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Tools for ambient air quality management*

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Lecture #1:

INTRODUCTION

It is now common knowledge that the atmospheric air is a finite resource, in the sense that its capacity to absorb and disperse pollutants injected into the atmosphere, although generally quite large, is not unlimited. The natural outcome of this fact is that the atmospheric air, like any other limited environmental (or other) resource, requires good management that will assure rational allocation of this resource to its many users (Suess & Craxford, 1976). This fact is one of the main conclusions of a recent report of an international committee headed by the-present Prime Minister of Norway (Brundtland, 1987). The well known phenomena of acid rain (NSEPB, 1983; Seinfeld, 1986, Ch. 18), stratospheric ozone depletion (Biswas, 1977; Tito, 1986; UNEP, 1987a), and the recent atmospheric warming due perhaps to the significant increase of the concentrations of certain man-made trace gases in the atmosphere (Bolin et al., 1986; UNEP; 1986; Tito, 1986), can be considered as examples of mismanagement of the atmospheric air on a global scale (Brown et al., 1987). Air pollution has now become an international issue, as is evident from the efforts of the Economic Commission for Europe (ECE) to establish a convention on transboundary air pollution (ECE/UN, 1987; and also: ECE/UN, 1984; 1985; 1986).

It should be noted that in response to these environmental problems on a global scale, documents that survey the condition of the environmental resources of the world, including the data relevant to its air quality, have been made available (UNEP, 1987b; WRI/IIED/UNEP, 1988).

These lectures, however, do not deal with air pollution problems on global or transboundary scales, but rather with the tools available for managing atmospheric resources on local, regional and national scales. The largest single sources of air pollution dealt with here are stationary sources such as electric power plants and oil refineries. Except for Lecture #3 (on air pollution inventories), these lectures do not deal with air pollution from traffic. However, it should be emphasized that, as can be concluded from emission inventories, in most countries of the world, traffic as a collective source is one of the largest sources of air pollution, and also, one of the most problematic (Georgiades et al., 1988).

The means how to achieve reduction in pollutant emissions in stationary sources, such as emission control technologies, modifications in industrial processes or changes of raw materials, are not discussed here. An exception is Lecture #8 on particulate matter filtration by electrostatic precipitation, which is used extensively by coal-fired power plants.

These lectures focus on air quality management tools such as:

- Emission Factors and Emission Inventories
- Emission Standards vs. Ambient Air Quality Standards
- Fuel Quality Standards
- Air Quality Dispersion Modeling
- Ambient Air Quality Monitoring
- Particulate Matter Filtration by Electrostatic Precipitation (ESPs), in Coal-Fired Power Plants
- For development projects, the Environmental Impact Assessment, as an integrative tool, utilizing some or all of the tools described above.

Lecture #2:

EMISSION STANDARDS VS. AMBIENT AIR QUALITY STANDARDS

Two very important tools for air quality management are emission standards and ambient air quality standards:

a) Ambient Air Quality Standards (sometimes also known as "Immission Standards") are the legally allowed concentration of pollutants in the ambient air, averaged over specified periods of time (Larsen, 1971; de Koning, 1987). Typical values of concentrations of pollutants in clean and polluted atmospheres are given in Table 1 (Seinfeld, 1986).

Ambient air is usually defined as the outdoor atmosphere in non-industrial areas, and beyond the fenceline of plants in industrial areas.

Air quality standards differ widely from one country to another. In some countries, different air quality standards exist for different parts of it, depending on the environmental sensitivity of the area. A comprehensive compilation of ambient air quality standards in effect over the world has been published recently by Bouscaren et al. (1986).

A guideline document published recently by the World Health Organization (WHO, 1987) suggests air quality standards based mainly on health criteria for 27 different noncarcinogenic pollutants (see Table 2). It should be emphasized that the position of WHO is that for carcinogenic substances there are no lower permissible concentrations and thus no ambient air quality standards are to be set for them. This document is sure to become one of the leading guidelines for internationally accepted levels of pollutant concentrations permitted in the atmosphere.

Well-known air quality standards are those published by the Environmental Protection Agency in the USA (USEPA, 40CFR50) and given in Table 3.

b) Emission Standards are another important tool required for air quality management. These standards are the rates of pollution legally allowed to be emitted into the atmosphere through the stack or ventilation vent of the pollution source. Like ambient air quality standards, they differ from one country to another. However, no attempt has yet been made to reach internationally agreed upon emission standards. A recent compilation of emission standards from over the world has been published by Bouscaren et al. (1986), and one covering European countries by the Economic

TABLE 1: Typical Values of Pollutant Concentrations in Clean and Polluted Atmospheres (Seinfeld, 1986) (in ppb)

Pollutant Species	Clean Atmosphere	Polluted Atmosphere
Sulfur Dioxide (SO_2)	1 - 10	20 -200 and much higher
Carbon Monoxide (CO)	120	1000 - 10,000 and much higher
Nitrogen Oxide (NO)	0.01 - 0.05	50 - 750
Nitrogen Dioxide (NO_2)	0.1 - 0.5	50 - 250
Ozone (O_3)	20 - 80	100 - 500
Non-Methane Hydro-Carbons (NMHC) (Reactive HC)	-	500 - 1200
Total Suspended Particulates (TSP)	0 - 20	50 - 500

TABLE 2: Guideline Values for Individual Substances Based on Effects Other than Cancer or Odor/Annoyance (WHO, 1987) (1)

Subsance	Time-weighted Average	Averaging Time
Cadmium	1 - 5 ng/m3	1 year (rural areas)
	10 - 20 ng/m3	1 year (urban areas)
Carbon disulfide	100 ug/m3	24 hours
Carbon monoxide	100 mg/m3	15 minutes
	60 mg/m3	30 minutes
	30 mg/m3	1 hour
	10 mg/m3	8 hours
1,2-Dichloroethane	0.7 mg/m3	24 hours
Dichloromethane (Methylene chloride)	3 mg/m3	24 hours
Formaldehyde	100 ug/m3	30 minutes
Hydrogen sulfide	150 ug/m3	24 hours
Lead	0.5 - 1.0 ug/m3	1 year
Manganese	1 ug/m3	1 year
Mercury	1 ug/m3 (indoor air)	1 year
Nitrogen oxide	400 ug/m3	1 hour
	150 ug/m3	24 hours
Ozone	150 - 200 ug/m3	1 hour
	100 - 120 ug/m3	24 hours
Styrene	800 ug/m3	24 hours
Sulfur dioxide	500 ug/m3	10 minutes
	350 ug/m3	1 hour
Tetrachloroethylene	5 mg/m3	24 hours
Toluene	8 mg/m3	24 hours
Trichloroetnylene	1 mg/m3	24 hours
Vanadium	1 ug/m3	24 hours

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(1) Information from this table should not be used without reference to the rationale given in the chapters dealing with the relevant substance in the WHO document (WHO, 1987).

Table 3: Ambient Air Quality Standards Published by the Environmental Protection Agency in the USA (USEPA, 40CFR50)

Pollutant	Averaging Time	Frequency Parameter	Concentration	
			ug/m3	ppm
SO_2	24 hr	Not to be exceeded more than once a year	365	0.14
	1 yr	Arithmetic Mean	80	0.03
	3 hr	Not to be exceeded more than once year	1300	0.5
TSP	24 hr	Not to be exceeded more than once a year	260	-
	1 yr	Geometric Mean	75	-
CO	1 hr	Not to be exceeded more than once a year	40,000	35
	8 hr	Not to be exceeded more than once a year	10,000	9
O_3	1 hr	Not to be exceeded more than once a year	235	0.12
NMHC* (reactive HC)	3 hr (6 - 9 a.m.)	Not to be exceeded more than once a year	160	0.24
NO_2	1 yr	Arithmetic Mean	100	0.05
Lead	3 mo	Arithmetic Mean	1.5	-

* A guide to be used for achieving the O_3 standard.

Commission for Europe (ECE/UN, 1987). The emission standards used in the OECD countries have been published in 1984 (OECD, 1984). Some of the emission standards published in the USA and applicable to new emission sources are given in Table 4.

It should be mentioned that in order to determine compliance of a pollution source with the relevant emission standards, the amount of pollution coming out of a the stack or ventilation vent has to be measured by a method called stack sampling (see Lecture #7).

The quality of the ambient air is determined by air quality monitoring instruments and networks (see Lecture #6). The concentrations of pollutants in the air as measured by these instruments is compared with the appropriate air quality standards to determine wether a given area complies or not with the standards.

Emission standards may be expressed as a limitation on the concentration of the pollutant in the emission gas (in units of milligram per cubic meter = mg/m3, or in units of parts per million = ppm), or on the the pollutant emission rate (as a function of time, in units of kilogram per hour = kg/hr, or as a function of the energy produced, in units of nanograms per joule = ng/J).

As an example of the conversion of the emission standards from one set of units into the others, consider the sulfur dioxide emission standard for coal-fired power plants adopted by the State of Punjab, India, which is 600 ng/J. With a coal calorific value of 4000 kcal/kg and consumption rate of 60 tons per hour (1 J = 0.2390 cal), one obtains:

$$\frac{600 \ast 10^{-9} \ast 60 \ast 10^{3} \ast 4000 \ast 1000}{0.2390} = 602.5 \ \frac{\text{kg SO2}}{\text{hr}} .$$

With an air flow through the stack of 200 Nm3/sec and a temperature of the flue gases of 145 deg C, this would be equal to a limitation on the SO2 concentration in the flue gases of:

$$\frac{602.5 \ast 10^{6} \ast (273 + 145)}{3600 \ast 200 \ast 273} = 836 \ \frac{\text{mg SO2}}{\text{Nm3}} .$$

TABLE 4: Some Emission Standards for New Plants (New Sources) Published by the Environmental Protection Agency in the USA (USEPA, 40CFR60)

Emission Source	Pollutant	Emission Source	Comments
A) Large (>25 MWe) Coal-Fired Electric Generating Units			
Boiler Stacks	Particulates Opacity	0.18 lb/10^6 BTU 20%; 27% for 6 min/hr	Continuous monitoring
	SO_2	1.2 lb/ 10^6 BTU	Continuous monitoring
	NO_x	0.7 lb/ 10^6 BTU	Continuous monitoring
B) Portland Cement Plants			
Kiln Stacks	Particulates	0.30 lb/ton	Stack sampling
	Opacity	20%	Continuous monitoring
Clinker Cooler	Particulates	0.10 lb/ton	Stack sampling
C) Lime Manufacturing Plants			
Rotary Kiln Stacks	Particulates	0.30 lb/ton	Monitoring of scrubber pressure loss and liquid pressure
	Opacity	10%	Continuous monitoring

To evaluate the actual emissions, one can use the appropriate emission factor described in Lecture #3, Table 5: E (kg SO_2/ton coal) = 19S, where S (the wt% of sulfur in the coal) in India is typically 0.5%:

$$19*0.5*60 = 507 \text{ kg } SO_2\text{/hr},$$

which is equal, for the flue gas conditions stated above, to:

$$\frac{507*10*(273 + 145)}{3600*200*273} = 704 \ \frac{\text{mg } SO_2}{\text{Nm}3} .$$

Thus, in this example, for a sulfur content in coal of 0.5%, the actual emissions are less than the emission standard set by the State of Punjab (i.e., 836 mg SO_2/Nm3).

Lecture #3:

EMISSION FACTORS AND EMISSION INVENTORIES

The information regarding the rate at which a given source emits pollutants into the air is necessary to perform emission inventories (Hammerle, 1976). An emission inventory is a most useful tool in management of air quality since it enables to estimate the quantities of pollutants emitted into the atmosphere, and to determine trends in these emissions.

Instead of carrying out a measurement of the actual emission from the given source, which could prove to be time-consuming, expensive and technically difficult, typical emission rates from various pollution sources are frequently estimated by applying emission factors.

An emission factor is an estimate of the typical rate at which a pollutant is released into the atmosphere as a result of a given activity (usually involving fuel burning or an industrial production process), divided by the level of that activity (also expressed in terms of a temporal rate).

Emission factors for various activities have been compiled by the Environmental Protection Agency in the USA and published in a document known as AP-42 (USEPA, 1985). The Dutch Ministry of Housing, Physical Planning and Environment has also published a useful compilation of emission factors (Reinders, 1983).

These emission factors where obtained from a wide range of data of varying degrees of accuracy. Also, they represent activities typical to the USA and Holland. Thus, whenever possible, pollutant emission rates should be determined from, or supplemented by, local on-site source tests which reflect emissions of local sources under existing conditions (activity, process etc.).

It should be noted that emission factors are strongly dependent on the type and efficiency of the technology used to control these emissions. For example, the collection efficiency for common types of fly-ash control equipment installed on coal-fired boilers may reach 99.5% for electrostatic precipitators and for bag houses (the most efficient equipment), to 90-95% for high efficiency cyclones, but only 80-85% for low resistance cyclones (USEPA, 1985). It should be noted that the collection efficiency of the control equipment is dependent also on the size distribution of the particulate matter in the flue gas, since the small particles are more difficult to filtrate. Also, when determining the effect of the application of various control devices, one should consider the age and level of maintenance of the particular control device.

Table 5 presents emission factors required for carrying out a national emission inventory of pollutants emitted into the air as a result of fuel burning. The additional data necessary for performing the emission inventory are the annual quantities of fuels used at stationary sources (LPG, kerosene, diesel and fuel oils and coal, see Lecture #4) and the annual mileage driven by gasoline and diesel vehicles.

TABLE 5: Emission Factors for Fuel Burning (Uncontrolled) for Sulfur Oxides (SOX), Carbon Monoxide (CO) Nitrogen Oxides (NOX), and Suspended Particulate Matter (SPM)

Fuel Type	Usage	SOX(=SO2 +SO3)(1)	CO	NOX	SPM
LPG (2)	Space Heating and Heat	0.00 (3)	0.39 kg/ton	1.86 kg/ton	0.00 (3)
Gasoline	Vehicles with Otto Engines (4)	20S kg/ton	29.1 g/km	1.85 g/km	0.042 g/km
Kerosene (6) (9)	Space Heating (7)	19S kg/ton	0.73 kg/ton	2.68 kg/ton	0.37 kg/ton
Diesel Fuel (9)	Trucks and Buses (4) (13)	17.24S kg/ton	12.5g/km	15.9g/km	3.4g/km
	Private & Public Diesel Cars (4)		12.5g/km	15.9g/km	0.4g/km
	Space Heating (7)		0.70kg/ton	2.59kg/ton	0.28kg/ton
	Gas Turbines (8)		2.17kg/ton	9.57kg/ton	0.71kg/ton
# 4 Fuel Oil (9)	Light to Medium Industry (7)	19S kg/ton	0.63 kg/ton	2.52 kg/ton	0.88S kg/ton
# 5 Fuel Oil (9)	Medium to Heavy Industry (7)	19S kg/ton	0.63 kg/ton	6.87 kg/ton	1.25S kg/ton
# 6 Fuel Oil (9)	Power Plants, Heavy Industry, Oil Refineries (7)	19S kg/ton	0.63 kg/ton	8.33 kg/ton	1.25S+0.4 kg/ton
	Cement Industry (10)	2.1S kg/ton	0	1.3 kg/ton	130 kg/ton 170 kg/ton
Bituminous and Subbituminous Coal	Power Plants (11)	19.5S kg/ton	0.5kg/ton	10.5kg/ton	5A kg/ton
	Industry (12)		1.0kg/ton	7.0kg/ton	30 kg/ton
	Cement (10)	3.4S kg/ton	0	1.3kg/ton	130 kg/ton 170 kg/ton

Specific Emission Factors for Gasoline Vehicles

a) Emissions of Lead (Pb) Particles (kg/ton):
= 1.38Pb (Pb is the gasoline lead content, in g/liter) (5)

b) Hydrocarbon Emissions (HC):
From the Tail Pipe = 1.218 g/km (4)
From the Carburetor = 2.616 g/km (13)

Comments to Table 5

(1) SOX emissions are mainly SO2 (about 98%) and the rest SO3. The emissions are given by E=Const.*S, where S is the sulfur content of the fuel (in %). Assuming that all the sulfur in the fuel is emitted into the atmosphere as SOX, E=20S. For #6 fuel oil, only 95% of the sulfur is emitted as SOX, thus E=19S. For coal, 2.5% of the SOX is adsorbed to the bottom ash and therefore E=19.5S.

(2) LPG = Liquid Petroleum Gas. These emission factors are based on AP-42, Vol. I, Sec. 1.5 (USEPA, 1985), corrected to units of kg/ton.

(3) Negligible emissions.

(4) Based on AP-42, Vol.II, App.H, Table 1.1.1A (1973 model year, without catalytic converters), corrected to units of g/km.

(5) Based on a specific density of gasoline of 0.73 kg/liter, and assuming that all the lead in the gasoline is emitted into the air.

(6) Emission factors for jet aircraft are not given in this table.

(7) Based on AP-42, Vol. I, Sec. 1.3, corrected to units of kg/ton.

(8) Based on AP-42, Vol.I, Sec.3.1, corrected to units of kg/ton.

(9) For definition of fuel oil grade, see ASTM (1985a).

(10) Based on AP-42, Vol. I, Sec. 8.6. For the SPM emissions, the high value refers to the dry process and the low value to the wet process.

(11) Based on AP-42, Vol. I, Sec. 1.1, assuming pulverized coal firing. The SPM emissions are given by E=Const.*A, where A is the ash content of the coal.

(12) Based on AP-42, Vol. I, Sec. 1.1, assuming spreader stocker firing.

(13) Based on AP-42, Vol. II, App. H, Table 1.1.1C, corrected to units of g/km.

Lecture #4:

AIR POLLUTION AND PROPERTIES OF HYDROCARBON FUELS

As is well known, air pollution is strongly affected by the properties and quality of the hydrocarbon fuels that are burned. Thus, for air pollution management it is important to be acquainted with the properties and qualities of the fuels that are utilized.

Table 6 presents the main parameters of hydrocarbon fuels, including liquid petroleum gas (LPG) which is burned as a gaseous fuel, hydrocarbon fuels which are burned as liquids (gasoline, kerosene, diesel oil and light to heavy fuel oils) and coal, which is a solid fuel.

a) Usage

LPG consists primarily of a mixture of propane and butane, in contrast to natural liquid gas (NLG), which is mainly methane. In many countries LPG is used mostly for cooking and residential space heating. However, in some countries where LPG is abundant, it is also used as a source of energy in industry and in power plants.

Gasoline (Petrol) is used mainly as fuel for vehicles with Otto engines. Gasoline is a mixture of many hydrocarbon components, the typical one being heptane (having 7 carbon atoms and referred to as the C7 hydrocarbon).

Kerosene is used mainly as jet fuel, but also as an energy source for residential space heating (with typical energy requirements of up to 25,000 kcal/hr). In the ASTM classification (see: D 386-80, In: ASTM, 1985a), kerosene is designated as distillate fuel oil #1.

Diesel Oil is used as fuel for all diesel engines, including those installed in vehicles (mainly trucks and buses, but also small sections of the private car fleet). Diesel oil is also used for electricity production in gas turbines, and for space heating and small industrial boilers (typical energy requirements of 20,000-300,000 kcal/hr). In the ASTM classification diesel oil is designated as distillate fuel oil #2.

Residual fuels are designated by ASTM according to their viscocity as fuel oil #4, #5 and #6 (it should be noted that #3 is not used in the present ASTM designation). The most viscous fuel is #6, whereas #4 and #5 are obtained by mixing #6 with the lighter and far less viscous distillate fuel oil #2. Fuel oil #4 is used for large space heating installations, medium sized

TABLE 6: Properties of Hydrocarbon Fuels (Curl & O'Donnell, 1977; ASTM, 1985a)

Parameter		Units	LNG	Gasoline (Petrol)	Kerosene & Jet Fuel	Diesel Oil	Fuel Oil	Fuel Oil	Fuel Oil	Bituminous Coal (Typical)
ASTM Classification		-	-	-	#1	#2	#4	#5	#6	-
Chemical Composition	C	wt%	82.2	84.0	85.6	86.2	86.2	86.3	86.5	72.8
	H	wt%	17.8	16.0	14.2	12.6	12.2	11.3	11.0	4.8
	S	wt%	150ppm	0.20	0.20	0.50	<2.0	<2.0	<3.5	<2.0
	Ash	wt%	-	-	-	0.01	0.1	0.1	0.2	9.0
	C/H	-	4.60	5.25	6.04	6.45	7.0	7.6	7.8	15.2
Organic Compound Composition	Paraffins	wt%	100	50 (1)	35	30	40% #2 plus 60% #6	20-25% #2 plus 75-80% #6	15	-
	Naphtanes	wt%	-	40	60	45			45	-
	Aromatics	wt%	-	10	15	25			25	-
	Others	wt%	-	-	-	-			15 (3)	-
Net Calorific Value		kcal/kg	11,660	10,650	10,400	10,100	9,900	9,700	9,500	>5500
Density (at 15.6 °C)		gram/m3	-	0.66-0.70	0.830-0.850	0.860-0.870	0.905-0.915	0.920-0.945	0.960-o.970	1.12-1.35
Viscosity (at 50 °C)		Centistokes	-	0.45-0.60	1.5-1.9	1.6-2.3	3-20	20-60	>150	-
Preheating at Burner Tip		-	N.R. (2)	N.R.	N.R.	N.R.	May Be Required	Required	Required	N.R.
Preheating at the Fuel Tank		-	N.R.	N.R.	N.R.	N.R.	Required	Required	Required	N.R.
Air Required for the Combustion of 1 kg of Fuel		m3 (STP) (3)	12.0	11.7	11.4	11.2	11.0	10.8	10.8	7.7
Flue Gases Generated by Burning 1kg of Fuel		m3 (STP, dry)	11.1	10.9	10.6	10.4	10.3	10.1	10.0	7.5
Max. CO2 Content in Dry Flue Gases		vol%	13.8	14.4	15.1	15.4	15.6	15.9	16.0	18.2

Comments:

(1) For virgin gasoline. Unleaded and low-leaded gasolines today are blended (i.e., they are a mixture of virgin gasoline, catalytically cracked gasoline and thermally reformed gasoline), and may contain up to 20% olefines and 40-45% aromatics.

(2) N.R. = Not Required.

(3) Polar Compounds containing nitrogen, oxygen or sulfur.

(4) STP = Standard temperature and pressure conditions.

industrial stoves (e.g., bakeries) and small steam boilers, which operate under conditions of varying loads (with typical energy requirements of 200,000-700,000 kcal/hr). Fuel oil #5, which requires preheating at the burner tip (see Table 3), is used mainly for medium to large industrial steam boilers (typical energy requirements of 500,00-1,500,000 kcal/hr). Fuel oil #6, which requires preheating also of the fuel tank, is used in large industrial installations operating under constant loads such as cement kilns or steam boilers of power plants (typical energy requirements of over 1,000,000 kcal/hr). It should be mentioned that residual fuel oils are generally more difficult to burn and create more severe air pollution problems compared to the distillate fuel oils (see paragraph (b) below). Their advantage lies, however, in their lower cost.

Bituminous Coal: The most frequently used coal is the bituminous coal. It is widely used as fuel in large industrial and power plant steam boilers, in cement kilns, and for metalurgical smelters.

b) Chemical Composition

Hydrocarbon fuels, as the name indicates, consist mainly of hydrogen and carbon. Distillate fuels, which are the product of the initial refining process at the oil refinery (LPG, gasoline, kerosene and diesel fuel), contain primarily paraffines, naphtenes and aromatics in different proportions. The residual fuel, which is the left-over from the distillation process, contains in addition to hydrocarbons also polar compounds containing oxygen (up to 6%), nitrogen (up to 1.5%) and sulfur (up to 4.5%). It should be mentioned that many countries have issued laws and regulations limiting the allowed level of sulfur in the fuel oil (ECE/UN, 1987). All liquid hydrocarbon fuels contain also some anorganic matter (usually referred to as ash). As a rule, the heavier the fuel, the higher the ash content, which in the heavy fuels (#6) may reach 0.2wt%. Heavy metals, such as Vanadium, Nickel and Iron can also be found in residual fuels in significant amounts (several hundred ppm) (Goldstein & Siegmund, 1977). It should be noted that Vanadium is a very efficient catalyst for converting the $SO2$ emissions in the flue gases into $SO3$, thus aggrevating the acid deposition problem.

Residual fuels contain also asphaltenes, which is a group of cyclic aromatic hydrocarbons which does not disolve in hexane. Asphaltenes have a high boiling point, and in the combustion process they do not easily oxidize into CO and $CO2$. Instead, they tend to carbonize and transform into soot particles. Burning residual fuels containing a high asphaltene content may cause, even under very good combustion conditions, severe environmental problems because of the heavy soot emissions (Taback, Hersh and Graber, 1983).

Coal, which is solid, has a much higher anorganic matter content than the liquid fuels, which for good quality coals is typically about 10%, but may reach much higher values. Sulfur in coal appears both as anorganic compounds (pyrites) or in organic compounds imbedded in the coal.

c) Specific Density

The specific density, together with the viscosity, are the most important parameters characterizing the liquid fuels. As can be seen from Table 6, the specific density of the fuels increase with their viscosity, from the light fuel (kerosene or #1) to the heavy fuel (residual fuel #6). This is the result of the higher hydrogen content of the lighter fuels.

d) Calorific Value

Since the calorific value (i.e., the quantity of heat , in kilocalories, that is obtained by burning one kg of the substance) for hydrogen is much higher than for carbon (34,100 kcal/kg for H_2, as compared to to 8,080 kcal/kg for carbon), the calorific value of the fuel increases with the hydrogen content. It should be mentioned that the burned hydrogen (i.e., water) is not considered to be a pollutant. On the other hand, water has to be vaporized in order to be emitted in the flue gases, and this requires large amounts of energy (the latent heat of vaporization). Thus, the actual heat (referred to as the lower or net calorific value) supplied by burning a hydrogen containing fuel is lower than the theoretical heat it contains (which is called the higher or gross calorific value).

In a complete combustion process, i.e., when the carbon is fully oxidized, it appears in the flue gases as a relatively non-toxic gas called carbon dioxide (CO_2). Depending on the carbon content of the fuel, the percentage of CO_2 in the flue gases vary from 13.8% of the volume of the flue gas for LPG fuel to more than 16% in the heavy #6 fuel. However, since the combustio process is not always complete, the carbon is sometimes only partially oxidized and significant amounts of the toxic carbon monoxide (CO) are observed in the flue gases. High CO emissions are characteristic of uncontrolled vehicles with both Otto and Diesel engines. In badly tuned Otto engines, CO emissions may reach 10% of the volume of the exhaust gases.

e) Viscosity

The property of viscosity is applicable only to the liquid fuels. It refers to the resistance of the fuel to flow in a pipe to the burner tip and to be sprayed into small droblets in it. Since viscosity decreases with increase in temperature, heavy liquid fuels are preheated both at the burner tip and in the fuel tank in order to ensure a good combustion process (see Table 6).

f) Gasoline Lead Content

Organic lead compounds (Tetra-ethyl-lead and Tetra-methyl-lead) have been added to gasoline to increase its octane rasting. Because of the toxicity of lead (causing at low concentrations adverse health and mental effects in children and high blood pressure in adults, see, e.g., WHO, 1987) it is now being phased out and alternative means of maintaining the required octane ratings of gasoline are being sought. Many countries have set a goal to reach in the early Nineties the limit of 0.15 gram lead per liter of gasoline. A few countries have imposed the use of altogether unleaded gasoline (e.g., the USA, Japan and West Germany).

g) Volatility

Volatile gasoline tends to emit larger amounts of hydrocarbons into the atmosphere. Hydrocarbons and NOX are the precurser pollutants necessary for the generation of photochemical pollutants (particularly, ozone). To curb the problem of rising ozone concentrations in the heavily trafficed urban areas, the tendency today is to limit the volatility (or the vapor pressure) of the gasoline supplied, especially in the warm summer months generally considered to be the "ozone season" (Halberstadt, 1984). However, it should be noted that this requirement might antagonize the requirement to reduce the content of lead compounds in the gasoline, since alternative octane boosters available (namely, the oxygenated fuels such as methanol, ethanol, methyl-tert-butyl-ether = MTBE, or tert-butyl-alcohol = TBA) are generally more volatile than the hydrocarbon compounds which are included in the mixture of hydrocarbons referred to as gasoline (or petrol).

Lecture #5:

AIR QUALITY DISPERSION MODELING

Air quality dispersion models (using computer software) are widely used as a complementary tool to air quality monitoring (Lecture #6) to estimate and evaluate pollutant concentrations in the air around pollution sources. Air quality monitoring networks supply data that represents only the adjacent neighborhood of the monitors. To obtain a description of the pollution concentrations in the whole area (in the form of isopleths or concentration contours), the data regarding the pollution in the space between the monitor stations can be interpolated using computer models which simulate the atmospheric dispersion of the air pollutants.

Air quality dispersion models are also a very useful tool within the framework of the environmental impact assessment (EIA) process, for evaluating air quality in future scenarios involving new projects with a potential to create air pollution problems (Lecture #9).

The theory of air quality modeling and description of the various models available have been reviewed by Gifford (1975), Turner (1979), Benarie (1980), Hanna et al. (1982), Pasquill & Smith (1983), Barr & Clements (1984) and Seinfeld (1986).

In particular, the UNAMAP package of computer air quality dispersion models issued by the Environmental Protection Agency in the USA (USEPA) and described in detail by USEPA (1986a), should be mentioned. Most of the models included in the package are Gaussian and applicable to an area not larger than several tens of km around the pollution source, but some of the models included are suitable to handle air pollution problems involving an area of hundreds of km (as a result of chemical transformation and long-range transport of the pollutants in the atmosphere (Knox & Walton, 1984). Specific models from the UNAMAP package are suitable to various applications such as: Short-term modeling and long-term modeling, modeling of single and multiple stationary (point) source(s), modeling of traffic pollution (line sources), modeling of chemically stable (nonreactive) and photochemical (reactive) pollutants.

UNAMAP models are recommended by the USEPA, to be used for proving compliance with air quality regulation requirements (see Lecture #3). They are checked by the USEPA for reliability, validity and accuracy. The package is periodically updated, and the most recent version (UNAMAP Version #6, see USEPA, 1986b), which includes 33 models, has been published in 1986 . UNAMAP models are written in the FORTRAN computer language and many of them are available in versions suitable for personal computers.

a) Short-Term Dispersion Formulas

In Gaussian air quality dispersion models, the basic formula which is applied to calculate short-term (i.e., 10-60 minutes to one month) ground level concentrations of gaseous pollutants, is given as (see, e.g., Turner, 1970):

$$C = \frac{Q}{\pi \sigma_y \sigma_z u} \exp[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2] \exp[-\frac{1}{2}\left(\frac{H_{eff}}{\sigma_z}\right)^2]$$

where: Q - the pollution emission rate (in gram/sec) of the pollution (see Lecture #4);

σ_y - the standard deviation of the pollution concentration along the horizontal y-direction, perpendicular to the direction of the wind, chosen to be in the x-direction (in m) (see Figs. 1, 2);

σ_z - the standard deviation of the pollution concentration along the vertical z-direction (in m);

$H_{eff} = H_o + \Delta h$, the effective stack height, equal to the sum of the physical stack height H_o, and the plume rise Δh (in m);

u - the wind velocity in the x- direction, usually at the height H_o above ground level (in m/sec).

It should be mentioned that σ_y and σ_z are dependent on the stability of the atmosphere, i.e., on its capability to disperse and dilute the pollutants emitted into it (see Sec. (f)).

b) Formula for Long-Term Dispersion Models

For long-term dispersion models which are intended to describe pollution concentrations averaged over periods of time extending from one month to a year (for example, the UNAMAP Climatological Dispersion Model CDM-2), a uniform horizontal concentration can be assumed within each sector of $2\pi/n$ radians, the is integrated out of the formula and one obtains (see: Hanna et al., 1982):

$$C = \sqrt{\frac{2}{\pi}} \; \frac{f Q n}{2\pi \sigma_z u x} \exp[-\frac{1}{2}\left(\frac{H_{eff}}{\sigma_z}\right)^2]$$

where: x - the distance downwind from the pollution source (m);

f - the fraction of time that the wind blows into that sector.

It should be noted that as a rule, the concentration of pollutants decrease with increasing averaging time. Turner (1970) suggested the following dependence of the concentration on averaging time:

$$C_l = C_s \left(\frac{t_s}{t_l} \right)^p$$

where the subscript l stands for the long averaging time and s for the short and p should be between 0.17 and 0.2. This formula probably would be applied most appropriately to extrapolate pollution concentrations of a short sampling time of 10 minutes to longer averaging times of less than 2 hours.

Another approach to extrapolate pollution concentrations from 1 hour sampling time (t_o) to other averaging times (t_l), which is based on the time-dependence of the dispersion parameters σ_y and σ_z, has been presented by Gifford (1975):

$$\sigma_l = \sigma_o \left(\frac{t_o}{t_l} \right)^q .$$

For longer time averages t_l from 1 to 100 hours, Gifford recommended to use q = 0.25 to 0.3. For time averages t_l ranging downward from 1 hour to a few minutes, most authors agree on a value for q of 0.2.

c) Mixing Height

In the application of the above dispersion equations it is important to know the thickness of the mixed layer, also called the mixing height (Holzworth, 1972). This is the atmospheric layer adjacent to the ground, typically a few hundred meters to a few kms thick, which is turbulent and where most of the mixing of the pollution is carried out. In the case of a mixing layer of limited thickness L, the value of σ_z in the dispersion equation will grow only to L.

For example, the thickness of the mixed layer over all of the USA as a function of the time of the day and of the season of the year was given by Holzworth (1972). An estimation of the morning mixing heights in India as a function of the season of the year is given by Satyanarayana (1986). A survey in Israel of the thickness of the mixed layer as a function of the distance from the sea shore has been published by Dayan et al. (1988). These results show that a relatively thin morning mixed layer (less than 300 m) extends over India during most of the time of the year, whereas the annual mean morning mixing height over the USA varies from 400 to 800 m. Measurements of the mixed layer in New Delhi using an acoustic radar (Singal et al., 1985) are corroborating Satyanarayana's results. For pollution sources located near the sea (such as thermal power plants), one has to take into account the fact that the mixed layer near the shoreline is very thin and increases with the distance inland from the sea.

d) Dispersion Models for Particulate Matter

For particulate matter (contrarily to gaseous pollutants), one has to account for the settling out of the heavier particles (those larger than 20 um; see: ASME, 1979; or Hanna et al., 1982) due to gravity. Many ways have been proposed to accomplish this (see, e.g., Hanna et al., 1982, Ch. 10).

e) Pollution Emission Rates

The pollution emission rate Q, or source strenght (in gram/sec), is determined by direct measurements (stack sampling, Lecture #8) or can be estimated from emission factors, as explained in Lecture #4.

f) Dispersion Parameters σ_y and σ_z and Pasquill-Gifford Curves

The results obtained from the Gaussian dispersion formulas are very sensitive to the specific σ_y and σ_z chosen. The curves describing the dependence of σ_y and σ_z on the distance x downwind from the pollution source, and on the atmospheric stability category, are known as the Pasquill-Gifford (or PG) curves. The analytical expressions for the PG curves, first suggested by Briggs and widely used today, are presented in Table 7 (see also Fig. 3).

It should be noted that under urban conditions, with a generally much higher value of the roughness parameter compared to rural conditions, the σ_y and σ_z both are larger, and thus the concentrations lower.

Table 8 presents the atmospheric stability classification consisting of 6 categories A to E, as suggested by Pasquill. This classification is based on the surface wind speed, daytime solar insolation and nighttime cloud coverage. Other classifications of atmospheric stability have been suggested (Table 9) which are based on thermal stratification of the atmosphere ($\partial T/\partial z$) (Seinfeld, 1986), on the standard deviation of the horizontal wind direction fluctuation measured over time periods of 15 to 60 minutes, and on atmospheric turbulence criteria such as the

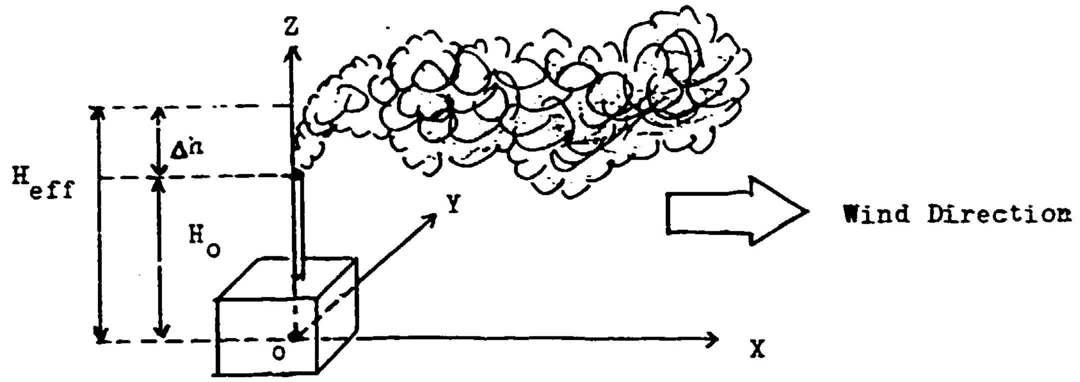

Fig. 1: The effective stack height.

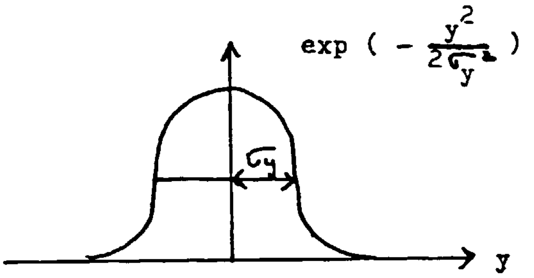

Fig. 2: Gaussian distribution and its standard deviation σ_y.

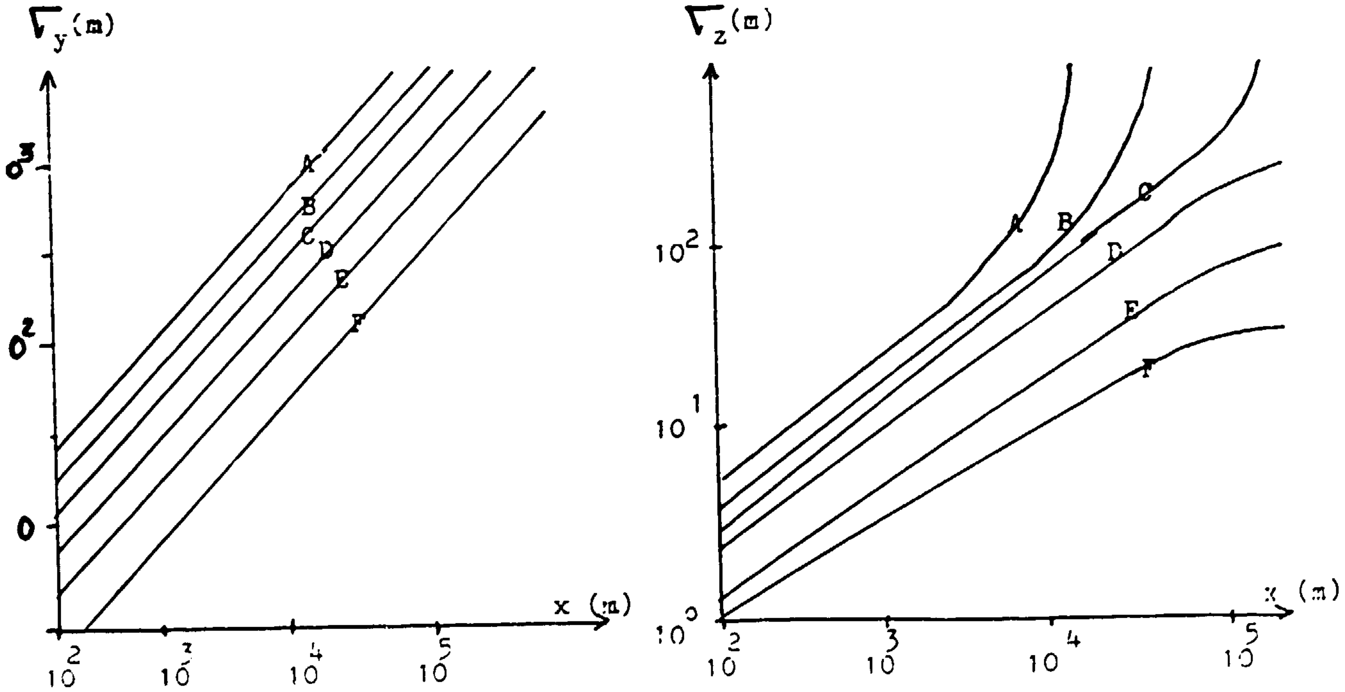

Fig. 3: The Pasquill-Gifford curves σ_y and σ_z (see Table 7).

TABLE 7: Formulas Recommended by Briggs for the PG Curves $\sigma_y(x)$ and $\sigma_z(x)$ for x-values $10^2 < x < 10^4$ m (see, e.g., Hanna et al., 1982, or Gifford, 1976)

Pasquill Stability Type	σ_y (m)	σ_z (m)
Open Country Conditions (also recommended by ASME, 1979)		
A	0.22x/T (*)	0.20x
B	0.16x/T	0.12x
C	0.11x/T	0.08x/(1+0.0002x)
D	0.08x/T	0.06x/(1+0.0015x)
E	0.06x/T	0.03x/(1+0.0003x)
F	0.04x/T	0.016x/(1+0.0003x)
Urban Conditions		
A-B	0.32x/R (**)	0.24x*(1+0.001x)
C	0.22x/R	0.20x
D	0.16x/R	0.14x/(1+0.0003x)
E-F	0.11x/R	0.08x/(1+0.0015x)

(*) T = (1+0.0001x)   (**) R = (1+0.0004x)

Richardson Number (Ri) and the Monin-Obukhov Length (L) (Gifford, 1976).

g) Wind Variation with Height Above Ground Level

Since most data on wind velocity is available only at ground level, whereas the dispersion of the pollutants in the atmosphere is affected by the wind velocity throughout the atmospheric mixed layer, a formula which gives an estimate of the changes of the wind velocity with height is very useful. Such a formula can also be used to derive the wind velocity at the top of the stack, as required by the Gaussian dispersion formula.

On theoretical grounds it can be shown that near the ground the wind should have a logarithmic profile (Sutton, 1953). However, very often it is assumed that the wind velocity increases with height according to a power law:

TABLE 8: Pasquill Atmospheric Stability Classification (Pasquill & Smith, 1983; Seinfeld, 1986)

Surface Wind Speed (at 10 m) (M/sec)	Daytime (1)			Nighttime (1)	
	Strong Insolation (>700W/m2)	Moderate Insolation (350 to 700W/m2)	Slight Insolation (<350W/m2)	Thinly Overcast or >4/8 Low Clouds	<3/8 Clouds
<2	A	A-B (2)	B	G (3)	G (3)
2-3	A-B (2)	B	C	E	E
3-5	B	B-C (2)	C	D	D
5-6	C	C-D (2)	D	D	D
>6	C	D	D	D	D

(1) Under overcast conditions, night or day, stability Class D should be used.

(2) The average value of both stability classes should be taken.

(3) Class G was not included in the original classification and was later added to represent "extremely stable" atmospheric conditions.

TABLE 9: The Relation Between Pasquill Atmospheric Stability Classes and (1) the Atmospheric Temperature Stratification (T/ z) (Seinfeld, 1986), (2) the Standard Deviation of Horizontal Wind Direction Fluctuation (σ_θ), (3) Richardson Number (Ri) and (4) Monin-Obukhov Length (L) (Gifford, 1976)

Pasquill Stability Class	Ambient Temperature Gradient (1) ($\partial T/\partial z$) (Deg C/100m)	σ_θ (Deg)	Richardson Number (at 2 m) (Ri)	Monin-Obukhov Length (L) (m)
A (Extremely Unstable)	< -1.9	25.0	-1.0- -0.7	-2 - -3
B (Moderately Unstable)	-1.9 - -1.7	20.0	-0.5- -0.4	-4 - -5
C (Slightly Unstable)	-1.7 - -1.5	15.0	-.17- -.13	-12 - -15
D (Neutral Stability)	-1.5 - -0.5	10.0	0	oo
E (Slightly Stable)	-0.5 - 1.5	5.0	0.03- 0.05	35 - 75
F (Moderately Stable)	> 1.5	2.5	0.05- 0.11	8 -35

(1) The Potential Temperature Gradient $\partial\theta/\partial z$ can be calculated by assuming $\partial\theta/\partial z = \partial T/\partial z + \Gamma$, where Γ is the adiabatic lapse rate: Γ = 0.986 Deg C/100m.

$$u(z) = u_o\,(z/z_o)^p$$

where u_o is the wind velocity at z_o= 10 m above the ground (the standard height above the ground prescribed by the World Meteorological Organization for wind measurements). The value p = 1/7 (= 0.143) has been frequently used in the past, giving the so-called "1/7 power law". However, it has been shown to be a good approximation only under neutral atmospheric conditions (Touma, 1977).

A better approximation of the power law seems to be based on specifying a different value for p for each one of the atmospheric stability classes. Values of p as proposed by different researchers are presented in Table 10. Again, it should be noted that larger p-values are given for urban conditions compared to rural conditions (Hanna et al., 1982), corresponding to a larger increase in wind velocity with height in urban conditions than in rural conditions.

TABLE 10: Values of p in Power Law for the Wind Profile

Stability Class	Hanna et al., 1982		ASME, 1979	Touma, 1977 (*)
	Urban	Rural		
A	0.15	0.07	0.12	0.10
B	0.15	0.07	0.16	0.15
C	0.20	0.10	0.20	0.20
D	0.25	0.15	0.25	0.25
E	0.40	0.35	0.30	0.25
F	0.60	0.55	0.40	0.30

(*) These values of p have been adopted in the 1986 version of the long-term climatological dispersion model CDM-2 (included in UNAMAP, Version 6: see USEPA, 1986b).

h) Estimating Wind Direction and Speed from Synoptic Weather Map

One can obtain the wind direction and wind speed from the synoptic weather map by using the geostrophic wind approximation (Byers, 1974) (see example in Fig. 4):

(1) The wind direction is approximately parallel to the isobars, so that the low pressure (L) is to your left when the wind is blowing at your back.

(2) The wind is approximately proportional to the pressure gradient $\Delta p/\Delta N$, where Δp is the pressure difference between two isobars and ΔN is the distance between them along the normal to the isobars.

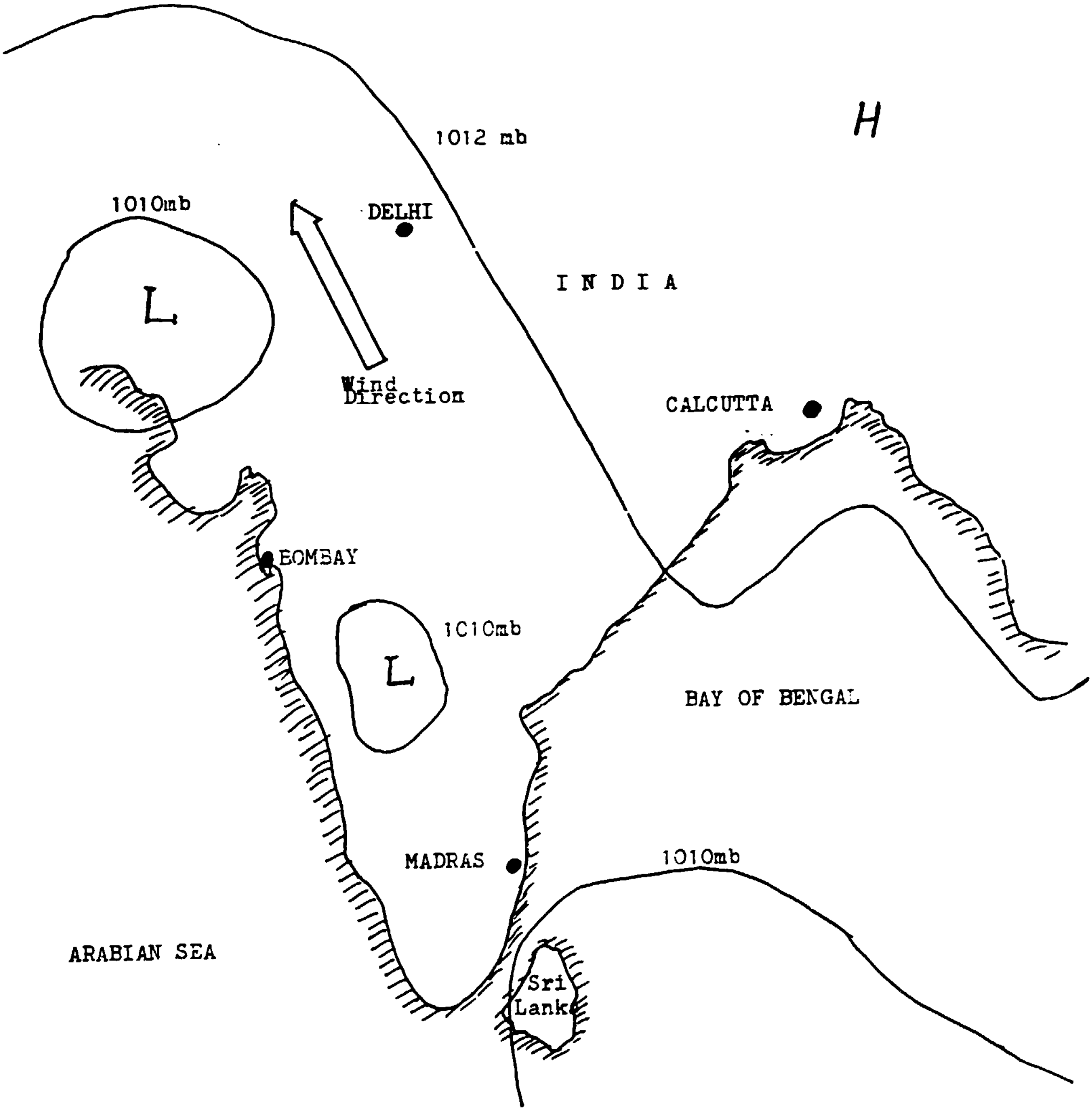

Fig. 4: Synoptic Weather Map of the Indian Subcontinent (from the New Delhi "Statesman", 13 August, 1987).

i) Plume Rise Formulas

Plume rise formulas for calculating H_{eff} are widely presented and discussed in the literature (see, e.g., Briggs 1969; 1975; 1984). Only the Briggs formula will be discussed here, since it appears now to be almost universally accepted.

The Briggs formula gives the following expression for the dependence of the plume rise Δh of buoyant plumes ($T_s > T_a$) on the vertical distance from the stack (x), known as the "2/3 law":

$$\Delta h(x) = 1.6F^{1/6}x^{2/3}/u \quad (x<x_o)$$

where: F is the buoyancy flux parameter (cm^4/sec^3), given by:

$$F = \frac{gd\,V_s^2}{4T_s}\,\Delta T$$

$g = 9.8\ m/sec^2$ - gravity

$\Delta T = T_s - T_a$

d - the stack diameter at the top (m)

x_o - the distance from the stack to maximum plume rise (m)

V_s - the vertical exit velocity from the stack (m/sec).

From the Briggs formula the maximum plume rise can be calculated for unstable and neutral atmospheric conditions and for stable conditions, for jets (i.e., plumes dominated by momentum) as well as for buoyant plumes. Table 11 presents a summary of the formulas for the different conditions. The stability parameter S (= $1/sec^2$) in the Briggs formulas is defined by:

$$S = \frac{g}{T}\frac{\partial \theta}{\partial z} \approx \frac{g}{T}\frac{\partial T}{\partial z} \quad .$$

TABLE 11: Final Plume Rise Formulas (Briggs, 1975; Seinfeld, 1986)

(1) Unstable and Neutral Atmospheric Conditions

Serial #	Dominant Plume Rise	F	Δh	x_m	Comments
1	Non-Buoyant ($T_s < T_a$)	-	$\frac{3V_s d}{u}$	-	-
2	Buoyant ($T_s > T_a$)	<55	$\frac{21.425\ F^{3/4}}{u}$	$49\ F^{5/8}$	If $\frac{21.425F^{3/4}}{u} < \frac{3V_s d}{u}$ use $\Delta h = \frac{3V_s d}{u}$
		>55	$\frac{38.71\ F^{3/5}}{u}$	$119\ F^{2/5}$	-

TABLE 11 (Continuation)

(2) Stable Atmospheric Conditions

Ser. #	Dominant Plume Rise	Δh	x_m	S	Comments
3	Momentum $(T_s < T_a)$	$\frac{3V_s d}{u}$	0	-	-
4	Momentum $(T_s > T_a)$	$\frac{3}{2S^{1/6}}\left(\frac{V_s^2 d^2 T_a}{4T_s u}\right)^{1/3}$	0	F Stability: S = 0.02 g/T G Stability: S = 0.035g/T	If $\frac{3}{2S^{1/6}}\left(\frac{V^2 d^2 T_a}{4T_s u}\right) < \frac{3V_s d}{u}$ use $\Delta h = \frac{3V_s d}{u}$
5	Buoyant (Calm $u = 0$)	$\frac{4F^{1/4}}{S^{3/8}}$	0	F Stability: S = 0.02 g/T G Stability: S = 0.035g/T	If $\frac{4F^{1/4}}{S} < \frac{3V_s d}{u}$ or $< 2.6F^{1/3}/(uS)^{1/3}$, use formula that gives least Δh
6	Buoyant $(u \neq 0)$	$2.6\left(\frac{F}{uS}\right)^{1/3}$	$\frac{2.0175u}{S^{1/2}}$	F Stability: S = 0.02 g/T G Stability: S = 0.035g/T	-

Lecture #6:

AMBIENT AIR QUALITY MONITORING

A very important tool for air quality management is the Air Quality Monitoring Network (AQMN). Such networks measure the concentrations of specific pollutants in the ambient air, as well as in the premises of industrial plants. In addition to pollutants, these networks also usually monitor local meteorological parameters (e.g., wind direction and speed) (Bryan, 1976; Noll & Davies, 1976; WHO/WMO, 1977; Noll & Miller, 1977).

It should be mentioned that air quality monitoring instruments are also extensively used to monitor indoor pollutant concentrations in industrial plants, and for research on residential indoor exposures to pollutants (ASHRAE, 1981; WHO/UNEP, 1982; WHO, 1983).

When establishing an AQMN, it is important to determine from the beginning the purpose of the project and what the particular AQMN is expected to do. Common aims in establishing AQMNs are the following (Rossano & Thielke, 1976):

(1) To determine the present level of pollution in a given area and to allow a follow-up on the air quality trend in the future. The output of such networks are essentially reports on the quality of the air. These reports contain data on average and maximum pollutant concentrations, for different averaging times. It is also costumary to express the air quality data in the form of an index. Such an air quality index describes the combined effects of the various pollutants as a single descriptor (Ott & Hunt, 1976; USEPA, 40CFR58);

(2) AQMNs are widely used in the USA to establish whether a given area conforms with the requirements of the regulations related to Prevention of Significant Deterioration (PSD) of the air quality in that area (USEPA, 1978; USEPA, 40CFR50, 40CFR58);

(3) To determine the air quality in a given area, as input to studies on health and environmental damage (i.e., research purposes);

(4) To determine the possible sources of air pollution in a given area. Recently, the sources of air pollution have become a concern on an international scale (i.e., the acid rain issue handled by ECE/UN (1984), and the problem of transboundary air pollution described in ECE/UN (1985; 1986]));

(5) To issue alerts on conditions of high concentrations of pollution. In this case, the AQMN should be part of a con-

tingency plan, which specifies the actions to be taken in these cases when high pollution concentrations occur (Tyler, 1976).

An example of an AQMN of the first kind is the global network set up by the WHO and UNEP. Reports on the trend of air pollution in many cities of the world are being published by WHO (WHO, 1984). Obviously, the air quality data obtained from this type of AQMN serves also for research on air pollution damage to health and to the environment. The time factor in obtaining the data from this type of AQMN is not so important. Thus, the data storage equipment required is minimal (magnetic tapes or even strip-charts might suffice) and no telemetry is installed.

For an AQMN to serve as an alert system, the data has to be transferred in *real time* to a control center. To meet this requirement, an air quality alert system must be based on telemetry and be computerized. An example of an air quality alert system is the one that was installed in the Netherlands (Evendijk & Post van der Burg, 1977).

Once a decision has been reached regarding the purpose of the AQMN, the following parameters of the network have to be determined:

a) Type of Pollutants to be Measured:

Usually, the list includes: SO2, NO/NO2/NOX, O3, CO, total suspended particulates (TSP) and respirable particulates (PM10), sometimes hydrocarbons (either total = THC, or non-methane = NMHC), and in some specific cases, also other types of pollutants are measured. In addition to the pollutants, it is customary to measure also the most relevant meteorological parameters such as the wind speed and direction (sometimes the wind direction fluctuation, which is a measure of the atmospheric turbulence) and solar radiation. To determine the type of pollutants to be measured, one has to take into consideration the sources of pollution (industry, traffic, home heating, etc.) and the meteorology of the area (which affects the photochemistry of the pollutants as well as their transport and dispersion).

The gaseous pollutants are reported in units of microgram per cubic meter (ug/m3) or parts per million (ppm), whereas TSP is measured only in ug/m3. To convert results given in ppm units to ug/m3, the following formula should be used:

$$[\mathrm{ug/m}^3] = 43.631 \times M \times \left(\frac{273}{Ta}\right) \times \left(\frac{Pa}{1013}\right) \times [\mathrm{ppm}],$$

where: M - the molecular weight of the gaseous pollutant
Ta - the ambient temperature, in deg C

Pa - the ambient pressure, in millibars

b) The Number of Monitoring Stations Required:

This issue is usually settled by the budget available to the project. However, guidelines do exist as to the optimal number of stations required for a given AQMN (see Table 12). For example, for a city the size of New Delhi (over 8 million inhabitants), WHO (1977) suggests 8 monitoring stations which include the following instruments:

- 10 sensors for SO2
- 10 sensors for TSP
- 5 sensors for NOX
- 4 sensors for O3
- 5 sensors for CO
- 3 sensors for wind speed and direction.

Modifying factors, which account for the local characteristics that exist in Delhi (such as described by Mangla, 1988), are given. According to them, the recommended number of stations or instruments could be somewhat different.

c) The Type of Instruments Required:

All the instruments installed in an AQMN should be able to record their results automatically and continuously. For the gaseous pollutants there exist a wide range of automatic and continuous instruments based on various measuring principles. The newer type of instruments tend to be based on physical (rather than chemical) principles utilizing specific molecular spectral emission or absorption lines. These methods ensure the specificity of the measurement (avoiding the interference of one pollutant on the measurement of another) and no replacement of liquid chemical reagents ("wet chemistry") is required. On the other hand, it involves sophisticated and expensive optical, electronic and computer components.

Descriptions of air quality monitoring instruments and their principles of operation is given by Bryan (1986), and in regulations issued by the Federal Environmental Protection Agency in the US (USEPA, 40CFR50; 40CFR53; 40CFR58). The USEPA issued regulations (USEPA, 40CFR50) describing the principles of operation of air quality monitors for SO2 (App. A), high volume samplers (the so-called Hi-Vols) for TSP (App. B), for CO (App. C), for O3 (App. D), for hydrocarbons corrected for methane (NMHC) (App. E), and for NO2 (App. F). Some of the details of the requirements of air quality monitoring instruments are also described in the regulations issued by the USEPA (USEPA, 40CFR53; 40CFR58) and in documents issued by the UmweltBundesAmt (the Federal Ministry of the Environment) in West Germany (UBA, 1983).

TABLE 12: Suggested Average Numbers of Stations for Air Quality Trend Monitoring in Urban Areas of Given Populations (WHO/WMO, 1977) (*)

Urban Population (million)	Average Number of Stations per Pollutant					
	SPM	SO2	NOX	OX	CO	WD+WS
<1.0	2	2	1	1	1	1
1.0 - 4.0	5	5	2	2	2	2
4.0 - 8.0	8	8	4	3	4	2
>8.0	10	10	5	4	5	3

(*) Comments:

Modifying factors are as follows:

a) In highly industrialized cities the number of stations for Suspended Particulate Matter (SPM) and Sulfur Dioxide (SO2) should be increased.
b) In areas where large amounts of heavy fuel rich in sulfur are used, the number of stations for SO2 should be increased.
c) In areas where not much heavy fuel is used, the number of stations for SO2 may be reduced.
d) In regions with irregular terrain it may be necessary to increase the number of monitoring stations for wind direction and speed (WD+WS), and for the pollutants.
e) In cities with extremely heavy traffic, the number of stations for Nitrogen Oxides (NOX), Ozone (O3) and Carbon Monoxide (CO) may need to be doubled.
f) In cities with a population of 4 million or more, with relative low traffic, the number of stations for NOX, O3 and CO may be reduced.

Automatic ambient dust sampling is still, in contrast to gaseous sampling, an "unsolved problem". The commonly accepted method for ambient dust measurement is based on the high-volume sampler (the Hi-Vol method) (see: App. B in: USEPA, 40CFR50; and Method D 4096-82, in: ASTM, 1985b). However, Hi-Vol samplers cannot be integrated into an automatic air quality monitoring station since the results are obtained by manual gravimetric methods. On the other hand, the results from automatic dust samplers available on the market such as the tape samplers (see: Method D 1704-78, in: ASTM, 1985b), do not correlate well with results from Hi-Vol samplers, and their use is therefore not recommended.

A newer type of tape sampler (the so-called Beta-Gauge instrument), where the mass of the dust is obtained from radioactive absorption measurement (rather than from the optical transmittance or reflectance of the dust sample, in the older type of instruments), seem to correlate much better with the results of the Hi-Vol sampler. However, the correlation is deemed by most experts not sufficiently good, and this type of instrument is not widely used as yet. Nevertheless, because of the obvious advantages of the Beta-Gauge instrument as automatic and semi-continuous, they are now being integrated into many air quality monitoring stations and air quality alert systems.

d) Choice of Sites for the Location of Air Quality Monitoring Stations

Detailed guidelines regarding the choice of adequate locations for air quality monitoring stations were published as regulations in the USA (USEPA, 40CFR58) and also by the WHO (WHO/WMO, 1977). These guidelines include criteria and instructions as to the minimal distances to be maintained between the station and neighboring air pollution sources and obstacles. From these instructions it is also clear that special care should be taken in the positioning of the input funnel, through which the sampled air enters the instrument.

e) Site Selection for a Mobile Air Quality Station

Most guidelines for selection of sites for air quality monitoring stations refer to stationary stations and are not suitable for a mobile station.

For a mobile air quality station, the following guidelines are suggested:

1) Site the mobile station first downwind from the polluting source affecting the area, then, on the upwind side. The distance of the mobile station from the source should be at least 3 times the height of the stack or vent of the source above the ground level

2) In a polluted area, choose a site that is downwind from the dominant pollution source in the area.

3) Site the station at least 25 m away from domestic chimney or an absorbing surface (such as trees or buildings).

4) Site the station on a level surface, off the road (so as not to disturb local traffic) and in a quiet place (were minimum disturbances from the local population are to be expected).

5) A rough idea regarding the dominant wind direction can be obtained from the synoptic weather map published in some of the daily newspapers (see Lecture #5, Sec. i and Fig. 4).

6) In order to be able to describe fully the air quality of a given site, a full year of continuous air quality data is required. This data would reflect seasonal changes in the atmospheric dispersion parameters, which affect the pollution concentrations in the air. (This is one of the reasons for establishing stationary, rather than mobile, air quality monitoring stations.)

However, one can get quite a good idea about the air quality of a given site using a mobile station for much shorter periods of time. The duration of the sampling at a given site should always be at least one full hour (for comparison of the results with air quality standards), although longer periods are preferable (3 hours or more).

It is advisable to obtain air quality data three times a day:

- In the afternoon (for photochemical pollutants such as NOx and ozone
- At night (under stable atmospheric conditions prevalent at night)
- In the morning.

7) Place the electricity generator of the mobile station downwind from the mobile station.

f) Calibration of Air Quality Instruments

Calibration procedures are a most important part in the proper operation of air quality monitoring instruments. They ensure that the data obtained from the equipment is indeed reliable (USEPA, 1976; Axelrod & Lodge, 1976). The commonly used calibration procedure is based on a comparison of the results read on the tested instrument, with a known concentration of pollutant injected into the instrument. The known concentrations of the pollutants are obtained from commercially available certified calibrated gases and specially designed gas dilution equipment.

Detailed descriptions of calibration procedures of air quality monitoring instruments were issued by the USEPA (USEPA, 1976) and incorporated into their regulations (USEPA, 40CFR58), and by the UBA in West Germany (UBA, 1983).

g) Computerization of the AQMNs

At the level of the air quality monitoring station, a local electronic data logger is mandatory. Its function is to receive the instantenous, or short-term output of all monitors in the station, calculate averages of the data over pre-determined time periods and store the averaged data for a limited time (from a few days up to 2 weeks, depending on the size of the memory of the data logger, on the selected averaging time period and on the number of parameters handled). In an AQMN, the local data logger serves also as a backup to the control center computer for data storage in case of communication failures.

For air quality alert systems, a computerized control center is required to accept and store all data transmitted by the outstations. This computer can also identify from the measured air quality data alert conditions and is capable of transmitting alert signals via radio or telephone lines to pre-determined addresses (e.g., to the inspecting authority at home, or to the nearest police station). For small AQMNs a personal computer (PC) can readily be adapted to perform these tasks. For an AQMN on a national scale, computers with larger data storage capacities are required.

Lecture #7:

SOURCE MONITORING OF EMISSIONS

Emissions from air pollution sources have to be measured and monitored. Stack sampling is widely used to determine the concentrations and the emission rates of given pollutants in the flue gases emitted into the atmosphere (Thorn, 1986). Recently, devices based on remote sensing principle have been introduced (Grant & Menzies, 1983). These instruments greatly simplify source monitoring since for their operation climbing up the stacks is not necessary. Instruments which enable continuous monitoring of the emissions have also been introduced recently. Most of these instruments (the best known amongst them is the opacimeter for monitoring flue gas opacity which is an indicator for particulate matter emissions) are based on optical measurement principles.

Stack sampling may be necessary for any one or more of the following reasons (Paulus & Thron, 1976):

a) To obtain data concerning the emissions into the atmosphere in order to compile a regional emission inventory and identify the dominant sources in the region;

b) To determine compliance with emission regulations (see Lecture #3) and to establish data as legal evidence;

c) To determine the efficiency of control equipment that has been installed to reduce emissions: Stack sampling tests are often part of the acceptance test of the control equipment;

d) To evaluate changes in the emissions as a result of process or equipment modification.

Stack sampling consists basically of drawing from the stack a sample of the flue gas for analysis. It provides data on the concentration of a given pollutant (expressed as pollutant mass per volume of flue gas, e.g., milligram/m3 or parts per million= ppm) or emission rate (as pollutant mass per time, e.g., kg/hr or gram/sec). To obtain this information several independent measurements have to be carried out:

a) The actual flow rate of the flue gas in the stack (m^3/sec);

b) The mass of the pollutant in the volume of flue gas measured (milligram);

c) The temperature of the flue gas (^oC or ^oK);

d) The humidity of the flue gas, i.e., its water vapor content (in wt%).

For combustion installations, stack sampling can provide also data required to determine the efficiency of the combustion process such as the contents of oxygen, carbon monoxide and carbon dioxide in the flue gas, as well as the ratio CO/(CO+CO2). Thus, very often stack sampling involves also the measurement of the content of the flue gas for O2 and CO2, which are not considered as pollutants.

Emission standards are usually given for standard conditions of temperature and pressure (i.e., STP conditions) and for a dry flue gas (i.e., after the deduction of the water vapor). The temperature and the water content of flue gases may vary within a wide range depending on the process and on the type of the installation. For example, the typical temperature of the flue gases for a large oil-fired combustion installation is 130-140 deg C and the water vapor content may reach 20%. The water vapor content in the flue gases of coal-fired combustion installations is lower because of the lower content of Hydrogen in the coal.

Stack sampling is divided into two different types of measurements:

a) Stack sampling for particulate matter emissions;
b) Stack sampling for gaseous emissions.

Stack sampling for particulate matter differs from stack sampling for gases because isokinetic sampling conditions are required to assure that the particulates in the sample correctly represent their concentration in the flue gases. An isokinetic sampling condition means that the velocity at which the sample is drawn into the probe is equal to flow velocity of the flue gases in the stack (Hawksley et al., 1977).

With respect to particulate emissions, in many cases it is of interest to know not only the concentration of all the particles but also their size distribution. This information is most important for the determination of the appropriate control equipment.

Since for the analysis of the sample a minimal quantity of the pollutant is required, the duration of the stack sampling is dependent on the concentration of the pollutant in the flue gas. The pollutant is collected by using different devices, including: filter paper (mainly for particulate matter), condensers (freeze-out method), bubblers, impingers, or Mylar bags for grab sampling (see, e.g.: Table V, p. 572-573, in Paulus & Thron, 1976).

A detailed description of close to 60 different methods for stack sampling have been published by the Environmental Protection Agency in the USA in regulations covering emissions into the air from new sources (USEPA, 40CFR60). These methods outline how to perform measurements of the flow rate of the flue gas, its temperature, contents of O2, CO2, of water vapor, and how to sample and analyze for a long list of pollutants (e.g., SO2, SO3, CO, H2S, fluorides, particulate matter, opacity, volatile organic matter etc.). Detailed guidelines for stack sampling have also been published by the Federal Ministry for the Environment in W. Germany (UBA, 1986). A discussion of stack sampling at various sources (such as at power plants, cement plants, iron cupolas, incinerators) is also given by Paulus & Thron (1976).

Lecture #8:

PARTICULATE MATTER FILTRATION BY ELECTROSTATIC PRECIPITATION (ESPs)

Electrostatic Precipitators (ESPs) are the most common high-efficiency devices used to control fly ash emissions from coal-fired electric power plants (USEPA, 1977a). The theory and practice of electrostatic precipitation of fly ash is described in detail in a number of documents: The well-known monogram by White (1963) and his series of papers (White, 1977) are dedicated to this subject. Electrostatic precipitation of fly ash is also dealt with in detail in special chapters in a number of other documents (Danielson, 1973; Oglesby & Nichols, 1976; USEPA, 1977b).

ESPs achieve high particle control efficiencies due to the electrostatic charging and attraction of the fly ash particles. However, ESPs are also huge settling chambers which can remove 30 to 40 % of the particles by gravitational settling, when all charging and collecting power is turned off.

Electrostatic precipitation consists of the following elements or mechanisms:

- Ionized gas molecules are created in the gas stream by means of high voltage corona discharge (usually produced by a negatively charged electrode)
- The gas ions attach themselves to the particulate matter suspended in the gas stream, and the particles are electrically charged
- Under influence of an electrostatic field, the charged particles migrate to the collecting electrodes (of opposite polarity to the charging electrodes)
- The charged particles are neutralized on the collecting electrodes and build up on it a layer of particulate matter
- The particulate matter is removed from the collecting electrodes by rapping, and collected into hoppers for storage and for subsequent removal.

Essential features of modern ESPs, designed for fly ash collection from coal-fired power plant emissions, include the following elements: Shell, charging electrodes, collecting electrodes, rappers, rectified high voltage power supply units, gas inlet, hoppers and hopper baffles, and a fly ash removal system (see Fig. 5).

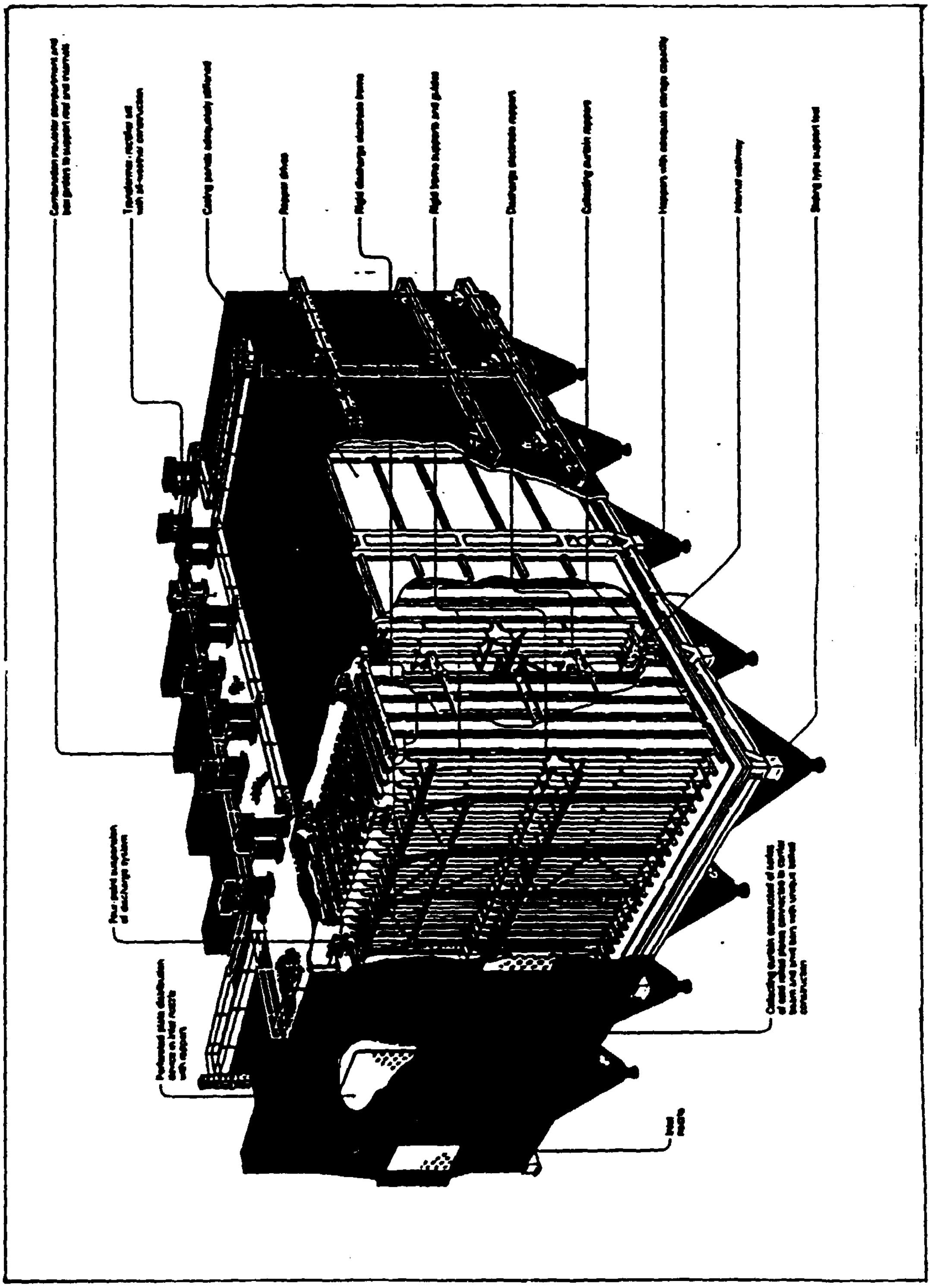

Fig. 5: General scheme of a European design ESP

The charging electrodes, which provide the corona discharge required to ionize the gas molecules, are made of wires of various shapes, strung on rectangular frames. This design (of European origin) is now replacing fly ash ESPs of the less sturdy American design invented by Cottrel, based on hanging wires with weights.

As the layer of deposited particles is built up, particularly on the collecting electrodes but also on the discharge electrodes and other internal parts of the ESP which control the gas stream flow, it is periodically knocked off by rapping those parts. The particulate matter falls down and is collected into a hopper.

For electrostatic precipitation of fly ash, the dust buildup on the collecting electrodes should be allowed to reach 4 to 6 mm, depending on the resistivity of the fly ash, before it is rapped off.

It is important to minimize dust re-entrainment into the gas stream during rapping. This is achieved by designing for slow gas velocities (0.6 to 2.4 m/sec) and a uniform flow within the ESP, as well as timely removal of the dust acumulated in the hoppers.

Rappers consist, frequently, of hammers which are lifted by a rotating shaft and then fall under force of gravity and strike anvils attached to the frames of the collecting plates and the charging electrodes.

The efficiency of the ESP is markedly affected by the rapping intensity, interval and lenght of each rapping cycle. Since more dust is being collected on the plates of the upstream fields, they have to be rapped more frequently compared to plates situated further downstream.

The ESP shell consists of an airtight housing made of sheet metal covered by a layer of thermal insulation. The function of the sheet metal housing is to prevent air leaks into, or out of, the ESP. Cold atmospheric air leaking into the ESP decreases the temperature inside the ESP to below the dew point of sulfuric acid, thus causing severe corrosion problems. The layer of thermal insulation serves the same purpose of maintaining a sufficiently high temperature inside the ESP.

It is thus very important to keep the ESP shell, both the sheet metal skin as well as the thermal insulation layer, in good condition and repair any damage that can lead to air leaks into the ESP or escape of heat out of it.

In modern high voltage ESPs, the power supply units consist of four components (see Fig. 6):

- High voltage step-up transformers, which can achieve the required operating voltages (20 to 100 kV)

- High voltage silicon rectifiers and high frequency choke coils, which convert the secondary alternating voltage to unidirectional voltage (half or full wave)

- An automatic control element, designed to maintain automatically the optimum operating levels inside the ESP of the spark rate, the voltage and the current, even when dust characteristics and concentrations exhibit temporal fluctuations (automatic control feedback)

- Sensors for the automatic control elements.

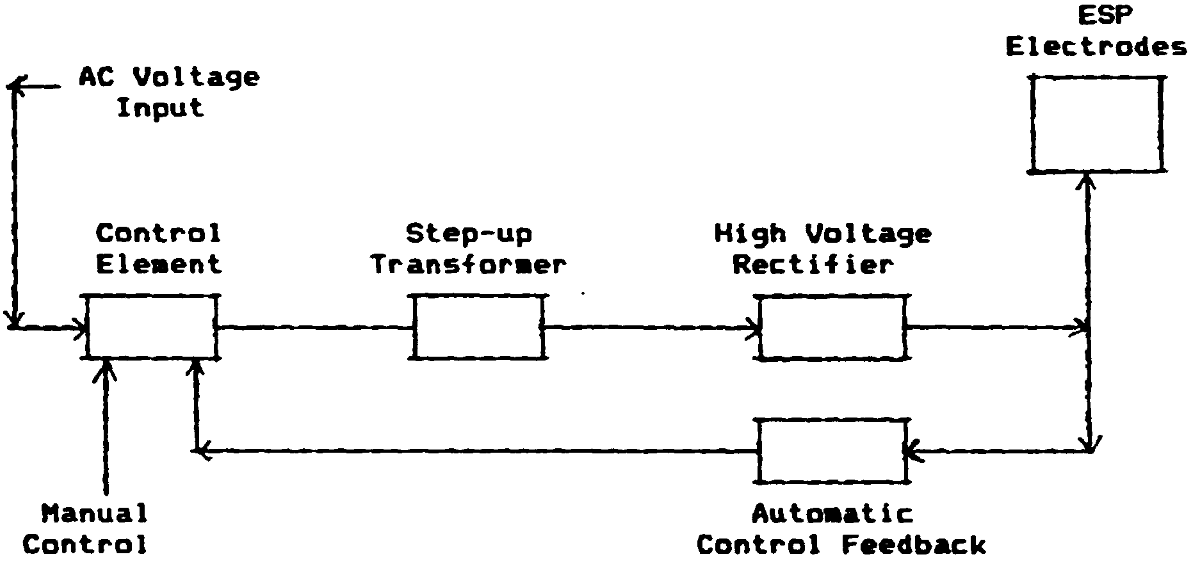

Figure 6: Scheme of ESP Electric Power Supply

The transformer ratings should be noted and reported. The voltage-limit and current-limit control settings should be adjusted according to the primary voltage and current ratings of the transformers.

The spark rate (i.e., the number of times per minute that electric breakdown occurs between the discharge and collecting electrodes) depends on many factors, such as ESP size, fly ash characteristics and concentration, temperature and moisture content. A typical spark rate is in the range of 50 to 150 sparks per minute, with maximum collection efficiency attained at 50-100 sparks per minute. The spark rate controller establishes the applied voltage at a point where a fixed spark rate occurs. Continued sparking to one spot will cause erosion of the electrode.

The transformer, rectifier and choke coils are submerged in a tank filled with dielectric fluid, located on the roof of the ESP, for easy access (see Fig. 5).

Hoppers are used to collect and store the fly ash removed from the electrodes. If the hoppers are allowed to overfill, the collected dust will be re-entrained, thereby greatly reducing precipitator efficiency. Baffles are frequently placed in the hoppers to minimize undesirable gas flow, which again may lead to re-entrainment (the so-called "hopper sweepage").

Several types of systems exist for removal of the fly ash accumulated in the hoppers. These include container removal, vacuum systems, screw conveyors and scrape bottom systems.

The perfomance of ESPs is usually judged by its collection efficiency E (in %), defined by:

$$E = (1 - \frac{C_o}{C_i})*100$$

where: C_o - the dust concentration in the outlet gas stream
C_i - the dust concentration in the inlet gas stream

One widely used expression for determining the efficiency of a given ESP is the Deutsch equation (also known as the "Deutsch-Anderson equation"):

$$E = (1 - q)*100 = [1 - \exp(- \frac{A\ w}{V})]*100$$

where: A - Total area of the collecting plates on both sides (m2)
V - Total volumetric flow rate (m3/sec)
w - Migration velocity of the charged particles in the vicinity of the collecting boundary (m/sec)
q - A parameter known as penetration.

It should be emphasized that the theoretical collection efficiencies as determined from the Deutsch equation are only qualitatively observed in practice. Difficulties in achieving ESP performances as predicted from theoretical design parameters has lead people to consider the operation of ESPs as an art rather than as a science.

Because of these difficulties, it has been suggested to discard the Deutsch equation altogether and replace it with a equation of the form:

$$E = (1 - \exp[- (\frac{w_m A}{V})^m])$$

where: w_k - the modified migration velocity (empirical) (m/sec)
m - determined empirically, for fly ash $0.4<m<0.8$.

However, most design engineers still use the Deutsch equation as presented by White. The theoretical migration velocity (w) used by Deutsch to derive his equation is replaced by an effective migration velocity (w_e) to which empirical values are assigned for given applications and given conditions, based on previous experience. In practice, w_e for the mean particle size of the fly ash is found to be smaller than w (i.e., actual collection efficiencies are lower than the theoretical efficiencies). This suggests that there is a mechanism, not accounted for by the simple ESP theory, which provides for the transport of particles away from the collecting surface (perhaps losses of collected material from the collecting surface by re-entrainment). In the Deutsch equation in the form:

$$E = (1 - \exp[- (\frac{A}{V} w_e)])*100,$$

the parameter A/V, called the Specific Collection Area of the ESP (SCA), is widely used to characterize a given ESP. It should be noted that for fly ash precipitation SCA values of 100 $m^2/(m^3/sec)$ (500 $ft^2/10^3$ acfm) are common, and for high resistivity fly ash the SCA can reach 130 $m^2/(m^3/sec)$ (800 $ft^2/10^3$ acfm), or more.

It should be noted that for the large particles, where field charging is the dominant charging process (particles with diameter larger than about 0.5 um), the electric migration velocity w_e is proportional to the radius of the particles. Thus we find for the fly ash particles larger than 0.5 um that the larger the particles, the easier it is to collect them in an ESP and the higher also is the ESP efficiency.

On the other hand, for particles smaller than about 0.2 um, diffusion charging becomes the dominant mode of charging and also, for such small particles, the viscous drag force of the gas stream is reduced (the "slip" phenomena), thus the migration velocity tends to increase as the particle diameter becomes smaller.

For these reasons, the ESP collecting efficiency for particles the size of which are in the range of $0.2<d<1.0$ um, exhibits a minimum value, with much higher efficiencies attained for particles larger than 1.0 um.

It should be emphasized that the determination of the fly ash size distribution is necessary if a reasonable analysis of the ESP performance is expected. The methods available are described in detail in a document issued by the USEPA (1977b).

Dust layers accumulated on the collecting electrodes affect the electrical behavior of the ESP by introducing a resistance element with a non-linear characteristic into the electrical circuit.

Theory and experience indicate that when dust resistivity exceeds a critical value of about 10^{10} ohm-cm, corona currents are limited by electric breakdown of the collected dust layer. This in turn limits the operating voltages and reduces the ESP efficiency. The loss in performance increases quite rapidly for resistivities greater than 10^{11} ohm-cm, and the resistivity of the fly ash is therefore a major factor in fly ash precipitation technology.

Fly ash resistivity values vary with the type of coal used, from the low value of 10^{7} ohm-cm, to the highest value of 10^{14} ohm-cm. It appears that for good ESP performance, the best range of fly ash resistivity is 10^{10} to 10^{11} ohm-cm.

Experience over many years has shown that fly ash from high sulfur coals have a relatively low resistivity, whereas low sulfur coals ($S<1\%$), such as exist in India, usually have high resistivity fly ash (10^{11} to 10^{13} ohm-cm), and are more difficult to precipitate.

The reason for the lower resistivity of fly ash from high sulfur coals is that although most of the sulfur in the coal is oxidized to SO_2, about 1% of it is converted to SO_3, most of which condenses on the surface of the fly ash particles. However, this relationship is only statistical, because of the influence of other variables, such as:

- It has been shown that the presence of sodium (as Na_2O) in the fly ash in sufficient amounts (more than 1.5-2.0 %), reduces the fly ash resistivity of low sulfur coals to levels below 10^{10} ohm-cm

- The effect of iron compounds in the coal (e.g., Fe_2O_3) on the conversion of SO_2 to SO_3 may be important

- It has been shown that the resistivity of the fly ash is strongly dependent on the ambient temperature inside the ESP. The resistivity attains its maximum value at a temperature of about 140 ° C, which happens to be the normal operating temperature inside most power plant ESPs

- Levels of combustibles (i.e., the coal particles that did not completely burn in the combustion zone) in the range of 3 to 6 wt% of the inlet ash to the ESP, are in most cases considered beneficial in reducing fly ash resistivity. However, amounts greater than 12% can begin to affect the resistivity adversely

- Problems of high fly ash resistivity can be abated as the moisture of the flue gas is increased.

In order to achieve higher ESP collection efficiencies with fly ash having a high resistivity, several methods are commonly used:

- Operating ESPs with relatively large SCA values (130 m2/(m3 /sec or more)

- Preventing the build-up of dust layers the thickness of which exceed 6 mm. This is achieved in the European ESP design by installing efficient rapping systems, characterized by high acceleration and frequency rapping

- Reducing the fly ash resistivity by injecting additives into the flue gas (the so-called "flue gas conditioning" method). The most common additive is moisture (water vapor), but SO3, NH3, alkali compounds and other materials have also been used.

It should be emphasized that since the electrical resistivity of fly ash is of such critical importance to ESP perfomance and its collecting efficiency, every effort should be devoted to obtain a reliable determination of the resistivity of the specific fly ash in question. Methods to determine fly ash resistivity were described by Oglesby & Nichols (1976) and in USEPA (1977b).

As has been noted by White, obtaining a good performance from a given ESP is considered not only a science but also much of an art. Nevertheless, no one doubts that good maintenance plays a crucial role in obtaining satisfactory ESP performance.

Most of the analyses of ESPs performance assume that the system being considered is either in the operating state or in the failed state. However, studies have also been performed which analyze the effect of partial failures (i.e., the ESP is operating, although under a certain degraded state).

Because an ESP is a relatively static device, with few moving parts, its maintenance requirements are relatively light and preventive in character. Routines for inspection and maintenance of ESPs have been proposed by the USEPA (1977a; 1977b).

Lecture #9:

AIR QUALITY EVALUATION THROUGH ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

Environmental Impact Assessment (EIA) is a most powerful tool for evaluating also the future air quality in relation to new projects. The EIA is, as a matter of fact , an integrative system utilizing all the management tools described in the previous sections (ESCAP, 1985; Biswas & Geping, 1987). As an example this lecture will focus on the air quality assessment for chemical plants within the framework of EIAs. The following pages will deal with guidelines for the preparation of the air quality section of an EIA for chemical plants, including the emission inventory, air quality assessment, and chemical incident hazard assessment.

a) Plant Emission Inventory

The objective of a plant emission inventory (namely, an inventory of all the pollutants and toxic materials emitted from a given plant into the atmosphere) is to supply information regarding the types of airborne substances emitted by the plant, the types of emission sources and their location inside the plant, the strength of these sources (in terms of quantities of pollution emitted and emission rates), expressed both as a function of the production rate and of the efficiency of the equipment installed to control those emissions (see also Lecture #3).

It should be noted that project proponents can be encouraged through the EIA process to adopt plant designs which are based on clean technologies which both reduce the emissions of pollutants into the atmosphere as well as use less energy (UNEP, 1982).

Types of Substances Emitted into the Atmosphere

An emission inventory should identify and list the different types of pollutants (including odorous and toxic substances, as well as fuel burning products such as SO2, NOX, CO, and particulate matter) emitted into the atmosphere from all the sources of the plant, including fugitive emissions, under both normal operating conditions and during chemical incidents.

Information on the Installations and Facilities in the Plant

In this section of the EIA, a description should be given of the installations and facilities of the plant, the production processes that are of relevance to airborne emissions, as well as the equipment installed to control air pollution emissions.

A summary listing all the installations and facilities of the plant emitting airborne pollutants (through stacks, vents, or fugitive emissions) under normal operating conditions should be provided. This summary should also list, for each type of pollutant and for every installation, the quantities of pollutant emitted and rates of emission, the airflow through the stacks and vents emitting airborne pollutants (under STP conditions), as well as the typical control efficiency of the equipment installed in that installation.

A process flow chart of the plant's production should be provided, as well as maps detailing the location of the installations inside the plant and the plant's location vis-a-vis its neighborhood.

Fuel and Raw Materials

A material inventory, i.e., a list of the main types and quantities used of raw materials (including fuel), intermediates and end products which have a potential impact on the air quality, should be provided. The annual consumption and production rates of these substances in the plant should be specified, as well as those for shorter periods of time (monthly, weekly, daily, and per hour for continuous processes and monthly, weekly, daily, and per batch for batch processes). Special attention should be given to toxic and volatile substances used in large quantities, as described in Table 14.

For fuels, details should be given as to the type of the fuel (gas, fuel oil, coal, or other), as well as its sulfur ash and trace metals contents (see Lecture #4).

Emission Rates of Airborne Pollutants

In this section, data should be presented on the emission rates of airborne pollutants from the various sources in the plant (such as its production facilities, storage areas, sewage treatment plant, sludge drying ponds etc.), under normal operating conditions (i.e., not involving accidents), including the unavoidable small leaks.

These airborne emission rates should be based as much as possible on field measurements and on stack samples (Lecture #7). However, in the absence of measured data, estimates can be based on emission factors (Lecture #3). It should be noted that for these estimates the data on the consumption rates of raw materials and fuel, as well as the gasflows, is essential.

To evaluate the pollution emission rates from the individual installations, they should be compared with relevant emission standards (Lecture #2).

Adding the emission rates of a given pollutant from all the installations of the plant, one obtains the total emission rate of the plant, which is sometimes referred to as the plant's "bubble" emission rate (Borowsky & Ellis, 1987). It should be noted that in the bubble approach total emission rates of the plant are controlled rather than the emission rates of the individual installations, thus providing the plant's management more flexibility in complying with the emission limitations.

b) <u>Air Quality Assessment</u>

Air quality in the vicinity of the proposed plant can be forecasted by using air pollution dispersion models (Lecture #5). The input data necessary for the models includes the pollution emission rates and atmospheric stability data such as wind speed and direction, depth of the mixed layer and the change of temperature with height above ground level (Lecture #5).

Air quality monitoring data obtained from field measurements is required to establish the levels of the background pollutant concentrations and also, to verify the results obtained by the air pollution dispersion models (Lecture #6).

Ambient monitoring of airborne pollutants such as SO2, NOX, CO (which are typically fuel burning products) and particulate matter is by now well established, as is the monitoring of atmospheric stability parameters. Instruments and equipment for monitoring these pollutants and atmospheric stability parameters are quite standardized and commercially available (Lecture #6). Statistical methods for analyzing the measured data and evaluating it are readily available (Gilbert, 1987; Seinfeld, 1986, Ch. 17).

On the other hand, methods for monitoring ambient airborne chemicals (toxic or odorous) are generally not standardized and for many substances monitoring instruments are not available as "off-the-shelf" equipment (Jayanty & Hochheiser, 1988). Thus, in the vicinity of chemical industry complexes, specially designed surveys might be necessary to establish their background pollution levels (Swallow et al., 1988).

To evaluate the ambient air quality in the vicinity of the proposed plant ("ambient" is defined as outside of the fenceline area), the pollutant concentrations calculated from the air quality dispersion model should be compared with ambient air quality standards or WHO guidelines (Lecture #2), but if not applicable, to the Levels of Concern (LOC) specified by the USEPA (USEPA/FEMA/DOT, 1987). Concentrations of odorous chemicals should be compared with odor threshold limits (N[illegible], 1979). For certain toxic chemicals, fractions of the Immediate Danger for Life and Health (IDLH) levels, Threshold Limit Values (TLVs) Median Lethal Concentrations (LC50), or Doses (LD50), may serve as guidelines for establishing the acceptable ambient levels of pollution (USEPA/FEMA/DOT, 1987).

c) Chemical Incident Hazard Assessment

Special interest should be focused on the incident potential in chemical plants, which might lead to the exposure of human populations living in the area surrounding the plant to high concentrations of airborne toxic substance. It should be noted that the most frequently occurring accidents in the chemical industry involve releases into the air of HCl, NH3 or Cl2 (Cutter, 1987). However, since airborne releases of other accutely lethal substances, while infrequent, can be catastrophic (such as, for example, the MIC release at Bhopal, or the Dioxin release at Seveso), special considerations are required in plants using hazardous chemicals, such as: Installations and maintenance of control equipment (USEPA, 1986) and alert systems, preparation of response plans (USDOT, 1987; NRT, 1987) and emergency evacuation plans (USEPA/FEMA/USDOT, 1987). It should be noted that through the EIA, project proponents should be encouraged to adopt plant designs which are "inherently safe" (Kletz, 1985), i.e., the inventories of toxic substances should be kept to a minimum (World Bank, 1985), rather than to rely on sophisticated and expensive control equipment and on emergency response procedures.

Guidelines as to how to carry out hazard assessment in the chemical industry have been published by UNEP (1982) and the World Bank (1985) and the International Labor Organization (ILO, 1988). Recently, official guidelines have been published in the USA as to how to perform hazard assessment for releases from chemical plants of what is termed "Extremely Hazardous (airborne) Substances" (EHSs) (NRT, 1987; USEPA/FEMA/USDOT, 1987). The USEPA identified, out of more than 60,000 chemicals used in commerce, a list of about 400 chemicals which are termed EHSs, on the basis of their acute toxicity data (see Table 13). The list of 400 EHSs includes also 24 substances, based on both the criterion of toxicity and on high production capacity (Table 14).

Hazard assessment in the USA involves the three following steps (NRT, 1987): Hazard identification, Vulnerability analysis and Risk analysis. It should be noted that in order to perform a risk assessment for a given plant, the "acceptable risk" (a nonzero probability of a chemical accident to happen, which never-the-less is low enough to be accepted by society) has to be defined (Graber, 1988).

TABLE 13: Criteria to Identify Extremely Hazardous Substances (EHSs) and other Hazardous Substances Produced in Large Quantities (OHSs) that May Present Severe Health Hazards to Humans During a Chemical Accident or Other Emergency (USEPA/FEMA/DOT, 1987)

Route of Exposure (1)	Acute Toxicity Measure (2)	Value	
		EHSs	OHSs
Inhalation	Median Lethal Concentration in Air (LC50)	Less than or equal to 0.5 milligram per liter of air for exposure times of 8 hours or less	Less than or equal to 2.0 milligram per liter of air for exposure times of 8 hours or less
Dermal	Median Lethal Dose (LD50)	Less than or equal to 50 milligram per kilogram of body weight	Less than or equal to 400 milligram per kilogram of body weight
Oral	Median Lethal Dose (LD50)	Less than or equal to 25 milligram per kilogram of body weight	Less than or equal to 200 milligram per kilogram of body weight

Comments:

(1) The route by which the test animals absorbed the chemical, i.e., by breathing it in air (inhalation), by absorbing it through the skin (dermal), or by ingestion (oral).

(2) LC50: The Concentration of the chemical in air at which 50 percent of the test animals died;
LD50: The dose that killed 50 percent of the test animals.
In the absence of LC50 or LD50 data, LCLO or LDLO data should be used.
LCLO: Lethal Concentration Low, the lowest concentration in air at which any test animals died;
LDLO: Lethal Dose Low, the lowest dose at which any test animals died.

TABLE 14: The US Environmental Protection Agency List of Extremely Hazardous Substances (EHSs) produced in large quantities (names, chemical abstracts registration number - CAS #, and United Nations Identification Number - UN #), and their corresponding Levels of Concern (LOC) (USEPA/FEMA/DOT, 1987)

#	Substance Name	CAS #	UN #	LOC (mg/m3)
1	Acrylamide	79-06-1	2074	111
2	Acrylonitrile	107-13-1	1093	111
3	Adiponitrite	111-69-3	2205	17
4	Ammonia	7664-41-7	1005	35
5	Aniline	62-53-3	1547	38
6	Bromine	7726-95-6	1744	6.5
7	Carbon disulfide	75-15-0	1131	160
8	Chlorine	7782-50-5	1017	7.3
9	Chloroform	67-66-3	1888	490
10	Cyclohexylamine	108-91-8	2357	160
11	Epichlorohydrin	106-89-8	2023	38
12	Ethylene oxide	75-21-8	1952	140
13	Formaldehyde	50-00-0	1198/2209	12
14	Hydrogen chloride (gas)	7647-01-0	1050	15
15	Hydrogen peroxide (>52%)	7722-84-1	2015	10
16	Hydrogen sulfide	7783-06-4	1053	42
17	Hydroquinone	123-31-9	2662	20
18	Methyl bromide	74-83-9	1062	780
19	Nitrobenzene	98-95-3	1662	100
20	Phosgene	75-44-5	1076	0.8
21	Propylene oxide	75-56-9	1280	480
22	Sulfur dioxide	7446-09-5	1079	26
23	Tetramethyl lead	75-74-1	1649	4
24	Vinyl acetate monomer	105-05-4	1301	54

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