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Environmental Risk Analysis for Oil from Shale

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Environmental Sciences Division
Publication No. 2605

ENVIRONMENTAL SCIENCES DIVISION
OAK RIDGE NATIONAL LABORATORY

ORNL ESD
ECOLOGICAL RISK ANALYSIS

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SUMMARY

The Environmental Sciences Division, Oak Ridge National Laboratory, is analyzing the potential environmental risks associated with commercial-scale synthetic liquid fuels technologies. The overall objective of the environmental risk analysis project, which is funded by the Office of Research and Development, U.S. Environmental Protection Agency, is to guide research on environmental aspects of synfuel technologies by identifying the most hazardous synfuel-derived contaminants and the most important sources of scientific uncertainty concerning the fate and effects of these contaminants.

The general strategy adopted for the project involves (1) grouping the contaminants present in effluents and products of commercial-scale processes into 38 categories termed risk analysis units (RACs); (2) defining generalized reference environments with characteristics representative of regions in which synfuels plants may be sited, and (3) assessing risks of five distinct, adverse ecological effects: reductions in fish populations, development of algal blooms that detract from water use, reductions in timber yield or undesirable changes in forest composition, reductions in agricultural production, and reductions in wildlife populations.

This report presents results of a risk analysis of the Paraho and TOSCO-II oil shale technologies. The source terms were estimated for commercial-scale operations producing 7.9 and 7.6 x 10^6 L/d of syncrude for Paraho and TOSCO-II, respectively. Because of Colorado State regulations, the plants were assumed to have no direct aqueous discharges. All wastewaters were assumed to be used to wet the spent shale, which is landfilled with other solid wastes. The chemical composition of the leachate from this mixture and its transport to ground and surface water were estimated. Atmospheric emissions were dispersed by a Gaussian-plume model, deposited on the landscape, and accumulated in the soil. The analyses, results, and conclusions of this research are intended to be generic and are not estimates of actual impacts of specific plants at specific sites.

The leachate was less dilute in the creek water than in the nearest well. Creek water contained several RACs in concentrations

that exceeded a hundredth of measured toxic concentrations for fish, algae, livestock, wildlife, or irrigated crops. They are benzene, mono/diaromatic hydrocarbons, polycyclic aromatic hydrocarbons, alkaline N heterocyclics, neutral N, O, or S heterocyclics, carboxylic acids, phenolics, nickel, cadmium, and total dissolved solids. All of these categories deserve additional attention in future research and assessments; however, total dissolved solids (TDS) is the category that appears most likely to cause environmental problems because its incremental concentration is quite high (290 mg/L) relative to potentially toxic levels, and because the leachate will enter the Colorado River system where TDS is already a problem for both agriculture and aquatic life.

Of the atmospheric emissions, only SO_2 and NO_2 had predicted concentrations in air that were within a factor of 100 of thresholds for effects on growth or yield of flowering plants. Although these gases are unlikely to reduce crop or range yield at the predicted concentrations, site-specific assessments should consider the effects of rough terrain and background pollution levels on concentrations of these gases. Arsenic was predicted to accumulate in soil to concentrations that were greater than a tenth of those that are reported to reduce plant growth. Future assessments should consider the speciation of the emitted arsenic, transformations in the soil, and background concentrations of toxic trace elements in the soil.

None of the RACs appear to pose a significant threat to wildlife due to inhalation. However, the available data on inhalation toxicology is almost entirely derived from mammals and other taxa, particularly birds that may be considerably more sensitive.

Although they are not considered in this analysis, it appears that construction, mining, and waste disposal are more likely to reduce the productivity of plants and animals than are the emissions from shale processing. Major sources of uncertainty include the composition and transport of leachate from the mixed solid waste and wastewater, effects of accumulation of chemicals in wildlife food chains, effects on nonmammalian wildlife, and effects of terrain on air pollutant concentrations.

ABSTRACT

SUTER, G. W., II, L. W. BARNTHOUSE, S. R. KRAEMER, M. E. GRISMER, D. S. DURNFORD, D. B. McWORTER, F. R. O'DONNELL, C. F. BAES III, and A. E. ROSEN. 1985. Environmental risk analysis for oil from shale. ORNL/TM-9808. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 130 pp.

This report presents the results of an ecological risk analysis of emissions from two oil shale technologies, Paraho and TOSCO-II. Because both technologies have no aqueous discharges, only waste leachates and air pollutants are considered. The formation of leachate from wastewater-moistened spent shale and the transport of the leachate to the nearest well and creek were modeled. The contaminated creek water did not contain any individual components that are expected to cause toxic effects on fish, livestock, wildlife, or irrigated crops. However, some of the components occur in high enough concentrations to raise concern and justify further research and assessment. Total dissolved solids appear to be the most significant problem in general. Sulfur oxides and nitrogen oxides in air and arsenic in soil are predicted to occur at concentrations that would be near those that cause reductions in plant growth. Interactions with background pollution, locally elevated concentrations because of terrain effects and other factors not included in this analysis might result in reduced plant yield. The most serious respiratory toxicants appear to be sulfur oxides, nitrogen oxides, and respirable particles. These do not seem likely to affect mammalian wildlife populations, but effects on other wildlife taxa are unknown.

1. INTRODUCTION

Environmental risk analysis is the process of identifying and quantifying probabilities of adverse changes in the environment resulting from human activities. This includes explicit incorporation and, to the extent possible, quantification of scientific uncertainties regarding the adverse effects being considered. The Environmental Sciences Division, Oak Ridge National Laboratory, has been developing and demonstrating methods for environmental risk analysis for the Office of Research and Development, U.S. Environmental Protection Agency. The methods being used in this project were described by Barnthouse et al. (1982). Although the concept of risk is applicable to many types of environmental problems, this project is focusing on risks associated with toxic environmental contaminants derived from synthetic liquid fuels technologies. The overall objective of the project is to guide research on environmental aspects of synfuel technologies by identifying the most hazardous contaminants (or classes of contaminants) and the most important sources of scientific uncertainty concerning the fate and effects of contaminants. The analyses, results, and conclusions of this research are intended to be generic and are not estimates of actual impacts of specific plants at specific sites.

For purposes of risk analysis, the thousands of potentially significant contaminants in waste streams and products of synthetic liquid fuels technologies have been grouped into the 38 categories, termed risk analysis categories (RACs), listed in Table 1.1. Five ecological end points are used: (1) reductions in fish populations, (2) development of algal populations that detract from water use, (3) reductions in timber yield or undesirable changes in forest composition, (4) reductions in agricultural production, and (5) reductions in wildlife populations. Rather than descriptions of specific sites, the risk analyses use generalized reference environments, with characteristics representative of regions in which synfuels plants may be sited. Two reference environments are being

Table 1.1. Risk analysis categories (RACs)

RAC No.	Category	Description
1	Carbon monoxide	CO
2	Sulfur oxides	SO_x
3	Nitrogen oxides	NO_x
4	Acid gases	H_2S, HCN
5	Alkaline gases	NH_3
6	Hydrocarbon gases	C_1-C_4 alkanes, alkynes and cyclo compounds; bp < ~20°C
7	Formaldehyde	HCHO
8	Volatile organochlorines	To bp ~120°C; CH_2CL_2, $CHCL_3$, CCl_4
9	Volatile carboxylic acids	To bp ~120°C; Formic and acetic acids only
10	Volatile O&S heterocyclics	To bp ~120°C; Furan, THF, thiophene
11	Volatile N-heterocyclics	To bp ~120°C; pyridine, piperidine, pyrrolidine, alkyl pyridines
12	Benzene	Benzene
13	Aliphatic/alicyclic	C_5 (bp ~ 40°C) and greater; paraffins, olefins, cyclocompounds, terpenoids, waxes, hydroaromatics
14	Mono/Diaromatic hydrocarbons (excluding benzene)	Toluene, xylenes, naphthalenes, biphenyls, alkyl derivatives
15	Polycyclic aromatic hydrocarbons	Three rings and greater; anthracene, BaA, BaP, alkyl derivatives
16	Aliphatic amines (excluding N-heterocyclics)	Primary, secondary and tertiary nonheterocyclic nitrogen, $MeNH_2$, DiMeNH, TriMeN
17	Aromatic amines (excluding N-heterocyclics)	Anilines, napthylamines, amino pyrenes; nonheterocyclic nitrogen
18	Alkaline nitrogen heterocyclics ["azaarenes"] (excluding "volatiles")	Quinolines, acridines, benzacridine; excluding pyridines
19	Neutral N, O, S heterocyclics (excluding "volatiles")	Indoles, carbazoles, benzofurans, dibenzothiophenes
20	Carboxylic acids (excluding "volatiles")	Butyric, benzoic, phthalic, stearic
21	Phenols	Phenol, cresols, catechol, resorcinol
22	Aldehydes and ketones ("carbonyls") (excluding formaldehyde)	Acetaldehyde, acrolein, acetone, thiophenols, CS_2
23	Nonheterocyclic organosulfur	Mercaptans, sulfides, disulfides,
24	Alcohols	thiophenols, CS_2
25	Nitroaromatics	Methanol, ethanol
26	Esters	Nitrobenzenes, nitropyrenes
27	Amides	Acetates, phthalates, formates
28	Nitriles	Acetamide, formamide, benzamides
29	Tars	Acrylonitrile, acetonitrile
30	Respirable particles	
31	Arsenic	
32	Mercury	As, all forms
33	Nickel	Hg, all forms
34	Cadmium	Ni, all forms
35	Lead	Cd, all forms
36	Other trace elements	Pb, all forms
37	Radioactive materials	
38	Other remaining materials	^{226}Ra

used in the research for EPA: an eastern environment resembling eastern Kentucky or West Virginia (for coal liquefaction), and a western environment resembling the western slope of the Rocky Mountains in northern Colorado or southern Wyoming. Descriptions of the meteorology, hydrology, demography, land-use patterns, and biota of these two reference environments have been developed by Travis et al. (1983).

This report analyzes risks associated with two oil shale technologies: TOSCO II and Paraho. The analyses assumed commercial-scale facilities, with identical feed shale capacities and similar environmental control technologies, sited in the western reference environment. The objectives of the risk analyses were:

1. to identify the RACs of greatest concern for each technology,
2. to compare, as far as possible, the risk associated with different technologies;
3. to relate the risks of the oil shale technologies to the ecological end points described above; and
4. to compare the magnitudes of uncertainty concerning risks of different RACs and different components of risk for each RAC.

The analysis does not include habitat loss resulting from physical disturbances such as mining and waste disposal, because these are not within the purview of this project.

2. SOURCE TERMS AND EXPOSURE

This section presents (1) a description of the source terms for two commercial-scale oil shale plants and (2) estimates of exposure concentrations for terrestrial biota near a hypothetical plant site with environmental characteristics that generally correspond to those of the proposed sites for oil shale facilities in western Colorado.

2.1 SOURCE TERMS

Under a subcontract with Oak Ridge National Laboratory, TRW, Inc. (TRW) described commercial-scale plant configurations for two oil shale processes: Paraho and TOSCO-II (TRW 1983). The plant configurations evaluated by TRW were adapted from design information provided by the developers of the technologies. The source term estimates developed by TRW were based largely on published process conceptual designs and test data obtained from bench-scale, pilot, or demonstration units. Control technology efficiencies were extrapolated from similar applications in other industries.

The plant configurations reflect base plant capacities of 7.9 and 7.5×10^6 L/d of syncrude for Paraho and TOSCO-II, respectively. TRW estimated quantities and compositions of all uncontrolled and controlled waste streams, expressed in terms of risk analysis units (RACs, Sect. 1). Because of the large number of atmospheric effluent sources associated with each technology, the atmospheric source terms are not presented in this report. They can be found in Tables 2-7 and 3-4 of TRW (1983). No aqueous source terms were presented because both plants were assumed to have no direct surface water discharge in compliance with Colorado State Law. Treated wastewaters were assumed to be used to wet the spent shale, which will be landfilled in a mixture with other solid wastes. Data on the composition of treated wastewater and of leachate from spent shale, along with climatic parameters and an assumed waste pile morphology, were used to estimate leachate volume and composition. These assumptions, models, and results are presented in the next section.

2.2 GROUNDWATER EXPOSURE ASSESSMENT

The exposure assessment has two major objectives:(1) to characterize the composition of leachate leaving a hypothetical disposal area, and (2) to estimate contaminant peak concentrations at discharge points of concern. A water balance at a conceptual reference pile gives an estimate of the long-term average annual production of leachate resulting from rainwater infiltration. The annual rate of production of various chemical species is estimated based on the range of concentrations reported in the literature in combination with the volume of water generated by the water balance. A soil compartment model estimates the contribution of moisturizing water to leachate production. The assessment then addresses the migration of the chemicals via the groundwater pathway to a nearby stream and well, represented in the reference site. A simple steady-state mass balance assumption allows the estimation of expected peak concentrations in a reference stream, whereas an analytic transport model gives estimates for concentrations at a reference well.

2.2.1 Reference Disposal Environment

The climate in the area is semiarid, with dramatic variability possible over relatively short distances and short time periods. Average annual precipitation ranges from 300 to 510 mm (12 to 20 in.) between elevations of 5500 and 8000 ft. Areas above 8000 ft may receive as much as 640 mm (25 in.) of precipitation each year. Average monthly precipitation throughout the basin is relatively constant at 29.7 mm (1.17 in), with average maximum deviations of −25.1 mm (0.99 in.) in November and +40.4 mm (1.59 in.) in August (Wymore, 1974). Winter temperatures may fall to −40°C, whereas summer temperatures may exceed 40°C.

Surface runoff is dominated by snowmelt. Precipitation received during the months of November through March is stored in a snowpack at the higher elevations. Discharge records indicate high flows beginning in March or April and continuing through June and July.

Most of the summer precipitation is lost to the evapotranspiration demands of the semiarid climate. Major streams such as Piceance Creek flow year round because of groundwater input. The smaller tributaries respond to high intensity thunderstorms, but otherwise contribute little to summer streamflow.

The aquifers and streams in the reference basin do not meet standards for public drinking water supplies because of high dissolved solids content (Office of Technology Assessment 1980). However, groundwater can be used to water livestock, and both groundwater and surface water can be used for irrigation.

2.2.2 Reference Disposal Pile

Distinct differences in spent shale handling and hydraulic properties, together with considerations of local topography and climate, have resulted in a variety of disposal plans (Wildung and Zachara 1981). Of these plans, the one gaining greatest acceptance involves placing spent shale and other waste materials within an earthen embankment. A conceptualized embankment, based on current knowledge, is given by Wildung et al. (1982). The processed shale and other waste materials are placed in a suitable valley where the resulting disposal pile may be visualized as an earthen dam retaining an earthen fill. The proposed Colony cross-valley fill plan (U.S. Department of the Interior 1975) specifies that the spent shale will be compacted to 1362 kg/m^3 (85 pcf) and moisturized to 10 to 20% by weight. Drainage systems would divert runoff and leachates to evaporation ponds during construction. On completion of the pile, the surface would be covered with soil and revegetated. Probable locations of the disposal piles are in the headwaters of small canyons in the Piceance basin.

The reference disposal pile (used for the water balance calculations) contains many of the features of proposed disposal plans. The reference disposal pile is a cross-valley fill with an earthen dam impoundment structure. It is located in the headwaters of a north-facing gulch or canyon with an elevation of about 2500 m (8000 feet). The pile surface is graded at a 5% north facing slope and covers approximately 3×10^6 m^2 (800 acres). Maximum pile depth is about 152 m (500 ft). Spent shale is compacted to 1.2 to 1.4×10^3 kg/m^3 (75-85 pcf), with 15% by weight initial moisture content. Upstream surface runoff, if any, is diverted around the disposal site. The pile rests on bedrock with the alluvial overburden used as cover. The pile is 15 km upgradient from a perennial creek. An agricultural well pumps from the aquifer underlying the pile at a location 10 km downgradient from the pile (see Fig. 2-1).

2.2.3 Water Balance

The water balance approach requires that the quantity of water entering the system (precipitation) must equal the amount of water leaving the system (runoff, evapotranspiration, and deep percolation), plus that which is added to or subtracted from the soil root zone.

The water balance calculations are based on what has been called a "reclamation zone" (Kunkel and Murphy 1983), as shown in Figure 2-2. It was assumed in the definition sketch of Fig. 2.2 that the depth of the root zone does not exceed 2 m below the surface. Topsoil depth and retorted shale densities were chosen to be representative of what may be anticipated from present disposal plans. The water balance for the reclamation zone illustrated Fig. 2.2 may be stated by Equation (2.1)

$$P - R = ET + D - \Delta S \text{ (initial-final)} \tag{2.1}$$

where

P = precipitation,

R = runoff,

ET = evapotranspiration,

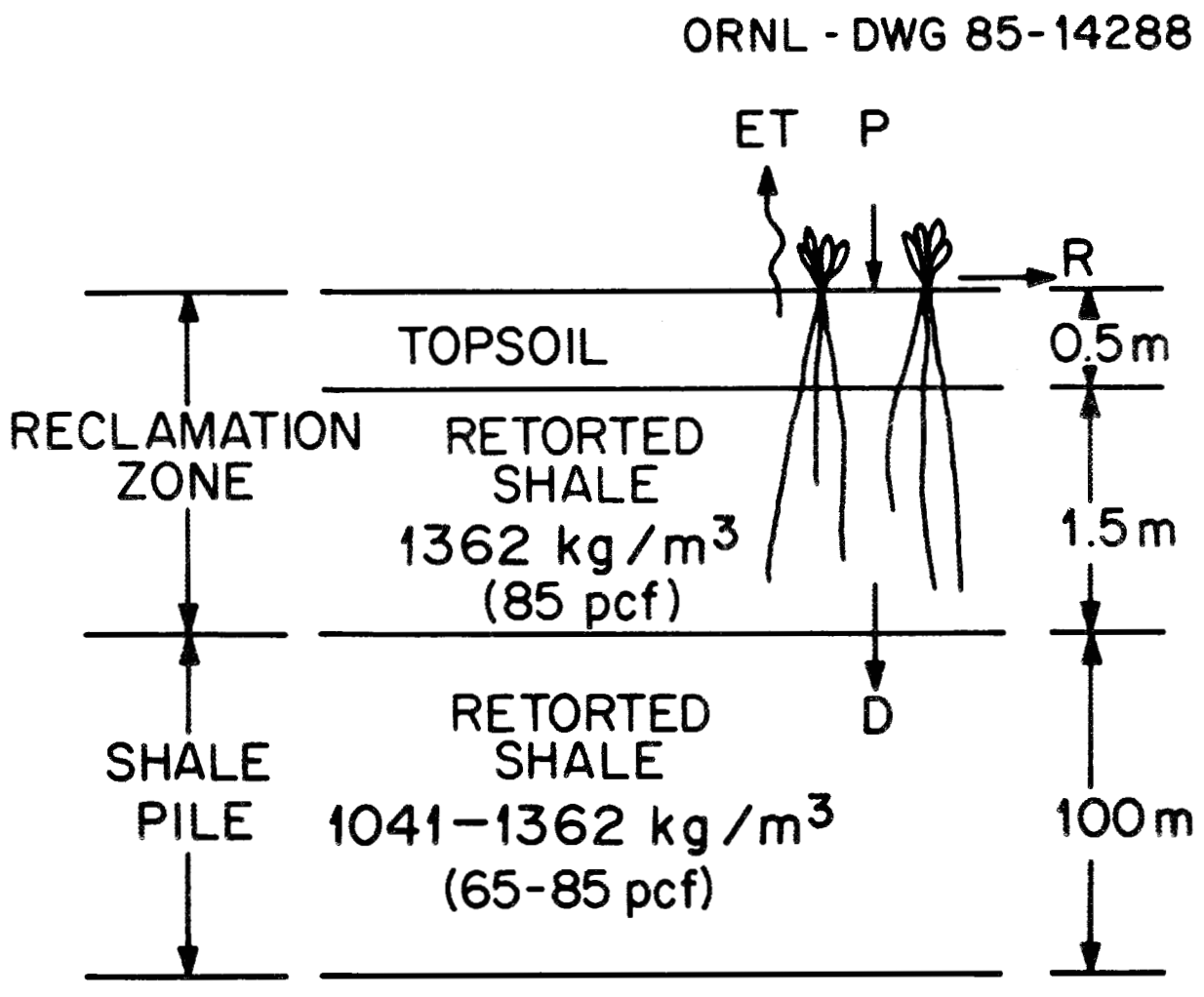

Figure 2.1. Schematic of the reference disposal pile and its relation to features of the reference site

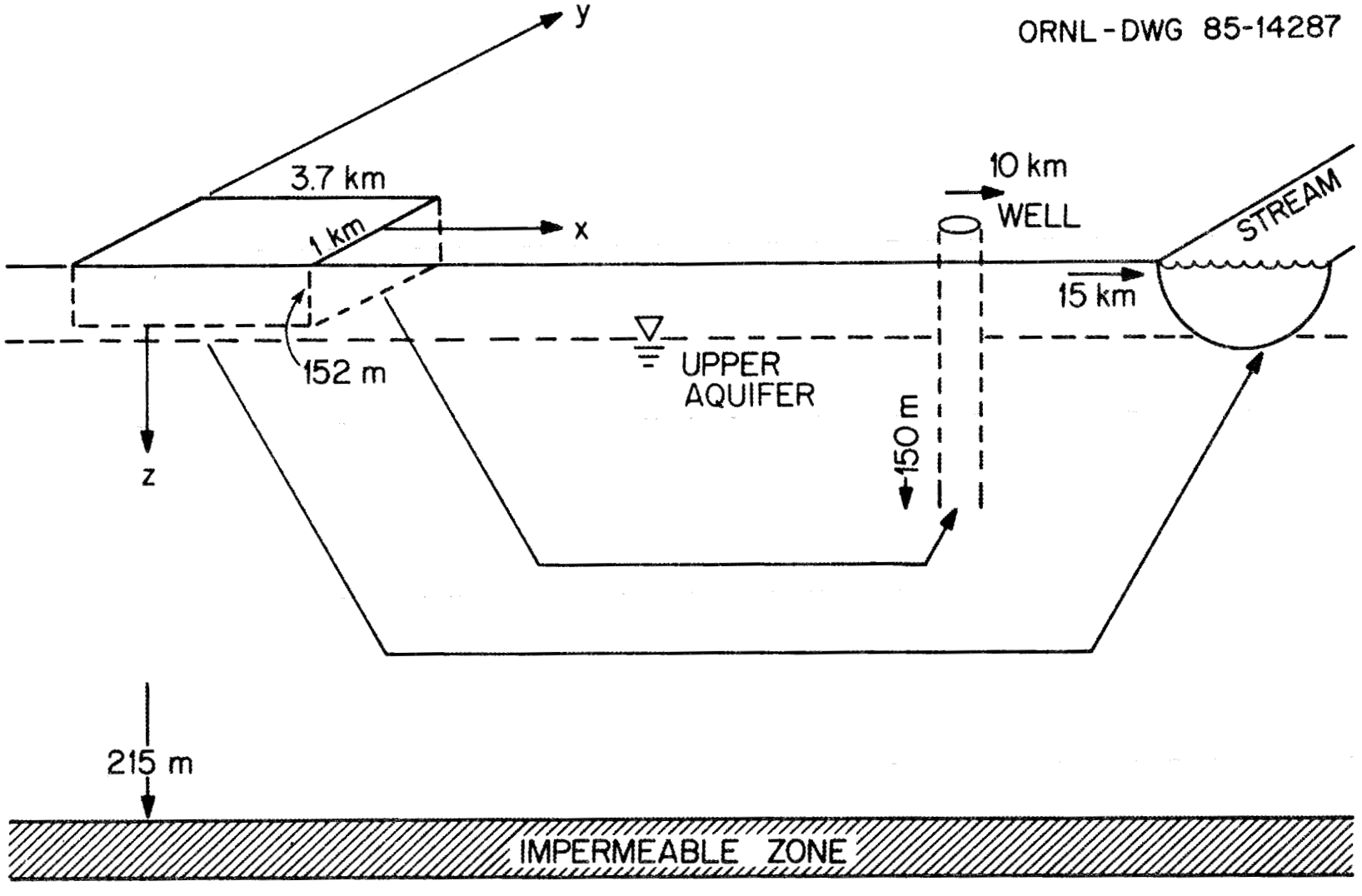

Figure 2.2. Definition sketch of the reference pile

D = deep percolation, and

ΔS = change in soil water held in storage.

2.2.3.1 Precipitation and runoff. A variety of factors influence precipitation in a particular region, and these factors interact and change from season to season. The distribution of precipitation throughout the year influences the extent to which it evapotranspirates, percolates, or forms runoff. The seasonal distribution of precipitation suggests that using monthly precipitation amounts is more appropriate in estimating the average annual water balance than are annual values.

A regression analysis, developed by Wymore (1974), of long-term precipitation records for eight regional weather stations as a function of elevation was used to develop an estimate of the monthly precipitation by elevation zone. Table 2.1 lists the estimated precipitation by season and by elevation zone for the Piceance Creek watershed. The estimates give in Table 2.1 are based on 20 years of regional precipitation records, isohyetal maps, vegetation indicators, and preliminary water balance calculations.

Table 2.2 lists the average monthly discharge for the record periods of three gaging stations in the Piceance Creek watershed. Values in the runoff column were calculated as the ratio of the net discharge to the basin drainage area. Variation in the average monthly runoff amounts is relatively small, particularly for the small Stewart Gulch watershed, suggesting that the streamflow is primarily generated by subsurface drainage of hillside soil profiles. Weeks et al. (1974) estimated that 80% of the runoff given in Table 2.3 is from alluvial discharge into Piceance Creek. The remaining 20% represents direct overland runoff for a total of 0.10 in./year. Wymore (1979) estimated that direct overland runoff from Union retorted shale placed on a 5% slope was 0.34 in. For purposes of analysis, direct annual runoff was taken to be the average of these two estimates, that is, 0.22 in./year. This runoff is confined to occur only during the spring and summer months of April through October.

Table 2.1. Estimated seasonal precipitation by elevation in piceance basin (Adapted from Wymore 1974)

Elevation zone (ft)	Precipitation (in.)		
	Nov.-March	April-Oct.	Annual
<6000	4.45	7.14	11.59
6-7000	5.51	8.62	14.13
7-8000	7.27	11.09	18.36
8-9000	9.03	13.56	22.59
>9000	10.09	15.03	25.12

Table 2.2. Estimated runoff from three gaging stations in Piceance Creek watershed

Month	Steward Gulch above[a] West Fork, 1975-82 (Drainage Area = 44 mile^2) Discharge (acre-ft)	Runoff (in.)	Piceance Creek below[b] Ryan Gulch, 1965-82 (Drainage Area = 495 mile^2) Discharge (acre-ft)	Runoff (in.)	Piceance Creek at[c] White River, 1965-82 (Drainage Area = 629 mile^2) Discharge (acre-ft)	Runoff (in.)
Jan.	104	0.044	1120	0.042	1450	0.043
Feb.	97.8	0.042	1200	0.045	1570	0.047
Mar.	108	0.046	1670	0.063	2320	0.069
Apr.	111	0.047	1290	0.049	1770	0.053
May	105	0.045	1750	0.066	2010	0.060
June	95.8	0.041	935	0.035	1030	0.030
July	97.8*	0.042	811	0.031	861	0.026
Aug.	92.8*	0.039	1390	0.053	1340	0.040
Sept.	94.0*	0.040	939	0.036	1080	0.032
Oct.	91.8	0.039	929	0.035	1240	0.037
Nov.	97.9	0.042	1270	0.048	1710	0.051
Dec.	106	0.045	1230	0.047	1590	0.047
Annual	1203	0.512	14503	0.548	17977	0.534

[a]USGS streamgage No. 93062.20.

[b]USGS streamgage No. 93062.

[c]USGS streamgage No. 93062.22.

[d]Includes estimated irrigation diversion ranging from 10 to 30 acre-ft.

Table 2.3. Estimation of monthly evapotranspiration demands

Month	T (°F)	R_s (in.)	ET_p^* (in.)	K_c^{**}	$ET_d^{\dagger\dagger}$ (in.)
Jan.	17.50	5.08	0.69	0.50	0.35
Feb.	19.90	6.14	0.91	0.50	0.46
Mar.	22.90	9.18	1.51	0.50	0.76
Apr.	33.60	10.90	2.17	0.60	1.30
May	38.80	12.94	3.50	0.80	2.80
June	48.70	13.89	5.64	0.80	4.51
July	54.90	13.83	6.79	0.80	5.43
Aug.	53.30	12.12	5.69	0.71	4.04
Sept.	44.90	10.27	3.64	0.53	1.93
Oct.	39.40	7.97	2.22	0.50	1.11
Nov.	30.60	5.35	1.11	0.50	0.56
Dec.	21.70	4.52	0.72	0.50	0.36

*Coefficients for April to October

T_{cf} = -1.2 (Fig. 2, Wymore 1974)

R_{cf} = 0.979 (Table 10, Wymore 1974)

E = 8 (elevation in thousands of feet)

Coefficients for November to March

T_{cf} = -1.2 (Fig. 2, Wymore 1974)

R_{cf} = 0.912 (Table 10, Wymore 1974)

**Water use coefficients for sagebrush (Wymore 1974)

$^{\dagger}ET_d = K_c \bullet ET_p$

2.2.3.2 Soil water holding capacity. The primary source of water for plant growth is held within the volume of soil invaded by plant roots. Total water holding capacity is a function of root depth and the specific water holding capacity of the material, which is largely dependent on the texture of the soil materials. Figure 2.3 illustrates the water retention relationship used by Wymore (1979) to assess the available water-holding capacity (AWC) of Union retorted shale. These curves were developed from the highest and lowest recorded neutron probe readings for various depths. The water-holding capacity of the bottom 1.5 m of the profile shown in Fig. 2-3 may be obtained by integrating the area between the two curves, which results in approximately 13 cm. Measurements of field capacity (water content at 1/3 bar suction) and permanent wilting point (water content at 15 bar suction) of Cathedral Bluffs topsoil compacted to a dry bulk density of 1.47 g/cm^3 at Colorado State University yielded values of 0.36 and 0.33 cm^3/cm^3. In the topsoil, the available water is considered to be that portion of the water held between the field capacity and the permanent wilting point. For a topsoil depth of 0.5 m, the net water-holding capacity of the 2 m profile would be increased by 0.59 in. to a net capacity of 5.70 in. This net capacity is greater than the value of 4.30 in. estimated by Wymore (1974) for a typical sagebrush soil profile in the Piceance basin.

2.2.3.3 Evapotranspiration. Evapotranspiration represents the consumptive use of water stored in the soil profile by vegetation in addition to evaporative losses of water to the atmosphere. Wymore (1974) developed a basic methodology for estimating evapotranspiration rates in the Piceance basin using a modified Jensen-Haise method. The original Jensen-Haise (1963) equation for potential evapotranspiration is

$$ET_p = (0.014T - 0.37)R_s \quad , \tag{2.2}$$

where

ET_p = potential evapotranspiration (inches)

T = mean air temperature (°F),

R_s = total solar and sky radiation converted to inches of evapotranspiration potential.

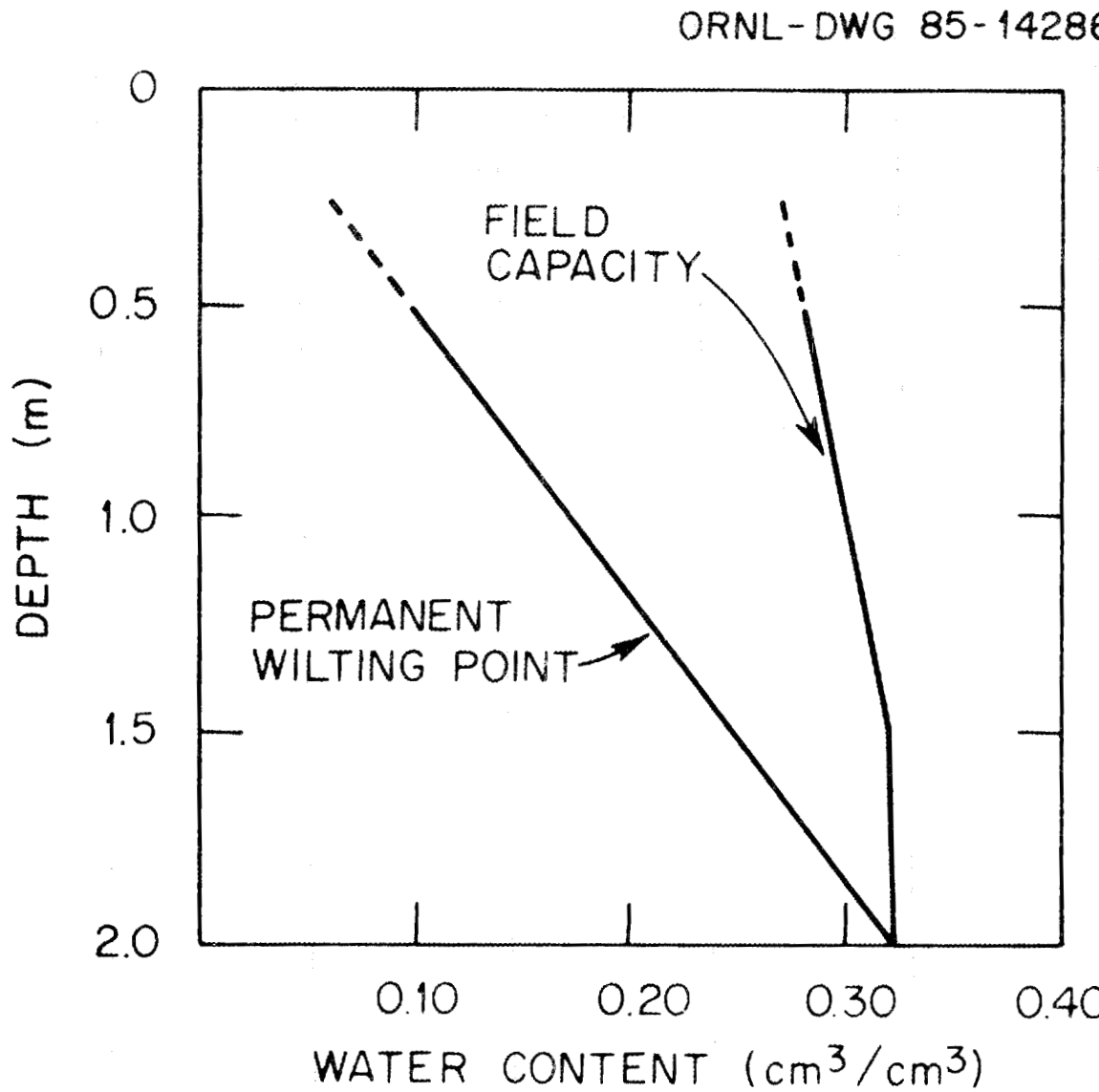

Figure 2.3. Water content of the reclamation zone at field capacity and the permanent wilting point as a function of depth

This original equation estimates potential evapotranspiration for the 5000 ft elevation zone. Wymore (1974) modified the equation using local data from the Piceance watershed to make estimates for elevation zones up to 9000 ft and include variations due to slope aspect and vegetative ground cover. The evaluation is made in two parts: the sum of the monthly potential evapotranspiration during the April to October season, ET_{ps}, and the sum of the evapotranspiration estimates for months in the November to March season, ET_{pw}. The values are given by the following equations for ET_{ps} and ET_{pw}

$$ET_{ps} = \sum_{i=1}^{7} [0.014(T_i + T_{cf}) - (0.57 - 0.04E)]R_{si}R_{cf} \tag{2.3}$$

and

$$ET_{pw} = \sum_{i=1}^{5} [0.006(T_i + T_{cf}) + 0.05]R_{si}R_{cf} \quad , \tag{2.4}$$

where

ET_{ps} = total potential evapotranspiration for months April to October,

ET_{pw} = total potential evapotranspiration for months November to March,

T_{cf} = temperature correction (°F),

R_{cf} = radiation correction factor,

E = elevation in thousands of feet.

It is assumed that the vegetative cover of the pile is similar to the sagebrush and grasses that cover the surrounding local terrain. Table 2.3 summarizes the calculations for monthly evapotranspiration demands for these conditions. Column 4 lists potential evapotranspiration, column 5 lists crop coefficients for sagebrush and column 6 gives the evapotranspiration demand that equals actual evapotranspiration only if water is readily available.

2.2.3.4 Calculation of deep percolation. Percolation of water through the reclamation zone, illustrated in Fig. 2.2, may eventually result in drainage from the disposal pile. On the long-term basis, (i.e., after steady-state conditions prevail), the drainage rate from the base of the pile will be equivalent to the percolation rate through the reclamation zone.

Table 2.4 outlines monthly calculations of the deep percolation rate through the base of the reclamation zone. The calculations are based on the disposal pile conditions discussed in the previous subsections.

Long-term annual drainage from the reclamation zone of the disposal pile totals 1.08 in./year (2.74 cm/year). This rate is in general agreement with results obtained in model studies by Wildung et al. (1982) and Kunkel and Murphy (1983), who estimated 8 and 1.1 cm/year, respectively, and greater than an estimate of 0.13 cm/year by Wymore (1979). We note that our estimate of 1.08 in./year is 5 % of the annual precipitation, a percentage that most hydrologists believe to be reasonable for even drier climates.

2.2.4 Leachate Production and Composition

The volume of leachate produced from the disposal pile is dependent in part on the exposed surface area of the disposal pile. For purposes of analysis, the disposal plans of Colony involving a land coverage of 800 acres was chosen as a representative pile. At an average annual drainage of 2.75 cm/year, a disposal pile covering 800 acres results in a leachate volume of approximately 72 acre-ft/year (8.9×10^7 L/year). Leachate production from the piles would be expected to be practically steady and constant because the huge unsaturated pile will act to damp the seasonal nature of net infiltration.

2.2.4.1 Leachate composition. Leachate composition investigations have generally focused on concentration measurements of various inorganic constituents of the leachate. Only quite recently have data on the organic constituents of the leachate (Fox et al. 1984)

Table 2.4. Calculation (in inches) of deep percolation from water balance[a]

Month	P	R	ET	S[b]	S[c]	D*[d]
Jan.	1.53	0	0.35	4.13	1.18	0
Feb.	1.53	0	0.46	5.2	1.07	0
Mar.	1.67	0	0.76	5.7	0.5	0.41
Apr.	2.03	0.06	1.3	5.7	0	0.67
May	1.55	0.05	2.8	4.4	-1.3	0
June	1.65	0.05	4.51	1.49	-2.91	0
July	1.57	0.02	3.04	0	-1.49	0
Aug.	2.18	0.02	2.16	0	0	0
Sept.	1.77	0.01	1.76	0	0	0
Oct.	1.57	0.01	1.11	0.45	0.45	0
Nov.	1.44	0	0.56	1.33	0.88	0
Dec.	1.98	0	0.36	2.95	1.62	0
Annual	20.47	0.22	19.17		0	1.08 (2.74 cm)

[a]See Eq. (2.1) for definitions.

[b]Initial.

[c]Final.

[d]Determination from water balance equation, D = P - R - ET - S; deep percolation occurs when the soil water-holding capacity of 5.7 in. is exceeded.

become available. Several investigations (Metcalf and Eddy 1975; Garland et al. 1979; Cleave et al. 1979; Jackson and Jackson 1982) have demonstrated that water-soluble organics are present in the leachate of retorted shales. Total organic carbon concentrations have ranged from about 1 to 650 mg/L. These organics probably originate from sorbed pyrolysis and recycle gas and unvolatilized kerogen decomposition products. The low concentrations of organic carbon in the leachate has made quantitative extraction and identification of organic compounds in this matrix extremely difficult. Consequently, most studies have focused on characterization of polycyclic aromatic compounds in benzene extracts of the retorted shales (Fox 1983).

This report uses only leachate composition data obtained under conditions closely related to those anticipated in the field. Studies involving field lysimeters perhaps most closely approximate the environmental conditions associated with a commercial disposal pile. Leachate composition data from these studies are used wherever possible to set probable ranges in concentrations. In addition to field lysimeter studies, Nazareth (1984) conducted reproducible leaching experiments capable of assessing ion concentrations of solutions associated with the high solid-to-liquid ratios expected in the field. Whenever necessary, Nazareth's data are used to extend the probable ranges in concentration determined from field lysimeter studies.

Setting probable concentration ranges for organic constituents of the leachate requires different procedures. Because of the paucity of information concerning the concentrations of organics in the leachate of retorted shale, the probable ranges in concentration were determined from whatever data were available. Data from benzene extracts of organics are used, assuming that the water soluble concentration is 100 times less than that soluble in benzene (Fox 1983).

Table 2.5 summarizes the probable ranges in concentrations of inorganic species in leachate of retorted shales. For many of the constituents listed in Table 2.5, the probable ranges span two orders of magnitude. This span is a reflection of the variability in test results and encompasses the wide range of leachate data currently available.

Table 2.5. Probable ranges of inorganic concentrations in disposal pile leachate

Parameter	Range in concentration (mg/L)	RAC No.
Ag	0.008-0.01	36
Al	0.09-50	
As	0.02-1.0	31
B	0.02-20	36
Ba	0.01-1.0	36
Be	0.01-1.0	36
Br	0.1-0.7	
Ca	1-600	
Cd	0.003-0.006	34
Cl	10-2,000	
Cr	0.003-0.02	36
Cu	0.06-0.3	36
EC(μmho/cm)[a]	1,000-50,000	
F	5-20	36
Fe	0.01-8	
Hg	3×10^{-6}-0.0005	32
K	10-1,000	
Li	0.007-1.1	
Mg	0.1-300	
Mn	0.01-0.5	
Mo	1-76	
Na	1,000-18,000	
Ni	0.01-0.6	33
Pb	0.003-0.004	35
Rb	0.01-0.03	
Se	0.02-2	36
Si	4-20	
SO_4	2,000-34,000	
Sn	0.003-0.005	
Sr	1-15	
TDS[b]	5,000-57,000	38
V	0.2-3	36
Zn	0.01-4.8	36

[a]Electrical conductivity

[b]Total dissolved solids.

Table 2.6 summarizes estimated ranges in concentrations of organic species in leachate of retorted shales. Fox et al. (1984) have tentatively identified several organic compounds in the leachate of Paraho retorted shale, including hydrocarbons ($<C_{12}$), ketones, aliphatic nitrogen heterocyclics, and oxygenated nitrogen heterocyclics. Until further work on the concentrations of organic compounds in leachate is conducted, Table 2.6 will necessarily remain incomplete.

Table 2.7 tabulates and expresses the leachate composition data in terms of annual production and risk analysis categories (RAC). Table 2.7 was generated from Tables 2.5 and 2.6 using a long-term annual leachate production rate of 8.9×10^7 L/year.

2.2.4.2 Contribution of moisturizing water to leachate production. The leachate composition studies reviewed in the previous section have generally been performed by leaching spent shale with distilled water. However, the spent shale disposal plan described by TRW (1985) specifies that treated process wastewaters will be used to moisturize the shale prior to disposal. These wastewaters contain organic and inorganic constituents that could contribute to leachate from the pile. TRW (1985) developed estimates of codisposed wastewater compositions for the TOSCO-II and Paraho processes. Contributions of this wastewater to leachate were estimated and added to the raw shale leachate estimates (described in the previous section) to obtain estimates of the total rate of release of each RAC in leachate.

A simple mass balance model was used to estimate the contribution of the organic constituents of the wastewater to leachate, based on the total mass of each RAC present in the pile, the partitioning of the RACs between shale particles and pore water, and the annual volume of leachate generated. The spent shale is assumed to be moisturized to 15% water content with process water (TRW 1985). The contaminants are assumed uniformly distributed in the moisture occupying the pore spaces in the spent shale. Under these assumptions, the annual mass of a given contaminant leached from the pile is given by

Table 2.6. Estimated ranges of organic concentrations in disposal pile leachate

Species observed	Range in concentration (μg/L)	RAC No.
Benzene soluble BaP[a]	0.2-0.4[b]	15
Carbazoles[c]	1,000-20,000	19
Benzene soluble acids[a]	2-7[b]	20
Phenols[d]	500-30,000	21
Benzene extracted S[a]	~1[b]	23

[b]Concentration taken as 1% of reported value based on solubility in water as compared with benzene.

[a]See Fox (1983) p. 4-39.

[c]See Fox et al. (1984).

[d]See Metcalf and Eddy (1975).

Table 2.7. Source term estimates for disposal pile leachate

RAC No.	RAC category	Leachate production (kg/year)
1	Carbon monoxide	0
2	Sulfur oxide	0
3	Nitrogen oxides	0
4	Acid gases	0
5	Alkaline gases	0
6	Hydrocarbon gases	0
7	Formaldehyde	NA[a]
8	Volatile organochlorines	NA
9	Volatile carboxylic acids	NA
10	Volatile O and S heterocyclics	NA
11	Volatile N-heterocyclics	NA
12	Benzene	NA
13	Aliphatic/alicyclic	NA
14	Mono/diaromatic hydrocarbons (excluding benzene)	NA
15	Polycyclic aromatic hydrocarbons	0.017-0.036
16	Aliphatic amines (excluding N-heterocyclics)	NA
17	Aromatic amines (excluding N-heterocyclics)	NA
18	Cyclics (Azarenes) (excluding volatiles)	NA
19	Neutral N, O, S heterocyclics (excluding volatiles)	89-1781
20	Carboxylic acids (excluding volatiles)	0.17-0.62
21	Phenols	45-2670
22	Aldehydes and ketones	NA
23	Nonheterocyclic organosulfur	0.1
24	Alcohols	NA
25	Nitroaromatics	NA
26	Esters	NA
27	Amides	NA
28	Nitriles	NA
29	Tars	0
30	Respirable particles	0
31	Arsenic	1.8-89
32	Mercury	0.00027-0.045
33	Nickel	0.89-53
34	Cadmium	0.27-0.53
35	Lead	0.27-0.36
36	Other trace elements	475-4641
37	Radioactive materials	0
38	Other remaining materials (dissolved solids)	4.5×10^5-51×10^5

[a]NA = data not available.

leachate production (kg/yr) = equilibrium pore concentration (kg/L) * drainage (L/year). (2.5)

To estimate the equilibrium concentration, a form of the Freundlich isotherm equation is used:

$$C_s = K_d * C \quad , \tag{2.6}$$

where the adsorbed concentration, C_s, is a linear function of the dissolved concentration, C, related by the distribution coefficient, K_d (L^3/M, mass of solute on the solid phase per unit mass of solid phase/concentration of solute in solution). The units of K_d are universally reported in mL/g. Lyman et al. (1982) have compiled techniques for estimating K_ds based, for organic chemicals, on the octanol:water partitioning coefficient (K_{ow}) or the solubility (S) of the chemical. Regression equations have been developed to estimate the organic carbon adsorption coefficient, K_{oc}, from which the distribution coefficient may be calculated:

$$\log K_{oc} = -0.55 \log S + 3.64 \text{ (mg/L)} \tag{2.7}$$

(Kenega and Goring 1980),

$$\log K_{oc} = 1.00 \log K_{ow} - 0.21 \tag{2.8}$$

(Karickhoff et al. 1979),

$$Kd = Koc * (\% \text{ organic carbon}/100).$$

It has been estimated that the spent shale will have an organic carbon content on the order of 1% (Amy et al. 1980).

Assuming the mass of the shale, M_s (kg), the volume of the pile, V_s (M^3), the moisture content, Θ and the total mass of contaminant, c_t (kg), are known, Eq. (2-6) may be written as:

$$(c_t - c)/M_s = K_d \, (c/\Theta * V_s). \tag{2.9}$$

It then follows that

$$c = (\Theta V_s/(\Theta V_s + M_s K_d)) * c_t, \quad (2.10)$$

or that the contaminant mass in the pore fluid at equilibrium is equal to a constant times the total contaminant mass introduced into the pile. The pore water concentration at equilibrium, C_{eq} (kg/L), may be calculated knowing the shale density, ρ (kg/L), and thus the volume of moisture within the pores, V_m (L).

$$V_m = (M_s / \rho) * \Theta \quad (2.11)$$

$$C_{eq} = c / V_m \quad (2.12)$$

Leachate production from the moisturizing water, M, can be calculated using the rewritten mass balance equation

$$M = Ceq * q \quad , \quad (2.13)$$

where q is the drainage rate (L/year).

The reference disposal pile covers approximately 800 acres and is 152 m deep. The TRW (1985) report assumes a production rate of spent shale to be 2.345×10^6 kg/h. Table 2.8 summarizes the relevant parameters.

Knowing the active life of the pile and the mass generation rates, the total mass (c_t) introduced into the pile is computed for each contaminant, as shown in Tables 2.9 and 2.10.

Tables 2.9 and 2.10 display (for each contaminant) the total mass, estimated adsoption coefficients, and calculated contribution of the moisturizing water to leachate production for the TOSCO-II and Paraho processes.

2.2.5 Transport Calculations

The migration of leachate via the groundwater pathway could result in environmental exposures at the reference creek and well. Because the

Table 2.8. Reference disposal pile

Symbol	Description	Value
V_s	Volume of shale pile (m^3)	4.92E8
Ms	Mass of pile (kg)	7.97E11
Θ	Moisture content (%)	15
P	Shale bulk density (kg/L)	1.62
V_m	Volume of moisture water (L)	7.38E10
q	Drainage rate (L/yr)	8.9E7
t	Active life of pile (h)	3.4E5

Table 2.9. Calculation of contribution of moisturizing water to leachate production, TOSCO-II process

RAU[a] No.	Reference chemical	Mass generation rate[b] (kg/h)	Total mass (kg)	K_{oc} (mL/g)	K_d (m^3/kg)	Leachate production (kg/year)
11	Pyridine	71	2.4E7	672[c]	6.7 E-3	395
12	Benzene	43	1.5E7	31.4[d]	3.14 E-4	4,019
13	Cyclohexane	120	4.0E7	6166	6.17 E-2	72
18	Quinoline	4.4	1.5E6	225[e]	2.25 E-3	74
19	Dibenzofuran	1.5	5.1E5	8128[f,g]	8.13 E-2	0.7
20	Butanoic acid	190	6.4E7	10.66[c]	1.07 E-4	36,000
21	Phenol	40	1.4E7	3.1E6[h]	31	0.04

[a]Risk Analysis category

[b]TRW (1985)

[c]Kenaga and Goring (1980)

[d]Chiou et al. (1977)

[e]Neely and MacKay (1982)

[f]Leo et al. (1971)

[g]Karickhoff et al. (1979)

[h]Isaacson and Frink (1984)

Table 2.10. Calculation of contribution of moisturizing water to leachate production - Paraho process

RAC[a] No.	Reference chemical	Mass generation rate[b] (kg/h)	Total mass (kg)	K_{oc} (mL/g)	K_d (m^3/kg)	Leachate production (kg/year)
13	Cyclohexane	226	7.68 E7	6,166	6.17 E-2	139
14	Toluene	79	2.68 E7	302[c]	3.02 E-3	961
15	Anthracene	12	4.08 E6	17400[c]	1.74 E-2	26.0
18	Quinoline	128	4.35 E7	225	2.25 E-3	2070
19	Dibenzofuran	108	3.67 E7	8128	8.13 E-2	50.4
21	Phenol	0.33	1.12 E5	3.16 E6	31	4.0 E-4

[a]Risk analysis category.

[b]TRW (1985)

[c]Leo et al. (1971)

modeling approach is of a regional scale, it is assumed appropriate to model the fractured aquifer as an equivalent porous medium (Freeze and Cherry 1979). The regional flow system is assumed to be in steady state.

The disposal pile is assumed to be a constant infinite source of chemical release. At the rechange rate of 0.027 m/year and a mean water content of 0.20 cm^3/cm^3 , it would take a water molecule over 1500 years to travel from top to bottom of the reference pile. As long as travel time to the discharge point is less than this estimate, the infinite source assumption is valid. The constant source assumption was checked to ensure that there is enough available mass of contaminant in the pile to supply a constant leaching rate over 1500 years.

2.2.5.1 Method. The peak concentration of chemical in the creek can be estimated based on a simple mass balance. Assuming no loss of mass by chemical reaction, fixation, or aquifer leakage, the rate of contaminant mass leaving the pile should equal the rate of mass entering the creek. Division by the rate of flow expected in the creek (annual mean flow) gives the expected peak concentration in the stream reach, assuming instantaneous mixing in the reach impacted. The average annual flow rate of 14,503 acre-ft measured over a 17-year period on Piceance Creek was used (USGS Streamgage No. 93062). The conservation of mass assumption is conservative in the sense that the mass flux actually reaching the stream could be lower than predicted because of chemical reaction or aquifer storage.

Dispersion of solute during plume migration can affect the concentration observed at the well of the reference site. The analytic groundwater transport model, AT123D (Yeh 1981), was used to simulate transport by advection-dispersion. The model achieves a closed-form solution to the governing advection-dispersion equation using Green's functions. The reference site was modeled in three dimensions with the steady-state source term. The source terms reported in Tables 2.7, 2.9, and 2.11 for each RAC converted into units of kilograms per hour for input into AT123D. Other input parameters characterize shale pile and aquifer geometries. Aquifer parameters include effective porosity (n_e), bulk density (ρ's), hydraulic conductivity (K), hydraulic

gradient (i), and dispersivity (α). Robson et. al. (1981) reported values for effective porosity (0.02) and hydraulic conductivity (~ 0.5 ft/d) for the upper aquifer of the Piceance basin. The hydraulic gradient was estimated based on the potentiometric surface maps of the Robson study.

Mercer et al. (1982) have reported values for dispersivity for various materials and geologic media. A conservative estimate (allowing minimal spreading of the plume) for fractured sandstone can be derived from the report (α = 10 m). Dispersion is a function of hydraulic conductivity; the greater the hydraulic conductivity, the greater the dispersivity. The ratio of hydraulic conductivities ($K_{xx} = K_{yy} = 2K_{zz}$) reported in Taylor (1982) was used to estimate the ratio of dispersivities ($\alpha_{xx} = \alpha_{yy} = 2\alpha_{zz}$). Table 2.11 summarizes the input data used to run AT123D.

2.2.5.2 Results. Tables 2.12 and 2.13 present, respectively, results of the groundwater exposure assessment for the TOSCO-II and Paraho processes. For the TOSCO-II process, the contributions of rainwater and moisturizing water to the total leachate are tabulated separately, along with the estimated maximum concentrations delivered to the reference well and creek. Estimates of rainwater contributions to leachate could not be developed for the Paraho process because shale leaching data are lacking. We note that, although the duration of the maximum exposures is unknown, changes in the rate of delivery should occur on relatively long time scales (years). Hence, the values in Tables 2.12 and 2.13 should be treated as chronic exposures for the purposes of ecological risk assessment. The results for organic contaminants are likely to be highly conservative, because they assume no degradation. Given the hundreds of years required for (1) saturation of the shale pile with rainwater so that leaching can begin, and (2) subsurface travel to the reference well and creek, substantial transformation and degradation of organic chemicals by microorganisms would be expected.

Table 2.11. AT123D input data

Aquifer depth = 0.0 for infinite depth (m).....	215
Aquifer width = 0.0 for infinite width (m).....	0
Beginning point of X-source location (m).....	0
End point of X-source location (m).....	0
Beginning point of Y-source location (m).....	0
End point of Y-source location (m).....	1000
Beginning point of Z-source location (m).....	0
End point of Z-source location (m).....	152
Porosity.....	0.02
Hydraulic conductivity (m/h).....	0.00254
Hydraulic gradient.....	0.017
Longitudinal dispersivity (m).....	10
Lateral dispersivity (m).....	10
Vertical dispersivity (m).....	5
Distribution coefficient, Kd (m^3/kg).....	0
Bulk density of the soil (kg/m^3).....	1470
Accuracy tolerance for reaching steady state.....	0.001
Density of water (kg/m^3).....	1000
Time interval for the desired solution (h).....	8766
Discharge time (h).....	3.829 x E7
Waste release rate (kg/h).....	RAC specific

Table 2.12. Leachate production/migration summary for TOSCO-II process

RAC[a] No.	Reference chemical	Leachate production (kg/year) Rain	Moisture	Total	Peak well concentration (mg/L)	Peak creek concentration (μg/L)
11	Pyridine	ND[b]	395	395	0.36	22
12	Benzene	ND	4019	4019	3.63	225
13	Cyclohexane	ND	72	72	0.068	4.1
15	Anthracene	0.036	0	0.036	3.26E-5	2.02E-3
18	Quinoline	ND	74	74	0.065	4.03
19	Dibenzofuran	1781	0.7	1782	1.6	99.8
20	Butanoic acid	0.62	3.6E4	3.6E4	33.1	2.1E3
21	Phenol	2670	0.04	2670	2.42	150
31	Arsenic	89	ND	89	0.08	5.0
32	Mercury	4.5E-2	ND	4.5E-2	4.1E-5	2.5E-3
33	Nickel	53	ND	53	0.05	3.0
34	Cadmium	0.53	ND	0.53	4.8E-4	0.03
35	Lead	0.36	ND	0.36	3.3E-4	0.02
38	Dissolved Solids	51E5	ND	51E5	4.6E3	2.9E5

[a]Risk analysis category.

Table 2.13. Leachate production/migration summary for Paraho process

RAU[a] No.	Reference chemical	Leachate production from moisturizing water (kg/year)	Peak well concentration (mg/L)	Peak Creek concentration (µg/L)
13	Cyclohexane	139	0.13	7.8
14	Toluene	961	0.87	54
15	Anthracene	26.0	0.023	1.5
18	Quinoline	2070	1.86	115
19	Dibenzofuran	50.4	0.045	2.8
21	Phenol	4.0 E-4	3.6 E-7	2.2 E-5

[a]Risk analysis category.

As previously discussed, estimation of time to pile stabilization and generation of leachate is a matter of controversy. AT123D gives estimates for time of travel from disposal pile to discharge area after stabilization. The resulting time of arrival of the peak concentration of the plume at the well and creek are 610 and 860 years respectively, assuming no retardation.

2.3 ATMOSPHERIC DISPERSION AND DEPOSITION

The short-range atmospheric dispersion code AIRDOS-EPA (Moore et al. 1979) was used in the environmental risk analysis to calculate ground-level atmospheric concentrations and deposition. This code is summarized by Travis et al. (1983), who also described the method for calculating accumulation in soil. Soil concentrations were calculated for a 35-year accumulation period using site-specific values for soil bulk density, precipitation, evapotranspiration, and irrigation and taking into account removal by leaching, biological degradation and chemical degradation. This calculation is performed using the food chain code TERREX.

Because most phytotoxicity studies are done in solution culture, we have added a calculated concentration in soil solution that is not described in previous documents. For calculating the soil solution concentration, the total accumulation in the soil compartment is first calculated by summing the depositing material over the lifetime of the facility and correcting for leaching, degradation, and other removal processes. The retained material is then partitioned between the solid and solution phases of the soil compartment assuming the relationship

$$C_{iss} = \frac{C_{is}}{K_d} \quad , \tag{2.14}$$

where

C_{iss} = the concentration of compound i in root zone soil solution (μg/L),

C_{is} = the concentration of compound i in root zone soil (μg/kg), and

K_d = the distribution coefficient (L/kg).

Because K_d is in the denominator of Eq. (2.14), the soil solution concentration C_{iss} could take on extremely high values with small values of K_d. To bound the maximum value of C_{iss}, it is assumed that the upper bound concentration is represented by the total deposited and retained material divided by the quantity of water in the root zone defined by d or

$$C_{iss}^{max} = \frac{D_i[1 - \exp(-\lambda_{si}\ t_b)]}{10\ \rho\ \Theta\ d\ \lambda_{si}} \tag{2.15}$$

where

D_i = the ground level deposition rate of compound i ($\mu gm^{-2}/s^{-1}$),

λ_{si} = the sum of all soil removal rate constants (L/s),

t_b = the period of long-term buildup in soil, equal to the length of time that the source term is in operation(s),

10 = a conversion factor from g/cm^2 to kg/m^2 [(10,000 cm^2/1 m^2) (1 kg/1000 g)],

ρ = soil bulk density (g/cm^3),

Θ = volumetric water content (cm^3/cm^3),

d = the depth of the root zone (cm), and

r = soil volumetric water content (mL/cm^3).

If C_{iss} calculated via Eq. (2.14) exceeds C^{max} calculated via Eq. (2.15), then C_{iss} is set equal to C^{max}. The value of Θ used in Eq. (2.15) is very important in providing a reasonable estimate of C^{max}. Since measured values of K_d are usually under saturated conditions, Θ in Eq. (2.15) represents total soil porosity.

These calculations generate sector-average ground-level concentrations in air, soil, and soil solution in 16 directions at 500 m intervals from 1,500 to 50,000 m from the source. The highest annual average concentrations in air and the highest soil and soil solution concentrations after 35 years of deposition are presented in Table 2.14 and 2.15.

Table 2.14. Maximum ambient atmospheric and soil concentrations for the Paraho Process

RAC[a] No.	RAC name	Annual average concentration in air (μg/m^3)	Concentration in soil (μg/kg)	Concentration in soil solution (μg/L)
1	Carbon monoxide	22.4	No accumulation in soil	
2	Sulfur oxides	2.04	No accumulation in soil	
3	Nitrogen oxides	80.2	No accumulation in soil	
4	Acid gases	1.46 E-02	No accumulation in soil	
5	Alkaline gases	0.329	No accumulation in soil	
6	Hydrocarbon gases	0.826	0.330	0.342
7	Formaldehyde		No emissions	
8	Volatile organochlorines		No emissions	
9	Volatile carboxylic acids		No emissions	
10	Volatile O&S heterocyclics		No emissions	
11	Volatile N-heterocyclics	0.719	3.49	7.21
12	Benzene		No emissions	
13	Aliphatic/alicyclic hydrocarbons	4.34	113	8.09
14	Mono/diaromatic hydrocarbons	1.92	1.11	0.223
15	Polycyclic aromatic hydrocarbons	1.01 E-02	0.887	1.36 E-02
16	Aliphatic amines		No emissions	
17	Aromatic amines		No emissions	
18	Alkaline nitrogen heterocyclics	1.05	9.48	3.65
19	Neutral N, O, S heterocyclics	2.47	9.36 E-02	2.46 E-02
20	Carboxylic acids	1.03	12.0	13.4
21	Phenols	0.32	51.4	75.6
22	Aldehydes and ketones		No emissions	
23	Nonheterocyclic organosulfur	1.98 E-02	2.35 E-02	1.41 E-02
24	Alcohols	0.738	191	394
25	Nitroaromatics		No emissions	
26	Esters		No emissions	
27	Amides		No emissions	
28	Nitriles		No emissions	
29	Tars		No emissions	
30	Respirable particles	118	No accumulation in soil	
31	Arsenic	2.08 E-02	507	2.54
32	Mercury	1.08 E-03	1.51 E-02	7.51 E-03
33	Nickel	1.73 E-02	386	2.57
34	Cadmium	3.25 E-03	7.04	1.08
35	Lead	1.10 E-02	87.3	9.7 E-02
36	Other trace elements	0.384	No accumulation soil	

[a]Risk analysis category.

Table 2.15. Maximum ambient atmospheric and soil concentrations for TOSCO II

RAC[a] No.	RAC name	Annual average concentration in air ($\mu g/m^3$)	Concentration in soil ($\mu g/kg$)	Concentration in soil solution ($\mu g/L$)
1	Carbon monoxide	5.98 E-01	No accumulation in soil	
2	Sulfur oxides	8.37	"	
3	Nitrogen oxides	60.5	"	
4	Acid gases	5.73 E-06	"	
5	Alkaline gases	1.35 E-02	"	
6	Hydrocarbon gases	8.60 E-01	3.43 E-01	3.55 E-01
7	Formaldehyde		No emissions	
8	Volatile Organochlorines		"	
9	Volatile carboxylic acids		"	
10	Volatile O&S heterocyclics		"	
11	Volatile N heterocyclics	4.77 E-01	2.32	4.78
12	Benzene		No emissions	
13	Aliphatic/alicyclic hydrocarbons	4.64	121	8.64
14	Mono/diaromatic hydrocarbons	2.39	1.38	2.77 E-01
15	Polycyclic aromatic hydrocarbons	1.89 E-03	1.66 E-01	2.55 E-03
16	Aliphatic amines		No emissions	
17	Aromatic amines		"	
18	Alkaline N heterocyclics	1.10	9.97	3.83
19	Neutral N, O, S heterocyclics	1.50	5.68 E-02	1.50 E-02
20	Carboxylic acids	1.03	16.1	13.4
21	Phenols	3.20 E-01	51.4	75.6
22	Aldehydes and ketones		No emissions	
23	Nonheterocyclic organosulfur		"	
24	Alcohols		"	
25	Nitroaromatics		"	
26	Esters		No emissions	
27	Amides		"	
28	Nitriles		"	
29	Tars		"	
30	Respirable particles	38.6	No accumulation in soil	
31	Arsenic	1.87 E-04	13.0	6.49 E-02
32	Mercury	3.29 E-06	2.28 E-04	2.28 E-05
33	Nickel	2.94 E-04	20.4	1.36 E-01
34	Cadmium	4.49 E-06	7.96 E-02	1.22 E-02
35	Lead	3.64 E-04	8.53	9.48 E-03
36	Other trace elements	6.70 E-02	No accumulation in soil	

3. AQUATIC END POINTS

3.1 QUOTIENT METHOD

The quotient method is the direct arithmetic comparison of a benchmark concentration (BC) from a toxicity test to an expected environmental concentration (EEC). It is calculated as the ratio EEC/BC. The method amounts to an assumption that the test benchmark is a good model for the assessment end point (in this case the end points are maintenance of fish populations and algal communities in the streams and rivers of West Central Colorado). Since the test data are not generally derived from tests of the species or waters found in the assessment region, the assumption is violated but the method can still be used as a screening tool.

Because this report compares potential toxic differences among groups of chemicals (RACs), benchmarks common to as many of the RACs as possible were preferred. The LC_{50} and TL_m (which are equivalent) were selected to represent acute toxicity (Table A-1). Chronic effects are presented as GMATCs (geometric mean maximum allowable toxicant concentrations, which is the geometric mean of the highest no-observed-effect concentration and the lowest-observed-effect concentration) (Table A-2). In contrast, benchmarks used in algal tests can vary between studies; therefore, a variety of test end points were selected for this report (Table A-3).

Appendix A does not include all extant data on the responses of freshwater organisms to the test chemicals. For example, with heavy metals, a representative sample of values is adequate for this purpose.

As in the selection of benchmarks, the test species chosen for tabulation were those that appear most frequently in the literature. Invertebrates were usually represented by cladocerans with insect data presented when available. The fish species selected are those usually

used in toxicity testing, namely, fathead minnows (Pimephales promelas), bluegills (Lepomis macrochirus), and rainbow trout (Salmo gairdneri). Data for algal assays are sparse; therefore, all species appearing in the literature (to our knowledge) were included in Table A-3.

Tables 3.1 and 3.2 present the highest quotients for each RAC and category of effect for the two oil shale technologies. The higher the value of these quotients the greater the risk of acute effects on organisms in the reference stream. Quotients are interpreted according to the best judgment of the analyst (Barnthouse et al. 1982a). A value of 0.01 (1.0×10^{2}) or less indicates little apparent environmental significance; 0.01 to 10 (1.0×10^{1}) suggests possible or potential adverse effects; greater than 10 describes possible or potential adverse effects; and greater than 100 describes a chemical of probable environmental concern. The utility of these screening criteria must be confirmed by further experience in risk analysis and by field studies.

The most serious ichthyotoxins in the TOSCO-II leachate appear to be benzene (RAC 12), carboxylic acids (RAC 20), phenolics (RAC 21), cadmium (RAC 34), and total dissolved solids, all of which have quotients between 0.01 and 0.1. The more limited data on Paraho leachates give quotients in the same range for mono/diaromatic hydrocarbons (RAC 14) and alkaline N heterocyclics (RAC 18). Only nickel (RAC 33) in the TOSCO-II leachate produces a quotient >0.01 for algae. These quotient values do not indicate that toxic effects will occur, but they do suggest that given the uncertainties in the exposure concentrations, these chemical categories deserve additional attention. Site hydrology and water quality will be particularly important considerations.

3.2 ANALYSIS OF EXTRAPOLATION ERROR

This method of risk analysis is based on the fact that application of the results of laboratory toxicity tests to field exposures requires a series of extrapolations, each of which is made with some error (Barnthouse et al. 1982a; Suter et al. 1983). The products of the

Table 3.1. Ratios of ambient concentrations (AC) to predicted MATCs and probabilities of exceeding the MATC (risks)

Technology	RAC[a] No.	RAC name	Predicted MATC (μg/L)	AC:MATC	Risk
TOSCO-II	12	Benzene	303	0.74	0.44
	20	Carboxylic acids	2.7 E 06	7.7 E-4	0.004
	21	Phenols	600	0.25	0.22
	34	Cadmium	0.29	0.10	0.09
Paraho	14	Mono/diaromatic hydrocarbons	124	0.43	0.32
	18	Alkaline N heterocyclics	1341	0.086	0.17

[a]Risk analysis category.

Table 3.2. Toxicity quotients for effects on fish and algae (ambient contaminant concentration/toxic benchmark concentration) for the TOSCO-II process.

RAC[a] No.	RAC name	Fish acute	Fish Chronic	Algae
11	Volatile N-heterocyclics	ND[b]	ND	ND
12	Benzene	4.25 E-02	ND	4.19 E-05
13	Aliphatic/alicyclic hydrocarbons	1.37 E-04	ND	ND
15	Polycyclic aromatic hydrocarbons	5.18 E-07	ND	3.71 E-08
18	Alkaline N heterocyclics	2.69 E-03	ND	ND
19	Neutral N, O, S heterocyclics	ND	ND	ND
20	Carboxylic acids	1.17 E-02	ND	ND
21	Phenols	1.68 E-02	6.85 E-02	7.50 E-03
31	Arsenic	3.75 E-04	ND	2.15 E-03
32	Mercury	1.61 E-05	ND	3.12 E-05
33	Nickel	6.55 E-04	2.75 E-02	3.00 E-02
34	Cadmium	1.71 E-02	1.76 E-02	4.92 E-03
35	Lead	2.00 E-05	1.05 E-03	4.00 E-05
38	Total dissolved solids[c]	1.7 E-02	ND	ND

[a]Risk analysis category.

[b]No data on toxicity.

[c]The 96-h LC_{50} for fathead minnows in raw shale leachate occurred at 17 g/L TDS and was accounted for by the major inorganic species (Meyer et al. 1985).

extrapolation are estimates of the centroid and distribution of the ambient concentration of a chemical at which a particular response will occur. The risk of occurrence of the prescribed response is equal to the probability that the response concentration is less than the ambient concentration, given the probability distribution of each. In this section, we extrapolate from acute toxic concentrations for test species of fish to chronic responses of the salmonids from the reference sites (Travis et al. 1983). The acute toxicity criterion is the 96-h LC_{50}. The chronic toxicity criterion is the life-cycle maximum allowable toxicant concentration (MATC), an interval bounded by the highest no-observed-effects concentration and the lowest concentration causing a statistically significant effect on growth, survival, or reproduction in a life-cycle toxicity test (Mount and Stephan 1969). The geometric mean of the bounds is used as a point estimate of the MATC, as was done in calculating the national water quality criteria (USEPA 1980a-p).

A detailed description of the computational methods used for the analysis of extrapolation error (AEE) is contained in Suter et al. (in press). Acute toxicity data from the Columbia National Fisheries Research Laboratory are used for the extrapolation between species. Chronic and subchronic toxicity data (Suter et al., in press) were used to develop a regression relationship between acute and chronic toxicity data. Variances associated with extrapolating acute toxicity between taxa and acute to chronic toxicity are accumulated to provide an estimate of the variability associated with the estimate of chronic toxicity and used in obtaining estimates of risk, given estimates of the distribution of the ambient contaminant concentrations.

The extrapolation error method has been applied to the six RACs with quotients >0.01 to determine the risk of exceeding the threshold for chronic effects (MATC) on a salmonid fish (i.e., trout). The results are presented in Table 3.1. The risks for benzene in the TOSCO-II leachate and mono/diaromatic hydrocarbons in the Paraho leachate are quite large, and all but one of the ratios are greater than the corresponding quotients in Tables 3.2 and 3.3, as would be

Table 3.3. Toxicity quotients for effects on fish and algae (ambient contaminant concentration/toxic benchmark concentration) for the Paraho process

RAC[a] No.	RAC name	Fish acute	Fish chronic	Algae
13	Aliphatic/alicyclic hydrocarbons	5.57 E-04	ND[b]	ND
14	Mono/Diaromatic hydrocarbons	2.35 E-02	8.71 E-02	1.57 E-03
15	Polycyclic aromatic hydrocarbons	3.85 E-04	ND	2.76 E-05
18	Alkaline N heterocyclics	7.67 E-02	ND	ND
19	Neutral N, O, S heterocyclics	ND	ND	ND
21	Phenols	2.84 E-09	8.59 E-09	1.10 E-09

[a]Risk analysis category

[b]No data on toxicity

expected with the greater sensitivity of chronic effects and the general sensitivity of salmonids. These results tend to reinforce the conclusion of the previous section that a real risk of toxic effects on fish is indicated and that these chemical categories deserve further study. The results for carboxylic acids are anomalous in that the predicted MATC for salmonids is higher than the measured LC_{50} for mosquito fish. This extrapolation (atheriniformes to salmoniformes) is based on only six points and its slope is unusually small. Therefore the result is unreliable and suggests the need for a better understanding of the relative sensitivity of atheriniform fish. The chronic toxicity of TDS (which had a high quotient for acute effects -- Table 3.2) can not be determined by this method, since the extrapolation equations were developed for single chemicals, and their applicability to mixtures of unrelated chemicals is problematical.

4. TERRESTRIAL END POINTS

The quotient method consists of dividing the ambient concentrations of toxicants by the concentration at which some toxic effect is induced. It is used in this section to provide an indication of the likelihood of effects from emissions of the individual RACs. Other risk analysis methods (Barnthouse et al. 1982) are not readily applicable to terrestrial organisms because of the small toxicological data base for most terrestrial taxa, the lack of standard tests and toxicological benchmarks in the data base, and the lack of agreed-upon standard responses for most terrestrial biota.

4.1 VEGETATION

4.1.1 Irrigation

Because of the importance of irrigated agriculture in this region, the toxicity of leachate-contaminated water must be considered. Table 4.1 presents quotients of the concentrations in creek water (Tables 2.12 and 2,13) divided by the lowest phytotoxic concentration from a solution culture test for each RAC (Appendix B-2). The results suggest that none of the individual components of the leachate will be toxic to crops. However, this analysis does not include the osmotic effects of the increment of total dissolved solids (TDS) in the leachate (290 mg/L). Although it is not possible to assign a toxic concentration to TDS because of the importance of irrigation practices, soil type, crop, and the background concentration of TDS to which the shale-derived TDS is added it can be said with confidence that this TDS increment will affect agriculture because TDS is already a problem in the Colorado River drainage. Although TDS from a single oil shale plant would be a small contribution to the problem, it is important when considering the economic costs to agriculture of an entire mature oil shale industry.

Table 4.1. Toxicity quotients for irrigation with leachate-contaminated creek water

Technology	RAC[a] No.	RAC name	Creek concentration/ phytotoxic concentration
TOSCO-II	11	Volatile N heterocyclics	2.4 E-4
	12	Benzene	ND[a]
	13	Aliphatic/alicyclic hydrocarbons	1.6 E-4
	15	Polycyclic aromatic hydrocarbons	4 E-3
	18	Alkaline N heterocyclics	ND
	19	Neutral N, O, S heterocyclics	1.0 E-2
	20	Carboxylic acids	1.3 E-6
	21	Phenols	7.5 E-5
	31	Arsenic	ND
	32	Mercury	5.0 E-7
	33	Nickel	3.7 E-3
	34	Cadmium	3.0 E-9
	35	Lead	4.0 E-9
Paraho	13	Aliphatic/alicyclic hydrocarbons	3.1 E-4
	14	Mono/diaromatic hydrocarbons	5.4 E-4
	15	Polycyclic aromatic hydrocarbons	3.0 E-1
	18	Alkaline N heterocyclics	ND
	19	Neutral N, O, S heterocyclics	2.8 E-4
	21	Phenols	1.1 E-11

[a]Risk analysis category.

[b]No data on toxicity.

4.1.2 Air Pollutants

The phytotoxicity data for the gaseous and volatile RACs are presented in Table B-1, the concentrations in ambient ground-level air are in Tables 2.14 and 2.15, and the quotients of the ratios of these values are in Tables 4.2 and 4.3. It is assumed that the RAC is composed entirely of the representative chemical and the background concentration is zero. Quotients are calculated from two classes of data: (1) the lowest toxic concentration found in the literature for any flowering plant species as an indication of maximum toxic potential of the RAC, and (2) the range across studies of the lowest concentrations causing effects on growth or yield of the whole plant or some plant part. The latter set of responses is relatively consistent and closely related to crop and forest yield.

The worst atmospheric toxicants in the Paraho and TOSCO-II emissions are hydrocarbon gases (RAC 6). This rank is biased since the worst-case representative chemical (ethylene) is a plant hormone, whereas most members of this RAC are essentially inert (National Research Council 1976). However, since atmospheric ethylene has caused significant damage to crops near urban areas and petrochemical plants (National Research Council 1976), the emission rate of this gas should be specifically considered in the future. The most serious phytotoxicants in air (ignoring ethylene) are CO, SO_x, and NO_x. The maximum annual average concentrations predicted for NO_x (RAC 3) from both technologies are within a tenth of those that cause reduced yield of cocksfoot and meadow grass. Concentrations of SO_2 are greater than a hundredth of those that reduce growth or yield of several plant species.

Because of its ubiquity and importance as a phytotoxicant, sulfur dioxide (RAC 2) has been relatively well studied for its effects on crop yield. McLaughlin and Taylor (in press) have proposed the following dose-response relationship for yield reduction of beans as a function of SO_2 exposure:

$$\text{percent yield reduction} = -17.4 + 29.2\ (\log \text{dose-ppmh}).$$

This empirical relationship is based on a regression of 20 points from five field experiments on soybeans and snap beans. Eighty percent

Table 4.2. Toxicity quotients for terrestrial plants for the Paraho process. Ambient concentrations in air (annual, median, ground level) and soil (soil solution or whole dry soil basis) are divided by concentrations causing reductions in growth, yield, or other toxic responses[a]

RAC[a] No.	RAC name	Air concentration/ lowest toxic concentration	Range of (air concentration/ growth effects concentration)	Soil concentration/ lowest toxic concentration	Range of (soil concentration/ growth effects concentration)
1	Carbon monoxide	1.24 E-02	2.04 E-06	No accumulation in soil	
2	Sulfur oxides	3.14 E-02	5.23 E-03 - 1.57 E-02	No accumulation in soil	
3	Nitrogen oxides	3.82 E-01	2.01 E-02 - 3.82 E-01	No accumulation in soil	
4	Acid gases	5.21 E-05	5.21 E-05	No accumulation in soil	
5	Alkaline gases	1.57 E-04		No accumulation in soil	
6	Hydrocarbon gases	7.18 E-01	3.46 E-04 - 1.21 E-03		
7	Formaldehyde	No emissions			
8	Volatile organochlorines	No emissions			
9	Volatile carboxylic acids	No emissions			
10	Volatile O&S heterocyclics	No emissions			
11	Volatile N-heterocyclics			7.74 E-05	7.74 E-05
12	Benzene	No emissions			
13	Aliphatic/alicyclic hydrocarbons	3.88 E-12		3.21 E-04	
14	Mono/diaromatic hydrocarbons	1.02 E-05		2.23 E-06	2.23 E-06
15	Polycyclic aromatic hydrocarbons			8.87 E-02[c]	2.72 E-02 - 8.87 E-02[c]
16	Aliphatic amines	No emissions			
17	Aromatic amines	No emissions			
18	Alkaline nitrogen heterocyclics	No phytotoxicity data			
19	Neutral N, O, S heterocyclics			2.46 E-06	2.46 E-07 - 2.46 E-05
20	Carboxylic acids			7.5 E-03[c]	5.36 E-04 - 7.5 E-03[c]
21	Phenols			3.78 E-05	
22	Aldehydes and ketones	No emissions			
23	Nonheterocyclic organosulfur	7.33 E-06	4.04 E-05	5.60 E-08[c]	
24	Alcohols			3.94 E-07	
25	Nitroaromatics	No emissions			
26	Esters	No emissions			
27	Amides	No emissions			
28	Nitriles	No emissions			
29	Tars	No emissions			
30	Respirable particles	No phytotoxicity data			
31	Arsenic			1.69 E-01[c]	7.92 E-03[b] - 1.69 E-01[c]
32	Mercury	1.08 E-04		7.51 E-06	6.89 E-08 - 7.51 E-06
33	Nickel			7.72 E-03[c]	9.15 E-06 - 7.72 E-03[c]
34	Cadmium			5.4 E-03	1.81 E-04[c] - 5.4 E-03
35	Lead			1.75 E-04[c]	1.56 E-06 - 1.75 E-04[c]

[a]Ambient air concentrations, soil, and soil solution concentrations are presented in Table 2.14. Toxic concentrations are presented in Appendix B.

[b]Risk analysis units.

[c]Quotients calculated from concentrations in soil and results of tests performed in soil. Quotients without superscript were calculated from concentrations in soil solution, and results of tests were performed in nutrient solution.

Table 4.3. Toxicity quotients for terrestrial plants for TOSCO-II. Ambient concentrations in air (annual, median, ground level) and soil (soil solution or whole dry soil basis) are divided by concentrations causing reductions in growth, yield, or other toxic responses[a]

RAC[a] No.	RAC name	Phytotoxicity in air: Ambient concentration/ lowest toxic concentration	Phytotoxicity in air: Range of (ambient concentration/ growth effects concentration)	Phytotoxicity in soil or soil solution: Soil concentration/ lowest toxic concentration	Phytotoxicity in soil or soil solution: Range of (soil concentration/ growth effects concentration)
1	Carbon monoxide	3.32 E-04	5.44 E-08	No accumulation in soil	
2	Sulfur oxides	1.29 E-01	2.15 E-02 - 6.44 E-02	No accumulation in soil	
3	Nitrogen oxides	2.88 E-01	1.51 E-02 - 2.88 E-01	No accumulation in soil	
4	Acid gases	2.05 E-08	2.05 E-08		
5	Alkaline gases	6.43 E-06		No accumulation in soil	
6	Hydrocarbon gases	7.48 E-01	3.60 E-04 - 1.26 E-03		
7	Formaldehyde		No Emissions		
8	Volatile organochlorines		No Emissions		
9	Volatile carboxylic acids		No Emissions		
10	Volatile O&S heterocyclics		No Emissions		
11	Volatile N-heterocyclics			5.13 E-05	5.13 E-05
12	Benzene		No Emissions		
13	Aliphatic/alicyclic hydrocarbons	4.14 E-12		8.43 E-04	
14	Mono/diaromatic hydrocarbons	1.27 E-05		2.77 E-06	2.77 E-06
15	Polycyclic aromatic hydrocarbons			1.66 E-02[c]	5.1 E-03 - 1.66 E-02[c]
16	Aliphatic amines		No Emissions		
17	Aromatic amines		No Emissions		
18	Alkaline nitrogen heterocyclics				
19	Neutral N, O, S heterocyclics			1.5 E-06	1.5 E-07 - 1.5 E-06
20	Carboxylic acids			1.01 E-02[c]	5.36 E-04 - 1.01 E-02[c]
21	Phenols			3.78 E-05	
22	Aldehydes and ketones		No Emissions		
23	Nonheterocyclic organosulfur		No Emissions		
24	Alcohols		No Emissions		
25	Nitroaromatics		No Emissions		
26	Esters		No Emissions		
27	Amides		No Emissions		
28	Nitriles		No Emissions		
29	Tars		No Emissions		
30	Respirable particles			No accumulation in soil	
31	Arsenic			4.33 E-03[c]	2.03 E-04[c] - 4.33 E-03[c]
32	Mercury	3.29 E-07		2.28 E-08	2.09 E-10 - 2.28 E-08
33	Nickel			4.08 E-04[c]	4.84 E-07 - 4.08 E-04[c]
34	Cadmium			6.1 E-05	1.36 E-06 - 6.1 E-05
35	Lead			1.71 E-05[c]	1.53 E-07 - 1.71 E-05[c]

[a]Air, soil, and soil solution concentrations are presented in Table 2.15; toxic concentrations are presented in Appendix B.

[b]Risk analysis units.

[c]Quotients calculated from concentrations in soil and results of tests performed in soil; quotients without superscript were calculated from concentrations in soil solution and results of tests were performed in nutrient solution.

of the variation in yield reduction was associated with variation in dosage, and the equation was significant at $\alpha = 0.0001$.

We used this relationship to examine the potential effects of a full growing season exposure to SO_2 on crop yield. If we assume a 200 d growing season for soybeans and a 12-h exposure day, the SO_2 dose at 2.04 $\mu g/m^3$ SO_2 from the Paraho plant is 1.85 ppmh. That dose results in no reduction in yield by McLaughlin and Taylor's formula, which has a threshold for effects on yield of 3.92 ppmh. The dose from TOSCO-II (7.59 ppmh) results in an 8.3% reduction in yield.

This predicted effect is remarkable in that it results from an SO_2 concentration that is more than ten times lower than the lowest concentration reported to affect yield. This anomaly is because of the great length of a growing season relative to the length of experiments. The longest fumigation available to McLaughlin and Taylor was 337 h. Thus, the use of their formula for a full growing season requires an extrapolation of almost a factor of 10 in the duration component of the dose. Because the experimental field fumigations are typically carried out in the most sensitive stage (assumed to be the pod-fill in the case of beans), use of the formula for the full growing season probably overestimates effects.

We might place a lower bound on the level of effect by assuming that effects only occur during pod-fill. If that stage is assumed to last 30 d, the dose is 1.14 ppmh. This is less than 30% of the threshold dose for effects on yield. In the case of a real synfuels plant, this SO_2 emission would be added to a background SO_2 concentration, which may reach 80 $\mu g/m^3$ under the current annual average ambient air quality standard, and would interact with ozone which reaches phytotoxic levels in many areas of the United States.

The phytotoxicity of materials deposited on the landscape is a more complex phenomenon than that of gases and vapors. Because the atmospheric transport model AIRDOS-EPA has a deposition velocity of zero for inorganic gases and does not model the formation of aerosols, RACs 1 through 5 are assumed to not accumulate in the soil. This assumption is likely to be acceptable except in the case of SO_4

deposition in forests with acid soils. The effects of SO_4 deposition in forests are highly controversial, resulting largely from regional-scale atmospheric processes and are beyond the scope of this report. Deposited nongaseous RACs were assumed to accumulate in the soil over the 35-year life of the liquefaction plant. Losses from decomposition and leaching from the root zone were calculated by the terrestrial food-chain model (Sect. 2.3). The toxicity data (Table B-2) were primarily derived from exposure of plants or plant parts to solutions of the chemicals rather than contaminated soil because few data are available on toxicity in soil. Whereas the results of tests conducted using soil can be directly compared with concentrations in the whole soil, results of tests conducted in solution must be compared with a calculated concentration in soil solution. Because the concentration in soil solution is more difficult to model than concentration in whole soil and requires more simplifying assumptions, solution concentrations are less reliable. In addition, as with gases and vapors, the toxicity data are from a wide variety of tests and measured responses that are not equivalent. For most of the RACs, only one or two chemicals have been tested. We cannot determine whether the chemicals used are representative of the entire RAC.

The most phytotoxic RACs deposited in soil are polycyclic aromatic hydrocarbons (PAHs-RAC 15) and arsenic (31). The high rank of RAC 15 is suspect because benzo(a)pyrene and some other PAHs appear to act as plant hormones and can (like some herbicides) stimulate growth at very low concentrations. While PAHs can modify plant growth at concentrations as low as 0.5 ng/g soil, there is no evidence that they reduce plant growth, even at relativity high experimental concentrations (Edwards 1983).

Compounds of arsenic (primarily sodium arsenite and arsenic trioxide) have been used as herbicides, but other forms, including elemental arsenic, are relatively nontoxic (Gough et al. 1979, Benenati et al. 1977). Studies of arsenic toxicity near atmospheric sources indicate that phytotoxic effects can result from atmospheric deposition. However, the co-occurrence of other pollutants and the effects of poorly defined soil properties have prevented the

determination of threshold effects in the field. The high quotients for arsenic results from studies of effects on growth and yield of legumes in soil (Table B-2), but these are calculated from extractable rather than total soil concentrations. Total soil concentrations are more nearly equivalent to our predicted soil concentration, but the only study of phytotoxicity that expresses arsenic exposure in those terms found a threshold for negative effects on corn growth that is more than 100 times the predicted concentration. This disparity could be because of the plant species, soils, or arsenic forms used in the tests. Because of these ambiguities, and because arsenic appears to be the most serious soil pollutant, methods for predicting its effects require attention.

4.2 WILDLIFE

4.2.1 Drinking Water

The leachates from the waste piles do not appear to be toxic to livestock and wildlife in the well water (which might be used in stock tanks) or the creek. However, the increment of total dissolved solids (TDS) derived from shale appears to pose some risk, since TDS is predicted to occur in the creek at approximately a tenth of the recommended criterion for livestock (3000 mg/L-Committee on Water Quality Criteria 1972). Although 290 µg/L is not an exceptionally high TDS value for this region, this value is highly uncertain, and the background TDS to which this increment is added may be high. In addition, sensitivities of most wildlife to salinity are unknown, and sensitivities to toxic materials commonly vary by more than a factor of 10 (e.g., Hudson et al. 1984). Therefore, toxic effects on wildlife, particularly nonmammalian wildlife, cannot be excluded.

4.2.2 Air Pollutants

Tables 4.4 and 4.5 present the lowest quotients for toxicity of air pollutants to terrestrial animals. The quotients are calculated

Table 4.4. Toxicity quotients for terrestrial animals for the Paraho process. Concentrations in air (annual, median, and ground level) are divided by lethal concentrations and the lowest toxic concentrations.[a]

RAC[b] No.	RAC name	Lowest lethal concentration	Lowest toxic concentration
1	Carbon monoxide	2.43 E-08	5.21 E-04
2	Sulfur oxides	1.13 E-04	2.04 E-02
3	Nitrogen oxides	3.49 E-03	8.53 E-02
4	Acid gases	6.95 E-08	2.09 E-07
5	Alkaline gases	4.7 E-07	2.53 E-05
6	Hydrocarbon gases		2.23 E-09
7	Formaldehyde	No emissions	
8	Volatile organochlorines	No emissions	
9	Volatile carboxylic acids	No emissions	
10	Volatile O&S heterocyclics	No emissions	
11	Volatile N-heterocyclics	5.53 E-08	5.53 E-08
12	Benzene	No emissions	
13	Aliphatic/alicyclic	4.72 E-08	3.1 E-06
14	Mono/diaromatic hydrocarbons	1.28 E-06	2.43 E-05
15	Polycyclic aromatic hydrocarbons	No data on respiratory toxicity	
16	Aliphatic amines	No emissions	
17	Aromatic amines	No emissions	
18	Alkaline nitrogen heterocyclics	No data on respiratory toxicity	
19	Neutral N, O, S heterocyclics	No data on respiratory toxicity	
20	Carboxylic acids	No data on respiratory toxicity	
21	Phenols	No data on respiratory toxicity	
22	Aldehydes and ketones	No emissions	
23	Nonheterocyclic organosulfur	1.32 E-07	1.98 E-06
24	Alcohols	5.68 E-07	9.84 E-06
25	Nitroaromatics	No emissions	
26	Esters	No emissions	
27	Amides	No emissions	
28	Nitriles	No emissions	
29	Tars	No emissions	
30	Respirable particles		2.57 E-01
31	Arsenic		8.32 E-04
32	Mercury		6.35 E-06
33	Nickel	7.21 E-08	7.21 E-08
34	Cadmium	6.5 E-07	3.25 E-04
35	Lead		2.2 E-05

[a]Ambient air concentrations are presented in Table 2.3-1. Toxic concentrations are presented in Appendix B.

[b]Risk analysis categories.

Table 4.5. Toxicity quotients for terrestrial animals for TOSCO-II. Concentrations in air (annual, median, and ground level) are divided by lethal concentrations and the lowest toxic concentrations[a]

RAC[b] No.	RAC name	Lowest lethal concentration	Lowest toxic concentration
1	Carbon monoxide	6.5 E-10	1.39 E-05
2	Sulfur oxides	4.65 E-04	8.37 E-02
3	Nitrogen oxides	2.63 E-03	6.44 E-02
4	Acid gases	2.73 E-11	8.19 E-11
5	Alkaline gases	1.93 E-08	1.04 E-06
6	Hydrocarbon gases		2.32 E-09
7	Formaldehyde	No Emissions	
8	Volatile organochlorines	No Emissions	
9	Volatile carboxylic acids	No Emissions	
10	Volatile O&S heterocyclics	No Emissions	
11	Volatile N heterocyclics	3.67 E-08	3.67 E-08
12	Benzene	No Emissions	
13	Aliphatic/alicyclic hydrocarbons	5.04 E-08	3.31 E-06
14	Mono/diaromatic hydrocarbons	1.59 E-06	3.03 E-05
15	Polycyclic aromatic hydrocarbons		
16	Aliphatic amines	No Emissions	
17	Aromatic amines	No Emissions	
18	Alkaline N heterocyclics		
19	Neutral N, O, S heterocyclics		
20	Carboxylic acids		
21	Phenols		
22	Aldehydes and ketones	No Emissions	
23	Nonheterocyclic organosulfur	No Emissions	
24	Alcohols	No Emissions	
25	Nitroaromatics	No Emissions	
26	Esters	No Emissions	
27	Amides	No Emissions	
28	Nitriles	No Emissions	
29	Tars	No Emissions	
30	Respirable particles		8.39 E-02
31	Arsenic		7.48 E-06
32	Mercury		1.94 E-08
33	Nickel	1.23 E-09	1.23 E-09
34	Cadmium	8.98 E-10	4.49 E-07
35	Lead		7.28 E-07

[a]Ambient air concentrations are presented in Table 2.3-2. Toxic concentrations are present in Appendix B.

[b]Risk analysis categories.

from the lowest lethal concentration for any species and from the lowest concentration producing any toxic effect (Table B-3) divided by the highest annual average ground-level concentration in air. Data from all species are pooled because there were not enough on the nonmammalian taxa for separate treatment. Carcinogenesis and other genotoxic effects were not included.

Lethality is considered because it is a consistent and frequently determined response that has clear population implications; however, all predicted concentrations are well below lethal levels. The lowest toxic concentrations include a diversity of end points, most of which cannot be readily related to effects on wildlife populations but do occur at concentrations that are as low as a ten-thousandth of lethal concentrations. These responses range from increased airway resistance in 1-h exposures of guinea pigs to impaired lung and liver function in human occupational exposures. The most toxic RACs by this sublethal criterion are the conventional combustion products sulfur oxides (2), nitrogen oxides (3), and respirable particulates (30). Whereas these concentrations may constitute a locally significant increment to the background concentration of these major pollutants, the significance of ambient air pollution to wildlife is largely unknown. The assumption that protection of human health will automatically protect wildlife is not scientifically defensible.

5. EVALUATION OF RISKS

The results of this analysis indicate that the leachate from spent shale that is wetted with retort wastewaters may enter surface waters and cause toxic effects on fish. Although none of the individual components of the leachate are expected to be toxic alone, total dissolved solids (TDS), cadmium, and a number of organic chemicals appear in high enough concentrations in the predicted stream water to show that the chemistry and toxicity of wastewater-spent shale leachate requires further attention. The predicted TDS in creek water is safe for livestock consumption but is high enough to raise concerns about sensitive wildlife. TDS is also a concern with respect to irrigated agriculture since the existing TDS load in the Colorado River basin is already a problem. These results depend on the models of leachate formation and transport which are highly uncertain, and the background water quality, which is unspecified. The leachate chemistry is not well defined, and the transport model, while reasonably simulating the generic conditions in the region, is unlikely to provide a good description of any particular site.

Gases and vapors emitted by the TOSCO-II and Paraho processes appear to pose a minor threat to terrestrial plants and animals. The most serious problems appear to arise from conventional products of combustion: sulfur oxides, nitrogen oxides, and respirable particles that may already be present in high concentrations at synfuels plant sites. Of the materials deposited on the soil, arsenic in the Paraho emissions is the most likely to become phytotoxic. However, it is unlikely to be a problem except when deposited on acid soils with preexisting high concentrations of toxic trace elements. Site-specific assessments will have to consider local soil chemistry as well as the effects of rugged terrain, which may cause local air pollutant deposition to be higher than predicted by our flat terrain atmospheric dispersion model. On the basis of this analysis, major pollutant effects on range, crop, and wildlife production seem unlikely. Mining, waste disposal, and other physical disruptions, which inevitably

destroy vegetation and wildlife habitat and were not within the scope of this analysis, seem likely to be the major causes of ecological effects.

It is not possible to state that either technology poses a greater environmental risk on the basis of this analysis. The characterization of the Paraho leachate is too incomplete because we do not have the necessary data from leaching studies. Of the three RACs that occur in significant amounts in the atmospheric emissions, SO_x emissions are greater for TOSCO-II; NO_x emissions are about equal, and arsenic emissions are greater for Paraho.

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APPENDIX A

Aquatic Toxicity Data

Table A-1. Acute toxicity of synfuels chemicals to aquatic animals

RAC	Representative chemical(s)	Test organism[a]	Test type[b]	Duration (h)	Concentration (mg/L)	Notes[c]	Reference
1	Carbon monoxide					No toxicity data	
2	Sulfur oxides					Aquatic problems associated with pH, not direct toxicity	
3	Nitrogen oxides					Aquatic problems associated with pH, not direct toxicity	
4	H_2S	Scud (*Gammarus pseudolimnaeus*)	LC_{50}	96	0.022		Oseid and Smith 1974
		Bluegill					
		(adults)	TL_m	96	0.0448	Flow-through test	Smith et al. 1976
		(juveniles)	TL_m	96	0.0478	Flow-through test	Smith et al. 1976
		(fry, 35-d-old)	TL_m	96	0.0131	Flow-through test	Smith et al. 1976
		(eggs)	TL_m	72	0.0190	Flow-through test	Smith et al. 1976
		Northern pike					
		(eggs)	TL_m	96	0.034-0.037	DO = 2-6 ppm	Adelman and Smith 1970
		(fry)	TL_m	96	0.009-0.026	DO = 2-6 ppm	Adelman and Smith 1970
5	Ammonia	Rainbow trout					
		(fry, 85-d-old)	TL_m	24	0.068		Rice and Stokes 1975
		(adults)	TL_m	24	0.097		Rice and Stokes 1975
		Rainbow trout	LC_{50}	24	0.50		Herbert and Shurben 1963
		Rainbow trout	LC_{50}	24	0.47		Lloyd and Orr 1969
		Rainbow trout (fry)	LC_{50}	24	0.2		EIFAC 1970
		(fingerlings)	LC_{50}	24	0.2		EIFAC 1970
6	Heptane	Mosquitofish	TL_m	96	4924		Wallen et al. 1957
7	Formaldehyde	Several fish species	LC_{50}	24	50-120		National Research Council 1981

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type[b]	Duration (h)	Concentration (mg/L)	Notes[c]	Reference
8	Carbon tetrachloride	*Daphnia magna*	LC_{50}	48	35.2		US EPA 1980a
		Fathead minnow	LC_{50}	96	43.1	Flow-through test	US EPA 1980a
		Bluegill	LC_{50}	96	27.3		US EPA 1980a
		Bluegill	LC_{50}	96	125.0		US EPA 1980a
	Chloroform	*D. magna*	LC_{50}	48	28.9		US EPA 1980b
		Bluegill	LC_{50}	96	100.0		US EPA 1980b
		Bluegill	LC_{50}	96	115.0		US EPA 1980b
		Rainbow trout	LC_{50}	96	43.8		US EPA 1980b
9	Acetic acid	Fathead minnow	LC_{50}	96	88.0		Mattson et al. 1976
		Mosquitofish	TL_m	96	251.0		Wallam et al. 1957
10	Volatile O- and S-heterocyclics					No toxicity data	
11	Pyridine	Ciliate (*Tetrahymena pyriforma*)	LC_{50}	72	1211.8	50% growth inhibition	Schultz et al. 1980
		D. magna	LC_{50}	48	1165		Canton and Adema 1978
		D. magna	LC_{50}	48	1755		Canton and Adema 1978
12	Benzene	*D. magna*	LC_{50}	48	203.0-620.0		US EPA 1980c
		D. magna	LC_{50}	48	426.0		Canton and Adema 1978
		Fathead minnow	LC_{50}	96	32.0		US EPA 1980c
		Fathead minnow	LC_{30}	96	15.1	Flow-through test	DeGraeve et al. 1982
		Mosquitofish	LC_{50}	96	1300.0		Wallam et al. 1957
		Rainbow trout	LC_{50}	96	5.3	Flow-through test	US EPA 1980c
13	Cyclohexane	Fathead minnow	LC_{50}	96	93.0		Mattson et al. 1976
		Fathead minnow	TL_m	96	30.0		Pickering and Henderson 1966a
		Fathead minnow	TL_m	96	32.0		Pickering and Henderson 1966a
		Bluegill	TL_m	96	31.0		Pickering and Henderson 1966a
	Indan	Fathead minnow	LC_{50}	96	14.0		Mattson et al. 1976

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type[b]	Duration (h)	Concentration (mg/L)	Notes[c]	Reference
14	Toluene	*D. magna*	LC_{50}	48	39.22		Millemann, et al. 1984
		Fathead minnow	TL_m	96	44.0		Pickering and Henderson 1966a
		Fathead minnow	TL_m	96	45.0		Pickering and Henderson 1966a
		Bluegill	TL_m	96	24.0		Pickering and Henderson, 1966a
		Bluegill	LC_{50}	96	12.7		US EPA 1980d
	Naphthalene	*D. magna*	LC_{50}	48	2.16		Millemann et al. 1984
		D. magna	LC_{50}	48	8.57		US EPA 1980e
		Fathead minnow	LC_{50}	48	3.14		Millemann et al. 1984
		Fathead minnow	LC_{50}	96	4.90-8.90	2 tests	US EPA 1980e
		Rainbow trout	LC_{50}	96	2.30		US EPA 1980e
	Xylene	Fathead minnow	TL_m	96	42.0		Mattson et al. 1976
		Goldfish	TL_m	96	17.0		Brenniman et al. 1976
15	Anthracene					Not toxic to fish, even in super-saturated solutions	McKee and Wolf 1963
	Phenanthrene	*D. magna*	LC_{50}	48	0.75		Millemann et al. 1984
		D. magna	LC_{50}	48	1.10		Parkhurst 1981
		Rainbow trout (embryo-larva)	LC_{50}	96	0.04		Birge and Black 1981
	Fluoranthene	*D. magna*	LC_{50}	48	325.0		US EPA 1980f
		Bluegill	LC_{50}	96	3.9		US EPA 1980f
16	Aliphatic amines					No toxicity data	
17	Aniline	*D. magna*	LC_{50}	48	0.65		Canton and Adema 1978
		Daphnia cucullata	LC_{50}	48	0.68		Canton and Adema 1978
		D. magna	LC_{50}	48	0.58		Millemann et al. 1984
	3,5-Dimethylaniline	*D. magna*	LC_{50}	48	1.29		Millemann et al. 1984

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type[b]	Duration (h)	Concentration (mg/L)	Notes[c]	Reference
18	Quinoline	Ciliate (*T. pyriforma*)	LC_{50}	72	125.7	50% growth inhibition	Schultz et al. 1980
		D. magna	LC_{50}	48	30.28		Millemann et al. 1984
		Fathead minnow	LC_{50}	48	1.50		Millemann et al. 1984
		Fathead minnow	LC_{50}	96	46.0		Mattson et al. 1976
	2-Methylquinoline	Ciliate (*T. pyriforma*)	EC_{50}	72	48.7	50% growth inhibition	Schultz et al. 1980
	2,6-Dimethylquinoline	Ciliate (*T. pyriforma*)	EC_{50}	72	33.0	50% growth inhibition	Schultz et al. 1980
19	Neutral N-,O-,S-heterocyclics					No toxicity data	
20	Benzoic acid	Mosquitofish	TL_m	96	180		Wallam et al. 1957
21	Phenol	*D. magna*	LC_{50}	48	19.79		Millemann et al. 1984
		D. magna	LC_{50}		9.6		US EPA 1980g
		D. magna (Young)	TL_m	50	7.0		Dowden and Bennett 1965
		Copepod (*Mesocyclops leukarti*)	LC_{50}		108.0		US EPA 1980g
		Fathead minnow	LC_{50}	48	25.6		Millemann et al. 1984
		Fathead minnow	LC_{50}	96	24.0-67.5	4 tests	US EPA 1980g
		Bluegill	LC_{50}		11.5-23.9	6 tests	US EPA 1980g
		Rainbow trout	LC_{50}		8.9-11.6	2 flow-through tests	US EPA 1980g
	2-Methyphenol	*D. magna*	LC_{50}	48	9.2		US EPA 1980g
		D. magna	LC_{50}	48	23.5		US EPA 1980g
		Fathead minnow	TL_m	96	12.55	Soft water	Pickering and Henderson 1966a
		Fathead minnow	TL_m	96	13.42	Hard water	Pickering and Henderson 1966a
		Bluegill	TL_m	96	20.78	Soft water	Pickering and Henderson 1966a
	4-Methylphenol	Fathead minnow	TL_m	96	19.0		Mattson et al. 1976

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type[b]	Duration (h)	Concentration (mg/L)	Notes[c]	Reference
	Mixed cresol isomers	Aquatic life	TL_m	96	1.0-10.0		Kingsbury et al. 1979
	2,4-Dimethylphenol	*D. magna*	LC_{50}	48	2.12		US EPA 1980h
		Fathead minnow (juvenile)	LC_{50}	96	16.75	Flow-through test	US EPA 1980h
		Bluegill	LC_{50}	96	7.75		US EPA 1980h
	3,4-Dimethylphenol	Fathead minnow	LC_{50}	96	14.0		Mattson et al. 1976
	2,5-Dimethylphenol	*D. magna*	LC_{50}	48	0.96		Millemann et al. 1984
22	Acrolein	*D. magna*	LC_{50}	48	0.057		US EPA 1980i
		D. magna	LC_{50}	48	0.080		US EPA 1980i
		Mosquitofish	LC_{50}	48	0.061		National Research Council 1981
		Bluegill	LC_{50}	96	0.100		US EPA 1980i
		Bluegill	LC_{50}	96	0.090		US EPA 1980i
		Brown trout	LC_{50}	24	0.046		National Research Council 1981
		Rainbow trout	LC_{50}	24	0.065		National Research Council 1981
		Largemouth bass	LC_{50}	96	0.160		US EPA 1980i
	Acetaldehyde	Bluegill	LC_{50}	96	53.0		National Research Council 1981
	Acetone	*D. magna*	LC_{50}	48	12,600		Canton and Adema 1978
23	Nonheterocylic organosulfur					No toxicity data	
24	Alcohols					No toxicity data	
25	Nitroaromatics					No toxicity data	
26	Di-2-ethylhexyl phthalate	*D. magna*	LC_{50}		11.1		US EPA 1980j

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type[b]	Duration (h)	Concentration (mg/L)	Notes[c]	Reference
	Diethyl phthalate	D. magna	LC_{50}		52.1		US EPA 1980j
		Bluegill	LC_{50}		98.2		US EPA 1980j
	Butylbenzl phthalate	D. magna	LC_{50}		92.3		US EPA 1980j
		D. magna	LC_{50}	48	3.7		Gledhill et al. 1980
		Fathead minnow	LC_{50}	96	5.3	Hardness: 160	Gledhill et al. 1980
		Fathead minnow	LC_{50}	96	2.1	Hardness: 40	Gledhill et al. 1980
		Bluegill	LC_{50}		43.3		US EPA 1980j
		Bluegill	LC_{50}	96	1.7		Gledhill et al. 1980
		Rainbow trout	LC_{50}	96	3.3		Gledhill et al. 1980
	Di-n-butyl phthalate	Scud (G. pseudo-limnaeus)	LC_{50}	96	2.1		Mayer and Sanders 1973
		Fathead minnow	LC_{50}	96	1.3		Mayer and Sanders 1973
		Bluegill	LC_{50}	96	0.73		Mayer and Sanders 1973
		Rainbow trout	LC_{50}	96	6.47		Mayer and Sanders 1973
27	Amides					No toxicity data	
28	Acrylonitrile	D. magna	LC_{50}		7.55		US EPA 1980k
		Fathead minnow	LC_{50}	96	14.3		US EPA 1980k
		Fathead minnow	LC_{50}	96	18.1		US EPA 1980k
		Fathead minnow	LC_{50}	96	10.1	Flow-through test	US EPA 1980k
		Bluegill	LC_{50}	96	11.8		US EPA 1980k
		Bluegill	LC_{50}		10.1		US EPA 1980k
29	Tars					No aquatic emissions	
30	Respirable particles					No aquatic emissions	
31	Arsenic	D. magna	TL_m	48	7.4		Hohreiter 1980
		D. magna	EC_{50}	48	5.28	Immobilization	Anderson 1946
		Daphnia pulex	EC_{50}	48	1.04	Immobilization	Sanders and Cope 1966
		Stonefly (Pteronarcys californica)	LC_{50}	96	22.04		Sanders and Cope 1968
		Fathead minnow (juvenile)	LC_{50}	96	15.66	Flow-through test	Cardwell et al. 1976
		Bluegill (juvenile)	LC_{50}	96	41.76	Flow-through test	Cardwell et al. 1976
		Bluegill	LC_{50}		15.37		US EPA 1980l
		Rainbow trout	LC_{50}		13.34		US EPA 1980l
		Brook trout	LC_{50}	93	14.96	Flow-through test	Cardwell et al. 1976

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type	Duration (h)	Concentration (mg/L)	Notes	Reference
32	Mercury (inorganic)	*D. magna*	LC_{50}	48	0.005		Biesinger and Christensen 1972
		Stonefly (*Acroneuria lycorius*)	TL_m	96	2.0		Warnick and Bell 1969
		Fathead minnow	LC_{50}		0.19		US EPA 1980m
		Rainbow trout	LC_{50}		0.31		Hohreiter 1980
		Coho salmon	LC_{50}		0.24		US EPA 1980m
		Rainbow trout (juvenile)	LC_{50}		0.155-0.4	4 tests	US EPA 1980m
	Methylmercury	Rainbow trout	LC_{50}		0.03		Hohreiter 1980
		Rainbow trout					
		(sac fry)	LC_{50}	96	0.024		Hohreiter 1980
		(fingerling)	LC_{50}	96	0.042		Hohreiter 1980
		(Juvenile)	LC_{50}		0.025		US EPA 1980m
		Brook trout					
		(juvenile)	LC_{50}	96	0.084	Flow-through test	McKim et al. 1976
		(yearling)	LC_{50}	96	0.065	Flow-through test	McKim et al. 1976
33	Nickel	*D. magna*	LC_{50}		1.81	Hardness: 51	US EPA 1980n
		D. magna	LC_{50}		2.34	Hardness: 100	US EPA 1980n
		Mayfly (*Ephemerella subvaria*)	TL_m	96	4.0	Hardness: 42	Warnick and Bell 1969
		Stonefly (*A. lycorius*)	TL_m	96	33.5	Hardness: 40	Warnick and Bell 1969
		Damselfly (unidentified)	TL_m	96	21.2	Hardness: 50	Rehwoldt et al. 1973
		Midge (*Chironomus* sp.)	TL_m	96	8.6	Hardness: 50	Rehwoldt et al. 1973
		Caddisfly (unidentified)	TL_m	96	30.2	Hardness: 50	Rehwoldt et al. 1973
		Fathead minnow	LC_{50}		4.58-5.18	Hardness: 20 2 flow-through tests	US EPA 1980n
		Fathead minnow	TL_m	96	25.0	Hardness: 210 flow-through test	Pickering 1974
		Bluegill	TL_m	96	5.18-5.36	Hardness: 20 2 tests	Pickering and Henderson 1966b
		Bluegill	TL_m	96	39.6	Hardness: 360	Pickering and

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type	Duration (h)	Concentration (mg/L)	Notes	Reference
							Henderson 1966b
		Rainbow trout	LC_{50}	96	35.5	Flow-through test	Hale 1977
		Fish sp., general	LC_{50}	96	4.6-9.8	Soft water	Hohreiter 1980
		Fish sp., general	LC_{50}	96	39.2-42.4	Hard water	Hohreiter 1980
34	Cadmium	*D. magna*	LC_{50}		0.0099	Hardness: 51	US EPA 1980o
		D. magna	LC_{50}		0.033	Hardness: 104	US EPA 1980o
		D. magna	LC_{50}		0.049	Hardness: 209	US EPA 1980o
		Mayfly (*Ephemerella grandis grandis*)	TL_m	96	28.0		Clubb et al. 1975
		Mayfly (*E. subvaria*)	TL_m	96	2.0	Hardness: 54	Warnick and Bell 1969
		Stonefly (*Pteronarcella badia*)	TL_m	96	18.0		Clubb et al. 1975
		Damselfly (unidentified)	TL_m	96	8.1	Hardness: 50	Rehwoldt et al. 1973
		Midge (*Chironomus*)	TL_m	96	1.2	Hardness: 50	Rehwoldt et al. 1973
		Caddisfly (unidentified)	TL_m	96	3.4	Hardness: 50	Rehwoldt et al. 1973
		Fathead minnow	TL_m	96	0.630	Hardness: 20	Pickering and Henderson 1966b
		Fathead minnow	TL_m	96	72.6	Hardness: 360	Pickering and Henderson 1966b
		Bluegill	TL_m	96	1.94	Hardness: 20	Pickering and Henderson 1966b
		Bluegill	LC_{50}		21.1	Hardness: 207	US EPA 1980o
		Rainbow trout (swim-up and parr)	LC_{50}	96	0.001-0.00175	Hardness: 23 2 flow-through tests	US EPA 1980o
		Rainbow trout	LC_{50}	96	0.00175	Hardness: 31; flow-through test	US EPA 1980o
		Carp	LC_{50}		0.24	Hardness: 55	US EPA 1980o
		Chinook salmon (Parr)	LC_{50}		0.0035	Hardness: 23	US EPA 1980o
		Brook trout	LC_{50}		0.0024	Hardness: 44 (sodium sulfate)	US EPA 1980o
		Green sunfish	LC_{50}		2.84	Hardness: 20	US EPA 1980o
		Pumpkinseed	LC_{50}		1.5	Hardness: 55	US EPA 1980o

Table A-1. (continued)

RAC	Representative chemical(s)	Test organism[a]	Test type	Duration (h)	Concentration (mg/L)	Notes	Reference
35	Lead	*D. magna*	LC_{50}		0.612	Hardness: 54	US EPA 1980p
		D. magna	LC_{50}		0.952	Hardness: 110	US EPA 1980p
		Fathead minnow	LC_{50}	96	2.4	Hardness: 20	US EPA 1980p
		Fathead minnow	TL_m	96	482.0	Hardness: 360	Pickering and Henderson 1966b
		Bluegill	TL_m	96	23.8	Hardness: 20	Pickering and Henderson 1966b
		Bluegill	TL_m	96	442.0	Hardness: 360	Pickering and Henderson 1966b
		Rainbow trout (fry)	LC_{50}	96	0.6		Hohreiter 1980
		Rainbow trout	LC_{50}	96	1.17	Hardness: 32; flow-through test	Davies et al. 1976
		Rainbow trout	LC_{50}	96	1.0		Hohreiter 1980
		Rainbow trout	LC_{50}	96	8.0		US EPA 1980p
		Brook trout	LC_{50}	96	4.1	Hardness: 44	US EPA 1980p
36	Fluorine	*D. magna*		48	270.0	"Toxic threshold"	Hohreiter 1980
		Goldfish		96	120.0	100% kill	Hohreiter 1980
		Goldfish		12-29	1000.0	100% kill in soft water	Hohreiter 1980
		Goldfish		60-102	1000.0	100% kill in hard water	Hohreiter 1980
		Rainbow trout	TL_m	240	2.3-7.5	TL_m varies with temperature	Angelovic et al. 1961

[a]Latin binomials are listed in Appendix C.

[b]LC_{50} = concentration required to kill 50% of test organisms.
TL_m = median tolerance limit.
EC_{20} = effective concentraton causing a designated effect on 20% of test organismsn.

[c]Hardness values are given in milligrams per liter as $CaCO_3$. DO = dissolved oxygen.

Table A-2. Chronic toxicity of synfuels chemicals to aquatic animals.

RAC	Representative chemical(s)	Test organism[a]	Test type	Duration (d)	Concentration (mg/L)	Notes	Reference
8	Carbon tetrachloride	Fathead minnow	Embryo-larval		>3.4		U.S. EPA, 1980a
	Chloroform	Rainbow trout	Embryo-larval	27	1.2	200 mg/L water hardness	U.S. EPA, 1980b
		Rainbow trout	Embryo-larval	27	2.0	50 mg/L water hardness	U.S. EPA, 1980b
		Rainbow trout	Embryo	23	10.6	40% teratogenesis	U.S. EPA, 1980b
12	Benzene	*Daphnia magna*	Life cycle		>98.0		U.S. EPA, 1980c
14	Naphthalene	Fathead minnow	Embryo-larval		0.62		U.S. EPA, 1980e
21	Phenol	Fathead minnow	Embryo-larval		2.56		U.S. EPA, 1980g
	2,4-Dimethylphenol	Fathead minnow	Embryo-larval		2.191		U.S. EPA, 1980h
		Fathead minnow	Embryo-larval		2.475		U.S. EPA, 1980h
22	Acrolein	*D. magna*	Life cycle		0.024		U.S. EPA, 1980i
		D. magna	Life cycle		0.034	Survival reduced after 64 days	National Research Council, 1981
		Fathead minnow	Life cycle		0.021		U.S. EPA, 1980i
26	Di-2-ethylhexyl phthalate	*D. magna*	Life cycle		<0.003		U.S. EPA, 1980j
		Rainbow trout	Embryo-larval		0.008		U.S. EPA, 1980j
	Butylbenzyl phthalate	*D. magna*	Life cycle		0.44		U.S. EPA, 1980j
		Fathead minnow	Embryo-larval		0.22		U.S. EPA, 1980j
28	Acrylonitrile	*D. magna*	Life cycle		>3.6		U.S. EPA, 1980k
		Fathead minnow	LC_{50}	30	2.6		U.S. EPA, 1980k
31	Arsenic	*D. magna*	Life cycle		0.912		U.S. EPA, 1980l
		D. magna	TLm	21	2.85		Hohreiter, 1980
		Bass sp., general		10	7.60	Toxic	Hohreiter, 1980
		Pink salmon		10	5.00	Lethal	Hohreiter, 1980
32	Mercuric chloride	*D. magna*	Life cycle		0.001 - 0.0025	4 tests	U.S. EPA, 1980m
	Methylmercuric chloride	*D. magna*	Life cycle		0.001		U.S. EPA, 1980m
		Fathead minnow			0.00023	92% dead, 3 months	Hohreiter, 1980
		Brook trout	Life cycle		0.00052		U.S. EPA, 1980m

Table A-2. (continued).

RAC	Representative chemical(s)	Test organism[a]	Test type	Duration (d)	Concentration (mg/L)	Notes	Reference
33	Nickel	*D. magna*	Life cycle		0.015	Hardness: 51 (mg/L as $CaCO_3$)	U.S. EPA, 1980n
		D. magna	Life cycle		0.123	Hardness: 105	U.S. EPA, 1980n
		Caddisfly (*Clistoronia magnifica*)	Life cycle		0.465	Hardness: 50	U.S. EPA, 1980n
		Fathead minnow	Embryo-larval		0.109	Hardness: 44	U.S. EPA, 1980n
		Fathead minnow	Life cycle		0.527	Hardness: 210	U.S. EPA, 1980n
		Rainbow trout	Embryo-larval		0.350	Hardness: 50	U.S. EPA, 1980n
34	Cadmium	*D. magna*	Life cycle		0.00015	Hardness: 53	U.S. EPA, 1980o
		D. magna	Life cycle		0.00021	Hardness: 103	U.S. EPA, 1980o
		D. magna	Life cycle		0.00044	Hardness: 209	U.S. EPA, 1980o
		Midge (*Tanytarsus dissimilis*)			0.0031		U.S. EPA, 1980o
		Fathead minnow	Life cycle		0.046	Hardness: 201	U.S. EPA, 1980o
		Bluegill	Life cycle		0.050	Hardness: 207	U.S. EPA, 1980o
		Brook trout	Embryo-larval		0.0017	Hardness: 36	U.S. EPA, 1980o
		Brook trout	Embryo-larval		0.0092	Hardness: 187	U.S. EPA, 1980o
35	Lead	*D. magna*	Life cycle		0.012	Hardness: 52	U.S. EPA, 1980p
		D. magna	Life cycle		0.128	Hardness: 151	U.S. EPA, 1980p
		Stonefly (*Acroneuria lycorias*)	LC_{50}	14	64.0		Hohreiter, 1980
		Mayfly (*Ephemerella subvaria*)	LC_{50}	7	16.0		Hohreiter, 1980
		Caddisfly (*Hydropsyche betteri*)	LC_{50}	7	32.0		Hohreiter, 1980
		Bluegill	Embryo-larval		0.092	Hardness: 41	U.S. EPA, 1980p
		Rainbow trout	Embryo-larval		0.019	Hardness: 28	U.S. EPA, 1980p
		Rainbow trout	Embryo-larval		0.102	Hardness: 35	U.S. EPA, 1980p
36	Fluorine	Rainbow trout		21	113.0	100% kill, 45 mg/L $CaCO_3$	Hohreiter, 1980
		Rainbow trout		21	250.0	100% kill, 320 mg/L $CaCO_3$, yearling trout	Hohreiter, 1980

[a]Latin binomials are listed in Appendix C.

Table A-3. Toxicity of synfuels chemicals to algae.

RAC	Representative chemical(s)	Test organism	Test type	Duration (h)	Concentration (mg/L)	Notes	Reference
12	Benzene	*Chlorella vulgaris*	EC_{50}	48	525.0	Reduction in cell numbers	U.S. EPA, 1980c
14	Toluene	*C. vulgaris*	EC_{50}	24	245.0	Reduction in cell numbers	U.S. EPA, 1980d
		Selenastrum capricornutum	EC_{50}	96	433.0	Reduction in cell numbers and chlorophyll *a* production	U.S. EPA, 1980d
	Naphthalene	*C. vulgaris*	EC_{50}	48	33.0	Reduction in extrapolated cell numbers	U.S. EPA, 1980e
		Chalamydomonas angulosa	EC_{61}	24	34.4	61% mortality of cells	U.S. EPA, 1980e
15	Fluoranthene	*S. capricornutum*	EC_{50}	96	54.4	Reduction in cell numbers	U.S. EPA, 1980f
		S. capricornutum	EC_{50}	96	54.6	Reduction in chlorophyll *a* production	U.S. EPA, 1980f
17	Aniline	*Agmenellum quadruplicatum*			0.010	Diffusion from disk onto algal lawn inhibited growth for 3-7 days	Batterton et al., 1978
	p-Toluidene	*A. quadruplicatum*			0.010	Same as above for all 4 species	Batterton et al., 1978
		Coccochloris elabens			0.010		
		Eucapsis sp.			0.010		
		Oscillatoria williamsii			0.010		
21	Phenol	*S. capricornutum*			20.0	Growth inhibition of 12-66% depending on time (2-3 d) and temperature (20, 24, 28°C)	U.S. EPA, 1980g
		S. capricornutum	EC_{50}	24	40.0	Reduction in cell numbers	U.S. EPA, 1980g
		Nitzschia linearis	EC_{50}	120	258.0	Reduction in cell numbers	U.S. EPA, 1980g
		Chlorella pyrenoidosa	EC_{100}	48	1500.0	Complete destruction of chlorophyll	U.S. EPA, 1980g
		C. vulgaris	EC_{20}	80	470.0	Growth inhibition	U.S. EPA, 1980g
	2,4-Dimethylphenol	*C. pyrenoidosa*	EC_{100}	48	500.0	Complete destruction of chlorophyll	U.S. EPA, 1980g

Table A-3. (continued).

RAC	Representative chemical(s)	Test organism	Test type	Duration (h)	Concentration (mg/L)	Notes	Reference
26	Butylbenzyl phthalate	*S. capricornutum*	EC_{50}	96	0.11	Reduction in chlorophyll *a*	U.S. EPA, 1980j
		S. capricornutum	EC_{50}	96	0.13	Reduction in cell numbers	U.S. EPA, 1980j
		Microcystis aeruginosa	EC_{50}	96	1000.0	Reduction in cell numbers	U.S. EPA, 1980j
		Navicula pelliculosa	EC_{50}	96	0.60	Reduction in cell numbers	U.S. EPA, 1980j
	Dimethyl phthalate	*S. capricornutum*	EC_{50}	96	42.7	Reduction in chlorophyll *a*	U.S. EPA, 1980j
		S. capricornutum	EC_{50}	96	39.8	Reduction in cell numbers	U.S. EPA, 1980j
	Diethyl phthalate	*S. capricornutum*	EC_{50}	96	90.3	Reduction in chlorophyll *a*	U.S. EPA, 1980j
		S. capricornutum	EC_{50}	96	85.6	Reduction in cell numbers	U.S. EPA, 1980j
31	Arsenic	*Cladophora*, *Spirogyra*, *Zygnema* sp.	EC_{100}	336	2.32	100% kill	U.S. EPA, 1980l
		Scenedesmus sp.		96	20.0	Threshold effects	Cushman et al., 1977
32	Mercuric chloride	*C. vulgaris*	EC_{50}	768	1.03	Cell division inhibition	U.S. EPA, 1980m
		Spring diatom assemblages	EC_{50}	2	0.08	Reduction in photosynthetic activity	U.S. EPA, 1980m
	Methylmercuric chloride	*Coelastrum microporum*	EC_{50}		2.4-4.8	Growth inhibition	U.S. EPA, 1980m
33	Nickel	*Chlamydomonas*, *Chlorella*, *Haematococcus*, *Scenedesmus* sp.			0.1-0.7	Growth reduced in all cultures in water with 50 mg/L $CaCO_3$	U.S. EPA, 1980n
		Phormidium ambiguum	EC_{16}	336	0.5-10.0	Growth inhibition	Cushman et al., 1977
		Scenedesmus			1.5	Threshold effects	Cushman et al., 1977
34	Cadmium	*Scenedesmus* sp.			0.0061	Reduction in cell numbers	U.S. EPA, 1980o
		Scenedesmus sp.			0.05-0.5	Growth inhibition	Cushman et al., 1977
		C. pyrenoidosa			0.25	Growth inhibition	U.S. EPA, 1980o
		C. vulgaris	EC_{50}		0.06	Growth reduction	U.S. EPA, 1980o
		S. capricornutum			0.05	Growth reduction	U.S. EPA, 1980o
		Mixed species			0.005	Population reduction	U.S. EPA, 1980o

Table A-3. (continued).

RAC	Representative chemical(s)	Test organism	Test type	Duration (h)	Concentration (mg/L)	Notes	Reference
35	Lead	Ankistrodesmus sp.	EC_{24}		1.00	Growth inhibition	U.S. EPA, 1980p
		Chlorella sp.	EC_{53}		0.50	Growth inhibition	U.S. EPA, 1980p
		Scenedesmus sp.	EC_{35}		0.50	Growth inhibition	U.S. EPA, 1980p
		Selenastrum sp.	EC_{52}		0.50	Growth inhibition	U.S. EPA, 1980p
		Anabaena sp.	EC_{50}	24	15.0-26.0	Reduction in CO_2 fixation	U.S. EPA, 1980p
		Chlamydomonas sp.	EC_{50}	24	17.0	Reduction in CO_2 fixation	U.S. EPA, 1980p
		Cosmarium sp.	EC_{50}	24	5.0	Reduction in CO_2 fixation	U.S. EPA, 1980p
		Navicula sp.	EC_{50}	24	17.0-28.0	Reduction in CO_2 fixation	U.S. EPA, 1980p
		Scenedesmus sp.			2.5	Threshold effects	Cushman et al., 1977

APPENDIX B

Terrestrial Toxicity Data

Table B-1. Toxicity of chemicals in air to vascular plants.

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration ($\mu g/m^3$)	Notes[b]	Reference
1	Carbon monoxide	Grapefruit	-CO_2 uptake		1.8 E03	Detached leaves	National Research Council, 1977a
		Red clover	-20% N fixation		1.1 E05		National Research Council, 1977a
		Several species	-Growth	552	1.1 E07		National Research Council, 1977a
		Popinac	Defoliation	24	2.3 E07		National Research Council, 1977a
2	Sulfur dioxide[c]	Barley	-44% yield	72/wk	3.9 E02	Field, growing season	U.S. EPA, 1982
		Durum wheat	-42% yield	72/wk	3.9 E02	Field, growing season	U.S. EPA, 1982
		Alfalfa	-26% foliage	100	1.3 E02	5 hr/d, 5 d/wk, 4 wk	U.S. EPA, 1982
		Tobacco, Bel W3	-22% foliage	100	1.3 E02	5 hr/d, 5 d/wk, 4 wk	U.S. EPA, 1982
		Cocksfoot	-40% total wt.	2070	1.78 E02	103.5 hr/wk, 20 wk	U.S. EPA, 1982
		Broadbean	Reduced net photosynthesis	8	9.2 E01		U.S. EPA, 1982
		White pine	Needle damage threshold	6	6.5 E01	sensitive clone	U.S. EPA, 1982
		Norway spruce	-25% volume growth	1680	1.3 E02		U.S. EPA, 1982
3	Nitrogen dioxide	Wheat	-12% straw yield	334	2 E03		Zahn, 1975
		Bush bean	-27% yield	639	2 E03		Zahn, 1975
		Spruce	-7% linear growth	1900	2-3 E03	-17% linear growth in following year	Zahn, 1975
		Endive	-37% yield	620	2 E03		Zahn, 1975
		Carrot	-30% yield	357	4 E03		Zahn, 1975
		Tobacco, bean, tomato, radish, oat, soybean	Visible foliar injury	4	3.8 E03		Heck and Tingey, 1979
		Cocksfoot and meadow grass	-Yield	2070	2.1 E02	103.5 h/wk, 20 wk	Ashenden and Mansfield, 1978
4	Hydrogen sulfide	Green bean	-20% photosynthesis	3	7.0 E02		Taylor, in press
		Green bean	-25% whole plant yield	64	2.8 E02	4 h/d, 4 d/wk for 4 wk	Taylor, in press
		Alfalfa	-39% yield	672-840	4.2 E02	continuous fumigation	Thompson and Kats, 1978
		Lettuce	-66% yield	2112	4.2 E02	continuous fumigation	Thompson and Kats, 1978
		Douglas-fir	-weight and linear growth	5904	4.2 E02	continuous fumigation	Thompson and Kats, 1978
		Sugar beets	-38% sugar	3216	4.2 E02	continuous fumigation	Thompson and Kats, 1978
			+43% sugar	3216	4.2 E01	continuous fumigation	Thompson and Kats, 1978
5	Ammonia	Mustard	Injury	4	2.1 E03		National Research Council, 1979b

Table B-1. (continued).

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration (μg/m³)	Notes[b]	Reference
6	Ethylene	African marigold	Epinasty	20	1.15 E00		National Air Pollution Control Administration, 1970
		Carnation	Flowers do not open	72	1.15 E02		National Air Pollution Control Administration, 1970
		Cotton	Growth inhibition	720	6.85 E02		National Air Pollution Control Administration, 1970
		Lily family	Growth inhibition	168	8.60 E02		National Air Pollution Control Administration, 1970
		Various plants	Growth inhibition	240	2.39 E03		National Air Pollution Control Administration, 1970
7	Formaldehyde	Alfalfa	Injury	5	4.9 E02		National Research Council, 1981
		Petunia	Necrosis and leaf symptoms	48	2.47 E02		Kingsbury et al., 1979
8	Vinyl chloride	Cowpea, cotton, squash	Injury	168	2.6 E05		Heck and Pires, 1962
12	Benzene	Pinto bean	Red-bordered spots	0.6	3.0 E04		Kingsbury et al., 1979
13	Cyclohexene	Runner bean	LD_{50}, toxicity to leaves	1	1.12 E12		Ivens, 1952
14	Toluene	Pinto bean	Bronze color	0.6	1.88 E05		Kingsbury et al., 1979
17	Aniline	Loblolly pine	Damage	3	2.7 E02		Cheeseman and Perry, 1977
22	Acrolein	Alfalfa	Oxident-type damage	9	2.5 E02		Kingsbury et al., 1979
23	Carbonyl sulfide	Runner bean	LD_{50}, toxicity to leaves	1	2.7 E03		Ivens, 1952
		Green bean	-13% growth	64	4.9 E02	4 h/d, 4 d/w for 4 wk	Taylor, in press

Table B-1. (continued).

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration ($\mu g/m^3$)	Notes[b]	Reference
32	Mercury (metalic)	Rose	Severe damage		1.0 E01		Stahl, 1969
		Sugar beet	Damage	5	2.8 E02		Waldron and Terry, 1975
		English ivy	Damage	12	1.5 E04		Waldron and Terry, 1975
		Coleus, Thevetia and Ricinus	Abscision	168	1.0 E01		Siegel and Siegel, 1979
	Mercuric chloride	Thevetia and Ricinus	Necrosis	168	1.0 E01		Siegel and Siegel, 1979
	Dimethylmercury	Coleus, Thevetia and Ricinus	Abscision	36	1.0 E01		Siegel and Siegel, 1979

[a]Latin binomials are listed in Appendix C.

[b]Unless "field" is noted, results are for laboratory studies.

[c]See also Table 4.

Table B-2. Toxicity of chemicals in soil or solution to vascular plants.

RAC	Representative chemical	Test organism* and life stage	Test medium	Response	Duration	Concentration (μg/g)	Reference
9	Acetic acid	Barley (seedling)	Solution in sand	Root growth inhibition	5d	600	Lynch, 1977
11	Methyl pyridine	Alfalfa (sprout)	Solution	Root growth inhibition	4d	93.1	Naik et al.,1972
13	Hexene	Oat (seedling)	Solution	Mortality		25.2	Chen and Elofson, 1978
14	Xylene	Sugar beet (seedling)	Solution	Root growth inhibition	2d	100	Allen et al., 1961
15	Benzo(a)pyrene	Corn (sprout)	Solution	Root growth stimulation	6h	0.0005	Deubert et al., 1979
	3,4-benzopyrene	Tobacco (seedling)	Soil	78% growth stimulation	60d	0.01	Graf and Nowak, 1966
	1,2-benzanthracene	Tobacco (seedling)	Soil	80% growth stimulation	60d	0.02	Graf and Nowak, 1966
	1,2,5-6-di-benzanthrancene	Tobacco (seedling)	Soil	130% growth stimulation	60d	0.02	Graf and Nowak, 1966
16	Dimethylalkylamine	Gram, rice	Solution	Mortality		7.0	Dutta et al., 1972
19	Benzothiophene	Cucumber (sprout)	Solution	9% root growth inhibition	4d	10	Schlesinger and Mowry, 1951
	Indole, 3-ethyl-1H	Oat, cress, mustard (sprout)	Solution	Growth inhibition		100	Davies et al., 1937
	Indole-3 -acetic acid, 1H	Oat, cress, mustard (sprout)	Solution	Growth inhibition		100	Davies et al., 1937
		Cucumber	Solution	Mortality	11d	35	Hilton and Nomura, 1964
		Pea (sprout)	Solution	Germination reduced by >50%	8h	10	Shukla, 1972
20	Benzoic acid	Lettuce (seedling)	Solution on filter paper	23% growth inhibition		25	Chou and Patrick, 1976
	2-hydroxy -benzoic acid	Rice (seedling)	Soil	Seedling growth inhibition	5d	1.6	Gaur and Pareek, 1976
		Lettuce (seedling)	Solution on filter paper	61% growth inhibition		25	Chou and Patrick, 1976
21	Phenol	Durum wheat (seed)	Solution	Germination inhibition	4d	2000	Badilescu et al., 1967
22	4-hydroxy -benzaldehyde	Lettuce (seedling)	Solution on filter paper	26% growth inhibition		100	Chou and Patrick, 1976

Table B-2. (continued).

RAC	Representative chemical	Test organism* and life stage	Test medium	Response	Duration	Concentration (μg/g)	Reference
22	Acrolein	Alfalfa		Oxidant-type damage	9h	0.1	Kingsbury et al., 1979
23	Carbon disulfide	Apple	Soil	Root injury		420	Underhill and Cox, 1940
24	Ethanol	Lettuce (seed)	Solution	Germination inhibition	44h	1,000,000	Meyer and Mayer, 1971
27	N,N-dimethyl-formamide	Lettuce (seed)	Solution	Nearly total suppression of germination	24h	1,000,000	Meyer and Mayer, 1971
	2-metnyl -benzamide	Poppy, chickweed, carrot, ryegrass corn, lucerne (mature)	Soil	13-87% reduction in yield	3-5w	220,000	Pizey and Wain, 1959
31	Arsenic[d]	Corn (seedling)	Soil	10% growth reduction (wet tissue weight)	4w	64	Woolson, et al., 1971
		Cotton (mature)	Soil (fine sandy loam)	Approx. 55% reduction in yield	6w	8[b]	Deuel and Swoboda, 1972
		Cotton (mature)	Soil (clay)	Approx. 40% reduction in yield	6w	28[b]	Deuel and Swoboda, 1972
		Soybean (mature)	Soil (fine sandy loam)	Approx. 45% reduction in yield	6w	3[b]	Deuel and Swoboda, 1972
		Soybean (mature)	Soil (clay)	Approx. 40% reduction in yield	6w	12[b]	Deuel and Swoboda, 1972
		Cowpea	-	Retarded growth	-	1[b]	Albert and Arndt, 1932
32	Mercury	Barley (seed-sprout)	Solution	12% growth reduction (fresh weight)	7d post germination	5 (as Hg^{++})	Mukhiya et al., 1983
		Barley (seed-sprout)	Solution	12% growth reduction (fresh weight)	7d post germination	1 (as PMA)[c]	Mukhiya et al., 1983
		Lettuce (seed-sprout)	Solution	68% reduction in elongation of lettuce hypocotyl	5d post germination	109 (as $HgCl_2$)	Nag et al., 1980
33	Nickel	Corn (mature)	Solution	10% decrease in net photosynthesis	7d	5	Carlson et al., 1975
		Sunflower (mature)	Solution	10% decrease in net photosynthesis	7d	0.8	Carlson et al., 1975

Table B-2. (continued).

RAC	Representative chemical	Test organism* and life stage	Test medium	Response	Duration	Concentration (μg/g)	Reference
33		Oats (seeds-seedlings)	Solution in coarse sand	Stunted growth	Up to 22d post germination	10	Vergnano and Hunter, 1953
		Oats (mature)	Soil	Decreased grain yield	Whole life	50	Halstead et al., 1969
		Barley (seedling)	Solution in sand	Over 50% reduction in whole plant fresh weight	3w	281 ($NiSO_4 \cdot 7H_2O$)	Agarwala et al., 1977
34	Cadmium	Corn (mature)	Solution	10% decrease in net photosynthesis	7d	0.9	Carlson et al., 1975
		Sunflower (mature)	Solution	10% decrease in net photosynthesis	7d	0.45	Carlson et al., 1975
		Soybeans (mature)	Solution in sand and vermiculite	35% decrease in fresh weight of pods	90d	2	Huang et al., 1974
		Bean (5 weeks old)	Solution	50% growth reduction	3w	0.2	Page et al., 1972
		Beet (5 weeks old)	Solution	50% growth reduction	3w	0.2	Page et al., 1972
		Turnip (5 weeks old)	Solution	50% growth reduction	3w	0.2	Page et al., 1972
		Corn (5 weeks old)	Solution	50% growth reduction	3w	1.2	Page et al., 1972
		Lettuce (5 weeks old)	Solution	50% growth reduction	3w	0.9	Page et al., 1972
		Tomato (5 weeks old)	Solution	50% growth reduction	3w	4.8	Page et al., 1972
		Barley (5 weeks old)	Solution	50% growth reduction	3w	5.6	Page et al., 1972
		Pepper (5 weeks old)	Solution	50% growth reduction	3w	2.0	Page et al., 1972
		Cabbage (5 weeks old)	Solution	50% growth reduction	3w	9.0	Page et al., 1972
		Soybean (seedling)	Soil (silty clay loam)	15% reduction in yield (dry weight)	5w	2.5	Haghiri, 1973
		Wheat (seedling)	Soil (silty clay loam)	20% reduction in yield (dry weight)	5w	2.5	Haghiri, 1973
		Lettuce (mature)	Soil (silty clay loam)	40% reduction in yield (fresh weight)	Whole life	2.5	Haghiri, 1973

Table 8-2. (continued).

RAC	Representative chemical	Test organism* and life stage	Test medium	Response	Duration	Concentration (μg/g)	Reference
34		Sycamore (sapling)	Soil (6:1 silty clay loam & perlite)	25% reduction in new stem growth	90d	39	Carlson and Bazzaz, 1977
35	Lead	Soybeans (mature)	Solution in sand and vermiculite	35% decrease in fresh weight of pods	90d	62	Huange et al., 1974
		Lettuce (44d old)	Soil (silty clay loam)	25% reduction in yield	30d	1000 ($Pb(NO_3)_2$	John and VanLaerhoven 1972
		Corn (25d seedling)	Vermiculite and solution	20% decrease in photosynthesis	11-21d	1000	Bazzaz et al., 1974
		Soybean (25d seedling)	Vermiculite and solution	20% decrease in photosynthesis	11-21d	2000	Bazzaz et al., 1974
		Sycamore (sapling)	Soil (6:1 silty clay loam & perlite)	25% reduction in new stem growth	90d	500	Carlson and Bazzaz, 1977

*Latin binomials are listed in Appendix C.

[a]Arsenic shows a stimulatory effect on plants when present at low concentrations (40-50 μg/g total As or 5 μg/g extractable As in soil) (Woolson et al., 1971).

[b]Concentration of contaminant available in solution.

[c](PMA-Phenyl mercuric acetate).

Table B-3. Toxicity of chemicals in air to animals.

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration (μg/m^3)	Notes	Reference
1	Carbon monoxide	Rabbit	Aortic lesions	4	1.51 E05		National Research Council, 1977a
		Dog	Heart damage	1008	4.3 E04		National Research Council, 1977a
		Chicken	75% egg hatch	432	4.9 E05	egg exposed	National Research Council, 1977a
		Rabbit	90% neonate survival	720	1.0 E05	mother exposed	National Research Council, 1977a
		Human	Lethality		9.2 E08		Cleland and Kingsbury, 1977
2	Sulfur dioxide	Guinea pig	Increased airway resistance	1	4.2 E02		U.S. EPA, 1982
		Guinea pig	LT_{50}	1.1	5.8 E06		U.S. EPA, 1982
		Dog	Increased airway resistance	5,400	1.3 E04		U.S. EPA, 1982
		Chicken	Modified nasal clearance		3.7 E03	Intermittent exposure, 7 d	Wakabayashi et al., 1977
	Sulfuric acid	Guinea pig	Respiratory function	1	1.0 E02		Wakabayashi et al., 1977
		Guinea pig	Lethality	8	1.8 E04		Wakabayashi et al., 1977
		Dog	Respiratory function	4,725	8.9 E02		Wakabayashi et al., 1977
3	Nitrogen dioxide	Guinea pig	LC_{50}	1	1.5 E05		National Research Council, 1977b
		Rat	11% lethality	5,120	2.3 E04		National Research Council, 1977b
		Rat	Bronchial damage	24	2.8 E04		National Research Council, 1977b
		Mouse	Defects in pulmonary microbial defense	24	3.8 E03		National Research Council, 1977b
		Rat and mouse	Pulmonary pathologies	Chronic	9.4 E02	Also decreased resistance to infection	National Research Council, 1977b
4	Hydrogen sulfide	Canaries, rats and dogs	Pulmonary irritation	Subacute	7.0 E04	No established chronic effects	National Research Council, 1979a

Table B-3. (continued).

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration ($\mu g/m^3$)	Notes	Reference
5	Ammonia	Chicken	Increased disease susceptibility	72	1.3 E04	Newcastle virus	National Research Council, 1979b
		Pig	Respiratory irritation	840	4.3 E04		National Research Council, 1979b
		Rabbit	LT_{50}	33	7.0 E06		National Research Council, 1979b
		Mouse	Lethal threshold	16	7.0 E05		National Research Council, 1979b
		Human	Throat irritation	Immediate	2.8 E05		National Research Council, 1979b
6	Acetylene	Human	Unconsciousness	0.08	3.7 E08		National Research Council, 1976
7	Formaldenyde	Rat	LC_{50}	4	5.7 E05		National Research Council, 1981
		Guinea pigs	Increased airway resistance	1	3.6 E02		National Research Council, 1981
		Rat	Respiratory and eye irritation and liver weight loss	1400	1.0 E03		National Research Council, 1981
8	Chloroform	Mouse	LC_{50}		1.4 E05		Kingsbury et al., 1979
		Human	Enlarged liver	Chronic	4.9 E04	In workplace air	Kingsbury et al., 1979
9	Acetic acid	Mouse	LC_{50}	1	1.4 E07		Kingsbury et al., 1979
		Human	Irritation	0.05	2.0 E06		Kingsbury et al., 1979
		Human	Respiratory, stomach and skin irritation	Chronic	1.5 E05	7-12 years, workplace exposure	National Research Council, 1976
10	Furan	Rat	Lethal threshold	8-48	2.4 E08		Kingsbury et al., 1979
	Thiophene	Mouse	Lethal threshold	8-48	3.0 E07		Kingsbury et al., 1979
11	Pyridine	Rat	LC_{50}	4	1.3 E07		Kingsbury et al., 1979
	2-Ethylpyridine	Rat	LC_{100}	3	2.4 E07		Kingsbury et al., 1979
12	Benzene	Human	Lethal threshold	Chronic	1.9 E05	Workplace exposure	National Research Council, 1976

Table B-3. (continued).

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration (μg/m³)	Notes	Reference
13	Pentane	Mouse	Lethality	--	3.8 E08		Kingsbury et al., 1979
	Cyclopentane	Mouse	Lethality	--	1.1 E08		Kingsbury et al., 1979
	Hexane	Mouse	Lethality		1.2 E08		Kingsbury et al., 1979
		Human	Dizziness	0.17	1.8 E07		Kingsbury et al., 1979
	Cyclonexane	Rabbit	Lethality	1	9.2 E07		Kingsbury et al., 1979
		Rabbit	Narcosis and convulsions	1	4.5 E07		Kingsbury et al., 1979
	Heptane	Human	Dizziness	0.10	4.1 E06		Kingsbury et al., 1979
	Butadiene	Human	Respirtory and eye irritation	8	1.8 E07		Kingsbury et al., 1979
	Cyclopentadine	Rat	Liver and kidney damage	245	1.4 E06	exposoure = 7 hr/day for 35 days	Kingsbury et al., 1979
14	Toluene	Rat	Lethal threshold	4	1.5 E07		Kingsbury et al., 1979
		Human	Psychological effects	--	3.8 E05		Kingsbury et al., 1979
	Ethyl benzene	Rat	Lethal threshold	4	1.7 E07		Kingsbury et al., 1979
		Human	Eye irritation	<0.08	8.8 E05		Kingsbury et al., 1979
	p-Xylene	Mouse	Lethal threshold	4	1.5 E07		Kingsbury et al., 1979
	Tetrahydro-naphthalene	Guinea pig	Lethal threshold	136	1.5 E06	8 hours for 17 days	Kingsbury et al., 1979
	Naphthalene	Human	Eye irritation and damage	--	7.9 E04		Kingsbury et al., 1979
15	(No data on respiratory toxicity but several members of this RAC are carcinogens)						Kingsbury et al., 1979
16	Ethylamine	Rat	Lethal threshold	4	5.5 E06		Kingsbury et al., 1979
		"Animals"	Lung, liver and kidney damage	1008	1.8 E05		Kingsbury et al., 1979
	1-Aminopropane	Rat	LC_{50}	4	5.6 E06		Kingsbury et al., 1979
17	Aniline	Rat	LC_{50}	4	9.5 E05		Kingsbury et al., 1979
	Dimethylanaline	Mouse	LC_{50}	7	7.4 E05	Mixed isomers	Kingsbury et al., 1979
18	(No data on respiratory toxicity)						
19	(No data on respiratory toxicity)						
20	(No data on respiratory toxicity)						
21	(No data on respiratory toxicity)						

Table B-3. (continued).

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration ($\mu g/m^3$)	Notes	Reference
22	Acrolein	Rat	LC_{50}	4	1.8 E04		National Research Council, 1981
		Monkey	Respiratory system damage	2,160	5.1 E02		National Research Council, 1981
	Acetaldehyde	Mice, rabbits and guinea pigs	LC_{50}	4	2.0 E06		National Research Council, 1981
	Proprionaldehyde	Rat	LC_{50}	0.5	6.2 E07		National Research Council, 1981
		Rat	Reduced weight gain	36	3.1 E06	6 h/d x 6 d	National Research Council, 1981
	butyraldehyde	Rat	LC_{50}	0.5	1.7 E08		National Research Council, 1981
	Butanone	Mouse	LC_{50}	0.75	6.1 E08		National Research Council, 1981
23	Methyl mercaptan	Rat	Lethal threshold	--	2.0 E07		Kingsbury et al., 1979
	Ethyl mercaptan	Rat	LC_{50}	--	1.1 E07		Kingsbury et al., 1979
		Human	Central nervous system effects	--	1.0 E04		Kingsbury et al., 1979
	n-Butyl mercaptan	Rat	LC_{50}	4	1.5 E07		Kingsbury et al., 1979
		Human	"Toxic effect"	3	1.0 E04		Kingsbury et al., 1979
	Thiophenol	Rat	LC_{50}	4	1.5 E05		Kingsbury et al., 1979
	Carbon disulfide	Human	Central nervous system effects		5.0 E04	7 years exposure	Cleland and Kingsbury, 1977
24	Methanol	Monkey	LC_{50}		1.3 E06		Kingsbury et al., 1979
		Human	Central nervous system effects		7.5 E04		Kingsbury et al., 1979
	Ethanol	Human	Eye and respiratory irritation and mental effects		1.9 E06		Kingsbury et al., 1979
25	(No data on respiratory toxicity)						Kingsbury et al., 1979
26	Methyl acetate	Human	Severe toxic effects	1	1.5 E06		Kingsbury et al., 1979
	Methyl methacrylate	Rat	LC_{50}	1	1.5 E07		Kingsbury et al., 1979
	Butyl acetate	Human	Throat irritation		9.6 E05		Kingsbury et al., 1979
		Human	Toxic effects	1	9.6 E06		Kingsbury et al., 1979
	n-Amyl acetate	Human	Toxic threshold	0.5	1.0 E06		Kingsbury et al., 1979
27	(No data on respiratory toxicity)						Kingsbury et al., 1979
28	Acetonitrile	Rat	Lethal threshold	4	1.3 E07		Kingsbury et al., 1979
		Human	Bronchial effects		2.7 E05		Kingsbury et al., 1979
	Acrylonitrile	Rat	Lethal threshold	4	1.1 E06		Kingsbury et al., 1979

Table B-3. (continued).

RAC	Representative chemical	Test organism[a]	Response	Exposure Duration (hours)	Exposure Concentration ($\mu g/m^3$)	Notes	Reference
29	(No data on respiratory toxicity)						Kingsbury et al., 1979
30	Fly ash	Monkey	Slight lung fibrosis	13,390	4.6 E02		National Research Council, 1979c
31	Arsenic trioxide	Rat	Weight lag and physiological effects	24	2.5 E01		National Research Council, 1977c
32	Mercury (metal)	Human	Toxic threshold		1.0 E03		Cassidy and Furr, 1978
		Rabbit	Toxic threshold		2.9 E04		Cassidy and Furr, 1978
		Human	Central nervous system effects		1.7 E02	40 yr. exposure	Kingsbury et al., 1979
33	Nickel carbonyl	Rat	LC_{50}	0.5	2.4 E05		National Research Council, 1975
34	Cadmium oxide fumes	Human	Lethality	8	5.0 E03		Hammons et al., 1978
	Cadmium oxide dust	Human	Impaired lung function		3.15 E03	20 yr. exposure	Hammons et al., 1978
	Cadmium	Human	Pulmonary and renal effects		1.0-27 E01	Occupational exposure	Kingsbury et al., 1979
35	Lead	Human	Threshold of overt poisoning		5.0 E02	Occupational exposure	National Research Council, 1972

[a]Latin binomials are lised in Appendix C.

APPENDIX C

Common and Scientific Names of Animals and Plants

Animals

Common name	Scienfitic name
Bigmouth buffalo	*Ictiobus cyprinellus*
Black crappie	*Pomoxis nigromaculatus*
Bluegill	*Lepomis macrochirus*
Brook trout	*Salvelinus fontinalis*
Brown trout	*Salmo trutta*
Canary	*Serinus canarius*
Carp	*Cyprinus carpio*
Channel catfish	*Ictalurus punctatus*
Chicken	*Gallus gallus*
Chinook salmon	*Oncorhynchus tshawytacha*
Coho salmon	*Oncorhynchus kisutch*
Dog	*Canis familiaris*
Fathead minnow	*Pimephales promelas*
Goldfish	*Carassius auratus*
Green sunfish	*Lepomis cyanellus*
Guinea pig	*Cavia cobaya*
Human	*Homo sapiens*
Largemouth bass	*Micropterus salmoides*
Monkey	*Macaca* sp.
Mosquitofish	*Gambusia affinis*
Mouse	*Mus musculus*
Northern pike	*Esox lucius*
Pig	*Sus scrofa*
Pink salmon	*Oncorhynchus gorbuscha*
Pumpkinseed	*Lepomis gibbosus*
Rabbit	*Oryctolagus cuniculus*
Rainbow trout	*Salmo gairdneri*
Rat	*Rattus rattus*
Smallmouth buffalo	*Ictiobus bulbalus*
White bass	*Morone chrysops*

Plants

Common name	Scientific name
African marigold	*Tagetes* sp.
Alfalfa	*Medicago sativa*
Apple	*Malus sylvestris*
Barley	*Hordeum vulgare*
Bean	*Phaseolus vulgaris*
Broadbean	*Vicia faba*
Bush bean	*Phaseolus vulgaris*
Cabbage	*Brassica oleracea*
Carnation	*Dianthus caryophyllos*
Carrot	*Daucus carota*
Chickweed, common	*Stellaria media*
Cocksfoot	*Dactylis glomerata*
Coleus	*Coleus blumei*
Corn	*Zea mays*
Cotton	*Gossypium hirsutum*
Cowpea	*Vigna sinensis*
Cress	*Lepidium sativum*
Cucumber	*Cucumis sativus*
Durum wheat	*Triticum durum*
Endive	*Cicorium endivia*
English ivy	*Hedera helix*
Gram	*Cicer arietinum*
Grapefruit	*Citrus paradisi*
Green bean	*Phaseolus vulgaris*
Lettuce	*Lactuca sativa*
Loblolly pine	*Pinus taeda*
Lucerne	*Medicago sativa*
Meadowgrass	*Poa pratensis*
Mustard	*Brassica alba*
Norway spruce	*Picea abies*
Oat	*Avena sativa*
Oat, wild	*Avena fatua*
Pea	*Psoralea corylifolia*
Pepper	*Capsicum frutescens*
Petunia	*Petunia* sp.
Pinto bean	*Phaseolus vulgaris*
Popinac	*Acacia farnesiana*
Poppy	*Papaver* sp.
Radish	*Raphanus sativus*
Red clover	*Trifolium pratense*
Rice	*Oryza sativa*
Ricinus	*Ricinus communis*
Rose	*Rosa* sp.
Runner bean	*Phaseolus vulgaris*
Ryegrass, Italina	*Lolium multiflorum*
Soybean	*Glycine max*
Spruce	*Picea abies*
Squash	*Cucurbita* sp.

Plants (continued)

Common name	Scientific name
Sugar beet	*Beta vulgaris*
Sunflower	*Helianthus annuus*
Sycamore	*Platanus occidentalis*
Thevetia	*Thevetia neriifolca*
Tobacco	*Nicotiana tabacum*
Tomato	*Lycopersicon esculentum*
Turnip	*Brassica napus*
Wheat	*Triticum durum*
White pine	*Pinus strobus*

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