A COURSE ON MULTIMEDIA ENVIRONMENTAL TRANSPORT, EXPOSURE, AND RISK ASSESSMENT

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The chemical engineering profession is undergoing an era of self-reflection (and evaluation) during which it has become apparent that chemical engineers must strive to design processes geared toward waste minimization (or pollution prevention). It is a long-range goal that must begin with the education of students in the fundamental and emerging concepts of pollution prevention.

In order to appreciate the need for pollution prevention, students must first be educated to understand the potential problems that can occur due to emission of pollutants into the environment. This awareness can, in principle, be introduced through regular course work. Recently, Lane [1] reviewed chemical engineering programs that incorporate health, safety, environmental, and ethical (HSE&E) issues into the curriculum. He concluded that most schools focus on the incorporation of HSE&E into existing courses, with the most popular course being the capstone design course. Such an approach, while attractive, is difficult to implement given the broad nature of environmental issues. As a result, often only a few lectures are devoted to environmental issues, and obviously a fundamental background dealing with environmental issues is not realized. Thus, although the optimal approach is to introduce environmental issues throughout the curriculum, there is still a need to teach fundamental environmental courses that clearly demonstrate that environmental issues are an integral part of the chemical engineer's responsibilities. Moreover, such courses should expose the student to the basics of pollution abatement.

The UCLA chemical engineering department has incorporated environmental issues throughout the undergraduate curriculum with special problems, assignments, and examples. In addition, an elective undergraduate course in the area of "Pollution Prevention" has been established. This course, which is one quarter in length (*i.e.*, ten weeks), is offered to students at the junior and senior level, but it is also suitable as a first-year level graduate course.

COURSE DESCRIPTION

General Guidelines

The course begins with a general discussion of the problems (see Table 1) that are associated with environmental pollution and the need for pollution abatement. The student is then introduced to various major environmental acts (such as the Clean Air Act, Clean Water Act, Resource Conservation Recovery Act, Comprehensive Environmental Response,

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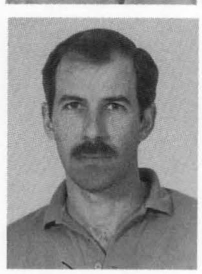

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Compensation, and Liability Act, *etc.*). Examples of health effects due to chronic and acute exposure to toxic chemicals, as well as ecological effects, are studied. This material covers about three lecture hours.

In the second part of the course, examples of emissions are given from various references, including the Toxic Release Inventory [2]. Subsequently, examples that pertain to the prevention of toxic chemical emission to the air, water, and soil media are discussed.

The third part of the course focuses on pollution prevention. The student learns to differentiate between source reduction (or waste minimization) strategies that are designed to prevent the generation of waste as part of the manufacturing process and treatment methods that are often referred to as "end-of-the-pipe" control methods. At least two case studies are reviewed through classroom discussion and homework assignments. The students go through a simple process analysis to discover the areas where simple process modification might be feasible in order to eliminate (or minimize) unnecessary waste streams [3,4]. Although the subject of remediation technologies (*e.g.*, the clean-up of existing disposal and storage sites) is of importance, only two lecture hours are devoted to this subject area. It is important to emphasize that disposal is not an acceptable pollution prevention strategy.

In the fourth part of the course the focus is on the transport of pollutants in the environment, with particular emphasis on the intermedia (or cross-media) transport of contaminants. The objective is to ensure that the student realizes that environmental pollution is a multimedia problem. Various intermedia transport processes that occur in the environment are described (shown in Table 2) in order to emphasize the idea that pollutants which are emitted into one environmental media (e.g., air, water, or soil) will migrate and partition into most other environmental media with which we come in contact. The potential hazards of various pollutants released into the environment will then depend upon the degree of multimedia exposure of human and ecological receptors to the chemicals and their associated risks. Therefore, in order to evaluate potential risks due to the release of various chemicals into the environment, one must be able to describe their probable concentrations in the environment, the exposure of human and ecological receptors to the chemicals, and the associated health and ecological risks.

TABLE 1
Course Outline

	# of Lecture Hours
1. Introduction	
A. Environmental pollution and its impact on our environment	1
B. Major environmental regulations	1
C. Exposure and risk	1
2. Sources	
A. Nature of emissions: gases, liquids, solids, aerosols	2
B. Emission inventories: engineering mass balances at trace concentrations	2
3. Pollution Control	
A. Source reduction	3
B. Treatment technologies	1
C. Disposal of chemical wastes	2
D. Remediation: The penalty for past environmental "crimes"	2
4. Transport of Chemicals Across Environmental Phase Boundaries	
A. Review of major intermedia transport processes (e.g., dry and wet deposition; volatilization from soils and water bodies)	5
B. Dynamic partitioning of chemicals in the multimedia environment: compartmental and spatial models	2
5. Multimedia Exposure	
A. Identification and review of the various exposure pathways	1
B. Estimation of exposure parameters	1
C. Determination of exposure based on multimedia transport information	2
D. Uncertainties in transport and exposure analyses	2
6. Multimedia Risk Analysis	
A. Health risks: chronic versus acute health risks	2
B. Toxicology and risk assessment: laboratory vs. epidemiological studies	1
C. Ecological risks (i.e., non-human health risks)	1
D. Societal risks - discussion	1
E. Uncertainties in risk analysis	1
7. Group Projects	
A. Group project: A multimedia exposure and risk assessment for a given chemical in a specific geographical region	4
B. Project presentations	2

TABLE 2
Summary of Major Intermedia Transport Processes

1. Transport from atmosphere to soil and water
- a. Dry deposition of gaseous and particulate pollutants
- b. Adsorption onto particle matter and subsequent dry and wet deposition
- c. Rain scavenging of gases and particles
- d. Infiltration
- e. Runoff

2. Transport from water to atmosphere, sediment, suspended solids, and biota
- a. Evaporation
- b. Aerosol formation at the air/water interface
- c. Sorption by sediment and suspended solids
- d. Sedimentation and resuspension of solids
- e. Uptake and release by biota

3. Transport from soil to atmosphere, water, sediment, and biota
- a. Volatilization from soil and vegetation
- b. Dissolution in rain water which is associated with infiltration and runoff
- c. Leaching to groundwater
- d. Adsorption on soil particles and transport by runoff or wind erosion
- e. Resuspension of contaminated soil particles by wind
- f. Uptake by biomass such as microorganisms, plants, and animals

The task of predicting the multimedia partitioning of pollutants in the environment is obviously very complex. The distribution of pollutants that are released into the environment is the result of complex physical, chemical, and biological processes. Nonetheless, it is possible to construct relatively simple, yet practical, models [5-7] that will allow the chemical engineering student to explore ideas that encompass the subject area of pollutant partitioning in the multimedia environment. For example, the concept of pollutant transport in the multimedia environment can be illustrated via a simple example such as an oil spill on water with pollutant exchange between the oil, air, and water phases. Subsequently, as described later, a group project is assigned where use is made of more sophisticated models which mimic the complex environmental system. Through such a study, for example, the student can gain an appreciation for the applications of transport phenomena and thermodynamics in the "real world."

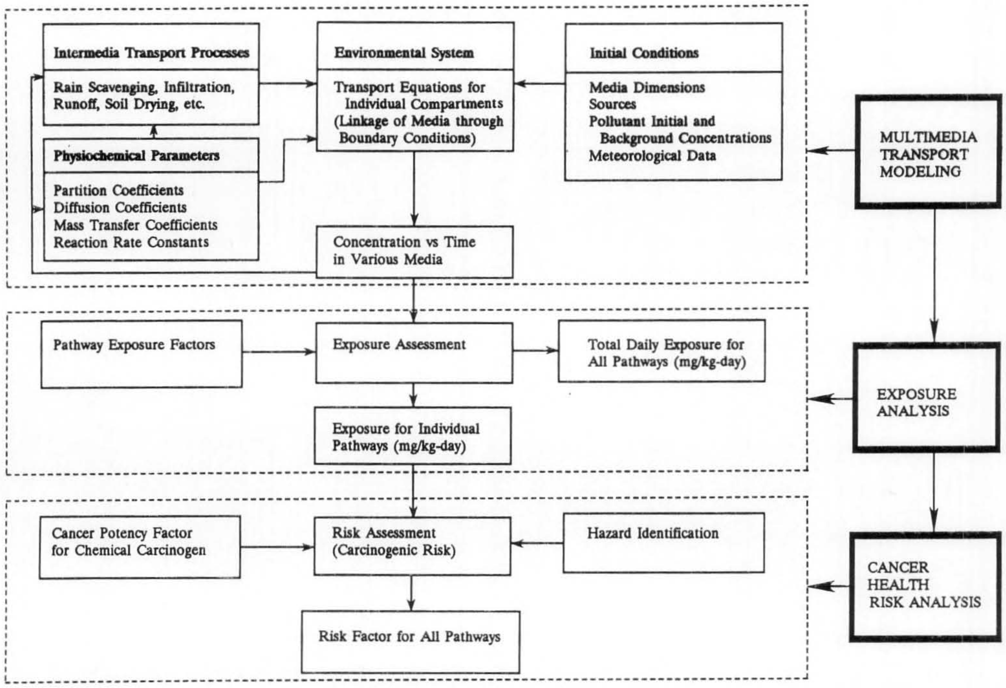

FIGURE 1. Schematic of risk analysis from a multimedia transport modeling approach.

In the fifth part of the course the student is introduced to the concept of exposure assessment due to chronic and acute exposure to chemical contaminants and the connection of risk analysis with the multimedia transport modeling, as illustrated in Figure 1. This part of the course focuses on the integrated multimedia approach to assessing the individual intake of contaminant via a variety of pathways (see Table 3). Given simple exposure scenarios, the students are asked to go through the exercise of calculating human exposure to different chemicals due to chronic exposure [8-10].

Topics four through six of the course, including the group project (Table 1), comprise about seventy percent of the course. This latter material, which is the core of the course, is discussed in the following sections.

Multimedia Exposure and Health Risk

The assessment of risks due to exposure of a receptor (usually a biological receptor) to pollutants is generally determined from appropriate dose-response relations. In order to utilize dose-response relations to predict the expected response of a target receptor, the dose must be determined. The dose, in turn, can be related to the exposure of the receptor to the given agent. The exposure, as discussed below, is a function (among other factors) of the pollutant concentration in various environmental media that affect the receptor either directly or indirectly [8,9,11].

The measure of exposure is the average amount of agent (*i.e.*, chemical contaminant) available per unit time at the exchange boundaries (*i.e.*, lungs, skin, intestinal tract) during a specified period of

TABLE 3
Potential Exposure Pathways to Humans

1. Inhalation
- a. Gases in outdoor and indoor air
- b. Particulates in outdoor and indoor air

2. Ingestion
- a. Drinking water (surface and ground waters)
- b. Fruits, vegetables, and grain
- c. Meat, milk, and dairy products
- d. Fish
- e. Soil

3. Dermal absorption
- a. Immersion in contaminated water such as swimming and showering
- b. Accumulation of contaminated soil and dust on skin

TABLE 4
Suggested References

Introduction

• "Are We Cleaning Up? 10 Superfund Case Studies," A Special Report of OTA's Assessment on Superfund Implementation, Congress of the U.S., Off. of Technology Assessment, Washington, DC, OTA-ITE-362, June (1988)

• "From Pollution to Prevention: A Progress Report on Waste Reduction," Congress of the U.S., Office of Technology Assessment, Washington, DC, OTA-ITE-347, June (1987)

• "New Perspectives on Pollution Control," The Conservation Foundation, Washington, DC (1984)

• "Wastes in the Marine Environment," Congress of the U.S., Office of Technology Assessment, Washington, DC, OTA-O-334 (1987)

Sources

• Macias, E.S., and P.K. Hopke (eds), *Atmospheric Aerosol: Source/Air Quality Relationships,* ACS Symp. Series 167, Am. Chem. Soc., Washington, DC (1981)

• Rogozen, M.B., R.D. Rapoport, and A. Sochet, "Development and Improvement of Organic Compound Emission Inventories for California," prepared under Contract AO-101-32, State of California Air Resource Board, Sacramento, CA (1985)

• Tate, R., P. Ayala, J. Curaan, H. Linnard, C. Nguyen, R. Bradley, and T. McGuire, "Preliminary Inventory: Substances of Special Interest," Technical Support Div., Emission Inventory Branch, Cal. Air Resources Board (1984)

• TRI, the Toxic Release Inventory, US Dept. of Health and Human Services, National Board of Health, Bethesda, MD (1989)

• Weiner, A.M., D.R. Fritz, P.R. Miller, R. Atkinson, D.E. Brown, W.P.L. Carter, M.C. Dodd, C.W. Johnson, M.A. Myers, K.R. Neises, M.P. Poe, and E.R. Stephens, "Investigation of the Role of Natural Hydrocarbons in Photochemical Smog Formation in California," Final Report, prepared under Contract No. AO-056-32 to the California Air Resources Board (1983)

Pollution Control

• Dawson, G.W., and B.W. Mercer, *Hazardous Waste Management,* John Wiley and Sons, New York (1986)

• *Handbook of Industrial Water Conditioning,* BETZ Laboratories, INBC, Trevose, PA 19047 (1980)

• Fawcett, H.H., *Hazardous and Toxic Materials: Safe Handling and Disposal,* John Wiley and Sons, New York (1984)

• *Multimedia Approaches to Pollution Control,* National Academy Press, Washington, DC (1987)

• Novotny, V., and G. Chesters, *Handbook of Nonpoint Pollution: Sources and Management,* Van Nostrand Reinhold, New York (1981)

• Purcell, R.Y., and G.S. Shareef, *Handbook of Control Technologies for Hazardous Air Pollutants,* Hemisphere Publishing Corp., New York (1988)

• Viessman, Jr., W., and M.J. Hammer, *Water Supply and Pollution Control,* Harper & Row Publishers, New York (1985)

• Wentz, C.A., *Hazardous Waste Management,* McGraw-Hill Book Co., New York (1989)

Pollutant Transport

• Cohen, Y., "Intermedia Transport Modeling in Multimedia Systems," in *Pollutants in a Multimedia Environment,* Cohen, Y.(ed), Plenum Press (1986)

• Cohen, Yoram, "Modeling of Pollutant Transport and Accumulation in a Multimedia Environment," in *Geochemical and Hydrologic Processes and Their Protection: The Agenda for Long Term Research and Development,* S. Draggan, J.J. Cohrssen, and R.E. Morrison (eds), Praeger Publishing Co., New York (1987)

• Cohen,Yoram, "Organic Pollutant Transport," *Environ. Sci. Tech.*, **20**, 538 (1986)

• Cohen, Yoram (ed), *Pollutants in a Multimedia Environment,* Plenum Press (1986)

• Cohen, Yoram, D. Mackay, and W.Y. Shiu, "Mass Transfer Rates Between Oil Slicks and Water," *Can. J. Chem. Eng.*, **58**, 569 (1980)

• Cohen, Yoram, H. Taghavi, and P.A. Ryan, "Contaminant Diffusion Under Non-Isothermal Conditions in Nearly Dry Soils," *J. Environ. Quality*, **17**, 198 (1988)

• Draggan, S., J.J. Cohrssen, and R.E. Morrison (eds), *Geochemical and Hydrologic Processes and Their Protection: The Agenda for Long Term Research and Development,* Praeger Publishing Co., New York (1987)

• Friedlander, S.K., *Smoke, Dust and Haze: Fundamentals of Aerosol Behavior,* John Wiley and Sons, New York (1977)

• Mackay, D., and S. Paterson, "Calculating Fugacity," *Environ. Sci. Tech.*, **15**, 106 (1981)

• Mackay, D., and S. Paterson, "The Fugacity Approach to Multimedia Environmental Modeling," in *Pollutants in a Multimedia Environment,* Cohen, Y. (ed), Plenum Press, New York (1986)

• Mackay, D., S. Paterson, B. Cheung, and W.B. Neely, "Evaluating the Environmental Behavior of Chemicals with a Level III Fugacity Model," *Chemosphere,* **14**, 335 (1985)

• Ryan, P.A., and Yoram Cohen, "Multiphase Chemical Transport in Soils," in *Intermedia Pollutant Transport: Modeling and Field Measurements,* D.T. Allen, I.R. Kaplan, and Y. Cohen (eds), Plenum Press, in press (1989)

• Swann, R.L., and A. Eschenroeder, "Fate of Chemicals in the Environment," ACS Symp. Series 225, Am. Chem. Soc., Washington, DC (1983)

• Thibodeaux, L.J., *Chemodynamics: Environmental Movement of Chemicals in Air, Water, and Soil,* John Wiley and Sons, New York (1970)

• Travis, C.C., J.W. Dennison, and A.D. Arms, "The Nature and Extent of Multimedia Partitioning of Chemicals," unpublished report, Health and Safety Research Div., Oak Ridge Nat. Lab., Oak Ridge, TN (1987)

Multimedia Exposure

• Kenaga, G.E., and C.A.I. Goring, "Relationship Between Water Solubility, Soil Sorption, Octanol-Water Partitioning and Concentration of Chemicals in Biota," *Aquatic Toxicology,* ASTM Stp 707, 78 (1980)

• McKone, T.E., and P.B. Ryan, "Human Exposure to Chemical Through Food Chains: An Uncertainty Analysis," *Environ. Sci. Tech.*, **23**, 1154 (1989)

•Ott, W.R., "Total Human Exposure," *Environ. Sci. Tech.*, **19**, 880 (1985)

• Travis, C.C., and A.D. Arms, "The Food Chain as a Source of Toxic Chemical Exposure," in *Toxic Chemicals, Health and the Environment,* L.B. Lave, A.C. Upton (eds), The John Hopkins U. Press, Baltimore, MD, 5, 95 (1987)

• United States Environmental Protection Agency, "Guidelines for Estimating Exposures," *Fed. Register,* **51**, 34092 (1988)

• Vaughan, B.E., "State of Research: Environmental Pathways and Food Chain Transfer," *Environ. Health Perspect.*, **54**, 353 (1984)

• Wallace, L.A., The Total Exposure Assessment Methodology (TEAM) Study: Project Summary, U.S. Environmental Protection Agency., Washington, DC, EPA/600/S6-87/002 (1987)

• Wallace, L., E. Pellizari, L. Sheldon, T. Harwell, C. Sparacino, and H. Zelon, "The Total Exposure Assessment Methodology (TEAM) Study: Direct Measurements of Personal Exposure Through Air and Water for 600 Residents of Several U.S. Cities," in *Pollution in a Multimedia Environment,* Y. Cohen (ed), Plenum Press, New York (1986)

Multimedia Risk Analysis

• Bolten, J.G., P.F. Morrison, K.A. Solomon, and K. Wolf, "Alternative Models for Risk Assessment of Toxic Emissions," Report N-2261-EPRI, The Rand Publication Series, Rand, Santa Monica, CA, April (1983)

• Bolten, J.G., P.F. Morrison, and K.A. Solomon, "Risk-Cost Assessment Methodology for Toxic Pollutants from Fossil Fuel Power Plants," Report R-2993-EPRI, The Rand Pub. Ser., Rand, Santa Monica, CA, June (1983)

• Conway, R.A. (ed), *Environmental Risk Analysis for Chemicals,* Van Norstrand Reinhold Co., New York (1982)

• Cothern, R., W.A. Coniglio, and W.L. Marcus, "Estimating Risk to Human Health," *Environ. Sci. Tech.*, **20**, 111 (1986)

• Dydek, T., "Comparison of Health Risk Assessment Approach for Carcinogenic Air Pollutants," paper no. 89-56.10, presented at 82nd Annual Meeting and Exhibition, Anaheim, CA, June (1989)

• McKone, T.E., and D.W. Layton, "Screening the Potential Risks of Toxic Substances Using a Multimedia Compartment Model, Estimation of Human Exposure," *Regulatory Toxicology and Pharmacology,* **6**, 359 (1986)

• McKone, T.E., and W.E. Kastenberg, "Applications of Multimedia Pollutant Transport Models to Risk Analysis," in *Pollutants in a Multimedia Environment,* Y. Cohen (ed), Plenum Press, New York (1986)

• Travis, C.C., and A.D. Arms, "Bioconcentration of Organics in Beef, Milk, and Vegetation," *Environ. Sci. Tech.*, **22,** 271 (1988)

• U.S. Environmental Protection Agency, "Guidelines for Carcinogen Risk Assessment," 51 Federal Register 33992, September 24 (1986)

Group Projects

• Cohen, Yoram, W. Tsai, and S. Chetty, *The SMCM Software (3.0) User's Manual,* the Regents of the University of California, Los Angeles, CA (1989)

time. The exposure via a specific pathway, during a time interval t, can be defined by the following expression:

$$E_i = \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} I_i(t)dt \qquad (1)$$

in which I_i is the intake rate (or intensity of contact) of the given agent by the receptor. The intake rate I_i is expressed by

$$I_i = L_i C_i \qquad (2)$$

TABLE 5
Features of the SMCM Model

1. The SMCM is a user-friendly software package that...
a. Can be used to answer "what if" type questions
b. Allows for rapid scenario changes
c. Minimizes data input
d. Provides a graphical output display for quick scenario analysis
e. Provides specific online help for input data fields
f. Provides a menu system for user selection of data input, simulation execution, plotting, and printing a summary report of the calculated results
g. Allows the software to be run on IBM-PC/XT/AT compatible computers
h. Allows an inexperienced user to run the SMCM software with virtually no background in transport phenomena.

2. The SMCM model applies a new modeling approach that...
a. Makes use of both uniform (air, water, biota, suspended solid) and non-uniform compartments (soil and sediment)
b. Allows for mass exchange of pollutant between the air compartment and its surrounding atmospheric environment. The water compartment is also treated in a similar way.
c. Treats non-uniform compartments as an unsteady state, one-dimensional diffusion type equation with convection and chemical reaction
d. Incorporates the simulation of a chemical buried in the soil compartment
e. Considers a variety of source types and allows the user to select and input source data through the data input screens
f. Applies flux boundary conditions for non-uniform compartments. Although groundwater is not treated as a compartment in the SMCM model, flux condition at the bottom boundary of the soil compartment can be incorporated to account for the chemical transport to groundwater.

3. The SMCM model accounts for the effects of rainfall and temperature on the environmental transport of pollutants.
a. The SMCM has a rain generation module which can generate rainfall in the form of a single event of specified intensity and duration, or randomly distribute rainfall within specified levels of rainfall intensity, duration, and total rainfall.
b. The transport processes associated with rainfall, such as rain scavenging, infiltration, runoff, and soil drying, are simulated by a water balance method which uses theoretically based correlations.
c. User-supplied average monthly temperatures are used to construct average daily temperatures.

4. Provides accurate and reliable parameter estimation methods
a. Physicochemical parameters such as mass transfer coefficient, diffusion coefficient, and partition coefficient are estimated using theoretical methods and empirical correlations. The user can input partition coefficients and diffusion coefficients if known. These will override any model-estimated values.
b. Temperature variations of diffusivities, partition coefficients, mass transfer coefficients, and reaction rate constants are included by either internal predictions or via user-input data.
c. Production or degradation rates are treated as first order reactions.

in which C_i is the concentration of the agent in environmental compartment i in contact with the receptor, and L_i is the extent of contact (*e.g.*, inhalation rate is given as volume of air/unit time/body weight). The extent of contact, L_i, is obviously characteristic of the behavior of the receptor (*i.e.*, its dynamics in the environment). For example, exposure that occurs through inhalation is a function of the time that the individual spends at various locations (indoors and outdoors) and the rate of inhalation, L_i, at each location. Such information can be obtained, for example, from population activity pattern studies [11,12]. The concentration C_i in compartment i can be determined from either monitoring studies or from appropriate transport and fate models. In the simplest approximation, once the exposure is known, the dose can be related to exposure by the following relationship:

$$D_i = E_i F_i \qquad (3)$$

in which F_i is an absorption factor associated with the absorption of the contaminant by the receptor

TABLE 6
Physicochemical Properties of TCE

Property	Value	Ref.
Molecular weights	131.4	[17]
Henry's law constant	1179 Pa-m^3/mol	[18]
Solubility	1103.8 mg/L	[18]
Boiling temperature	360.25 K	[17]
Molal volume	89.9 cm^3/mol	[17]
Reaction rate constants		
Air	0.01 hr^{-1}	[19]
Water	1.24 x 10^{-4} hr^{-1}	[19]
Soil	0	
Sediment	0	
Biota	0	
Suspended solids	0	
Diffusion coefficients		
Air	2.89 x 10^{-2} m^2/hr	*
Water	3.43 x 10^{-6} m^2/hr	*
Soil	9.07 x 10^{-4} m^2/hr	*
Sediment	3.59 x 10^{-7} m^2/hr	*
Partition coefficients		
Octanol/water, K_{ow}	214.6	[19]
Air/water	4.87	*
Air/soil	1.43	*
Water/sediment	0.28	*
Water/biota	0.10	*
Water/suspended solids	0.18`	*
Mass transfer coefficients		
Air/water	0.14 m/hr	*
Air/soil	0.07 m/hr	*
Water/sediment	7.0 x 10^{-4} m/hr	*
Biota/water	0.10 hr^{-1}	*
Water/suspended solids	0.73 m/hr	*

** Calculated by the SMCM model (at the first step of model integration) using theoretical methods and empirical correlations. The temperature variations of diffusivities, partition, and mass transfer coefficients are taken into account.*

attributed to exposure pathway i. Detailed evaluation of the absorption factor requires either experimental data or prediction using appropriate pharmacokinetic models.

The exposure of the population to various pollutants can occur via three major exposure routes: inhalation, dermal absorption, and ingestion. The ingestion pathway refers to the consumption of both food and drinking water and other liquids. The intake of contaminants via food consumption is particularly significant since contaminants may accumulate in the food chain [10,13,14]. Thus, exposure can be strongly affected by multimedia transfers.

Multimedia health risk analysis is covered in the sixth part of the course. For example, the risk associated with chronic exposure to chemical carcinogens can be estimated using cancer potency factors [15] which relate the average daily intake per unit body mass to the risk of developing cancer as defined below:

$$R_{ij} = 1.0 - \exp\left(-\dot{D}_{ij} q_i\right) \tag{4}$$

where R_{ij} is the health risk for exposure to chemical carcinogen i for exposure pathway j (dimensionless), $\dot{D}_{ij}$ is the average daily intake (or dose) rate of chemical carcinogen i [mg/kg·day] and q_i is the corresponding cancer potency factor [(mg/kg·day)$^{-1}$]. In contrast to carcinogens, the risk associated with noncarcinogens is difficult to quantify. However, the regulatory approach to establishing guidelines such as with the reference dose (Rfd) method are discussed in the sixth part of the course (see Table 1). The concepts of multimedia pollutant transport, exposure, and risk analyses are covered through the lectures and a group project as described below. Materials from pertinent literature sources are utilized as listed in the sample of suggested references (Table 4).

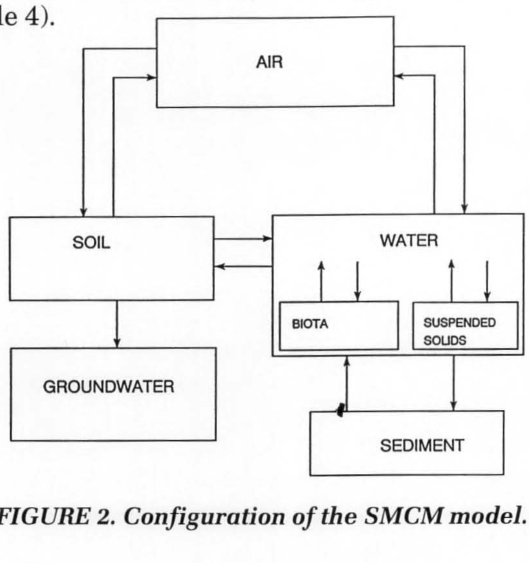

FIGURE 2. Configuration of the SMCM model.

The group project is designed to illustrate the concepts of pollutant partitioning in the environment, the subsequent chronic exposure of human receptors, and the potential risk as well as the uncertainties associated with such estimates of health risks.

Group Project

The group project is designed to illustrate the concepts of pollutant partitioning in the environment, the subsequent chronic exposure of human receptors, and the potential risk as well as the uncertainties associated with such estimates of health risks. Groups of two or three students (depending on the size of the class) are assigned a particular chemical and must estimate exposure and risk to an individual within a given environmental region (a particular geographical location or a fictitious region). The group projects are assigned once the topic of multimedia transport has been covered (see Table 1).

In order to determine the multimedia distribution of the chemical given estimated emissions, the students utilize the Spatial-Multimedia-Compartmental (SMCM) pollutant transport and fate model. The SMCM model [16] was developed at UCLA through the sponsorship of the UCLA/EPA National Center for Intermedia Transport Research. The SMCM software is user-friendly and runs on IBM PC/XT/AT compatible computers. The SMCM model was designed to allow the student to get a better understanding of pollutant distribution in the environment without the need to develop special computer-related skills or even knowledge in transport phenomena or thermodynamics. The student is required, however, to obtain some basic physicochemical and thermodynamic information for the chemical that is assigned, as well as information regarding the climate, size, and simple meteorological information for the region of interest.

The various environmental compartments included in the SMCM model are shown in Figure 2. The student can simulate various scenarios for source emissions, rain events, and temperature variations in the region as described in Table 5. This introduces the student to the concept of pollutant movement across environmental phase boundaries and, thus, the role of mass transfer in the natural environment. Also, the concept of equilibrium partitioning and local equilibrium calculation assumptions are introduced. Once pollutant concentrations are obtained, the students utilize a simple procedure to determine the average daily exposure of an average adult to the given chemical for a prescribed period (usually a lifetime period of about seventy years). The latter part of the analysis relies on recommended EPA values for human intake of beef, milk, vegetables, etc., inhalation, water consumption, and other activities such as swimming that may lead to exposure to chemical contaminants.

Example of a Group Case Study

An example of a potential group project is the analysis of the steady state partitioning of trichloroethylene (TCE) in the Los Angeles area and the determination of the resulting exposure and health risks. The pertinent physicochemical properties for TCE and the appropriate compartmental data for Los Angeles are shown in Tables 6 and 7, respectively. The results of an analysis for the multimedia partitioning of TCE in Los Angeles are shown in Table 8. Given the predicted TCE concentrations in different media, and with the estimates of various partition coefficients and pathway exposure factors [10] between beef, milk, vegetables, *etc.*, the average daily exposure for all pathways over a seventy-year lifetime was calculated to be 1.00×10^{-4} mg/kg·day (Table 9). Moreover, using the appropriate cancer potency factors for TCE (0.011 $\{mg/kg \cdot day\}^{-1}$ for oral intake, and 0.0046 $\{mg/kg \cdot day\}^{-1}$ for inhalation intake) [15], the associated lifetime cancer health risk for chronic exposure was found to be 7.47×10^{-7}. The health risk is interpreted as the probability of cancer occurring over the lifetime of the individual due to exposure to TCE. Alternatively, one can view this health risk as implying that 7.47 cancer cases are to be expected for a population of 1.0×10^{7}. Thus, by comparing results for different chemicals, the students can determine the difference in the potential exposures and health risks associated with the release of toxic chemicals to the environment.

CONCLUSIONS

Chemical engineering students must be made aware of their responsibilities as engineers to design processes that will operate safely and with minimal environmental impact. The course described in this article should allow the student to gain a scientific appreciation for the magnitude and source of potential environmental health risks. Through such a course, the student also learns that the various chemical engineering fundamentals provide a solid foundation for covering topics such as environmental transport and exposure and risk analysis, as well as pollution control.

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TABLE 7
Compartmental Data for Los Angeles‡

Parameter	*Value*
1. Air	
Air viscosity	1.78×10^{-5} Pa-s
Wind velocity	270 cm
Mixing height	400 m
Pressure	1 atm
Source strength of pollutant†	92.4 mol/hr
2. Water	
Depth	4.9 m
Air/water interfacial area	5.27×10^{7} m^2
Temperature	12.6° C
Flow rate	0 m^3/hr
Source strength	0.9 mol/hr
3. Soil	
Depth	8 m
Density	1.5×10^{6} g/m^3
Air/soil interfacial area	1.04×10^{10} m^2
Organic carbon fraction	0.04
Source strength	0 mol/hr
Type of soil	Nickel gravelly sand loam*
4. Sediment	
Depth	1 m
Density	1.5×10^{6} g/m^3
Sediment/water interfacial area	4.94×10^{7} m^2
Organic carbon fraction	0.04
Source strength	0 mol/hr
5. Suspended solids	
Density	1.5×10^{6} g/m^3
Organic carbon fraction	0.04
Average diameter	0.001 cm
Suspended solids/water interfacial area	7.75×10^{6} m^2
Suspended solids vol/water volume %	5×10^{-4}
6. Biota	
Biota volume/water volume %	5×10^{-5}

‡ *Without rainfall*

† *In this simulation, the source strengths of pollutant in air, water, soil and sediment compartments are assumed to be non-repetitious constant sources. However, other types of source such as non-repetitious sinusoidal, constant repetitious, and sinusoidal repetitious sources are also provided for the air and water compartments in the SMCM model.*

* *This type of soil corresponds to average conditions in the soil of 34% air content, 8% water content, and 58% occupied by soil solids.*

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REFERENCES

1. Lane, A.M., "Incorporating Health, Safety, Environmental, and Ethical Issues into the Curriculum," Chem. Eng. Ed., 23, 70 (1989)
2. TRI, the Toxic Release Inventory, U.S. Dept. of Health and Human Services, National Inst. of Health., Bethesda, MD (1989)
3. Purcell, R.Y., and G.S. Shareef, Handbook of Control Technologies for Hazardous Air Pollutants, Hemisphere Publishing Corp., New York (1988)
4. Wentz, C.A., Hazardous Waste Management, McGraw-Hill Book Co., New York (1989)
5. Cohen, Yoram, "Intermedia Transport Modeling in Multimedia Systems," in Pollutants in a Multimedia Environment, Cohen, Y. (editor), Plenum Press (1986)
6. Cohen, Yoram (editor), Pollutants in a Multimedia Environment," Plenum Press (1986)
7. Cohen, Yoram, "Organic Pollutant Transport," Environ. Sci. Tech., 20 538 (1986)
8. McKone, T.E., and D.W. Layton, "Screening the Potential Risks of Toxic Substances Using a Multimedia Compartment Model: Estimation of Human Exposure," Regulatory Toxicology and Pharmacology, 6, 359 (1986)
9. McKone, T.E., and W.E. Kastenberg, "Applications of Multimedia Pollutant Transport Models to Risk Analysis," in Pollutants in a Multimedia Environment, Cohen, Y. (editor), Plenum Press, New York (1986)
10. McKone, T.E., and P.B. Ryan, "Human Exposure to Chemical Through Food Chains: An Uncertainty Analysis," UCRL-99290, preprint, Lawrence Livermore Nat. Lab., submitted to Environ. Sci. Tech. (1989)
11. Ott, W.R., "Total Human Exposure," Environ. Sci. Tech., 19, 880 (1985)
12. Wallace, L., E. Pellizari, L. Sheldon, T. Harwell, C. Sparacino, and H. Zelon, "The Total Exposure Assessment Methodology (TEAM) Study: Direct Measurements of Personal Exposures Through Air and Water for 600 Residents of Several U.S. Cities," in Pollution in a Multimedia Environment," Cohen, Y. (editor), Plenum Press, New York (1986)
13. Travis, C.C., and A.D. Arms, "Bioconcentration of Organics in Beef, Milk, and Vegetation" Environ. Sci. Tech., 22, 271 (1988)
14. Vaughan, B.E., "State of Research: Environmental Pathways and Food Chain Transfer," Environ. Health Perspect., 54, 353 (1984)
15. EPA, Superfund Public Health Evaluation Manual, U.S. Environ. Protection Agency, Washington, DC, EPA/540/1-86-060 (1986)
16. Cohen, Yoram, W. Tsai, and S. Chetty, *The SMCM Software (3.0) User's Manual,* the Regents of the Univ. of California, Los Angeles, CA (1989)
17. Perry, R.H., D.W. Green, and J.O. Maloney, Perry's Chemical Engineers' Handbook, 6th ed., McGraw-Hill Book Co., New York (1984)
18. Dilling,, W.L., N.B. Tefertiller, and G.J. Kallos, "Evaporation Rates and Reactivities of Methylene Chloride, Chloroform, 1,1,1-Trichloroethane, Trichloroethylene, Tetrachloroethylene, and Other Chlorinated Compounds in Dilute Aqueous Solutions," Environ. Sci. Tech., 9, 833 (1975)
19. Cohen, Yoram, and P.A. Ryan, "Multimedia Modeling of Environmental Transport: Trichloroethylene Test Case," Environ. Sci. Tech., 19, 412 (1985) ❐

TABLE 8
Results of Multimedia Partitioning of TCE in Los Angeles

Compartment	Predicted Concentrations $[gmol/m^3](\times 10^8)$	Predicted Concentrations in Other Units	% Chemical in Compartment*	Monitored Concentration†
Air	0.2	0.2 ($\mu g/m^3$)	97.10	0.1 ($\mu g/m^3$)
Water	21.2	0.03 ($\mu g/L$)	0.73	0.08 ($\mu g/L$)
Soil	0.8	0.72 (ng/kg)	2.16	- - -
Sediment	18.0	15.8 (ng/kg)	9.03×10^{-3}	- - -
Biota	218.0	287.0 (ng/kg)	3.74×10^{-6}	- - -
Suspended Solids	116.0	102.0 (ng/kg)	1.99×10^{-5}	- - -

** Predicted total amount of trichloroethylene (gmols) in the multimedia system is 7.5×10^3 at the simulation time 1000 hrs: the simulation started from February 1, 1984.*
† The reported environmental concentrations are average values [12].

TABLE 9
Predicted Average Daily Exposure and Cancer Health Risk for Chronic Exposure to Trichloroethylene in Los Angeles

Exposure Pathway	*Dose Rate* (mg/kg.day)*	*Risk†*
Drinking water	6.15×10^{-7}	6.76×10^{-9}
Ingestion of meat	1.04×10^{-5}	1.15×10^{-7}
Ingestion of milk	6.34×10^{-6}	6.97×10^{-8}
Ingestion of vegetable	2.26×10^{-10}	2.49×10^{-12}
Ingestion of root vegetable	2.72×10^{-5}	2.99×10^{-7}
Ingestion of fish	2.06×10^{-8}	2.26×10^{-10}
Ingestion of soil	4.59×10^{-13}	5.05×10^{-15}
Inhalation of air	5.57×10^{-5}	2.56×10^{-7}
Dermal adsorption of water via showering	1.43×10^{-9}	1.58×10^{-11}
Dermal adsorption of water via swimming	2.92×10^{-10}	3.21×10^{-12}
Dermal absorption of soil	4.01×10^{-14}	4.42×10^{-16}

** Total avg. daily intake for all pathways over 70 years is 1.00×10^{-4} mg/kg.day.*
† Lifetime risk for adult (all pathways combined) is 7.47×10^{-7}. Also note that the above calculations for cancer health risk is based on carcinogenic potency factors of 0.011 $[(mg/kg.day)^{-1}]$ for oral intake, and 0.0046 $[(mg/kg.day)^{-1}]$ for inhalation intake [15].