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Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations

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ABSTRACT

Pacific Northwest Laboratory, under contract to the U.S. Nuclear Regulatory Commission (NRC), identified and evaluated methods for estimating radioactive and toxic particulate and gaseous airborne releases from uranium milling operations. Such methods need to be standardized so that all uranium mills can provide adequate data for NRC evaluation of potential environmental impacts and of compliance with 10 CFR 20, 40 CFR 190, and the National Environmental Policy Act. The general method for calculating source terms is to multiply together a normalized emission rate, contaminant content, emission control factor, and processing rate for each process being evaluated. This report describes the sources of airborne releases (ore storage area, ore crushing and grinding, ore processing, yellowcake production, and tailings impoundment) and the calculational procedures for estimating radioactive and toxic source terms. Example calculations are provided.

EXECUTIVE SUMMARY

Standardized methods for estimating airborne radioactive and toxic material releases from the various operations in uranium mills are needed in order to provide adequate data for evaluation of the source impacts. These data would enable the evaluation of potential effects and environmental impacts of the milling operations, including evaluation of compliance with 10 CFR 20 and 40 CFR 190, and assessment of overall radiological impact as part of the complete environmental impact assessment required by the National Environmental Policy Act (NEPA).

Pacific Northwest Laboratory, under contract to the U.S. Nuclear Regulatory Commission, identified and evaluated methods for estimating radioactive and toxic particulate and gaseous airborne releases from uranium milling operations. This report describes the sources of release and calculational procedures for estimating radioactive and toxic source terms, and provides example calculations.

The major sources of airborne releases (radon and radioactive and toxic particulates) are the ore storage area, ore crushing and grinding, ore processing, yellowcake production, and tailings impoundment. Nonradioactive and radioactive particulate emissions are estimated in a similar manner given an estimate of the radioactive and toxic material composition of the ore or tailings.

The general method for calculating particulate source terms is to multiply together a normalized emission rate, contaminant content, emission control factor, and processing rate for each process being evaluated. Typical equations, data, and example calculations are presented for process and windblown emissions.

The major pathways for radon release were identified as occurring from ore storage, ore crushing and grinding and from the tailings. The amount of radon release from these sources depends on the ore and milling operations and tailings disposal practices. The factors affecting radon release common to all source pathways are radium content, radon emanating power (coefficient), bulk density, radon diffusion coefficient, and physical configuration.

Methods available to estimate radon release from the above sources were identified and evaluated. Typical equations, data, and example calculations are presented for the various source pathways. The two most common methods to calculate radon release are: 1) to use a radon flux factor of 1 pCi ^{222}Rn/m^2.s per pCi/g ^{226}Ra when there are only limited data available on the ore or tailings and 2) in those cases where measured data on radon emanating power and radon diffusion coefficients are available, the radon flux from the surface of

ore or tailings can be estimated with a more rigorous approach using a one-dimensional steady-state radon diffusion equation.

Nonradioactive gas emission sources are from the leach circuit, solvent extraction circuit, yellowcake precipitator and dryer, analytical laboratory, mill power plant and heating system, and plant research. Airborne release factors were identified for these source pathways and example calculations are presented.

CONTENTS

ABSTRACT iii

EXECUTIVE SUMMARY v

INTRODUCTION 1

SOURCE TERMS 3

- NEED FOR SOURCE TERMS 3
- IDENTIFICATION AND DESCRIPTION OF RELEASE POINTS 4
  - Ore Storage 4
  - Ore Crushing and Grinding 7
  - Ore Processing 7
  - Yellowcake Production 8
  - Tailings Impoundment 8
  - Heap Leaching 10
  - Ore Leaching In Situ 10
- CURRENT NRC METHOD FOR ESTIMATING RADIOACTIVE SOURCE TERMS 11

SOURCE TERM PREDICTION 13

- RADIOACTIVE PARTICLE EMISSION SOURCE TERMS 13
  - Process Emissions 13
  - Windblown Emissions 16
  - Parameter Selection 19
- RADON EMISSION SOURCE TERM 20
  - Run-of-Mine Ore Storage 20
  - Hopper, Feeder, Crushing, and Grinding 24
  - Leaching and Extraction 24
  - Yellowcake Drying and Packaging 24

Tailings Disposal 24

Radon Release During In-Situ Operations 31

NONRADIOACTIVE EMISSION SOURCE TERMS 35

Nonradioactive Particulate Emission Source Terms 35

Nonradioactive Gas Emission Source Terms 37

REFERENCES 41

APPENDIX A - PRIMARY PARAMETERS NEEDED TO ESTIMATE SOURCE TERMS FOR URANIUM MILL OPERATIONS A.1

APPENDIX B - EMISSION FACTORS B.1

APPENDIX C - ORE PROCESSING PARTICULATE EMISSION REDUCTION FACTORS C.1

APPENDIX D - EMISSION FACTORS FROM FUEL COMBUSTION WITHOUT EMISSION CONTROL D.1

FIGURES

1 Decay Scheme for Uranium-238 5

2 Major Source Pathways for Uranium Milling Processes 6

3 Effect of Ore Pile Thickness on Hyperbolic Tangent Term in Radon Flux Equation 23

4 Normalized Surface Flux Versus Tailings Depth 30

TABLES

1 Parameter Values for Calculations of Annual Dusting Rate for Exposed Tailings Sands 17

2 Parameters for Calculating Example Tailings Emission Factor 18

3 Data Needed to Estimate Radon Release from Ore Storage, Using Diffusion Equation 21

4 Radium Content of Selected Tailings 26

5 Emanating Power of Uranium Mill Tailings 27

6 Diffusion Coefficients for Radon in Uranium Mill Tailings and Similar Materials 28

7 Parameters Used to Determine Radon Release from In-Situ Mining 31

8 Nonradioactive Emissions Generated by Uranium Milling 35

9 Chemical Airborne Release Factors for Acid Leach Mill 38

INTRODUCTION

Each licensee who processes or refines uranium ores in a milling operation is required by § 20.1 of 10 CFR Part 20, "Standards for Protection Against Radiation," to make every effort to maintain as low as reasonably achievable (ALARA) radiation exposures and releases of radioactive materials in effluents to unrestricted areas, taking into account the state of technology and the economics of improvements in relation to benefits to the public health and safety. Under 10 CFR 40, mill operations are to be conducted so that all airborne effluent releases are reduced to ALARA levels. In addition, 40 CFR Part 190, "Environmental Radiation Standards for Nuclear Power Operations," requires that the maximum annual radiation dose to individual members of the public resulting from fuel-cycle operations be limited to 25 millirems to the whole body (radon and its daughters excepted) and to all organs except the thyroid, which must be limited to 75 millirems. In order to establish that the radiation exposure and releases are minimized and meet requirements, methods are needed for estimating radioactive and toxic source terms.

In response to this need, the U.S. Nuclear Regulatory Commission (NRC) requested the Pacific Northwest Laboratory (PNL)(a) to identify and evaluate methods, models, data, and assumptions for estimating airborne emissions of radioactive and toxic materials from steps in uranium milling. Identification of emissions and methods for estimating the source terms for those emissions were based on:

- NRC licensing actions on uranium mills
- evaluations and monitoring of mill operations
- research programs conducted to identify and improve on methods for retention and stabilization of mill tailings
- methods and practices used by NRC staff to generate the estimates.

Methods, models, data, or assumptions used for estimating source terms will be reviewed by the NRC staff to determine their acceptability.

NRC regulatory guides provide direction on radiological effluent and environmental monitoring (NRC 1980b), compliance with radiation procedures (NRC 1982b), and calculation of radiation doses from airborne materials (NRC 1982a). Related reports are being prepared that evaluate air pollution control devices, determine compliance for radon cover systems, etc. The EPA has established

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(a) Operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

- year prior to tailings impoundment reclamation - representing particulate and radon releases as the tailings dry out

- postreclamation of the tailings impoundment - representing the long-term impacts.

The radionuclides in the uranium ore are generally assumed to be in secular equilibrium with uranium-238. Figure 1 depicts the decay scheme for uranium-238. After the uranium is leached from the ore, long-lived daughter-product isotopes are controlling factors in the tailings. Radon is considered separately since it emanates both from the ore and from the tailings and therefore is released to the environment independently from other radioisotopes of the uranium decay chain. Thus, since models used in predicting radiological and environmental impact include the impacts of the short-lived decay products from longer-lived radionuclides, source term estimates for natural uranium, uranium-238, thorium-230, radium-226, lead-210, and radon-222 provide a sufficient base. Since the uranium-235 in natural uranium represents only about 0.7% of natural uranium, radionuclides from its decay chain contribute only a small fraction of the total radioactivity for natural uranium and therefore are not included in the source term estimates.

Uranium ores usually contain small amounts of toxic elements such as arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. The release of these elements is also included in source term estimates.

IDENTIFICATION AND DESCRIPTION OF RELEASE POINTS

Radioactive and nonradioactive dusts and gases are released from several steps in uranium mill processes. Figure 2 shows the major processing steps and the airborne release sources. These steps and sources are described in the following sections. Methods for estimating quantities released are discussed in the section on Source Term Prediction.

Ore Storage

The quantity of airborne dust generated and radon released from ore pads is dependent on the physical characteristics of the ore, the height of the ore pad relative to adjacent land, the geography of the mill site, and weather conditions including wind channeling, shear velocity, and profile. Generally a sizeable ore backlog may be maintained at the mill with the ore segregated according to ore composition (rock, clay, organic content, and uranium concentration) and blended to provide a uniform feed to the mill.

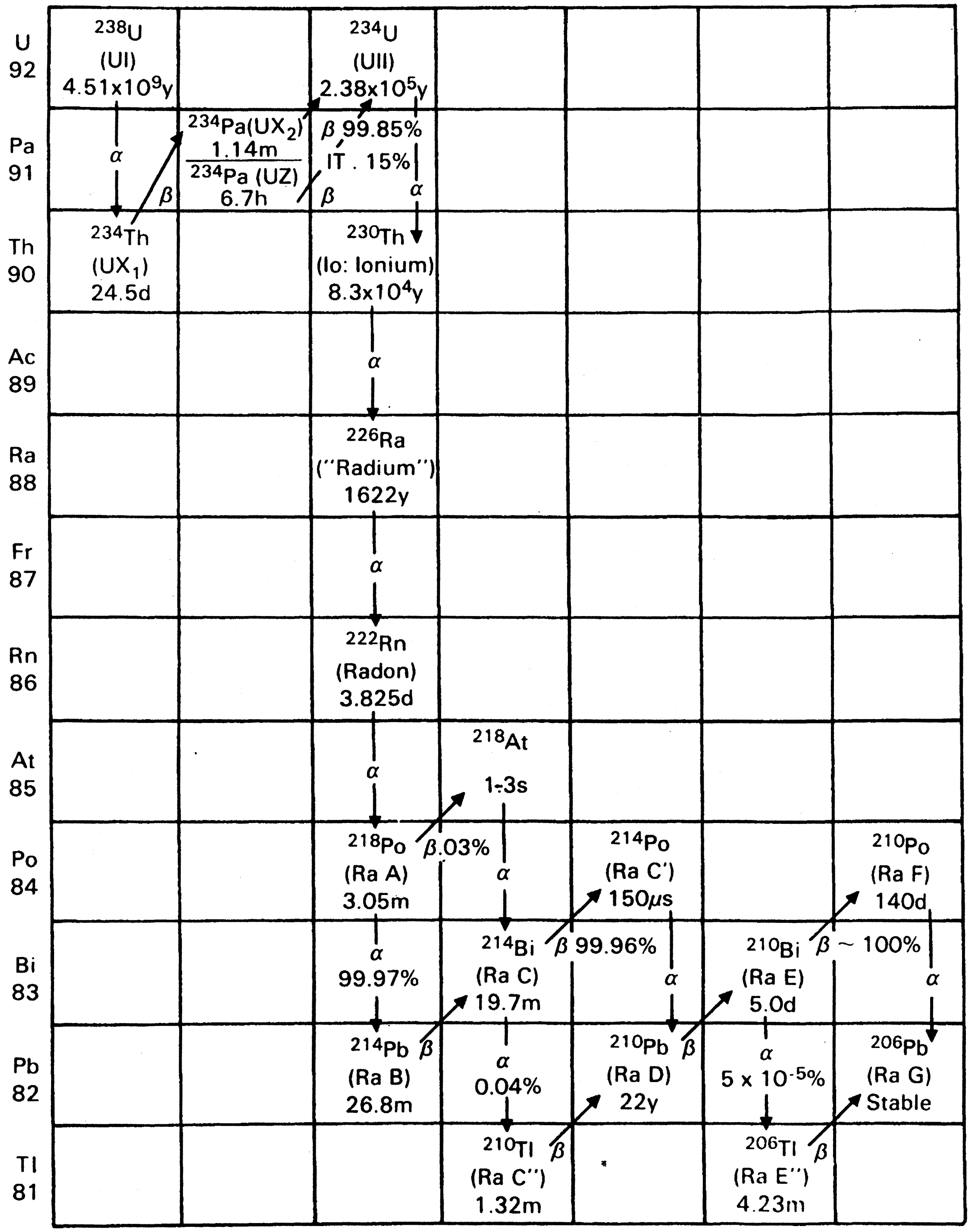

FIGURE 1. Decay Scheme for Uranium-238

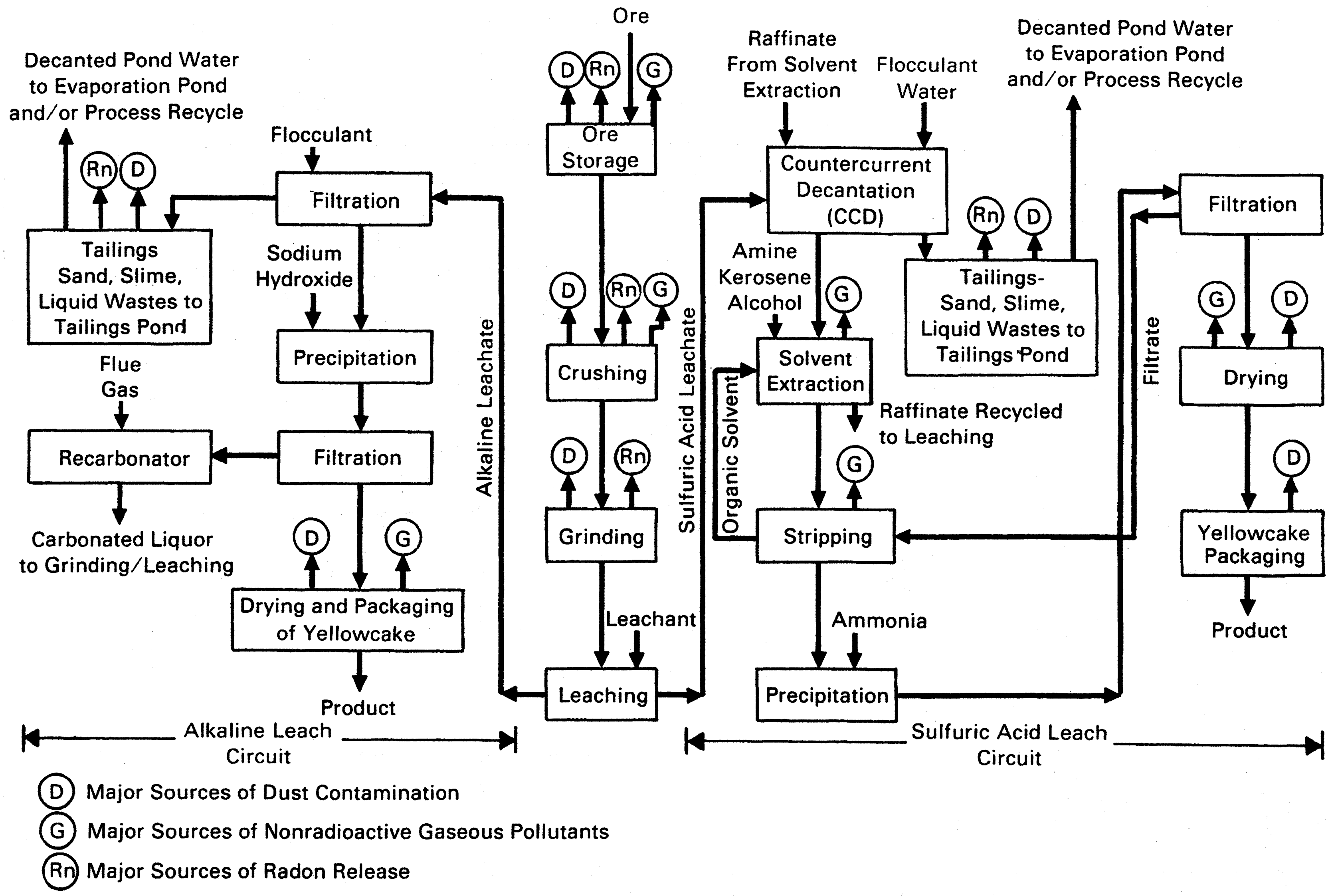

FIGURE 2. Major Source Pathways for Uranium Milling Processes

Information needed to estimate source terms depends in part on operational procedures that determine the quantity of ores stored at the mill, climatic conditions, need for blending widely varying ore compositions, and general requirements on backlogging. In addition, moisture content, which is a function of mine source, age in storage and climatic conditions, contributes to the degree to which ore dust is dispersed. The ore may dry out in the stockpile, making it more susceptible to dispersion. The quantity of dust that may be dispersed may be controlled by keeping the stockpile wet and/or spraying it with chemical suppressants as an interim measure. This will have little effect on radon release from the ore storage unless the ore is kept saturated and not allowed to dry out.

Ore Crushing and Grinding

Detailed information on the steps and controls used in ore crushing and grinding is needed since ore dust containing radioactivity can be released to the environment during these operations. Ore received from the mine(s) is blended and successively reduced in size by, for example, jaw crushers, cone crushers, and ball mills, reducing the size to permit ready leaching of the uranium. Dust generated during these process steps is not generally confined within the equipment, although off-gases from the smaller-size reduction equipment are usually scrubbed. The ore is transported between stations by belt conveyors, usually canopied, in enclosed structures in which entrained particles are filtered out before the air is discharged from stacks. The last stages of grinding are usually done wet to eliminate the free flow of airborne particulates from the finely ground product.

Some of the radon formed from decay of radium-226 in the ore is released during the ore handling and crushing activities. The fraction of radon released varies according to the physical characteristics and chemical composition of the ore. Although radon-222 (the primary radon isotope released from uranium ores) is chemically inert and has a short half-life (3.8 days), its decay products reach secular equilibrium quickly and are dispersed and therefore subject to inhalation by man and animals.

Ore Processing

Since ore processing operations are conducted in solution and/or slurries, particulate emissions are negligible and therefore present little hazard. However, nonradioactive gaseous effluents could be released, some of which are toxic and consist of carbon dioxide, sulfur dioxide, water vapor, and sulfuric acid mist from the leaching step. Organic chemical vapors consisting of kerosene with small amounts of amine and alcohol are released from the open solvent extraction settling chambers. Ion exchange processes are enclosed and chemical vapor releases are negligible.

The finely ground ore is leached with either sulfuric acid or sodium carbonate solution containing an oxidant to dissolve 90% to 95% of the uranium. The uranium-bearing solution is separated from the barren waste (raffinate) by countercurrent decantation (CCD), using thickeners to assist in settling.

Uranium in the pregnant liquor from the acid-leach process is recovered by solvent extraction or ion exchange, and recovered in most cases as ammonium diuranate by precipitation with ammonia. Uranium in the pregnant liquor from the alkaline-leach process is recovered and isolated as sodium diuranate by precipitation with sodium hydroxide (caustic).

Yellowcake Production

The uranium concentrate (yellowcake) recovered by solvent extraction or ion exchange is neutralized, generally with ammonia, to precipitate ammonium diuranate, called "yellowcake." Yellowcake from alkaline leach is precipitated by treating the leachate with sodium hydroxide. The yellowcake is separated by filtration or centrifuging. The compact yellowcake may be packaged in this form and shipped to a facility where it can be converted to uranium hexafluoride. Alternatively, the yellowcake may be dried to a powder or calcined to a crude uranium oxide before packaging and shipping. The uranium content of yellowcake solids varies from 70% to 80% (approximately 85% to 95% U_3O_8), depending on the degree of drying and calcining.

The potential for particulate releases during yellowcake production depends on the degree to which the product is dried or calcined, and on the effectiveness of off-gas filtration. Particulate releases from the drying, calcination, and packaging steps are dependent on the control used to prevent release of excessive amounts of uranium in the off-gases. Off-gases are scrubbed and/or filtered before release through a stack.

Off-gases contain small quantities of ammonia and water vapor. The dryers emit carbon dioxide, sulfur dioxide, and nitrogen oxides from the combustion of fuel.

Since the ore processing steps reject nearly all the radium to the tailings, very little radon is released during the production of yellowcake.

Tailings Impoundment

The processing of ore in uranium mills generates radioactive and nonradioactive wastes generally referred to as tailings. They consist of the majority of ore solids, process additives and water. The industry uses different scenarios for storage of tailings. The tailings together with the earthen dams or cells that contain these wastes are referred to as impoundments, and the impounded liquids are called tailings ponds.

Release of dust from tailings impoundments varies significantly from mill to mill according to a number of factors such as impoundment design, tailings composition, site characteristics, operational practices, and reclamation plans.

- impoundment design: Most tailings are contained within manmade dams. When the mill raffinate is discharged to the sides of the impoundment system and the discharge pipe is moved from point to point around the pond, beaches of tailings are deposited. In some recent impoundment systems using a below-grade design, deep ponds are forming without beaches as the mill raffinate is discharged to the middle of the pond.

- tailings composition: Beaches containing tailings sand deposited from processing highly siliceous or granitic ores quickly dry out as the discharge pipe is moved about the pond. These dried sands are readily dispersed by winds. Beaches formed from tailings that are produced in processing ores that contain high concentrations of limestone are much less subject to wind erosion. In these cases sulfuric acid leachant used to extract uranium from the ore also attacks the limestone, saturating the solution with calcium sulfate. Hydrated calcium sulfate (gypsum) deposits on the beaches with the tailings in the raffinate and tends to fix the sand, reducing the potential for wind erosion (dusting).

- site characteristics: In a few cases trees surrounding the impoundment area protect it from wind erosion. However, in most cases tailings ponds in arid locations are subject to frequent wind erosion. High berms can to some extent protect the dried beaches from the wind. Below-grade impoundments eliminate beaches until the pond is filled and allowed to dry.

- operational practices: The frequency and uniformity with which the tailings discharge pipe is moved about the tailings pond affect the degree to which the beaches are dried and therefore subjected to wind erosion. Dust emissions are negligible from below-grade impoundments, but are high from areas in which tailings are allowed to accumulate and be exposed to direct winds. In all cases the degree of dust emissions can be controlled significantly by keeping the sands wet, spraying with chemical suppressants such as synthetic polymers, applying mulch, revegetating, covering with soil or rock, or erecting windscreens.

- reclamation plans: Impoundments are required to be reclaimed when their usefulness is completed. The reclamation procedure will depend on the tailings disposal and impoundment design. In most cases the site can be reclaimed after the impoundment is filled with tailings or when the mill operation is over. Reclamation can sometimes take place in stages when, for example, smaller impoundment cells are used for tailings disposal. This would permit each cell to be reclaimed after it is filled and would help to minimize wind erosion.

The release of radon from the tailings impoundments depends on similar factors. A fraction of radon formed from decay of radium in the tailings emanates from the crystalline structure of the tailings residues. The radon then diffuses through the tailings pile and escapes to the atmosphere where it and its decay products are dispersed.

Heap Leaching

Heap leaching involves leaching low-grade ore (<0.04% U_3O_8) either by gravitational flow of the leachant through an open pile or by flooding a confined ore pile (NRC 1980a). The leachate is treated on site by ion exchange or solvent extraction and a crude yellowcake is precipitated which may be shipped to a nearby mill for refinement. When the ore dumps are reasonably near a mill, acid solutions from the mill may be used for the heap leaching and returned to the mill circuit for processing (Merritt 1971).

Heap leaching has little impact on airborne environmental impacts. Radon-222 and its decay products are released and dispersed. The leached ore may be mixed with mill tailings. If the tailings are maintained as an isolated leached ore pile, control of fugitive dust is required.

Ore Leaching In Situ

Low-grade ores can be leached in situ using a network of wells to inject a leach solution into the ore formation, mobilizing the uranium through formation of a soluble complex uranium salt, and removing the pregnant solution from the ore body through production wells. The solubilized uranium is recovered by uranium mill processing operations producing yellowcake.

Radioactive airborne releases from in-situ leaching are primarily limited to radon emanations from the solution resulting from the leaching of the ore. Some releases may occur from yellowcake dryers and packaging if such operations are used on site. Nonradioactive gases form from machinery using fuel oils. Airborne releases from the chemical processing steps are comparable to those encountered during conventional mill operations.

Solid wastes are generated that require controlled disposal; however, the volume produced is much less than that created by conventional uranium mining and milling. Dried evaporative ponds can contain residual radionuclides and toxic minerals leached along with the uranium. If disposed of into the tailings pond at a conventional mill, the waste solutions will be only a minor increment to the tailings impoundment system.

CURRENT NRC METHOD FOR ESTIMATING RADIOACTIVE SOURCE TERMS

The present NRC procedure for estimating radioactive airborne release rates (source terms) from uranium milling facilities involves the characterization of such releases by radionuclide, particle size, and density (NRC 1980a). These data, when combined with a meteorological dispersion model representing the annual average meteorological conditions of the mill site, provide a basis from which NRC staff can estimate concentrations, which in turn are used to calculate radiation doses as described in NRC Regulatory Guide 3.51 (NRC 1982a).

The primary calculational tool used by the NRC staff to evaluate radiological impact of uranium milling operations is the MILDOS code (NRC 1981). As MILDOS is used by the NRC staff, only five primary radionuclides in the uranium-238 decay chain are treated explicitly as source terms: uranium-238, thorium-230, radium-226, lead-210, and radon-222. Release rates are required for these radionuclides for each potential release source. The code accounts for releases and ingrowth of other radionuclides, assuming secular equilibrium. For radon-222 decay products, which grow in during transport of radon-222 from the site, the code calculates the resulting ingrowth. These radon-222 daughters include polonium-218, lead-214, bismuth-214, lead-210, and polonium-210.

SOURCE TERM PREDICTION

Methods are described below for estimating radioactive and nonradioactive source terms from uranium milling operations and tailings disposal. Certain bases and assumptions used in making acceptable calculations are identified and explained. Nonradioactive particulate emission source terms may be estimated in the same way as radioactive particulate emissions, given an estimate of the toxic element composition of the ore (or tailings). Estimates of nonradioactive gas emissions from process operations are based on raw material and fuel uses. Principal parameters needed to estimate source terms are listed in Appendix A.

RADIOACTIVE PARTICLE EMISSION SOURCE TERMS

The major particle emission sources at a uranium mill include ore handling, ore storage crushing and grinding, yellowcake production (especially drying and packaging), and tailings piles. Much of the useful data for calculating source terms is enumerated in Appendix A of NRC Regulatory Guide 3.51 and Appendices A, B, and C of NRC Regulatory Guide 3.8. The general method for calculating source terms is to multiply together the normalized emission rate, contaminant content, emission control factor, and processing rate for each process being evaluated. The following discussion incorporates equations and sample calculations for process and windblown emissions typical of uranium mills.

Process Emissions

Processes that release particles include ore handling, grinding and crushing, conveying, and yellowcake drying and packaging.

The basic equation is:

$$S = M\ C\ E\ N\ (1 - R) \tag{1}$$

where S = source term, quantity/time, such as kg ^{238}U/hour or Ci ^{238}U/yr
M = process rate, mass/time, such as metric ton ore/day
C = contaminant concentration, such as percent or pCi/g of uranium or ppm of toxic elements in ore
E = emission factor for process, such as dust released per metric ton of ore dumped to the grizzly
N = activity enrichment ratio, dimensionless
R = emission control factor, dimensionless.

The activity enrichment ratio, N, expresses the extent to which the contaminant concentration is higher in the suspended airborne particles of <20 μm diameter than in the bulk material. A value of N = 2.5 can be used and is conservatively based on measured values (Sears et al. 1975; Schwendiman 1980) in which the content of uranium-238 and its progeny in fines was found to be up to 2.5 times higher than in the bulk ore. The emission factor, E, is tabulated for various common operations in Appendix B. The reduction factor, R, is tabulated in Appendix C for various control measures. Examples of calculating particle source terms follow.

Example Calculation: Crushing

The source terms for radionuclides in the chain for uranium-238 decay are the same as those for uranium-238 since they are in secular equilibrium. The following parameters are supplied by the applicant:

M = 145,000 MT processed per year
C = 420 pCi ^{238}U/g bulk ore
N = 2.5 times greater ^{238}U content in dust than in bulk ore.

The emission control device is a baghouse with an expected efficiency of about 80% for the dust produced by the operation. The applicant has determined that the moisture content of the stored ore, at the time of crushing, is 7 wt%. Tertiary crushing is not used. Therefore, the estimated uncontrolled emission factor, E, from Appendix B is 0.16 lb/ton. Using Equation (1), the estimated uranium-238 source term is:

$$\begin{aligned} S &= 145{,}000 \text{ MT/yr} \times 420 \text{ pCi/g} \times 0.16 \text{ lb/ton} \times 2.5 \times (1 - 0.80) \\ &\quad \times 1.1025 \text{ ton/MT} \times 454 \text{ g/lb} \times 10^{-12} \text{ Ci/pCi} \\ &= 2.4 \times 10^{-3} \text{ Ci/yr.} \end{aligned}$$

Example Calculation: Truck Unloading to Ore Pad

The ore processing rate, M, is 193,000 MT/yr. The bulk ore content, C, of uranium-238 and progeny in secular equilibrium is 435 pCi/g. The ore is end-dumped from a truck. No control measures are used. Thus the emission factor, E, is 0.04 lb/yd^3, based on Appendix B. The bulk density of the ore is 1.5 ton/yd^3. Using Equation (1) and the dust/ore specific activity ratio, N = 2.5, the source term for uranium-238 and progeny is:

$$\begin{aligned} S &= 193{,}000 \text{ MT/yr} \times 435 \text{ pCi/g} \times 0.04 \text{ lb/yd}^3 \times 1 \text{ yd}^3/1.5 \text{ ton} \\ &\quad \times 1.1025 \text{ ton/MT} \times 454 \text{ g/lb} \times 2.5 \times 10^{-12} \text{ Ci/pCi} \\ &= 2.8 \times 10^{-3} \text{ Ci/yr.} \end{aligned}$$

Example Calculation: Fine Ore Storage

In this case, the fine ore is conveyed to and from the fine ore storage area for a total of four conveyor transfers. Ore is handled at a rate of

135,000 MT/yr and the bulk uranium-238 and progeny content is 350 pCi/g. The 2.5 dust/ore activity ratio is applied. The operation occurs in an enclosed structure with a reduction factor of 75% based on engineering judgment (Appendix C). The emission factor for each transfer is 0.023 lb/ton (Appendix B). The combined emission factor for the fine ore storage conveying is:

$$E = 4 \text{ transfers} \times 0.023 \text{ lb/ton per transfer} = 0.092 \text{ lb/ton.}$$

The uranium-238 and progeny source term is then:

$$\begin{aligned} S &= 135{,}000 \text{ MT/yr} \times 350 \text{ pCi/g} \times 0.092 \text{ lb/ton} \times 1.1025 \text{ ton/MT} \\ &\quad \times 454 \text{ g/lb} \times 10^{-12} \text{ Ci/pCi} \times (1 - 0.75) \times 1 \\ &= 5.4 \times 10^{-4} \text{ Ci/yr.} \end{aligned}$$

Example Calculation: Yellowcake Drying and Packaging

Releases from the stack for off-gases from the yellowcake drying and packaging operations are quite variable (Fort et al. 1980). Variability among mills and uniqueness of each mill are important factors. Also, changes in operating parameters can change emission rates over time. Maintenance and repair work, malfunction of the exhaust air cleanup systems, and intermittent shutdown and startup are among other variables that can impact the emissions from this operation. Emission estimates can be based on measurements made at operating mills (Fort et al. 1980), and on the release assumed for the model mill in the generic environmental impact statement (GEIS) on uranium milling (NRC 1980a), which in turn were based on recommendations of Momeni et al. (1979). Accordingly, it is estimated that 0.1% of yellowcake produced is released from the stack in the drying and packaging operations based upon EPA-measured releases at six mills.

For a mill with a yellowcake production of 200 MT/yr, of which 90% is U_3O_8, the estimated release from the yellowcake stack(s) would therefore be:

$$\begin{aligned} S &= 200 \text{ MT/yr} \times 0.90 \times 10^{6} \text{ g/MT} \times 3.33 \times 10^{-7} \text{ Ci/g } ^{238}\text{U} \\ &\quad \times 0.85 \text{ g U/g } U_3O_8 \times 0.001 \\ &= 5.1 \times 10^{-2} \text{ Ci } ^{238}\text{U/yr.} \end{aligned}$$

In the absence of firm data, it can be assumed that 0.5% of thorium and 0.1% lead and radium are processed along with the yellowcake. Since the decay products of uranium in the ore are in secular equilibrium with the uranium, the radioactivity of thorium-230 released from the stack is estimated to be 0.005 of the radioactivity of the uranium released. Thus the thorium, lead, and radium release for the example mill is calculated as follows:

$$\begin{aligned} S &= 5 \times 10^{-2} \text{ Ci } ^{238}\text{U/yr} \times 0.005 \\ &= 2.5 \times 10^{-4} \text{ Ci } ^{230}\text{Th/yr} \end{aligned}$$

$$S = 5 \times 10^{-2}\ \text{Ci}\ ^{238}\text{U/yr} \times 0.001$$
$$= 5 \times 10^{-5}\ \text{Ci/yr of either}\ ^{210}\text{Pb or}\ ^{226}\text{Ra}.$$

Reliable monitoring data should be used when available. Renewal of licenses or modification of licenses are examples of when such data may be applicable.

It is noteworthy that particulate releases from the yellowcake production step arise almost entirely from drying and/or calcining operations. If the yellowcake product were to be packaged as a slurry, or as a damp filter-cake product, particulate emissions from this operation would be negligible.

Windblown Emissions

Fugitive dust emission varies significantly from mill to mill. Meteorological conditions (wind, rainfall, temperature), exposed surfaces, ore compositions, and physical characteristics, particle size distributions, site characteristics, and operational procedures, among others, affect the degree to which dust is blown about.

Example Calculations: Tailings Pile

Windblown particle emissions can be estimated using the method described in MILDOS (NRC 1981, Appendix A). In using this approach, the emission factor, E_w, is calculated as follows:

$$E_w = \frac{3.156 \times 10^7}{0.5} \times \Sigma_s\left(R_s\ F_s\right) \tag{2}$$

where E_w = annual dust loss per unit area, $g/m^2 \cdot yr$

3.156×10^7 = number of seconds per year

0.5 = fraction of the total dust loss constituted by particles <20 μm diameter

R_s = resuspension rate for tailings sands at the average wind speed for wind speed group s, for particles <20 μm diameter, $g/m^2 \cdot s$.

F_s = annual average frequency of occurrence of wind speed group s, dimensionless, obtained from joint relative frequency wind distribution for the site.

The MILDOS-calculated resuspension rates for tailings sands are tabulated in Table 1 for each wind speed group, s.

TABLE 1. Parameter Values for Calculations of Annual Dusting Rate for Exposed Tailings Sands

Wind Speed Group, knots	Average Wind Speed, mph	Dusting Rate (R_s), $g/m^2 \cdot s$
0 to 3	1.5	0
4 to 6	5.5	0
7 to 10	10.0	3.92×10^{-7}
11 to 16	15.5	9.68×10^{-6}
17 to 21	21.5	5.71×10^{-5}
>21	28.0	2.08×10^{-4}

The source term for each tailings beach area is then calculated as:

$$S = E_w \, A \, C \, fN(1 - R) \tag{3}$$

where E_w = emission factor in $g/m^2 \cdot yr$, as calculated above
A = exposed surface area (of the beach at the tailings impoundment, or of the ore pad, for example) in m^2
C = contaminant concentration in percent or pCi/g of uranium, or ppm for toxic elements in the initial ore
f = fraction of a particular contaminant present
N = activity enrichment ratio of concentration in dust/bulk material, dimensionless
R = a dimensionless control factor depending on the degree of control applied (see Appendix C).

The first example below estimates the radium-226 release from an abandoned tailings pile temporarily stabilized with a synthetic polymer coating sprayed onto the sand ($R = 0.85$, from Appendix C). The control of fugitive dust emissions from U mill tailings using chemical stabilizers and windscreens is evaluated in a report by Elmore and Hartley (1985). The pile area, A, is 53 acres and contains 99.5% of the 300 pCi $^{226}Ra/g$ originally in the ore, enriched in the fines by a factor $N = 2.5$. The annual average frequency of occurrence of each wind speed group, resuspension factor, and their product are shown in Table 2.

The calculated emission factor (annual average dust loss rate) is:

$$\begin{aligned} E_w &= 3.156 \times 10^7 \text{ s/yr} \times 6.75 \times 10^{-6} \text{ g/m}^2 \cdot \text{s}/(0.5) \\ &= 4.3 \times 10^2 \text{ g/m}^2 \cdot \text{yr}. \end{aligned}$$

The Ra-226 source term is, therefore, using Equation (3):

TABLE 2. Parameters for Calculating Example Tailings Emission Factor

Wind Speed Group, knots	Resuspension Rate[(a)] (R_s), $g/m^2 \cdot s$	Frequency of Occurrence,[(b)] F_s	Product, $R_s \times F_s$ $g/m^2 \cdot s$
0 to 3	0	--	0
4 to 6	0	--	0
7 to 10	3.92×10^{-7}	0.4035 — 0.28	1.58×10^{-7} 1.09E-7
11 to 16	9.68×10^{-6}	0.1942 — 0.26	1.88×10^{-6} 2.52E-6
17 to 21	5.71×10^{-5}	0.0501 — 0.13	2.86×10^{-6} 7.42E-6
>21	2.08×10^{-4}	0.0089 — 0.06	1.85×10^{-6} 1.248E-5
			$\Sigma_s = 6.75 \times 10^{-6}$ 2.25E-5

(a) Dusting rate of a function of wind speed is computed by the MILDOS code (NRC 1981).

(b) Wind speed frequencies obtained from annual joint frequency data for the site.

$$\begin{aligned} S &= 4.3 \times 10^{2}\ g/m^{2} \cdot yr \times 53\ acres \times 4047\ m^{2}/acre \times 300\ pCi\ {}^{226}Ra/g \\ &\quad \times 10^{-12}\ Ci/pCi \times 0.995 \times 2.5 \times (1 - 0.85) \\ &= 1.0 \times 10^{-2}\ Ci\ {}^{226}Ra/yr. \end{aligned}$$

The second example considers an active tailings impoundment at the same site (same wind frequency occurrence as above). Beaches are maintained wet, as needed (R = 25%, Appendix C), and are approximately 50% of the total impoundment area of 45 acres. Using Equation (3) and a specific activity concentration ratio of N = 2.5, the radium-226 source term is estimated to be:

$$\begin{aligned} S &= 4.3 \times 10^{2}\ g/m^{2} \cdot yr \times 45\ acres \times 0.50 \times 4047\ m^{2}/acre \\ &\quad \times 300\ pCi\ {}^{226}Ra/g \times 10^{-12}\ Ci/pCi \times 0.995 \times 2.5 \times (1 - 0.25) \\ &= 2.2 \times 10^{-2}\ Ci\ {}^{226}Ra/yr. \end{aligned}$$

For an active below-grade impoundment system, particulate releases during operation can be considered negligible since solid tailings material is covered by tailings solution and thus there are few, if any, exposed solids subject to wind erosion.

Example Calculations: Ore Pad

Particulates on the ore pad are less subject to wind erosion than those from tailings piles since the ore has not yet been ground. The fugitive dust release from the ore pad can be based on an emission factor estimated to be 10% of that calculated for the tailings pile. Equation (2) for ore pads is thus modified to read:

$$E_w = 0.1 \times \frac{3.156 \times 10^7}{0.5} \times \sum_s R_s F_s$$

Thus, for the site with the wind frequency occurrence described above, the annual average dust loss rate is estimated to be:

$$\begin{aligned} E_w &= 0.1 \times 3.156 \times 10^7 \text{ s/yr} \times 6.75 \times 10^{-6} \text{ g/m}^2\text{·s/(0.5)} \\ &= 43 \text{ g/m}^2\text{·yr.} \end{aligned}$$

The source term for an ore pad of 10 acres containing ore with 300 pCi $^{238}U/g$, using a specific activity concentration ratio of N = 2.5, and without any control (R = 0), is thus estimated to be, using Equation (3):

$$\begin{aligned} S &= 43 \text{ g/m}^2\text{·yr} \times 10 \text{ acres} \times 4047 \text{ m}^2\text{/acre} \times 300 \text{ pCi/g} \\ &\quad \times 10^{-12} \text{ Ci/pCi} \times 2.5 \\ &= 1.3 \times 10^{-3} \text{ Ci } ^{238}\text{U/yr.} \end{aligned}$$

Since the progeny from uranium-238 are in secular equilibrium in the ore, the source term for uranium-234, thorium-230, radium-226, lead-210, and polonium-210 would each also be 1.3×10^{-3} Ci/yr. Any control such as keeping the ore pile wet would reduce fugitive dust by the appropriate factor as shown in Appendix C.

Parameter Selection

Reasonably well identified parameters used in particle source term measurements include production rate, pile areas, description of operation, and contaminant species contents. Less certain parameters include emission factors and emission control reduction factors. Of course, many of these factors are difficult to measure (e.g., the tails resuspension factor and the control factor for chemical dust suppressants). Factors measured by the applicant or by others in the regulatory and emission control fields may be used. Examples of such measured values include the efficiency of emission control devices installed in stacks and the historical emission measurements at an applicant's yellowcake dryer stack. It is better to use measured values of parameters. Design parameters are generally chosen only when other data are unavailable. An adjustment should be made for expected performance, and minimum performance should be noted. The following information sources can be used in source term estimates:

- applicant's measurements
- default values listed in this report

- other measurements or estimates shown by the applicant to be acceptable
- manufacturers' specifications
- best engineering judgment.

Section 9 of the GEIS for uranium mills (NRC 1980a) indicated that tailings surface control and an efficient yellowcake dust collection system are the major factors necessary to maintain acceptable airborne emissions.

Alternative methods for treating mill tailings in ways to reduce the potential of fugitive dust are discussed in the GEIS (Sections 8 and 9) for uranium mills, and in a recent report by Elmore and Hartley (1985). Various strategies can be used for controlling dust, including vegetative cover; gravel, crushed rock or riprap cover; manmade covers; chemical stabilizers; windscreens; and combinations. Some of these are also useful in reducing radon emissions. Progressive reclamation (drying up and covering tailings piles in sections as they are filled), as now practiced by several mills in the United States, is an effective method for reducing airborne particulates from the tailings.

RADON EMISSION SOURCE TERM

Processing of uranium ore and subsequent tailings disposal presents pathways for release of radon to the environment. The major pathways for radon release occur from ore storage, ore crushing and grinding, and the mill tailings disposal site. The amount of radon released through each of the pathways depends on the ore type, ore storage procedures, crushing or grinding operations, and tailings disposal practices. The factors affecting radon release common to all the source pathways are: 1) radium content of ore and tailings; 2) emanating power (coefficient) of ore or tailings; 3) radon diffusion coefficient of ore and tailings; and 4) physical characteristics including configuration of ore storage and tailings pile. The following sections describe methods that can be used to estimate the release of radon from ore storage, crushing and grinding, leaching and extraction, and the tailings impoundment. Example calculations illustrate the procedures.

Run-of-Mine Ore Storage

Ore received at the mill is stockpiled on ore storage pads in sufficient quantity to provide for a continuous supply to the mill. Radon release from the ore storage area depends on: 1) the characteristics of the ore, 2) the area and thickness of the ore pads, and 3) the storage time. The quality of the ore received varies according to ore concentration, grade, and size.

Selection of ores from the stockpile is generally made to allow for a reasonably consistent composition as feed to the mill chemical processes.

Estimation Using Flux Factor

In cases where only limited data are available, radon release can be estimated using a specific radon flux factor of 1 pCi ^{222}Rn/m^2•s per pCi/g ^{226}Ra (NRC 1980a). Only the area of the ore stockpile and the average radium content need be known to make the calculation of yearly release. An example calculation for radon release, F, from an ore pad covering 3 ha and containing an average radium-226 concentration of 300 pCi/g is:

$$
\begin{aligned}
F &= (1 \text{ pCi } ^{222}\text{Rn/m}^2 \cdot \text{s})/(\text{pCi/g } ^{226}\text{Ra}) \times 300 \text{ pCi } ^{226}\text{Ra/g} \times 3 \text{ ha} \\
&\quad \times 10^4 \text{ m}^2\text{/ha} \times 3.156 \times 10^7 \text{ s/yr} \times 10^{-12} \text{ Ci/pCi} \\
&= 285 \text{ Ci } ^{222}\text{Rn/yr}.
\end{aligned}
$$

Alternative Estimation Using Diffusion Equation

In those cases in which measured data on radon emanation and radon diffusion in the ore are available, the radon flux at the ore pile surface (in pCi/m^2•s) can be estimated with a more rigorous approach using a one-dimensional steady-state radon diffusion equation (Freeman and Hartley 1984; Rogers et al. 1984):

$$\text{Radon flux, } J = RE\rho\sqrt{\lambda D} \tanh\left(\sqrt{\lambda/D} \cdot T\right) \qquad (4)$$

where λ is the radon decay constant, 2.1×10^{-6}/s, and the other symbols are defined in Table 3.

The hyperbolic tangent expression can be omitted from the equation under certain conditions, for instance if the thickness of the ore pad is greater than 3 m and D equals less than 5×10^{-2} cm^2/s since this would not change the

TABLE 3. Data Needed to Estimate Radon Release from Ore Storage, Using Diffusion Equation

Symbol	Description
A	Area of ore, m^2
T	Thickness of ore, m
R	Radium-226 concentration in ore, pCi/g
ρ	Bulk density of ore, g/cm^3
E	Emanating power of ore
p	total porosity of the ore
D	Diffusion coefficient = effective bulk radon diffusion coefficient/porosity, D_e/p, cm^2/s

calculated radon release estimate (i.e., the tanh function approaches one). The equation can be simplified to:

$$J = R\rho E\sqrt{\lambda D} \qquad (5)$$

The parameters needed for Equations (4) and (5) include easily measurable physical properties, such as bulk density and tailings thickness, as well as properties that are more difficult to measure, such as radium content, emanating power, and radon diffusion coefficient. Each one of these properties may differ significantly from site to site and even from location to location at a site.

In using Equations (4) and (5), the radium content of tailings is the most important parameter because it is the source of the radon. The radium concentration can be found by direct gamma counting, sealed-can radon equilibration, or chemical separation and subsequent alpha spectroscopy.

If radium analysis is not available, the radium content can be estimated based on the uranium content of the ore by using Ra = KU, where K = 2800 pCi/g ^{226}Ra/g ore/wt% U_3O_8 and U = wt% U_3O_8. This equation assumes that the amounts of uranium and radium in the original ore are in secular equilibrium. This estimation does not indicate how the radium is distributed in the ore pile, which can affect the average annual radon flux from the pile.

The emanating power, E, is defined as the fraction of radon-222 generated by decay of radium-226 that escapes from the mineral grains, enters the intergranular pore space, and diffuses through the tailings to the atmosphere. It depends on many factors such as porosity of the ore and ore pile, particle size distribution, moisture, mineralogy, and process conditions. After values for the emanating power, effective bulk radon diffusion coefficients (D_e) and porosity (p) of the ore and ore pile are determined, the radon flux from the ore can be calculated using Equation (4). The emanating power of 950 ore samples was determined by the U.S. Bureau of Mines to range from 0.01 to 0.91 with an average of 0.27 and a median of 0.21 (Austin and Droullard 1978). Based on these data, an emanating power for radon release from the ore stockpile of 0.2 is used. The diffusion coefficient (D) is the measured effective bulk diffusion coefficient (D_e) divided by the porosity (p). D is for air and water in the pore spaces of the ore and is generally affected by the moisture content of the ore. Data on radon diffusion in ore have not been published. A conservative value for the radon diffusion coefficient D of the ore is 5×10^{-2} cm^2/s, which is representative of a relatively sandy material, as measured for uranium mill tailings.[a]

(a) Measurements of diffusion coefficients for uranium mill tailings are shown in Table 5.

For ore and storage area with the following characteristics:

R = 300 pCi/g
ρ = 1.6 g/cm^3
T = ore pad thickness = 3 m
A = ore pad = 6 acres = 2.4×10^4 m^2
E = 0.2
D = 5.0×10^{-2} cm^2/s,

and from Figure 3, it can be seen that for a 3-m ore pile with a $D = 5.0 \times 10^{-2}$ cm^2/s the tanh $\sqrt{\lambda/D} \cdot T$ is near unity (0.96). Therefore the radon flux may be calculated, using the simplified Equation (5) as follows:

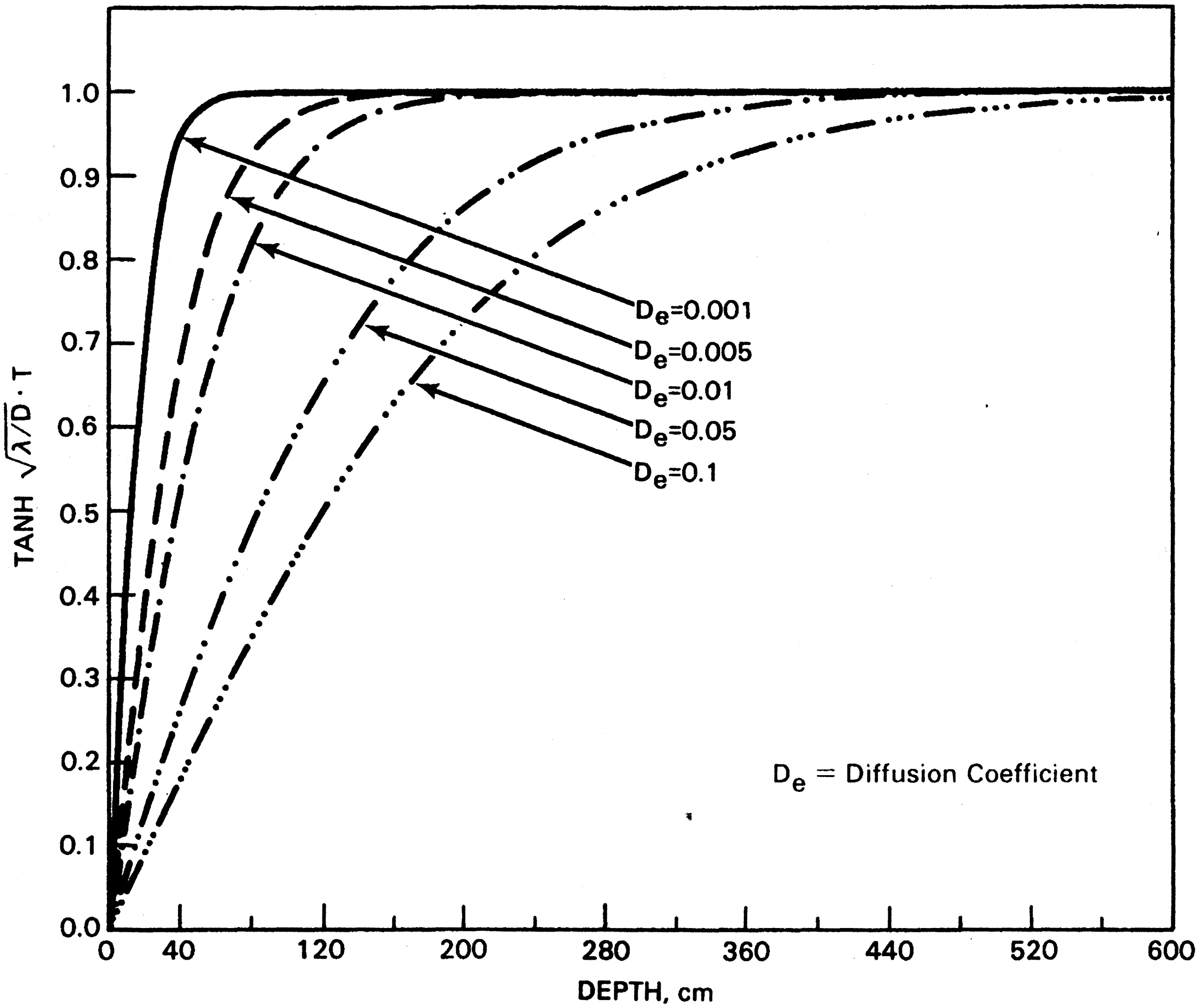

FIGURE 3. Effect of Ore Pile Thickness on Hyperbolic Tangent Term in Radon Flux Equation

$$
\begin{aligned}
J &= RE\rho\sqrt{\lambda D} \\
&= 300\ \text{pCi/g} \times 1.6\ \text{g/cm}^3 \times 0.2 \\
&\quad \times [2.1 \times 10^{-6}/\text{s} \times 5 \times 10^{-2}\ \text{cm}^2/\text{s}]^{1/2} \times 10^4\ \text{cm}^2/\text{m}^2 \\
&= 310\ \text{pCi/m}^2\bullet\text{s}.
\end{aligned}
$$

The radon release in Ci/yr for this ore pile is therefore:

$$310\ \text{pCi/m}^2\bullet\text{s} \times 3.165 \times 10^7\ \text{s/yr} \times 10^{-12}\ \text{Ci/pCi} \times 2.4 \times 10^4\ \text{m}^2 = 240\ \text{Ci/yr}.$$

Note that for the conditions assumed, $D = 5 \times 10^{-2}$ cm^2/s, $E = 0.2$ and $\rho = 1.6$ g/cm^3, the simplified relationship, 1 pCi ^{222}Rn/m$^2\bullet$s per pCi^{226}Ra/g, is a reasonable approximation. Using the diffusion equation, lower emanations or lower diffusion coefficients would result in lower radon release estimates than obtained using the flux factor. However, thinner piles, higher emanations, higher densities, and higher diffusion coefficients would result in higher estimates of radon release.

Hopper, Feeder, Crushing, and Grinding

Feed to the crushing and grinding circuits is blended run-of-mine ore from the storage pile. Because of the short residence time in the crushing and grinding circuits only a small amount of radon will be released. It is estimated that less than 10% of the radon in the ore will be released during crushing and grinding (Sears et al. 1975). The radon released during crushing and grinding is estimated as follows:

$$135{,}000\ \text{MT/yr} \times 350\ \text{pCi/g} \times 10^6\ \text{g/MT} \times 10^{-12}\ \text{Ci/pCi} \times 0.1 = 4.73\ \text{Ci/yr}.$$

Leaching and Extraction

Leaching and extraction are wet processes and again require short residence times; therefore, radon-222 release is estimated not to be significant.

Yellowcake Drying and Packaging

Since only ~0.1% of the original radium-226 in the ore finds its way to the yellowcake, no significant radon release occurs.

Tailings Disposal

The major waste discharged from a mill is the tailings slurry, which contains the barren ore plus process solutions. The tailings liquid contains residual acid or residual alkaline (depending on the leaching agent) and dissolved solids from the leaching steps. Some of the liquid (~1/3) may be returned to the mill for reuse. The tailings consist of sand, slimes, and a mixture of sand and slimes which are the sources of radon. Estimates of radon release are based upon about 99.9% of the radium-226 remaining with the tailings, unless measurements are available which indicate smaller amounts of radium.

Radon will be released from the exposed tailings. During the active period of the tailings pile, the impoundment is assumed to have areas of saturated tailings (slimes) mostly covered with raffinate solution and areas of relatively dry tailings (beach sands). The factors affecting the release of radon from the tailings pile are basically the same as those for the ore storage pads including: 1) radium concentration, 2) emanating power, 3) diffusion coefficient (moisture, porosity), 4) density, and 5) tailings thickness. The basic difference, however, is that during the active life of the tailings pile there are two areas on the tailings piles: the drier beach areas and the saturated slimes area which is generally covered with the raffinate pond. The tailings in the beach areas generally contain less radium than the tailings in the slimes areas (NRC 1980a). The relative amounts of slimes and sands or mixtures on the surface of a tailings pile depend not only on the quantity of sands and slimes but also on the procedure used to distribute the tailings on the pile. The beach areas have tailings with a higher radon diffusion coefficient resulting from the larger particle sizes and lower moisture contents. The slime areas have tailings with finer particle sizes and higher moisture content which reduce the radon coefficient.

To illustrate the wide range of radium content of tailings, the radium contents at several DOE/UMTRAP sites are presented in Table 4. The radium content ranges from 17.4 to 1915 pCi/g, which illustrates the need to determine the average radium content for a site before reasonable estimates of the bare tailings flux can be made. The site-weighted radium content average is the most appropriate value to use in the flux equations.

Alternative Estimation Using Diffusion Equation

When sufficient information is available on the distribution of slimes and sands, on both their area distribution and their radium-226 content, a more rigorous estimate of radon release may be made using the diffusion Equations (4) or (5).

If measured values of the emanating power, E, of the tailings are available, those measurements would be used. In their absence, an emanating power of 0.2 can be used (NRC 1980a). Although the emanating power of the tailings varies significantly, as shown in Table 5, with E ranging from ~0.1 to ~0.4, an average E for the tailings is about 0.2. It should be noted that the emanating power is reduced substantially when tailings are dried below ~5 wt%, dropping by as much as a factor of 4 (Freeman and Hartley 1984; Strong 1982; Nielson

TABLE 4. Radium Content of Selected Tailings

Location	Radium Content Range, pCi/g	Reference
Ambrosia Lake, NM	400 to 760	UMTRA-DOE/ALO-180
Grand Junction, CO	143 to 1150	UMTRA-DOE/ALO-174
Grand Junction, CO	337 to 1920 (135)[a]	Hartley 1983
Gunnison, CO	138 to 569	UMTRA-DOE/ALO-173
Maybell, CO	17.4 to 164	UMTRA-DOE/ALO-177
Mexican Hat, UT	91 to 782	UMTRA-DOE/ALO-181
New Rifle, CO	178 to 1195	UMTRA-DOE/ALO-176
Old Rifle, CO	260 to 586	UMTRA-DOE/ALO-175
Riverton, WY	26 to 413	UMTRA-DOE/ALO-178
Shiprock, NM	74 to 744	UMTRA-DOE/ALO-172
Shiprock, NM	477 (site-weighted average) (348)	(b)
Spook, WY	328 to 528	UMTRA-DOE/ALO-179
Tuba City, AR	132 to 833	UMTRA-DOE/ALO-182
Vitro Site, UT	44 to 1902	UMTRA-DOE/ALO-171
Vitro Site, UT	597 (site-weighted average) (180)	(b)

(a) Number in parentheses is number of samples.

(b) Information provided by M. Jackson, Jacobs Engineering, Albuquerque, New Mexico.

1982; Hartley 1982). Thus the dried-out areas of the berm may have a lower emanating power indicating a potentially lower radon flux as well. However, as the berm dries out the diffusion coefficient increases.

Data on radon diffusion through tailings (Table 6) are very limited. As shown in the table, the diffusion coefficients are affected by the moisture content of the tailings. Radon diffusion measurements have been correlated with moisture contents for tailings cover soils. From this data a predictive correlation between the radon diffusion coefficient, D, and moisture saturation, M, has been developed (Rogers et al. 1982; Gee et al. 1984). The relationship is expressed as:

$$D = 0.07 \exp [-4m(m^4-p^2+1)] \tag{6}$$

where D = radon diffusion coefficient, cm^2/s
m = moisture saturation ratio
p = porosity of tailings, cm^3/cm^3.

TABLE 6. Diffusion Coefficients for Radon in Uranium Mill Tailings and Similar Materials

Material	Moisture, wt%	D, cm^2/s	Reference
Grand Junction tailings			
Mixed sands/slimes	1.8	2.2 x 10^{-2}	Freeman and Hartley 1984
Mixed sands/slimes	24.2	6.8 x 10^{-3}	"
Slimes	34.0	6.4 x 10^{-3}	"
Slimes	29.2	5.3 x 10^{-3}	"
Slimes	4.7	1.4 x 10^{-2}	"
Sand	3.7	1.9 x 10^{-2}	"
Sand	4.3	1.3 x 10^{-2}	"
Sand	4.5	2.6 x 10^{-2}	"
Sand	4.7	1.9 x 10^{-2}	"
Sand	3.7 to 4.7	1.6 x 10^{-2} to 2.6 x 10^{-2}	"
Vitro sand	0.1	7.3 x 10^{-3}	"
Shiprock slimes	0.1	1.1 x 10^{-2}	"
Ambrosia Lake tailings	NA	8.8 x 10^{-2}	Rogers 1980
Vitro tailings	NA	3.8 x 10^{-2} to 6.0 x 10^{-2}	MacBeth 1978
Tailings A	0.7	7.1 x 10^{-2}	Strong 1981
Tailings B	1.5	5.4 x 10^{-2}	Strong 1981
Wet beach (average)	--	2.7 x 10^{-3}	Silker 1979
Dry beach (average)	--	3.7 x 10^{-3}	"
Berm (average)	--	1.7 x 10^{-2}	"
Kerr-McGee 5 (dry beach)	16.3	3.0 x 10^{-3}	"
Kerr-McGee 6 (dry beach)	11.8	3.7 x 10^{-3}	"
UNC Nuclear-13 (berm)	6.3	1.2 x 10^{-2}	"
Fine quartz sand	0	6.8 x 10^{-2}	Tanner 1964
	8.1	5.0 x 10^{-2}	"
	15.2	1.0 x 10^{-2}	"
	17.0	5.0 x 10^{-3}	"
Building sand	4.0	5.4 x 10^{-2}	"

10^{-2} cm^2/s (beach sands) and 1 x 10^{-2} cm^2/s (slimes under dry conditions). Examining these data, the values chosen are believed to be conservative. As shown in Equation (4), the radon flux is directly proportional to the emanating power but varies as the square root of the diffusion coefficient. Thus, an increase in D of a factor of 4 will only double the calculated radon flux at a constant emanating power.

TABLE 5. Emanating Power of Uranium Mill Tailings

Tailings Pile	Number of Samples	Emanating Power, E	Reference
Shirley Basin	2	0.08, 0.12	Rogers 1980
Gas Hills	4	0.08 to 0.31	"
Ambrosia Lake	5	0.10 to 0.24	"
Powder River	4	0.06 to 0.19	"
Alkaline Leach	13		Silker and Heasler 1979
Wet beach		0.36	
Dry beach		0.43	
Berm		0.12	
Acid Leach	6		Silker and Heasler 1979
Wet beach		0.20	
Dry beach		0.19	
Berm		0.12	
Grand Junction			
Field test areas	135	0.084 to 0.45 0.38 average	Hartley 1982; Freeman and Hartley 1984
Radon flux test area	15	0.27 to 0.40	Freeman and Hartley 1984
Vitro	9	0.1 to 0.25	Nielson 1982
Jabiluka	-		Strong 1982
Dry 2 wt%		0.072	
Saturated		0.29	
Mary Kathleen	-		Strong 1982
Dry 2 wt%		0.067	
Saturated		0.31	
Riverton	13	0.02 to 0.13	Rogers 1983
Mexican Hat	14	0.14 to 0.28	"
Durango	13	0.06 to 0.26	"
Monument Valley	5	0.10 to 0.15	"
Monticello Acid Leach	5	0.19 to 0.26	"
Monticello Alkaline Leach	5	0.35 to 0.43	"

Even though this relationship was derived from soil data, tailings materials should generally follow the same relationship. Therefore, the D for tailings can be predicted if the moisture content and porosity are known.

Based on the limited data in Table 5, the radon diffusion coefficients chosen for calculational purposes in absence of specific measurements are 2 x

When the data are available, the radon release from the tailings pile should be calculated based on the two distinct areas: dry, porous beach sand areas and wet, relatively nonporous slime areas. During the active life of the tailings pile the slime area (which for the following sample calculation is estimated to represent about 60% of the tailings area) is generally covered with raffinate solution, which significantly reduces the release of radon from the slime.

For the example calculation, the tailings pile conditions are chosen so that the tailings solution is allowed to evaporate and the tailings to dry (maximum radon release) and the radium enrichment in the slimes is N = 5 (NRC 1980a). The enrichment may vary somewhat from site to site but N = 5 is reasonable for illustrating the calculational procedure.

^{226}Ra slimes = 250 pCi/g
^{226}Ra sands = 50 pCi/g
D slimes = 1×10^{-2} cm^2/s
D sands = 2×10^{-2} cm^2/s
ρ = 1.6 g/cm^3 for both slimes and sands
E = 0.2 for both slimes and sands
t = >3 m.

Measured values for D are preferred when available. As noted above, the chosen values are believed to be conservative. Using these data, the radon flux from the beach sands is estimated using the modified Equation (4) as follows:

$$
\begin{aligned}
J &= RE\rho\sqrt{\lambda D} \\
&= 50 \text{ pCi/g} \times 0.2 \times 1.6 \text{ g/cm}^3 \times [2.1 \times 10^{-6}\text{/s} \times \\
&\quad 2 \times 10^{-2} \text{ cm}^3\text{/s}]^{1/2} \times 10^4 \text{ cm}^2\text{/m}^2 \\
&= 32 \text{ pCi/m}^2\cdot\text{s.}
\end{aligned}
$$

The radon flux from the slimes, which are dry at closure (not covered by raffinate solution), is estimated as follows:

$$
\begin{aligned}
J &= 250 \text{ pCi/g} \times 0.2 \times 1.6 \text{ g/cm}^3 \times [2.1 \times 10^{-6}\text{/s} \times 1 \times 10^{-2} \text{ cm}^2\text{/s}]^{1/2} \\
&\quad \times 10^4 \text{ cm}^2\text{/m}^2 \\
&= 116 \text{ pCi/m}^2\cdot\text{s.}
\end{aligned}
$$

The total release, F_{total}, for a 50-ha tailings pile not covered by raffinate would be estimated as follows (under dry conditions, typical of closure):

$$
\begin{aligned}
F_1 \text{ (beach)} &= 32 \text{ pCi/m}^2\cdot\text{s} \times 10^4 \text{ m}^2\text{/ha} \times 3.165 \times 10^7 \text{ s/yr} \\
&\quad \times 10^{-12} \text{ Ci/pCi} \times 50 \text{ ha} \times 0.4 \text{ ha beach/ha} \\
&= 199 \text{ Ci } ^{222}\text{Rn/yr}
\end{aligned}
$$

$$F_2 \text{ (slimes)} = 116 \text{ pCi/m}^2\cdot\text{s} \times 10^4 \text{ m}^2\text{/ha} \times 3.165 \times 10^7 \text{ s/yr} \times 10^{-12} \text{ Ci/pCi} \times 50 \text{ ha} \times 0.6 \text{ ha slimes/ha} = 1100 \text{ Ci } ^{222}\text{Rn/yr.}$$

$$F_{total} = F_1 + F_2 = 199 + 1100 = 1299 \text{ Ci } ^{222}\text{Rn/yr.}$$

To simplify the calculation of surface radon flux, the normalized radon flux versus tailings depth is plotted in Figure 4 for several tailings diffusion coefficients (Freeman and Hartley 1984). To calculate the radon flux using Figure 4, the normalized radon flux is first determined from the known tailings depth and the diffusion coefficient. This value is then multiplied by the source term ($R\rho E$) to obtain the surface radon flux (in pCi/m$^2\cdot$s^1). An example of how to use the figure to calculate the flux is shown below.

Using the same tailings properties as in the last example, the normalized flux for the sand fraction and slime fraction from Figure 4 for a 3-m tailings pile is 1.4 and 2.0, respectively. This value is multiplied by the source term, 16 pCi/cm^3 for the sand and 80 pCi/cm^3 for the slimes. This results in a

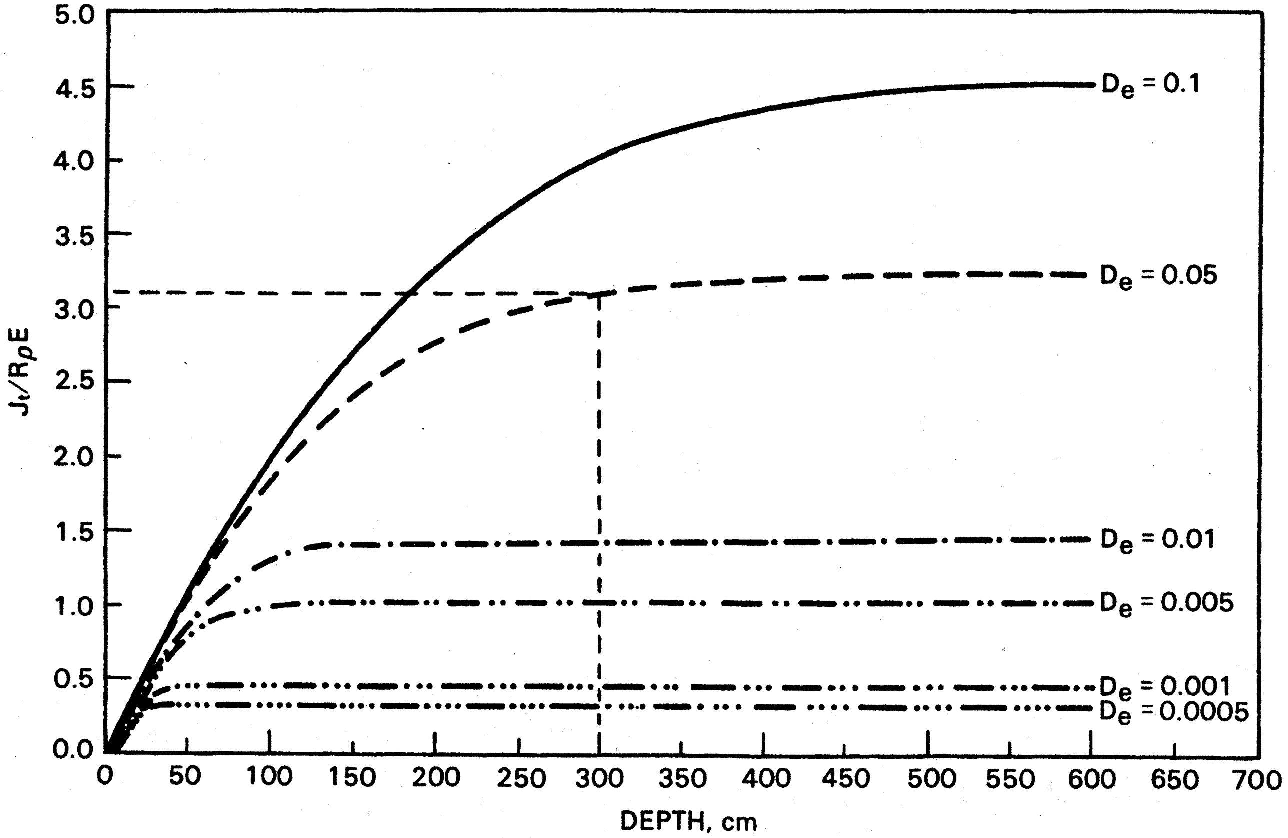

FIGURE 4. Normalized Surface Flux Versus Tailings Depth

tailings surface flux (J_t) of 32 $pCi/m^2 \cdot s^1$ for the sand and 112 $pCi/m^2 \cdot s^1$ for the slimes fractions, which is nearly the same as for the previous example (within the error of the graph).

Radon Release During In-Situ Operations

The major source of radon release during in-situ mining operations is the lixiviant, which when exposed to the atmosphere will release radon. The release will occur when the lixiviant arrives at the process recovery surge tanks, ion exchange tanks, or columns or evaporation ponds.

Aquifer restoration that includes ground-water sweeping and clean water circulation is also a source of radon that must be considered.

The key parameters used to determine the average annual radon release are listed in Table 7.

In order to determine a reasonably conservative annual radon release, it is assumed that one mining unit will be mined, one unit soaked, and one unit restored during the year. The radon release from these operations is discussed in the following paragraphs.

Radon Release from Mining

If the radium-226 content of the ore has not been measured, then it is assumed that the uranium-238 is in equilibrium with all its daughters. The radium-226 and radon-222 concentration present in the ore would therefore be

TABLE 7. Parameters Used to Determine Radon Release from In-Situ Mining

Ore grade, % U_3O_8
Radium-226 concentration in the ore body, pCi/g
Mined area per year, m^2
Average lixiviant flow rate, L/min
Average restoration flow rate, L/min
Number of operating days
Formation thickness, T
Formation porosity, %
Rock density, g/cm^3
Residence time for lixiviant, days
Residence time for restoration solution, days
Emanating power of ore

2820 pCi/g per % U_3O_8. The radon emanating power is assumed to average 0.2 unless otherwise determined. The radon release at equilibrium, G, in 1 m^3 of rock may be calculated as:

$$G = R\rho E\ (1 - p)/p \times 10^{-6} \tag{7}$$

where G = radon release, Ci/m^3 of rock
R = radium content, pCi/g
ρ = rock density, g/cm^3
E = emanating power
p = formation porosity.

The yearly radon release, Y, in Ci/yr may be calculated as follows:

$$Y = GM\varepsilon D \times 1.44 \tag{8}$$

where M = lixiviant production rate, L/min
ε = equilibrium factor for radon
D = production days per year.

The equilibrium factor, ε, equals $1 - e^{-\lambda t}$ where λ is the radon decay constant and t is the residence time. This is a conservative estimate since it assumes that the radon immediately goes into the lixiviant solution.

Radon Release from Soaking

In addition to the release of radon from the lixiviant dissolution, it is estimated that one pore volume of nonproduction solution will be removed as each mining unit is put into service. The startup radon release, S, may be calculated as:

$$S = GATp \tag{9}$$

where A = area of mining unit, m^2
T = thickness of ore, m.

For a mining unit that will be soaked for 1 year, it is also assumed that one pore volume of mining solution will be removed when the lixiviant is added. Therefore, the release of radon would be the same as during the startup.

Radon Release During Restoration

The annual radon released during restoration, r, in Ci/yr is calculated using:

$$r = GN\varepsilon D \times 1.44 \qquad (10)$$

where G = radon release at equilibrium, Ci/m^3 of rock
N = restoration solution rate, L/min.
E = equilibrium factor
D = restoration days per year.

It is also assumed that one pore volume of solution will be removed before restoration begins, similar to startup.

Example Calculation: Radon Release from an In-Situ Mine

The following is a sample calculation of the total release of radon from a hypothetical in-situ uranium mining operation.

Assumptions:

Ore grade	0.1% U_3O_8
Average area to be mined	10 acres
Average lixiviant flow	4000 L/min
Average restoration flow	400 L/min
Operating days per year	365
Formation thickness	3 m
Formation porosity	0.3
Rock density	1.8 g/cm^3
Residence time for lixiviant	5 days
Residence time for restoration solution	10 days
Emanating power	0.2

From mining and soaking, the radon release per m^3 of the rock is estimated using Equation (7).

The radium content, R is first calculated assuming secular equilibrium between the U^{238} and Ra^{226}.

$$\begin{aligned} R &= 3.33 \times 10^5 \text{ pCi } U^{238}/\text{g U} \times 0.001 \text{ g } U_3O_8/\text{g ore} \times 0.85 \text{ g U/g } U_3O_8 \\ &= 283 \text{ pCi/g ore.} \end{aligned}$$

Next the radon release, G, is calculated.

$$\begin{aligned} G &= R\rho E(1 - p)/p \times 10^{-6} \\ &= 283 \text{ pCi/g} \times 1.8 \text{ g/cm}^3 \times 0.2 \\ &\quad \times (1 - 0.3)/0.3 \times 10^{-6} \\ &= 2.4 \times 10^{-4} \text{ Ci/m}^3. \end{aligned}$$

Next the radon release, G, is calculated using Equation (8).

$$Y = GM\varepsilon D \times 1.44$$
$$\varepsilon = 1 - e^{-(0.181/d)(5\ d)} = 0.6$$
$$Y = 2.4 \times 10^{-4}\ Ci/m^3 \times 4000\ L/min \times 0.6$$
$$\times\ 365\ days/yr \times 1.44$$
$$= 303\ Ci/yr.$$

The radon released from the startup solution and soaking is calculated using Equation (9).

$$S = GATp$$
$$= 2.4 \times 10^{-4}\ Ci/m^3 \times 10\ acres \times 4074\ m^2/acre \times 3\ m \times 0.3$$
$$= 8.8\ Ci/yr.$$

The total release of radon from the startup solution, production lixiviant, and soaking solution is:

Startup solution	8.8 Ci/yr
Production	303 Ci/yr
Soaking solution	8.8 Ci/yr
	320.6 Ci/yr

The radon release from the restoration operation is calculated using Equation (10):

$$r = GN\varepsilon D \times 1.44$$
$$\varepsilon = 1 - e^{-(0.181/d)(10\ d)} = 0.84$$
$$r = 2.4 \times 10^{-4}\ Ci/m^3 \times 400\ L/min \times 0.84 \times 365\ d/yr \times 1.44$$
$$= 42.4\ Ci/yr$$

The total radon release from restoration includes a small increment of release similar to that from the startup solution. Therefore, the total release would be:

$$42.4\ Ci/yr + 8.8\ Ci/yr = 51.2\ Ci/yr.$$

The total release from this 10-acre hypothetical in-situ mining operation is then 320.6 + 51.2 = 371.8 Ci/yr.

NONRADIOACTIVE EMISSION SOURCE TERMS

During uranium milling some nonradioactive contaminants and toxic elements are also released to the environment, as shown in Table 8. In addition, combustion products are released from burning of fuel in the process and heating boilers.

Nonradioactive Particulate Emission Source Terms

The major sources of nonradioactive particulate emissions are the same as the sources of radioactive particulate emissions, previously described. The general method for calculating source terms is also the same as for the radioactive source term previously discussed. Example calculations of nonradioactive particulate source terms follow.

Example Calculation: Crushing

Source terms for toxic elements in the ore are estimated in a parallel manner to the radioactive particulate emissions. For example, if the applicant has indicated that the manganese content of the ore is 500 ppm (500 g/MT) the annual release of manganese from ore crushing, assuming no enrichment of Mn in the fines, N = 1, and assuming that the process conditions and emission factor, E = 0.16 lb/ton, are identical to those in the crushing example (p. 14), is then estimated as follows using Equation (1):

TABLE 8. Nonradioactive Emissions Generated by Uranium Milling

Source	Emission
Ore storage and crushing/grinding	Ore dust
Leaching tanks vent	Sulfuric acid mist Sulfur dioxide
Solvent extraction vent	Organic solvent (kerosene)
Burning of fuel oil	SO_2, NO_2
Yellowcake precipitation	Ammonia
Yellowcake centrifuge or filter and calciner	Ammonia
Laboratory hood	Miscellaneous vapors
Tailings pile	Tailings dust

$$S = 145{,}000\ \text{MT/yr} \times 500\ \text{g Mn/MT} \times 0.16\ \text{lb/ton} \times 1\ \text{ton/2000 lb} \times (1 - 0.80) \times 1 = 1.2 \times 10^3\ \text{g Mn/yr}.$$

Example Calculation: Truck Unloading to Ore Pad

If for example, the ore contained 250 ppm (250 g/MT) of lead, assuming no enrichment of lead in the fines, N = 1, and assuming that the conditions are identical to those given in the unloading example on p. 14, the estimate of annual lead release would be:

$$S = 193{,}000\ \text{MT/yr} \times 250\ \text{g/MT} \times 0.04\ \text{lb/yd}^3 \times 1\ \text{yd}^3/1.5\ \text{ton} \times 1\ \text{ton/2000 lb} \times 1 = 643\ \text{g Pb/yr}.$$

Example Calculation: Fine Ore Storage

In this example, the fine ore is conveyed to and from the fine ore storage area for a total of four conveyor transfers. Ore is handled at a rate of 135,000 MT/yr. The operation occurs in an enclosed structure with a reduction factor of 75% based on engineering judgment (Appendix C). The emission factor for each transfer is 0.023 lb/ton (Appendix B). The combined emission factor for conveying the fine ore storage is:

$$E = 4\ \text{transfers} \times 0.023\ \text{lb/ton per transfer} = 0.092\ \text{lb/ton}.$$

If for example the dust had an arsenic content of 50 ppm (50 g/MT) and assuming that the arsenic concentration was uniform regardless of ore particle size (N = 1), then the estimate of annual arsenic release would be:

$$S = 135{,}000\ \text{MT/yr} \times 0.092\ \text{lb/ton} \times 1\ \text{ton/2000 lb} \times 50\ \text{g/MT} = 311\ \text{g As/yr}.$$

Windblown Emissions

The nonradioactive windblown particle emissions are estimated in a manner similar to the radioactive particulate emissions described earlier.

Example Calculation: Tailings Pile

Using the assumptions on p. 18 and Equations (2) and (3), the toxic element releases can be estimated. For the ore with an initial lead concentration of 250 ppm (250 g/MT) regardless of particle size (N = 1), and with essentially all (99.9%) of the lead disposed of to the tailings pile, the source term for lead for the abandoned tailings pile radioactive particulate release example is:

$$S = 4.3 \times 10^2 \text{ g/m}^2\cdot\text{yr} \times 53 \text{ acres} \times 4047 \text{ m}^2\text{/acre} \times 250 \text{ g Pb/MT} \times 1 \text{ MT}/10^6 \text{ g} \times (1 - 0.85) = 3.5 \times 10^3 \text{ g Pb/yr.}$$

Example Calculations: Ore Pad

The modified equations for ore pads are discussed and presented in the radioactive particulate emission section. Thus, for the site with the previously described wind frequency occurrence, the annual average dust loss rate is estimated to be:

$$E_w = 0.1 \times 3.156 \times 10^7 \text{ s/yr} \times 6.75 \times 10^{-6} \text{ g/m}^2\cdot\text{s}/(0.5) = 43 \text{ g/m}^2\cdot\text{yr.}$$

The toxic source term for an ore pad of 10 acres containing ore with 200 ppm (200 g/MT) Pb, regardless of ore particle size (N = 1), and no emission control, R = 0, is estimated using Equation (3):

$$S = 43 \text{ g/m}^2\cdot\text{yr} \times 10 \text{ acres} \times 4047 \text{ m}^2\text{/acre} \times 200 \text{ g Pb/MT} \times 1 \text{ MT}/10^6 \text{ g} \times 1 = 348 \text{ g Pb/yr.}$$

Any control such as keeping the ore pile wet, applying chemical stabilizers or installing windscreens (Elmore and Hartley 1984) would reduce fugitive dust by the appropriate factor, as shown in Appendix C.

Nonradioactive Gas Emission Source Terms

Milling operations will result in the release of nonradioactive gases and vapors to the atmosphere (Table 8). The main sources of these emissions are the leach circuit, the solvent extraction circuit, yellowcake precipitator and dryer, the analytical laboratory, and the mill power plant and heating systems. The annual average concentrations off site are expected to be below background and in general too low to measure (NRC 1980a).

Leaching

Small amounts of sulfuric acid mist can escape from the vent system. Carbon dioxide can also be produced as a result of acid reaction with carbonate materials present in the ore. Trace quantities of sulfur dioxide and free chlorine may also be released. A demister can be used to remove greater than 99% of the acid mist. Release of hydrides such as arsine, stibine, and hydrogen sulfide during leaching is considered negligible (NRC 1982c). Release factors that can be used to estimate releases from an acid circuit are shown in Table 9.

TABLE 9. Chemical Airborne Release Factors for Acid Leach Mill

Material Released	Release Factor, kg/kg U
Sulfur oxides	2×10^{-4}
Nitrogen oxides	2×10^{-3}
Ammonia	2×10^{-3}
Kerosene	2×10^{-4}
Organic acids	5×10^{-3}
Aldehydes	8×10^{-4}
Hydrocarbons	3×10^{-3}

Source: Schneider and Kabele 1979.

Solvent Extraction

Solvent extraction and stripping result in some evaporative loss of exposed organic solvents. Kerosene represents about 92% of the organic solvent, with the remaining 8% an organic acid such as alkyl phosphoric acid. A wet scrubber can be used to reduce emissions by greater than 99%. A source term may be calculated using data in Table 9 as shown.

For a mill processing 145,000 MT/yr with an average U_3O_8 content of 0.1% and a wet scrubber with 99% efficiency (organic acid plus kerosene), the emission source term from solvent extraction is calculated as:

$$\begin{aligned} S = {} & 145{,}000 \text{ MT/ore/yr} \times 0.1 \text{ kg } U_3O_8\text{/MT ore} \\ & \times 0.85 \text{ kg U/kg } U_3O_8 \times (5 \times 10^{-3} \text{ kg/g U} + 0.2 \times 10^{-3} \text{ kg/kg U}) \\ & \times (1 - 0.99) \\ = {} & 0.64 \text{ g organic acid plus kerosene/yr.} \end{aligned}$$

Analytical Laboratory

Various process reagents and products will be analyzed. The fume hoods will collect air and a mixture of chemical fumes and mists. A wet scrubber can be used to reduce the emission by more than 99%.

Mill Power Plant and Building Heat Boiler

The source term for mill electrical power and process heat will depend on the system and fuel used. For example, if a diesel-generating unit were to be used with number 2 diesel fuel (maximum 1% sulfur) several gaseous emissions would result--CO, hydrocarbons, NO_x and SO_2. If an oil-fired boiler were used for process and building heat, the emissions would be similar. Emission factors for fuel combustion have been developed by the EPA (1977). For convenience, conservative values have been abstracted from the compilation and summarized in Appendix D. These data can be used to calculate appropriate combustion source terms.

To illustrate how to calculate the source term for a heat boiler, the following example is provided. Assume that the boiler will be used to supply supplementary heat during cold weather, and that it will burn an average of 23 L/h fuel oil (distillate) with a 0.1% sulfur content. The unit will operate for 120 days during the year. Based on the emission factors from fuel combustion presented in Appendix D, the following average estimate emissions would result.

	$kg/10^3$ L	L/h	h/d	d/yr	kg/yr
Sulfur dioxide	17 x 0.001(a)	x 23	x 24	x 120	= 1.1
Carbon monoxide	0.63	x 23	x 24	x 120	= 41.7
Hydrocarbons	0.12	x 23	x 24	x 120	= 7.9
Nitrogen oxides	2.8	x 23	x 24	x 120	= 185

(a) Sulfur content in fuel oil.

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APPENDIX A

PRIMARY PARAMETERS NEEDED TO ESTIMATE SOURCE TERMS FOR URANIUM MILL OPERATIONS

APPENDIX A

PRIMARY PARAMETERS NEEDED TO ESTIMATE SOURCE TERMS FOR URANIUM MILL OPERATIONS(a)

Ore Quality

Concentration of U_3O_8 in ore, % by weight, including ranges
Processing rate, MT/day
Radionuclide content (^{238}U and daughter products), pCi/g
Concentration of nonradioactive toxic elements, g/MT (ppm)
Dust/ore activity ratio, 2.5(b)
Moisture content, % by weight
Bulk density, g/cm^3
Diffusion coefficient, D, for radon in ore piles, cm^2/s, if available(c,d)
Emanating power for radon, E, if available.(e)

(a) Default values listed in these footnotes or in the text can be used unless measured values are provided.

(b) A dust/ore activity ratio of 2.5 can be used unless there is specific, convincing evidence that the enrichment factor should be another ratio, either lower or higher. The dust/bulk activity ratio used for tailings sands is also 2.5. (Used for radioactivity releases only.)

(c) If no data are available, the following diffusion coefficients, D, for radon may be considered:

2×10^{-2} cm^2/s for ores and beach sands (tailings)
5×10^{-3} cm^2/s for wet slimes (tailings)
1×10^{-2} cm^2/s for dry slimes (tailings).

These values are representative data as shown in Table 6. As new data are obtained, these values will be changed, as applicable.

(d) The operation radon emission from ore stockpiles and tailings impoundments can normally be calculated using the flux ratio (1.0 pCi/m$^2\cdot$s of ^{222}Rn)/(pCi/g of ^{226}Ra).

(e) If specific data are not otherwise available, 0.2 can be used as the emanating power of radon.

Ore Unloading and Storage Data

Area of each pile or bin complex and total area, m^2
Average depth of pile, m
Annual average quantity of ore in storage, MT
Porosity of the ore pile, %
Receipt rates (truck or rail unloading rate), MT/d
Operational period, d/yr
Description of dusting control[(a)]
Quantity of each range of ore quality
Radon emission,[(b)] Ci/yr
Vehicle requirements

- type
- number
- capacity, MT or m^3/vehicle
- frequency of operation (deliveries/day, MT/delivery).

Crushing/Grinding

Description of ventilation air treatment

- design efficiency of scrubbers and filters
- expected efficiency of scrubbers and filters
- minimum efficiency of scrubbers and filters

Uncontrolled emission factors[(c)]
Description of emission controls.

Leaching/Extraction

Ratio of leachant to ore, L/kg
Composition of leachant, $\underline{M}$
Composition of solvent, if used
Ion exchange medium, if used
Residence time of ore in mill, d.

(a) Various emission reduction factors used by the NRC are listed in Appendix C.

(b) The operation radon emission from ore stockpiles and tailings impoundments can normally be calculated using the flux ratio (1.0 pCi/m^2·s of ^{222}Rn)/(pCi/g of ^{226}Ra).

(c) If not available from onsite operations, uncontrolled emission factors used by the NRC staff are shown in Appendix B.

Yellowcake Drying and Packaging

Yellowcake characteristics
- bulk density, g/cm^3
- purity, % U_3O_8

Production rates, MT/yr
- drying
- packaging

Processing times, h/d and d/yr

Description of air ventilation controls
- design efficiencies
- expected efficiencies
- minimum efficiencies.

Tailings Impoundment Systems

Tailings characteristics
- average radionuclide contents (^{238}U, ^{230}Th, ^{226}Ra, ^{210}Pb), pCi/g
  - beach sands
  - slimes
- dust/bulk solids activity ratio of tailings sands
- bulk density, g/cm^3
- moisture content, % by weight
- diffusion coefficients for radon, cm^2/s, if available
- emanating power for radon, E, if available
- radon emission,(a) Ci/yr.

Impoundment Area,(b) m^2

- total
- beach sands
- under water
- exposed wet slimes
- dried slimes

(a) The operation radon emission from ore stockpiles and tailings impoundments can normally be calculated using the flux ratio (1.0 pCi/m^2·s of ^{222}Rn)/(pCi/g of ^{226}Ra).

(b) The indicated information is needed for varying operational periods. For example:
- last year of mill operations
- period just before pond dry-up
- period just before reclamation
- period of maximum generation, if different from above.

Description of dust control
Estimated drying time required before initiation of reclamation procedures, and basis
Estimated time required to stabilize and reclaim after drying, and basis.

Energy Requirements

Electricity, kWh/yr
Diesel oil and gasoline, L/yr
Fuel oil, L/yr
Fuel gas, m^3/yr
Coal, MT/yr.

Process Chemical Requirements

Sulfuric acid, concentration and MT/yr
Sodium carbonate, MT/yr
Solvent, composition and MT/yr
Oxidant, kg/yr
Ammonia, kg/yr
Others, annual use.

APPENDIX B

EMISSION FACTORS

APPENDIX B

EMISSION FACTORS

Process	Uncontrolled Emission
Ore loadout to grizzly or stockpile	0.002 lb/yd^3 truck bottom-dump(a) 0.04 lb/yd^3 truck end-dump(a) 0.04 lb/ton conveyor transfer point(a)
Primary crushing, secondary crushing, and screening combined (The addition of tertiary crushing will double the chosen factor.)	0.002 lb/ton (moisture $\geq$9%)(a) 0.04 lb/ton (moisture 8 to 9%)(a) 0.16 lb/ton (moisture <8%)(a)
Transfer point such as conveyor loading	0.023 lb/ton(a)
Conveying	0.2 lb/ton
Yellowcake drying and packaging	0.1%(b)

(a) Tistinic, T. 1981. Fugitive Dust Emissions. Interoffice communication of the Colorado Department of Health, APCD.
(b) Based on EPA-measured releases at six mills.

APPENDIX C

ORE PROCESSING PARTICULATE EMISSION REDUCTION FACTORS

APPENDIX C

ORE PROCESSING PARTICULATE EMISSION REDUCTION FACTORS[(a)]

Emission Control	% Reduction
Ore pads, heap leach piles, or tailings piles	
Chemical suppressant (synthetic polymer usually)	80 to 85
Mulch	85
Rapid revegetation	75
Wind breaks - mature forest	75
Wind breaks = height of pile	50
Wind breaks < height of pile	30
Frequent water (twice daily)	50
Water sprinkle as needed	25
Chemical and vegetation stabilization	93
Water cover	99
Soil cover	100
Riprap + soil cover	100
Oiling	80
Complete enclosure (includes silos)	99
Partial enclosure	50
Canvas covers	80
Ore loadout to grizzly or stockpile	
Negative pressure with fabric filter	85
Chemical suppressants	85
Enclosed structure	75
Telescopic chute	75
Stacker - water spray	75
Water spray	50
Wind guard	50
Stacker - height adjustable	25
Stone ladder	80
Ore crushing and grinding	
Bag filter	33
Semiautogenous grinding	100
Conveying (includes transfer points)	
Bag filter	99
Water spray	99
Enclosed	85
Partially enclosed	70
Partially enclosed with water spray	85
Chemical surfactants (open)	85
Water spray (open)	70
Yellowcake drying and packaging	
Venturi scrubber and demister	90
Slurry product	100

(a) Most data from T. Tistinic. 1981. Fugitive Dust Emissions. Interoffice communication from the Colorado Department of Health, APCD. Other information based on engineering judgment and:
Midwest Research Institute. 1977. A Study of Fugitive Emissions from Metallurgical Processes. Contract No. 68-02-2120 for Industrial Environmental Research Laboratory, EPA, Research Triangle Park, North Carolina.
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APPENDIX D

EMISSION FACTORS FROM FUEL COMBUSTION WITHOUT EMISSION CONTROL

APPENDIX D

EMISSION FACTORS FROM FUEL COMBUSTION WITHOUT EMISSION CONTROL(a)

Source of Emissions	Particulates	Sulfur Oxides	Hydrocarbons	Carbon Monoxide	Nitrogen Oxides	Aldehydes
Coal, kg/MT						
Anthracite	8.5A(b)	19S(c)	Neg. (1.25)(d)	0.5 (45)(d)	9	
Bituminous	8.5A (10)(d)	19S	0.5 (10)(d)	5 (45)(d)	28	0.0025
Fuel oil, kg/10^3 L						
Distillate oil	0.25	17S	0.12	0.63	2.8	
Natural gas, kg/10^6 m^3	240	9.6	128	320	3680	
Liquid petroleum gas (LPG), kg/10^3 L	0.23	0.09S	0.096	0.24	1.5	
Vehicles,(e) g/km						
Gasoline-powered						
Light duty truck			2.1	26.6	3.3	
Heavy duty truck			8.4	117.	7.8	
Diesel-powered						
Heavy duty truck	0.81	1.7	2.9	18	21	0.2
Off-highway, stationary sources						
Gas-fired, kg/10^6 m^3	220	83	670	1800	6600	
Oil-fired, kg/10^3 L	0.60	0.4	0.7	1.9	8.1	
Gasoline-powered, kg/10^3 L	0.78	0.64	16	470	12	0.52
Diesel-powered, kg/10^3 L	4.0	3.7	4.5	12	56	0.84

(a) Emission factors are abstracted on a conservative basis (higher values) from EPA. 1977. Compilation of Air Pollution Factors, and Supplements. 3rd ed. PB-275-525, Office of Air and Waste Management, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

(b) "A" represents the weight percentage of ash in the fuel.

(c) "S" represents the weight percentage of sulfur in the fuel.

(d) For hand-fired units.

(e) Data are for 1972 model year and for emissions at either high or low altitudes depending on which value is higher. For earlier model years consult the reference.

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