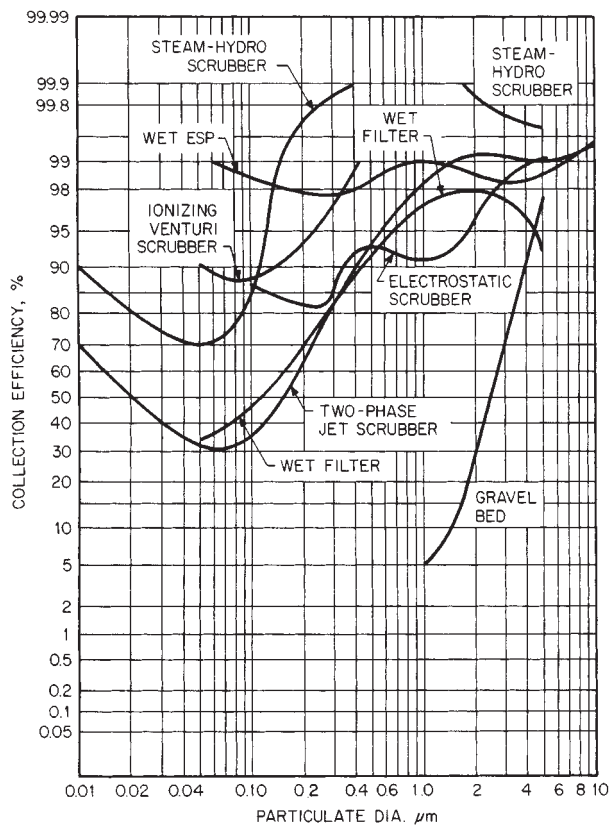


FIG. 25-24 Fractional efficiency curves for novel air-pollution-control devices. [Chem. Eng., 87(13), 85 (June 30, 1980).]

EMISSIONS MEASUREMENT

Introduction An accurate quantitative analysis of the discharge of pollutants from a process must be determined prior to the design and/or selection of control equipment. If the unit is properly engineered by utilizing the emission data as input to the control device and the code requirements as maximum-effluent limitations, most pollutants can be successfully controlled.

Sampling is the keystone of source analysis. Sampling methods and tools vary in their complexity according to the specific task; therefore, a degree of both technical knowledge and common sense is needed to design a sampling function. Sampling is done to measure quantities or concentrations of pollutants in effluent gas streams, to measure the efficiency of a pollution-abatement device, to guide the designer of pollution-control equipment and facilities, and/or to appraise contamination from a process or a source. A complete measurement requires a determination of the concentration and contaminant characteristics as well as the associated gas flow. Most statutory limitations require mass rates of emissions; both concentration and volumetric-flow-rate data are therefore required.

The selection of a sampling site and the number of sampling points required are based on attempts to get representative samples. To accomplish this, the sampling site should be at least eight stack or duct diameters downstream and two diameters upstream from any flow disturbance, such as a bend, expansion, contraction, valve, fitting, or visible flame.

Once the sampling location has been decided on, the flue cross section is laid out in a number of equal areas, the center of each being the point where the measurement is to be taken. For rectangular stacks, the cross section is divided into equal areas of the same shape, and the traverse points are located at the center of each equal area, as shown

in Fig. 25-25. The ratio of length to width of each elemental area should be selected. For circular stacks, the cross section is divided into equal annular areas, and the traverse points are located at the centroid of each area. The location of the traverse points as a percentage of diameter from the inside wall to the traverse point for circular-stack sampling is given in Table 25-30. The number of traverse points necessary on each of two perpendiculars for a particular stack may be estimated from Fig. 25-26.

Once these traverse points have been determined, velocity measurements are made to determine gas flow. The stack-gas velocity is usually determined by means of a pitot tube and differential-pressure gauge. When velocities are very low (less than 3 m/s [10 ft/s]) and when great accuracy is not required, an anemometer may be used. For gases moving in small pipes at relatively high velocities or pressures, orifice-disk meters or venturi meters may be used. These are valuable as continuous or permanent measuring devices.

Once a flow profile has been established, sampling strategy can be considered. Since sampling collection can be simplified and greatly reduced depending on flow characteristics, it is best to complete the flow-profile measurement before sampling or measuring pollutant concentrations.

Sampling Methodology The following subsections review the methods specified for sampling commonly regulated pollutants as well as sampling for more exotic volatile and semivolatile organic compounds. In all sampling procedures, the main concern is to obtain a representative sample; the U.S. EPA has published reference sampling methods for measuring emissions of specific pollutants so that uniform procedures can be applied in testing to obtain a representative sample. Table 25-31 provides an overview of the regulatory citation for selected test methods. The test methods reviewed in the following subsections address measuring the emissions of the following pollutants: particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, fluorides, hydrogen chloride, total gaseous organics, multiple metals, volatile organic compounds, and semivolatile organic compounds.

Each sampling method requires the use of complex sampling equipment that must be calibrated and operated in accordance with specified reference methods. Additionally, the process or source that is being tested must be operated in a specific manner, usually at rated capacity, under normal procedures.

Velocity and Volumetric Flow Rate The U.S. EPA has published Method 2 as a reference method for determining stack-gas velocity and volumetric flow rate. At several designated sampling points, which represent equal portions of the stack volume (areas in the stack), the velocity and temperature are measured with instrumentation shown in Fig. 25-27.

Measurements to determine volumetric flow rate usually require approximately 30 min. Since sampling rates depend on stack-gas velocity, a preliminary velocity check is usually made prior to testing for pollutants to aid in selecting the proper equipment and in determining the approximate sampling rate for the test.

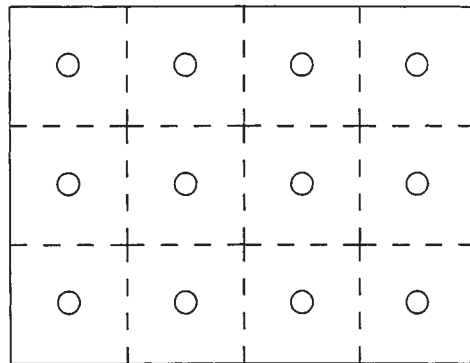


FIG. 25-25 Example showing rectangular stack cross section divided into 12 equal areas, with a traverse point at centroid of each area.

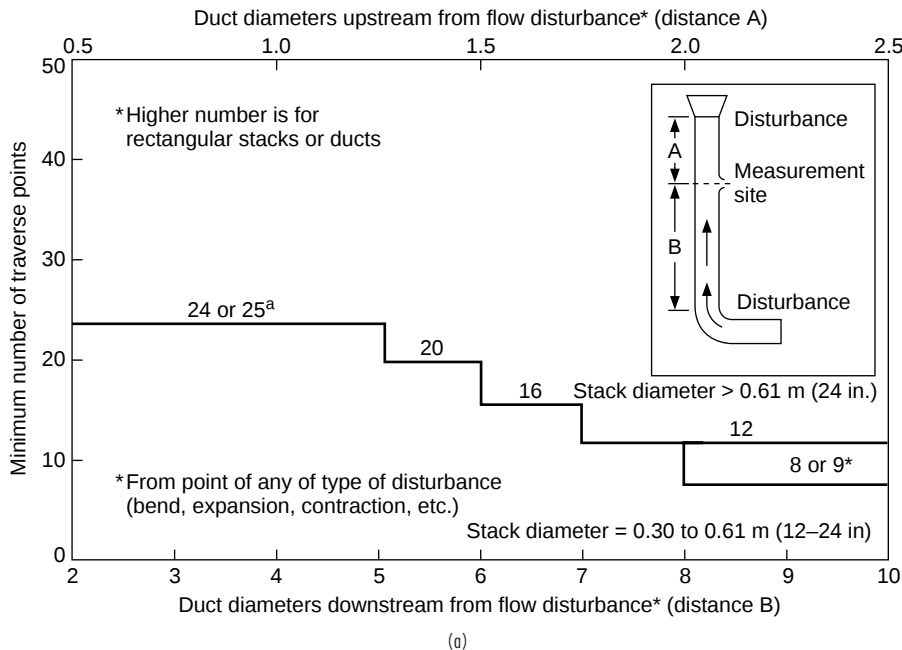


FIG. 25-26a Minimum number of traverse points for particulate traverses.

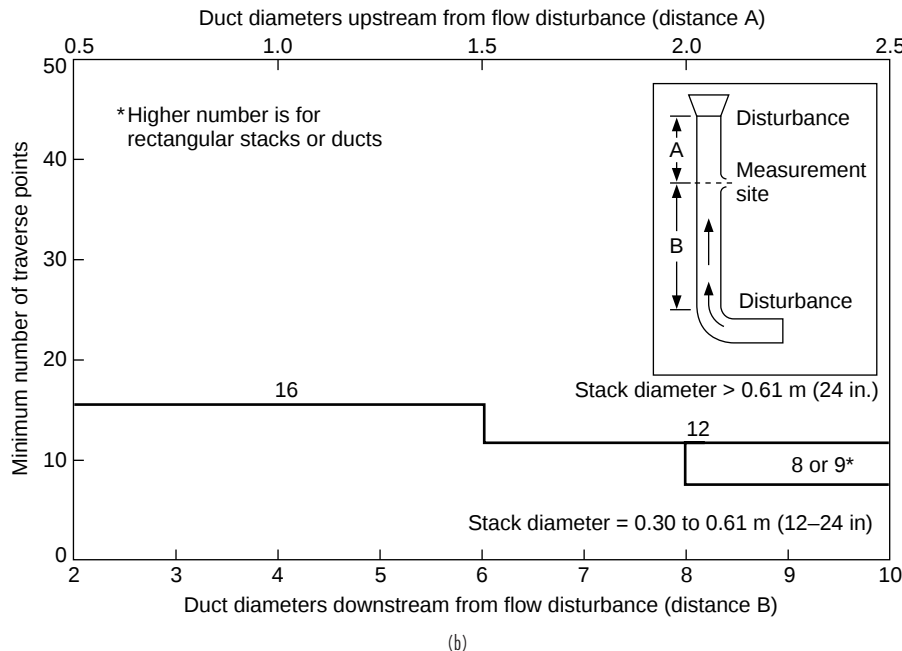


FIG. 25-26b Minimum number of traverse points for velocity (nonparticulate) traverse.

The volumetric flow rate determined by this method is usually within ± 10 percent of the true volumetric flow rate.

Molecular Weight EPA Method 3 is used to determine carbon dioxide and oxygen concentrations and dry molecular weight of the stack-gas stream. Depending on the intended use of the data, these values can be obtained with an integrated sample (see Fig. 25-28) or a grab sample (see Fig. 25-29). In addition, the instrumental analyzer

method, EPA Method 3A, is used for gas compositional analyses (O_2 and CO_2) in determining the sample gas molecular weight.

With the grab sampling technique, a sampling probe is placed at the center of the stack, and a sample is drawn directly into an Orsat analyzer or a Fyrite-type combustion-gas analyzer. The sample is then analyzed for carbon dioxide and oxygen content. With these data, the dry molecular weight of the gas stream can then be calculated.

TABLE 25-30 Location of Traverse Points in Circular Stacks

(Percent of stack diameter from inside wall to traverse point)

Traverse point number on a diameter	Number of traverse points on a diameter										
	2	4	6	8	10	12	14	18	20	22	24
1	14.6	6.7	4.4	3.2	2.6	2.1	1.8	1.4	1.3	1.1	1.1
2	85.4	25.0	14.6	10.5	8.2	6.7	5.7	4.4	3.9	3.5	3.2
3		75.0	29.6	19.4	14.6	11.8	9.9	7.5	6.7	6.0	5.5
4		93.3	70.4	32.3	22.6	17.7	14.6	10.9	9.7	8.7	7.9
5			85.4	67.7	34.2	25.0	20.1	14.6	12.9	11.6	10.5
6			95.6	80.6	65.8	35.6	26.9	18.8	16.5	14.6	13.2
7				89.5	77.4	64.4	36.6	23.6	20.4	18.0	16.1
8				96.8	85.4	75.0	63.4	29.6	25.0	21.8	19.4
9					91.8	82.3	73.1	38.2	30.6	26.2	23.0
10					97.4	88.2	79.9	61.8	38.8	31.5	27.2
11						93.3	85.4	70.4	61.2	39.3	32.3
12						97.9	90.1	76.4	69.4	60.7	39.8
13							94.3	81.2	75.0	68.5	60.2
14							98.2	85.4	79.6	73.8	67.7
15								89.1	83.5	78.5	72.8
16								92.5	87.1	82.0	77.0
17								95.6	90.3	85.4	80.8
18								98.6	93.3	88.4	83.9
19									96.1	91.3	86.8
20									96.7	94.0	89.5
21										96.5	92.1
22										98.9	94.5
23											96.8
24											96.9

TABLE 25-31 Regulatory Citations for Selected Test Methods

Citation	Description	Selected methods included	Test parameter(s)
40 CFR Part 60 (Appendix A)	New source performance standards	Methods 1–4 Method 5 Method 6/6C Method 7/7E Method 9 Method 10 Method 13A or 13B Method 23 Method 25/25A Method 26/26A Method 201A	Test location, volumetric flow rate, gas composition, moisture content Particulate matter Sulfur dioxide Nitrogen oxides Opacity of visible emissions Carbon monoxide Total fluoride Dioxins and furans Total gaseous non-methane organics (VOCs) Halogens, halides (primarily HCl, HF, Cl ₂)
40 CFR Part 51 (Appendix M) 40 CFR Part 266 (Appendix IX)	State implementation plans Boiler and industrial furnace (BIF) regulations	Method 201A “Multiple metals”*	Particulate matter of less than or equal to 10 µg (PM ₁₀) Cr, Cd, As, Ni, Mn, Be, Cu, Zn, Pb, Se, P, Tl, Ag, Sb, Ba, Hg
40 CFR Part 61 (Appendix B)	NESHAP regulations	Method Cr+6 Method 0050 Method 101A Method 104 Method 108 Method 0010 Method 0030	Hexavalent chromium Isokinetic HCl/Cl ₂ Mercury Beryllium Arsenic Semivolatile organics Volatile organics
SW-846†			

NOTES:

*The multiple metals method is also currently published as Draft EPA Method 29 for inclusion in 40 CFR 60.

†Full citation is: *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods*, SW-846, 3d ed., July 1992.

The instrumental analyzer procedure, EPA Method 3A, is commonly used for the determination of oxygen and carbon dioxide concentrations in emissions from stationary sources. An integrated continuous gas sample is extracted from the test location and a portion of the sample is conveyed to one or more instrumental analyzers for determination of O₂ and CO₂ gas concentrations (see Fig. 25-30). The sample gas is conditioned prior to introduction to the gas analyzer by removing particulate matter and moisture. Sampling is conducted at a constant rate for the entire test run. Performance specifications and test procedures are provided in the method to ensure reliable data.

Moisture Content EPA Method 4 is the reference method for determining the moisture content of the stack gas. A value for moisture content is needed in some of the calculations for determining pollution-emission rates.

A sample is taken at several designated points in the stack, which represent equal areas. The sampling probe is placed at each sampling

point, and the apparatus is adjusted to take a sample at a constant rate. As the gas passes through the apparatus, a filter collects the particulate matter, the moisture is removed, and the sample volume is measured. The collected moisture is then measured, and the moisture content of the gas stream is calculated. A schematic of the sampling used in this reference method is shown in Fig. 25-31.

Particulates Procedures for testing a particulate source are more detailed than those used for sampling gases. Because particulates exhibit inertial effects and are not uniformly distributed within a stack, sampling to obtain a representative sample is more complex than for gaseous pollutants. EPA Method 5 (as shown in Fig. 25-32) is the most widely used procedure for determination of particulate emissions from a stationary source. In-stack sampling guidelines are presented in EPA Method 17.

According to Method 5 (except as applied to fossil-fuel-fired steam generators), a particulate is defined as any material collected at

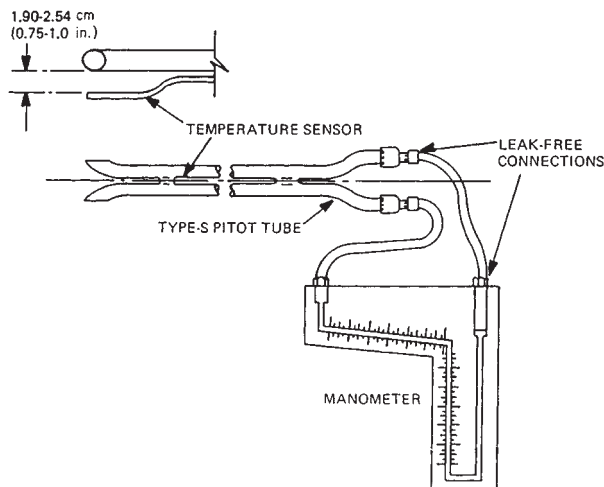


FIG. 25-27 Velocity-measurement system.

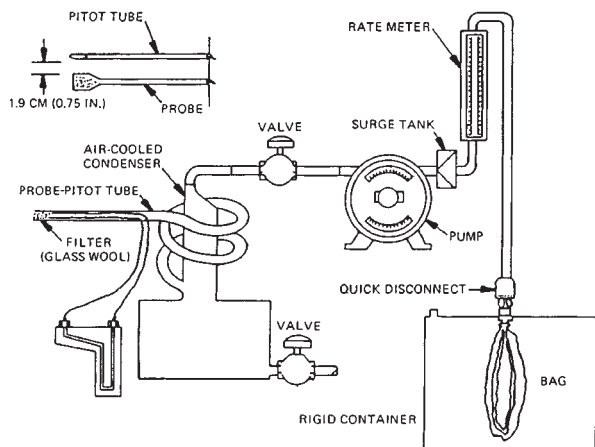


FIG. 25-28 Integrated-sample setup for molecular-weight determination.

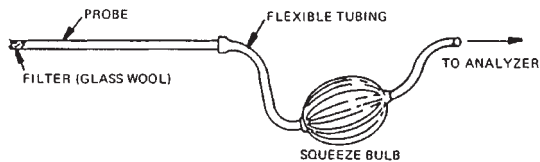


FIG. 25-29 Grab-sample setup for molecular-weight determination.

121° C (250° F) on a filtering medium. The sampling apparatus, however, may have to be modified to conform with the state's definition of a particulate. For example, a state may define *particulate* as any material collectible at stack conditions, a definition that would allow the filtering medium to be located in the stack.

In performing a particulate source test, samples are taken at several designated sampling points in the stack, which represent equal areas. At each sampling point, the velocity, temperature, molecular weight, and static pressure of the particulate-laden gas stream are measured. The sampling probe is placed at the first sampling point, and the sampling apparatus is adjusted to take a sample at the conditions measured at this point, and the process is repeated continuously until a

sample has been taken from each designated sampling point. To achieve valid results in a particulate-source test, the sample must be taken isokinetically. Measurement of stack conditions allows adjustment of the sampling rate to meet this requirement.

As the gas stream proceeds through the sampling apparatus, the particulate matter is trapped on a filter, the moisture is removed, and the volume of the sample is measured. Upon completion of sampling, the collected material is recovered and sent to a laboratory for a gravimetric determination or analysis.

Sulfur Dioxide EPA Method 6 is the reference method for determining emissions of sulfur dioxide (SO₂) from stationary sources. As the gas goes through the sampling apparatus (see Fig. 25-33), the sulfuric acid mist and sulfur trioxide are removed, the SO₂ is removed by a chemical reaction with a hydrogen peroxide solution, and, finally, the sample gas volume is measured. Upon completion of the run, the sulfuric acid mist and sulfur trioxide are discarded, and the collected material containing the SO₂ is recovered for analysis at the laboratory. The concentration of SO₂ in the sample is determined by a titration method.

For determination of the total mass-emission rate of SO₂, the moisture content and the volumetric flow rate of the exhaust gas stream must also be measured.

The minimum detectable limit has been determined to be 3.4 mg of SO₂ per cubic meter of gas (2.1×10^{-7} lb of SO₂ per cubic foot of gas). Although no upper limit has been established, the theoretical upper concentration limit in a 20-liter sample is about 93,300 mg/m³.

EPA Method 6C is the instrumental analyzer procedure used to determine sulfur dioxide emissions from stationary sources (see Fig. 25-30). An integrated continuous gas sample is extracted from the test location, and a portion of the sample is conveyed to an instrumental analyzer for determination of SO₂ gas concentration using an ultraviolet (UV), nondispersive infrared (NDIR), or fluorescence analyzer. The sample gas is conditioned prior to introduction to the gas analyzer by removing particulate matter and moisture. Sampling is conducted at a constant rate for the entire test run.

Quality control elements required by the instrumental analyzer method include: analyzer calibration error (± 2 percent of instrument span allowed); verifying the absence of bias introduced by the sampling system (less than ± 5 percent of span for zero and upscale calibration gases); and verification of zero and calibration drift over the test period (less than ± 3 percent of span of the period of each run).

The analytical range is determined by the instrumental design. For this method, a portion of the analytical range is selected by choosing the span of the monitoring system. The span of the monitoring system is selected such that the pollutant gas concentration equivalent to the emission standard is not less than 30 percent of the span. If at any time during a run the measured gas concentration exceeds the span, the run is considered invalid.

The minimum detectable limit depends on the analytical range, span, and signal-to-noise ratio of the measurement system. For a well-designed system, the minimum detectable limit should be less than 2 percent of the span.

Nitrogen Oxides (NO_x) EPA Method 7 is the reference method for determining emissions of nitrogen oxides from stationary sources. Sampling for NO_x by this method is relatively simple with the proper equipment.

A sampling probe is placed at any location in the stack, and a grab sample is collected in an evacuated flask. This flask contains a solution of sulfuric acid and hydrogen peroxide, which reacts with the NO_x. The volume and moisture content of the exhaust-gas stream must be determined for calculation of the total mass-emission rate. The sample is sent to a laboratory, where the concentration of nitrogen oxides, except nitrous oxide, is determined colorimetrically.

Each grab sample is obtained fairly rapidly (15 to 30 s), and four grab samples constitute one run; a total of 12 grab samples is required for a complete series of three runs. An interval of 15 min between grab samples is required. The range of this method has been determined to be 2 to 400 mg of NO_x (as NO₂) per dry standard cubic meter (without dilution). Figure 25-34 shows a schematic of the sampling apparatus for an NO_x source test.

EPA Method 7E is the instrumental analyzer procedure used to

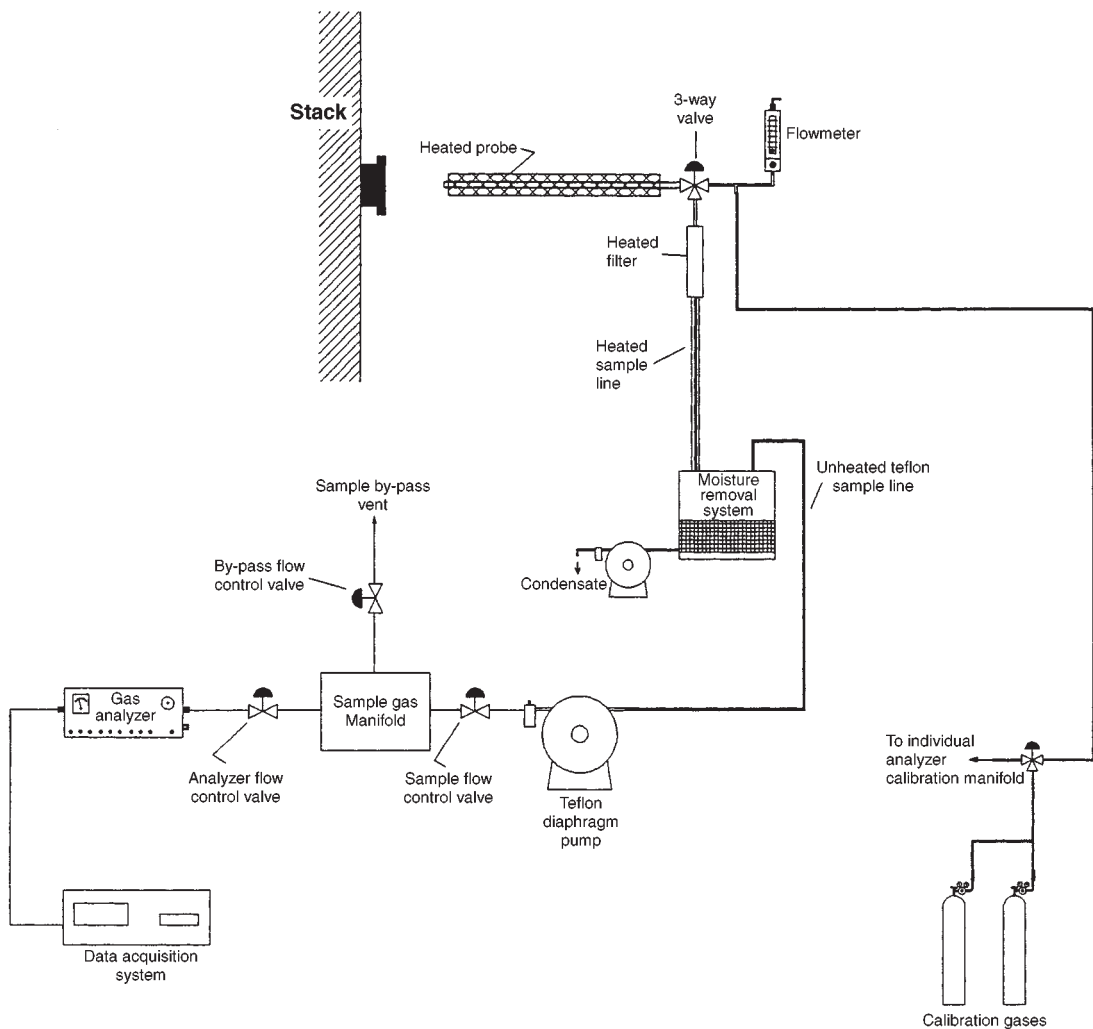


FIG. 25-30 Measurement system schematic for continuous emissions sampling (EPA Method 3A, 6C, or 7E).

determine NO_x emissions from stationary sources (see Fig. 26-28). An integrated continuous gas sample is extracted from the test location, and a portion of the sample is conveyed to an instrumental chemiluminescent analyzer for determination of NO_x gas concentration. The sample gas is conditioned prior to introduction to the gas analyzer by removing particulate matter and moisture. Sampling is conducted at a constant rate for the entire test run.

The NO_x analyzer is based on the principles of chemiluminescence to determine continuously the NO_x concentration in the sample gas stream. The analyzer should contain a NO_2 -to- NO converter, which converts the nitrogen dioxide (NO_2) in the sample gas to nitrogen oxide (NO). An NO_2 -to- NO converter is not necessary if data are presented to demonstrate that the NO_2 portion of the exhaust gas is less than 5 percent of the total NO_2 concentration.

Quality control elements required by the instrumental analyzer method include: analyzer calibration error (± 2 percent of instrument span allowed); verifying the absence of bias introduced by the sampling system (less than ± 5 percent of span for zero and upscale calibration gases); verification of zero and calibration drift over the test period (less than ± 3 percent of span of the period of each run).

Carbon Monoxide (CO) EPA Method 10 is the reference method for determining emissions of carbon monoxide from station-

ary sources. An integrated or a continuous gas sample may be required, depending on operating conditions.

When the operating conditions are uniform and steady (there are no fluctuations in flow rate or in concentration of CO in the gas stream), the continuous sampling method can be used. A sampling probe is placed in the stack at any location, preferably near the center. The sample is extracted at a constant sampling rate. As the gas stream passes through the sampling apparatus, any moisture or carbon dioxide in the sample gas stream is removed. The CO concentration is then measured by a nondispersive infrared analyzer, which gives direct readouts of CO concentrations.

Figure 25-35 is a schematic of an assembled sampling apparatus used to determine CO concentrations by the continuous sampling method.

For an integrated sample, the sampling probe is located at any point near the center of the stack, and the sampling rate is adjusted proportionately to the stack-gas velocity. As the stack gas passes through the sampling apparatus, moisture is removed and the sample gas is collected in a flexible bag. Analysis of the sample is then performed in a laboratory with a nondispersive infrared analyzer. Figure 25-36 is a schematic of an assembled apparatus for the integrated sampling of CO.

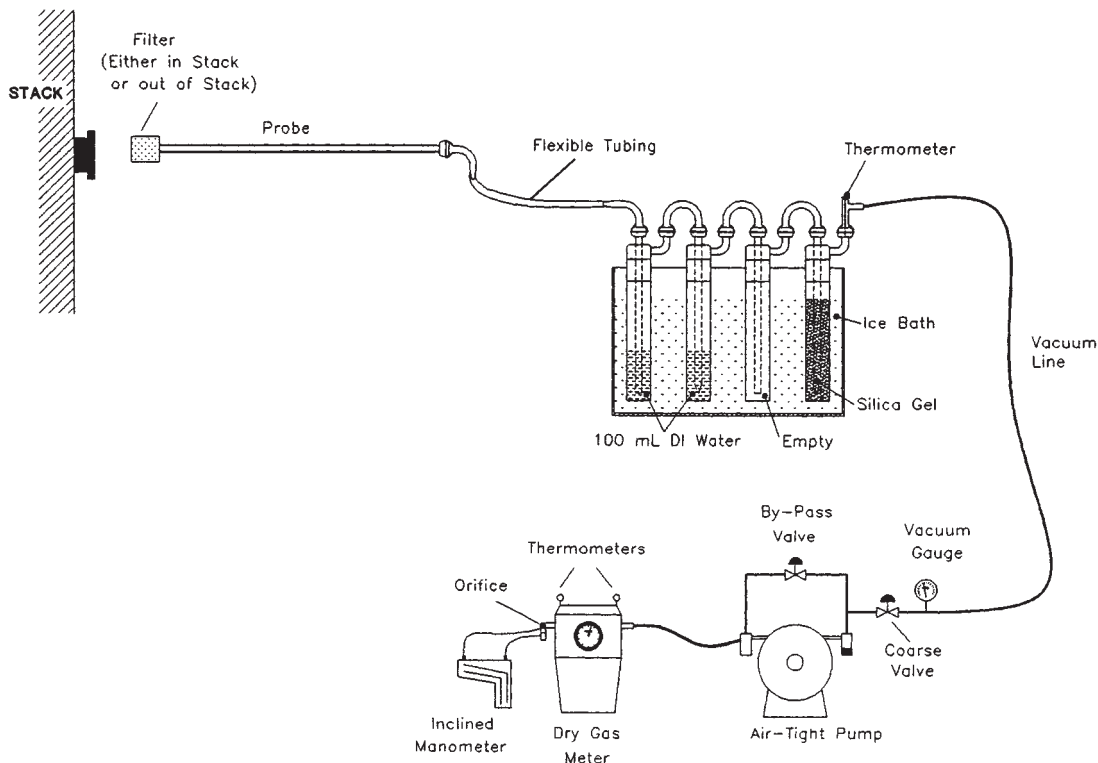


FIG. 25-31 EPA Method 4: moisture sampling train.

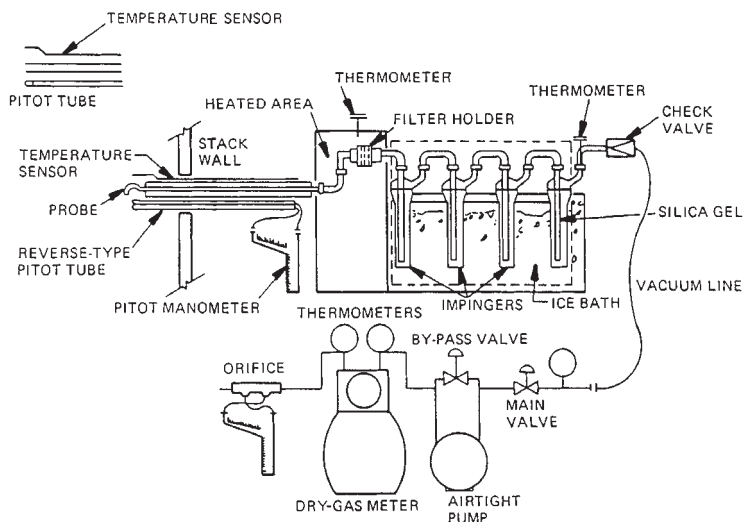


FIG. 25-32 EPA Method 5 particulate-sample apparatus.

A one-hour sampling period is generally required for this method. Sampling periods are specified by the applicable standard; e.g., standards for petroleum refineries require sampling for one hour or more.

For Method 10, the minimum detectable concentration of CO has been determined to be 20 ppm in a range of 1 to 1000 ppm.

Fluorides Two EPA reference methods, Method 13A and Method 13B, can be used to determine total fluoride emissions from a stationary source. The difference in the two methods is the analyti-

cal procedure for determining total fluorides. Fluorides can occur as particulates or as gaseous fluorides; the particulates are captured on a filter, and the gaseous fluorides are captured in a chemical reaction with water.

Samples for either Method 13A or Method 13B are obtained by the procedures outlined in Method 5 for particulates. As the gas stream passes through the sampling apparatus, the gaseous fluorides are removed by a chemical reaction with water, the particulate fluorides

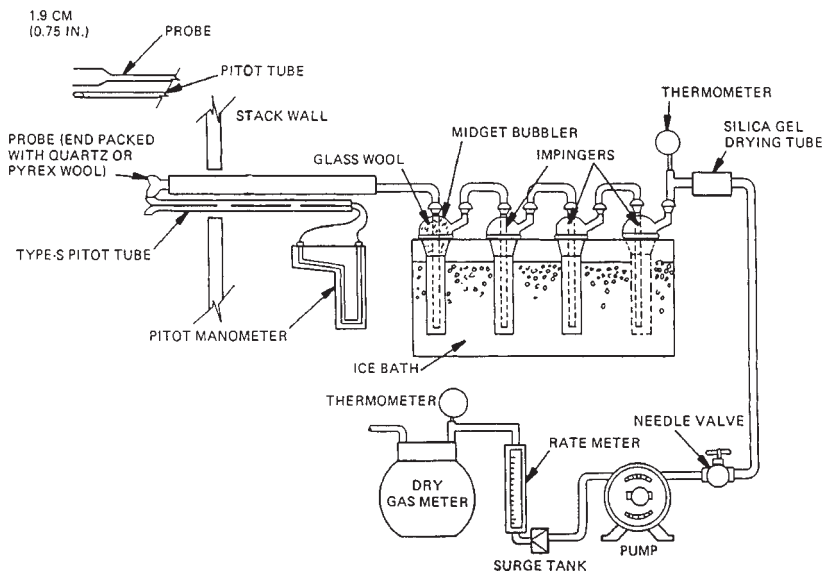


FIG. 25-33 EPA Method 6 sulfur dioxide sample train.

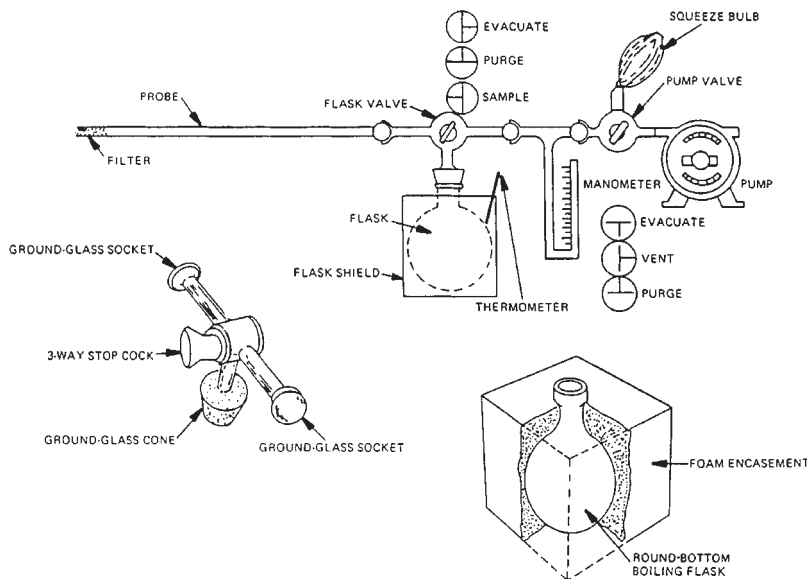


FIG. 25-34 EPA Method 7 nitrogen oxide sample train.

are captured on a filter, and the sample volume is measured. The sample is recovered and sent to the laboratory for analysis. Procedures of Methods 13A and 13B are complex and should be performed by an experienced chemist. Method 13A is a colorimetric method, and Method 13B utilizes a specific ion electrode.

A one-hour sampling period is generally required for both methods. Sampling periods are specified by the applicable standard; e.g., standards applicable to triple-superphosphate plants require sampling of one hour or more. The standard may also specify a minimum sample volume that will dictate the minimum length of the sampling period.

The determination range of Method 13A is 0 to 1.4 μg of fluoride per milliliter; the range of Method 13B is 0.02 to 2000 μg of fluo-

ride per milliliter. Figure 25-37 is a schematic of an assembled fluoride sampling apparatus used in Methods 13A and 13B.

Total Gaseous Organics Concentration The U.S. EPA has published two reference-source testing methods for determination of total gaseous organics: EPA Method 25 for the determination of total gaseous nonmethane organics (TGNMO) and EPA Method 25A as the instrumental analyzer method for determination of total gaseous organics.

Method 25 applies to the measurement of volatile organic compounds (VOC) as nonmethane organics (TGNMO), reported as carbon. Organic particulate matter will interfere with the analysis, and, therefore, in some cases, an in-stack particulate filter will be required. The method requires an emission sample to be withdrawn at a con-

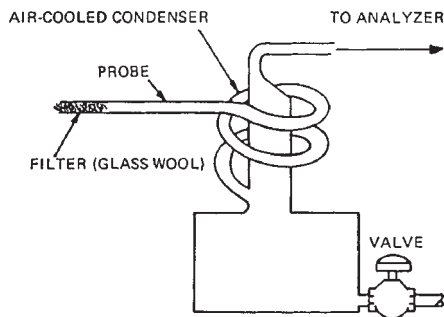


FIG. 25-35 Continuous sample train for CO.

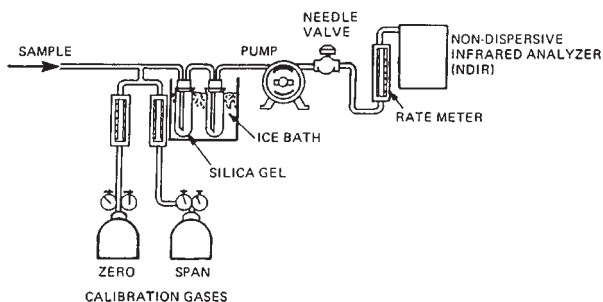


FIG. 25-36 Sampling apparatus for CO.

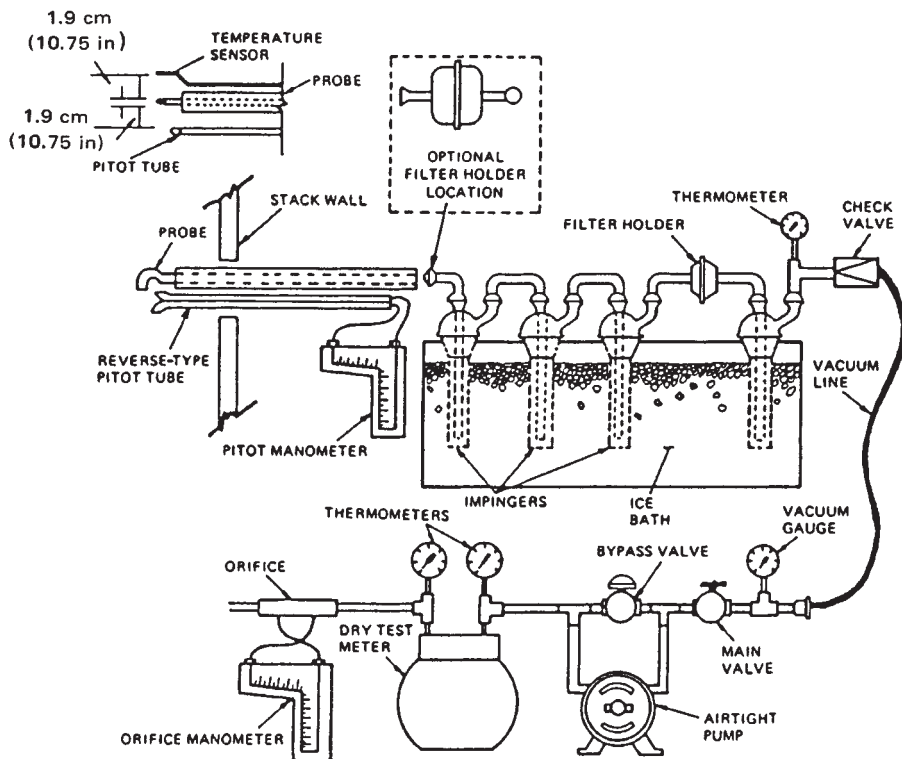


FIG. 25-37 Sampling apparatus for fluoride.

stant rate through a chilled-condensate trap by means of an evacuated-sample tank.

TGNMO are determined by combining the analytical results obtained from independent analyses of the condensate-trap and sample-tank fractions. After sampling has been completed, the organic contents of the condensate trap are oxidized to carbon dioxide, which is quantitatively collected in an evacuate vessel; then a portion of the CO_2 is reduced to methane and measured by a flame ionization detector (FID). The organic content of the sample fraction collected in the sampling tank is measured by a chromatographic column to achieve separation of the nonmethane organics from carbon monoxide (CO), CO_2 , and CH_4 ; the nonmethane organics (NMO) are oxidized to CO_2 , reduced to CH_4 , and measured by an FID. In this manner, the variable response of the FID associated with different types of organics is eliminated.

The sampling system consists of a condensate trap, flow-control system, and sample tank (Fig. 25-38). The analytical system consists of two major subsystems: an oxidation system for the recovery and conditioning of the condensate-trap contents and an NMO analyzer. The NMO analyzer is a gas chromatograph with backflush capability for NMO analysis and is equipped with an oxidation catalyst, a reduction catalyst, and an FID. The system for the recovery and conditioning of the organics captured in the condensate trap consists of a heat source, an oxidation catalyst, a nondispersive infrared (NDIR) analyzer, and an intermediate collection vessel.

EPA Method 25A is the instrumental analyzer method for determination of total gaseous organic concentration using a flame ionization analyzer. The method applies to the measurement of total gaseous organic concentration of vapors consisting primarily of alkanes, alkenes, and/or arenes (aromatic hydrocarbons). The concentration is expressed in terms of propane (or other appropriate organic calibration gas) or in terms of carbon.

A gas sample is extracted from the source through a heated sample line, if necessary, and glass fiber filter to a flame ionization analyzer

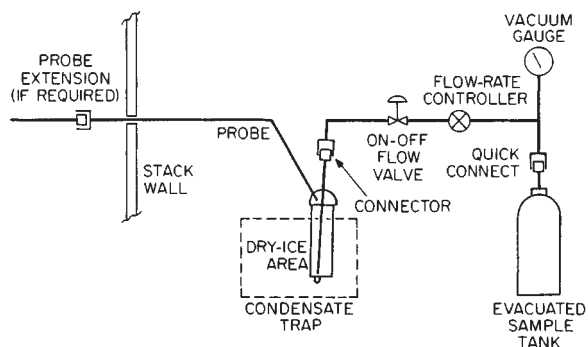


FIG. 25-38 EPA Method 25 sampling system.

(FIA). Figure 25-39 presents a schematic of the sampling system. Results are reported as volume concentration equivalents of the calibration gas or as carbon equivalents.

The upper limit of a gas concentration measurement range is usually 1.5 to 2.5 times the applicable emission limit. If no span value is provided, a span value equivalent to 1.5 to 2.5 times the expected concentration is used. For convenience, the span value should correspond to 100 percent of the recorder scale.

Hydrogen Chloride (HCl) EPA Method 26 is the reference method used to measure hydrogen chloride emissions from stationary sources. The method is applicable for determining emissions of hydrogen halides (HX) such as hydrogen chloride (HCl), hydrogen

bromide (HBr), and hydrogen fluoride (HF), and halogens (X_2) like chlorine (Cl_2) and bromine (Br_2), from stationary sources. Sources, such as those controlled by wet scrubbers, that emit acid particulate matter must be sampled using Method 26A.

An integrated sample is extracted from the source and passed through a prepurged heated probe and filter into dilute sulfuric acid and dilute sodium hydroxide solutions that collect the gaseous hydrogen halides and halogens, respectively. The filter collects other particulate matter, including halide salts. The hydrogen halides are solubilized in the acidic solution and form chloride (Cl^-), bromide (Br^-), and fluoride (F^-) ions. The halogens have a very low solubility in the acidic solution and pass through to the alkaline solution, where they are hydrolyzed to form a proton (H^+), the halide ion, and the hypohalous acid (HOX or $HBrO$). Sodium thiosulfate is added in excess to the alkaline solution to assure reaction with the hypohalous acid to form a second halide ion such that two halide ions are formed for each molecule of halogen gas. The halide ions in the separate solutions are measured by ion chromatography (IC).

Volatile materials, such as chlorine dioxide (ClO_2) and ammonium chloride (NH_4Cl), which produce halide ions upon dissolution during sampling, are potential interferences. Interferents for the halide measurements are the halogen gases, which disproportionate to a hydrogen halide and a hydrohalous acid upon dissolution in water. However, the use of acidic rather than neutral or basic solutions for collection of the hydrogen halides greatly reduces the dissolution of any halogens passing through this solution. The simultaneous presence of HBr and Cl_2 may cause a positive bias in the HCl result with a corresponding negative bias in the Cl_2 result as well as affecting the HBr/ Br_2 split. High concentrations of nitrogen oxides (NO_x) may produce sufficient nitrate (NO_3^-) to interfere with measurements of very low Br^- levels.

The collected Cl^- samples can be stored for up to 4 weeks. The ana-

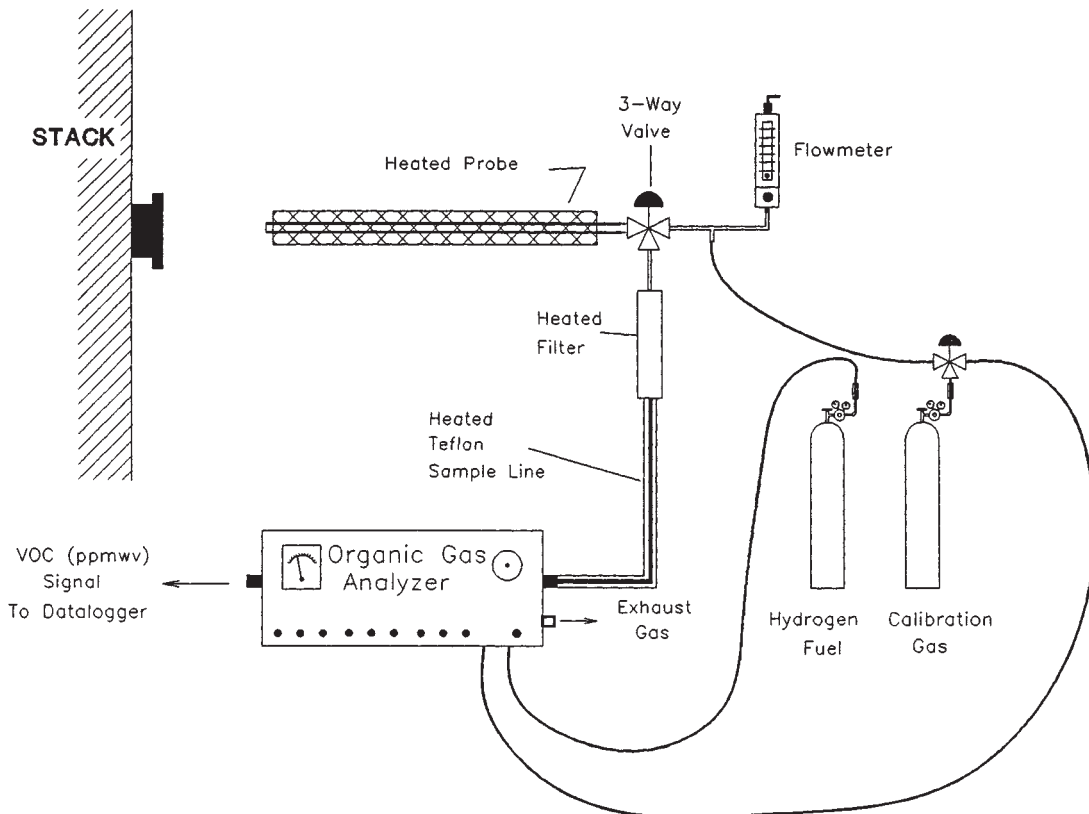


FIG. 25-39 Measurement system schematic for continuous emissions sampling for total gaseous organics.

lytical detection limit for Cl^- is 0.1 $\mu\text{g}/\text{ml}$. Detection limits for the other analyses should be similar.

The previous discussion of test methods has reviewed selected reference methods contained in Title 40 the Code of Federal Regulations, Part 60 (40 CFR 60), Appendix A. The following subsections review test methods contained in other regulations and publications. These additional test methods are employed at a greater frequency as emissions of hazardous air pollutants have become increasingly regulated. The regulatory citation for each method is provided in the narrative for each test procedure reviewed. In addition, Table 26-22 provides a reference listing of selected test methods.

Multiple Metals Testing The sampling method commonly used to measure emissions of metals from stationary sources is contained in 40 CFR 266, Appendix IX. The procedure is titled "Methodology for the Determination of Metals Emissions in Exhaust Gases from Hazardous Waste Incineration and Similar Combustion Processes." It is also currently published as Draft EPA Method 29 for inclusion in 40 CFR 60.

This method is used for the determination of total chromium (Cr), cadmium (Cd), arsenic (As), nickel (Ni), manganese (Mn), beryllium (Be), copper (Cu), zinc (Zn), lead (Pb), selenium (Se), phosphorus (P), thallium (Tl), silver (Ag), antimony (Sb), barium (Ba), and mercury (Hg) stack emissions from stationary sources. This method may also be used for the determination of particulate emissions following the procedures and precautions described. However, modifications to the sample recovery and analysis procedures described in the method for the purpose of determining particulate emissions may potentially impact the front-half mercury determination.

The stack sample is withdrawn isokinetically from the source, with

particulate emissions collected in the probe and on a heated filter and gaseous emissions collected in a series of chilled impingers containing an aqueous solution of dilute nitric acid combined with dilute hydrogen peroxide in each of two impingers, and acidic potassium permanganate solution in each of two impingers (see Fig. 25-40). Sampling train components are recovered and digested in separate front- and back-half fractions. Materials collected in the sampling train are digested with acid solutions to dissolve organics and to remove organic constituents that may create analytical interferences. Acid digestion is performed using conventional Parr® Bomb or microwave digestion techniques. The nitric acid and hydrogen peroxide impinger solution, the acidic potassium permanganate impinger solution, the HCl rinse solution, and the probe rinse and digested filter solutions are analyzed for mercury by cold-vapor atomic absorption spectroscopy (CVAAS). The nitric acid and hydrogen peroxide solution and the probe rinse and digested filter solutions of the train catches are analyzed for Cr, Cd, Ni, Mn, Be, Cu, Zn, Pb, Se, P, Tl, Ag, Sb, Ba, and As by inductively coupled argon plasma emission spectroscopy (ICAP) or atomic absorption spectroscopy (AAS). Graphite furnace atomic absorption spectroscopy (GFAAS) is used for analysis of antimony, arsenic, cadmium, lead, selenium, and thallium, if these elements require greater analytical sensitivity than can be obtained by ICAP.

Volatile Organics Sampling EPA Method 0030 as contained in *Test Methods for Evaluating Solid Waste*, 3d ed., Report No. SW-846, is used to measure emissions of volatile organic compounds with boiling points less than 100° C. Method 0030 is designed to determine destruction and removal efficiency (DRE) of volatile principal organic hazardous constituents (POHCs) from stack gas effluents of hazardous waste incinerators. The lower boiling point POHCs (less than

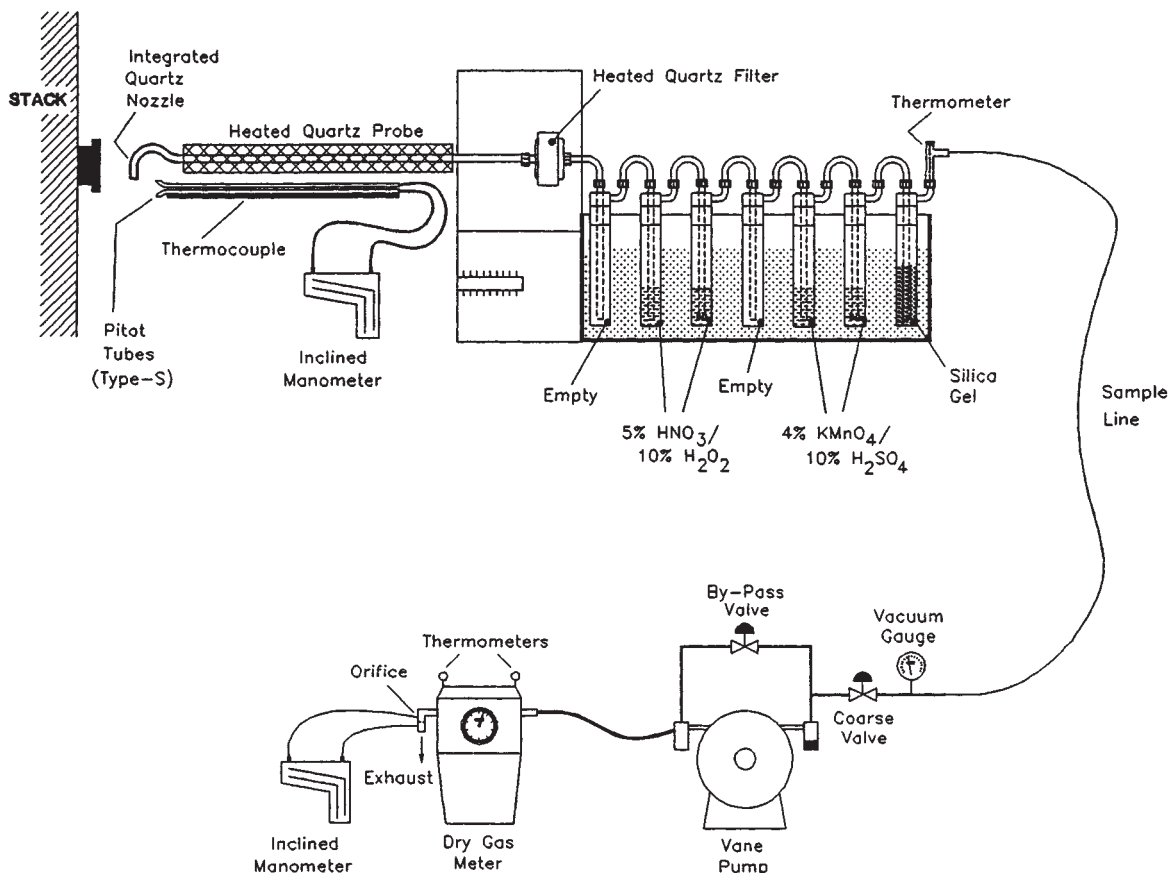


FIG. 25-40 Multiple-metals sampling train.

30° C) may break through the sorbent under the conditions of the sample collection procedure.

The procedure involves withdrawing a 20-L sample of effluent gas from the source at a flow rate of 1 L/min, using a glass-lined probe and a volatile organic sampling train (VOST). Figure 25-41 provides a schematic of the VOST set-up. The gas sample is cooled to 20° C by passage through a water-cooled condenser and volatile POHCs are collected on a pair of sorbent resin traps. Liquid condensate is collected in an impinger placed between the two resin traps. The first resin trap (front trap) contains approximately 1.6 g Tenax® resin and the second trap (back trap) contains approximately 1 g each of Tenax® and petroleum-based charcoal, 3:1 by volume. The first trap retains most of the higher boiling analytes. Lower boiling analytes and the portion of the higher boiling analytes that break through the first cartridge are retained on the second trap. Analytes that collect in the condensate trap are purged into the second trap and condenser units. The VOST sorbent cartridges are thermally desorbed and analyzed by gas chromatography with mass spectroscopy (GC/MS).

Semivolatile Organics Sampling EPA Method 0010 as contained in *Test Methods for Evaluating Solid Waste*, 3d ed., Report No.

SW-846, is used to measure emissions of semivolatile principal organic constituents. Method 0010 is designed to determine destruction and removal efficiency (DRE) of POHCs from incineration systems. The method involves a modification of the EPA Method 5 sampling train and may be used to determine particulate emission rates from stationary sources. The method is applied to semivolatile compounds, including polychlorinated biphenyls (PCBs), chlorinated dibenzodioxins and dibenzofurans, polycyclic organic matter, and other semivolatile organic compounds.

Gaseous and particulate pollutants are withdrawn isokinetically from an emission source and collected in a multicomponent sampling train. Principal components of the train include a high-efficiency glass- or quartz-fiber filter and a packed bed of porous polymeric adsorbent resin (typically XAD-2® or polyurethane foam for PCBs). The filter is used to collect organic-laden particulate materials and the porous polymeric resin to adsorb semivolatile organic species (compounds with a boiling point above 100° C). Figure 25-42 presents an illustration of the Method 0010 sampling train. Comprehensive chemical analyses, using a variety of applicable analytical methodologies, are conducted to determine the identity and concentration of the organic materials.

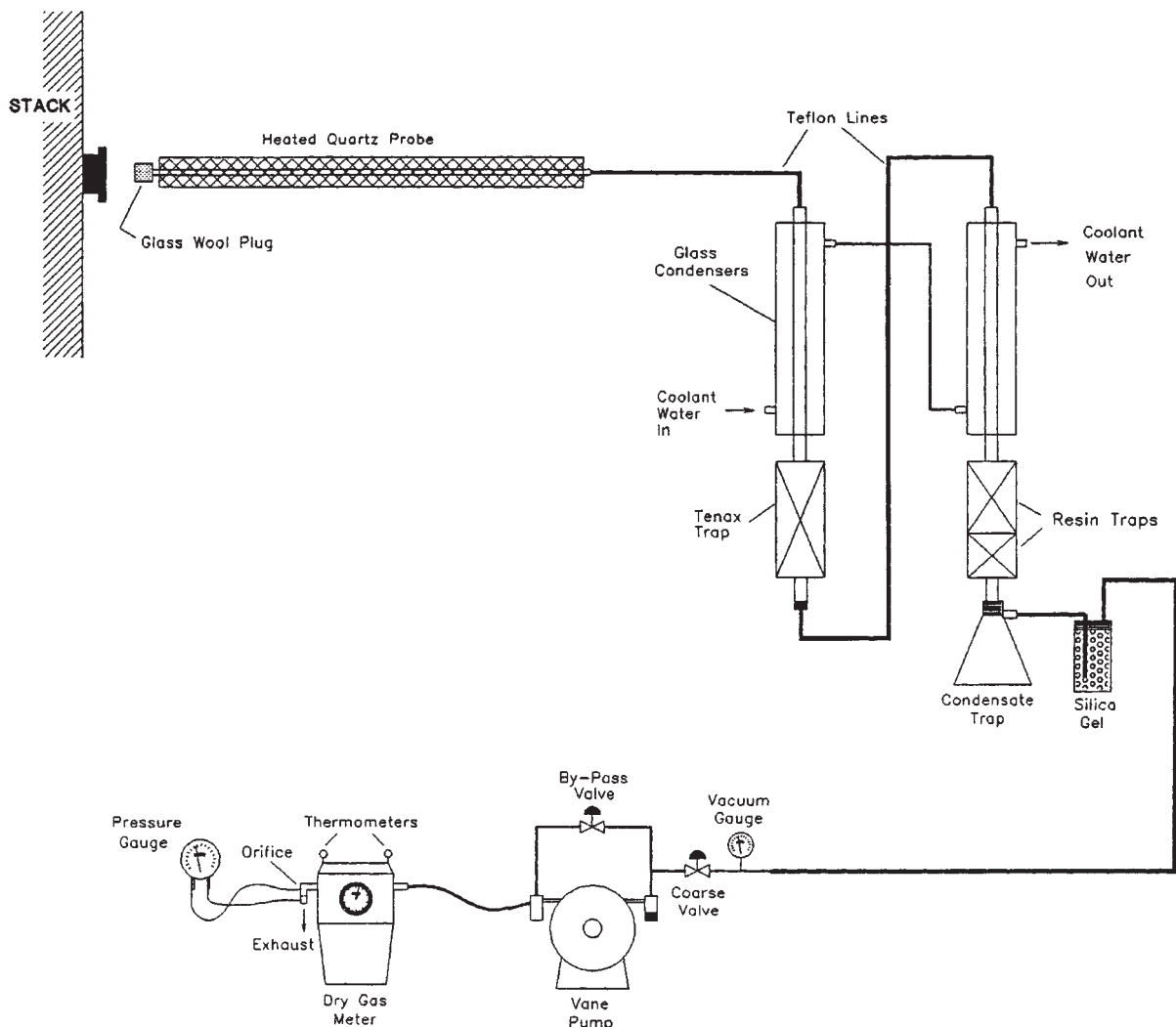


FIG. 25-41 Volatile organic sampling train (Method 0030).

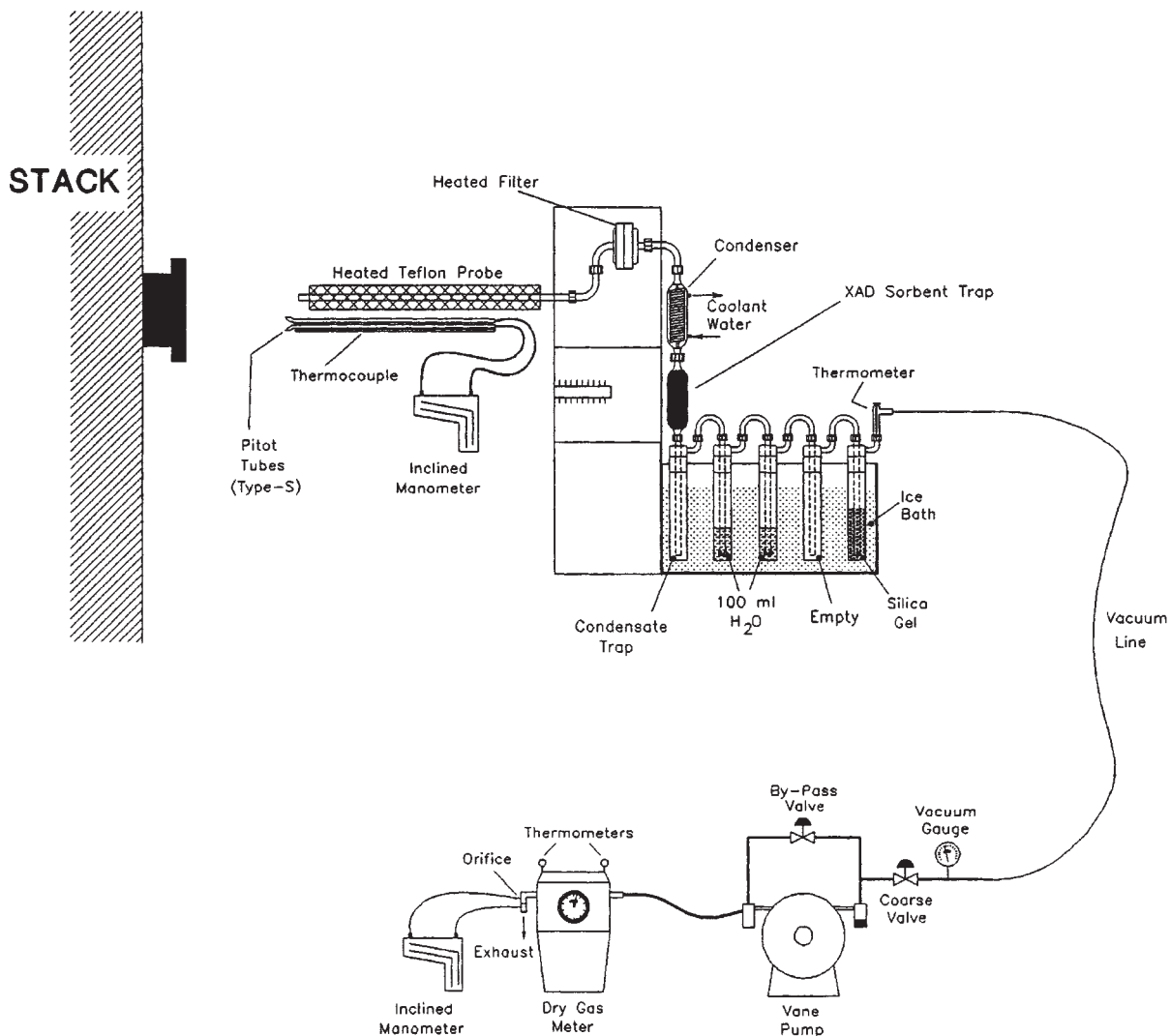


FIG. 25-42 Method 0010: sampling train for semivolatile organics.

INDUSTRIAL WASTEWATER MANAGEMENT

FURTHER READING: Eckenfelder, W. W., *Industrial Water Pollution Control*, 2d ed., McGraw-Hill, 1989. Metcalf & Eddy, Inc., *Wastewater Engineering, Treatment, Disposal and Reuse*, 3d ed., McGraw-Hill, 1990. Nemerow, N. L. and A. Dasgupta, *Industrial and Hazardous Waste Treatment*, Van Nostrand Reinhold, New York, 1991.

INTRODUCTION

All industrial operations produce some wastewaters which must be returned to the environment. Wastewaters can be classified as (1) domestic wastewaters, (2) process wastewaters, and (3) cooling wastewaters. Domestic wastewaters are produced by plant workers, shower facilities, and cafeterias. Process wastewaters result from spills, leaks, and product washing. Cooling wastewaters are the result of various cooling processes and can be once-pass systems or multiple-recycle cooling systems. Once-pass cooling systems employ large volumes

of cooling waters that are used once and returned to the environment. Multiple-recycle cooling systems have various types of cooling towers to return excess heat to the environment and require periodic blow-down to prevent excess buildup of salts.

Domestic wastewaters are generally handled by the normal sanitary-sewerage system to prevent the spread of pathogenic microorganisms which might cause disease. Normally, process wastewaters do not pose the potential for pathogenic microorganisms, but they do pose potential damage to the environment through either direct or indirect chemical reactions. Some process wastes are readily biodegraded and create an immediate oxygen demand. Other process wastes are toxic and represent a direct health hazard to biological life in the environment. Cooling wastewaters are the least dangerous, but they can contain process wastewaters as a result of leaks in the cooling systems. Recycle cooling systems tend to concentrate both inorganic and organic contaminants to a point at which damage can be created.

Recently, concern for subtle aspects of environmental damage has started to take precedence over damage referred to above. It has been realized that the presence of substances in water at concentrations far below those that will produce overt toxicity or excessive reduction of dissolved oxygen levels can have a major impact by altering the predomination of organisms in the aquatic ecosystem. This is beginning to have an effect on water-quality standards and, consequently, allowable discharges. Unfortunately, the extent of knowledge is not sufficient upon which to base definitive standards for these subtle effects. Over the next decade, it is anticipated that accumulation of knowledge will make it possible to delineate defensible standards. Another recent concern is that of contaminated storm water from industrial sites. Federal guidelines to control this wastewater are presently being developed. Most concern is for product spills on plant property but outside the production facility and from rain contact with spoil piles.

UNITED STATES LEGISLATION, REGULATIONS, AND GOVERNMENTAL AGENCIES

Federal Legislation Public Law 92-500 promulgated in 1972 created the primary framework for management of water pollution in the United States. This act has been amended many times since 1972. Major amendments occurred in 1977 (Public Laws 95-217 and 95-576), 1981 (Public Laws 97-117 and 97-164), and 1987 (Public Law 100-4). This law and its various amendments are referred to as the Clean Water Act. The Clean Water Act addresses a large number of issues of water pollution management. A general review of these issues has been presented in an earlier chapter in this handbook. Primary with respect to control of industrial wastewater is the National Pollutant Discharge Elimination System (NPDES), originally established by PL 92-500. Any municipality or industry that discharges wastewater to the navigable waters of the United States must obtain a discharge permit under the regulations set forth by the NPDES. Under this system, there are three classes of pollutants (conventional pollutants, priority pollutants, and nonconventional/nonpriority pollutants). Conventional pollutants are substances such as biochemical oxygen demand (BOD), suspended solids (SS), pH, oil and grease, and coliforms. Priority pollutants are a list of 129 substances originally set forth in a consent decree between the Environmental Protection Agency and several environmental organizations. This list was incorporated into the 1977 amendments. Most of the substances on this list are organics, but it does include most of the heavy metals. These substances are generally considered to be toxic. However, the toxicity is not absolute; it depends on the concentration. In addition, many of the organics on the list are under appropriate conditions biodegradable. In reality, substances for inclusion on the priority pollutant list were chosen on the basis of a risk assessment rather than only a hazard assessment. The third class of pollutants could include any pollutant not in the first two categories. Examples of substances that are presently regulated in the third category are nitrogen, phosphorous, sodium, and chlorine residual. The overall goals of the Clean Water Act are to restore and maintain water quality in the navigable waters of the United States. The initial standard was to ensure that these waters would be clean enough for recreation (swimmable) and ecologically secure (fishable). Initially this was to be achieved by curtailment of the discharge of pollutants. Eventually the regulatory system was essentially to phase out discharge of any pollutant into water. Obviously, if no discharge of pollutants occurs, the waters will be maintained in close to a pristine condition. However, the early reduction of pollutant discharge to zero was realized as impractical. Thus, at present, the NPDES has prescribed the limits on discharges as a function of the type of pollutant, the type of industry discharging, and the desired water quality. The specific requirements for each individual discharger are established in the NPDES permit issued to the discharger. These permits are reviewed every five years and are subject to change at the time of review.

A major tactic that was adopted in the Clean Water Act was to establish uniform technology standards, by class of pollutant and specific industry type, which applied nationwide to all dischargers. Thus, a kraft mill in Oregon would have to meet essentially the same discharge standards as a kraft mill in New York. In establishing these

standards, the EPA took into account the state of the art of waste treatment in each particular industry as well as cost and ecological effectiveness. These discharge standards have been published in the *Federal Register* for more than thirty industrial categories and several hundred subcategories (the Commerce Department Industrial Classification System was used to establish these categories) in the *Federal Register*. These have been promulgated over an extensive period of time. The reader is advised to consult the index to this document to ascertain regulations that apply to a particular industry. Table 25-32 presents the major industrial categories.

As indicated above, not only are the discharge standards organized on an industry-by-industry basis, but they are different depending upon which of the three classes of pollutants is being regulated. The standards for conventional pollutants are referred to as best conventional technology (BCT). The standards for priority pollutants are referred to as best available technology (BAT), as are those for nonconventional, nonpriority pollutants. These standards envision that the technology will not be limited to treatment but may include revision in the industrial processing and/or reuse of effluents (pollution prevention). They are usually presented as mass of pollutant discharged per unit of product produced.

In some situations it is anticipated that application of BCT and BAT may not be sufficient to ensure that water-quality standards are achieved in a stream segment. Studies have indicated that approximately 10 percent of the stream segments in the United States will have their water-quality standards violated, even if all the dischargers to that stream segment meet BCT and BAT regulations. These segments are referred to as water quality limited segments. The NPDES permit for those who discharge into water quality limited segments must provide for pollutant removal in excess of that required by BCT and BAT so that water-quality standards (which are jointly established by each state and EPA) are achieved. The stream segments in which water-quality standards will be met by application of BCT and BAT are referred to as "effluent quality limited segments."

For industrial discharges that enter municipal sewers and thus eventually municipal treatment plants, NPDES regulations are nominally the same as for industries that discharge directly to navigable

TABLE 25-32 Industry Categories

1. Adhesives and sealants
2. Aluminum forming
3. Asbestos manufacturing
4. Auto and other laundries
5. Battery manufacturing
6. Coal mining
7. Coil coating
8. Copper forming
9. Electric and electronic components
10. Electroplating
11. Explosives manufacturing
12. Ferroalloys
13. Foundries
14. Gum and wood chemicals
15. Inorganic chemicals manufacturing
16. Iron and steel manufacturing
17. Leather tanning and finishing
18. Mechanical products manufacturing
19. Nonferrous metals manufacturing
20. Ore mining
21. Organic chemicals manufacturing
22. Pesticides
23. Petroleum refining
24. Pharmaceutical preparations
25. Photographic equipment and supplies
26. Plastic and synthetic materials manufacturing
27. Plastic processing
28. Porcelain enamelling
29. Printing and publishing
30. Pulp and paperboard mills
31. Soap and detergent manufacturing
32. Steam electric power plants
33. Textile mills
34. Timber products processing

waters; i.e., they must meet BCT and BAT standards. These are referred to as “categorical industrial pretreatment standards.” However if it can be demonstrated that the municipal treatment plant can remove a pollutant in the industrial waste, a “removal credit” can be assigned to the permit, thus lowering the requirement on the industrial discharger. The monetary charge to the industry by the municipality for this service is negotiable but must be within parameters established by EPA for industrial user charges if the municipality received a federal grant for construction of the treatment plant. A removal credit cannot be assigned if removal of the industrial pollutant results in difficulty in ultimate disposal of sludge from the municipal plant. In addition, an industry cannot discharge any substance that can result in physical damage to the municipal sewer and/or interfere with any aspect of treatment plant performance even, if the substance is not covered by BCT or BAT regulations.

Environmental Protection Agency President Nixon created the EPA in 1970 to coordinate all environmental pollution-control activities at the federal level. The EPA was placed directly under the Office of the President so that it could be more responsive to the political process. In the succeeding decade, the EPA produced a series of federal regulations increasing federal control over all wastewater-pollution-control activities. In January 1981, President Reagan reversed the trend of greater federal regulation and began to decrease the role of the federal EPA. However, during the 1980s, an equilibrium was achieved between those who wish less regulation and those who wish more. In general, industry and the EPA reached agreement on the optimum level of regulation.

State Water-Pollution-Control Offices Every state has its own water-pollution-control office. Some states have reorganized along the lines of the federal EPA with state EPA offices, while others have kept their water-pollution-control offices within state health departments. Prior to 1965, each state controlled its own water-pollution-control programs. Conflicts between state and uneven enforcement of state regulations resulted in the federal government’s assuming the leadership role. Unfortunately, conflicts between states shifted to being conflicts between the states and the federal EPA. By 1980, the state water-pollution-control offices were primarily concerned with handling most of the detailed permit and paperwork for the EPA and in furnishing technical assistance to industries at the local level. In general, most of the details of regulation are carried out by state water-pollution-control agencies with oversight by EPA.

WASTEWATER CHARACTERISTICS

Wastewater characteristics vary widely from industry to industry. Obviously, the specific characteristics will affect the treatment techniques chosen for use in meeting discharge requirements. Some general characteristics that should be considered in planning are given in Table 25-33. Because of the large number of pollutant substances, wastewater characteristics are not usually considered on a substance-

by-substance basis. Rather, substances of similar pollution effects are grouped together into classes of pollutants or characteristics as indicated below.

Priority Pollutants Recently, greatest concern has been for this class of substances for the reasons given previously. These materials are treated on an individual-substance basis for regulatory control. Thus, each industry could receive a discharge permit that lists an acceptable level for each priority pollutant. Table 25-34 presents a list of these substances; most are organic, but some inorganics are included. All are considered toxic, but, as indicated previously, there is wide variation in their toxicity. Most of the organics are biologically degradable despite their toxicity (Refs. 30 and 31). USEPA has collected data on the occurrence of these substances in various industrial wastes and their treatability. A recent trend has been to avoid their use in industrial processing.

Organics The organic composition of industrial wastes varies widely, primarily due to the different raw materials used by each specific industry. These organics include proteins, carbohydrates, fats and oils, petrochemicals, solvents, pharmaceutical, small and large molecules, solids and liquids. Another complication is that a typical industry produces many diverse wastestreams. Good practice is to conduct a material balance throughout an entire production facility. This survey should include a flow diagram, location and sizes of piping, tanks and flow volumes, as well as an analysis of each stream. Results of an industrial waste survey for an industry are given in Table 25-35. Noteworthy is the range in waste sources, including organic soap, toilet articles, ABS (alkyl benzene sulfonate), and the relatively clean but hot condenser waste that makes up half the plant flow, while the strongest wastes—spent caustic and fly ash—have the lowest flows. See Tables 25-35 and 25-36 for information on the average characteristics of wastes from specific industries.

An important measure of the waste organic strength is the 5-day biochemical oxygen demand (BOD₅). As this test measures the demand for oxygen in the water environment caused by organics released by industry and municipalities, it has been the primary parameter in determining the strength and effects of a pollutant. This test determines the oxygen demand of a waste exposed to biological organisms (controlled seed) for an incubation period of five days. Usually this demand is caused by degradation of organics according to the following simplified equation, but reduced inorganics in some industries may also cause demand (i.e., Fe²⁺, S²⁻, and SO₃²⁻).



This wet lab test measures the decrease in dissolved oxygen (D.O.) concentration in 5 days, which is then related to the sample strength. If the test is extended over 20 days, the BOD₂₀ (ultimate BOD) is obtained and corresponds more closely to the Chemical Oxygen Demand (COD) test. The COD test uses strong chemical oxidizing agents with catalysts and heat to oxidize the wastewater and obtain a value that is almost always larger than the 5- and 20-day BOD values. Some organic compounds (like pyridene, a ring structure containing nitrogen) resists chemical oxidation giving a low COD. A major advantage of the COD test is the completion time of less than 3 hours, versus 5 days for the BOD₅ test. Unfortunately, state and federal regulations generally require BOD₅ values, but approximate correlations can be made to allow computation of BOD from COD. A more rapid measure of the organic content of a waste is the instrumental test for total organic carbon (TOC), which takes a few minutes and may be correlated to both COD and BOD for specific wastes. Unfortunately, BOD₅ results are subject to wide statistical variations and require close scrutiny and experience. For municipal wastewaters, BOD₅ is about 67 percent of the ultimate BOD and 40–45 percent of the COD, indicating a large amount of nonbiodegradable COD and the continuing need to run BOD as well as COD and TOC. An example of BOD, COD, and TOC relationships for chemical industry wastewater is given in Table 25-36. The concentrations of the wastewaters vary by two orders of magnitude, and the BOD/COD, COD/TOC, and BOD/TOC ratios vary less than twofold. The table indicates that correlation/codification is possible, but care and continual scrutiny must be exercised.

TABLE 25-33 Wastewater Characteristics

Property	Characteristic	Example	Size or concentration
Solubility	Soluble	Sugar	>100 gm/L
	Insoluble	PCB	<1 mg/L
Stability, biological	Degradable	Sugar	
	Refractory	DDT, metals	
Solids	Dissolved	NaCl	<10 ⁻⁹ m
	Colloidal	Carbon	>10 ⁻⁶ –<10 ⁻⁹ m
	Suspended	Bacterium	>10 ⁻⁶ m
	Carbon	Alcohol	
Organic	Inorganic	Cu ²⁺	
	Acidic	HNO ₃	
	Neutral	Salt (NaCl)	1–12
	Basic	NaOH	
Temperature	Cooling		>5°
	Heat exchange		>30°
Toxicity	Biological effect	Heavy metals	Varies
		Priority compounds	
Nutrients	N	NH ₃	Varies
	P	PO ₄ ³⁻	

TABLE 25-34 List of Priority Chemicals*

Compound name	Compound name	Compound name
1. Acenaphthene†	37. 1,2-Diphenylhydrazine†	83. Indeno (1,2,3-cd) pyrene (2,3- <i>o</i> -phenylene-pyrene)
2. Acrolein†	38. Ethylbenzene†	84. Pyrene
3. Acrylonitrile†	39. Fluoranthene†	85. Tetrachloroethylene†
4. Benzene†		86. Toluene†
5. Benzidine†		87. Trichloroethylene†
6. Carbon tetrachloride† (tetrachloromethane)	Haloethers† (other than those listed elsewhere)	88. Vinyl chloride† (chloroethylene)
Chlorinated benzenes (other than dichlorobenzenes)	40. 4-Chlorophenyl phenyl ether	
7. Chlorobenzene	41. 4-Bromophenyl phenyl ether	Pesticides and metabolites
8. 1,2,4-Trichlorobenzene	42. Bis(2-chloroisopropyl) ether	89. Aldrin†
9. Hexachlorobenzene	43. Bis(2-chloroethoxy) methane	90. Dieldrin†
Chlorinated ethanes† (including 1,2-dichloroethane, 1,1,1-trichloroethane, and hexachloroethane)		91. Chlorodane† (technical mixture and metabolites)
10. 1,2-Dichloroethane	Halomethanes† (other than those listed elsewhere)	
11. 1,1,1-Trichloroethane	44. Methylene chloride (dichloromethane)	DDT and metabolites†
12. Hexachloroethane	45. Methyl chloride (chloromethane)	92. 4,4'-DDT
13. 1,1-Dichloroethane	46. Methyl bromide (bromomethane)	93. 4,4'-DDE (<i>p,p'</i> -DDX)
14. 1,1,2-Trichloroethane	47. Bromoform (tribromomethane)	94. 4,4'-DDD (<i>p,p'</i> -TDE)
15. 1,1,2,2-Tetrachloroethane	48. Dichlorobromomethane	
16. Chloroethane (ethyl chloride)	49. Trichlorofluoromethane	Endosulfan and metabolites†
Chloroalkyl ethers† (chloromethyl, chloroethyl, and mixed ethers)	50. Dichlorodifluoromethane	95. α -Endosulfan- α
17. Bis(chloromethyl) ether	51. Chlorodibromomethane	96. β -Endosulfan- β
18. Bis(2-chloroethyl) ether	52. Hexachlorobutadiene†	97. Endosulfan sulfate
19. 2-Chloroethyl vinyl ether (mixed)	53. Hexachlorocyclopentadiene†	
Chlorinated naphthalene†	54. Isophorone†	Endrin and metabolites†
20. 2-Chloronaphthalene	55. Naphthalene†	98. Endrin
Chlorinated phenols† (other than those listed elsewhere; includes trichlorophenols and chlorinated cresols)	56. Nitrobenzene†	99. Endrin aldehyde
21. 2,4,6-Trichlorophenol	Nitrophenols† (including 2,4-dinitrophenol and dinitroresol)	
22. <i>para</i> -Chloro- <i>meta</i> -cresol	57. 2-Nitrophenol	Heptachlor and metabolites†
23. Chloroform (trichloromethane)†	58. 4-Nitrophenol	100. Heptachlor
24. 2-Chlorophenol†	59. 2,4-Dinitrophenol†	101. Heptachlor epoxide
	60. 4,6-Dinitro- <i>o</i> -cresol	
Dichlorobenzenes†	Nitrosamines†	Hexachlorocyclohexane (all isomers)†
25. 1,2-Dichlorobenzene	61. <i>N</i> -Nitrosodimethylamine	102. α -BHC- α
26. 1,3-Dichlorobenzene	62. <i>N</i> -Nitrosodiphenylamine	103. β -BHC- β
27. 1,4-Dichlorobenzene	63. <i>N</i> -Nitrosodi- <i>n</i> -propylamine	104. γ -BHC (lindane)- γ
Dichlorobenzidine†	64. Pentachlorophenol†	105. δ -BHC- δ
28. 3,3'-Dichlorobenzidine	65. Phenol†	
Dichloroethylenes† (1,1-dichloroethylene and 1,2-dichloroethylene)	Phthalate esters†	Polychlorinated biphenyls (PCB)†
29. 1,1-Dichloroethylene	66. Bis(2-ethylhexyl) phthalate	106. PCB-1242 (Arochlor 1242)
30. 1,2- <i>trans</i> -Dichloroethylene	67. Butyl benzyl phthalate	107. PCB-1254 (Arochlor 1254)
31. 2,4-Dichlorophenol†	68. Di- <i>n</i> -butyl phthalate	108. PCB-1221 (Arochlor 1221)
Dichloropropane and dichloropropene†	69. Di- <i>n</i> -octyl phthalate	109. PCB-1232 (Arochlor 1232)
32. 1,2-Dichloropropane	70. Diethyl phthalate	110. PCB-1248 (Arochlor 1248)
33. 1,2-Dichloropropylene (1,2-dichloropropene)	71. Dimethyl phthalate	111. PCB-1260 (Arochlor 1260)
34. 2,4-Dimethylphenol†		112. PCB-1016 (Arochlor 1016)
Dinitrotoluene†	Polynuclear aromatic hydrocarbons (PAH)†	113. Toxaphene†
35. 2,4-Dinitrotoluene	72. Benzo(a)anthracene (1,2-benzanthracene)	114. antimony (total)
36. 2,6-Dinitrotoluene	73. Benzo(a)pyrene (3,4-benzopyrene)	115. arsenic (total)
	74. 3,4-Benzofluoranthene	116. asbestos (fibrous)
	75. Benzo(k)fluoranthene (11,12-benzofluoranthene)	117. beryllium (total)
	76. Chrysene	118. cadmium (total)
	77. Acenaphthylene	119. chromium (total)
	78. Anthracene	120. copper (total)
	79. Benzo(ghi)perylene (1,12-benzoperylene)	121. cyanide (total)
	80. Fluorene	122. lead (total)
	81. Phenanthrene	123. mercury (total)
	82. Dibenzo(a,h)anthracene (1,2,5,6-dibenzanthracene)	124. nickel (total)
		125. selenium (total)
		126. silver (total)
		127. thallium (total)
		128. zinc (total)
		129. 2,3,7,8-Tetrachlorodibenzo- <i>p</i> -dioxin (TCDD)

*Adapted from Eckenfelder, W. W. Jr., *Industrial Water Pollution Control*, 2d ed., McGraw-Hill, New York, 1989.

†Specific compounds and chemical classes as listed in the consent degree.

Another technique for organics measurement that overcomes the long period required for the BOD test is the use of continuous respirometry. Here the waste (full-strength rather than diluted as in the standard BOD test) is contacted with biomass in an apparatus that continuously measures the dissolved oxygen consumption. This test determines the ultimate BOD in a few hours if a high level of biomass is used. The test can also yield information on toxicity, the need to

develop an acclimated biomass, and required rates of oxygen supply.

In general, low-molecular-weight water-soluble organics are biodegraded readily. As organic complexity increases, solubility and biodegradability decrease. Soluble organics are metabolized more easily than insoluble organics. Complex carbohydrates, proteins, and fats and oils must be hydrolyzed to simple sugars, aminos, and other organic acids prior to metabolism. Petrochemicals, pulp and paper,

TABLE 25-35 Industrial Waste Components of a Soap, Detergents, and Toilet Articles Plant

Waste source	Sampling station	COD, mg/l	BOD, mg/l	SS, mg/l	ABS, mg/l	Flow, gal/min
Liquid soap	D	1,100	565	195	28	300
Toilet articles	E	2,680	1,540	810	69	50
Soap production	R	29	16	39	2	30
ABS production	S	1,440	380	309	600	110
Powerhouse	P	66	10	50	0	550
Condenser	C	59	21	24	0	1100
Spent caustic	B	30,000	10,000	563	5	2
Tank bottoms	A	120,000	150,000	426	20	1.5
Fly ash	F			6750		10
Main sewer		450	260	120	37	2150

NOTE: gal/min = 3.78×10^{-3} m³/min.
SOURCE: Eckenfelder, W. W., *Industrial Water Pollution Control*, 2d ed., McGraw-Hill, New York, 1989.

TABLE 25-36 BOD, COD, and TOC Relationships

Type of waste	BOD ₅ , mg/L	COD, mg/L	TOC, mg/L	BOD ₅ /COD	COD/TOC	BOD ₅ /TOC
Chemical	700	1,400	450	0.50	3.12	1.55
Chemical	850	1,900	580	0.45	3.28	1.47
Chemical	8,000	17,500	5,800	0.46	3.02	1.38
Chemical	9,700	15,000	5,500	0.65	2.72	1.76
Chemical	24,000	41,300	9,500	0.58	4.35	2.53
Chemical	60,700	78,000	26,000	0.78	3.00	2.34
Chemical	62,000	143,000	48,140	0.43	2.96	1.28

Adapted from Eckenfelder, W.W. and D.L. Ford, *Water Pollution Control*, Pemberton Press, Austin and New York, 1970.

slaughterhouse, brewery, and numerous other industrial wastes containing complex organics have been satisfactorily treated biologically, but proper testing and evaluation is necessary.

Inorganics The inorganics in most industrial wastes are the direct result of inorganic compounds in the carriage water. Soft-water sources will have lower inorganics than hard-water or saltwater sources. However, some industrial wastewaters can contain significant quantities of inorganics which result from chemical additions during plant operation. Many food processing wastewaters are high in sodium. While domestic wastewaters have a balance in organics and inorganics, many process wastewaters from industry are deficient in specific inorganic compounds. Biodegradation of organic compounds requires adequate nitrogen, phosphorus, iron, and trace salts. Ammonium salts or nitrate salts can provide the nitrogen, while phosphates supply the phosphorus. Either ferrous or ferric salts or even normal steel corrosion can supply the needed iron. Other trace elements needed for biodegradation are potassium, calcium, magnesium, cobalt, molybdenum, chloride, and sulfur. Carriage water or demineralizer wastewaters or corrosion products can supply the needed trace elements for good metabolism. Occasionally, it is necessary to add specific trace elements or nutrient elements.

pH and Alkalinity Wastewaters should have pH values between 6 and 9 for minimum impact on the environment. Wastewaters with pH values less than 6 will tend to be corrosive as a result of the excess hydrogen ions. On the other hand, raising the pH above 9 will cause some of the metal ions to precipitate as carbonates or as hydroxides at higher pH levels. Alkalinity is important in keeping pH values at the right levels. Bicarbonate alkalinity is the primary buffer in wastewaters. It is important to have adequate alkalinity to neutralize the acid waste components as well as those formed by partial metabolism of organics. Many neutral organics such as carbohydrates, aldehydes, ketones, and alcohols are biodegraded through organic acids which must be neutralized by the available alkalinity. If alkalinity is inadequate, sodium carbonate is a better form to add than lime. Lime tends to be hard to control accurately and results in high pH levels and precipitation of the calcium which forms part of the alkalinity. In a few instances, sodium bicarbonate may be the best source of alkalinity.

Temperature Most industrial wastes tend to be on the warm side. For the most part, temperature is not a critical issue below 37° C

if wastewaters are to receive biological treatment. It is possible to operate thermophilic biological wastewater-treatment systems up to 65° C with acclimated microbes. Low-temperature operations in northern climates can result in very low winter temperatures and slow reaction rates for both biological treatment systems and chemical treatment systems. Increased viscosity of wastewaters at low temperatures makes solid separation more difficult. Efforts are generally made to keep operating temperatures between 10 and 30° C if possible.

Dissolved Oxygen Oxygen is a critical environmental resource in receiving streams and lakes. Aquatic life requires reasonable dissolved-oxygen (DO) levels. EPA has set minimum stream DO levels at 5 mg/L during summer operations, when the rate of biological metabolism is a maximum. It is important that wastewaters have maximum DO levels when they are discharged and have a minimum of oxygen-demanding components so that DO remains above 5 mg/L. DO is a poorly soluble gas in water, having a solubility around 9.1 mg/L at 20° C and 101.3-kPa (1-atm) air pressure. As the temperature increases and the pressure decreases with higher elevations above sea level, the solubility of oxygen decreases. Thus, DO is a minimum when BOD rates are a maximum. Lowering the temperature yields higher levels of DO saturation, but the biological metabolism rate decreases. Warm-wastewater discharges tend to aggravate the DO situation in receiving waters.

Solids Total solids is the residue remaining from a wastewater dried at 103–105° C. It includes the fractions shown in Fig. 25-43. The first separation is the portion that passes through a 2-μm filter (dissolved) and those solids captured on the filter (suspended). Combustion at 500° C further separates the solids into volatile and ash (fixed) solids. Although ash and volatile solids do not distinguish inorganic from organic solids exactly, due to loss of inorganics on combustion, the volatile fraction is often used as an approximate representation of the organics present. Another type of solids, settleable solids, refers to solids that settle in an Imhoff cone in one hour. Industrial wastes vary substantially in these types of solids and require individual wastewater treatment process analysis. An example of possible variation is given in Table 25-37.

Nutrients and Eutrophication Nitrogen and phosphorus cause significant problems in the environment and require special attention in industrial wastes. Nitrogen, phosphorus, or both may cause aquatic biological productivity to increase, resulting in low dissolved oxygen and eutrophication of lakes, rivers, estuaries, and marine waters. Table 25-38 gives the primary nutrient forms causing problems, while the following equation shows the biological oxidation or oxygen-consuming potential of the most common nitrogen forms.

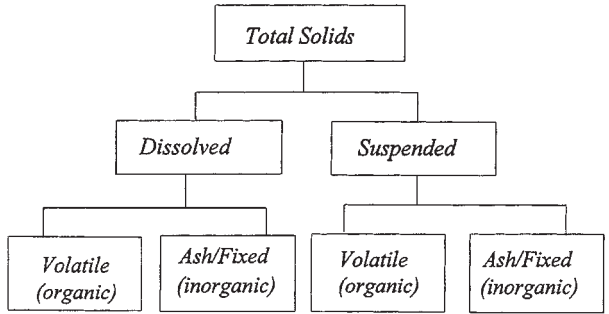


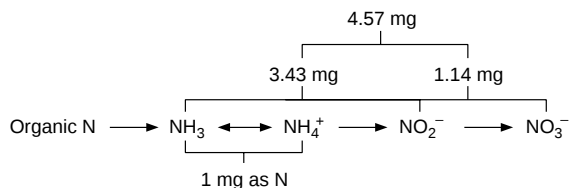
FIG. 25-43 Solids identification. Abbreviations: TS, total solids; SS, suspended solid; D, dissolved; V, volatile.

TABLE 25-37 Solids Variation in Industrial Wastewater

Type of solids	Plating	Pulp and paper
Total	High	High
Dissolved	High	High
Suspended	Low	High
Organic	Low	High
Inorganic	High	High

TABLE 25-38 Nutrient Forms

Parameter	Example
Organic N	protein
Ammonia	NH_3
Ammonium	NH_4^+
Nitrite	NO_2^-
Nitrate	NO_3^-
Organic P	malathion
Ortho-P	PO_4^{3-}
Poly-P	$(\text{PO}_4^{3-})_x$



When organics containing reduced nitrogen are degraded, they usually produce ammonium, which is in equilibrium with ammonia. As the pK for $\text{NH}_3 \leftrightarrow \text{NH}_4^+$ is 9.3, the ammonium ion is the primary form present in virtually all biological treatment systems, as they operate at $\text{pH} < 8.5$ and usually in the pH range of 6.5–7.5. In aerobic reactions, ammonium is oxidized by nitrifying bacteria (nitrosomonas) to nitrite and each mg of NH_4^+ -N oxidized will require 3.43 mg D.O. Further oxidation of nitrite by nitrobacter yields nitrate and uses an additional 1.14 mg of D.O. for a total D.O. consumption of 4.57 mg . Thus, organic and ammonium nitrogen can exert significant biochemical oxygen demand in the water environment. This nitrogen demand is referred to as nitrogenous or NBOD, whereas organic BOD is CBOD (carbonaceous). In treatment of wastewaters with organics and ammonium, the total oxygen demand (TOD) may have to be satisfied in accordance with the approximate formula:

$$\text{TOD} \cong 1.5 \text{ BOD}_5 + 4.5 (\text{TKN})$$

where TKN (total Kjeldahl nitrogen) = Organic N + NH_4^+ —N.

Phosphorus is not oxidized or reduced biologically, but ortho-P may be formed from organic and poly-P. Ortho-P may be removed by chemical precipitation or biologically with sludges and will be covered in a later section.

While many industrial wastes are so low in nitrogen and phosphorus that these must be added if biologically based treatment is to be used, others contain very high levels of these nutrients. For example, paint-production wastes are high in nitrogen, and detergent production wastes are high in phosphorus. Treatment for removal of these nutrients is required in areas where eutrophication is a problem.

Oil and Grease These substances are found in many industrial wastes (i.e., meat packing, petrochemical, and soap production). They tend to float on the water surface, blocking oxygen transfer, interfering with recreation, and producing an aesthetically poor appearance in the water. Measurement is by a solvent extraction procedure. Many somewhat different substances will register as oil and grease in this test. Often oil and grease interfere with other treatment operations, so they must be removed as part of the initial stages of treatment.

WASTEWATER TREATMENT

As indicated above, industrial wastewater contains a vast array of pollutants in soluble, colloidal, and particulate forms, both inorganic and organic. In addition, the required effluent standards are also diverse, varying with the industrial and pollutant class. Consequently, there can be no standard design for industrial water-pollution control. Rather, each site requires a customized design to achieve optimum performance. However, each of the many proven processes for industrial waste treatment is able to remove more than one type of pollutant and is in general applicable to more than one industry. In the sections that follow, waste-treatment processes are discussed more from the

broad-based generalized perspective than with narrow specificity. Generally, a combination of several processes is utilized to achieve the degree of treatment required at the least cost.

Much of the experience and data from wastewater treatment has been gained from municipal treatment plants. Industrial liquid wastes are similar to wastewater but differ in significant ways. Thus, typical design parameters and standards developed for municipal wastewater operations must not be blindly utilized for industrial wastewater. It is best to run laboratory and small pilot tests with the specific industrial wastewater as part of the design process. It is most important to understand the temporal variations in industrial wastewater strength, flow, and waste components and their effect on the performance of various treatment processes. Industry personnel in an effort to reduce cost often neglect laboratory and pilot studies and depend on waste characteristics from similar plants. This strategy often results in failure, delay, and increased costs. Careful studies on the actual waste at a plant site cannot be overemphasized.

PRETREATMENT

Many industrial-wastewater streams should be pretreated prior to discharge to municipal sewerage systems or even to a central industrial sewerage system. Pretreatment of individual streams should be considered whenever these streams might have an adverse effect on the total treatment system.

Equalization Equalization is one of the most important pretreatment devices. The batch discharge of concentrated wastes is best suited for equalization. It may be important to equalize wastewater flows, wastewater concentrations, or both. Periodic wastewater discharges tend to overload treatment units. Flow equalization tends to level out the hydraulic loads on treatment units. It may or may not level out concentration variations, depending upon the extent of mixing within the equalization basin. Mechanical mixing may be adequate if the wastes are purely chemical in their reactivity. Biodegradable wastes normally require aeration mixing so that the microbes are kept aerobic and nuisance odors are prevented. Diffused aeration systems offer better mixing under variable load conditions than mechanical surface aeration equipment. Mixing and oxygen transfer are both important with biodegradable wastewaters. Operation on regular cycles determines the size of the equalization basin. There is no advantage in making the equalization basin any larger than necessary to level out wastewater variations. Industrial operation on a 5-day, 40-h week will normally make a 2-day equalization basin as large as needed for continuous operation of the wastewater-treatment system under uniform conditions.

Neutralization Acidic or basic wastewaters must be neutralized prior to discharge. If an industry produces both acidic and basic wastes, these wastes may be mixed together at the proper rates to obtain neutral pH levels. Equalization basins can be used as neutralization basins. When separate chemical neutralization is required, sodium hydroxide is the easiest base material to handle in a liquid form and can be used at various concentrations for in-line neutralization with a minimum of equipment. Yet, lime remains the most widely used base for acid neutralization. Limestone is used when reaction rates are slow and considerable time is available for reaction. Sulfuric acid is the primary acid used to neutralize high- pH wastewaters unless calcium sulfate might be precipitated as a result of the neutralization reaction. Hydrochloric acid can be used for neutralization of basic wastes if sulfuric acid is not acceptable. For very weak basic wastewaters carbon dioxide can be adequate for neutralization.

Grease and Oil Removal Grease and oils tend to form insoluble layers with water as a result of their hydrophobic characteristics. These hydrophobic materials can be easily separated from the water phase by gravity and simple skimming, provided they are not too well mixed with the water prior to separation. If the oils and greases form emulsions with water as a result of turbulent mixing, the emulsions are difficult to break. Separation of oil and grease should be carried out near the point of their mixing with water. In a few instances, air bubbles can be added to the oil and grease mixtures to separate the hydrophobic materials from the water phase by flotation. Chemicals have also been added to help break the emulsions. American Petro-

leum Institute (API) separators have been used extensively by the petroleum industry to remove oils from wastewaters. The food industries use grease traps to collect the grease prior to its discharge. Unfortunately, grease traps are designed for regular cleaning of the trapped grease. Too often they are allowed to fill up and discharge the excess grease into the sewer or are flushed with hot water and steam to fluidize the grease for easy discharge to the sewer. A grease trap should be designed for a specific volume of grease to be collected over specific time periods. Care should be taken to design the trap so that the grease can easily be removed and properly handled. Neglected or poorly designed grease traps are worse than no grease traps at all.

Toxic Substances Recent federal legislation has made it illegal for industries to discharge toxic materials in wastewaters. Each industry is responsible for determining if any of its wastewater components are toxic to the environment and to remove them prior to the wastewater discharge. The EPA has identified a number of priority pollutants which must be removed and kept under proper control from their origin to their point of ultimate disposal. Major emphasis has recently been placed on heavy metals and on complex organics that have been implicated in possible cancer production. Pretreatment is essential to reduce heavy metals below toxic levels and to prevent discharge of any toxic organics. Fortunately, toxic organics can ultimately be destroyed by various chemical oxidation systems. Incineration appears to be the most economical method for destroying toxic organics. To make incineration economical, the organics must be kept separated from the dilute wastewaters and treated in their concentrated form. If the heavy metals cannot be reused, they must be concentrated and placed into insoluble materials which will not leach the heavy metals. Toxic substances currently pose the greatest challenge to industries since very little attention has been paid to these materials in the past.

PRIMARY TREATMENT

Wastewater treatment is directed toward removal of pollutants with the least effort. Suspended solids are removed by either physical or chemical separation techniques and handled as concentrated solids.

Screens Fine screens such as hydroscreens are used to remove moderate-size particles that are not easily compressed under fluid flow. Fine screens are normally used when the quantities of screened particles are large enough to justify the additional units. Mechanically cleaned fine screens have been used for separating large particles. A few industries have used large bar screens to catch large solids that could clog or damage pumps or equipment following the screens.

Grit Chambers Industries with sand or hard, inert particles in their wastewaters have found aerated grit chambers useful for the rapid separation of these inert particles. Aerated grit chambers are relatively small, with total volume based on 3-min retention at maximum flow. Diffused air is normally used to create the mixing pattern shown in Fig. 25-44, with the heavy, inert particles removed by centrifugal action and friction against the tank walls. The air flow rate is adjusted for the specific particles to be removed. Floatable solids are removed in the aerated grit chamber. It is important to provide for

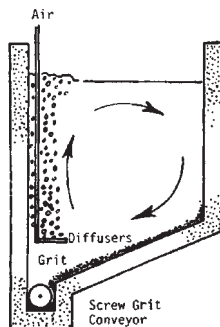


FIG. 25-44 Schematic diagram of an aerated grit chamber.

regular removal of floatable solids from the surface of the grit chamber; otherwise, nuisance conditions will be created. The settled grit is normally removed with a continuous screw and buried in a landfill.

Gravity Sedimentation Slowly settling particles are removed with gravity sedimentation tanks. For the most part, these tanks are designed on the basis of retention time, surface overflow rate, and minimum depth. A sedimentation tank can be rectangular or circular. The important factor affecting its removal efficiency is the hydraulic flow pattern through the tank. The energy contained in the incoming wastewater flow must be dissipated before the solids can settle. The wastewater flow must be distributed properly through the sedimentation volume for maximum settling efficiency. After the solids have settled, the settled effluent should be collected without creating serious hydraulic currents that could adversely affect the sedimentation process. Effluent weirs are placed at the end of rectangular sedimentation tanks and around the periphery of circular sedimentation tanks to ensure uniform flow out of the tanks. Once the solids have settled, they must be removed from the sedimentation-tank floor by scraping and hydraulic flow. Conventional sedimentation tanks have sludge hoppers to collect the concentrated sludge and to prevent removal of excess volumes of water with the settled solids. Cross-sectional diagrams of conventional sedimentation tanks are shown in Figs. 25-45 and 25-46.

Design criteria for gravity sedimentation tanks normally provide for 2-h retention based on average flow, with longer retention periods used for light solids or inert solids that do not change during their retention in the tank. Care should be taken that sedimentation time is not too long; otherwise, the solids will compact too densely and affect solids collection and removal. Organic solids generally will not compact to more than 5 to 10 percent. Inorganic solids will compact up to 20 or 30 percent. Centrifugal sludge pumps can handle solids up to 5 or 6 percent, while positive-displacement sludge pumps can handle solids up to 10 percent. With solids above 10 percent the sludge tends to lose fluid properties and must be handled as a semi-solid rather than a fluid. Circular sedimentation tanks have steel truss boxes with angled sludge scrapers on the lower side. As the sludge scrapers rotate, the solids are pushed toward the sludge hopper for removal on a continuous or semicontinuous basis. The rectangular sedimentation tanks employ chain-and-flight sludge collectors or rail-mounted sludge collectors. When floating solids can occur in primary sedimentation tanks, surface skimmers are mounted on the sludge scrapers so that the surface solids are removed at regular intervals.

The surface overflow rate (SOR) for primary sedimentation is normally held close to $40.74 \text{ m}^3/(\text{m}^2 \cdot \text{day})$ [$1000 \text{ gal}/(\text{ft}^2 \cdot \text{day})$] for average flow rates, depending upon the solids characteristics. Lowering the SOR below $40.74 \text{ m}^3/(\text{m}^2 \cdot \text{day})$ does not produce improved effluent

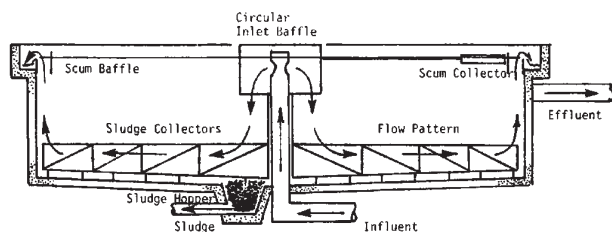


FIG. 25-45 Schematic diagram of a circular sedimentation tank.

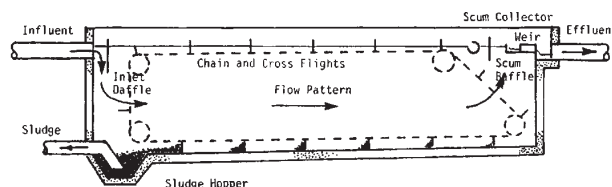


FIG. 25-46 Schematic diagram of a rectangular sedimentation tank.

quality in proportion to the reduction in SOR. Generally, the minimum depth of sedimentation tanks is 3.0 m (10 ft), with circular sedimentation tanks having a minimum diameter of 6.0 m (20 ft) and rectangular sedimentation tanks having length-to-width ratios of 5:1. Chain-and-flight limitations generally keep the width of rectangular sedimentation tanks to increments of 6.0 m (20 ft) or less. While hydraulic overflow rates have been limited on the effluent weirs, operating experience has indicated that the recommended limit of 186 m³/(m-day) [15,000 gal/(ft-day)] is lower than necessary for good operation. A circular sedimentation tank with a single-edge weir provides adequate weir length and is easier to adjust than one with a double-sided weir. More problems appear to be created from improper adjustment of the effluent weirs than from improper length.

Chemical Precipitation Lightweight suspended solids and colloidal solids can be removed by chemical precipitation and gravity sedimentation. In effect, the chemical precipitate is used to agglomerate the tiny particles into large particles that settle rapidly in normal sedimentation tanks. Aluminum sulfate, ferric chloride, ferrous sulfate, lime, and polyelectrolytes have been used as coagulants. The choice of coagulant depends upon the chemical characteristics of the particles being removed, the pH of the wastewaters, and the cost and availability of the precipitants. While the precipitation reaction results in removal of the suspended solids, it increases the amount of sludge to be handled. The chemical sludge must be considered along with the characteristics of the original suspended solids in evaluating sludge-processing systems.

Normally, chemical precipitation requires a rapid mixing system and a flocculation system ahead of the sedimentation tank. With a rectangular sedimentation tank, the rapid-mixer and flocculation units are added ahead of the tank. With a circular sedimentation tank the rapid-mixer and flocculation units are built into the tank. Schematic diagrams of chemical treatment systems are shown in Figs. 25-47 and 25-48. Rapid mixers are designed to provide 30-s retention at average flow with sufficient turbulence to mix the chemicals with the incoming wastewaters. The flocculation units are designed for slow mixing at 20-min retention. These units are designed to cause the particles to collide and increase in size without excessive shearing. Care must be taken to move the flocculated mixture from the flocculation unit to the sedimentation unit without disrupting the large floc particles.

The parameter used to design rapid mix and flocculation systems is the root mean square velocity gradient G , which is defined by equation

$$G = \left(\frac{P}{VU} \right)^{1/2} \left(\frac{1}{\text{sec}} \right)$$

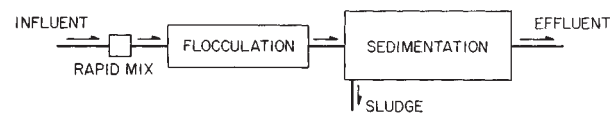


FIG. 25-47 Schematic diagram of a chemical precipitation system for rectangular sedimentation tanks.

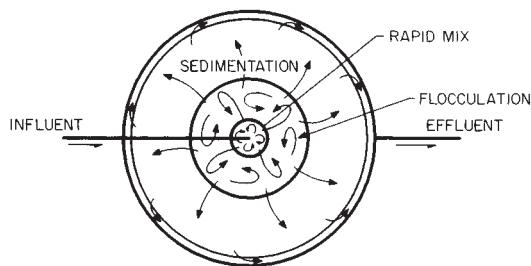


FIG. 25-48 Schematic diagram of a chemical precipitation system for circular sedimentation tanks.

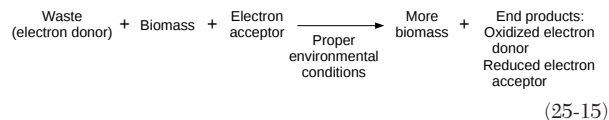
where: P = Power input to the water (ft-lb/sec)
 V = Mixer or flocculator volume (ft³)
 U = Absolute viscosity of water (lb-sec/ft²)

Optimum mixing usually requires a G value of greater than 1000 inverse seconds. Optimum flocculation occurs when G is in the range 10–100 inverse seconds.

Chemical precipitation can remove 95 percent of the suspended solids, up to 50 percent of the soluble organics and the bulk of the heavy metals in a wastewater. Removal of soluble organics is a function of the coagulant chemical, with iron salts yielding best results and lime the poorest. Metal removal is primarily a function of pH and the ionic state of the metal. Guidance is available from solubility product data.

SECONDARY TREATMENT

Secondary treatment utilizes processes in which microorganisms, primarily bacteria, stabilize waste components. The mixture of microorganisms is usually referred to as biomass. A portion of the waste is oxidized, releasing energy, the remainder is utilized as building blocks of protoplasm. The energy released by biomass metabolism is utilized to produce the new units of protoplasm. Thus, the incentive for the biomass to stabilize waste is that it provides the energy and basic chemical components required for reproduction. The process of biological waste conversion is illustrated by Eq. (25-15).



As this equation indicates, the waste generally serves as an electron donor, necessitating that an electron acceptor be supplied. A variety of substances can be utilized as electron acceptors, including molecular oxygen, carbon dioxide, oxidized forms of nitrogen, sulfur, and organic substances. The characteristics of the end products of the reaction are determined by the electron acceptor. Table 25-39 is a list of typical end products as a function of the electron acceptor. In general, the end products of this reaction are at a much lower energy level than the waste components, thus resulting in the release of energy referred to above. Although this process is usually utilized for the stabilization of organic substances, it can also be utilized for oxidation of inorganics. For example, biomass-mediated oxidation of iron, nitrogen, and sulfur is known to occur in nature and in anthropogenic processes.

Equation (25-15) describes the biomass-mediated reaction and indicates that proper environmental conditions are required for the reaction to take place. These conditions are required by the biomass, not the electron donor or acceptor. The environmental conditions include pH, temperature, nutrients, ionic balance, and so on. In general, biomass can function over a wide pH range generally from 5 to 9. However, some microbes require a much narrower pH range; i.e., effective methane fermentation requires a pH in the range of 6.5–7.5. It is just as important to maintain a relatively constant pH in the process as it is to stay within the range given above. Microorganisms can function effectively at the extremes of their pH range provided they are given the opportunity to acclimate to these conditions. Continual changes in pH are detrimental, even if the organisms are on the average near the middle of their effective pH range. A similar situa-

TABLE 25-39 Electron Acceptors and End Products for Biological Reactions

Electron acceptors	End product
Molecular oxygen	Water, CO ₂ , oxidized nitrogen
Oxidized nitrogen	N ₂ , N ₂ O, NO, CO ₂ , H ₂ O
Oxidized sulfur	H ₂ S, S, CO ₂ , H ₂ O
CO ₂ , acetic acid, formic acid	CH ₄ , CO ₂ , H ₂
Complex organics	H ₂ , simple organics, CO ₂ , H ₂ O

tion prevails for temperature. Most organisms can function well over a broad range of temperature but do not adjust well to frequent fluctuations of even a few degrees. There are three major temperature ranges in which microorganisms function. The psychrophilic range (5° C to 20° C), the mesophilic range (20° C to 45° C), and the thermophilic range (45° C to 70° C). In general the microbes that function in one of these temperature ranges cannot function efficiently in the other ranges. As it is generally uneconomical to adjust the temperature of a waste, most processes are operated in the mesophilic range. If the normal temperature of the waste is above or below the mesophilic range, the process will be operated in the psychrophilic or thermophilic range as appropriate. However, occasionally the temperature of the waste is altered to improve performance. For example, some anaerobic treatment processes are operated under thermophilic conditions, even though the waste must be heated to achieve this temperature range. This is carried out in order to speed up the degradation of complex organics and/or to achieve kill of mesophilic pathogens. It should be noted that any time the biological operation of a process moves away from its optimum or most effective range, be it pH, temperature, nutrients, or what have you, the rate of biological processing is reduced.

All microorganisms require varying amounts of a large number of nutrients. These are required because they are necessary components of bacterial protoplasm. The nutrients can be divided into three groups: macro, minor, and micro. The macronutrients are those that comprise most of the biomass. These are given by the commonly accepted formula for biomass (C₆₀H₈₇O₂₃N₁₂P). The carbon, hydrogen, and oxygen are normally supplied by the waste and water, but the nitrogen and phosphorous must often be added to industrial wastes to ensure that a sufficient amount is present. A good rule is that the mass of nitrogen should be at least 5 percent of the BOD, and the mass of phosphorous should be at least 20 percent of the mass of nitrogen. One of the major operational expenses is the purchase of nitrogen and phosphorous for addition to biologically based treatment processes. The quantities of nitrogen and phosphorous referred to above as required are actually in excess of the minimum amounts needed. The actual amount required depends upon the quantity of excess biomass wasted from the system and the amount of N and P available in the waste. This will be expanded upon later in this section. The minor nutrients include the typical inorganic components of water. These are given in Table 25-40. The range of concentrations required in the wastewater for the minor nutrients is 1–100 mg/L. The micronutrients include the substances that we normally refer to as trace metals and vitamins. It is interesting to note that the trace metals include virtually all of the toxic heavy metals. This reinforces the statement made above that toxicity is a function of concentration and not an absolute parameter. Whether or not the substances referred to as vitamins will be required depends upon the type of microorganisms required to stabilize the waste materials. Many microorganisms have the ability to make their own vitamins from the waste components; thus, a supplement is not needed. However, occasionally the addition of an external source of vitamins is essential to the success of a biologically based waste-treatment system. In general, the trace nutrients must be present in a waste at a level of a few micrograms per liter.

One aspect of the basic equation describing biological treatment of waste that has not been referred to previously is that biomass appears on both sides of the equation. As was indicated above, the only reason that microorganisms function in waste-treatment systems is because it enables them to reproduce. Thus, the quantity of biomass in a waste-treatment system is higher after the treatment process than before it.

TABLE 25-40 Minor and Micro Nutrients Required for Biologically Mediated Reactors

Minor 1–100 mg/L
Sodium, potassium, calcium, magnesium, iron, chloride, sulfate
Micro 1–100 µg/L
Copper, cobalt, nickel, manganese, boron, vanadium, zinc, lead, molybdenum, various organic vitamins, various amino acids

This is favorable in that there is a continual production of the organisms required to stabilize the waste. Thus, one of the major reactants is, in effect, available free of charge. However, there is an unfavorable side in that unless some organisms are wasted from the system, an excess level will build up, and the process could choke on organisms. The wasted organisms are referred to as sludge. A major cost component of all biologically based processes is the need to provide for the ultimate disposal of this sludge.

Biologically based treatment processes probably account for the majority of the treatment systems used for industrial waste management because of their low cost and because most substances are amenable to biological breakdown. However, some substances are difficult to degrade biologically. Unfortunately, it is not possible at present to predict a priori the biodegradability of a specific organic compound; rather, we must depend upon experience and testing. The collective experience of the field has been put into compendia by EPA in a variety of documents. However, these data are primarily qualitative. There have been some attempts to develop a system of prediction of biodegradability based on a number of compound parameters such as solubility, presence or absence of certain functional groups, compound polarity, and so on. Unfortunately, none of these systems has advanced to the point where reliable quantitative predictions are possible. Another complication is that some organics that are easily biodegradable at low concentration exert a toxic effect at high concentration. Thus, literature data can be confusing. Phenol is a typical compound that shows ease of biodegradation when the concentration is below 500 mg/L but poor biodegradation at higher concentrations. Another factor affecting both biodegradation and toxicity is whether or not a substance is in solution. In general, if a substance is not in solution, it is not available to affect the biomass. Thus, the presence of a waste in substances that can precipitate, complex, or absorb other waste components can have a significant effect on reports of biodegradability and/or toxicity. A quantitative estimate of toxicity can be obtained in terms of the change in kinetic parameters of a system. These kinetic parameters are discussed below.

Design of Biological Treatment Systems In the past, the design of biologically based waste-treatment systems has been derived from rules of thumb. During the past two decades, however, a more fundamental system has been developed and is presently widely used to design such systems. This system is based upon a fundamental understanding of the kinetics and stoichiometry of biological reactions. The system is codified in terms of equations in which four pseudo constants appear. These pseudo constants are *k_m*, the maximum substrate utilization rate (1/time); *K_s*, the half maximal velocity concentration (mg/L); *Y*, the yield coefficient; and *b*, the endogenous respiration rate (1/time). These are referred to as pseudo constants because, in the mathematical manipulation of the equations in which they appear, they are treated as constants. However, the value of each is a function of the nature of the microbes, the pH, the temperature, and the components of the waste. It is important to remember that if any of these change, the value of the pseudo constants may change as well. The kinetics of biological reactions are described by Eq. (25-16).

$$\frac{dS}{dt} = \frac{k_m SX}{K_s + S} \tag{25-16}$$

where *t* = time (days)
S = waste concentration (mg/L)
X = biomass concentration (mg/L)
k_m = (mg/L substrate ÷ mg/L biomass) – time

The accumulation or growth of biosolids is given by Eq. (25-17).

$$\frac{dX}{dt} = Y \frac{dS}{dt} - bX \tag{25-17}$$

where *X* = biomass level (mg/L).

The equations that have been developed for design using these pseudo constants are based on steady-state mass balances of the biomass and the waste components around both the reactor of the system and the device used to separate and recycle microorganisms. Thus, the equations that can be derived will be dependent upon the characteristics of the reactor and the separator. It is impossible here to

present equations for all the different types of systems. As an illustration, the equations for a common system (a complete mix – stirred tank reactor with recycle) are presented below.

$$S_e = \frac{K_s[1 + \text{BSRT}(b)]}{\text{BSRT}(YK_m - b) - 1} \quad (25-18)$$

$$X = \frac{(\text{BSRT})(Y)(S_o - S_e)}{\text{HRT}[1 + (b)\text{BSRT}]} \quad (25-19)$$

where: S_o = influent waste concentration (mg/L)

S_e = treated waste concentration (mg/L)

HRT = reactor hydraulic retention time

Note that these equations predict some unexpected results. The strength of the untreated waste (S_o) has no effect on the strength of the treated waste (S_e). Neither does the size of the reactor (HRT). Rather, a parameter referred to as the biomass solids retention time (BSRT) is the key parameter determining the system performance. This is illustrated in Fig. 25-49. As the BSRT increases, the concentration of untreated waste in the effluent decreases irrespective of the reactor size or the waste strength. However, the reactor size and waste strength have a significant effect on the level of biomass (X) that is maintained in the system at steady state. Since the development of an excess level of biomass in the system can lead to system upset, it is important to take cognizance of the waste strength and the reactor size. But treatment performance with respect to removal of the waste components is again a function only of BSRT and the value of the pseudo constants referred to above. The BSRT also has an effect on the level of biomass in the system and the quantity of excess biomass produced (Fig. 25-50). The latter will determine the quantity of waste sludge which must be dealt with as well as the N and P requirement. The N and P in the biomass removed from the system each day must be replaced. From the formula given previously for biomass, N is 12 percent and P is 2.3 percent by weight in biomass grown under ideal conditions (see Fig. 25-50). Also, note that m , the minimum BSRT, is the minimum time required for the microorganisms to double in mass. Below this minimum, washout occurs and substrate removal approaches zero.

Although identical results are not obtained for other reactor configurations, the design equations yield similar patterns. The dominant parameters in determining system performance are again the BSRT and the pseudo constants. The latter are not under the control of the design engineer as they are functions of the waste and the microorganisms that developed in the system. The BSRT is the major design parameter under the control of the design engineer. This parameter has been defined as the ratio of the biomass in the reactor to the biomass produced from the waste each day. At steady state, the level of biomass in the system is constant; thus, the biomass produced must equal the biomass wasted. The minimum BSRT that can be utilized is that which will produce the degree of treatment required. Generally,

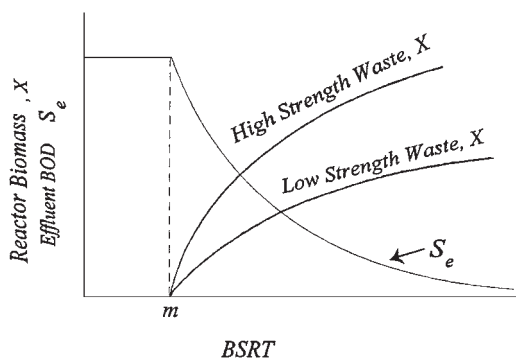


FIG. 25-49 Effect of BSRT on biological treatment process performance. m = minimum BSRT.

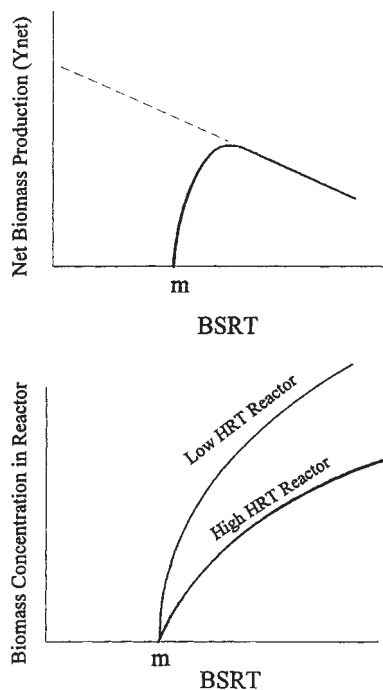


FIG. 25-50 Biomass production.

this minimum value is less than the range of BSRT used in design and operation. This provides not only a safety factor, but, in addition, it is necessary in order to foster the growth of certain favorable groups of microorganisms in the system. Generally, BSRT values in the range of 3–15 days are utilized in most systems, although BSRT values of less than 1 day for high rate systems are usually adequate to ensure greater than 95 percent destruction of waste components in all but anaerobic systems. For the latter, a minimum BSRT of 8 days is needed for 95 percent destruction. BSRT is controlled by the concentration of biomass (X) in the system and the quantity wasted each day; thus, the treatment plant operator can alter BSRT by altering the rate of biomass wasting.

Reactor Concepts A large number of reactor concepts seem to be used in biologically based treatment systems. However, this diversity is more apparent than real. In reality, there are only two major reactor types that are used. One is referred to as a suspended growth reactor, the other is referred to as a fixed film reactor. In the former, the waste and the microorganisms move through the reactor, with the microorganisms constantly suspended in the flow. After exiting the reactor, the suspension flows through a separator, which separates the organisms from the liquid. Some of the organisms are wasted as sludge, while the remainder are returned to the reactor. The supernatant is discharged either to the environment or to other treatment units (Fig. 25-51). The functioning of the separator is very important, as poor performance of the separator will result in high solids in the effluent and reduction of organisms in the recycle and eventually also in the reactor. As indicated above, the level of the BSRT used in design of suspended growth systems is set to produce a biomass of the proper level in the system; i.e., a level at which waste degradation is rapid but not so high that excess loading on the separator will occur. BSRT also influences the ability of biomass to self flocculate and thus be removed in the separator (usually a clarifier).

In the fixed-film reactor, the organisms grow on an inert surface that is maintained in the reactor. The inert surface can be granular material, proprietary plastic packing, rotating discs, wood slats, mass-transfer packing, or even a sponge-type material. The reactor can be flooded or have a mixed gas-liquid space (Fig. 25-52). The biomass level on the

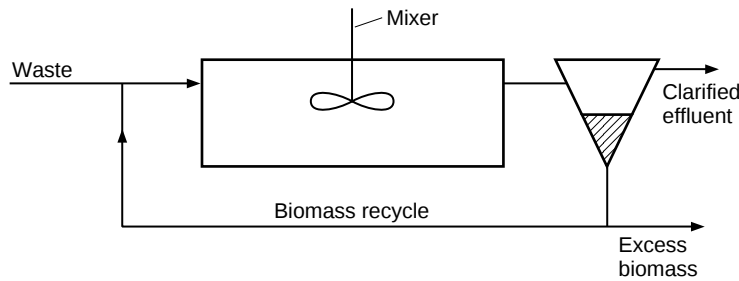


FIG. 25-51 Diagram of a suspended growth system.

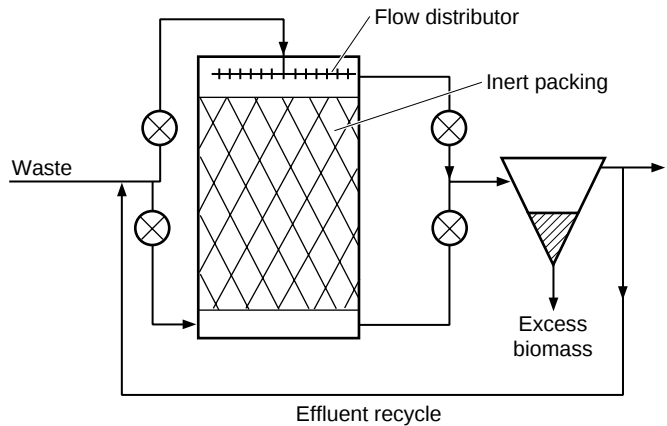


FIG. 25-52 Diagram of a fixed-film system.

packing is controlled by hydraulic scour produced as the waste liquid flows through the reactor. There is no need of a separator to ensure that the biomass level in the reactor is maintained. The specific surface area of the packing is the design parameter used to ensure an adequate level of biomass. However, a separator is usually supplied to capture biomass washed from the packing surface by the flow of the waste, thus providing a clarified effluent. As with the suspended growth system, if this biomass escapes the system, it will result in a return to the environment of organic laden material, thus negating the effectiveness of the waste treatment. As indicated above, biomass level in a fixed film reactor is maintained by a balance between the rate of growth on the packing (which is a function of the strength of the waste, the yield coefficient and the BSRT), and the rate of hydraulic flushing by the waste flow. Recycle of treated wastewater is used to control the degree of hydraulic flushing. Thus, typical design parameters for fixed film reactors include both an organic loading and a hydraulic loading. Details on the typical levels for these will be given in a later section.

The reactor concepts described above can be utilized with any of the electron acceptor systems previously discussed, although some reactor types perform better with specific electron acceptors. For example, suspended growth systems are generally superior to fixed film systems when molecular oxygen is the electron acceptor because it is easier to supply oxygen to suspended growth systems.

On the other hand, fixed film systems are superior for systems in which nitrate is the electron acceptor because the nitrogen bubbles produced in suspended growth systems tend to float sludge to the top of the clarifiers used as biomass separators. Another factor affecting reactor type and electron acceptor selection is waste strength. The higher the waste strength, the higher the level of biomass in the reactor and vice versa. When waste strength is low, fixed film reactors are favored as it is easier to maintain an adequate biomass level. When waste strength is high, it is better to use anaerobic electron acceptors than aerobic because oxygen supply is not limiting for anaerobic sys-

tems. In addition, the yield coefficient Y is much lower for anaerobic systems, so the probability of excessive biomass development in the system is much less. Table 25-41 summarizes the advantages and disadvantages of various combinations of reactor type, electron acceptor, and waste strength.

Recently, a new concept in fixed film reactors that uses an expanded or fluidized bed of particles as the biomass support medium has been introduced. This reactor type can easily handle both low- and high-strength wastes with most electron acceptors. It will be discussed in detail in a later section.

TABLE 25-41 Favorable (F) and Unfavorable (U) Combinations of Electron Acceptor, Waste Strength, and Reactor Type

Suspended growth reactor		
Electron acceptor	Waste strength	Condition
Aerobic	Low–modest	F
Aerobic	High	U
Anoxic	Low–modest	F
Anoxic	High	U
Anaerobic	Low–modest	U
Anaerobic	High	F
Fixed film reactor		
Electron acceptor	Waste strength	Condition
Aerobic	Low	F
Aerobic	Modest–high	U
Anoxic	Low–modest	F
Anoxic	High	U
Anaerobic	Low–modest	F
Anaerobic	High	F

Determination of Kinetic and Stoichiometric Pseudo Constants As indicated above, these parameters are most important for predicting the performance of biologically based treatment systems. It would be ideal if tabulations of these were available for various industrial wastes as a function of pH temperature and nutrient levels. Unfortunately, little reliable data has been codified. Only certain trends have been established, and these are primarily the result of studies on municipal wastewater. For example, the yield coefficient Y has been shown to be much higher for systems that are aerobic (molecular oxygen as the electron acceptor) than for anaerobic systems (sulfate or carbon dioxide as the electron acceptors). Systems where oxidized nitrogen is the electron acceptor (termed *anoxic*) exhibit yield values intermediate between aerobic and anaerobic systems. The endogenous respiration rate is higher for aerobic and anoxic systems than anaerobic systems. However, no trends have been established for values of the maximum specific growth rate or the half maximal velocity concentration. Thus, the values applicable to a specific waste must be determined from laboratory studies.

The laboratory studies utilized small-scale (1–5-L) reactors. These are satisfactory because the reaction rates observed are independent of reactor size. Several reactors are operated in parallel on the waste, each at a different BSRT. When steady state is reached after several weeks, data on the biomass level (X) in the system and the untreated waste level in the effluent (usually in terms of BOD or COD) are collected. These data can be plotted for equation forms that will yield linear plots on rectangular coordinates. From the intercepts and the slope of the lines, it is possible to determine values of the four pseudo constants. Table 25-42 presents some available data from the literature on these pseudo constants. Figure 25-53 illustrates the procedure for their determination from the laboratory studies discussed previously.

Activated Sludge This treatment process is the most widely used aerobic suspended growth reactor system. It will consistently produce a high-quality effluent (BOD₅ and SS of 20–30 mg/L). Operational costs are higher than for other secondary treatment processes primarily because of the need to supply molecular oxygen using energy-intensive mechanical aerator- or sparger-type equipment. Removal of soluble organics, colloidal, particulates, and inorganics are achieved in this system through a combination of biological metabolism, adsorption, and entrapment in the biological floc. Indeed, many pollutants that are not biologically degradable are removed during activated sludge treatment by adsorption or entrapment by the floc. For example, most heavy metals form hydroxide or carbonate precipitates under the pH conditions maintained in activated sludge, and most organics are easily adsorbed to the surface of the biological floc. A qualitative guide to the latter is provided by the octanol-water partition coefficient of a compound.

All activated sludge systems include a suspended growth reactor in which the wastewater, recycled sludge, and molecular oxygen are mixed. The latter must be dissolved in the water; thus the need for an energy-intensive pure oxygen or air supply system. Usually, air is the source of the molecular oxygen rather than pure oxygen. Energy for mixing of the reactor contents is supplied by the aeration equipment. All systems include a separator and pump station for sludge recycle and sludge wasting. The separator is usually a sedimentation tank that is designed to function as both a clarifier and a thickener. Many modifications of the activated sludge process have been developed over

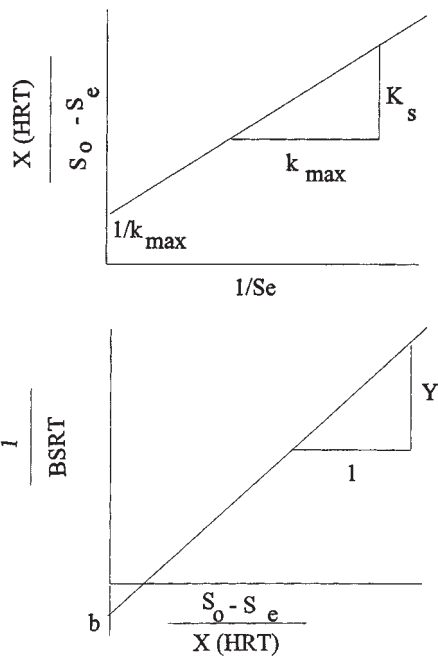


FIG. 25-53 Determination of pseudo-kinetic constants.

the years and are described below. Most of these involve differences in the way the reactor is compartmentalized with respect to introduction of waste, recycle, and/or oxygen supply.

Modifications The modifications of activated sludge systems offer considerable choice in processes. Some of the most popular modifications of the activated sludge process are illustrated in Fig. 25-54. Conventional activated sludge uses a long narrow reactor with air supplied along the length of the reactor. The recycle sludge and waste are introduced at the head end of the reactor producing a zone of high waste to biomass concentration and high oxygen demand. This modification is used for relatively dilute wastes such as municipal wastewater. Step aeration systems distribute the waste along the length of the aerator, thus reducing the oxygen demand at the head end of the reactor and spreading the oxygen demand more uniformly over the whole reactor. In the complete mix system, the waste and sludge recycle are uniformly distributed over the whole reactor, resulting in the waste load and oxygen demand being uniform in the entire reactor. Complete-mixing activated sludge is the most popular system for industrial wastes because of its ability to absorb shock loads better than other modifications. Contact stabilization is a modification of activated sludge that is best suited to wastewaters having high suspended solids and low soluble organics. Contact stabilization employs a short-term mixing tank to adsorb the suspended solids and metabolize the soluble organics, a sedimentation tank for solids separation,

TABLE 25-42 Typical of Values for Pseudo Constants

Biomass type	Substrate	$k_{\max}$ mg substrate mg biomass-day	Y , mg biomass mg substrate	K_s , mg substrate liter	b , 1/day	Remarks
Mixed culture	Sewage (COD)	5–10	0.5	50	0.05	Aerobic 20°C
Mixed culture	Glucose (COD)	7.5	0.6	10	0.07–.1	Aerobic 20°C
Mixed culture	Skim milk (COD)	5	—	100	0.05	Aerobic 20°C
Mixed culture	Soybean waste (COD)	12	—	355	0.144	Aerobic 20°C
Methane bacteria	Acetic acid (COD)	8.7	.04	165	0.035	35°C
Anaerobic mixed	Propanoic acid (COD)	7.7	.04	60	0.035	35°C
Anaerobic mixed	Sewage sludge (COD)	6.7	.04	1,800	0.03	35°C
Anoxic	NO ₃ as N	0.375	0.8	0.1	0.04	Methanol feed
Aerobic	NH ₄ ⁺ as N	5	0.2	1.4	.05	20°C

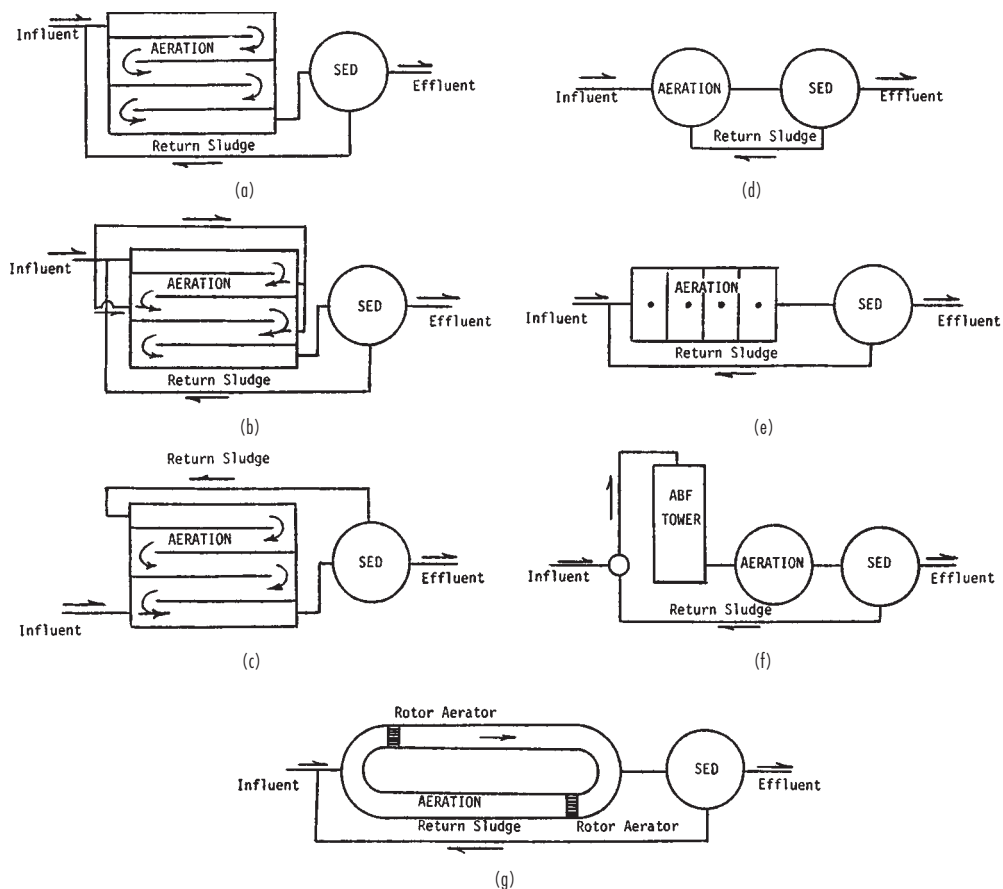


FIG. 25-54 Schematic diagrams of various modifications of the activated-sludge process. (a) Conventional activated sludge. (b) Step aeration. (c) Contact stabilization. (d) Complete mixing. (e) Pure oxygen. (f) Activated biofiltration (ABF). (g) Oxidation ditch.

and a reaeration tank for stabilization of the suspended organics. Extended-aeration systems are actually long-term-aeration, completely mixed activated-sludge systems. They employ 24- to 48-h aeration periods and high mixed-liquor suspended solids to provide complete stabilization of the organics and aerobic digestion of the activated sludge in the same aeration tank. The oxidation ditch is a popular form of the extended-aeration system employing mechanical aeration. Pure-oxygen systems are designed to treat strong industrial wastes in a series of completely mixed units having relatively short contact periods. One of the latest modifications of activated sludge employs powdered activated carbon to adsorb complex organics and assist in solids separation. Another modification employs a redwood-medium trickling filter ahead of a short-term aeration tank with mixed liquor recycled over the redwood-medium tower to provide heavy microbial growth on the redwood as well as in the aeration tank.

As indicated previously, success with the activated sludge process requires that the biomass have good self-flocculating properties. Significant research effort has been expended to determine the conditions that favor the development of good settling biomass cultures. These have indicated that nutritional deficiency, levels of dissolved oxygen between 0 to 0.5 mg/L, and pH values below 6.0 will favor the predomination of filamentous biomass. Filamentous organisms settle and compact poorly and thus are difficult to separate from liquid. By avoiding the above conditions, and with the application of selector technology, the predomination of filaments in the biomass can be eliminated. A selector is often a short contact (15–30 min) reactor set ahead of the main activated sludge reactor. All of the recycle sludge

and all of the waste are routed to the selector. In the selector, either a high rate of aeration (aerobic selector) is used to keep the dissolved oxygen above 2 mg/L, or no aeration occurs (anaerobic selector) so that the dissolved oxygen is zero. Because filamentous organisms are microaerophilic, they cannot predominate when the dissolved oxygen level is zero or high. The anaerobic selector not only selects in favor of nonfilamentous biomass but also fosters luxury uptake of phosphorous and is used in systems where phosphorous removal is desired.

Aeration Systems These systems control the design of aeration tanks. Aeration equipment has two major functions: mixing and oxygen transfer. Diffused-aeration equipment employs either a fixed-speed positive-displacement blower or a high-speed turbine blower for readily adjustable air volumes. Air diffusers can be located along one side of the aeration tank or spread over the entire bottom of the tank. They can be either fine-bubble or coarse-bubble diffusers. Fine-bubble diffusers are more efficient in oxygen transfer but require more extensive air-cleaning equipment to prevent them from clogging as a result of dirty air. Mechanical-surface-aeration equipment is more efficient than diffused-aeration equipment but is not as flexible. Economics has dictated the use of large-power aerators, but tank configuration has tended to favor the use of greater numbers of lower-power aerators. Oxidation ditches use horizontal rotor-type aerators. Mixing is a critical problem with mechanical-surface aerators since they are a point-source pump of limited capacity. Experience has indicated that bearings are a serious problem with mechanical-aeration equipment. Wave action generated within the aeration tank tends to produce lateral stresses on the bearings and has resulted in failures and increased

maintenance costs. Slow-speed mechanical-surface-aeration units present fewer problems than the high-speed mechanical-surface-aeration units. Deep tanks, greater than 3.0 m (10 ft), require draft tubes to ensure proper hydraulic flow through the aeration tank. Short-circuiting is one of the major problems associated with mechanical aeration equipment. Combined mechanical- and diffused-aeration systems have enjoyed some popularity for industrial-waste systems that treat variable organic loads. The mechanical mixers provide the fluid mixing with the diffused aeration varied for different oxygen-transfer rates.

Diffused-aeration systems transfer from 20 to 40 mg/(L O₂-h). Combined mechanical- and diffused-aeration systems can transfer up to 65 mg/(L O₂-h), while mechanical-surface aerators can provide up to 90 mg/(L O₂-h). Pure-oxygen systems can provide the highest oxygen-transfer rate, up to 150 mg/(L O₂-h). Aeration equipment must provide sufficient oxygen to meet the peak oxygen demand; otherwise, the system will fail to provide proper treatment. For this reason, the peak oxygen demand and the rate of transfer for the desired equipment determine the size of the aeration tank in terms of retention time. Economics dictates a balance between the size of the aeration tank and the size of the aeration equipment. As the cost of power increases, economics will favor constructing a larger aeration tank and smaller aerators. It is equally important to examine the hydraulic flow pattern around each aerator to ensure maximum efficiency of oxygen transfer. Improper spacing of aeration equipment can waste energy.

There is no standard aeration-tank shape or size. Aeration tanks can be round, square, or rectangular. Shallow aeration tanks are more difficult to mix than deeper tanks. Yet aeration-tank depths have ranged from 0.6 m (2 ft) to 18 m (60 ft). The oxidation-ditch systems tend to be shallow, while some high-rate diffused-aeration systems have used very deep tanks to provide more efficient oxygen transfer.

Regardless of the aeration equipment employed, oxygen-transfer rates must provide from 0.6 to 1.4 kg of oxygen/kg BOD₅ (0.6 to 1.4 lb oxygen/lb BOD₅) stabilized in the aeration tank for carbonaceous-oxygen demand. Nitrogen oxidation can increase oxygen demand at the rate of 4.3 kg (4.3 lb) of oxygen/kg (lb) of ammonia nitrogen oxidized. At low oxygen-transfer rates more excess activated sludge must be removed from the system than at high oxygen-transfer rates. Here again the economics of sludge handling must be balanced against the cost of oxygen transfer. The quantity of waste activated sludge will depend upon wastewater characteristics. The inert suspended solids entering the treatment system must be removed with the excess activated sludge. The soluble organics are stabilized by converting a portion of the organics into suspended solids, producing from 0.3 to 0.8 kg (0.3 to 0.8 lb) of volatile suspended solids/kg (lb) of BOD₅ stabilized. Biodegradable suspended solids in the wastewaters will result in destruction of the original suspended solids and their conversion to a new form. Depending upon the chemical characteristics of the biodegradable suspended solids, the conversion factor will range from 0.7 to 1.2 kg (0.7 to 1.2 lb) of microbial solids produced/kg (lb) of suspended solids destroyed. If the suspended solids produced by metabolism are not wasted from the system, they will eventually be discharged in the effluent. While considerable efforts have been directed toward developing activated-sludge systems which totally consume the excess solids, no such system has proved to be practical. The concept of total oxidation of excess sludge is fundamentally unsound and should be recognized as such.

A definitive determination of the waste sludge production and the oxygen requirement can be obtained using the pseudo constants referred to previously. The ultimate BOD in the waste will be accounted for by the sum of the oxidation and sludge synthesis (Eq. 25-20).

Thus:

$$\text{Waste BOD}_u = \text{Oxygen required} + \text{BOD}_u \text{ of sludge produced} \quad (25-20)$$

where: $\text{BOD}_u \text{ of sludge} = (Y_{\text{net}})/(1.42)(\text{Waste BOD}_u)$

$$Y_{\text{net}} = \frac{Y}{1 + b(\text{BSRT})}$$

1.42 = Factor converting biomass to oxygen units; i.e.,
BOD_u ≈ COD

Sedimentation Tanks These tanks are an integral part of any activated-sludge system. It is essential to separate the suspended solids from the treated liquid if a high-quality effluent is to be produced. Circular sedimentation tanks with various types of hydraulic sludge collectors have become the standard secondary sedimentation system. Square tanks have been used with common-wall construction for compact design with multiple tanks. Most secondary sedimentation tanks use center-feed inlets and peripheral-weir outlets. Recently, efforts have been made to employ peripheral inlets with submerged-orifice flow controllers and either center-weir outlets or peripheral-weir outlets adjacent to the peripheral-inlet channel.

Aside from flow control, basic design considerations have centered on surface overflow rates, retention time, and weir overflow rate. Surface overflow rates have been slowly reduced from 33 m³/(m²-day) [800 gal/(ft²-day)] to 24 m³/(m²-day) to 16 m³/(m²-day) [600 gal/(ft²-day) to 400 gal/(ft²-day)] and even to 12 m³/(m²-day) [300 gal/(ft²-day)] in some instances, based on average raw-waste flows. Operational results have not demonstrated that lower surface overflow rates improve effluent quality, making 33 m³/(m²-day) [800 gal/(ft²-day)] the design choice in most systems. Retention time has been found to be an important design factor, averaging 2 h on the basis of raw-waste flows. Longer retention periods tend to produce rising sludge problems, while shorter retention periods do not provide for good solids separation with high-return sludge flow rates. Effluent-weir overflow rates have been limited to 186 m³/(m-day) [15,000 gal/(ft-day)] with a tendency to reduce the rate to 124 m³/(m-day) [10,000 gal/(ft-day)]. Lower effluent-weir overflow rates are obtained by using dual-sided effluent weirs cantilevered from the periphery of the tank. Unfortunately, proper adjustment of dual-side effluent weirs has created more hydraulic problems than the weir overflow rate. Field data have shown that effluent quality is not really affected by weir overflow rates up to 990 m³/(m-day) [80,000 gal/(ft-day)] or even 1240 m³/(m-day) [100,000 gal/(ft-day)] in a properly designed sedimentation tank. A single peripheral weir, being easy to adjust and keep clean, appears to be optimal for secondary sedimentation tanks from an operational point of view.

Depth tends to be determined from the retention time and the surface overflow rate. As surface overflow rates were reduced, the depth of sedimentation tanks was reduced to keep retention time from being excessive. It was recognized that depth was a valid design parameter and was more critical in some systems than retention time. As mixed-liquor suspended-solids (MLSS) concentrations increase, the depth should also be increased. Minimum sedimentation-tank depths for variable operations should be 3.0 m (10 ft) with depths to 4.5 m (15 ft) if 3000 mg/L MLSS concentrations are to be maintained under variable hydraulic conditions. With MLSS concentrations above 4000 mg/L, the depth of the sedimentation tank should be increased to 6.0 m (20 ft). The key is to keep a definite freeboard over the settled-sludge blanket so that variable hydraulic flows do not lift the solids over the effluent weir.

Scum baffles around the periphery of the sedimentation tank and radial scum collectors are standard equipment to ensure that rising solids or other scum materials are removed as quickly as they form. Hydraulic sludge-collection tubes have replaced the center sludge well, but they have caused a new set of operational problems. These tubes were designed to remove the settled sludge at a faster rate than conventional sludge scrapers. To obtain good hydraulic distribution in the sludge-collection tubes, it was necessary to increase the rate of return sludge flow and decrease the concentration of return sludge. The higher total inflow to the sedimentation tank created increased forces that lifted the settled-solids blanket at the wall, causing loss of excessive suspended solids and lower effluent quality. Operating data tend to favor conventional secondary sedimentation tanks over hydraulic sludge-collection systems. Return-sludge rates normally range from 25 to 50 percent for MLSS concentrations up to 3300 mg/L. Most return-sludge pumps are centrifugal pumps with capacities up to 100 percent raw-waste flow.

Gravity settling can concentrate activated sludge to 10,000 mg/L, but hydraulic sludge-collecting tubes tend to operate best below 8,000 mg/L. The excess activated sludge can be wasted either from the return sludge or from a separate waste-sludge hopper near the center of the

tank. The low solids concentrations result in large volumes of waste activated sludge in comparison with primary sludge. Unfortunately, the physical characteristics of waste activated sludge prevent significant concentration without the expenditure of considerable energy. Gravity thickening can produce 2 percent solids, while air flotation can produce 4 percent solids concentration. Centrifuges are able to concentrate activated sludge from 10 to 15 percent solids, but the capture is limited. Vacuum filters can equal the performance of centrifuges if the sludge is chemically conditioned. Filter presses and belt-press filters can produce cakes with 15 to 25 percent solids. It is very important that the excess activated sludge formed in the aeration tanks be wasted on a regular basis; otherwise, effluent quality will deteriorate. Care should be taken to ensure that sludge-thickening systems do not control activated-sludge operations. Alternative sludge-handling provisions should be available during maintenance on sludge-thickening equipment. At no time should final sedimentation tanks be used for the storage of sludge beyond that required by daily operational variations.

Anaerobic/Anoxic Activated Sludge The activated sludge concept (i.e., suspended growth reactor) can be used for anaerobic or anoxic systems in which no oxygen or air is added to the reactor. An anoxic activated sludge is used for systems in which removal of nitrate is a goal or where nitrate is used as the electron acceptor. These systems (denitrification) will be successful if the nitrate is reduced to low levels in the reactor so that nitrate reduction to nitrogen gas does not take place in the clarifier-thickener. Nitrogen gas production in the clarifier will result in escape of biological solids with the effluent as nitrogen bubbles floating sludge to the clarifier surface. For nitrogen reduction, a source of organics (electron donor) is required. Any inexpensive carbohydrate can be effectively used for nitrate removal. Many systems utilize methanol as the donor because it is rapidly metabolized; others use the organics in sewage in order to reduce chemical costs. Nitrate reduction is invariably used as part of a system in which organics and nitrogen removal are goals. In such systems, the nitrogen in the waste is first oxidized to nitrate and then reduced to nitrogen gas. Figure 25-55 presents some flow sheets for such

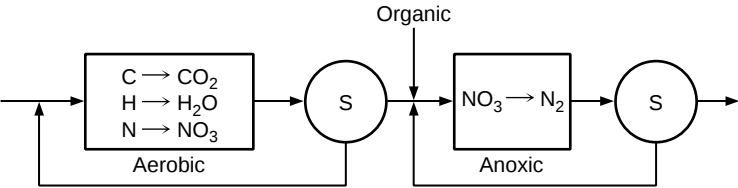
TABLE 25-43 Design Parameter for Nitrogen Removal				
System	BSRT, d	HRT, h	X, mg/L	pH
Carbon removal†	2–5	1–3	1000–2000	6.5–8.0
Nitrification†	10–20	0.5–3	1000–2000	7.4–8.6
Denitrification†	1–5	0.2–2	1000–2000	6.5–7.0
Internal recycle*	10–40	8–20	2000–4000	6.5–8.0

*Total for all reactors
†Separate reactors

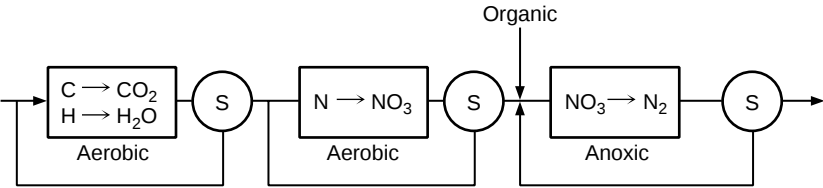
systems. Table 25-43 presents some design parameters for nitrate-reduction-activated sludge systems. Anaerobic activated sludge has been used for strong industrial wastes high in degradable organic solids. In these systems, a high rate of gasification takes place in the sludge separator so that a highly clarified effluent is usually not obtained. A vacuum degasifier is incorporated in such systems to reduce solids loss. Such systems have been used primarily with meat packing wastes that are warm, high in BOD and yield a high level of bicarbonate buffer as a result of ammonia release from protein breakdown. All of these conditions favor anaerobic processing. The use of this process scheme provides a high BSRT (15–30 days), usually required for anaerobic treatment, at a low HRT (1–2 days).

Lagoons Lagoons are low-cost, easy-to-operate wastewater-treatment systems capable of producing satisfactory effluents. Nominally, a lagoon is a suspended-growth no-recycle reactor with a variable degree of mixing. In lagoons in which mechanical or diffused aeration is used, mixing may be sufficient to approach complete mixing (i.e., solids maintained in suspension). In other types of lagoons, most solids settle and remain on the lagoon bottom, but some mixing is achieved as a result of gas production from bacterial metabolism and wind action. Lagoons are categorized as aerobic, facultative, or anaerobic on the basis of degree of aeration. Aerobic lagoons primarily depend on mechanical or diffused air supply. Significant oxygen supply is also realized through natural surface aeration. A facultative lagoon is dependent primarily on natural surface aeration and oxygen

Two-sludge system



Three-sludge system



Internal recycle

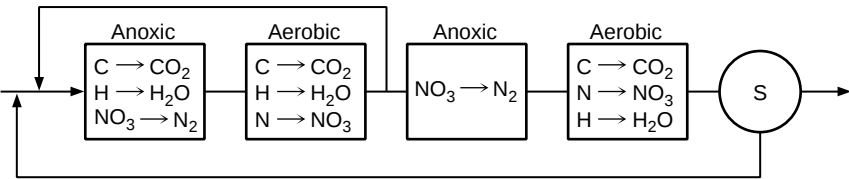


FIG. 25-55 Nitrogen removal systems.

generated by algal cells. These two lagoon types are relatively shallow to encourage surface aeration and provide for maximum algal activity. The third type of lagoon is maintained under anaerobic conditions to foster methane fermentation. This system is often covered with floating polystyrene panels to block surface aeration and help prevent a drop in temperature. Anaerobic lagoons are several meters deeper than the other two types. Lagoon flow schemes can be complex, employing lagoons in series and recycle from downstream to upstream lagoons. The major effect of recycle is to maintain control of the solids. If solids escape the lagoon system, a poor effluent is produced. Periodically controlled solids removal must take place or solids will escape.

Lagoons are, in effect, inexpensive reactors. They are shallow basins either cut below grade or formed by dikes built above grade or a combination of a cut and dike. The bottom must be lined with an impermeable barrier and the sides protected from wind erosion. These systems are best used where large areas of inexpensive land are available.

Facultative Lagoons These lagoons have been designed to use both aerobic and anaerobic reactions. Normally, facultative lagoons consist of two or more cells in series. The settleable solids tend to settle out in the first cell and undergo anaerobic metabolism with the production of organic acids and methane gas, which bubbles out to the atmosphere. Algae at the surface of the lagoon utilize sunlight for their energy in converting carbon dioxide, water, and ammonium ions into algal protoplasm with the release of oxygen as a waste product. Aerobic bacteria utilize the oxygen released by the algae to stabilize the soluble and colloidal organics. Thus, the bacteria and algae form a symbiotic relationship as shown in Fig. 25-56. The interesting aspect of facultative lagoons is that the organic matter in the incoming wastewaters is not stabilized but rather is converted to microbial protoplasm, which has a slower rate of oxygen demand. In fact, in some facultative lagoons inorganic compounds in the wastewaters are converted to organic compounds with a total increase in organics within the lagoon system.

Facultative lagoons are designed on the basis of organic load in relationship to the potential sunlight availability. In the northern part of the United States facultative lagoons are designed on the basis of $2.2 \text{ g}/(\text{m}^2\text{-day})$ [$20 \text{ lb BOD}_5/(\text{acre}\text{-day})$]. In the middle part of the United States the organic load can be increased to 3.4 to $4.5 \text{ g}/(\text{m}^2\text{-day})$ [30 to $40 \text{ lb BOD}_5/(\text{acre}\text{-day})$], while in the southern part the organic load can be increased to $6.7 \text{ g}/(\text{m}^2\text{-day})$ [$60 \text{ lb BOD}_5/(\text{acre}\text{-day})$]. The depth of lagoons is normally maintained between 1.0 and 1.7 m (3 and 5 ft). A depth less than 1.0 m (3 ft) encourages the growth of aquatic weeds and permits mosquito breeding. In dry areas the maximum depth may be increased above 1.7 m (5 ft) depending upon evaporation. Most facultative lagoons depend upon natural wind action for mixing and should not be placed in screened areas where wind action is blocked.

Effluent quality from facultative lagoons is related primarily to the suspended solids created by living and dead microbes. The long retention period in the lagoons allows the microbes to die off, leaving a small particle that settles slowly. The release of nutrients from the dead microbes permits the algae to survive by recycling the nutrients.

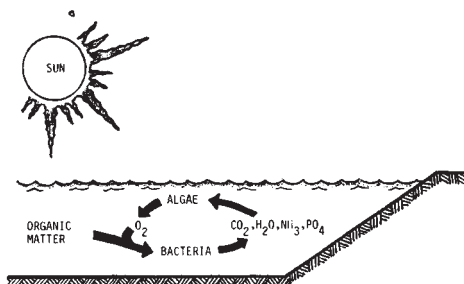


FIG. 25-56 Schematic diagram of oxidation-pond operations.

Thus, the algae determine the ultimate effluent quality. Use of series ponds with well-designed transfer structures between ponds permits maximum retention of algae within the ponds and the best-quality effluent. Normally the soluble BOD_5 is under 5 or 10 mg/L with a total effluent BOD_5 under 30 mg/L . The effluent suspended solids will vary widely during the different seasons of the year, being a maximum of 70 to 100 mg/L in the summer months and a minimum of 10 to 20 mg/L in the winter months. If suspended-solids removal is essential, chemical precipitation is the best method available at the present time. Slow sand filters and rock filters have been studied for suspended-solids removal; they work well as long as the effluent suspended solids are relatively low, 40 to 70 mg/L .

Aerated Lagoons These lagoons originated from efforts to control overloaded facultative lagoons. Since the lagoons were deficient in oxygen, additional oxygen was supplied by either mechanical surface aerators or diffused aerators. Mechanical surface aerators were quickly accepted as the primary aerators because they could be quickly added to existing ponds and moved to strategic locations. Unfortunately, the high-speed, floating surface aeration units were not efficient, and large numbers were required for existing lagoons. The problem was simply one of poor mixing in a very shallow lagoon.

Eventually, diffused aeration equipment was added to relatively deep lagoons [3.0 to 6.0 m (10 to 20 ft)]. Mixing became the most significant parameter for good oxygen transfer in aerated lagoons. From an economical point of view, it was found that a completely mixed aerated lagoon with 24-h retention provided the best balance between mixing and oxygen transfer. As the organic load increased, the fluid-retention time also increased. Short-term aeration permitted metabolism of the soluble organics by the bacteria, but time did not permit metabolism of the suspended solids. The suspended solids were combined with the microbial solids produced from metabolism and discharged from the aerated lagoon to a solids-separation pond. Data from the short-term aerated lagoon indicated that 50 percent BOD_5 stabilization occurred, with conversion of the soluble organics to microbial cells. The problem was separation and stabilization of the microbial cells. Short-term sedimentation ponds permitted separation of the solids without significant algae growths but required cleaning at frequent intervals to keep them from filling with solids and flowing into the effluent. Long-term lagoons permitted solids separation and stabilization but also permitted algae to grow and affect effluent quality.

Aerated lagoons were simply dispersed microbial reactors which permitted conversion of the organic components in the wastewaters to microbial solids without stabilization. The residual organics in solution were very low, less than 5 mg/L BOD_5 . By adding oxygen and improving mixing, the microbial metabolism reaction was speeded up, but the stabilization of the microbial solids has remained a problem to be solved.

Anaerobic Lagoons These lagoons were developed when a major fraction of the organic contaminants consisted of suspended solids that could be removed easily by gravity sedimentation. The anaerobic lagoons are relatively deep [8.0 to 6.0 m (10 to 20 ft)], with a short fluid-retention time (3 to 5 days) and a high BOD_5 loading rate, up to $3.2 \text{ kg}/(\text{m}^3\text{-day})$ [$200 \text{ lb}/(1000 \text{ ft}^3\text{-day})$]. Microbial metabolism in the settled-solids layer produces methane and carbon dioxide, which quickly rise to the surface, carrying some of the suspended solids. A scum layer that retards oxygen transfer and release of obnoxious gases is quickly produced in anaerobic lagoons. Mixing with a grinder pump can provide a better environment for metabolism of the suspended solids. The key for anaerobic lagoons is adequate buffer to keep the pH between 6.5 and 8.0 . Protein wastes have proved to be the best pollutants to be treated by anaerobic lagoons, with the ammonium ions reacting with carbon dioxide and water to form ammonium bicarbonate as the primary buffer. High-carbohydrate wastes are poor in anaerobic lagoons since they produce organic acids without adequate buffer, making it difficult to maintain a suitable pH for good microbial growth.

Anaerobic lagoons do not produce a high-quality effluent but are able to reduce the BOD load by 80 to 90 percent with a minimum of effort. Since anaerobic lagoons work best on strong organic wastes, their effluent must be treated by either aerated lagoons or facultative

lagoons. An anaerobic lagoon is simply the first stage in the treatment of strong organic wastewaters.

Fixed Film Reactor Systems A major advantage of fixed film systems is that a flocculent-type biomass is not necessary as the biomass remains in the reactor attached to inert packing. Biomass does periodically slough off or break away from the packing, usually in large chunks that can be easily removed in a clarifier. On the other hand, the time of contact between the biomass and the waste is much shorter than in suspended growth systems, making it difficult to achieve the same degree of treatment especially in aerobic systems. Aerobic, anoxic, and anaerobic fixed film systems are utilized for waste treatment.

Aerobic systems including trickling filters and rotating biological contactors (RBC) are operated in a nonflooded mode to ensure adequate oxygen supply. Other aerobic, anoxic, and anaerobic systems employ flooded reactors. The most common systems are packed beds (anaerobic trickling filter) and fluidized or expanded bed systems.

Trickling Filters For years trickling filters were the mainstay of biological wastewater treatment systems because of their simplicity of design and operation. Trickling filters were displaced as the primary biological treatment system by activated sludge because of better effluent quality. Trickling filters are simply fixed-medium biological reactors with the wastewaters being spread over the surface of a solid medium where the microbes are growing. The microbes remove the organics from the wastewaters flowing over the fixed medium. Oxygen from the air permits aerobic reactions to occur at the surface of the microbial layer, but anaerobic metabolism occurs at the bottom of the microbial layer where oxygen does not penetrate.

Originally, the medium in trickling filters was rock, but rock has largely been replaced by plastic, which provides greater void space per unit of surface area and occupies less volume within the filter. A plastic medium permitted trickling filters to be increased from a medium depth of 1.8 m (6 ft) to one of 4.2 m (14 ft) and even 6.0 m (20 ft). The wastewaters are normally applied by a rotary distributor or a fixed-spray nozzle. The spraying or discharging of wastewaters above the trickling-filter medium permits better distribution over the medium and oxygen transfer before reaching the medium. The effluent from the trickling-filter medium is captured in a clay-tile underdrain system or in a tank below the plastic medium. It is important that the bottom of the trickling filter be open for air to move quickly through the filter and bring adequate oxygen for the microbial reactions.

If a high-quality effluent is required, trickling filters must be operated at a low hydraulic-loading rate and a low organic-loading rate. Low-rate trickling filters are operated at hydraulic loadings of 2.2×10^{-5} to 4.3×10^{-5} $\text{m}^3/(\text{m}^2 \cdot \text{s})$ [2 million to 4 million $\text{gal}/(\text{acre} \cdot \text{day})$]. High-rate trickling filters are designed for 10.8×10^{-5} to 40.3×10^{-5} $\text{m}^3/(\text{m}^2 \cdot \text{s})$ [10 million to 40 million $\text{gal}/(\text{acre} \cdot \text{day})$] hydraulic loadings and organic loadings up to 1.4 $\text{kg}/(\text{m}^3 \cdot \text{day})$ [90 lb $\text{BOD}_5/(\text{1000 ft}^3 \cdot \text{day})$]. Plastic-medium trickling filters have been designed to operate up to 108×10^{-5} $\text{m}^3/(\text{m}^2 \cdot \text{s})$ [100 million $\text{gal}/(\text{acre} \cdot \text{day})$] or even higher, with organic loadings up to 4.8 $\text{kg}/(\text{m}^3 \cdot \text{day})$ [300 lb $\text{BOD}_5/(\text{1000 ft}^3 \cdot \text{day})$]. Low-rate trickling filters will produce better than 90 percent BOD_5 and suspended-solids reductions, while high-rate trickling filters will produce from 65 to 75 percent BOD_5 reduction. Plastic-medium trickling filters will produce from 59 to 85 percent BOD_5 reduction depending upon the organic-loading rate. It is important to recognize that concentrated industrial wastes will require considerable hydraulic recirculation around the trickling filter to obtain the proper hydraulic-loading rate without excessive organic loads. With high recirculation rates the organic load is distributed over the entire volume of the trickling filter for maximum organic removal. The short fluid-retention time within the trickling filter is the primary reason for the low treatment efficiency.

Rotating Biological Contactors (RBC) The newest form of trickling filter is the rotating biological contactor with a series of circular plastic disks, 3.0 to 3.6 m (10 to 12 ft) in diameter, immersed to approximately 40 percent diameter in a shaped contact tank. The RBC disks rotate at 2 to 5 r/min. As the disks travel through the wastewaters, a small layer adheres to them. As the disks travel into the air, the microbes on the disk surface oxidize the organics. Thus, only a small amount of energy is required to supply the required oxygen for

wastewater treatment. As the microbes build up on the plastic disks, the shearing velocity that is created by the movement of the disks through the water causes the excess microbes to be removed from the disks and discharged to the final sedimentation tank.

Rotating biological contactors have been very popular in treating industrial wastes because of their relatively small size and their low energy requirements. Unfortunately, there have occurred a number of problems which should be recognized prior to using RBCs. Strong industrial wastes tend to create excessive microbial growths which are not easily sheared off and which create high oxygen-demand rates with the production of hydrogen sulfide and other obnoxious odors. The heavy microbial growths have damaged some of the disks and caused some shaft failures. The disks are currently being covered with plastic shells to prevent nuisance odors from occurring. Air must be forced through the covered RBC systems and be chemically treated before being discharged back into the environment. Recirculation of wastewater flow around the RBC units can distribute the load over all the units and reduce the heavy initial microbial growths. RBC units also work best under uniform organic loads, requiring surge tanks for many industrial wastes. The net result has been for the cost of RBC units to approach that of other treatment units in terms of organic matter stabilized.

RBCs should be designed on both a hydraulic-loading rate and an organic-loading rate. Normally, hydraulic-loading rates of up to 0.16 $\text{m}^3/(\text{m}^2 \cdot \text{day})$ [4 $\text{gal}/(\text{ft}^2 \cdot \text{day})$] of surface area are used with organic loading rates up to 44 $\text{kg}/(\text{m}^2 \cdot \text{day})$ [9 lb $\text{BOD}_5/(\text{ft}^2 \cdot \text{day})$]. Treatment efficiency is primarily a function of the fluid-retention time and the organic-loading rate. At low organic-loading rates the RBC units will produce nitrification in the same way as low-rate trickling filters.

Packed-Bed Fixed-Film Systems These systems were originally termed anaerobic trickling filters because the first systems were submerged columns filled with stones run under anaerobic conditions (Fig. 25-57). A wide variety of packed media is now used ranging in size from granules 40 mesh to 7.5-cm (3-in) stones. Many systems use open structure plastic packing similar to that used in aerobic trickling filters.

The systems using granular media packing are used for anoxic denitrification. They are usually downflow, thus serving the dual function of filtration and denitrification. Contact times are short (EBCT < 15 min), but excellent removal is achieved due to the high level of biomass retained in the reactor. Pacing the methanol dose to the varying feed nitrate concentration is crucial. Frequent, short-duration backwash (usually several times per day) is required or the nitrogen bubbles formed will bind the system, causing poor results. Extended backwash every two to three days is required or the system will clog on the biomass growth. Thus, several units in parallel or a large holding tank are needed to compensate for the down time during backwash. Backwash does not remove all the biomass; a thin film remains coating the packing. Thus, denitrification begins immediately when the flow is restored.

The systems using the larger packing are used in the treatment of relatively strong, low-suspended-solids industrial waste. These systems are closed columns usually run in an upflow mode with a gas space at the top. These are operated under anaerobic conditions with waste conversion to methane and carbon dioxide as the goal. Effluent recycle is often used to help maintain the pH in the inlet zone in the correct range 6.5–7.5 for the methane bacteria. Some wastes require the addition of alkaline material to prevent a pH drop. Sodium bicarbonate is often recommended for pH control because it is easier to handle than lime or sodium hydroxide, and because an overdose of bicarbonate will only raise the pH modestly. An overdose of lime or sodium hydroxide can easily raise the pH above 8.0. Table 25-44 gives some performance data with systems treating industrial wastes. HRTs of 1 to 2 days are used, as the buildup of growth on the packing ensures a BSRT of 20–50 days. It should be possible to lower the HRT further, but in practice this has not been successful because biomass starts to escape from the system or plugging occurs. Some escape is due to high gasification rates, and some is due to the fact that anaerobic sludge attaches less tenaciously to packing than aerobic or anoxic sludge. These systems can handle wastes with moderate solids levels. Periodically, solids must be removed from the reactor to prevent plugging of the packing or loss of solids in the effluent.

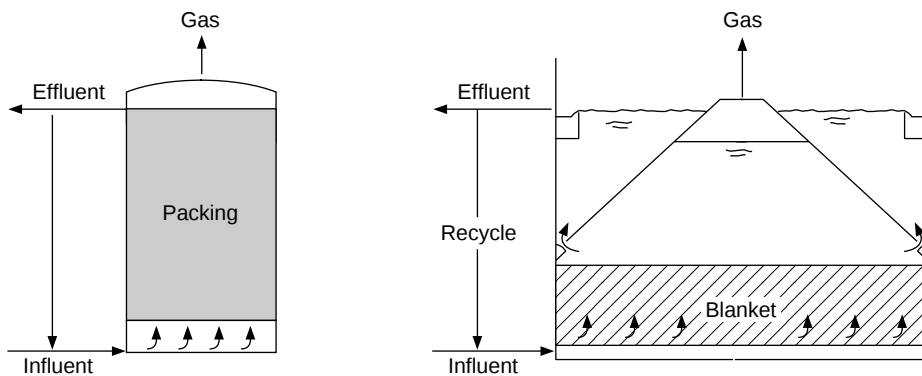


FIG. 25-57 Anaerobic processes.

Biological Fluidized Beds This high-rate process has been used successfully for aerobic, anoxic, and anaerobic treatment of municipal and industrial wastewaters. Numerous small- and large-scale applications for hazardous waste, contaminated groundwater, nontoxic industrial waste and municipal wastewater have been reported (Refs. 32 and 33). The basic element of the process is a bed of solid carrier particles, such as sand or granular activated carbon, placed in a reactor through which wastewater is passed upflow with sufficient velocity to impart motion or fluidize the carrier. An active growth of biological organisms grow as firmly attached mass surrounding each of the carrier particles. As the wastewater contaminants pass by the biologically covered carrier, they are removed from the wastewater through biological and adsorptive mechanisms. Figure 25-58 is a schematic of the process.

The influent wastewater enters the reactor through a pipe manifold and is introduced downflow through nozzles that distribute the flow uniformly at the base of the reactor. Reversing direction at the bottom, the flow fluidizes the carrier when the fluid drag overcomes the buoyant weight of the carrier and its attached biomass layer. During startup (before much biomass has accumulated), the flow velocity required to achieve fluidization is higher than after the biomass attaches. Recycle of treated effluent is adjusted to achieve the desired degree of fluidization. As biomass accumulates, the particles of coated biomass will separate to a greater extent at constant flow velocity. Thus, as the system ages and more biomass accumulates, the extent of bed expansion increases (the volume of voids increases). This phenomenon is advantageous because it prevents clogging of the bed with biomass. Consequently, higher levels of biomass attachment are possible than in other types of fixed film systems. However, eventually, the degree of bed expansion may become excessive. Reduction of recycle

will reduce expansion but may not be feasible because recycle has several purposes (i.e., supply of nutrients, alkalinity, and dilution of waste strength). Control of the expanded bed surface level is automatically accomplished using a sensor that activates a biomass growth control system at a prescribed level and maintains the bed at the proper depth. A pump removes a portion of the attached biomass, separates the biomass and inert carrier by abrasion, and pumps the mixture into a separator. Here the heavy carrier settles back into the fluidized bed and the abraded biomass, which is less dense, is removed from the system by gravity or a second pump. Other growth control designs are also used. Effluent is withdrawn from the supernatant layer above the fluidized bed. The reactor is usually not covered unless it is operating under anaerobic conditions and methane, odorous gases, or other safety precautions are mandated.

When aerobic treatment is to be provided to high concentrations of organics, pure oxygen or hydrogen peroxide may be injected into the wastewater prior to entering the reactor. Liquid oxygen (LOX) or pressure swing absorption (PSA) systems have been used to supply oxygen. Air may be used at low D.O. demands.

In full-scale applications, this process has been found to operate at significantly higher volumetric loading rates for wastewater treatment than other processes. The primary reasons for the very high rates of contaminant removal is the high biologically active surface area available (approximately 1000 ft²/ft³ of reactor) and the high concentration of reactor biological solids (8,000–40,000 mg/L) that can be maintained (Table 25-45). Because of these atypical high values, designs usually indicate a 200–500 percent reduction in reactor volume when compared to other fixed film and suspended growth treatment processes. In Table 25-46, is a list of full-scale commercial applications of the process operated at high wastewater concentrations including

TABLE 25-44 Anaerobic Process Performance on Industrial Wastewater UASB, Submerged filter (SF), FBR

Process	Wastewater	Reactor size, MG	COD, g/l	OVL, kg/m ³ d	%COD _r	HRT-d	°C
SF	Rum slops	3.5	80–105	15	71	7.8	35
SF	Modified guar	0.27	9.1	7.5	60	1.0	37
SF	Chemical	1.5	14	11	90	0.7	H
SF	Milk	0.2	3	7.5	60	0.5	32
SF	PMFC	10 ⁻⁵	13.7	23	72	0.6	36
UASB	Potato	0.58	2.5	3	85	0.7	35
UASB	Sugar beet	0.21	3	16	88	—	—
UASB	Brewery	1.16	1.6–2.2S	4.4	83	0.4	30
UASB	Brewery	1.16	2.0–2.4S	8.7	78	0.2	30
UASB	PMFC	10 ⁻⁵	13.7	4–5	87	2.9	36
FBR	PMFC	10 ⁻⁵	13.7	35–48	88	0.4	36
FBR	Soft drink	0.04	3.0	6–7	75	0.5	35
FBR	Chemical	0.04	35	14	95	2.5	35

OVL = organic volumetric load (COD)

S = settled effluent

H = heated

PMFC = paper mill foul condensate (5,6)

NOTE: MG = 3785 m³.

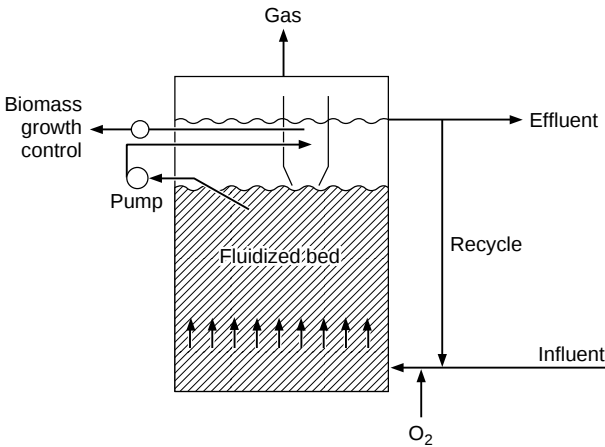


FIG. 25-58 Schematic of fluidized bed process.

aerobic oxidation of organics, anoxic denitrification and anaerobic treatment systems.

Of special note is the enhancement to the process when granular activated carbon (GAC) is used as the carrier. Because GAC has adsorptive properties, organic compounds present in potable waters and wastewater at low concentrations, often less than ten mg/L, are removed by adsorption and subsequently consumed by the biological organisms that grow in the fluidized bed. The BTEX compounds, methylene chloride, chlorobenzene, plastics industry toxic effluent, and many others are removed in this manner. BTEX contamination of groundwater from leaking gasoline storage tanks is a major problem, and sixteen full-scale fluidized bed process applications have been made. Contaminated groundwater is pumped to the ground surface for treatment using the fluidized bed in the aerobic mode. Often the level of BTEX is 1–10 mg/L and about 99 percent is removed in less than ten minutes detention time. Installations in operation range in size from 30 to 3000 gpm. The smaller installations are often skid-

TABLE 25-45 Process Comparisons

Biological process	MLVSS, mg/L	Surface area, ft ² /ft ³
Activated sludge	1500–3000	—
Pure oxygen activated sludge	2000–5000	—
Suspended growth nitrification	1000–2000	—
Suspended growth denitrification	1500–3000	—
Fluidized bed-CBOD removal	12,000–20,000	800–1200
Fluidized bed-nitrification	8,000–12,000	800–1200
Fluidized bed-denitrification	25,000–40,000	800–1200
Trickling filter-CBOD removal	—	12–50
RBC-CBOD removal	—	30–40

TABLE 25-46 Full-Scale Commercial Applications of Fluidized Bed Process

Application	Type	Reactor volume, m ³
CBOD—paint—General Motors	Aerobic	108
C,NBOD—sanitary and automotive—GM	Aerobic	165
Chemical—Grindsted Products Denmark	Aerobic	730
Nitrification—fish hatchery—Idaho	Aerobic	820
BTEX, groundwater—Ohio	Aerobic	250
Chemical, Toxicity reduction—Texas	Aerobic	225
Denitrification, Nuclear Fuel, DOE, Fernald, OH	Anoxic	53
CBOD, Denitrification—municipal, Nevada	Anoxic	1450
Petrochemical—Reliance Ind. India	Anaerobic	850
Soft drink, Delaware	Anaerobic	166
Brewery—El Aguila, Spain	Anaerobic	1570

mounted and may be moved from location to location at a given site. A major advantage of this process over stripping towers and vacuum systems for treating volatile organics (VOCs) is the elimination of effluent gas treatment.

Also, pilot plant and laboratory scale anaerobic studies have demonstrated successful treatment of wastewaters of 5,000 to 50,000 mg/L COD from corn chips containing soluble and colloidal corn starch and protein, cheese whey, organic chemicals, food, bakery, brewery, paper mill foul condensate, paint, and numerous other hazardous and non-hazardous materials.

Design criteria for satisfactory biological fluidized bed treatment systems include the major parameters given in Table 25-47.

Earlier the anaerobic trickling filter was discussed and in the above section the fluidized bed reactor was reviewed. A third type of reactor system with some similarity is the upflow anaerobic sludge blanket (UASB) system. Here, a flocculent biomass is retained in the reactor with no recycle of sludge necessary. The sludge is maintained in the system by the use of a relatively low flow rate. The sludge formed seems to be granular in nature and has a relatively high specific gravity. It is thought that the presence of small particles of CaCO₃ and/or clay in the waste may contribute to the formation of the dense sludge. A diagram of this system is shown in Fig. 25-56. The supplier of this system provides a startup seed of this granular-type biomass.

The anaerobic filter, UASB, and fluidized bed reactors have all been used for anaerobic treatment of industrial wastes, as each is especially suited for use in anaerobic treatment. Table 25-44 presents results from these applications.

PHYSICAL-CHEMICAL TREATMENT

Processes and/or unit operations that fall under this classification include adsorption, ion exchange, stripping, chemical oxidation, and membrane separations. All of these are more expensive than biological treatment but are used for removal of pollutants that are not easily removed by biomass. Often these are utilized in series with biological treatment; but sometimes they are used as stand-alone processes.

Adsorption This is the most widely used of the physical-chemical treatment processes. It is used primarily for the removal of soluble organics with activated carbon serving as the adsorbent. Most liquid-phase-activated carbon adsorption reactions follow a Freundlich Isotherm [Eq. (25-21)].

y = kc^{1/n} (25-21)

where: y = adsorbent capacity, mass pollutant/mass carbon
c = concentration of pollutant in waste, mass/volume
k and n = empirical constants

EPA has compiled significant data on values of k and n for environmentally significant pollutants with typical activated carbons. Assuming equilibrium is reached, the isotherm provides the dose of carbon required for treatment. In a concurrent contacting process, the capacity is set by the required effluent concentration. In a countercurrent process, the capacity of the carbon is set by the untreated waste pollutant concentration. Thus countercurrent contacting is preferred.

Activated carbon is available in powdered form (200–400 mesh) and granular form (10–40 mesh). The latter is more expensive but is easier to regenerate and easier to utilize in a countercurrent contactor. Powdered carbon is applied in well-mixed slurry-type contactors for

TABLE 25-47 Typical Design Parameters for Fluidized Beds

Waste	Mode	Influent concentration, mg/L	Volumetric load, lb/ft ³ -d	Hydraulic detention time, hr	Volatile solids (biosolids), g/L
Organic COD	Aerobic	<2000	0.1–0.6	0.5–2.5	12–20
Organic COD	Aerobic	<10	0.02–0.1	0.1–0.5	4–8
NH ₃ -N	Aerobic	<25	0.05–0.3	0.1–0.5	7–14
NO ₃ ⁻ -N	Anoxic	<5,000	0.4–2	0.1–2.4	20–40
Organic COD	Anaerobic	>4000	0.5–4	2–24	20–40

NOTE: lb/ft³-d = 16 kg/m³-d.

detention times of several hours after which separation from the flow occurs by sedimentation. Often coagulation, flocculation, and filtration are required in addition to sedimentation. As it is difficult to regenerate, powdered carbon is usually discarded after use. Granular carbon is used in column contactors with EBCT of 30 minutes to 1 hour. Often several contactors are used in series, providing for full countercurrent contact. A single contactor will provide only partial countercurrent contact. When a contactor is exhausted, the carbon is regenerated either by a thermal method or by passing a solvent through the contactor. For waste-treatment applications where a large number of pollutants must be removed but the quantity of each pollutant is small, thermal regeneration is favored. In situations where a single pollutant in large quantity is removed by the carbon, solvent extraction regeneration can be used, especially where the pollutant can be recovered from the solvent and reused. Thermal regeneration is a complex operation. It requires removal of the carbon from the contactor, drainage of free water, transport to a furnace, heating under controlled conditions of temperature, oxygen, time, water vapor partial pressure, quenching, transport back to the reactor, and reloading of the column. Five to ten percent of the carbon is lost in this regeneration process due to burning and attrition during each regeneration cycle. Multiple hearth, rotary kiln, and fluidized bed furnaces have all been successfully used for carbon regeneration.

Pretreatment prior to carbon adsorption is usually for removal of suspended solids. Often this process is used as tertiary treatment after primary and biological treatment. In either situation, the carbon columns must be designed to provide for backwash. Some solids will escape pretreatment, and biological growth will occur on the carbon, even with extensive pretreatment. Originally carbon treatment was viewed only as applicable for removal of toxic organics or those that are difficult to degrade biologically. Present practice applies carbon adsorption as a procedure for removal of all types of organics. It is realized that some biological activity will occur in virtually any activated carbon unit, so the design must be adjusted accordingly.

Ion Exchange This process has been employed for many years for treatment of industrial water supplies but not for wastes. However, some new ion-exchange materials have recently been developed that can be used for removal of specific pollutants. These new resins are primarily useful for selective removal of heavy metals, even though the target metals are present at low concentration in a wastewater containing many other inorganics. An ion-exchange process is usually operated with the waste being run downflow through a series of columns containing the appropriate ion-exchange resins. EBCT contact times of 30 min to 1 hour are used. Pretreatment for suspended solids and organics removal is practiced as well as pH adjustment.

The capacity of an ion-exchange resin is a function of the type and concentration of regenerant. Because ion-exchange resins are so selective for the target compound, a significant excess of the regenerant must be used. Up to a point, the more regenerant, the greater the capacity of the resin. Unfortunately, this results in waste of most of the regenerant. In fact, the bulk of the operational cost for this process is for regenerant purchase and its disposal; thus, regeneration must be optimized. Regenerants used (selection depends on the ion exchange resin) include sodium chloride, sodium carbonate, sulfuric acid, sodium hydroxide, and ammonia. Table 25-48 gives information on some of the new highly selective resins. These resins may provide the only practical method for reduction of heavy metals to the very low levels required by recent EPA regulations.

Stripping Air stripping is applied for the removal of volatile substances from water. Henry's law is the key relationship for use in design of stripping systems. The minimum gas-to-liquid ratio required for stripping is given by:

$$\frac{G}{L} = \frac{S_{in} - X_{out}}{(H)X_{out}}$$

for a concurrent process and

$$\frac{G}{L} = \frac{X_{in} - X_{out}}{(H)X_{in}}$$

for a countercurrent process where:

G = air flow rate, mass/time

L = waste flow rate, volume/time

X = concentration of pollutant in waste, mass/volume

H = Henry's constant for the pollutant in water, volume/mass

Higher ratios of gas to liquid flow are required than those computed above because mass-transfer limitations must be overcome. Stripping can occur by sparging air into a tank containing the waste. Indeed, stripping of organics from activated sludge tanks is of concern because of the possibility that the public will be exposed to airborne pollutants including odors. A much more efficient stripping procedure is to use countercurrent or crossflow contact towers. Procedures for design of these and mass-transfer characteristics of various packings are available elsewhere in this handbook.

Stripping has been successfully and economically employed for removal of halogenated organics from water and wastes with dispersion of the effluent gas to the atmosphere. However, recent EPA regulations have curtailed this practice. Now removal of these toxic organics from the gas stream is also required. Systems employing activated carbon (prepared for use with gas streams) are employed as well as systems to oxidize the organics in the gas stream. However, the cost of cleaning up the gas stream often exceeds the cost of stripping these organics from the water.

Chemical Oxidation This process has not been widely utilized because of its high cost. Only where the concentration of the target compound is very low will the quantity of oxidant required be low enough to justify treatment by chemical oxidation. The efficiency of this process is also low, as many side reactions can occur that will consume the oxidant. In addition, complete oxidation of organics to carbon dioxide and water often will not occur unless a significant overdose is used. However, renewed interest has recently occurred for two reasons.

1. It has been found that partial oxidation is satisfactory as a pretreatment to biological or carbon adsorption treatment. Partial oxidation often seems to make recalcitrant organics easier to degrade biologically and easier to adsorb.

2. A combination of ozone oxidation with simultaneous exposure to ultraviolet light seems to produce a self-renewing chain reaction that can significantly reduce the dose of ozone needed to accomplish oxidation.

Oxidants commonly used include ozone, permanganate, chlorine, chlorine dioxide, and ferrate, often in combination with catalysts. Standard-type mixed reactors are used with contact times of several minutes to an hour. Special reactors for use with ultraviolet light have been developed.

Membrane Processes These processes use a selectively permeable membrane to separate pollutants from water. Most of the mem-

TABLE 25-48 Selective Ion-Exchange Resins

Application	Exchanger type	Composition	Regenerant
Softening	Cation	Polystyrene matrix Sulfonic acid functional groups	NaCl
Heavy metals	Cation	Polystyrene matrix Chelating functional groups	Mineral acids
Chromate	Anion	Polystyrene matrix Tertiary or quaternary ammonium functional groups	Sodium carbonate or alkaline NaCl
Nitrate	Anion	Polystyrene matrix Tributyl ammonium functional group	NaCl

branes are formulated from complex organics that polymerize during membrane preparation. This allows the membrane to be tailored to discriminate by molecular size or by degree of hydrogen bonding potential. Ultrafiltration membranes discriminate by molecular size or weight, while reverse osmosis membranes discriminate by hydrogen-bonding characteristics. The permeability of these membranes is low: from 0.38–3.8 m/day (10–100 gal/d/ft²). The apparatus in which they are used must provide a high surface area per unit volume. The membranes are also fragile and are often subjected to several hundred psi of pressure. Thus the apparatus must provide a rugged support structure and efficient seals to prevent leakage. Membrane support configurations include tubular, spiral-wound, and hollow fine fiber systems. An operational problem is the buildup of pollutant on the side of the membrane where rejection occurs. This leads to fouling of the membrane surface which initially reduces water flux. Eventually, deterioration and membrane failure occur. Membrane life is in the range 1–2 years. New membrane materials with improved properties are being sought. Membrane separation-based systems require extensive pretreatment and continual maintenance to reduce fouling. These systems have significant potential, but much developmental work is needed on membrane characteristics and the support apparatus.

SLUDGE PROCESSING

Objectives Sludges consist primarily of the solids removed from liquid wastes during their processing. Thus, sludges could contain a wide variety of pollutants and residuals from the application of treatment chemicals; i.e., large organic solids, colloidal organic solids, metal sulfides, heavy-metal hydroxides and carbonates, heavy-metal organic complexes, calcium and magnesium hydroxides, calcium carbonate, precipitated soaps and detergents, and biomass and precipitated phosphates. As sludge even after extensive concentration and dewatering is still greater than 50 percent by weight water, it can also contain soluble pollutants such as ammonia, priority pollutants, and nonbiologically degradable COD.

The general treatment or management of sludge involves stabilization of biodegradable organics, concentration and dewatering, and ultimate disposal of the stabilized and dewatered residue. A large number of individual unit processes and unit operations are used in a sludge-management scheme. Those most frequently used are discussed below. Occasionally, only one of these is needed, but usually several are used in a series arrangement.

Because of the wide variability in sludge characteristics and the variation in acceptability of treated sludges for ultimate disposal (this is a function of the location and characteristics of the ultimate disposal site), it is impossible to prescribe any particular sludge-management plan. In the sections below, general performance of individual sludge-treatment processes and operations is presented.

Concentration: Thickening and Flotation Generated sludges are often dilute (1–2 percent solids by weight). In order to reduce the volumetric loading on other processes, the first step in sludge processing is often concentration. The most popular process is gravity thickening which is carried out in treatment units similar to circular clarifiers. Organic sludges from primary treatment can usually be concentrated to 5–8 percent solids. Sludges from secondary treatment can be thickened to 2 percent solids. The potential concentration with completely inorganic sludges is higher (greater than 10 percent solids) except for sludges high in metal hydroxides. Polymers are often used to speed up thickening and increase concentration. Thickening is enhanced by long retention of the solids in the thickening apparatus. However, when biodegradable organics are present, solids retention time must be at a level that will not foster biological activity, lest odors, gas generation, and solids hydrolysis occur. Loading rates on thickeners range from 50–122 kg/m²/d (10–25 lb/ft²/d) for primary sludge to 12–45 kg/m²/d (2.5–9 lb/ft²/d). Solids detention time is 0.5 days in summer to several days in winter.

Flotation Air flotation has proved to be successful in concentrating secondary sludges to about 4 percent solids. The incoming solids are normally saturated with air at 275 to 350 kPa (40 to 50 psig) prior to being released in the flotation tank. As the air comes out of solution, the fine bubbles are trapped under the suspended solids and carry

them to the surface of the tank. The air bubbles compact the solids as a floating mass. Normally, the air-to-solids ratio is about 0.01–0.05 L/g (0.16–0.8 ft³/lb). The thickened solids are scraped off the surface, while the effluent is drawn off the middle of the tank and returned to the treatment system. In large flotation tanks with high flows the effluent rather than the incoming solids is pressurized and recycled to the influent. The size of the flotation tanks is determined primarily by the solids-loading rate, directly or indirectly. A solids loading of 25 to 97 kg/(m²·day) [5 to 20 lb/(ft²·day)] has been found to be adequate. On a flow basis this translates into 0.14 to 2.7 L/(m²·day) [0.2 to 4 gal/(ft²·min)] surface area.

As with thickening, air flotation is enhanced by the addition of polymers. Flotation has been successfully used with wholly inorganic metal hydroxide sludges. Polymers and surfactants are used as additives. Engineering details on air flotation equipment has been developed by and is available from various equipment manufacturing companies. Liquid removed during thickening and flotation is usually returned to the head end of the plant.

Stabilization (Anaerobic Digestion, Aerobic Digestion, High Lime Treatment) Sludges high in organics can be stabilized by subjecting them to biological treatment. The most popular system is anaerobic digestion.

Anaerobic Digestion Anaerobic digesters are large covered tanks with detention times of 30 days, based on the volume of sludge added daily. Digesters are usually heated with an external heat exchanger to 35–37° C to speed the rate of reaction. Mixing is essential to provide good contact between the microbes and the incoming organic solids. Gas mixing and mechanical mixers have been used to provide mixing in the anaerobic digester. Following digestion, the sludge enters a holding tank, which is basically a solids-separation unit and is not normally equipped for either heating or mixing. The supernatant is recycled back to the treatment plant, while the settled sludge is allowed to concentrate to 3–6 percent solids before being further processed.

Anaerobic digestion results in the conversion of the biodegradable organics to methane, carbon dioxide, and microbial cells. Because of the energy in the methane, the production of microbial mass is quite low, less than 0.1 kg/kg (0.1 lb volatile suspended solids (VSS)/lb) BCOD metabolized except for carbohydrate wastes. The production of methane is 0.35 m³/kg (5.6 ft³/lb) BCOD destroyed. Digester gases range from 50 to 80 percent methane and 20 to 50 percent carbon dioxide, depending on the chemical characteristics of the waste organics being digested. The methane is often used on site for heat and power generation.

There are three major groups of bacteria that function in anaerobic digestion. The first group hydrolyzes large soluble and nonsoluble organic compounds such as proteins, fats and oils (grease), and carbohydrates, producing smaller water-soluble compounds. These are then degraded by acid-forming bacteria, producing simple volatile organic acids (primarily acetic acid) and hydrogen. The last group (the methane bacteria) split acetic acid to methane and carbon dioxide and produce methane from carbon dioxide and hydrogen. Good operation requires the destruction of the volatile acids as quickly as they are produced. If this does not occur, the volatile acids will build up and depress the pH, which will eventually inhibit the methane bacteria. To prevent this from occurring, feed of organics to the digester should be as uniform as possible.

If continuous addition of solids is not possible, additions should be made at as short intervals as possible. Alkalinity levels are normally maintained at about 3000 to 5000 mg/L to keep the pH in the range 6.5–7.5 as a buffer against variable organic-acid production with varying organic loads. Proteins will produce an adequate buffer, but carbohydrates will require the addition of alkalinity to provide a sufficient buffer. Sodium bicarbonate should be used to supply the buffer.

An anaerobic digester is a no-recycle complete mix reactor. Thus, its performance is independent of organic loading but is controlled by hydraulic retention time (HRT). Based on kinetic theory and values of the pseudo constants for methane bacteria, a minimum HRT of 3 to 4 days is required. To provide a safety factor and compensate for load variation as indicated earlier, HRT is kept in the range 10 to 30 days. Thickening of feed sludge is used to reduce the tank volume required

to achieve the long HRT values. When the sludge is high in protein, the alkalinity can increase to greater than 5000 mg/L, and the pH will rise past 7.5. This can result in free ammonia toxicity. To avoid this situation, the pH should be reduced below 7.5 with hydrochloric acid. Use of nitric or sulfuric acid will result in significant operational problems.

Aerobic Digestion Waste activated sludge can be treated more easily in aerobic treatment systems than in anaerobic systems. The sludge has already been partially aerobically digested in the aeration tank. For the most part, only about 25 to 35 percent of the waste activated sludge can be digested. An additional aeration period of 15 to 20 days should be adequate to reduce the residual biodegradable mass to a satisfactory level for dewatering and return to the environment. One of the problems in aerobic digestion is the inability to concentrate the solids to levels greater than 2 percent. A second problem is nitrification. The high protein concentration in the biodegradable solids results in the release of ammonia, which can be oxidized during the long retention period in the aerobic digester. Limiting oxygen supply to the aerobic digester appears to be the best method to handle nitrification and the resulting low pH.

A new concept is to use an on/off air supply cycle. During aeration, nitrates are produced. When the air is shut off, nitrates are reduced to nitrogen gas. This prevents acid buildup and removes nitrogen from the sludge. High power cost for aerobic digestion restricts the applicability of this process.

High Lime Treatment Uses doses of lime sufficient to raise the pH of sludge to 12 or above. As long as the pH is maintained at this level, biological breakdown will not occur. In this sense, the sludge is stable. However, any reduction of pH as a result of contact with CO₂ in the air will allow biological breakdown to begin. Thus, this technique should only be used as temporary treatment until further processing can occur. It is not permanent stabilization as is provided by anaerobic or aerobic digestion.

Sludge Dewatering Dewatering is different from concentration in that the latter still leaves a substance with the properties of a liquid. The former produces a product which is essentially a friable solid. When the water content of sludge is reduced to <70–80 percent, it forms a porous solid called sludge cake. There is no free water in the cake, as the water is chemically combined with the solids or tightly adsorbed on the internal pores. The operations below which are used to dewater sludge can be applied at any stage of the sludge management process, but often they follow concentration and/or biological stabilization. Chemical conditioning is almost always used to aid dewatering.

Lime, alum, and various ferric salts have been used to condition sludge prior to dewatering. Lime reacts to form calcium carbonate crystals, which act as a solid matrix to hold the sludge particles apart and allow the water to escape during dewatering. Alum and iron salts help displace some of the bound water from hydrophilic organics and form part of the inorganic matrix. Chemical conditioning increases the mass of sludge to be ultimately handled from 10 to 25 percent, depending upon the characteristics of the individual sludge. Chemical conditioning can also help remove some of the fine particles by incorporating them into insoluble chemical precipitates. The water (supernatant) removed from the sludge during dewatering is often high in suspended solids and organics. Addition of polymers prior to, during, or after dewatering will often reduce the level of pollutants in the supernatant.

Centrifugation Both basket and solid-bowl centrifuges have been used to concentrate waste sludges. Field data have shown that it is possible to obtain 10 to 20 percent solids with waste activated sludge, 15 to 30 percent solids with a mixture of primary and waste activated sludge, and up to 30 to 35 percent solids with primary sludge alone. Centrifuges result in 85 to 90 percent solids capture with good operation. The problem is that the centrate contains the fine solids not easily removed. The centrate is normally returned to the treatment process, where it may or may not be removed. Economics do not favor centrifuges unless the sludge cake produced is at least 25 to 30 percent solids. For the most part, centrifuges are designed by equipment manufacturers from field experience. With varying sludge characteristics centrifuge characteristics will also vary widely.

Vacuum Filtration Vacuum filtration has been the most common method employed in dewatering sludges. Vacuum filters consist of a rotary drum covered with a cloth-filter medium. Various plastic fibers as well as wool have been used for the filter cloth. The filter operates by drawing a vacuum as the drum rotates into chemically conditioned sludge. The vacuum holds a thin layer of sludge, which is dewatered as the drum rotates through the air after leaving the vat. When the drum rotates the cloth to the opposite side of the apparatus, air-pressure jets replace the vacuum, causing the sludge cake to separate from the cloth medium as the cloth moves away from the drum. The cloth travels over a series of rollers, with the sludge being separated by a knife edge and dropping onto a conveyor belt by gravity. The dewatered sludge is moved on the conveyor belt to the next concentration point, while the filter cloth is spray-washed and returned to the drum prior to entering the sludge vat. Vacuum filters yield the poorest results on waste activated sludge and the best results on primary sludge. Waste activated sludge will concentrate to between 12 and 18 percent solids at a rate of 4.9 to 9.8 kg dry cake/(m²·h) [1 to 2 lb/(ft²·h)]. Primary sludge can be dewatered to 25 to 30 percent solids at a rate of 49 kg dry cake/(m²·h) [10 lb/(ft²·h)].

Pressure Filtration Pressure filtration has been used increasingly since the early 1970s because of its ability to produce a drier sludge cake. The pressure filters consist of a series of plates and frames separated by a cloth medium. Sludge is forced into the filter under pressure, while the filtrate is drawn off. When maximum pressure is reached, the influent-sludge flow is stopped and the pressure filter is allowed to discharge the residual filtrate prior to opening the filter and allowing the filter cake to drop by gravity to a conveyor belt below the filter press. The pressure filter operates at a pressure between 689 and 1350 kPa (100 and 200 psig) and takes 1.5 to 4 h for the pressure cycle. Normally, 20 to 30 min is required to remove the filter cake. The sludge cakes will vary from 20 to 25 percent for waste activated sludge to 50 percent for primary sludge. Chemical conditioning is necessary to obtain good dewatering of the sludges.

Belt-Press Filters The newest filter for handling waste activated sludge is the belt-press filter. The belt press utilizes a continuous cloth-filter belt. Waste activated sludge is spread over the filter medium, and water is removed initially by gravity. The open belt with the sludge moves into contact with a second moving belt, which squeezes the sludge layer between rollers with ever-increasing pressure. The sludge cake is removed at the end of the filter press by a knife blade, with the sludge dropping by gravity to a conveyor belt. Belt-press filters can produce sludge with 20–30 percent solids.

Sand Beds Sand filter beds can be used to dewater either anaerobically or aerobically digested sludges. They work best on relatively small treatment systems located in relatively dry areas. The sand bed consists of coarse gravel graded to fine sand in a series of layers to a depth of 0.45 to 0.6 m (1.5 to 2 ft). The digested sludge is placed over the entire filter surface to a depth of 0.3 m (12 in) and allowed to sit until dry. Free water will drain through the sand bed to an open pipe underdrain system and be removed from the filter. Air drying will slowly remove the remaining water. The sludge must be cleaned from the bed by hand prior to adding a second layer of sludge. The sludge layer will drop from an initial thickness of 3 m (12 in) to about 0.006 m (¼ in). An open sand bed can generally handle 49 to 122 kg dry solids/(m²·year) [10 to 25 lb/(ft²·year)]. Covered sand beds have been used in wet climates as well as in cold climates, but economics does not favor their use.

SLUDGE DISPOSAL

Incineration Incineration has been used to reduce the volume of sludge after dewatering. The organic fractions in sludges lend themselves to incineration if the sludge does not have an excessive water content. Multiple-hearth and fluid-bed incinerators have been extensively used for sludge combustion.

A multiple-hearth incinerator consists of several hearths in a vertical cylindrical furnace. The dewatered sludge is added to the top hearth and is slowly pushed through the incinerator, dropping by gravity to the next lower layer until it finally reaches the bottom layer. The top layer is used for drying the sludge with the hot gases from the

lower layers. As the temperature of the furnace increases, the organics begin to degrade and undergo combustion. Air is used to add the necessary oxygen and to control the temperature during combustion. It is very important to keep temperatures above 600° C to ensure complete oxidation of the volatile organics. One of the problems with the multiple-hearth incinerator is volatilization of odorous organics during the drying phase before the temperature reaches combustion levels. Even afterburners on the exhaust-gas line may not be adequate for complete oxidation. Air-pollution-control devices are required on all incinerators to remove fly ash and corrosive gases. The ash from the incinerator must be cooled, collected, and conveyed back to the environment, normally to a sanitary landfill for burial. The residual ash will weigh from 10 to 30 percent of the original dry weight of the sludge. Supplemental fuels are needed to start the incinerator and to ensure adequate temperatures with sludges containing excessive moisture, such as activated sludge. Heat recovery from wastes is being given more consideration. It is possible to combine the sludges with other wastes to provide a better fuel for the incinerator.

A fluid-bed incinerator uses hot sand as a heat reservoir for dewatering the sludge and combusting the organics. The turbulence created by the incoming air and the sand suspension requires the effluent gases to be treated in a wet scrubber prior to final discharge. The ash is removed from the scrubber water by a cyclone separator. The scrubber water is normally returned to the treatment process and diluted with the total plant effluent. The ash is normally buried.

Sanitary Landfills Dewatered sludge, either raw or digested, is often buried in a sanitary landfill to minimize the environmental impact. Increased concern over sanitary landfills has made it more difficult simply to bury dewatered sludge. Sanitary landfills must be

made secure from leachate and be monitored regularly to ensure that no environmental damage occurs. The moisture content of most sludges makes them a problem at sanitary landfills designed for solid wastes, requiring separate burial even at the same landfill.

Land Spreading The nutrient content of most sludges makes them useful as fertilizers or as soil conditioners if properly mixed with the surface soil. Land spreading has gained in popularity in agricultural areas. Normally, the rate of application of sludge to land is controlled by the nitrogen content of the sludge. Since nitrogen uptake varies with different crops, nitrogen application is limited to approximately twice the annual uptake of nitrogen by the proposed crop. Approximately one-half of the nitrogen is readily available in sludge. Nutrient release with sludge is slower than with chemical fertilizers, allowing the nutrients to become available as the crop needs it. Activated sludge appears to be an excellent soil conditioner because the humus material in the sludge provides a good matrix for root growth, while the nutrient elements are released in approximately the right combination for optimal plant growth. There is a growing concern over heavy metals in some sludge, and care should be taken to minimize heavy-metal concentrations in sludges placed on the land. Since heavy metals cannot be easily removed from sludges, it is important to prevent them from entering the wastewater-treatment system. Greater concern will be placed on other potentially toxic or hazardous materials, including some organic compounds such as pesticides and PCBs. Land spreading of sludge requires careful application of the sludge at the surface and its mixing with the soil. Soil microbes will assist in further stabilization of any biodegradable organics remaining. Land spreading of sludge will become more popular as energy and nutrients become scarcer.

MANAGEMENT OF SOLID WASTES

INTRODUCTION

"Solid wastes" are all the wastes arising from human and animal activities that are normally solid and that are discarded as useless or unwanted. The term as used in this subsection is all-inclusive, and it encompasses the heterogeneous mass of throwaways. The three R's should be applied to Solid Wastes: Reuse, Recycle, and Reduce. When these have been implemented, management of residual solid waste can be addressed.

Functional Elements The activities associated with the management of solid wastes from the point of generation to final disposal have been grouped into the functional elements identified in Fig. 25-59. By considering each fundamental element separately, it is possible to (1) identify the fundamental element and (2) develop, when possible, quantifiable relationships for the purpose of making engineering comparisons, analyses, and evaluations.

Waste Reduction Processes can be redesigned to reduce the amount of waste generated. For example, transfer lines between processes can be blown clear pneumatically to drive liquid into the batch mix tank.

Waste Generation Waste generation encompasses those activities in which materials are identified as no longer being of value and are either thrown away or gathered together for disposal. From the standpoint of economics, the best place to sort waste materials for recovery is at the source of generation.

Reuse Waste may be diverted to reuse. For example, containers may be cleaned and reused or the waste from one process may become the feedstock for another.

On-Site Handling, Storage, and Processing This functional element encompasses those activities associated with the handling, storage, and processing of solid wastes at or near the point of generation. On-site storage is of primary importance because of the aesthetic considerations, public health, public safety, and economics involved.

Collection The functional element of collection includes the gathering of solid wastes and the hauling of wastes after collection to the location where the collection vehicle is emptied. As shown in Fig.

25-59, this location may be a transfer station, a processing station, or a landfill disposal site.

Transfer and Transport The functional element of transfer and transport involves two steps: (1) the transfer of wastes from the smaller collection vehicle to the larger transport equipment and (2) the subsequent transport of the wastes, usually over long distances, to the disposal site.

Processing and Recovery The functional element of processing and recovery includes all the techniques, equipment, and facilities used both to improve the efficiency of the other functional elements and to recover usable materials, conversion products, or energy from solid wastes. Materials that can be recycled are exported to facilities equipped to do so. Residues go to disposal.

Disposal The final functional element in the solid-waste-management system is disposal. Disposal is the ultimate fate of all solid wastes, whether they are wastes collected and transported directly to a landfill site, semisolid wastes (sludge) from industrial treatment plants and air-pollution-control devices, incinerator residue, compost, or other substances from various solid-waste processing plants that are of no further use.

Solid-Waste-Management Systems Practical aspects associated with solid-waste-management systems not covered in the presentation include financing, operations, equipment management, personnel, reporting, cost accounting and budgeting, contract administration, ordinances and guidelines, and public communications.

UNITED STATES LEGISLATION, REGULATIONS, AND GOVERNMENTAL AGENCIES

Much of the current activity in the field of solid-waste management, especially with respect to hazardous wastes and resources recovery, is a direct consequence of legislation. It is imperative to have a working knowledge of waste regulations, including RCRA (for EPA hazardous waste); TSCA (Toxic Substances Control Act) for PCBs and toxic waste; Solid Waste Disposal Act; the Clean Air Act; and PSD (prevention of

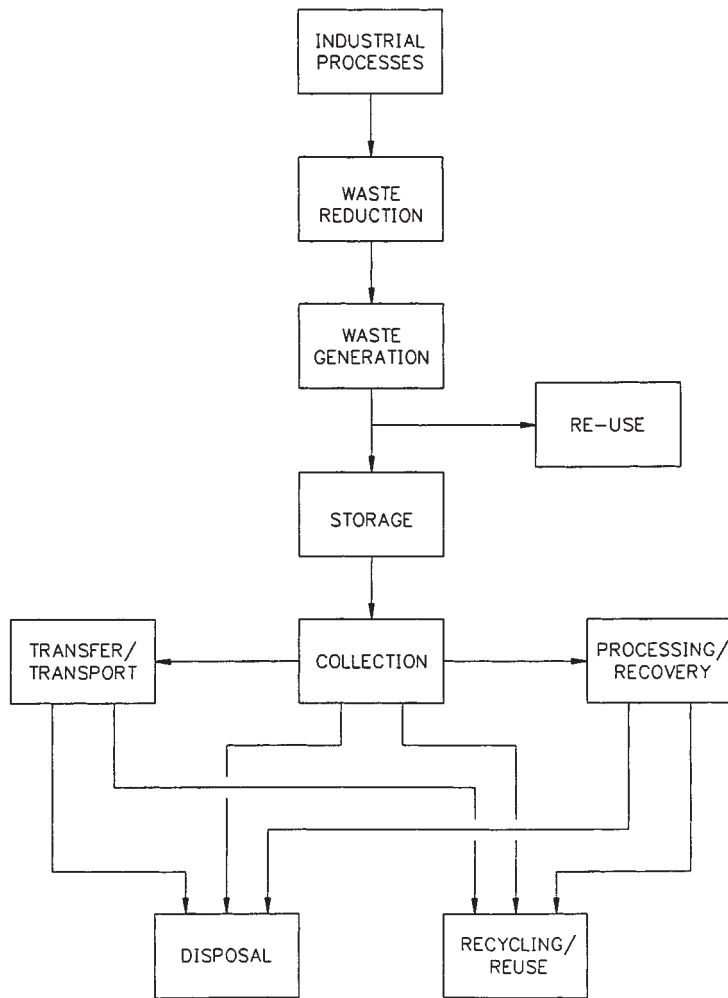


FIG. 25-59 Functional elements in a solid-waste management system. (Updated from G. Tchobanoglous, H. Theisen, and R. Eliassen, *Solid Wastes: Engineering and Management Issues*, McGraw-Hill, New York, 1977.)

significant deterioration) regulations. The Clean Air Act has far-reaching implications for any waste-related operation (e.g., incineration or landfill) that emits particulates or gaseous emissions. Primary elements of the act are Title I, dealing with fugitive emissions monitoring, Title III with reduction of organic hazardous air pollutants, and Title V, operating permits. The 1990 amendments have added a significant permitting burden for industrial plants and require additional controls for HAPs (hazardous air pollutants). In addition, state and local regulations apply to waste operations. Regulations are explored in detail in "Introduction to Waste Management" elsewhere in this section.

Regulations have been adopted by federal, state, and local agencies to implement the legislation. Before any design and construction work is undertaken, these regulations must be monitored due to continuous revisions.

GENERATION OF SOLID WASTES

Solid wastes, as noted previously, include all solid or semisolid materials that are no longer considered of sufficient value to be retained in a given setting. The types and sources of solid wastes, the physical and chemical composition of solid wastes, and typical solid-waste generation rates are considered in this subsection.

Types of Solid Wastes The term *solid wastes* is all-inclusive and encompasses all sources, types of classifications, compositions, and properties. As a basis for subsequent discussions, it will be helpful to define the various types of solid wastes that are generated. It is important to note that the definitions of solid-waste terms and the classifications vary greatly in practice and in literature. Consequently, the use of published data requires considerable care, judgment, and common sense. The following definitions are intended to serve as a guide.

1. **Food wastes.** Food wastes are the animal, fruit, or vegetable residues (also called *garbage*) resulting from the handling, preparation, cooking, and eating of foods. The most important characteristic of these wastes is that they are putrescible and will decompose rapidly, especially in warm weather.

2. **Rubbish.** Rubbish consists of combustible and noncombustible solid wastes, excluding food wastes or other putrescible materials. Typically, combustible rubbish consists of materials such as paper, cardboard, plastics, textiles, rubber, leather, wood, furniture, and garden trimmings. Noncombustible rubbish consists of items such as glass, crockery, tin cans, aluminum cans, ferrous and other nonferrous metals, dirt, and construction wastes.

3. **Ashes and residues.** These are the materials remaining from the burning of wood, coal, coke, and other combustible wastes.

Residues from power plants normally are composed of fine, powdery materials, cinders, clinkers, and small amounts of burned and partially burned materials.

4. *Demolition and construction wastes.* Wastes from razed building and other structures are classified as demolition wastes. Wastes from the construction, remodeling, and repair of commercial and industrial buildings and other similar structures are classified as construction wastes. These wastes may include dirt, stones, concrete, bricks, plaster, lumber, shingles, and plumbing, heating, and electrical parts.

5. *Special wastes.* Wastes such as street sweepings, roadside litter, catch-basin debris, dead animals, and abandoned vehicles are classified as special wastes.

6. *Treatment-plant wastes.* The solid and semisolid wastes from water, wastewater, and industrial waste-treatment facilities are included in this classification.

7. *Agricultural wastes.* Wastes and residues resulting from diverse agricultural activities, such as the planting and harvesting of row, field, and tree and vine crops, the production of milk, the production of animals for slaughter, and the operation of feedlots are collectively called agricultural wastes.

Hazardous Wastes The U.S. EPA has defined hazardous waste in RCRA regulations, CFR Parts 260 and 261. A waste may be hazardous if it exhibits one or more of the following characteristics: (1) ignitability, (2) corrosivity, (3) reactivity, and (4) toxicity. A detailed definition of these terms was first published in the *Federal Register* on May 19, 1980, pages 33, 121–122. A waste may be hazardous if listed in Appendix VIII.

In the past, hazardous wastes were often grouped into the following categories: (1) radioactive substances, (2) chemicals, (3) biological wastes, (4) flammable wastes, and (5) explosives. The chemical category included wastes that were corrosive, reactive, and toxic. The principal sources of hazardous biological wastes are hospitals and biological-research facilities.

Sources of Industrial Wastes Knowledge of the sources and types of solid wastes, along with data on the composition and rates of generation, is basic to the design and operation of the functional elements associated with the management of solid wastes.

Conventional Wastes Sources and types of industrial solid wastes generated by Standard Industrial Classification (SIC) group classification are reported in Table 25-49. The expected specific wastes in the table are those that are most readily identifiable.

Hazardous Wastes Hazardous wastes are generated in limited amounts throughout most industrial activities. In terms of generation, concern is with the identification of amounts and types of hazardous wastes developed at each source, with emphasis on those sources where significant waste quantities are generated.

The USEPA released "Biennial RCRA Hazardous Waste Report" in November 1994. The six-volume report, which represents comprehensive data on the generation and management of hazardous waste in the United States during 1991, noted that 306 million tons of hazardous waste generated that year represented an increase of 108 million tons compared with the 198 million tons generated in 1989. The number of large-quantity generators increased by about 3000 from 20,426 reporting in 1989. The number of waste treatment, storage, and disposal (TSD) facilities increased from 3000 to 3862 during the same period. Less than 5 percent—13 million tons—of the 306 million tons generated during 1991 were shipped offsite to commercial TSD facilities.

The majority—76 percent—of the 306 million tons of hazardous waste generated during 1991 was managed in aqueous waste-treatment units. Land disposal accounted for another 9 percent of the total, divided as follows: 23 million tons injected into underground wells; 1.7 million tons sent to landfills; 240,00 tons placed in surface impoundments; and 52,000 tons managed by land farming. Resource-recovery operations managed 2 percent of the 306 million tons, with solvent-recovery units managing 3.6 million tons; fuel-blending units, 1.4 million tons; metals recovery, 1 million tons; and other methods such as acid regeneration and waste oil recovery accounting for 480,000 tons. Thermal treatment systems burned 1.1 percent of the hazardous wastes generated in 1991: 1.9 million tons were inciner-

ated, and 1.5 million tons were used as fuel in boilers and industrial furnaces.

The generation of hazardous wastes by spillage must also be considered. The quantities of hazardous wastes that are involved in spillage usually are not known. After a spill, the wastes requiring collection and disposal are often significantly greater than the amount of spilled wastes, especially when an absorbing material, such as straw, is used to soak up liquid hazardous wastes or when the soil into which a hazardous liquid waste has percolated must be excavated. Both the straw and liquid and the soil and the liquid are classified as hazardous wastes.

Properties of Solid Wastes Information on the properties of solid wastes is important in evaluating alternative equipment needs, systems, and management programs and plans.

Physical Composition Information and data on the physical composition of solid wastes including (1) identification of the individual components that make up industrial and municipal solid wastes, (2) density of solid wastes, and (3) moisture content are presented below.

1. *Individual components.* Components that typically make up most industrial and municipal solid wastes and their relative distribution are reported in Table 25-50. Although any number of components could be selected, those listed in the table have been chosen because they are readily identifiable, are consistent with component categories reported in the literature, and are adequate for the characterization of solid wastes for most applications.

2. *Density.* Typical densities for various wastes as found in containers are reported by source in Table 25-50. Because the densities of solid wastes vary markedly with geographical location, season of the year, and length of time in storage, great care should be used in selecting typical values.

3. *Moisture content.* The moisture content of solid wastes usually is expressed as the mass of moisture per unit mass of wet or dry material. In the wet-mass method of measurement, the moisture in a sample is expressed as a percentage of the wet mass of the material; in the dry-mass method, it is expressed as a percentage of the dry mass of the material. In equation form, the wet-mass moisture content is expressed as follows:

$$\text{Moisture content (\%)} = \left(\frac{a - b}{a} \right) \times 100 \quad (25-22)$$

where: a = initial mass of sample as delivered
 b = mass of sample after drying

Typical data on the moisture content for the solid-waste components are given in Table 25-51. For most industrial solid wastes, the moisture content will vary from 10 to 25 percent.

Chemical Composition Information on the chemical composition of solid wastes is important in evaluating alternative processing and recovery options. If solid wastes are to be used as fuel, the four most important properties to be known are:

1. Proximate analysis
 - a. Moisture (loss at 105° C for 1 h)
 - b. Volatile matter (additional loss on heating to 950° C)
 - c. Ash (residue after burning)
 - d. Fixed carbon (remainder)
2. Fusion point of ash
3. Ultimate analysis, percent of C (carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulfur), and ash
4. Heating value
5. Organic chlorine

Typical proximate-analysis data for the combustible components of industrial and municipal solid wastes are presented in Table 25-52.

Typical data on the inert residue and energy values for solid wastes may be converted to a dry basis by using Eq. (25-23).

$$\frac{\text{kJ}}{\text{kg (dry basis)}} = \frac{\text{kJ}}{\text{kg (as discarded)}} \left(\frac{100}{100 - \% \text{ moisture}} \right) \quad (25-23)$$

The corresponding equation on an ash-free dry basis is

TABLE 25-49 Sources and Types of Industrial Wastes*

Code	SIC group classification	Waste-generating processes	Expected specific wastes
19	Ordnance and accessories	Manufacturing, assembling	Metals, plastic, rubber, paper, wood, cloth, chemical residues
20	Food and kindred products	Processing, packaging, shipping	Meats, fats, oils, bones, offal, vegetables, fruits, nuts and shells, cereals
22	Textile mill products	Weaving, processing, dyeing, shipping	Cloth and filter residues
23	Apparel and other finished products	Cutting, sewing, sizing, pressing	Cloth, fibers, metals, plastics, rubber
24	Lumber and wood products	Sawmills, millwork plants, wooden containers, miscellaneous wood products, manufacturing	Scrap wood, shavings, sawdust; in some instances, metals, plastics, fibers, glues, sealers, paints, solvents
25a	Furniture, wood	Manufacture of household and office furniture, partitions, office and store fixtures, mattresses	Those listed under Code 24; in addition, cloth and padding residues
25b	Furniture, metal	Manufacture of household and office furniture, lockers, springs, frames	Metals, plastics, resins, glass, wood, rubber, adhesives, cloth, paper
26	Paper and allied products	Paper manufacture, conversion of paper and paperboard, manufacture of paperboard boxes and containers	Paper and fiber residues, chemicals, paper coatings and filters, inks, glues, fasteners
27	Printing and publishing	Newspaper publishing, printing, lithography, engraving, bookbinding	Paper, newsprint, cardboard, metals, chemicals, cloth, inks, glues
28	Chemicals and related products	Manufacture and preparation of inorganic chemicals (ranging from drugs and soaps to paints and varnishes and explosives)	Organic and inorganic chemicals, metals, plastics, rubber, glass, oils, paints, solvents, pigments
29	Petroleum refining and related industries	Manufacture of paving and roofing materials	Asphalt and tars, felts, paper, cloth, fiber
30	Rubber and miscellaneous plastic products	Manufacture of fabricated rubber and plastic products	Scrap rubber and plastics, lampblack, curing compounds, dyes
31	Leather and leather products	Leather tanning and finishing, manufacture of leather belting and packing	Scrap leather, thread, dyes, oils, processing and curing compounds
32	Stone, clay, and glass products	Manufacture of flat glass, fabrication or forming of glass, manufacture of concrete, gypsum, and plaster products; forming and processing of stone products, abrasives, asbestos, and miscellaneous non-mineral products	Glass, cement, clay, ceramics, gypsum, asbestos, stone, paper, abrasives
33	Primary metal industries	Melting, casting, forging, drawing, rolling, forming, extruding operations	Ferrous and non-ferrous metals scrap, slag, sand, cores, patterns, bonding agents
34	Fabricated metal products	Manufacture of metal cans, hand tools, general hardware, non-electrical heating apparatus, plumbing fixtures, fabricated structural products, wire, farm machinery and equipment, coating and engraving of metal	Metals, ceramics, sand, slag, scale, coatings, solvents, lubricants, pickling liquors
35	Machinery (except electrical)	Manufacture of equipment for construction, elevators, moving stairways, conveyors, industrial trucks, trailers, stackers, machine tools, etc.	Slag, sand, cores, metal scrap, wood, plastics, resins, rubber, cloth, paints, solvents, petroleum products
36	Electrical	Manufacture of electrical equipment, appliances and communication apparatus, machining, drawing, forming, welding, stamping, winding, painting, plating, baking, firing operations	Metal scrap, carbon, glass, exotic metals, rubber, plastics, resins, fibers, cloth residues, PCBs
37	Transportation equipment	Manufacture of motor vehicles, truck and bus bodies, motor-vehicle parts and accessories, aircraft and parts, ship and boat building, repairing motorcycles and bicycles and parts, etc.	Metal scrap, glass, fiber, wood, rubber, plastics, cloth, paints, solvents, petroleum products
38	Professional scientific controlling instruments	Manufacture of engineering, laboratory, and research instruments and associated equipment	Metals, plastics, resins, glass, wood, rubber, fibers, abrasives
39	Miscellaneous manufacturing	Manufacture of jewelry, silverware, plated ware, toys, amusement, sporting and athletic goods, costume novelties, buttons, brooms, brushes, signs, advertising displays	Metals, glass, plastics, resin, leather, rubber, composition, bone, cloth, straw, adhesives, paints, solvents

*From C.L. Mantell (ed.), *Solid Wastes: Origin, Collection, Processing and Disposal*, Wiley-Interscience, New York, 1975. PCBs added to item 36.

$$\frac{\text{kJ}}{\text{kg (ash-free dry basis)}} = \frac{\text{kJ}}{\text{kg (as discarded)}} \times \left(\frac{100}{100 - \% \text{ ash} - \% \text{ moisture}} \right) \quad (25-24)$$

Representative data on the ultimate analysis of typical industrial and municipal-waste components are presented in Table 25-53. If energy values are not available, approximate values can be determined by using Eq. (25-25), known as the modified Dulong formula, and the data in Table 25-53.

$$\frac{\text{kJ}}{\text{kg}} = 337C + 1428 \left(H - \frac{1}{8} O \right) + 95S \quad (25-25)$$

where: C = carbon, percent
 H = hydrogen, percent
 O = oxygen, percent
 S = sulfur, percent

Quantities of Solid Wastes Representative data on the quantities of solid wastes and factors affecting the generation rates are considered briefly in the following paragraphs.

TABLE 25-50 Typical Data on Distribution of Industrial Wastes Generated by Major Industries and Municipalities*

SIC code	Percent by mass									
	Food wastes†	Paper	Wood	Leather	Rubber	Plastics	Metals	Glass	Textiles	Miscellaneous
20 Food and kindred products	15–20	50–60	5–10	0–2	0–2	0–5	5–10	4–10	0–2	5–15
22 Textile mill products	0–2	40–50	0–2	0–2	0–2	3–10	0–2	0–2	20–40	0–5
23 Apparel and other finished products	0–2	40–60	0–2	0–2	0–2	0–2	0–2	0–2	30–50	0–5
24 Lumber and wood products	0–2	10–20	60–80	0–2	0–2	0–2	0–2	0–2	0–2	5–10
25a Furniture, wood	0–2	20–30	30–50	0–2	0–2	0–2	0–2	0–2	0–5	0–5
25b Furniture, metal	0–2	20–40	10–20	0–2	0–2	0–2	20–40	0–2	0–5	0–10
26 Paper and allied products	0–2	40–60	10–15	0–2	0–2	0–2	5–15	0–2	0–2	10–20
27 Printing and publishing	0–2	60–90	5–10	0–2	0–2	0–2	0–2	0–2	0–2	0–5
28 Chemicals and related products	0–2	40–60	2–10	0–2	0–2	5–15	5–10	0–5	0–2	15–25
29 Petroleum refining and related industries	0–2	60–80	5–15	0–2	0–2	10–20	2–10	0–12	0–2	2–10
30 Rubber and miscellaneous plastic products	0–2	40–60	2–10	0–2	5–20	10–20	0–2	0–2	0–2	0–5
31 Leather and leather products	0–2	5–10	5–10	40–60	0–2	0–2	10–20	0–2	0–2	0–5
32 Stone, clay, and glass products	0–2	20–40	2–10	0–2	0–2	0–2	5–10	10–20	0–2	30–50
33 Primary metal industries	0–2	30–50	5–15	0–2	0–2	2–10	2–10	0–5	0–2	20–40
34 Fabricated metal products	0–2	30–50	5–15	0–2	0–2	0–2	15–30	0–2	0–2	5–15
35 Machinery (except electrical)	0–2	30–50	5–15	0–2	0–2	1–5	15–30	0–2	0–2	0–5
36 Electrical	0–2	60–80	5–15	0–2	0–2	2–5	2–5	0–2	0–2	0–5
37 Transportation equipment	0–2	40–60	5–15	0–2	0–2	2–5	0–2	0–2	0–2	15–30
38 Professional scientific controlling instruments	0–2	30–50	2–10	0–2	0–2	5–10	5–15	0–2	0–2	0–5
39 Miscellaneous manufacturing	0–2	40–60	10–20	0–2	0–2	5–15	2–10	0–2	0–2	5–15
Municipal	10–20	40–60	1–4	0–2	0–2	2–10	3–15	4–16	0–4	5–30

*Adapted in part from D. G. Wilson (ed.), *Handbook of Solid Waste Management*, van Nostrand Reinhold, New York, 1977.

†With the exception of food and kindred products, food wastes are from company cafeterias, canteens, etc.

Typical Generation Rates Typical unit waste-generation rates for selected industrial sources are reported in Table 25-54. Because waste-generation practices are changing so rapidly, the presentation of “typical” waste-generation data may not be reliable.

Factors That Affect Generation Rates Factors that influence the quantity of industrial wastes generated include (1) the extent of salvage and recycle operations, (2) company attitudes, and (3) legislation. The existence of salvage and recycling operations within an industry definitely affects the quantities of wastes collected. Whether such operations affect the quantities generated is another matter. The section entitled “Pollution Prevention” by Louis Theodore points out activities by industrial plants as a result of the 1990 Pollution Prevention Act. Significant reductions in the quantities of solid wastes that are generated will occur when and if companies are willing to change—on their own volition—to conserve national resources, handle waste at its source rather than “end of pipe” pollution control, and to reduce the economic burdens associated with the management of solid wastes. Perhaps the most important factor affecting the generation of certain types of wastes is the existence of local, state, and federal regulations concerning the use and disposal of specific material. In general, the more regulated the waste, the higher the cost for treat-

ment and disposal and the greater the incentive to reduce generation of the waste.

ON-SITE HANDLING, STORAGE, AND PROCESSING

The handling, storage, and processing of solid wastes at the source before they are collected is the second of the six functional elements in the solid-waste-management system.

On-Site Handling On-site handling refers to the activities associated with the handling of solid wastes until they are placed in the containers used for storage before collection. Depending on the type of collection service, handling may also be required to move loaded containers to the collection point and to return the empty containers to the point where they are stored between collections.

Conventional Solid Wastes In most office, commercial, and industrial buildings, solid wastes that accumulate in individual offices or work locations usually are collected in relatively large containers mounted on casters. Once filled, these containers are removed by means of the service elevator, if there is one, and emptied into (1) large storage containers, (2) compactors used in conjunction with the storage containers, (3) stationary compactors that can compress the

TABLE 25-51 Typical Density and Moisture-Content Data for Domestic, Commercial, and Industrial Solid Waste

Item	Density, kg/m ³		Moisture content, % by mass	
	Range	Typical	Range	Typical
Residential (Uncompacted)				
Food wastes (mixed)	130–480	290	50–80	70
Paper	40–130	85	4–10	6
Cardboard	40–80	50	4–8	6
Plastics	40–130	65	1–4	2
Textiles	40–100	65	6–15	10
Rubber	100–200	130	1–4	2
Leather	100–260	160	8–12	10
Garden trimmings	60–225	100	30–80	60
Wood	130–320	240	15–40	20
Glass	160–480	195	1–4	2
Tin cans	50–160	90	2–4	3
Nonferrous metals	65–240	160	2–4	2
Ferrous metals	130–1150	320	2–4	2
Dirt, ashes, etc.	320–1000	480	6–12	8
Ashes	650–830	745	6–12	6
Rubbish (mixed)	90–180	130	5–20	15
Residential (compacted)				
In compactor truck	180–450	300	15–40	20
In landfill (normally compacted)	360–500	450	15–40	30°
In landfill (well-compacted)	590–740	600	15–40	30°
Commercial				
Food wastes (wet)	475–950	535	50–85	75
Appliances	150–200	180	0–5	
Wooden crates	110–160	110	10–30	20
Tree trimmings	100–180	150	20–80	50
Rubbish (combustible)	50–180	120	5–25	15
Rubbish (non-combustible)	180–360	300	5–15	10
Rubbish (mixed)	140–180	160	5–20	12
Construction; demolition				
Mixed demolition (non-combustible)	1000–1600	1420	2–10	4
Mixed demolition (combustible)	300–400	360	4–15	8
Mixed construction (combustible)	180–360	260	4–15	8
Broken concrete	1200–1800	1540	0–5	
Industrial wastes				
Chemical sludges (wet)	800–1100	1000	75–99	80
Fly ash	700–900	800	2–10	4
Leather scraps	100–250	160	6–15	10
Metal scraps (heavy)	1500–2000	1780	0–5	
Metal scrap (light)	500–900	740	0–5	
Metal scrap (mixed)	700–1500	900	0–5	
Oils, tars, asphalt	800–1000	950	0–5	2
Sawdust	100–350	290	10–40	15
Textile wastes	100–220	180	6–15	10
Wood (mixed)	400–675	500	10–40	20
Agricultural wastes				
Agricultural (mixed)	400–750	560	40–80	50
Fruit wastes (mixed)	250–750	360	60–90	75
Manure (wet)	900–1050	1000	75–96	94
Vegetable wastes (mixed)	200–700	360	50–80	65

*Depends on degree of surface-water infiltration.

material into bales or into specially designed containers, or (4) other processing equipment.

Hazardous Wastes When hazardous wastes are generated, special containers are usually provided, and trained personnel (OSHA 1910.120 required such workers to have HAZWOPER training) are responsible (or should be) for the handling of these wastes. Hazardous wastes include solids, sludges, and liquids; hence, container requirements vary with the form of waste.

On-Site Storage Factors that must be considered in the on-site storage of solid wastes include (1) the type of container to be used, (2) the container location, (3) public health and aesthetics, (4) the collection methods to be used, and (5) future transport method.

Containers To a large extent, the types and capacities of the containers used depend on the characteristics of the solid wastes to be collected, the collection frequency, and the space available for the placement of containers.

1. *Containers for conventional wastes.* The types and capacities of containers now commonly used for on-site storage of solid wastes

are summarized in Table 25-55. The small containers are used in individual offices and work stations. The medium-size and large containers are used at locations where large volumes are generated.

2. *Containers for hazardous wastes.* On-site storage practices are a function of the types and amounts of hazardous wastes generated and the time period over which waste generation occurs. Usually, when large quantities are generated, special facilities that have sufficient capacity to hold wastes accumulated over a period of several days are used. When only small amounts of hazardous wastes are generated on an intermittent basis, they may be containerized, and limited quantities may be stored for periods covering months or years. General information on the storage containers used for hazardous wastes and the conditions of their use is presented in Table 25-56.

Container Location. The location of containers at existing commercial and industrial facilities depends on both the location of available space and service-access conditions. In newer facilities, specific service areas have been included for this purpose. Often, because the containers are not owned by the commercial or industrial activity, the

TABLE 25-52 Typical Proximate-Analysis and Energy-Content Data for Components in Domestic, Commercial, and Industrial Solid Waste*

Component	Proximate analysis, % by mass				Energy content, kJ/kg		
	Moisture	Volatile matter	Fixed carbon	Non-combustible	As collected	Dry	Moisture- and ash-free
Food and food products							
Fats	2.0	95.3	2.5	0.2	37,530	38,296	38,374
Food wastes (mixed)	70.0	21.4	3.6	5.0	4,175	13,917	16,700
Fruit wastes	78.7	16.6	4.0	0.7	3,970	18,638	19,271
Meat wastes	38.8	56.4	1.8	3.1	17,730	28,970	30,516
Paper products							
Cardboard	5.2	77.5	12.3	5.0	16,380	17,278	18,240
Magazines	4.1	66.4	7.0	22.5	12,220	12,742	16,648
Newsprint	6.0	81.1	11.5	1.4	18,550	19,734	20,032
Paper (mixed)	10.2	75.9	8.4	5.4	15,815	17,611	18,738
Waxed cartons	3.4	90.9	4.5	1.2	26,345	27,272	27,615
Plastics							
Plastics (mixed)	0.2	95.8	2.0	2.0	32,000	32,064	32,720
Polyethylene	0.2	98.5	<0.1	1.2	43,465	43,552	44,082
Polystyrene	0.2	98.7	0.7	0.5	38,190	38,266	38,216
Polyurethane	0.2	87.1	8.3	4.4	26,060	26,112	27,316
Polyvinyl chloride	0.2	86.9	10.8	2.1	22,690	22,735	23,224
Wood, trees, etc.							
Garden trimmings	60.0	30	9.5	0.5	6,050	15,125	15,316
Green wood	50.0	42.3	7.3	0.4	4,885	9,770	9,848
Hardwood	12.0	75.1	12.4	0.5	17,100	19,432	19,542
Wood (mixed)	20.0	67.9	11.3	0.8	15,444	19,344	19,500
Leather, rubber, textiles, etc.							
Leather (mixed)	10	68.5	12.5	9.0	18,515	20,572	22,858
Rubber (mixed)	1.2	83.9	4.9	9.9	25,330	25,638	28,493
Textiles (mixed)	10	66.0	17.5	6.5	17,445	19,383	20,892
Glass, metals, etc.							
Glass and mineral	2	—	—	96–99+	196†	200	200
Metal, tin cans	5	—	—	94–99+	1,425†	1,500	1,500
Metals, ferrous	2	—	—	96–99+	—	—	—
Metals, nonferrous	2	—	—	94–99+	—	—	—
Miscellaneous							
Office sweepings	3.2	20.5	6.3	70	8,535	8,817	31,847
Multiple wastes	20 (15–40)	53 (30–60)	7 (5–15)	20 (9–30)	10,470	13,090	17,450
Industrial wastes	15 (10–30)	58 (30–60)	7 (5–15)	20 (10–30)	11,630	13,682	17,892

* Adapted in part from D. G. Wilson (ed.), *Handbook of Solid Waste Management*, Van Nostrand Reinhold, New York, 1977, and G. Tchobanoglous, H. Theisen, and R. Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1977.

† Energy content is from coatings, labels, and attached materials.

locations and types of containers to be used for on-site storage must be worked out jointly between the industry and the public or private collection agency.

On-Site Processing of Solid Wastes On-site-processing methods are used to (1) recover usable materials from solid wastes, (2) reduce the volume, or (3) alter the physical form. The most common on-site-processing operations as applied to large commercial and industrial sources include manual sorting, compaction, and incineration. These and other processing operations are considered in the portion of this section dealing with processing and resource recovery. Factors that should be considered in the selection of on-site-processing equipment are summarized in Table 25-57.

COLLECTION OF SOLID WASTES

Information on collection, one of the most costly functional elements, is presented in four parts dealing with (1) the types of collection services, (2) the types of collection systems, (3) an analysis of collection systems, and (4) the general methodology involved in setting up collection routes.

Collection Services The various types of collection services now used for commercial-industrial sources are described in this subsection.

Commercial-Industrial The collection service provided to large commercial and industrial activities typically is centered in the use of large moveable and stationary containers and large stationary com-

pactors. Compactors are of the type that can be used to compress material directly into large containers (see Fig. 25-60) or to form bales that are then placed in large containers.

Hazardous Wastes Hazardous Wastes for delivery to a treatment or disposal facility normally are collected by the waste producer or a licensed, specialized hauler. Typically, the loading of collection vehicles is completed in one of two ways: (1) wastes stored in large-capacity tanks are either drained or pumped into collection vehicles, and (2) wastes stored in sealed drums or other sealed containers are loaded by hand or by mechanical equipment onto flatbed trucks. To avoid accidents and possible loss of life, two collectors should always be assigned when hazardous wastes are to be collected.

Types of Collection Systems On the basis of their mode of operation, collection systems are classified into two categories: (1) hauled-container systems and (2) stationary-container systems.

Hauled-Container Systems (HCS) Collection systems in which the containers used for storage of wastes are hauled to the processing, transfer, or disposal site, emptied, and returned to either their original location or some other location are defined as “hauled-container systems.” In most hauled-container systems, a single collector is used. The collector is responsible for driving the vehicle, loading full containers and unloading empty containers, and emptying the contents of the container at the disposal site. In some cases, for safety reasons, both a driver and helper are used.

There are three main types of hauled-container systems: (1) hoist

TABLE 25-53 Typical Ultimate-Analysis Data for Components in Domestic, Commercial and Industrial Solid Waste*

Components	Percent by mass (dry basis)					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Foods and food products						
Fats	73.0	11.5	14.8	0.4	0.1	0.2
Food wastes (mixed)	48.0	6.4	37.6	2.6	0.4	5.0
Fruit wastes	48.5	6.2	39.5	1.4	0.2	4.2
Meat wastes	59.6	9.4	24.7	1.2	0.2	4.9
Paper products	45.4	6.1	42.1	0.3	0.1	6.0
Cardboard	43.0	5.9	44.8	0.3	0.2	5.0
Magazines	32.9	5.0	38.6	0.1	0.1	23.3
Newsprint	49.1	6.1	43.0	<0.1	0.2	23.3
Paper (mixed)	43.4	5.8	44.3	0.3	0.2	6.0
Waxed cartons	59.2	9.3	30.1	0.1	0.1	1.2
Plastics						
Plastics (mixed)	60.0	7.2	22.8	—	—	10.0
Polyethylene	85.2	14.2	—	<0.1	<0.1	0.4
Polystyrene	87.1	8.4	4.0	0.2	—	0.3
Polyurethane†	63.3	6.3	17.6	6.0	<0.1	4.3
Polyvinyl chloride†	45.2	5.6	1.6	0.1	0.1	2.0
Wood, trees, etc.						
Garden trimmings	46.0	6.0	38.0	3.4	0.3	6.3
Green timber	50.1	6.4	42.3	0.1	0.1	1.0
Hardwood	49.6	6.1	43.2	0.1	<0.1	0.9
Wood (mixed)	49.5	6.0	42.7	0.2	<0.1	1.5
Wood chips (mixed)	48.1	5.8	45.5	0.1	<0.1	0.4
Glass, metals, etc.						
Glass and mineral‡	0.5	0.1	0.4	<0.1	—	98.9
Metals (mixed)	4.5	0.6	4.3	<0.1	—	90.5
Leather, rubber, textiles						
Leather (mixed)	60.0	8.0	11.6	10.0	0.4	10.0
Rubber (mixed)	69.7	8.7	—	—	1.6	20.0
Textiles (mixed)	48.0	6.4	40.0	2.2	0.2	3.2
Miscellaneous						
Office sweepings	24.3	3.0	4.0	0.5	0.2	68.0
Oils, paints	66.9	9.6	5.2	2.0	—	16.3
Refuse-derived fuel (RAF)	44.7	6.2	38.4	0.7	<0.1	9.9

*Adapted in part from D. G. Wilson (ed.), *Handbook of Solid Waste Management*, Van Nostrand Reinhold, New York, 1977, and G. Tchobanoglous,

H. Theisen, and R. Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1977.

†Remainder is chlorine.

‡Organic content is from coatings, labels, and other attached materials.

truck, (2) tilt-frame container, and (3) tractor trailer. Typical data on the containers and collection vehicles used with these systems are reported in Tables 25-58 and 25-59, respectively.

1. *Container carrier systems.* Container carrier systems are being used in a limited number of cases, the most important of which are (1) the collection of wastes from only a few pickup points at which a considerable amount of waste is generated and (2) the collection of bulky items and industrial rubbish not suitable for collection with compaction vehicles, and (3) small, heavy loads such as scrap metal.

2. *Roll-off container systems.* Systems that use tilt-frame-loaded vehicles and large containers, often called "roll-off boxes," are ideally suited for the collection of all types of solid waste and rubbish from locations where the generation rate warrants the use of large containers. Open-top containers are used routinely at warehouses and construction sites. Large containers used in conjunction with stationary compactors are common at commercial and industrial services and transfer stations. Because of the large volume that can be hauled, the use of tilt-frame hauled-container systems has become widespread, especially among private collectors servicing industrial accounts. Roll-off boxes now predominate; however, permanently-attached, open-top, self-dumping containers are still in use. Self-contained compactors of 14–30 m³ capacity are used in conjunction with hoist trucks. This type has an integral ram and cylinder permanently built into the roll-off container. Other compactors are of the external type, with a detachable roll-off container. Compactors are excellent for volume reduction of bulky material such as cardboard boxes. In many areas, cardboard-recycling facilities will provide the compacting equipment, and the generator experiences a reduction in waste disposal costs.

3. *Tractor-trailer systems.* The application of tractor trailers is similar to that for tilt-frame-container systems. The use of a separate tractor increases the number of axes and the net weight of waste that can be hauled. Tractor trailers are better for the collection of especially heavy rubbish, such as sand, timber, and metal scrap, and they are often are used for the collection of demolition wastes at construction sites.

Stationary-Container Systems (SCS) Collection systems in which the containers used for the storage of wastes remain at the point of waste generation, except for occasional short trips to the collection vehicle, are defined as stationary-container systems. Labor requirements for mechanically loaded stationary-container systems are essentially the same as for hauled-container systems. There are two main types of stationary-container systems: (1) those in which self-loading compactors are used and (2) those in which manually loaded vehicles are used.

1. *Systems with self-loading compactors.* Container size and utilization are not as critical in stationary-container systems using self-loading collection vehicles equipped with a compaction mechanism (see Fig. 25-61 and Table 25-59) as they are in hauled-container systems. Trips to the disposal site, transfer station, or processing station are made after the contents of a number of containers have been collected and compacted and the collection vehicle is full. Because a variety of container sizes and types are available, these systems may be used for the collection of all types of wastes. Container sizes vary from relatively small sizes (0.6 m³) to sizes comparable to those handled with a hoist truck (see Table 25-58).

2. *Systems with manually loaded vehicles.* The major application of manual transfer and loading methods is in the collection of res-

TABLE 25-54 Unit Solid-Waste-Generation Rates for Selected Industrial Sources

Source	Unit	Range
Canned and frozen foods	Metric tons/metric tons of raw product	0.04–0.06
Printing and publishing	Metric tons/metric tons of raw paper	0.08–0.10
Automotive	Metric tons/vehicle produced	0.6–0.8
Petroleum refining	Metric tons/(employee day)	0.04–0.05
Rubber	Metric tons/metric tons of raw rubber	0.01–0.3

TABLE 25-55 Data on the Types and Sizes of Containers Used for On-Site Storage of Solid Wastes

Container type	Capacity			Dimensions*	
	Unit	Range	Typical	Unit	Typical
Small capacity					
Plastic or metal (office type)	L	16–40	28	mm	(180 × 300) B × (260 × 380) T × 380 H
Plastic or galvanized metal	L	75–150	120	mm	510 D × 660 H
Barrel, plastic, aluminum, or fiber barrel	L	20–250	120	mm	510 D × 660 H
Disposable paper bags (standard, leak-resistant, and leakproof)	L	75–210	120	mm	380 W × 300 d × 1100 H
Disposable plastic bag	L	20–200	170	mm	460 W × 380 d × 1000 H
Medium capacity					
Side or top loading	m ³	0.75–9	3	mm	1830 W × 1070 d × 1650 H
Bulk bags	m ³	0.3–2	1	mm	1000 W × 1000 d × 1000 H
Large capacity					
Open-top, roll-off (also called debris boxes)	m ³	9–38	27	mm	2440 W × 1830 H × 6100 L
Used with stationary compactor	m ³	15–30	23	mm	2440 W × 1830 H × 5490 L
Equipped with self-contained compaction mechanism	m ³	15–30	23	mm	2440 W × 2440 H × 6710 L
Trailer-mounted					
Open-top	m ³	15–38	27	mm	2440 W × 3660 H × 6100 L
Enclosed, equipped with self-contained compaction mechanism	m ³	15–30	27	mm	2440 W × 3660 H × 7320 L

*B = bottom, T = top, D = diameter, H = height, L = length, W = width, and d = depth.

TABLE 25-56 Typical Data on Containers Used for Storage and Transport of Hazardous Wastes

Waste category	Container		Auxiliary equipment and conditions of use
	Type	Capacity	
Radioactive substances	Lead encased in concrete Lined metal drums	Varies with waste 210 L	Isolated storage buildings; high-capacity hoists and lighting equipment; special container markings
Corrosive, reactive, and toxic chemicals	Metal drums Plastic drums Lined metal drums Lined and unlined storage tanks	210 L 210 L, up to 500 L 210 L Up to 20 m ³	Washing facilities for empty containers; special blending precautions to prevent hazardous reactions; incompatible wastes stored separately
Liquids and sludges	Drums Trucks Vacuum tankers	142–3,400 L 11–30 m ³ 11–15 m ³	Drum hand-trucks, pallets, forklifts Transfer piping, hoses, pumps Transfer piping, hoses, pumps
Biological wastes	Sealed plastic bags Lined boxes, Lined metal drums	120 L 57 L	Heat sterilization prior to bagging; special heavy-duty bags with hazard warning printed on sides
Flammable wastes	Metal drums Storage tanks	210 L Up to 20 m ³	Fume ventilation; temperature control
Explosives	Shock-absorbing containers	Varies	Temperature control; special container markings

idental wastes and litter. For industrial and hazardous waste, manual loading is the exception, not the rule. It is used for the collection of industrial wastes when pickup points are inaccessible to the collection vehicle.

Equipment for Hazardous-Wastes Collection The equipment used for collection varies with the characteristics of the wastes. For short-haul distances, drum storage and collection with an enclosed trailer are often preferred methods. Full-size drums are usually shipped four to a pallet. Smaller sizes are stacked and/or wrapped up to 10 per pallet. As hauling distances increase, larger tank trucks, trailers, and railroad tank cars are used.

Equipment for Superfund Waste Shipment RCRA hazardous waste that has been spilled, improperly landfilled, or dredged from defunct lagoons is a CERCLA waste, more commonly referred to as a Superfund waste. For clean-ups where offsite treatment is the chosen solution, soil is excavated and placed in 15-m³ roll-off box or dump body truck. The trucks may be lined with polyethylene to reduce

decontamination and eliminate sticking of the load to the steel body during freezing weather. The waste is shipped to a landfill, incinerator, or other treatment facility. If the waste is a sludge (as found in a lagoon), dewatering to 50 percent solids is normally performed on site via plate and frame filter press. This may be followed by mixing with bulking reagents to eliminate free water. The alternative is shipping the waste in a tanker or other container that retains free liquid.

Occasionally, a small clean-up of a few tons may occur. These are usually handled via placing the waste in open-topped drums that are sealed with a lid and ring closure. Consultation with the ultimate treatment facility is important to select the correct drum size and material and eliminate the need for repackaging the waste.

Transportation Costs Most waste trucking is done by commercial and hazardous waste firms. Costs are quoted per load, based on cost for transport (charged per load mile) from point of generation to its destination at a landfill or TSD facility. A strategy which permits shipment of full truckloads minimizes the transportation cost per ton.

TABLE 25-57 Factors That Should Be Considered in Evaluating On-Site Processing Equipment

Factor	Evaluation
Capabilities	What will the device or mechanism do? Will its use be an improvement over conventional practices?
Reliability	Will the equipment perform its designated functions with little attention beyond preventive maintenance? Has the effectiveness of the equipment been demonstrated in use over a reasonable period of time or merely predicted?
Service	Will servicing capabilities beyond those of the local building maintenance staff be required occasionally? Are properly trained service personnel available through the equipment manufacturer or the local distributor?
Safety of operation	Is the proposed equipment reasonably foolproof so that it may be operated by tenants or building personnel with limited mechanical knowledge or abilities? Does it have adequate safeguards to discourage careless use?
Ease of operation	Is the equipment easy to operate by a tenant or by building personnel? Unless functions and actual operations of equipment can be carried out easily, they may be ignored or bypassed by paid personnel and most often by "paying" tenants.
Efficiency	Does the equipment perform efficiently and with a minimum of attention? Under most conditions, equipment that completes an operational cycle each time that it is used should be selected.
Environmental effects	Does the equipment pollute or contaminate the environment? When possible, equipment should reduce environmental pollution presently associated with conventional functions.
Health hazards	Does the device, mechanism, or equipment create or amplify health hazards?
Aesthetics	Do the equipment and its arrangement offend the senses? Every effort should be made to reduce or eliminate offending sights, odors, and noises.
Economics	What are the economics involved? Both first and annual costs must be considered. Future operation and maintenance costs must be assessed carefully. All factors being equal, equipment produced by well-established companies, having a proven history of satisfactory operation, should be given appropriate consideration.
Flexibility	Will the equipment or its placement allow future changes to the process to handle wastes with differing characteristics?

*From G. Tchobanoglous, H. Theisen, and R. Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1977.

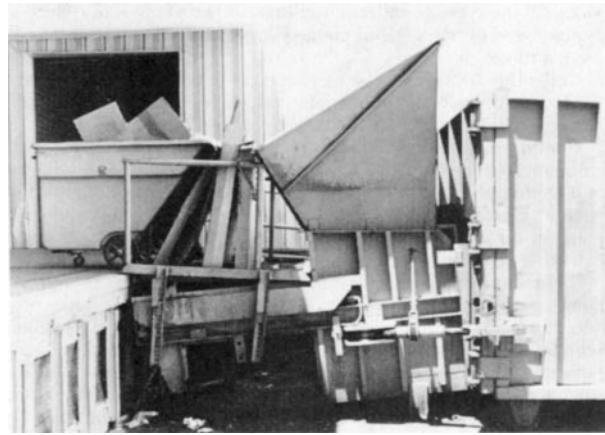


FIG. 25-60 Small compactor used in conjunction with a detachable roll-off container. Note the wheeled container used to collect wastes within the warehouse.

TRANSFER AND TRANSPORT

The functional element of transfer and transport refers to the means, facilities, and appurtenances used to effect the transfer of wastes from relatively small collection vehicles to larger vehicles and to transport them over extended distances to either processing centers or disposal sites. Transfer and transport operations become a necessity when haul distances to available disposal sites or processing centers increase to a point at which direct hauling is no longer economically feasible.

Transfer Stations Important factors that must be considered in the design of transfer stations include (1) the type of transfer operation to be used, (2) capacity requirements, (3) equipment and accessory requirements, and (4) environmental requirements.

Types of Transfer Stations Depending on the method used to load the transport vehicles, transfer stations may be classified into three types: (1) direct-discharge, (2) storage-discharge, and (3) combined direct- and storage-discharge.

1. **Direct discharge.** In a direct-discharge transfer station, wastes from the collection vehicles are usually emptied directly into the vehicle to be used to transport them to a place of final disposition. To accomplish this, these transfer stations are usually constructed in a two-level arrangement. Either the unloading dock or platform from which wastes from collection vehicles are discharged into the transport trailers is elevated, or the transport trailers are located in a depressed ramp (see Fig. 25-62). Direct-discharge transfer stations employing stationary compactors also are popular.

TABLE 25-58 Typical Data on Container Capacities for Use with Various Collection Systems for Solid Waste

Vehicle	Collection	Typical range of container capacities,* m ³
	Container type	
Hauled-container systems		
Hoist-truck	Open and covered, also used with stationary compactor	2-9
Tilt-frame/roll-off container	Open-top, roll-off containers	8-40
	Can be used in conjunction with stationary compactor	10-30
	Equipped with self-contained compaction mechanism	15-30
Tractor trailer	Open-top trash trailers	10-30
	Enclosed trailer-mounted containers equipped with self-contained compaction mechanism	15-30
Stationary-container systems	Long-body dump trailer	15-30
Compactor, mechanically loaded	Open-top and enclosed top- and front- or rear-loading	0.6-6
Compactor, manually loaded	Small plastic or galvanized metal containers, disposable paper and plastic bags	75-200 L†

*See Table 25-55 for typical dimensions.

†Loaded mass of container should not exceed 30 kg.

TABLE 25-59 Typical Data on Vehicles Used for Collection of Solid Wastes

Collection vehicle		Number of axles	Typical overall collection-vehicle dimensions				Unloading method
Type	Available container or truck body capacities, ° m³		With indicated container or truck body capacity, ° m³	Width, mm	Height, mm	Length, ° mm	
Hauled-container systems							
Hoist-truck	2–9	2	7.6	2440	2030–2540	2800–3800	Gravity, bottom-opening
Tilt-frame	8–40	3	22.9	2440	2030–2290	5590–7620	Gravity, inclined-tipping
Truck-tractor trash trailer	10–30	3	30.6	2440	2290–3800	5590–11,430	Gravity, inclined-tipping
Roll-off container	8–30	3–4	37	2440	12400–2700	9100–10,000	Gravity, inclined tipping
Stationary-container systems							
Compactor (mechanically loaded)							
Front-loading	15–35	3	22.9	2440	3560–3800	6100–7370	Hydraulic ejector panel
Side-loading	6–28	3	22.9	2440	3350–3000	5590–6600	Hydraulic ejector panel
Rear-loading	6–24	2	15.3	2440	3175–3430	5330–5824	Hydraulic ejector panel
Compactor (manually loaded)							
Side-loading	6–28	3	28.3	2440	3350–3800	6100–7620	Hydraulic ejector panel
Rear-loading	6–24	2	15.3	2440	3175–3430	5330–5840	Hydraulic ejector panel

*From front of truck to rear of container or truck body.

2. *Storage discharge.* In the storage-discharge transfer station, wastes are emptied either into a storage pit or onto a platform from which they are loaded into transport vehicles by various types of auxiliary equipment. In a storage-discharge transfer station, storage volume varies from about one-half to 2 days' volume of wastes.

3. *Combined direct and storage discharge.* In some transfer stations, both direct-discharge and storage-discharge methods are used. Usually, these are multipurpose facilities designed to service a broader range of users than a single-purpose facility. In addition to serving a broader range of users, a multipurpose transfer station may house a materials-salvage operation recovery facility.

Capacity Requirements The operating capacity of a transfer station must be such that collection vehicles do not have to wait long to unload. In most cases, it will not be cost-effective to design the station to handle the ultimate peak number of hourly loads. An economic trade-off analysis should be made between the annual cost for the time spent by the collection vehicles waiting to unload against the incremental annual cost of a larger transfer station and/or the use of more transport equipment. Because of the increased cost of transport equipment, a trade-off analysis must also be made between the capacity of the transfer station and the cost of the transport operation, including both equipment and labor components.

Equipment and Accessory Requirements The types and amounts of equipment required vary with the capacity of the station and its function in the waste-management system. Specifically, truck

scales should be provided at all medium-size and large transfer stations, both to monitor the operation and to develop meaningful management and engineering data.

Environmental Requirements Most large modern transfer stations are enclosed and are constructed of materials that can be maintained and cleaned easily. For direct-discharge transfer stations with open loading areas, special attention must be given to the problem of blowing papers. Windscreens or other barriers are commonly used. Regardless of type, the station should be designed and constructed so that all accessible areas where rubbish or paper can accumulate are eliminated.

Transfer Means and Methods Motor vehicles, railroads, and barges are the principal means used to transport solid wastes. Pneumatic and hydraulic systems have also been used.

Motor-Vehicle Transport Motor vehicles used to transport solid wastes on highways should satisfy the following requirements: (1) Wastes must be transported at minimum cost. (2) Wastes must be covered during the haul operation. (3) Vehicles must be designed for highway traffic. (4) Vehicle capacity must be such that allowable weight limits are not exceeded. (5) Methods used for unloading must be simple and dependable. The maximum volume that can be hauled in highway transport vehicles depends on the regulations in force in the state in which these vehicles are operated.

1. *Trailers and semitrailers.* In recent years, because of their simplicity and dependability, open-top trailers and semitrailers have found wide acceptance (see Table 25-60). Some trailers are equipped with sumps to collect any liquids that accumulate from the solid wastes. The sumps are equipped with drains so that they can be emptied at the disposal site.



FIG. 25-61 Typical front-loading compactor used in a stationary-container collection system.



FIG. 25-62 Direct-discharge transfer station with open-top trailers located in a depressed ramp under the loading hoppers.

TABLE 25-60 Typical Data on Haul Vehicles Used at Transfer Stations

Type	Capacity per trailer		Dimensions of single trailer			Length of tractor and trailer units, m
	m ³	Metric tons	Width, m	Length, m	Approximate height, empty, m	
Tractor-tandem-trailer	54	11.4	2.44	8.25	4.12	19.8
Tractor-trailer	54	10.0	2.44	8.50	4.12	12.0
	74	17.3	2.44	12.2	4.12	16.0
Tractor-compactor-trailer	58	18.0	2.44	10.2	4.12	14.0

Methods used to unload the transport trailers may be classified as (1) self-emptying and (2) requiring the aid of auxiliary equipment. Self-emptying transport trailers are equipped with mechanisms such as pusher rams, dump body, and moving floors that are part of the vehicle. An advantage of the moving-floor trailer is the rapid turn-around time (typically 6 to 10 min) achieved at the disposal site without the need for auxiliary equipment. Unloading systems that require auxiliary equipment are usually of the pull-off type, in which the wastes are pulled out of the truck by either a moveable bulkhead or wire-cable slings placed forward of the load. Walking floor trailers are self-unloading.

Another auxiliary unloading system that has proven to be very effective and efficient involves the use of moveable, hydraulically operated truck dumps located at the disposal site. Operationally, the trailer is backed up onto one of the tipping ramps, with or without its tractor. The back of the trailer is opened, and the unit is then tilted upward until the wastes fall out by gravity. The time required for the entire unloading operation typically is about 5 min per trip.

2. **Compactors.** Large-capacity containers and container-trailers are used in conjunction with stationary compactors at transfer stations. In some cases, the compaction mechanism is an integral part of the container. When containers are equipped with a self-contained compaction mechanism, the moveable bulkhead used to compress the wastes is also used to discharge the compacted wastes.

Railroad Transport Renewed interest is developing in the use of railroads for hauling solid wastes, especially in heavily populated areas where landfill space is scarce and tipping fees are high. Containerized waste on "piggyback" rail cars are used. Full-size bulk material cars are also used for shipping solid wastes.

Water Transport Barges, scows, and special boats have been used in the past to transport solid wastes to processing locations and to seaside and ocean disposal sites, but ocean disposal is no longer practiced by the United States. Although some self-propelled vessels (such as U.S. Navy garbage scows and other special boats) have been used, most common practice is to use vessels towed by tugs or other special boats.

Pneumatic Transport Both low-pressure air-vacuum conduit transport systems have been used to transport solid wastes. The most common application is the transport of wastes from high-density apartments or commercial activities to a central location for processing or for loading into transport vehicles. The largest pneumatic system in use in the United States is at the Walt Disney World amusement park in Orlando, Florida.

Location of Transfer Stations Whenever possible, transfer stations should be located (1) as near as possible to the weighted center of the individual solid-waste-production areas to be served, (2) within easy access of major arterial highways as well as near secondary or supplemental means of transportation, (3) where there will be a minimum of public and environmental objection to the transfer operations, and (4) where construction and operation will be most economical. Additionally, if the transfer-station site is to be used for processing operations involving material recovery and/or energy production, the requirements for those operations must be considered.

Transfer and Transport of Hazardous Wastes The facilities of a hazardous-waste transfer station are quite different from those of an industrial or municipal solid-waste transfer station. Typically, hazardous wastes are not compacted (mechanical volume reduction),

discharged at differential levels, or delivered by numerous collection companies. Instead, liquid hazardous wastes are generally pumped from collection vehicles, and sludges or solids are reloaded without removal from the collection containers for transport to processing and disposal facilities. Repacking may occur at a TSD (transport, storage, and disposal facility) to put the waste into standard size and weight containers for reshipment to final treatment facilities. Most often, this involves subdividing larger containers into smaller containers and/or use of compatible container material. Examples are the use of fiber drums rather than steel barrels and prepacking to limit the heat content or volatility of waste destined for hazardous waste incineration.

It is unusual to find a hazardous-waste-transfer facility at which wastes are simply transferred to larger transport vehicles. Some processing and storage facilities are often part of the materials-handling sequence at a transfer section. For example, neutralization of corrosive wastes will result in the use of lower-cost holding tanks on transport vehicles.

PROCESSING AND RESOURCE RECOVERY

The purpose of this subsection is to introduce the reader to the techniques and methods used to recover materials, conversion products, and energy from solid wastes. Topics to be considered include (1) processing techniques for solid waste, (2) processing techniques for hazardous wastes, (3) materials-recovery systems, (4) recovery of biological conversion products, (5) thermal processes, and (6) waste-to-energy systems.

Because many of the techniques, especially those associated with the recovery of materials and energy and the processing of solid hazardous wastes, are in a state of flux with respect to application and design criteria, the objective here is only to introduce them to the reader. If these techniques are to be considered in the development of waste-management systems, current engineering design and performance data must be obtained from consultants, operating records, field tests, equipment manufacturers, and available literature.

Processing Techniques for Solid Wastes Processing techniques are used in solid-waste-management systems to (1) improve the efficiency of the systems, (2) to recover resources (usable materials), and (3) to prepare materials for recovery of conversion products and energy. The more important techniques used for processing solid wastes are summarized in Tables 25-61 and 25-62.

Manual Component Separation The manual separation of solid-waste components can be accomplished at the source where solid wastes are generated, at a transfer station, at a centralized processing station, or at the disposal site. Manual sorting at the source of generation is the most positive way to achieve the recovery and reuse of materials. The number and types of components salvaged or sorted (e.g., cardboard and high-quality paper, metals, and wood) depend on the location, the opportunities for recycling, and the resale market. There has been an evolution in the solid waste industry to combine manual and automatic separation techniques to reduce overall costs and produce a cleaner product, especially for recyclable materials.

Storage and Transfer When solid wastes are to be processed for material recovery, storage and transfer facilities should be considered

an essential part of the processing operation. Important factors in the design of such facilities include (1) the size of the material before and after processing, (2) the density of the material, (3) the angle of repose before and after processing, (4) the abrasive characteristics of the material, and (5) the moisture content.

Mechanical Volume Reduction Mechanical volume reduction is perhaps the most important factor in the development and operation of solid-waste-management systems. Vehicles equipped with compaction mechanisms are used for the collection of most industrial solid wastes. To increase the useful life of landfills, wastes are compacted. Paper for recycling is baled for shipping to processing centers. When compacting industrial solid wastes, it has been found that the final density (typically about 1,100 kg/m³) is essentially the same regardless of the starting density and applied pressure. This fact is important in evaluating manufacturers' claims.

Chemical Volume Reduction Incineration has been the method commonly used to reduce the volume of wastes chemically. One of the most attractive features of the incineration process is that it can be used to reduce the original volume of combustible solid wastes by 80 to 90 percent. The technology of incineration has advanced since 1960 with many mass burn facilities now have two or more combustors with capacities of 1000 tons per day of refuse per unit. However, regulations of metal and dioxin emissions have resulted in higher costs and operating complexity.

Mechanical Size Alteration The objective of size reduction is to obtain a final product that is reasonably uniform and considerably reduced in size in comparison to its original form. It is important to note that size reduction does not necessarily imply volume reduction. In some situations, the total volume of the material after size reduction may be greater than the original volume. Shredding is most often used for size reduction. Use of two-stage (coarse, fine) low-speed shredders or a single-stage shredder with screen and recycle of over-size are the most common systems. The gain in ease of material handling must be weighed against the substantial operating costs for shredding equipment.

Mechanical Component Separation Component separation is a necessary operation in the recovery of resources from solid wastes and in instances when energy and conversion products are to be recovered from processed wastes. Mechanical separation techniques that have been used are reported in Table 25-61.

Magnetic and Electromechanical Separation Magnetic separation of ferrous materials is a well-established technique. More recently, a variety of electromechanical techniques have been developed for the removal of several nonferrous materials (see Table 25-62).

Drying and Dewatering In many solid-waste energy-recovery and incineration systems, the shredded light fraction is predried to decrease weight. Although energy requirements for drying wastes

vary with the application, the required energy input can be established by using a value of about 4300 kJ/kg of water evaporated. Drying can frequently increase waste throughput in many treatment systems and for incinerators; it produces more stable combustion and better ash quality.

Processing of Hazardous Wastes As with conventional solid wastes, the processing of hazardous wastes is undertaken for three purposes: (1) to recover useful materials, (2) to reduce the amount of wastes that must be disposed in landfills, and (3) to prepare the wastes for ultimate disposal.

Processing Techniques The processing of hazardous wastes on a batch basis can be accomplished by physical, chemical, thermal, and biological means. The various individual processes in each category are reported in Table 25-63. Clearly, the number of possible treatment-process combinations is staggering. In practice, the physical, chemical, and thermal treatment operations and processes are the ones most commonly used.

Identification of Waste Constituents In any processing (and disposal) scheme, the key item is knowledge of the characteristics of the wastes to be handled. Without this information, effective processing or treatment is impossible. For this reason, the characteristics of the wastes must be known before they are accepted and hauled to a treatment or disposal site. In most states, proper identification of the constituents of the waste is the responsibility of the waste generator.

Materials-Recovery Systems Paper, rubber, plastics, textiles, glass, metals, and organic and inorganic materials are the principal recoverable materials contained in industrial solid wastes.

Once a decision has been made to recover materials and/or energy, process flow sheets must be developed for the removal of the desired components, subject to predetermined materials specifications. A typical flow sheet for the recovery of specific components and the preparation of combustible materials for use as a fuel source is presented in Fig. 25-63. The light combustible materials are often identified as refuse-derived fuel (RDF).

The design and layout of the physical facilities that make up the processing-plant flow sheet are an important aspect in the implementation and successful operation of such systems. Important factors that must be considered in the design and layout of such systems include (1) process performance efficiency, (2) reliability and flexibility, (3) ease and economy of operation, (4) aesthetics, and (5) environmental controls.

Recovery of Biological Conversion Products Biological conversion products that can be derived from solid wastes include compost, methane, various proteins and alcohols, and a variety of other intermediate organic compounds. The principal processes that have been used are reported in Table 25-64. Composting and anaerobic digestion, the two most highly developed processes, are considered further. The recovery of gas from landfills is discussed in the portion of this section dealing with ultimate disposal.

TABLE 25-61 Mechanical Methods for Separating Solid-Waste Components

Method	Function	Equipment and/or facilities and applications	Method	Function
Screening	Used to separate solid waste components by size	Trommels and horizontal and vibrating screens for unprocessed and processed wastes; disk screens with processed wastes	Optical sorting	Used to separate plastics
Air separation	Used to separate light (organic) materials from heavy (inorganic) materials in solid waste	Zig-zag-air, vibrating-air, rotary-air, and air-knife classifiers used with processed wastes	Sink-float, flotation, Inertial, Inclined-table, shaking-table	Used to separate light and heavy materials in solid wastes
Jig separation	Used to separate light and heavy materials in solid waste by means of density separation			
Pneumatic separation (stoners)	Used to separate light and heavy materials in solid waste			

TABLE 25-62 Summary of Techniques Used for Processing Solid Wastes

Processing technique	Function	Representative equipment and/or facilities and applications
Manual component separation	Separation of recoverable materials, usually at point of generation	Visual inspection and removal via conveyor belt picking stations
Storage and transfer	Storage and transfer of wastes to be processed	Open storage pits for unprocessed wastes, storage bins and silos for processed wastes; transfer equipment including front-end loaders, metal and rubber belt conveyors, vibratory conveyors with unprocessed wastes, pneumatic conveyors, and screw conveyors with processed wastes
Mechanical volume reduction	Reduction of solid-waste volume; alteration of shape of solid-waste components; all modern collection vehicles essentially equipped with compaction equipment	Hydraulic piston-type compactors for collection vehicles, on-site compactors, and transfer-station compactors; roll crushers used to fracture brittle materials and to crush tin and aluminum cans and other ductile materials
Chemical volume reduction	Reduction of volume of solid wastes through burning (incineration)	Mass-fired incinerators, with and without heat recovery, for unprocessed wastes; rotary kilns for hazardous/containerized and bulk solid/sludge waste
Mechanical size and shape alteration	Alteration of size and shape of solid-waste components	Equipment used to reduce the size of solid waste including hammer mills, shredders, roll crushers, grinders, chippers, jaw crushers, rasp mills, and hydropulpers; briquettes (See Table 26-40)
Mechanical component separation	Separation of recoverable materials, usually at a processing facility	
Magnetic and electro-mechanical separation	Separation of ferrous and nonferrous materials from processed solid wastes	Magnetic separation for ferrous materials; eddy-current separation for aluminum; electrostatic separation for glass from wastes free of ferrous and aluminum scrap; magnetic fluid separation for nonferrous materials from processed wastes
Drying and dewatering	Removal of moisture from solid wastes	Convection, conduction, and radiation dryers used for solid wastes and sludge; centrifuge and filtration used to dewater treatment-plant sludge

Composting If the organic materials, excluding plastics, rubber, and leather, are separated from municipal solid wastes and subjected to bacterial decomposition, the end product remaining after dissimilatory and assimilatory bacterial activity is called *compost* or *humus*. The entire process involving both separation and bacterial conversion of the organic solid wastes is known as *composting*. Decomposition of the organic solid wastes may be accomplished either aerobically or anaerobically, depending on the availability of oxygen.

Most composting operations involve three basic steps: (1) preparation of solid wastes, (2) decomposition of the solid wastes, and (3) product preparation and marketing. Receiving, sorting, separation, size reduction, and moisture and nutrient addition are part of the preparation step. Several techniques have been developed to accomplish the decomposition step. Once the solid wastes have been converted to a humus, they are ready for the third step of product preparation and marketing. This step may include fine grinding, blending with various additives, granulation, bagging, storage, shipping, and, in some cases, direct marketing. The principal design considerations associated with the biological decomposition of prepared solid wastes are presented in Table 25-65.

Anaerobic Digestion Anaerobic digestion or anaerobic fermentation, as it is often called, is the process used for the production of methane from solid wastes. In most processes in which methane is to be produced from solid wastes by anaerobic digestion, three basic steps are involved. The first step involves preparation of the organic fraction of the solid wastes for anaerobic digestion and usually includes receiving, sorting, separation, and size reduction. The second step involves the addition of moisture and nutrients, blending, pH adjustment to about 6.7, heating of the slurry to between 327 and 333 K (130 and 140° F), and anaerobic digestion in a reactor with continuous flow, in which the contents are well mixed for a period of time varying from 8 to 15 days. The third step involves capture, storage, and, if necessary, separation of the gas components evolved during the digestion process. The fourth step is the disposal of the digested sludge is an additional task that must be accomplished. Some important design considerations are reported in Table 25-66. Because of the variability of the results reported in the literature, it is recommended that pilot-plant studies be conducted if the digestion process is to be used for the conversion of solid wastes.

Thermal Processes Conversion products that can be derived

from solid wastes include heat, gases, a variety of oils, and various related organic compounds. The principal thermal processes that have been used for the recovery of usable conversion products from solid wastes are reported in Table 25-64.

Incineration with Heat Recovery Heat contained in the gases produced from the incineration of solid wastes can be recovered as steam. The low-level heat remaining in the gases after heat recovery can also be used to preheat the combustion air, boiler makeup water, or solid-waste fuel.

1. *In existing incinerators.* With existing incinerators, waste-heat boilers can be installed to extract heat from the combustion gases without introducing excess amounts of air or moisture. Typically, incinerator gases will be cooled from a range of 1250 to 1375 K (1800 to 2000° F) to a range from 500 to 800 K (600 to 1000° F) before being discharged to the air pollution control system. Apart from the production of steam, the use of a boiler system is beneficial in reducing the volume of gas to be processed in the air-pollution-control equipment. The compounds in the waste stream will generate products of combustion and ash that may create serious corrosion and fouling problems in waste-heat boilers.

2. *In water-wall incinerators.* The internal walls of the combustion chamber are lined with boiler tubes that are arranged vertically and welded together in continuous sections. When water walls are employed in place of refractory materials, they are not only useful for the recovery of steam but also extremely effective in controlling furnace temperature without introducing excess air; however, they are subject to corrosion by the hydrochloric acid produced from the burning of some plastic compounds and the molten ash containing salts (chlorides and sulfates) that attach to the tubes.

Combustion Combustion of industrial and municipal waste is an attractive waste management option because it reduces the volume of waste by 70 to 90 percent. In the face of shrinking landfill availability, municipal waste combustion capacity in the United States has grown at an astonishing rate, significantly faster than the growth rate for municipal refuse generation.

Types of Combustors The three main classes of facilities used to combust municipal refuse are mass burn, modular, and RDF-fired facilities. Mass-burn combustors are field erected and generally range in size from 50 to 1000 tons/day of refuse feed per unit (Fig. 25-64). Modular combustors burn waste with little more pre-

TABLE 25-63 Treatment Operations and Processes for Hazardous Wastes^a

Operation or process	Functions performed ^b	Types of wastes ^c	Forms of waste ^d
Physical treatment			
Adsorption ^e	Se	1, 2, 3,	L
Aeration	Se	1, 2, 3, 4, 5	L
Ammonia stripping	VR, Se	1, 2, 3, 4	L
Carbon sorption	VR, Se	1, 2, 3, 4, 5	L, G
Centrifugation	VR, Se	1, 2, 3, 4, 5	L
Dialysis	VR, Se	1, 2, 3, 4	L
Distillation ^e	VR, Se	1, 2, 3, 4, 5	L
Electrodialysis	VR, Se	1, 2, 3, 4, 6	L
Encapsulation	St	1, 2, 3, 4, 6	L, S
Evaporation	VR, Se	1, 2, 5	L
Filtration ^e	VR, Se	1, 2, 3, 4, 5	L, G
Flocculation or setting	VR, Se	1, 2, 3, 4, 5	L
Flotation ^e	Se	1, 2, 3, 4	L
Reverse osmosis	VR, Se	1, 2, 4, 6	L
Screening	Se	1, 2, 3, 4, 5	L
Sedimentation ^e	VR, Se	1, 2, 3, 4, 5	L
Shredding	VR, Se	1, 2, 3, 4	S
Solar evaporation ^e	VR, Se	1, 2, 5	L
Solvent extraction	Se	1, 2, 3, 4, 5	L
Thickening	Se	1, 2, 3, 4	L
Ultrafiltration	Se	1, 2, 3, 4, 5	L
Vapor scrubbing	VR, Se	1, 2, 3, 4	L
Chemical treatment			
Calcination	VR	1, 2, 5	L
Chemical dechlorination	De	1, 3	L
Ion exchange	VR, Se, De	1, 2, 3, 4, 5	L
Neutralization ^e	De	1, 2, 3, 4	L
Oxidation	De	1, 2, 3, 4	L
Precipitation ^e	VR, Se	1, 2, 3, 4, 5	L
Reduction	De	1, 2	L
Sorption	De	1, 2, 3, 4	L
Stabilization or solidification ^e	De	1, 2, 3, 4	L
Thermal treatment			
Desorption	VR, De	1, 2, 3, 4	S
Incineration ^e	VR, De	3, 5, 6, 7, 8	S, L, G
Pyrolysis	VR, De	3, 4, 6	S, L, G
Biological treatment			
Activated sludge ^e	De	3	L
Aerated lagoons	De	3	L
Anaerobic digestion	De	3	L
Anaerobic filters	De	3	L
Trickling filters	De	3	L
Waste-stabilization ponds ^e	De	3	L

^aAdapted from *Report to Congress: Disposal of Hazardous Wastes*, U.S. EPA Publ. SW-115, 1974.

^bFunctions: VR, volume reduction; Se, separation; De, detoxification; St, storage.

^cWaste types: 1, inorganic chemical without heavy metals; 2, inorganic chemical with heavy metals; 3, organic chemical without heavy metals; 4, organic chemical with heavy metals; 5, radiological; 6, biological; 7, flammable; 8, explosive.

^dWaste forms: S, solid; L, liquid; G, gas.

^eMost widely used technologies for hazardous-waste management.

processing than do the mass-burn units. These range in size from 5 to 100 tons/day. The third major class of municipal waste combustor burns RDF. The types of waste-to-energy boilers used to combust RDF can include suspension, stoker, and fluidized bed designs. RDF fuels can also be fired directly in large industrial boilers that are now used for the production of power with pulverized or stoker coal, oil, and gas. Although the process is not well established with coal, it appears that about 15 to 20 percent of the heat input can be from RDF. With oil as the fuel, about 10 percent of the heat input can be from RDF. Depending on the degree of processing, suspension, spreader-stoker, and double-vortex firing systems have been used.

Gasification The gasification process involves the partial combustion of a carbonaceous or hydrocarbon fuel to generate a combustible fuel gas rich in carbon monoxide and hydrogen. A gasifier is basically an incinerator operating under reducing conditions. Heat to sustain the process is derived from exothermic reactions, while the combustible components of the low-energy gas are primarily generated by endothermic reactions. The reaction kinetics of the gasification process are quite complex and still the subject of considerable debate.

When a gasifier is operated at atmospheric pressure with air as the oxidant, the end products of the gasification process are a low-energy gas typically containing (by volume) 10 percent CO₂, 20 percent CO, 15 percent H₂, and 2 percent CH₄, with the balance being N₂, and a carbon-rich ash. Because of the diluting effect of the nitrogen in the input air, the low-energy gas has an energy content in the range of the 5.2 to 6.0 MJ/m³ (140 to 160 Btu/ft³). When pure oxygen is used as the oxidant, a medium-energy gas with an energy content in the range of 12.9 to 13.8 MJ/m³ (345 to 370 Btu/ft³) is produced. Gasifiers were in widespread use on coal and wood until natural gas displaced them in the 1930s–1950s. Some large coal gasifiers are in use today in the United States and worldwide. While the process can work on solid waste, incinerators (which gasify and burn in one chamber) are favored over gasifiers.

Pyrolysis Of the many alternative chemical conversion processes that have been investigated, pyrolysis has received the most attention. Pyrolysis has been tested in countless pilot plants, and many full-scale demonstration systems have been operated. Few attained any long-term commercial use. Major issues were lack of market for the unstable and acidic pyrolytic oils and the char.

Depending on the type of reactor used, the physical form of solid wastes to be pyrolyzed can vary from unshredded raw wastes to the finely ground portion of the wastes remaining after two stages of shredding and air classification. Upon heating in an oxygen-free atmosphere, most organic substances can be split via thermal cracking and condensation reactions into gaseous, liquid, and solid fractions. Pyrolysis is the term used to describe the process. In contrast to the combustion process, which is highly exothermic, the pyrolytic process is highly endothermic. For this reason, the term *destructive distillation* is often used as an alternative for *pyrolysis*.

The characteristics of the three major component fractions resulting from the pyrolysis are (1) a gas stream containing primarily hydrogen, methane, carbon monoxide, carbon dioxide, and various other gases, depending on the organic characteristics of the material being pyrolyzed; (2) a fraction that consists of a tar and/or oil stream that is liquid at room temperatures and has been found to contain hundreds of chemicals such as acetic acid, acetone, methanol, and phenols; and (3) a char consisting of almost pure carbon plus any inert material that may have entered the process. It has been found that distribution of the product fractions varies with the temperature at which the pyrolysis is carried out. Under conditions of maximum gasification, the energy content of the resulting gas is about 26.1 MJ/kg (700 Btu/ft³). The energy content of pyrolytic oils has been estimated to be about 23.2 MJ/kg (10,000 Btu/lb).

Waste-to-Energy Systems The preceding section ended at production of steam. WTE (waste-to-energy) systems take over at this point, using high-pressure/high-temperature steam to drive turbines and produce shaft horsepower for prime movers at industrial plants or to generate electricity.

The fuel may be solid waste or gas or oil from a gasifier or pyrolysis system.

Typical flow sheets for alternative energy-recovery systems are shown in Fig. 25-65. Perhaps the most common flow sheet for the production of electric energy involves the use of a steam turbine-generator combination (see Fig. 25-65). As shown, when solid wastes are used as the basic fuel source, four operating modes are possible. A flow sheet using a gas-turbine-generator combination is shown in Fig. 25-65. The low-energy gas is compressed under high pressure so that it can be used more effectively in the gas turbine. Use of low- or medium-Btu gas for gas turbines has been attempted, and success requires good design and operation of gas cleaning equipment prior to introduction into the combustor of the gas turbine.

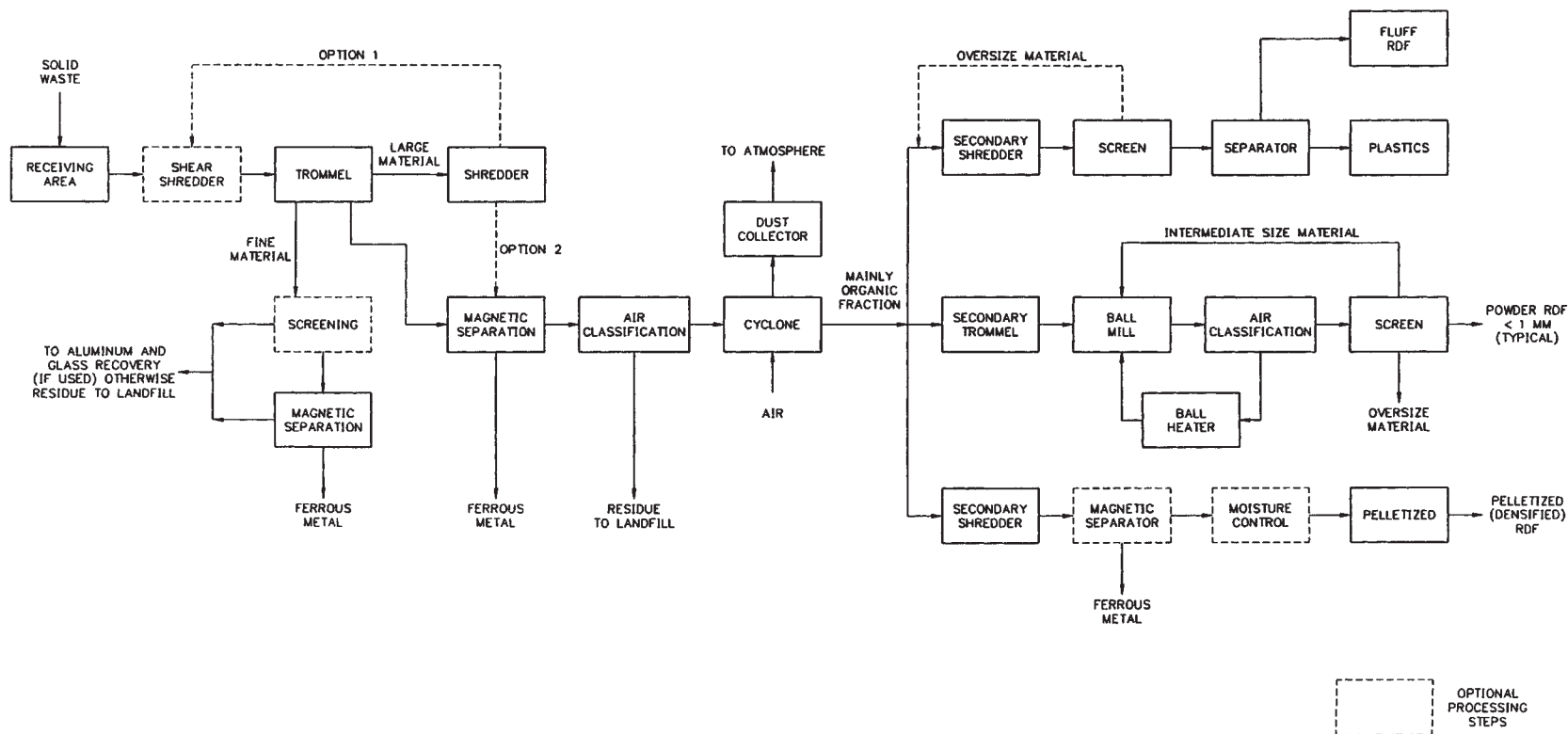


FIG. 25-63 Typical flow sheet for the recovery of materials and production of refuse-derived fuels (RDF). [Adapted in part from D. C. Wilson (ed.), Waste Management: Planning, Evaluation, Technologies, Oxford University Press, Oxford, 1981.]

TABLE 25-64 Biological and Thermal Processes Used for Recovery of Conversion Products from Solid Waste

Process	Conversion product	Preprocessing required	Comments
Biological			
Composting	Humuslike material	Shredding, air separation	Lack of markets primary shortcoming; technically proven in full-scale application
Anaerobic digestion	Methane gas	Shredding, air separation	Technology on laboratory scale only
Biological conversion to protein	Protein, alcohol	Shredding, air separation	Technology on pilot scale only
Biological fermentation	Glucose, furfural	Shredding, air separation	Used in conjunction with the hydrolytic process
Thermal			
Incineration with heat recovery	Energy in the form of steam	None	Markets for steam required; proven in numerous full-scale applications; air-quality regulations possibly prohibiting use
Supplementary fuel firing in boilers	Energy in the form of steam	Shredding, air separation, magnetic separation	If least capital investment desired, existing boiler required to be capable of modification; air-quality regulations possibly prohibiting use
Gasification	Energy in the form of low energy gas	Shredding, air separation, magnetic separation	Gasification also capable of being used for codisposal for industrial sludges
Pyrolysis	Energy in the form of gas or oil	Shredding, magnetic separation	Technology proven only in pilot applications; even though pollution is minimized, air-quality regulations possibly prohibiting use
Hydrolysis	Glucose, furfural	Shredding, air separation	Technology on pilot scale only
Chemical conversion	Oil, gas, cellulose acetate	Shredding, air separation	Technology on pilot scale only

TABLE 25-65 Important Design Considerations for Aerobic-Composting Processes*

Item	Comment
Particle size	For optimum results the size of solid wastes should be between 25 and 75 mm (1 and 3 in).
Seeding and mixing	Composting time can be reduced by seeding with partially decomposed solid wastes to the extent of about 1 to 5 percent by weight. Sewage sludge can also be added to prepared solid wastes. When sludge is added, the final moisture content is the controlling variable.
Mixing or turning	To prevent drying, caking, and air channeling, material in the process of being composted should be mixed or turned on a regular schedule or as required. Frequency of mixing or turning will depend on the type of composting operation.
Air requirements	Air with at least 50 percent of the initial oxygen concentration remaining should reach all parts of the composting material for optimum results, especially in mechanical systems.
Total oxygen requirements	The theoretical quantity of oxygen required can be estimated.
Moisture content	Moisture content should be in the range between 50 and 60 percent during the composting process. The optimum value appears to be about 55 percent.
Temperature	For best results temperature should be maintained between 322 and 327 K (130 and 140°F) for the first few days and between 327 and 333 K (130 and 140°F) for the remainder of the active composting period. If temperature goes beyond 339 K (150°F), biological activity is reduced significantly.
Carbon-nitrogen ratio	Initial carbon-nitrogen ratios (by mass) between 35 and 50 are optimum for aerobic composting. At lower ratios ammonia is given off. Biological activity is also impeded at lower ratios. At higher ratios nitrogen may be a limiting nutrient.
pH	To minimize the loss of nitrogen in the form of ammonia gas, pH should not rise above about 8.5.
Control of pathogens	If the process is properly conducted, it is possible to kill all the pathogens, weeds, and seeds during the composting process. To do this, the temperature must be maintained between 333 and 344 K (140 and 160°F) for 24 h.

*Adapted from G. Tchobanoglous, H. Theisen, R. Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1977.

Efficiency Factors Representative efficiency data for boilers, pyrolytic reactors, gas turbines, steam-turbine-generator combinations, electric generators, and related plant use and loss factors are given in Table 25-67. In any installation in which energy is being produced, allowance must be made for the power needs of the station or process and for unaccounted-for-process-heat losses. Typically, the auxiliary power allowance varies from 4 to 8 percent of the power produced. Process-heat losses usually will vary from 2 to 8 percent. In general, steam pressures of 600 psig and temperatures of 650° F are considered minimum for economical power generation. Industrial plants may choose a cogeneration topping cycle, with steam exhaust from the turbine at the plant's process steam pressure, typically in the 125–250-psig range. For commercial WTE plants, condensing turbines are the norm.

Determination of Energy Output and Efficiency for Energy-Recovery Systems An analysis of the amount of energy produced

TABLE 25-66 Important Design Considerations for Anaerobic Digestion*

Item	Comment
Size of material shredded	Wastes to be digested should be shredded to a size that will not interfere with the efficient functioning of pumping and mixing operations.
Mixing equipment	To achieve optimum results and to avoid scum buildup, mechanical mixing is recommended.
Percentage of solid wastes mixed with sludge	Although amounts of waste varying from 50 to 90+ percent have been used, 60 percent appears to be a reasonable compromise.
Hydraulic and mean cell residence time, $\Theta_h = \Theta_c$	Washout time is in the range of 3 to 4 days. Use 8 to 15 days for design or base design on results of pilot-plant studies.
Loading rate	0.6 to 1.6 kg/(m ³ ·day) [0.04 to 0.10 lb/(ft ³ ·day)]. Not well defined at present time. Significantly higher rates have been reported.
Temperature	Between 327 and 333 K (130 and 140°F).
Destruction of volatile solid wastes	Varies from about 60 to 80 percent; 70 percent can be used for estimating purposes.
Total solids destroyed	Varies from 40 to 60 percent, depending on amount of inert material present originally.
Gas production	0.5 to 0.75 m ³ /kg (8 to 12 ft ³ /lb) of volatile solids destroyed (CH ₄ = 60 percent; CO ₂ = 40 percent).

*From G. Tchobanoglous, H. Theisen, and R. Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1977.

†Actual removal rates for volatile solids may be less, depending on the amount of material diverted to the scum layer.

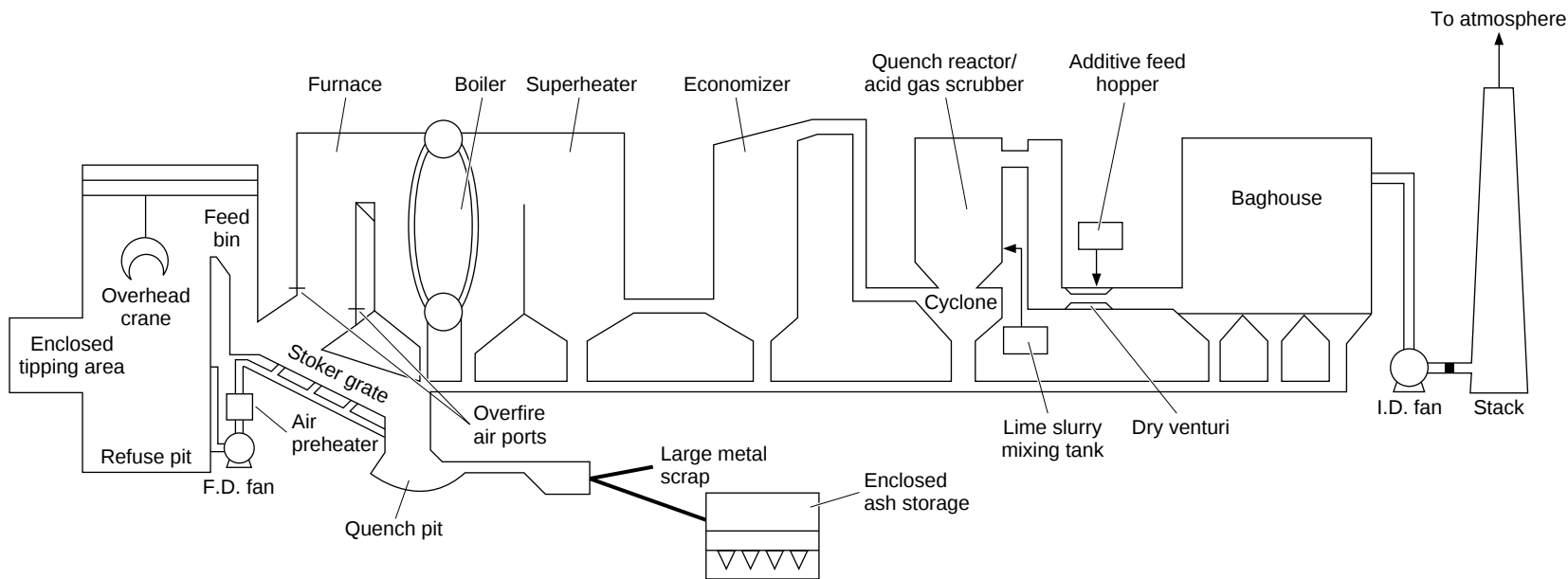
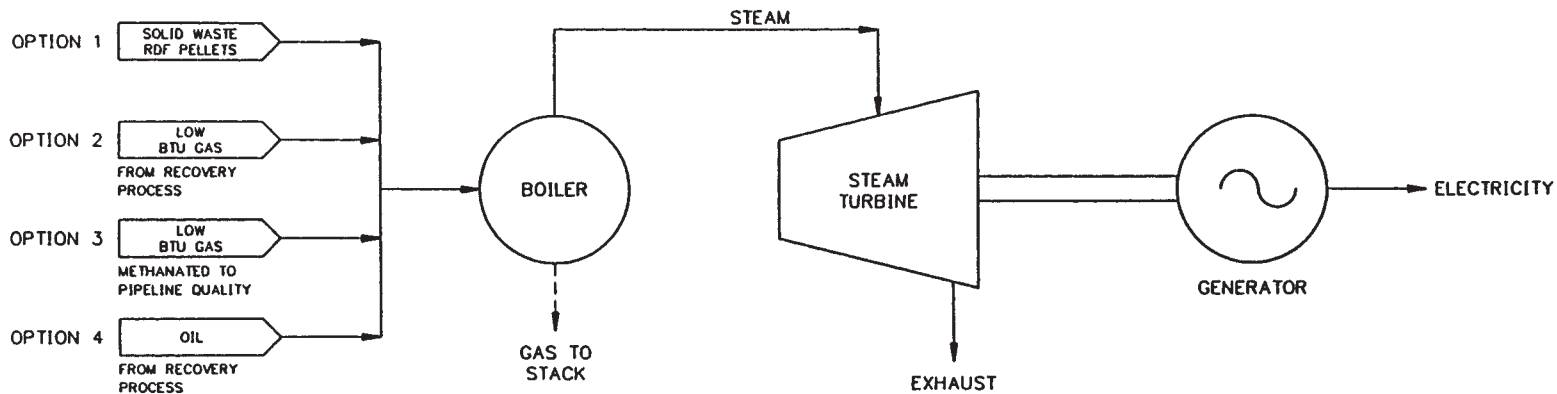
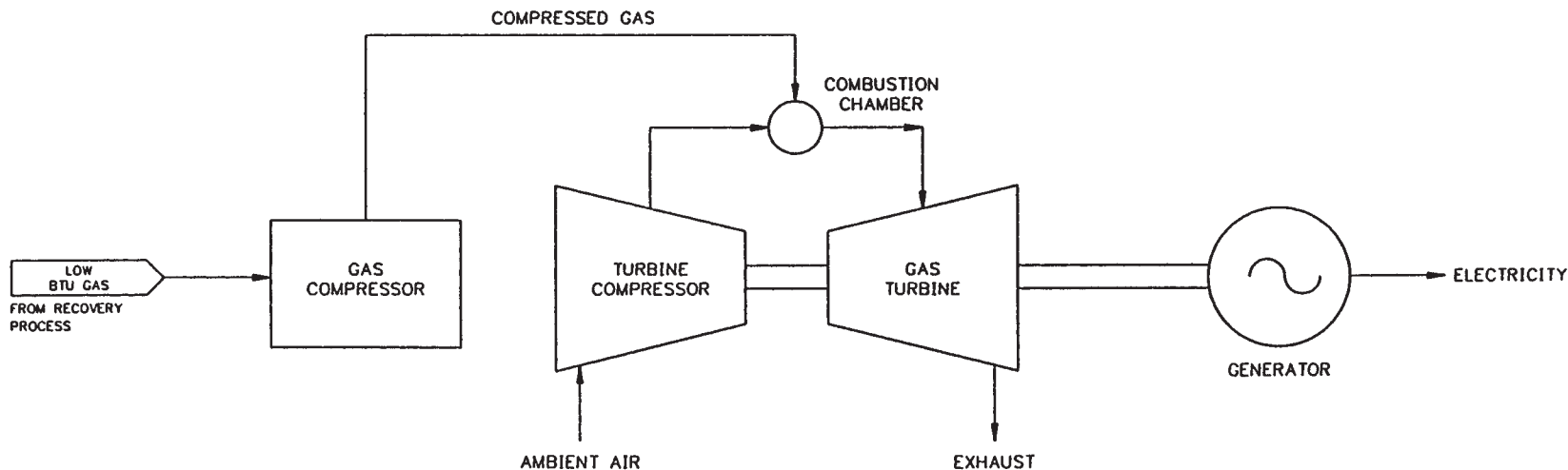


FIG. 25-64 Diagram of a modern mass-burn facility. (From *Municipal Waste Combustion Study Report to Congress*, June 1982, PB87-206074.)



OPTIONS WITH STEAM-TURBINE-GENERATOR COMBINATION



OPTIONS WITH GAS-COMPRESSOR-GAS-TURBINE-GENERATOR COMBINATION

FIG. 25-65 Flow sheet—alternative energy recovery systems.

TABLE 25-67 Typical Thermal Efficiency and Plant Use and Loss Factors for Individual Components and Processes Used for Recovery of Energy from Solid Wastes

Component	Efficiency*		Comments
	Range	Typical	
Incinerator-boiler	40–68	63	Mass-fired
Boiler			
Solid fuel	60–75	72	Processed solid wastes (RDF)
Low-Btu gas	60–80	75	Necessity to modify burners
Oil-fired	65–85	80	Oils produced from solid wastes possibly required to be blended to reduce corrosiveness
Casifier	60–70	70	
Pyrolysis reactor	65–75	70	
Turbines			
Combustion gas			
Simple cycle	8–12	10	
Regenerative	20–26	24	Including necessary appurtenances
Expansion gas	30–50	40	
Steam-turbine-generator system			
Less than 10 MW	24–40	29†‡	Including condenser, heaters, and all other necessary appurtenances but not boiler
Over 10 MW	28–32	31.6†‡	
Electric generator			
Less than 10 MW	88–92	90	
Over 10 MW	94–98	96	
Plant use and loss factors			
Station-service allowance			
Steam-turbine-generator plant	4–8	6	
Unaccounted heat losses	2–8	5	

*Theoretical value for mechanical equivalent of heat = 3600 kJ/kWh.

†Efficiency varies with exhaust pressure. Typical value given is based on an exhaust pressure in the range of 50 to 100 mmHg.

‡Heat rate = 11,395 kJ/kWh = (3600 kJ/kWh)/0.316.

TABLE 25-68 Energy Output and Efficiency for 1000 Metric Ton of Waste/Day Steam-Boiler Turbine-Generator Energy-Recovery Plant Using Unprocessed Industrial Solid Wastes with Energy Content of 12,000 kJ/kg

Item	Value
Energy available in solid wastes, million kJ/h [(1000 metric tons/day × 1000 kg/metric ton × 12,000 kJ/kg)/(24h/day × 10 ⁶ kJ/million kJ)]	500
Steam energy available, million kJ/h (500 million kJ/h × 0.7)	350
Electric power generation, kW (350 million kJ/h)/(11,395 kJ/kWh)*	30,715
Station-service allowance, kW [30,715 (0.06)]	-1,843
Unaccounted heat losses, kW [30,715 (0.05)]	-1,536
Net electric power for export, kW	27,336
Overall efficiency, percent {(27,336 kW)/[(500,000,000 kJ/h)/(3,600 kJ/kWh)](100)}	19.7

*11,395 kJ/kWh = (3600 kJ/kWh)/0.316.

from a solid-waste energy conversion system using an incinerator-boiler-steam-turbine-electric-generator combination with a capacity of 1000 metric tons per day of waste is presented in Table 25-68. If it is assumed that 10 percent of the power generated is used for the front-end processing system (typical values vary from 8 to 14 percent), then the net power for export is 24,604 kW and the overall efficiency is 17.5 percent.

Concentration of WTE Incinerators The total number of municipal waste incinerator facilities as listed in the *Solid Waste Digest*, vol. 4, no. 9 September 1994 (a publication of Chartwell Information Publishers of Alexandria, VA) is 62. See Table 25-69, which covers over 200 existing units. The wastes burned in these facilities totals 8.44 percent of total municipal wastes managed in landfills, incinerators, and transfer stations. This amounts to 88,470 tons per day combusted municipal waste.

One notes that the heavily populated areas of the country also have the highest number of WTE facilities as well as the highest intake of municipal waste into incinerators. This is also due to the lack of open space for landfills compared to the midwest and western states. The amount of waste combusted in the northeastern states is 20.7 percent of the total generated compared to 8.44 per-

cent of all municipal wastes combusted nationwide. The cost per ton averages \$77 in New Jersey and New York compared to \$57 for the nation. Incinerator costs are similar to landfill costs in the northeastern states. However, landfill costs are far lower than WTE tipping fees. For example, in states like Idaho (landfill costs, \$12/ton) and Texas (landfill costs, \$10/ton), WTE incinerator plants cannot compete. The NIMBY (Not in my Backyard) syndrome concerning incineration systems has also hurt the siting and permitting of many of these facilities. Figure 25-66 shows the range of costs for incineration in September 1994. Figure 25-67 shows the range costs for all solid waste management in September 1994. The National index was \$37.93/ton in 1994, up from \$33.64/ton in 1992. This is an average increase of 6.5% per year which is above the inflation rate for this two-year period.

REGULATIONS APPLICABLE TO MUNICIPAL WASTE COMBUSTORS

New Source Performance Standards (NSPS) were promulgated under Sections 111(b) and 129 of the CAA Amendments of 1990. The NSPS applies to new municipal solid-waste combustors (MWCs) with

TABLE 25-69 Solid Waste Price Index, WTE Incinerator Intake TPD-Tip Fee, September 1994

Region	Number of facilities	Intake, TPD	% of daily intake	Tip fee, \$/ton
Northeastern states				
Connecticut	5	6410	60.63	66.35
Delaware	0	0	0	n/a
Massachusetts	2	2460	13.33	60.52
Maryland	3	3562	19.78	64.65
Maine	3	2407	77.94	61.55
New Hampshire	1	997	19.76	52.70
New Jersey	4	6575	22.64	80.40
New York	8	14,150	29.22	74.22
Pennsylvania	6	7580	10.32	62.57
Rhode Island	0	0	0	n/a
Vermont	0	0	0	n/a
Total northeastern states	32	44,141	20.7	66.56
Southern states				
Alabama	1	690	6.39	39.00
Arkansas	0	0	0	n/a
Florida	10	16,633	26.08	58.20
Georgia	0	0	0	n/a
Kentucky	0	0	0	n/a
Louisiana	0	0	0	n/a
Mississippi	0	0	0	n/a
North Carolina	0	0	0	n/a
South Carolina	1	600	4.44	51.50
Tennessee	2	1970	9.81	28.64
Virginia	3	4975	11.12	45.04
West Virginia	0	0	0	n/a
Total southern states	17	24,868	10.32	52.53
Midwestern states				
Iowa	0	0	0	n/a
Illinois	0	0	0	n/a
Indiana	1	2362	6.45	25.00
Kansas	0	0	0	n/a
Michigan	1	1630	5.22	52.66
Minnesota	3	5187	35.4	61.56
Missouri	0	0	0	n/a
North Dakota	0	0	0	n/a
Nebraska	0	0	0	n/a
Ohio	4	5437	9.16	31.32
South Dakota	0	0	0	n/a
Wisconsin	0	0	0	n/a
Total midwestern states	9	14,616	5.89	43.41
Western states				
Arizona	0	0	0	n/a
Colorado	0	0	0	n/a
Idaho	0	0	0	n/a
Montana	0	0	0	n/a
New Mexico	0	0	0	n/a
Nevada	0	0	0	n/a
Oklahoma	1	1230	15.1	41.91
Texas	0	0	0	n/a
Utah	0	0	0	n/a
Wyoming	0	0	0	41.91
Total western states	1	1230	0.76	41.91
Pacific states				
Alaska	0	0	0	n/a
California	2	2673	1.79	27.50
Hawaii	0	0	0	n/a
Oregon	0	0	0	n/a
Washington	1	944	5	87.61
Total Pacific states	3	3617	1.95	43.91
National total	62	88,471	8.44	57.49

capacity to combust more than 250 tons per day of municipal solid waste that commenced construction after December 20, 1989. The proposed standards and guidelines were published in the *Federal Register* on December 20, 1989.

Section 129 of the CAAA of 1990 applies to a range of solid waste incinerators including MWCs, medical waste incinerators (MWIs)

and industrial waste incinerators. Incinerators for hazardous solid and liquid wastes are covered under RCRA regulations (40 CFR Parts 260 through 272) and TSCA, Toxic Substances Control Act, 1976 (40 CFR Parts #700–766).

Regulated Pollutants The NSPS regulates MWC emissions, and nitrogen oxides (NO_x) emissions from individual MWC units larger

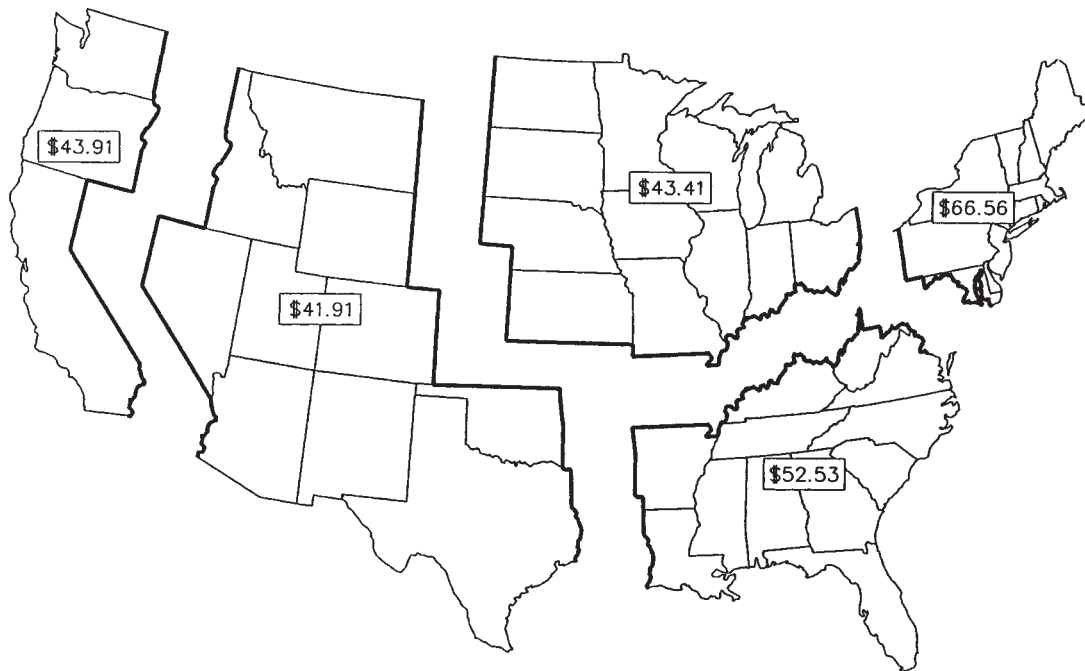


FIG. 25-66 Waste-to-energy price index. National index, September 1994, \$57.49/ton. (Data from Solid Waste Digest, vol. 4, no. 9, Sept. 1994. Published by Chartwell Information Publishers, Alexandria, VA.)

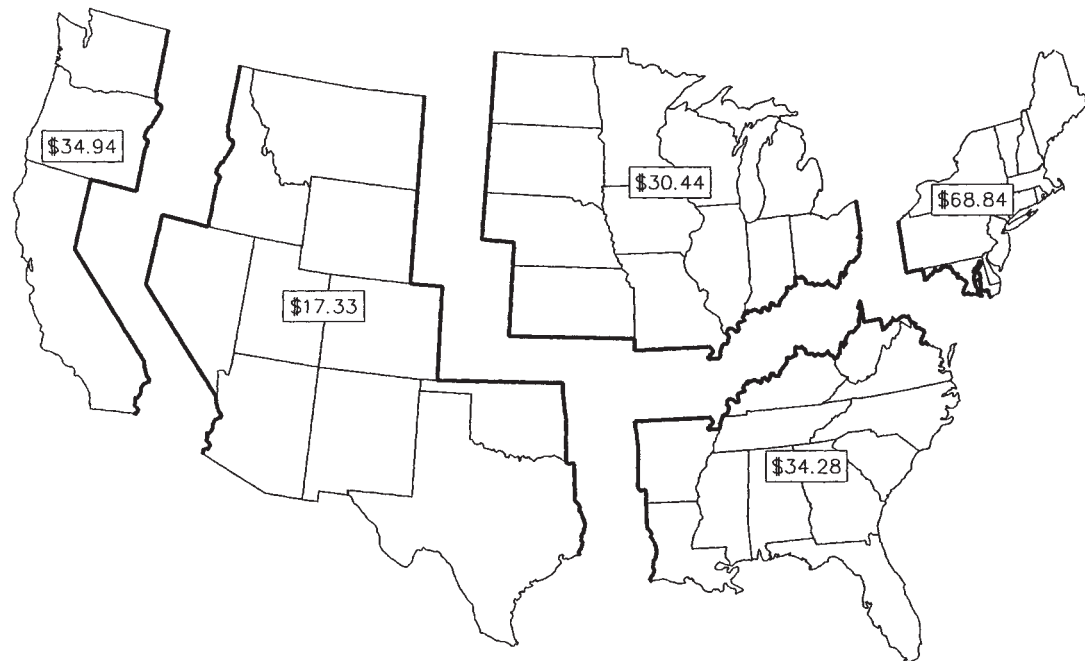


FIG. 25-67 Solid Waste Price Index™. National index, September 1994, \$37.93/ton; September 1992, \$33.64/ton. (Data from Solid Waste Digest, vol. 4, no. 9, Sept. 1994. Published by Chartwell Information Publishers, Alexandria, VA.)

than 250 tpd capacity. MWC emissions are subcategorized as MWC metal emissions, MWC organic emissions, and MWC acid gas emissions. The NSPS establishes emission limits for organic emissions (measured as dioxins and furans), MWC metal emissions (measured as particulate matter [PM]), and MWC acid gas emissions (measured as sulfur dioxide [SO₂] and hydrogen chloride [HCl]), as well as NO_x emission limits.

MWCs Organic Emissions The NSPS limits organic emissions to a total dioxin plus furan emission limit of 30 ng/dscm (at 7 percent O₂ dry volume). This level is approximately equivalent to a toxic equivalent (TEQ) of 1.0 ng/dscm, using the 1990 international toxic equivalency factor (I-TEF) approach.

MWCs Metal Emissions The NSPS includes a PM emission limit of 0.015 grains per dry standard cubic feet (gr/dscf) at 7 percent oxygen dry/volume and an opacity limit of 10 percent (6 minute average).

MWCs Acid Gas Emissions The NSPS requires a 95 percent reduction of HCl emissions and an 80 percent reduction of SO₂ emissions for new MWCs or an emission limit of 25 ppmv for HCl and 30 ppmv for SO₂ (at 7 percent O₂ dv).

Nitrogen Oxides Emissions The NSPS limits NO_x emissions to 180 ppmv (at 7 percent O₂ dv).

MSC Air-Pollution-Control Systems MSCs generate flue gas that contains particulates, acid gases and trace amounts of organic and volatile metals. Particulates have traditionally been removed by use of cyclone separators and electrostatic precipitators. Acid gases require neutralization and removal from the gas stream. This can be accomplished by adding solutions or chemicals to the gas stream and removing the products of the chemical reaction when these materials are mixed together. Two major types of APCs are employed:

- Dry systems, where the gas stream is humidified and chemicals are added to the system
- Wet systems, where large quantities of water containing chemicals wash the gas stream

Incinerator Performance Environmental organizations have had concerns regarding performance of existing incineration plants. Major concerns focus on dioxin, mercury, and ash. Groups opposing a proposed WTE facility in New York State set emission standards for the facility. Table 25-70 compares the recommendations for emission levels made by the Natural Resources Defense Council, Environmental Defense Fund, INFORM, Environmental Action Coalition, and Scenic Hudson in *A Solid Waste Blue Print for New York State*, (March, 1988), New York State regulations (GNYCRR Part 219), and actual tests performed at Hempstead in the summer of 1990. Note that the results from the Hempstead stack testing performed in August, 1990 exceed the New York State regulations as well as the environmentalists' recommendation in every category. This was not necessarily true in the case of many MSC plants without proper com-

bustion controls or APC systems. With the standards established in Section 129 of the CAAA of 1990, all facilities must retrofit to conform to these standards or be shut down.

MSC Facilities are required to meet some of the toughest environmental air emission standards in the country. Complying with these standards makes modern waste combustors among the cleanest producers of electricity—and may even provide a means of improving a community's overall air quality.

ULTIMATE DISPOSAL

Disposal on or in the earth's mantle is, at present, the only viable method for the long-term handling of (1) solid wastes that are collected and are of no further use, (2) the residual matter remaining after solid wastes have been processed, and (3) the residual matter remaining after the recovery of conversion products and/or energy has been accomplished. The three land disposal methods used most commonly are (1) landfilling, (2) landfarming, and (3) deepwell injection. Although incineration is being used more often as a disposal method, it is, in reality, a processing method. Recently, the concept of using muds in the ocean floor as a waste-storage location also has received some attention.

Landfilling of Solid Wastes Landfilling involves the controlled disposal of solid wastes on or in the upper layer of the earth's mantle. Important aspects in the implementation of sanitary landfills include (1) site selection, (2) landfilling methods and operations, (3) occurrence of gases and leachate in landfills, (4) movement and control of landfill gases and leachate, and (5) landfill design. The landfilling of hazardous wastes is considered separately.

Site Selection Factors that must be considered in evaluating potential solid-waste-disposal sites are summarized in Table 25-71. Final selection of a disposal site usually is based on the results of a preliminary site survey, results of engineering design and cost studies, and an environmental-impact assessment.

Landfilling Methods and Operations To use the available area at a landfill site effectively, a plan of operation for the placement of solid wastes must be prepared. Various operational methods have been developed primarily on the basis of field experience. The principal methods used for landfilling dry areas may be classified as (1) area, and (2) depression.

1. **Area method.** The area method is used when the terrain is unsuitable for the excavation of trenches in which to place the solid wastes. The filling operation usually is started by building an earthen levee against which wastes are placed in thin layers and compacted (see Fig. 25-68). Each layer is compacted as the filling progresses until the thickness of the compacted wastes reaches a height varying from 2 to 3 m (6 to 10 ft). At that time and at the end of each day's operation, a 150- to 300-mm (6- to 12-in) layer of cover material is placed

TABLE 25-70 Hempstead Emissions Comparison

Parameter*	Environmentalists recommendations	New York State regulations	Actual test results from Hempstead
Particulates (gr/dscf)	0.010	0.010	0.00053
Opacity (clarity of air from the stack)	5%	10%	<5%
Dioxin† (ng/dscm)	0.1	0.2 (goal)	0.0155
Hydrogen chloride (ppmv)	50	50 ppmv or 90% removal	41.7
Sulfur dioxide‡ (ppmv)	50	Use HCl	22.9
Lead (lb/ton)	0.0005	Risk assessment	0.000011
Arsenic (lb/ton)	0.00001	Risk assessment	<0.000003
Mercury (lb/ton)	0.0015	Risk assessment	0.0006
Cadmium (lb/ton)	0.00002	Risk assessment	<0.000003
Carbon monoxide§ (ppmv)	50	Use combustion efficiency	46.2

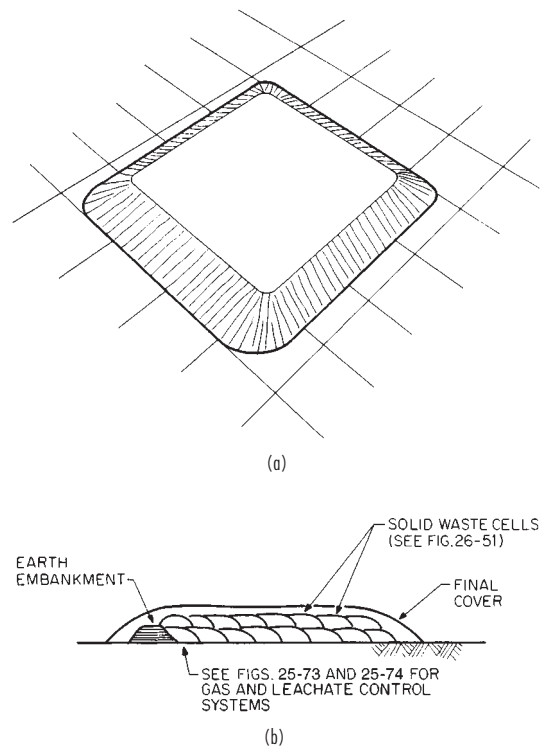
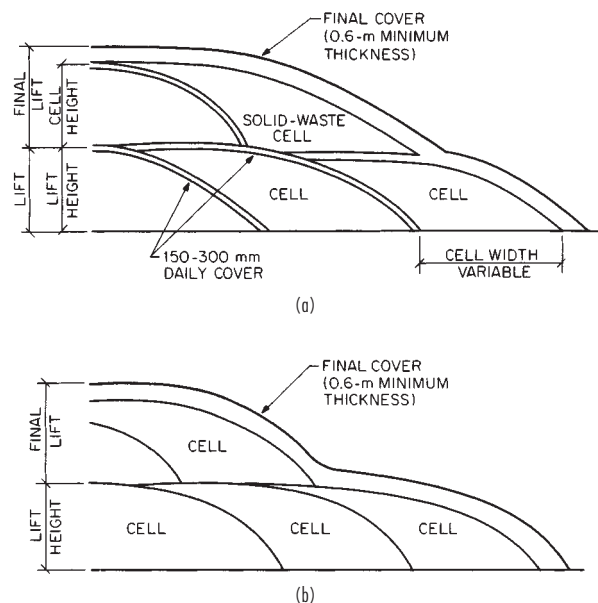
gr/dscf = grains per dry standard cubic foot
ng/dscm = nanograms per dry standard cubic meter
ppmv = parts per million by volume
lb/ton = pounds per ton of refuse processed
*Concentrations are corrected to 12 percent CO₂ basis.
†PCDD/PCDF toxic equivalents as defined by NYSDEC.
‡8-hour average.
§4-hour average.

Data provided by Taconic Resources, Inc., Jan. 12, 1993. Inform Publication, *A Solid Waste Blueprint for New York State*, March 1988.

TABLE 25-71 Important Factors in Preliminary Selection of Landfill Sites

Factor	Remarks
Available land area	In selecting potential land disposal sites, it is important to ensure that sufficient land area is available. Sufficient area to operate for at least 1 year at a given site is needed to minimize costs.
Impact of processing and resource recovery	It is important to project the extent of resource-recovery-processing activities that are likely to occur in the future and determine their impact on the quantity and condition of the residual materials to be disposed of.
Haul distance	Although minimum haul distances are desirable, other factors must also be considered. These include collection-route location, types of wastes to be hauled, local traffic patterns, and characteristics of the routes to and from the disposal site (condition of the routes, traffic patterns, and access conditions).
Soil conditions and topography	Because it is necessary to provide material for each day's landfill and a final layer of cover after the filling has been completed, data on the amounts and characteristics of the soils in the area must be obtained. Local topography will affect the type of landfill operation to be used, equipment requirements, and the extent of work necessary to make the site usable.
Climatological conditions	Local weather conditions must also be considered in the evaluation of potential sites. Under winter conditions where freezing is severe, landfill cover material must be available in stockpiles when excavation is impractical. Wind and wind patterns must also be considered carefully. To avoid blowing or flying papers, windbreaks must be established.
Surface-water hydrology	The local surface-water hydrology of the area is important in establishing the existing natural drainage and runoff characteristics that must be considered. Other conditions of flooding must also be identified.
Geologic and hydrogeologic conditions	Geologic and hydrogeologic conditions are perhaps the most important factors in establishing the environmental suitability of the area for a landfill site. Data on these factors are required to assess the pollution potential of the proposed site and to establish what must be done to the site to control the movement of leachate or gases from the landfill.
Local environmental conditions	The proximity of both residential and industrial developments is extremely important. Great care must be taken in their operation if they are to be environmentally sound with respect to noise, odor, dust, flying paper, and vector control.
Ultimate uses	Because the ultimate use affects the design and operation of the landfill, this issue must be resolved before the layout and design of the landfill are started.

over the completed fill. The cover material must be hauled in by truck or earth-moving equipment from adjacent land or from borrow-pit areas. In some newer landfill operations, the daily cover material is omitted. A completed lift, including the cover material is called a "cell" (see Fig. 25-69). Successive lifts are placed on top of one another until the final grade called for in the ultimate development plan is reached. A final layer of cover material is used when the fill reaches the final design height.

**FIG. 25-68** Area method for landfilling solid wastes. (a) Pictorial view of completed landfill. (b) Section through landfill.**FIG. 25-69** Typical section through a landfill. (a) With daily or intermediate cover. (b) Without daily or intermediate cover.

2. *Depression method.* At locations where natural or artificial depressions exist, it is often possible to use them effectively for land-filling operations. Canyons, ravines, dry borrow pits, and quarries have been used for this purpose. The techniques to place and compact solid wastes in depression landfills vary with the geometry of the site, the characteristics of the cover material, the hydrology and geology of the site, and access of the site.

In a canyon site, filling starts at the head end of the canyon (see Fig. 25-70) and ends at the mouth. The practice prevents the accumulation of water behind the landfill. Wastes usually are deposited on the canyon floor and from there are pushed up against the canyon face at a slope of about 2 to 1. In this way, a high degree of compaction can be achieved.

3. *Landfills in wet areas.* Because of the problems associated with contamination of local groundwaters, the development of odors, and structural stability, landfills must be avoided in wetlands. If wet areas such as ponds, pits, or quarries must be used as landfill sites, special provisions must be made to contain or eliminate the movement of leachate and gases from completed cells. Usually this is accomplished by first draining the site and then lining the bottom with a clay liner or other appropriate sealants. If a clay liner is used, it is important to continue operation of the drainage facility until the site is filled to avoid the creation of uplift pressures that could cause the liner to rupture from heaving.

Occurrence of Gases and Leachate in Landfills The following biological, physical, and chemical events occur when solid wastes are placed in a sanitary landfill: (1) biological decay of organic materials, either aerobically or anaerobically, with the evolution of gases and liquids; (2) chemical oxidation of waste materials; (3) escape of gases from the fill; (4) movement of liquids caused by differential heads; (5) dissolving and leaching of organic and inorganic materials by water and leachate moving through the fill; (6) movement of dissolved material by concentration gradients and osmosis; and (7) uneven settlement caused by consolidation of material into voids.

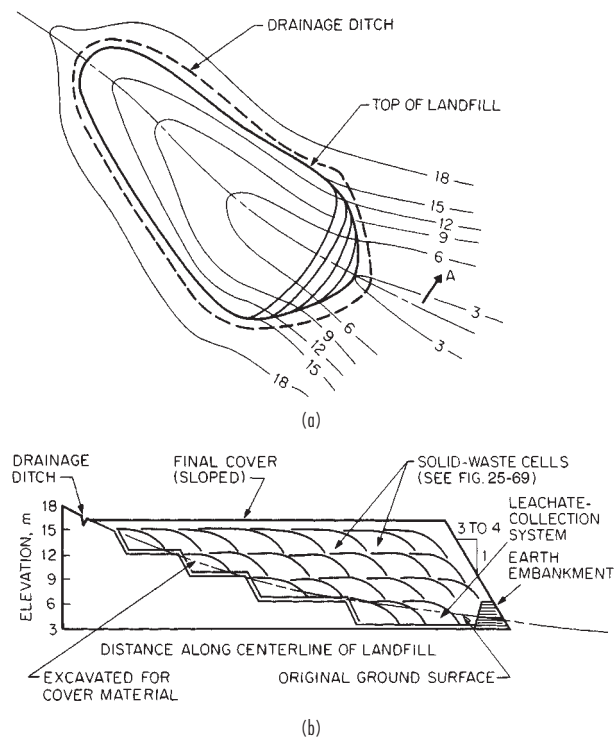
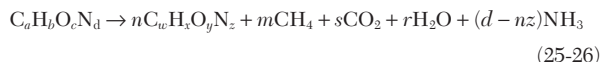


FIG. 25-70 Depression method for landfilling solid wastes. (a) Plan view: canyon-site landfill. (b) Section through landfill.

With respect to item 1, bacterial decomposition initially occurs under aerobic conditions because a certain amount of air is trapped within the landfill. However, the oxygen in the trapped air is exhausted within days, and long-term decomposition occurs under anaerobic conditions.

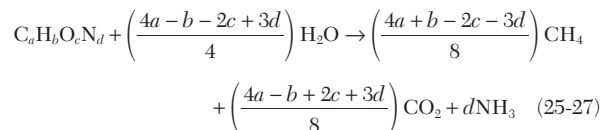
1. *Gases in landfills.* Gases found in landfills include air, ammonia, carbon dioxide, carbon monoxide, hydrogen, hydrogen sulfide, methane, nitrogen, and oxygen. Data on the molecular weight and density of these gases are presented in Sec. 2. Carbon dioxide and methane are the principal gases produced from the anaerobic decomposition of the organic solid-waste components.

The anaerobic conversion of organic compounds is thought to occur in three steps: The first involves the enzyme-mediated transformation (hydrolysis) of higher-weight molecular compounds into compounds suitable for use as a source of energy and cell carbon; the second is associated with the bacterial conversion of the compounds resulting from the first step into identifiable lower-molecular-weight intermediate compounds; and the third step involves the bacterial conversion of the intermediate compounds into simpler end products, such as carbon dioxide (CO_2) and methane (CH_4). The overall anaerobic conversion of organic industrial wastes can be represented with the following equation:



where $s = a - nw - m$
 $r = c - ny - 2s$

The terms $\text{C}_a\text{H}_b\text{O}_c\text{N}_d$ and $\text{C}_w\text{H}_x\text{O}_y\text{N}_z$ are used to represent on a molar basis the composition of the material present at the start of the process. If it is assumed that the organic wastes are stabilized completely, the corresponding expression is



The rate of decomposition in unmanaged landfills, as measured by gas production, reaches a peak within the first 2 years and then slowly tapers off, continuing in many cases for periods up to 25 years or more. The total volume of the gases released during anaerobic decomposition can be estimated in a number of ways. If all the organic constituents in the wastes (with the exception of plastics, rubber, and leather) are represented with a generalized formula of the form $\text{C}_a\text{H}_b\text{O}_c\text{N}_d$, the total volume of gas can be estimated by using Eq. (25-27) with the assumption of completed conversion to carbon dioxide and methane.

2. *Leachate in landfills.* Leachate may be defined as liquid that has percolated through solid waste and has extracted dissolved or suspended materials from it. In most landfills, the liquid portion of the leachate is composed of the liquid produced from the decomposition of the wastes and liquid that has entered the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs. Representative data on chemical characteristics of leachate are reported in Table 25-72.

Gas and Leachate Movement and Control Under ideal conditions, the gases generated from a landfill should be either vented to the atmosphere or, in larger landfills, collected for the production of energy. Landfills with >2.5 million cubic meters of waste or >50 Mg/y NMOC (nonmethane organic compounds) emissions may require landfill-gas collection and flare systems, per EPA support WWW, CFR 60 Regulations. The leachate should be either contained within the landfill or removed for treatment.

1. *Gas movement.* In most cases, over 90 percent of the gas volume produced from the decomposition of solid wastes consists of methane and carbon dioxide. Although most of the methane escapes to the atmosphere, both methane and carbon dioxide have been found in concentrations of up to 40 percent at lateral distances of up to 120 m (400 ft) from the edges of landfills. Methane can accumulate below buildings or in other enclosed spaces on or close to a sanitary landfill. With proper venting, methane should not pose a problem.

TABLE 25-72 Typical Leachate Quality of Municipal Waste

S1 Number	Parameter	Overall range (mg/liter except as indicated)
1	TDS	584–55,000
2	Specific conductance	480–72,500 μ mho/cm
3	Total suspended solids	2–140,900
4	BOD	ND–195,000
5	COD	6.6–99,000
6	TOC	ND–40,000
7	pH	3.7–8.9 units
8	Total alkalinity	ND–15,050
9	Hardness	0.1–225,000
10	Chloride	2–11,375
11	Calcium	3.0–2,500
12	Sodium	12–6,010
13	Total Kjeldahl nitrogen	2–3,320
14	Iron	ND–4,000
15	Potassium	ND–3,200
16	Magnesium	4.0–780
17	Ammonia-nitrogen	ND–1,200
18	Sulfate	ND–1,850
19	Aluminum	ND–85
20	Zinc	ND–731
21	Manganese	ND–400
22	Total phosphorus	ND–234
23	Boron	0.87–13
24	Barium	ND–12.5
25	Nickel	ND–7.5
26	Nitrate-nitrogen	ND–250
27	Lead	ND–14.2
28	Chromium	ND–5.6
29	Antimony	ND–3.19
30	Copper	ND–9.0
31	Thallium	ND–0.78
32	Cyanide	ND–6
33	Arsenic	ND–70.2
34	Molybdenum	0.01–1.43
35	Tin	ND–0.16
36	Nitrite-nitrogen	ND–1.46
37	Selenium	ND–1.85
38	Cadmium	ND–0.4
39	Silver	ND–1.96
40	Beryllium	ND–0.36
41	Mercury	ND–3.0
42	Turbidity	40–500 Jackson units

From McGinley, P. M. and Kmet, P., *Formation Characteristics, Treatment, and Disposal of Leachate from Municipal Solid Waste Landfills*, Bureau of Solid Waste Management, Wisconsin Department of Natural Resources, Madison, 1984.

Because carbon dioxide is about 1.5 times as dense as air and 2.8 times as dense as methane, it tends to move toward the bottom of the landfill. As a result, the concentration of carbon dioxide in the lower portions of landfill may be high for years. Ultimately, because of its density, carbon dioxide will also move downward through the underlying formation until it reaches the groundwater. Because carbon dioxide is readily soluble in water, it usually lowers the pH, which in turn can increase the hardness and mineral content of the groundwater through the solubilization of calcium and magnesium carbonates.

2. *Control of gas movement.* The lateral movement of gases produced in a landfill can be controlled by installing vents made of materials that are more permeable than the surrounding soil. Typically, as shown in Fig. 25-71a, gas vents are constructed of gravel. The spacing of cell vents depends on the width of the waste cell but usually varies from 18 to 60 m (60 to 200 ft). The thickness of the gravel layer should be such that it will remain continuous even though there may be differential settling; 300 to 450 mm (12 to 18 in) is recommended. Barrier vents (see Fig. 25-71b) also can be used to control the lateral movement of gases. Well vents are often used in conjunction with lateral surface vents buried below grade in a gravel trench (see Fig. 25-71c). Details of a gas vent are shown in Fig. 25-72. Control of the downward movement of gases can be accomplished by installing perforated pipes in the gravel layer at the bottom of the landfill. If the gases cannot be vented laterally, it may be necessary to install gas wells

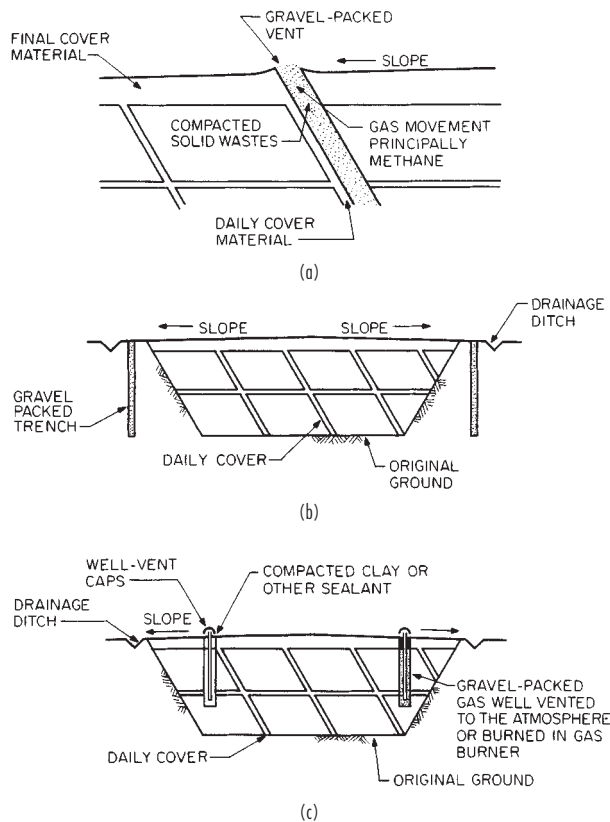


FIG. 25-71 Vents used to control the lateral movement of gases in landfills. (a) Cell. (b) Barrier. (c) Well. (From G. Tchobanoglous, H. Theisen, and R. Eliassen, *Solid Wastes: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1977.)

and vent the gas to the atmosphere. This is considered a passive venting system. See Fig. 25-73.

The movement of landfill gases through adjacent soil formations can be controlled by constructing barriers of materials that are more impermeable than the soil (see Fig. 25-74a). Some of the landfill

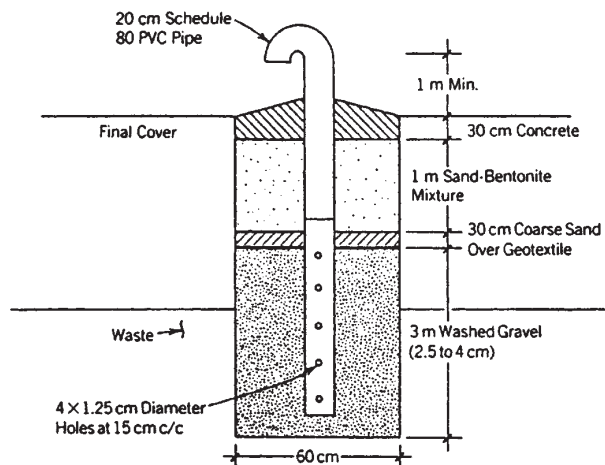


FIG. 25-72 Typical detail of an isolated gas vent. (From Bagchi, A., *Design, Construction, and Monitoring of Sanitary Landfill*, Wiley, 1990.)

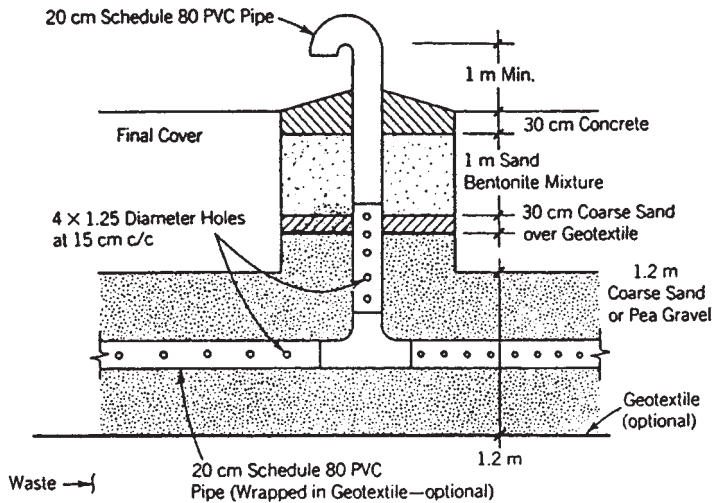


FIG. 25-73 Typical detail of a passive gas venting system with a header pipe. (From Bagchi, A., Design, Construction, and Monitoring of Sanitary Landfill, Wiley, 1990.)

sealants that are available for this use are identified in Table 25-73. Of these, the use of compacted clays is the most common. The thickness will vary depending on the type of clay and the degree of control required; thickness ranging from 0.15 to 1.25 m (6 to 48 in) have been used. Covers of landfills are also typically multi-layer foundation layer, clay layer, membrane, drainage layer (synthetic or natural) root zone layer, or soil.

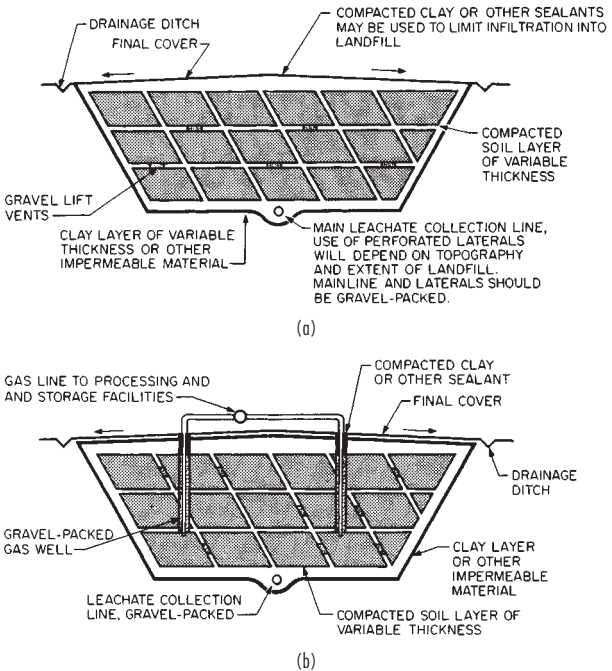


FIG. 25-74 Use of an impermeable liner to control the movement of gases and leachate in landfills. (a) Without gas recovery. (b) With gas recovery. (From G. Tchobanoglous, H. Theisen, and R. Eliassen, Solid Wastes: Engineering Principles and Management Issues, McGraw-Hill, New York, 1977.)

3. Control of gas movement by recovery. The movement of gases in landfills can also be controlled by installing gas-recovery wells in completed landfills (see Fig. 25-74b). This is considered an active venting system. Clay and other liners are used when landfill gas is to be recovered. In some gas-recovery systems, leachate is collected and recycled to the top of the landfill and reinjected through perforated lines located in drainage trenches. Typically, the rate of gas production is greater in leachate-recirculation systems.

Gas-recovery systems have been installed in some large municipal landfills. The economics of such operations must be reviewed for each

Sealant		Remarks
Classification	Representative types	
Compacted soil		Should contain some clay or fine silt.
Compacted clay	Bentonites, illites, kaolinites	Most commonly used sealant for landfills; layer thickness varies from 0.15–1.25 m; layer must be continuous and not be allowed to dry out and crack.
Inorganic chemicals	Sodium carbonate, silicate, or pyrophosphate	Use depends on local soil characteristics.
Synthetic chemicals	Polymers, rubber latex	Experimental; use not well established.
Synthetic membrane liners	Polyvinyl chloride, butyl rubber, Hypalon, polyethylene, nylon-reinforced liners	Expensive; may be justified where gas is to be recovered.
Asphalt	Modified asphalt, asphalt-covered polypropylene fabric, asphalt concrete	Layer must be thick enough to maintain continuity under differential settling conditions.
Others	Gumite concrete, soil cement, plastic soil cement	

*From G. Tchobanoglous, H. Theisen, and R. Eliassen, Solid Wastes: Engineering Principles and Management Issues, McGraw-Hill, New York, 1977.

site. The end use of gas will affect the overall economics. The cost of gas-cleanup and -processing equipment will limit the recovery of landfill gases, especially from small landfills.

4. *Leachate movement.* Under normal conditions, leachate is found in the bottom of landfills. From there it moves through the underlying strata, although some lateral movement may also occur, depending on the characteristics of the surrounding material. The rate of seepage of leachate from the bottom of a landfill can be estimated by Darcy's law by assuming that the material below the landfill to the top of the water table is saturated and that a small layer of leachate exists at the bottom of the fill. Under these conditions, the leachate discharge rate per unit area is equal to the value of the coefficient of permeability K , expressed in meters per day. The computed value represents the maximum amount of seepage that would be expected, and this value should be used for design purposes. Under normal conditions, the actual rate would be less than this value because the soil column below the landfill would not be saturated. Models have been developed to aid in the estimation of leachate quantity. Bagchi has covered details of these models in the *Design, Construction, and Monitoring of Sanitary Landfill*.

5. *Control of leachate movement.* As Leachate percolates through the underlying strata, many of the chemical and biological constituents originally contained in it will be removed by the filtering and adsorptive action of the material composing the strata. In general, the extent of this action depends on the characteristics of the soil, especially the clay content. Because of the potential risk involved in allowing leachate to percolate to the groundwater, best practice calls for its elimination or containment. Ultimately, it will be necessary to collect and treat the leachate.

The use of clay has been the favored method of reducing or eliminating the percolation of leachate (see Fig. 25-74 and Table 25-73). Membrane liners are used most often today but require care so that they will not be damaged during the filling operations. Equally important in controlling the movement of leachate is the elimination of surface-water infiltration, which is the major contributor to the total volume of leachate. With the use of an impermeable clay layer, mem-

brane liners, an appropriate surface slope (1 to 2 percent), and adequate drainage, surface infiltration can be controlled effectively.

6. *Settlement and structural characteristics of landfills.* The settlement of landfills depends on the initial compaction, characteristics of wastes, degree of decomposition, and effects of consolidation when the leachate and gases are formed in the landfill. The height of the completed fill will also influence the initial compaction and degree of consolidation.

Design and Operation of Landfills Important design considerations in the design and operation of landfills include (1) land requirements, (2) types of wastes that must be handled, (3) evaluation of seepage potential, (4) design of drainage and seepage-control facilities, (5) development of a general operation plan, (6) design of solid-waste-filling plan, and (7) determination of equipment requirements. The more important individual factors that must be considered in the design of a landfill are reported in Table 25-74. The last three items are considered further in the following discussion.

1. *Landfill-operation plan.* The layout of the site and the development of a workable operating schedule are the main features of a landfill-operation plan. In planning the layout of a landfill site, the location of the following must be determined: (1) access roads; (2) equipment shelters; (3) scales, if used; (4) storage sites for special wastes; (5) topsoil-stockpile sites; (6) landfill areas; and (7) plantings.

2. *Solid-waste-filling plan.* The specific method of filling will depend on the characteristics of the site, such as the amount of available cover material, the topography, and local hydrology and geology. To assess future development plans, it will be necessary to prepare a detailed plan for the layout of the individual solid-waste cells. On the basis of the characteristics of the site or the method of operation (e.g., gas recovery), it may be necessary to incorporate special features for the control of the movement of gases and leachate from the landfill.

3. *Equipment requirements.* The types of equipment that have been used at sanitary landfills include both crawler and rubber-tired tractors, scrapers, compactors, draglines, and graders. The size and amount of equipment required will depend primarily on local site

TABLE 25-74 Important Factors That Must Be Considered in Design and Operation of Solid-Waste Landfills

Factor	Remarks	Factor	Remarks
Design		Landfilling method	Selection of method will vary with terrain and available cover.
Access	Paved all-weather access roads to landfill site; temporary roads to unloading areas.	Litter control	Use movable fences at unloading areas; crews should pick up litter at least once per month or as required.
Cell design and construction	Will vary depending on terrain, landfilling method, and whether gas is to be recovered.	Operation plan	With or without the codisposal of treatment-plant sludges and the recovery of gas.
Cover material	Maximize use of on-site earth materials; approximately 1 m ³ of cover material will be required for every 4 to 6 m ³ of solid wastes; mix with sealants to control surface infiltration. In some designs, intermediate cover is not used.	Spread and compaction	Spread and compact waste in 0.6-m (2-ft) layers.
Drainage	Install drainage ditches to divert surface-water runoff; maintain 1 to 2 percent grade on finished fill to prevent ponding. TCLP Tests	Unloading area	Keep small, generally under 30 m (100 ft).
Equipment requirements	Vary with size of landfills.	Operation	
Fire prevention	Water on site; if nonpotable, outlets must be marked clearly; proper cell separation prevents continuous burn-through if combustion occurs.	Communications	Telephone for emergencies.
Groundwater protection	Divert any underground springs; if required, install sealants for leachate control; install wells for gas and groundwater monitoring.	Days and hours of operation	Usual practice is 5 to 6 days/week and 8 to 10 h/day.
Land area	Area should be large enough to hold all wastes for a minimum of 5 years but preferably for 25 to 30 years.	Employee facilities	Rest rooms and drinking water should be provided.
		Equipment maintenance	A covered shed should be provided for field maintenance of equipment.
		Operational records	Tonnage, transactions, and billing if a disposal fee is charged.
		Salvage	No scavenging; salvage should occur away from the unloading area; no salvage storage on site.
		Scales	Essential for record keeping.

conditions, the size of the landfill operation, and the method of operation.

Landfilling of Hazardous Wastes In many states, the only disposal option available for most hazardous wastes is landfilling. The basis for the management of hazardous-waste landfills is set forth in the Resource Conservation and Recovery Act of 1976. In general, disposal sites for hazardous wastes should be separate from sites for municipal solid wastes. If separate sites are not possible, great care must be taken to ensure that separate disposal operations are maintained.

Requirements The requirements for a hazardous-waste landfill are detailed in RCRA and the regulations developed to implement the act. From a design standpoint, two of the most important requirements are (1) complete leachate containment, and (2) control of the surface water on and around the site.

Site Selection Factors that must be considered in evaluating potential sites for the disposal of hazardous waste are covered in state and federal regulations. In California, landfills where hazardous wastes can be received are referred to as Class I disposal sites. To qualify as a Class I site, it must be shown that:

1. Geological conditions are naturally capable of preventing vertical hydraulic continuity between liquids and gases emanating from the waste in the site and usable surface or groundwaters.
2. Geological conditions are naturally capable of preventing lateral hydraulic continuity between liquids and gases emanating from wastes in the site and usable surface or groundwaters, or the disposal area has been modified to achieve such capability.
3. Underlying geological formations that contain rock fractures or fissures of questionable permeability must be permanently sealed to provide a competent barrier to the movement of liquids or gases from the disposal site to usable water.
4. Inundation of disposal areas shall not occur until the site is closed in accordance with requirements of the regional board.
5. Disposal areas shall not be subject to washout.
6. Leachate and subsurface flow into the disposal areas shall be contained within the site unless other disposition is made in accordance with requirements of the regional board.
7. Site shall not be located over zones of active faulting or where other forms of geological change would impair the competence of natural features or artificial barriers which prevent continuity with usable waters.
8. Sites made suitable for use by human-made physical barriers shall not be located where improper operations or maintenance of such structures could permit the waste, leachate, or gases to contact usable groundwater of surface water.

9. Sites that comply with the above-noted clauses but would be subject to inundation by a tide or a flood of greater than 100-year frequency may be considered by the regional board as limited Class I disposal sites.

Landfilling Methods and Operations Operation of a landfill for hazardous wastes is quite different from that of a conventional landfill.

Many but not all hazardous wastes can be disposed of on land in properly designed landfills. To minimize potentially adverse environmental effects from wastes deposited at hazardous-waste landfill sites, the U.S. Environmental Protection Agency (EPA) has developed specific regulations regarding the characteristics of wastes suitable for landfilling. These regulations (40 CFR 265) include a prohibition on the placement of:

- Noncontainerized hazardous wastes containing free liquids, whether or not adsorbents have been added.
- Containers holding free liquids unless all freestanding liquid has been removed by decanting or other methods or has been mixed with absorbent or solidified so that freestanding liquid is no longer observed. Such containers must be at least 90 percent full or, if empty, reduced in size as much as possible via crushing or shredding prior to disposal.

The following containers are exempt from the above regulations:

- Very small containers, such as ampules, and containers holding liquids for use other than storage, such as batteries, which may be disposed directly in a hazardous-waste landfill.
- Small lab-pack containers of hazardous waste if they are first placed in nonleaking, larger containers. These containers must be filled to capacity and surrounded by enough absorbent material to contain the liquid contents of the lab pack. The resultant container must then be placed in a larger container packed with absorbent material which will not react with, become decomposed by, or ignited by the contents of the inside containers. Incompatible wastes may not be packed and disposed of together in this manner.

Design of Hazardous-Waste Landfills Most of the regulations governing the design of hazardous-waste landfills have been resolved. Although specific requirements will vary, the factors identified in Table 25-74 can be used as a design guide. Some special precautions that can be taken to prevent contamination of underlying strata are shown in Figs. 25-75 to 25-77. Figures 25-76 and 25-77 illustrate a conceptual design for a typical control-cell grid system for a hazardous waste landfill.

Landfarming Landfarming is a waste-disposal method in which the biological, chemical, and physical processes that occur in the surface of the soil are used to treat biodegradable industrial wastes. Wastes to be treated are either applied on top of the land which has

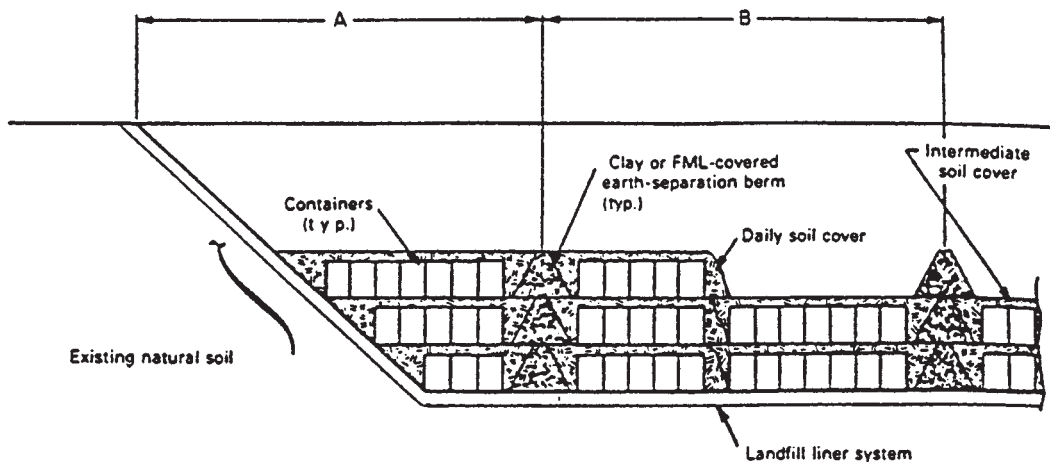


FIG. 25-75 Conceptual design for control cells for hazardous-waste disposal (section view). FML = flexible-membrane liner. (From Freeman, H. M., *Standard Handbook of Hazardous Waste Treatment and Disposal*, McGraw-Hill, 1988.)

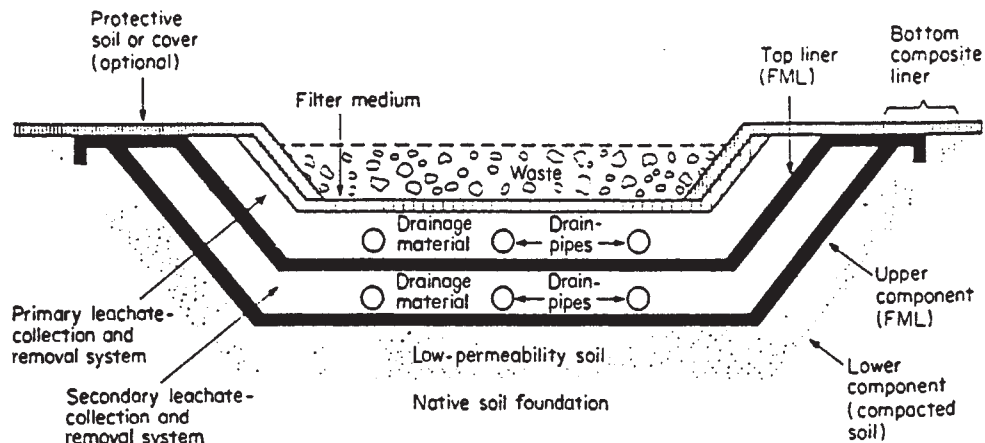
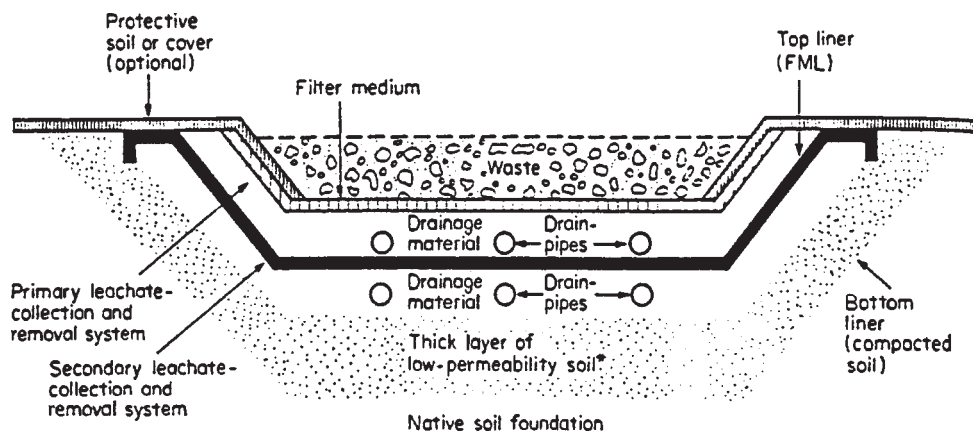


FIG. 25-76 Schematic of an FML plus compacted-soil double-liner system for a landfill. (Drawing not to scale.) (U.S. EPA, EPA/530/SW-85-012, Washington, D.C., 1985. From Freeman, H. M., Standard Handbook of Hazardous Waste Treatment and Disposal, McGraw-Hill, 1988.)



*Thickness to be determined by breakthrough time.

FIG. 25-77 Schematic of an FML plus composite double-liner system for a landfill. (Drawing not to scale.) (U.S. EPA, EPA/530/SW-85-012, Washington, D.C., 1985. From Freeman, H. M., Standard Handbook of Hazardous Waste Treatment and Disposal, McGraw-Hill, 1988.)

been prepared to receive the wastes or injected below the surface of the soil.

Process Description When organic wastes are added to the soil, they are subjected simultaneously to the following processes: (1) bacterial and chemical decomposition, (2) leaching of water-soluble components in the original wastes and from the decomposition products, and (3) volatilization of selected components in the original wastes and from the products of decomposition.

Factors that must be considered in evaluating the biodegradability of organic wastes in a landfilling application include (1) composition of the waste; (2) compatibility of wastes and soil microflora; (3) environmental requirements including oxygen, temperature, pH, and inorganic nutrients; and (4) moisture content of soil-waste mixture.

Although most of the volatile components are released to the atmosphere, a small fraction is dissolved and/or carried away with the water in the soil matrix. Leached waters are carried with the water as it percolates through the underlying soil strata. Most of the organic constituents contained in the leachate receive additional treatment as they pass through the soil column. Leached wastes can also be lost in surface runoff.

Applications Landfarming is suitable for wastes that contain organic constituents that are biodegradable and are not subject to significant leaching while the bioconversion process is occurring. For example, petroleum oily wastes and oily sludges are ideally suited for disposal by landfarming. A variety of other organic wastes with similar characteristics are also suitable. Properly managed landfarming sites can be reused at frequent intervals with no adverse effects.

Design and Operation Important consideration in the design and operation of landfarming systems include (1) site selection, (2) site preparation, (3) waste characteristics, (4) method of waste application, (5) waste-application rate, (6) site management, and (7) monitoring. Important factors related to these design and operation considerations are reported in Table 25-75.

Deep-Well Injection Deep-well injection for the disposal of liquid wastes involves injecting the wastes deep in the ground into permeable rock formation (typically limestone or dolomite) or underground caverns.

Process Description The installation of deep wells for the injection of wastes closely follows the practices used for the drilling and completion of oil and gas wells.

TABLE 25-75 Important Design and Operation Considerations for Landfarming Systems Used for Waste Treatment

Item	Remarks
Site selection location	Proximity to critical areas specified in government regulations, accessibility, site geology and hydrology.
Site selection: soil characteristics	Adequate area soil cover and depth to groundwater usually greater than 1.5 m (4 ft). Slope should not exceed 5 to 8 percent. Soil type, including ion-exchange capacity.
Site preparation	Area should be fenced, graded for runoff control, and disked or plowed before waste application.
Waste characterization	Suspended solids, organic content, nitrogen (all forms), phosphorus pH, and inorganic metals including arsenic, barium, cadmium, chromium, copper, lead, mercury, selenium, silver, sodium, and zinc.
Method of waste application	Ridge and furrow, sprinkling (fixed or portable systems), tank-truck spreading, subsurface injection.
Waste-application rates	For petroleum crude oil and lubricating oils the range is from 250 to 1250 bbl/(ha · year) with a value of 400 bbl/(ha · year) being typical. A typical value for general refinery oils and wastes would be about 150 bbl/(ha · year).
Site management	Wastes spread on the surface should be disked or plowed into the soil soon after application (1 to 7 days). To promote aerobic conditions and rapid bioconversion of the wastes the soil-waste mixture should be cultivated periodically.
Monitoring	Periodic samples should be taken to assess the extent of completion of the bioconversion process. Core samples should be taken annually to monitor the movement of leached wastes in the underlying strata.

Examination of the records of wastewater injection wells that have been constructed in the United States shows that almost all the wells constructed thus far have been completed by one of three methods or close variations of them. The methods are:

- 1. Open-hole completion in competent formations

- 2. Screened or screened and gravel-packed in incompetent sands and gravels

- 3. Fully cased and cemented with the casing perforated in either competent or somewhat incompetent formations

Most wastewater injection wells will be constructed with injection

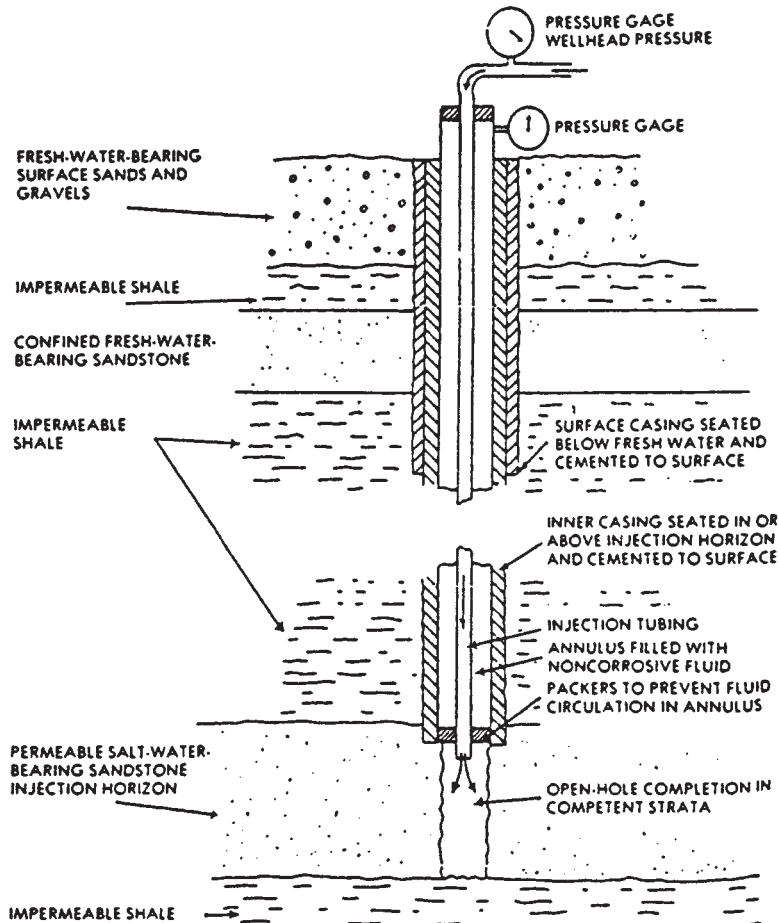


FIG. 25-78 Schematic diagram of an industrial-waste injection well completed in competent sandstone. (From Freeman, H. M., Standard Handbook of Hazardous Waste Treatment and Disposal, McGraw-Hill, 1988.)

TABLE 25-76 Important Design and Operation Considerations for Deep Wells Used for Waste Injection

Item	Remarks	Item	Remarks
Well-site selection	Criteria for assessing the feasibility of a deep-well injection site include (1) uniformity, (2) large extent, (3) substantial thickness, (4) high porosity and permeability, (5) low pressure, (6) saline aquifer, (7) separation from potable-water horizons, (8) adequate overlying and underlying aquicludes, (9) no poorly plugged wells nearby, and (10) compatibility between the mineralogy and fluids of the reservoir and the injected wastes.	Deep-well installation	injection formation). Adjustment of pH and buffering of the waste may be necessary. Well depths vary from 550 to 3660 m (1800 to 1200 ft); well-injection rates vary from 4 to 60 L/s; rates in the range from 15 to 20 L/s are typical. Operation pressures up to 27,600 kPa (4000 psig) are used.
Waste pretreatment	Suspended solid less than 10 to 15 mg/L; particle sizes equal to or less than 1 to 5 μm (depends on	Monitoring	Continuous monitoring facilities should be installed when wells are put into operation. Irregularities in the pressure may require changes in operating procedures.

tubing inside the long casing string, and with a packer set between the tubing and the casing near the bottom of the casing (Fig. 25-78). This design is not entirely free of problems, particularly with the packer, but experience has proved it generally superior to other designs. Some wells are completed with an annulus open at the bottom. The annulus is filled with a lighter-than-waste liquid that "floats" on the aqueous waste. This type of well completion has been referred to as a *fluid-seal completion*.

Applications Deep-well injection has been used principally for liquid wastes that are difficult to treat and dispose of by more conventional methods and for hazardous wastes. Chemical, petrochemical, and pharmaceutical wastes are those most commonly disposed of with this method. The waste may be liquid, gases, or solids. The gases and solids are either dissolved in the liquid or are carried along with the liquid.

Design and Operation Important design and operation considerations for deep-well injection are related to (1) well-site selection, (2) pretreatment, (3) installation of an injection well, and (4) monitoring. Important factors related to these design and operation considerations are reported in Table 25-76. As noted in the table, wastes are usually treated prior to injection to prevent clogging of the formation and damage to equipment. Particles greater than about 1 to 5 μm must be removed. Typically, treated wastes must be filtered prior to

injection. Wastes must also be compatible with the characteristics of the aquifer. This may require pH adjustment and the use of compatible buffers.

Ocean Disposal of Solid Wastes Although ocean dumping of municipal solid wastes was abandoned in the United States in 1933, the concept has persisted throughout the years and is still frequently discussed today. Some industrial wastes are still discharged at sea. Within the past few years, the idea that the ocean is a gigantic sink, into which an infinite amount of pollution of all types can be dumped, has been discarded. On the other hand, it is argued that many of the wastes now placed in landfills or on land could be used as fertilizers to increase the productivity of the ocean. It is also argued that the placement of wastes in ocean-bottom trenches where tectonic folding is occurring is an effective method of waste disposal.

PLANNING

Because of the ever-growing number of federal regulations governing the disposal of nonhazardous and hazardous solid wastes, it is prudent to develop both short-term and long-term action programs to deal with all aspects of solid-waste management. Important short- and long-term actions are identified in Table 25-77.

TABLE 25-77 Short- and Long-Term Actions for Effective Industrial Solid-Waste Management*

Actions	Remarks	Actions	Remarks
Short-term		Long-term	
1. Inventory wastes.	Document all types, quantities, and sources of wastes (both nonhazardous and hazardous wastes).	1. Remove all accumulated wastes.	Develop a systematic program for removing all accumulated wastes stored on the plant site.
2. Inventory inactive sites.	All inactive sites where wastes have been disposed of in the past should be inventoried. Data should be gathered on buried wastes, including types, quantity, and sources. A groundwater-monitoring program should be developed.	2. Separate wastes.	Institute a long-term program to separate wastes at the source of production.
3. Characterize wastes.	In addition to general information on the characteristics of the wastes, all hazardous wastes should be individually characterized.	3. Reduce wastes.	A systematic program should be undertaken to examine all sources of waste production and to develop alternative operations and processes to reduce waste generation.
4. Assign responsibilities.	Assign responsibilities and authority at plant and headquarters for the storage, collection, treatment, and disposal of all types of hazardous wastes.	4. Improve facilities.	Upgrade facilities to meet RCRA requirements. A data-collection program should be instituted to obtain any needed data.
5. Track the movement of wastes.	Develop a logging system for hazardous wastes containing the date, waste description, source, volume shipped or hauled, name of hauler, and destination. Follow through to be sure that wastes reach destination.	5. Review all waste-management agreements.	Develop detailed contracts with outside waste-management firms. Define clearly the duties and responsibilities of plant personnel and waste-collection personnel.
6. Develop emergency procedures.	Develop procedures for dealing with with emergency situations involving the storage, collection, treatment, and disposal of hazardous wastes.	6. Review and develop disposal-site options.	Develop long-term projections for landfill requirements and initiate a program to secure the needed sites.
7. Obtain permits.	Start obtaining the necessary waste-disposal permits as soon as possible.	7. Secure appropriate engineering and consulting services.	Make sure that your engineering departments are involved early in the process. Retain outside consultants for specific tasks.
		8. Monitor legislative programs.	Develop a program for monitoring new regulations and for inputting to appropriate federal, state, and local agencies on the modification and development of new regulations.

*Adapted in part from R. Sobel, "How Industry Can Prepare for RCRA," *Chem. Eng.*, **86**(1), 82 (Jan. 29, 1979).