MASTER

RADON AND RADON-DAUGHTER CONCENTRATIONS IN AIR IN THE VICINITY OF THE ANACONDA URANIUM MILL

by

**Michael H. Momeni, J. B. Lindstrom,
C. E. Dungey, and Walter E. Kisielewski**

**HUMAN-EXPOSURE PATHWAYS FROM
URANIUM-MINING AND -MILLING FACILITIES**

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Abstract

Radon concentration, working level, and meteorological variables were measured continuously from June 1977 through June 1978 at three stations in the vicinity of the Anaconda Uranium Mill with measurements integrated to hourly intervals. Both radon and daughters show strong variations associated with low wind velocities and stable atmospheric conditions, and diurnal variations associated with thermal inversions. Average radon concentration shows seasonal dependence with highest concentrations observed during fall and winter. Comparison of radon concentrations and working levels between three stations shows strong dependence on wind direction and velocity. Radon concentrations and working-level distributions for each month and each station were analyzed. The average maximum, minimum, and modal concentration and working levels were estimated with observed frequencies. The highest concentration is 11 000 pCi/m³ on the tailings. Working-level variations parallel radon variations but lag by less than one hour. The highest working levels were observed at night when conditions of higher secular radioactive equilibrium for radon daughters exist. Background radon concentration was measured at two stations, each located about 25 km from the mill, and the average is 408 pCi/m³. Average working-level background is 3.6×10^{-3} .

INTRODUCTION

The projected increasing demand during the coming decade for uranium as one of the fuels for the generation of electricity has focused public attention on the potential long-term radiological impacts of processing natural uranium. The radiological impact of uranium mining and milling in the United States is primarily associated with uranium-238 and its radioactive daughters present in the ore. Figure 1 gives the sequence of radionuclides in the uranium-238 decay chain. Naturally occurring uranium ore contains uranium-238 and uranium-235 at 99.28% and 0.72% by weight, respectively. Because the natural abundance activity ratio of uranium-235 to uranium-238 is only 4.54×10^{-2} , the effects of uranium-235 and its radioactive progeny are much

smaller than the effects of the uranium-238 series. Our measurements of uranium ore in the United States indicate that the natural abundance of thorium-232, another long-lived parent of a series of radioactive daughter nuclides, is much less than that of uranium-238.

A major source of exposure to the population in the vicinity of uranium-mining and -milling operations results from inhalation of the radon-222 daughters polonium-218, lead-214, bismuth-214, and polonium-214. Radon-222 is a noble gas generated from decay of radium-226, which is present in almost all soils and ores, especially uranium ore. Radon can escape to the atmosphere by diffusing several meters through soil and tailings. Because of its relatively long half-life of 3.8 days, it can then be transported by atmospheric diffusion several hundred kilometers from its release point. The principal natural source of radon background is the soil.

The concentration of radon daughters in air is inherently dependent on the ambient radon concentration, on atmospheric dilution (dispersion), and the buildup time during which the radon daughters have accumulated. After formation, radon daughters are ionic and reactive and will associate with natural atmospheric aerosols. After association, they behave as particulates in atmospheric transport and deposition.

Concentration of radon daughters in air is often expressed in units of working level (WL). One WL is defined as any combination of radon daughters in one liter of air that ultimately will result in the emission of 1.3×10^5 MeV of alpha energy. Under conditions of secular equilibrium, one pCi/L of radon-222 produces 1×10^{-2} WL. This equilibrium condition will seldom be attained in a free atmosphere because normally dispersion will limit radon-daughter concentration to about 10% of the equilibrium value in areas adjacent to the release site. Farther from the site, dispersion results in further reduction of radon-daughter concentration even though the equilibrium ratio approaches unity (Momeni et al. 1979a).

Respiratory diseases including lung neoplasia, the principal biological effect of inhalation of radon daughters (Lundin et al. 1971, de Villiers and Windish 1964), are induced by polonium-218 and -214 alpha irradiation. Because of the longer range of the polonium-214 alpha (7.68 MeV) its contribution to exposure of the sensitive respiratory epithelium may exceed that of the polonium-218 (6.00 MeV) alpha irradiation. Even though bismuth-214 and lead-214 are beta emitters (Fig. 1), their transition to polonium-214 results in significant contributions to respiratory pathogenesis.

Working level has been used for quantification of potential inhalation exposure from radon daughters. Radon, by itself, delivers only about 0.3% of the total dose resulting from inhalation of radon accompanied by its daughters in an equilibrium mixture (Morgan 1951). Radon daughters are not inert gases and are most readily deposited in the respiratory passages. The deposition fraction is a function of particle size associated with radon daughters, tidal volume, respiratory frequency, and breathing habits (via mouth or nasal passages). The particle-size distribution is not uniform in either time or space; it is dependent on wind velocity and ground-surface structure.

Predictions of radiological impacts on man from radon and progeny released from milling operations are based on:

1. Spatial and temporal distribution of the concentration of radon and progeny in the vicinity of the mill,
2. Estimates of the resulting dose and dose rate to the population, and
3. Estimates of health effects based on dose-effect and dose-rate-effect relationships.

Major sources of release of radon are (1) the ore pad, where ore is stored for blending and continuous-feeding operation of the mill; (2) crushing and grinding of the ore to maximize the uranium extraction; and (3) tailings-retention area. Rate of release of radon from each source is dependent on the procedures enacted to mitigate the radon release (Momeni et al. 1979b, Sears et al. 1975).

Estimates of airborne concentration of radon and radon daughters based on "grab sampling" are unreliable due to temporal variability of the ambient environment. Measurements based on either "integrated air samples," giving an average concentration, or continuous monitoring, displaying temporal variations in concentration, overcome the difficulty.

Concentration of radon in the vicinity of inactive tailings has been reported (Shearer and Sill 1969, Snelling 1971, Schiager 1974), but concentration of radon and working level in the vicinity of an active mill has not been reported. The purpose of this study was to obtain long-term experimental data for the prediction of radiological impacts of uranium-milling operations. These data will be used for the development and testing of existing methodologies such as the UDAD code (Momeni et al. 1979a) to predict airborne concentration of the radionuclides for comparison with environmental standards. The UDAD code has already been used for the generic radiological evaluation of uranium-milling operations, known as UMOGES (U.S. Nuclear Regulatory Commission 1979).

The measurements listed in Table 1 were made at the Anaconda Uranium Mill (Fig. 2), Bluewater, New Mexico; more limited measurements were made at Exxon Highland, Wyoming, and at Union Carbide Mill, Uravan, Colorado. In this report, the data collected at the Anaconda Uranium Mill are described; data obtained at the other mills will be reported elsewhere.

1. Meteorological Measurements

Windspeed and direction were measured at three locations (stations) continuously for a period of about one year. In addition, station temperature and atmospheric stability were recorded. Figure 3 and Table 1 give the locations of the stations and the type of data collected.

2. Radon-222 Measurements

- a. Radon-222 was continuously measured at three stations for a period of about one year. Background concentrations of radon

were monitored continuously at two stations located about 25 km from the millsite.

- b. Air samples for measurement of radon concentration were collected for periods of 24 hours duration at various locations relative to the millsite.

3. Radon-Daughter Measurements

- a. WLs were measured continuously at three locations for a period of about one year.
- b. WLs were also determined in grab samples of air using an American National Standards Institute (ANSI) technique.

Rates of release of radon (source terms) were also measured for major sources of release (ore pads, ore crusher, tailings-retention area). Excerpts of these studies have been reported previously (Momeni et al. 1978, 1979b).

In this report, meteorology, radon concentrations, and working levels at the Anaconda Uranium Mill are described. Reports in preparation describe the measurement methodology and application of the data.

Figure 1. The Uranium-238 Radioactive-Decay Series.

Figure 2. The Anaconda Uranium Mill.

Figure 3.

Experimental Stations at the
Anaconda Uranium Mill, Bluewater,
New Mexico.

[Designated areas are:

- A (stations 101 & 102),
- B (station 103),
- C (station 104),
- D (station 105), and
- E (station 100).

Inactive tailings are ACID &
ALKO. The still-active
tailings-retention area is
designated MAIN. The ANL
field laboratory is adjacent
to the water tower.]

Table 1. Protocol of Measurement

<i>Measurement</i>	<i>Sampling Points</i>
<u>Meteorological variable</u>	
Windspeed	Stations 102, 103, 104
Wind direction	Stations 102, 103, 104
Stability	Station 102
<u>Radon concentration</u>	
Continuous monitoring	Stations 102, 103, 104
Background monitoring	Elkins, McBride
Integrated air sampling	Tailings, ore pile (pad)
Direction	South of tailings
Distance	0, 100, 250, 375, 525, 600, 705, 825 m
Direction	Southwest of tailings
Distance	0, 10, 75, 125, 325 m
Direction	East of tailings
Distance	0, 200, 400, 1120, 1630, 2970, 3170 m
Grab sampling	Inactive acid leach, carbonate leach, stations 100, 101, 102, 104, 105, field laboratory
<u>Working level</u>	
Continuous monitoring	Stations 102, 103, 104
ANSI technique	Stations 100, 101, 102, 103, 104, 105

:

SITE CHARACTERISTICS

A major part of the field study has been conducted at the Anaconda Uranium Mill (Fig. 2, 3), Bluewater, New Mexico (Fig. 4), since June 1977 in cooperation with William E. Gray, Director of Environmental Affairs, Uranium Mining and Refining. Between 1955 and 1978 the Anaconda Mill extracted uranium using an acid leaching process from a throughput of 3500 tonnes per day of ore containing about 0.25% uranium (U_3O_8). At present, the mill processes 5400 tonnes per day of ore with an ore quality of less than 0.2%.

Tailings from the mill are pumped to a retention area (Fig. 3) with an area of about 8×10^5 m². Photographs (Figs. 5, 6, and 7) show this area. Before reconstruction of the present dikes, tailings overflows were collected in catch basins. These deposits in the catch basins are about 125 cm deep. Between 1953 and 1956 Anaconda also operated a carbonate leach process, with tailings deposited separately. Locations of these various tailings areas are indicated in Figure 3; they are designated ACID (old acid tailings), ALKO (old carbonate tailings), and MAIN (current tailings). In the latter part of 1977, the old tailings were covered with silt-clay to an average depth of 85 cm. The tailings management was altered in 1978 when additional evaporation ponds were built and a new tailings discharge process was implemented in an attempt to increase moisture in the beach area. This technique is similar to that described by Momeni et al. (1979b).

ANACONDA-MILL ENVIRONS

The Anaconda Uranium Mill is located in Valencia County, New Mexico, at 35°15'30" N Lat. and 107°55'50" W Long., in the heart of the Grants Uranium District. It lies about 15 km (10 mi) northwest of Grants in a small alluvium- and volcanic-filled valley known as the San Jose River Valley (Fig. 4). The Zuni Mountains, a northwest-trending range, lie about 25 km (15 mi) southwest of the mill. Mesas surround the San Jose River Valley to the north, east, and south.

Elevation at the mill site is 2000 m (6500 ft). Nearby mesas range in height from 2180 to 2600 m (7156 to 8400 ft). The Zuni Mountains average only 2100 m (7000 ft). Mount Taylor, an extinct volcano located about 30 km (18 mi) to the east, is the highest point in the vicinity, with an elevation of 3471 m (11 389 ft).

Flow in surface streams near the site is intermittent. This includes the Rio San Jose and the San Mateo Creek (located 8 km or 5 mi from the mill) and numerous other small drainages. The Rio San Jose becomes a permanent stream near Grants where it is fed by springs and sewage-treatment effluents (Anaconda 1976). The surficial alluvium and porous basalt flows make a good shallow aquifer.

The Bluewater Mill and its accompanying tailings pond are situated in a part of the valley that was partially covered by a Quaternary basalt flow (Fig. 8). The basalt, known as the Malpais, is scoriaceous and contains numerous caverns and collapse features together with the Quaternary alluvium, and makes an important shallow aquifer. The San Andres-Glorieta aquifer (Permian), which is the most highly used in the Bluewater vicinity, comes into direct contact with the Malpais under the mill and tailings pond, as shown in Figure 9 (Kaufmann et al. 1975). The Yeso formation, also Permian, is conformable with the San Andres-Glorieta; an injection well disposed of the effluents into this formation (Anaconda 1976). Hydrologic properties of all the formations are given in the appendix (Table A1).

The geologic section at the mill site includes formations from the pre-Cambrian, Pennsylvanian, Permian, and Traissic eras. The Rio San Jose Valley and the Zuni Mountains constitute the southwestern edge of the San Juan Basin (Anaconda 1976). The Zuni Uplift was a source for some of the detrital material of the Pennsylvanian Maders Formation and is primarily a limestone. Detailed geology of this region is described by Mallory (1972), Rascoe and Baars (1972), and MacLachlan (1972).

The Bluewater Mill is located in Seismic Zone 2 (probable moderate earthquake damage), corresponding to an intensity of VII on the Modified Mercalli Scale. There are no visually identifiable structural deformations within 1 km of the mill site. However, pre-Quaternary rocks nearby are cut by many small-displacement normal faults. Many are en echelon faults and the fault zones are complex. Most of the faults cannot be traced through the Quaternary alluvium or basalt.

EXPERIMENTAL METHODS

Continuous measurements of radon concentration in air and working level at a height of 1 m were made at three stations (102, 103, and 104) on the Anaconda mill site (Fig. 3), and at two stations (Elkins and McBride, shown in Fig. 4) each located about 25 km from the mill. Stations 100 and 102 are shown in Figures 10 and 11.

A description of the continuous radon monitor has been previously reported (Momeni et al. 1978). Detailed description and calibration of these systems are described in an upcoming report. Figure 12 shows a prototype of the continuous radon and working-level monitor (CRWM).^{*} The scintillation cells are constructed of lucite with a volume of 1400 cm³. The air inlet is about 75 cm from the ground. The temperature inside the system is regulated to reduce condensation within the cell. The systems were continuously operated at 10 L/min. Air at a constant flow rate of about 10 L/min is passed through a 47-mm membrane filter where the airborne particulates and ions are removed. A fraction (1 L/min) of the radon-free air is subsequently passed through the

^{*}The prototype of this system (CRWM-100) was developed in cooperation with M.R. Morley, H. Beene, and E.L. Geiger and was constructed by Eberline Instrument Corporation.

radon scintillation cell. Response of the scintillation cell to radon is between 3 and 5 cpm/(pCi/L) of radon with a system background of 1 to 4 cpm.

Alpha particles from polonium-218 and -214 collected on the membrane filter are counted by a silicon diffused junction detector (490 mm²). The background for the silicon detector and holders is less than five counts per hour. During the continuous full year under field conditions these detectors have not shown any serious degradation in efficiency or background. Overall, the efficiency of the detectors using thin alpha sources is between 10% and 15%. During the past year of operation they have shown no change in efficiency or background. The combined root-mean-square error estimates for continuous radon and working level monitors are less than 50% of the means at lower levels (< 0.15 pCi/L radon, < 1×10^{-4} WL) and less than 15% of the means at upper ranges of concentrations and WLs.

Radon concentration was also measured in integrated 24-hour air samples collected by use of burst pumps (AQS sampler, Environmental Measurements, Inc., San Francisco, California). The air was stored in 30-liter 2-mil polyvinyl-fluoride bags (Tedlar bag, E. I. du Pont) and a sample of this air was subsequently transferred into evacuated 1.4-liter scintillation cells for measurement of radon activity.

Radon concentration was also measured using grab samples. Air samples were collected in 1.4-liter evacuated scintillation cells (Eberline Co., Santa Fe, New Mexico). After an elapsed time of about four hours, radon concentrations were measured using Eberline SAC-R5 alpha scintillation counters. Each cell was cross calibrated using quartz-window Lucas cells (LAC-2; Johnston Laboratories, Inc.) with a volume of 95 cm³. Radon in the Lucas cells was measured using scintillation counters (Model 182-2000, Ludlum Measurements, Inc., Sweetwater, Texas). This system provides a reproducibility of about 5%, and an efficiency of 0.85 counts/alpha (5 cpm/pCi radon-222). The cell background under vacuum is about 0.1 cpm. The cells were calibrated using a radon generator and techniques described by Lucas (1957, 1977). The calibrations are related to a National Bureau of Standards radium-226 standard.

In addition to the continuous measurements, working level also was measured using an American National Standards Institute technique (N13-8-1973). This method consists of grab collection of radon daughters on an open-faced filter and subsequent measurement of gross-alpha activity. Typical air-flow rates are 2 to 10 L/min. Often a 2.5-cm glass fiber of Gelman type E is used for collection of radon daughters. Self-absorption of these filters is less than 10% and they are rugged for field use. Typical collection periods are five minutes. Alpha counting is initiated anytime from 40 to 90 minutes after the sampling. Factors for determination of working level from these parameters are given in ANSI N13-8-1973. Working level is computed by:

$$WL = \frac{\text{cpm}}{E \times V \times F}$$

where cpm is the measured alpha count rate, E is the detector efficiency, V is the volume of air (in liters) passed through the filter, and F is an ANSI factor. The values for F are tabulated in Table 2.

Figure 4. Locations of the Anaconda Mill at Bluewater in the Grants Mineral Belt and the Elkins and McBride Background Stations.

Figure 5. Aerial View of the Anaconda Uranium Mill. (Facilities to the northeast of the MAIN tailings area were installed in 1978.)

Figure 6. MAIN Tailings Area.

Figure 7. MAIN Tailings Area.

Figure 8. Surface Geology in the Vicinity of the Anaconda Mill Site. (Anaconda 1976.)

Figure 9. Generalized Geological-Structure Section from Bluewater to Ambrosia Lake. (Kaufmann et al. 1975.)

Figure 10. Experimental Station 100.

Figure 11. Experimental Station 102.

Figure 12. Continuous Radon and Radon-Daughter Monitor (CRWM-100 series).

Table 2. ANSI Factor (F) for Computation of Working Level as a Function of Time after Collection of the Sample

<i>Time (minutes)</i>	<i>F</i>
40	150
45	140
50	130
55	120
60	110
70	90
90	60

METEOROLOGY

Rates of release and dispersion of radioactivity from the Anaconda operations depend on both the local climatology and meteorology, which are strongly affected by the ruggedness of the surrounding mountains and the slope of the terrain. Channeling of the winds through the valleys and cold drainage are evident at night during periods of low windspeeds.

The federal- or state-maintained precipitation- and temperature-recording station nearest to the mill is at Grants Airport (National Oceanic and Atmospheric Administration 1974, 1977), 16 km SSE, and the nearest first-order National Weather Service Station is in Albuquerque (National Oceanic and Atmospheric Administration 1978), 115 km E. In 1977 the total precipitation at Grants Airport was 234 mm (National Oceanic and Atmospheric Administration 1977), which is below the average of about 280 mm (National Oceanic and Atmospheric Administration 1974). Summer thunderstorms, which number around 40 each year (National Oceanic and Atmospheric Administration 1978), account for most of the precipitation. The remaining precipitation is evenly distributed throughout the rest of the year. Potential evaporation exceeds 1300 mm each year.

The mean January temperature at the Anaconda mill is -2°C , with mean minimum and maximum temperatures of -11°C and 7°C , respectively. The same figures for July are 22°C , 13°C , and 31°C , respectively (National Oceanic and Atmospheric Administration 1974). The area's extreme temperatures for 1977 were -27°C on 10 January and 35°C on 17 June (National Oceanic and Atmospheric Administration 1977). These are lower than the average New Mexico temperatures because of the greater elevation of the mill.

There are three onsite recording stations consisting of a 10-m tower and two 3-m towers. Hourly onsite wind data were collected and analyzed for a one-year period. The stations with the 3-m towers are: station 102 situated 700 m west of the tailings pile and station 104 located 1500 m south of the tailings pile. The instrument packages each consist of an anemometer, wind vane, and electronics (Climatronics Corp.). The tower of station 104 is set on a 2-m platform making the overall height of the sensors 5 m. The anemometer has a maximum threshold of 0.37 m/s and a chart resolution of 0.25 m/s. The wind-direction indicator has a range of 0° to 540° with an accuracy within 5° . The strip-chart data from stations 102 and 104 were digitized using a GICO Corporation Micro Datatizer. The average hourly windspeed, wind direction, and atmospheric stability were calculated using the Argonne National Laboratory computer.

Pasquill stability classes and an alternative classification based on the standard deviation of wind-direction fluctuation, σ_{θ} , are given in Table 3. The standard deviation was estimated by dividing the range of the fluctuations over a 15-minute period by 6.0 (Slade 1968).

The first meteorological data were taken on 3 July 1977 at noon and the last on 3 July 1978 at 9 a.m. Of a possible 8760 hourly observations, 86.9% were recovered. Major losses of data occurred during electrical-power outages.

Pooled observations made at stations 102 and 104 of windspeed, wind direction, and stability class are given in the appendix (Tables A2 through A9). Figure 13 shows the same data depicted as a wind rose. About 50% of the observed wind directions were from the southwest to northwest quadrant; at night during stable and low-windspeed conditions this percentage increased to almost 60%. This bias of wind direction is due to the orientation of the valley; the increase at night reflects the cold drainage flow down the gradient of the valley (Los Alamos Scientific Laboratory 1979).

Seasonal and annual windspeed distributions by hour are given in Table 4; the windspeed varies diurnally and is lower at night. Annual frequency distributions of windspeeds less than 3.5 mph during the period from 6 p.m. to 6 a.m. are presented in Table 5.

Another parameter affecting dispersion is the mixing height, which is the vertical extent of the atmosphere available for dilution of pollutants; it varies both seasonally and diurnally. Mean mixing heights for the Anaconda mill at different times of the year are given in Table 6 (U.S. Environmental Protection Agency 1972).

Figure 13. Wind Rose. (Data from stations 102 & 104, 3-m towers.)

Table 3. Pasquill Stability Categories^a

<i>Pasquill Stability</i>	σ_θ
A. Extremely unstable	> 22.5
B. Moderately unstable	22.5 - 17.5
C. Slightly unstable	17.5 - 12.5
D. Neutral	12.5 - 7.5
E. Slightly stable	7.5 - 3.8
F. Moderately stable	3.8 - 2.1
G. Extremely stable	< 2.1

^aFrom "Onsite Meteorological Program," U.S. Atomic Energy Commission, Regulatory Guide 1.23, October 1972.

Table 4. Daily Windspeed Distribution (mph)

<i>Hour</i>	<i>Summer</i>	<i>Autumn</i>	<i>Winter</i>	<i>Spring</i>	<i>Annual</i>
0100	3.5	4.3	4.0	3.2	3.8
0200	3.3	4.1	4.3	3.3	3.7
0300	2.8	3.9	4.3	2.8	3.5
0400	2.6	3.5	4.7	2.5	3.4
0500	2.4	3.4	4.7	2.3	3.2
0600	2.2	3.3	4.0	2.0	2.9
0700	2.1	3.1	3.5	2.3	2.8
0800	2.6	3.6	4.5	2.9	3.4
0900	3.4	4.3	6.1	4.2	4.5
1000	5.1	4.7	7.9	6.3	5.9
1100	6.2	6.0	8.2	7.4	6.9
1200	7.3	6.8	9.3	8.2	7.8
1300	7.6	7.5	9.7	9.0	8.4
1400	8.3	8.1	10.3	9.3	8.9
1500	8.7	8.2	10.0	10.1	9.2
1600	8.5	7.8	9.4	10.6	9.0
1700	8.3	6.9	8.1	10.5	8.3
1800	8.2	5.9	6.2	10.3	7.5
1900	7.4	4.7	5.0	8.4	6.3
2000	5.6	4.4	4.5	6.0	5.1
2100	4.7	4.1	4.0	4.6	4.4
2200	4.0	4.1	3.8	3.5	3.9
2300	3.6	4.2	3.7	3.5	3.8
2400	<u>3.6</u>	<u>4.1</u>	<u>3.9</u>	<u>3.4</u>	<u>3.8</u>
Average	5.1	5.0	6.0	5.7	5.4

Table 5. Annual Frequency
Distribution, All
Stability Classes

<i>Direction</i>	<i>Windspeed</i>
	<i>0-3 mph</i>
N	84
NNE	66
NE	47
ENE	47
E	34
ESE	35
SE	33
SSE	43
S	77
SSW	139
SW	148
WSW	209
W	316
WNW	277
NW	196
NNW	157

Table 6. Mean Mixing
Heights (m)

<i>Season</i>	<i>Morning</i>	<i>Afternoon</i>
Summer	400	3900
Autumn	320	2250
Winter	320	1400
Spring	500	3300
Annual	400	2650

RADON CONCENTRATION IN AIR

Natural atmospheric radon-222 comes mainly from soil and the aeration of groundwater. Its concentration is enhanced by man's technological activities such as tilling of the soil, construction of buildings from materials containing appreciable radium-226, and use of phosphate fertilizers. Among such human technological activities is the production of energy from natural gas, coal, petroleum, geothermal sources, and uranium fuel (Gessel and Prichard 1975, 1977).

Israel (1962), Barton et al. (1973a, 1973b), Wilkening et al. (1975), Harley (1973), and Travis et al. (1979) have estimated an average natural radon concentration in the United States of 100 to 150 pCi/m³. Because the emanation rates from natural sources of radon, and dispersion, are not spatially or temporally uniform, local natural radon concentrations may exceed this average radon concentration significantly. In addition to meteorological influences, other parameters affecting radon release rate are radium-226 concentration in the soil, and soil moisture and porosity (Momeni et al. 1979b, Tanner 1964). Contributions to the natural background radon concentration from all sources have recently been estimated (Travis et al. 1979). These authors suggest an average contribution of 840 pCi/m³ to inside air from building materials, 10 pCi/m³ from domestic heaters using natural gas, with other sources in combination contributing less than 10 pCi/m³. Our selected measurements of inside air during winter indicate a radon-222 concentration in the range of 1500 to 5000 pCi/m³ in selected residences in the southwestern suburban area of Chicago.

BACKGROUND RADON CONCENTRATION

Inasmuch as separation of natural-background radon concentration from all other sources of radon is not feasible, only total "backgrounds" are reported herein. Background radon-222 concentration was measured at two stations (Elkins Station 701 and McBride Station 702), each located about 25 km from the Anaconda Uranium Mill to the northwest and southeast, respectively (Fig. 4). Their combined environments seem to represent the natural environment of the Bluewater area before construction of the mill. Because the tailings release is the major source of radon at the Anaconda mill, the background radon was also estimated from extrapolation of radon concentration as a function of distance from the tailings.

The Elkins station is located at an elevation of about 2250 m, generally flanked by a smooth, rolling, east-to-west shallow valley. The nearby elevations to the south rise to about 2500 m, and north to a mesa with a 2400-m elevation at a distance of about 10 km. The valley is flanked on the west by the continental divide with an elevation of about 2300 m. On the eastern side of the Elkins station is the Grants Basin with an elevation of about 2000 m.

The McBride station is located at the southern base of Horace Mesa, which terminates about 20 km northeast of the station at an elevation of 3450 m. About 1 km from the station, Horace Mesa rises sharply from 1950 m to 2425 m. South of the station, the Malpais lava beds cover an extensive area of 150 km² ending at the San Rafael Mesa and Las Ventanas Ridge. This east-to-west valley is interrupted by Mount Taylor and is greatly affected by cold drainage flow from the adjacent mesas. The McBride station, because of both geophysical structure and higher flux expected from porous lava beds, is prone both to larger diurnal variation and level of radon concentration.

Radon concentrations and working level were measured over a period exceeding 12 months, and the bulk of tabulated data exceeds 1000 printed pages. Thus, a representative sample of these data is given in this report (Tables 7 and 8).

Radon-concentration "background" at the Elkins and McBride stations was continuously measured using Continuous Radon and Working-Level Monitors (CRWM-100) (Momeni et al. 1978). A random selection of these hourly averaged measurements on four dates from February to September 1978 is given in Tables 7 and 8. The average (mean) background concentration and the standard error (SE) of these measurements is also given. The diurnal variation is clearly evident. The relatively large standard error (of the order of 20%) is a result of the range of dispersion of the measurements (a factor of about 20). In addition, the measurements are influenced by nonrandom impacts of climate and meteorology. The negative radon concentration, e.g. at 11 a.m. on 17 June (Table 8) reflects statistical problems associated with the assignment of a mean background activity to a detector. At low levels of radon, the measured count rate and the separately determined mean background count rate are nearly equal; thus the random hourly detector background count may at times exceed the preassigned estimated mean value. This apparent discrepancy could be resolved by counting for longer periods.

The distribution of background radon concentration as a function of time at the Elkins station for February and March 1978 is displayed in Figure 14 (see also App., Fig. A1). The predominant characteristic of these variations is the periodic occurrence of minimums and maximums. Radon concentration at the Elkins station is affected by west-to-east drainage of cold air. However, thermal inversion results in increasing radon concentration after sunset, producing a daily maximum concentration at about 4 a.m. to 6 a.m.

Frequencies of occurrence of given radon concentrations, determined from about 620 hourly measurements, are given in Figure 15 (see also App., Fig. A2). Radon-concentration frequency shows the most probable concentration is near 100 pCi/m³ and accounts for about 20% of the measurements. Concentrations as high as 2700 pCi/m³ were measured in December 1977, but with a frequency less than 0.5%.

Radon concentrations measured at the McBride station, using continuous radon and working-level monitors are displayed in Figure 16 (see also App., Fig. A3). The first graph shows variations of radon concentration observed for February 1978, and is notable for a period of low-level radon concentrations with small diurnal variations. It also shows periods of well-defined diurnal variations with pronounced changes in radon concentration. Similar behavior is evident in other months.

Frequency of observation of radon concentration at the McBride station is given in Figure 17 for February and March 1978 (see also App., Fig. A4). During December 1977 the maximum incidence (20%) was at about 750 pCi/m³ radon-222. Radon concentrations as high as 8000 pCi/m³ were observed with a frequency of occurrence of 0.3%. The highest radon concentration observed, 10 000 pCi/m³, occurred during a period of calm in February 1978.

Background radon concentrations measured at the McBride station on 20 December 1977 and 15 February, 18 April, and 17 June 1978 are given in Table 8. The hourly average concentrations (pCi/m³) at this station on those dates are 1098.9 (SE 45.7), 578.1 (SE 100.5), 521.9 (SE 112.9), and 113.7 (SE 48.9), respectively. The diurnal background distribution on 20 December does not indicate a well-defined thermal-inversion pattern; the concentration was elevated during the entire period. On the other hand, the distribution for 15 February shows a well-defined maximum (1603 pCi/m³) at 5 a.m. and a minimum (133.3 pCi/m³) at 3 p.m. Similar observations are applicable to 18 April and 17 June.

Table 9 summarizes the radon concentrations in air at the Elkins station, about 25 km northwest of the Anaconda mill. The average value during December 1977 was 271 pCi/m³. The daily-average maximum radon concentration was 898 pCi/m³. Modal concentration of radon in air, i.e. the most frequently observed concentration, was less than 75 pCi/m³, observed 21.2% of the time among all data collected during December 1977. During the same month, the average concentration of radon in air at the McBride station (Table 10), about 25 km southeast of the Anaconda mill, was 1690 pCi/m³. The ratio of monthly averages for all months except December 1977 is between 1.0 and 2.7. The averages of the observed daily-average maximum and minimum concentrations for December 1977 were 4220 and 784 pCi/m³, respectively. The two stations are remotely situated from any previous mining and milling operations, yet the average concentration of radon in air at the McBride station was 6.2 times higher than at the Elkins station, and the ratio of the observed daily-average maximum radon concentrations was 4.7. Inasmuch as the radon concentrations were measured using nearly identical systems, which were calibrated by the same technique and then cross-calibrated, the difference in measured radon concentrations is an indication of dissimilarity of the regional radon backgrounds and local atmospheric dispersion. The reason for much higher radon concentration during December 1977 at the McBride station relative to the Elkins station and to other months is not understood.

RADON CONCENTRATION AROUND THE ORE PILE

Concentrations of radon-222 in air near the Anaconda ore pile were determined using 24-hour integrated air samples and the procedure described under "Experimental Methods." Air-sampling equipment was placed at distances of about 30 to 100 m from the pile center. The choice of locations was dictated by the milling operations and front-loading tractor movement. Individual- and average-concentration measurements for each location are given in Table 11. The average radon concentrations for each of the five sampling locations range from 600 to 200 pCi/m³. The maximum and minimum individual measurements are 4200 and 200 pCi/m³, and the average of all measurements is 1300 pCi/m³.

Radon concentration at a station located between the ore pad and ore-grinding and ore-feeding systems is given in Table 12 using two nearly identical systems for continuous monitoring of radon concentration (CRM-1 and CRM-2).

Comparison of the mean radon concentrations measured by the two systems indicates good agreement. Comparison of radon concentrations measured at location 4 adjacent to the stockpile (Table 11), using 24-hour integrated air samples, with the radon concentrations measured at a location between the ore stockpile and ore-grinding and ore-feeding systems (Table 12) also indicates good agreement. Location 4 is adjacent to the location of the continuous radon monitors, CRM-1 and CRM-2. But the other locations, especially location 5, is situated at the eastern flank of the ore pad and far from the ore-grinding and ore-feeding systems. The annual average concentration of radon, as estimated from Table 12, is 2.5×10^3 pCi/m³ from the combined operations of ore grinding, ore feeding, and ore storage. Inasmuch as the mean radon concentrations measured during the four months of January through April 1978 are all about the same, it may be concluded that this concentration is mostly dependent on mill operations.

RADON CONCENTRATION AROUND TAILINGS

Radon concentrations were measured at six locations over the Anaconda MAIN beach tailings and at stations various distances to the south, southwest, and east; concentrations were measured in 24-hour integrated air samples. Individual and average concentrations tabulated as a function of distance from the tailings are presented in Tables 13 through 16. Figure 18 shows the averaged measured radon concentrations as a function of distance from the center of the tailings. The excess radon to the east is a result of prevailing winds from the west and southwest. The radon in this area is also augmented by windblown tailings (Momeni et al. 1979b) spread over the eastern and northeastern flanks of the MAIN tailings beach (Fig. 3). Furthermore, the United Nuclear Homestake Partners Mill is located about 8 km to the east and could contribute to this elevated concentration of radon-222.

Carbonate tailings (ALKO) from previous milling operations are stored to the south of the MAIN tailings (Fig. 3) and, prior to reconstruction of the present dikes, tailings overflow (ACID) was collected in catch basins. Even though the ACID and ALKO deposits were covered in late 1977 by about 85 cm of silt-clay soil, they still contribute to the airborne concentration in adjacent areas (Momeni et al. 1979b). This cover attenuates the radon flux only by about 50% (Momeni et al. 1979b).

Radon concentration in air directly over the ALKO and ACID tailings, as measured by a grab-sampling technique, are given in Tables 17 and 18, which show the elevated radon concentration before covering compared with the lowered concentration thereafter. The average radon concentration above the ALKO tailings ranged from 7800 pCi/m³ before November 1977 to 2500 pCi/m³, and that above the ACID tailings from 5400 pCi/m³ to 1900 pCi/m³ after covering with soil.

TOTAL CONCENTRATION OF RADON IN AIR

Concentrations of radon were measured at stations 100, 101, and 105 (Fig. 3) using the grab-sampling technique (Tables 19 to 21). These are combined concentrations from natural background and from mill operations. Station 100 is located in the southeastern section of the mill property adjacent to the Anaconda Village. Station 101 is located at the northwest corner of the Anaconda property beyond station 102, but within 1 km of the MAIN tailings. Station 105 is located at the northeast corner of the Anaconda property at about 2.5 km from the tailings and 4 km from the mill buildings.

Samples were obtained between 9 a.m. and noon to reduce their variability due to local diurnal meteorological effects. The average radon concentrations at stations 100, 101, and 105 were 600 (range 100 to 1700), 700 (range 400 to 1100), and 300 (range 100 to 500) pCi/m³, respectively. Radon concentration at station 105 is about the same as that of radon background for observation periods between 9 a.m. and noon. For all practical purposes, the average value of 300 pCi/m³ may be taken to represent the mean value for the Anaconda area during the late-morning hours. The daily-average background would be greater than 300 pCi/m³ because the minimum in the diurnal variation of radon concentration often occurs during the late morning and early afternoon.

Concentrations of radon were measured in 24-hour integrated air samples collected at stations 102, 104, and the ANL field laboratory on the site (Fig. 3). Also, continuous monitors for radon and working level were operated at stations 102 and 104. Station 102 is located less than 0.5 km north of the MAIN tailings, station 103 is about 0.3 km east, and station 104 is located to the south within 2 km of the tailings and at the north edge of the Anaconda Village. The ANL field laboratory is within 0.5 km of the ore pads and mill buildings. The average concentrations of radon at stations 102, 104 and ANL were 1140 (range 600 to 1400), 830 (range 730 to 900), and 2040 (range 500 to 5400) pCi/m³, respectively (Tables 22 to 24).

Radon concentrations in air were measured continuously at stations 102, 103, and 104 (Fig. 3) and are given as a function of time for selected dates at those stations in Tables 25 to 27. Diurnal variations similar to those described for the background stations, Elkins and McBride, are evident. Average radon concentrations (pCi/m³) at station 102 on 20 and 29 September and 5 and 13 October 1977 are 732, 1090, 1570, and 1530, respectively. Radon concentrations in 24-hour integrated air samples measured on the same dates at the same station are 600, 1210, 1330, and 1400 pCi/m³, respectively (Table 22). The ratios of estimated concentrations for each date by these two techniques (continuous/24-hour samples) are 1.2, 0.9, 1.3, and 1.1, respectively. The corresponding ratios for station 104 are 0.98, 0.96, 1.1, and 0.95, respectively. These ratios indicate that the techniques are fairly well correlated.

Temporal distributions of radon concentration at the above stations are shown in Figures 19 to 21 (see also App., Figs. A5 to A7). The diurnal radon-concentration profile shows the same pattern of variations described for the background stations, Elkins and McBride. Comparison of these variations for the month of July 1977 at the three stations indicates that the magnitude of change was relatively less at station 102, and this situation

seems to hold for the entire experimental period. Variations of radon concentration at the three stations are directly dependent on wind direction and windspeed (Momeni et al. 1979b).

Frequencies of occurrence of given radon concentrations are presented in Figures 22 to 24 (see also App., Figs. A8 to A10). The frequencies are similar to those at the background stations, Elkins and McBride. The modal concentration for July 1977 at station 102 is 500 pCi/m³ with a frequency of about 14%, at station 103 it is 1500 pCi/m³ with a frequency of about 8%, and at station 104 it is near 100 pCi/m³ with a frequency of about 15%. The measurements at station 103 in July show that for a large fraction of time concentrations exceeding 1500 pCi/m³ were observed; in general, the distribution is broader and further skewed toward higher concentrations than are those for stations 102 and 104.

The average radon concentrations for the summer of 1977 at the three continuous-monitoring stations, 102, 103, and 104, are 448, 2275, and 651 pCi/m³, respectively (Tables 28 to 30). At station 102 the average radon concentration in July is about 6.7 times higher than it is in August. The average concentration for the summer of 1977 at station 103 is 5.8 times and 3.3 times larger than at stations 102 and 104, respectively. Station 103 is located about 0.5 km east and downwind of the Anaconda MAIN tailings.

STATION 701, FEBRUARY 1978

STATION 701, MARCH 1978

Figure 14. Radon Concentration by Hour at the Elkins Background Station 701.

STATION 701, FEBRUARY 1978

STATION 701, MARCH 1978

Figure 15. Radon-Concentration Frequency at the Elkins Background Station 701.

STATION 702, FEBRUARY 1978

STATION 702, MARCH 1978

Figure 16. Radon Concentration by Hour at the McBride Background Station 702.

STATION 702, FEBRUARY 1978

STATION 702, MARCH 1978

Figure 17. Radon-Concentration Frequency at the McBride Background Station 702.

Figure 18. Radon Concentration vs. Distance from the Center of the Tailings.

STATION 102, JANUARY 1978

STATION 102, FEBRUARY 1978

Figure 19. Radon Concentration by Hour at Station 102.

STATION 103, JANUARY 1978

STATION 103, FEBRUARY 1978

Figure 20. Radon Concentration by Hour at Station 103.

STATION 104, JANUARY 1978

STATION 104, FEBRUARY 1978

Figure 21. Radon Concentration by Hour at Station 104.

STATION 102, JANUARY 1978

STATION 102, FEBUARY 1978

Figure 22. Radon-Concentration Frequency at Station 102.

STATION 103, JANUARY 1978

STATION 103, FEBUARY 1978

Figure 23. Radon-Concentration Frequency at Station 103.

STATION 104, JANUARY 1978

STATION 104, FEBRUARY 1978

Figure 24. Radon-Concentration Frequency at Station 104.

Table 7. Background Radon Concentration at the Elkins Station

ELKINS BACKGROUND STATION ANACONDA			ELKINS BACKGROUND STATION ANACONDA		
STATION 701 25/ 2/78			STATION 701 1/ 4/78		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1		343.3	1		370.0
2		440.0	2		450.0
3		566.7	3		660.0
4		780.0	4		806.7
5		643.3	5		996.7
6		800.0	6		863.3
7		1016.7	7		546.7
8		1133.3	8		333.3
9		1073.3	9		206.7
10		823.3	10		110.0
11		500.0	11		73.3
12		326.7	12		73.3
13		186.7	13		43.3
14		163.3	14		80.0
15		96.7	15		76.7
16		130.0	16		46.7
17		83.3	17		70.0
18		150.0	18		90.0
19		100.0	19		66.7
20		53.3	20		126.7
21		170.0	21		136.7
22		226.7	22		93.3
23		490.0	23		260.0
24		730.0	24		86.7
AVERAGE		459.4	AVERAGE		277.8
STD. ERROR		70.2	STD. ERROR		59.3

ELKINS BACKGROUND STATION ANACONDA			ELKINS BACKGROUND STATION ANACONDA		
STATION 701 22/ 5/78			STATION 701 26/ 9/78		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1		610.0	1		80.0
2		320.0	2		213.3
3		423.3	3		313.3
4		390.0	4		236.7
5		196.7	5		320.0
6		643.3	6		273.3
7		500.0	7		323.3
8		476.7	8		266.7
9		586.7	9		253.3
10		353.3	10		180.0
11		116.7	11		56.7
12		36.7	12		163.3
13		26.7	13		303.3
14		46.7	14		276.7
15		100.0	15		140.0
16		30.0	16		223.3
17		66.7	17		310.0
18		46.7	18		363.3
19		73.3	19		440.0
20		213.3	20		453.3
21		153.3	21		326.7
22		1036.7	22		596.7
23		246.7	23		410.0
24		186.7	24		856.7
AVERAGE		286.7	AVERAGE		307.5
STD. ERROR		52.3	STD. ERROR		34.2

Table 8. Background Radon Concentration at the McBride Station

MCBRIDE BACKGROUND STATION ANACONDA			MCBRIDE BACKGROUND STATION ANACONDA		
STATION 702 20/12/77			STATION 702 15/ 2/78		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1		1123.3	1		1023.3
2		903.3	2		1060.0
3		990.0	3		1226.7
4		1136.7	4		1523.3
5		1036.7	5		1603.3
6		893.3	6		1433.3
7		853.7	7		885.7
8		1063.3	8		683.3
9		893.3	9		753.3
10		913.3	10		623.3
11		920.0	11		463.3
12		923.3	12		270.0
13		850.0	13		246.7
14		926.7	14		136.7
15		1136.7	15		133.3
16		1016.7	16		180.0
17		900.0	17		226.7
18		1190.0	18		186.7
19		1036.7	19		320.0
20		1416.7	20		216.7
21		1453.3	21		206.7
22		1356.7	22		166.7
23		1350.0	23		153.3
24		1636.7	24		150.0
AVERAGE		1098.9	AVERAGE		578.1
STD. ERROR		45.7	STD. ERROR		100.5

MCBRIDE BACKGROUND STATION ANACONDA			MCBRIDE BACKGROUND STATION ANACONDA		
STATION 702 18/ 4/78			STATION 702 17/ 6/78		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1		1216.7	1		106.7
2		1263.3	2		-16.7
3		1640.0	3		63.3
4		1335.7	4		303.3
5		1043.3	5		396.7
6		803.3	6		390.0
7		996.7	7		316.7
8		706.7	8		160.0
9		260.0	9		56.7
10		40.0	10		-46.7
11		-20.0	11		-36.7
12		36.7	12		-70.0
13		-10.0	13		-80.0
14		-13.3	14		-146.7
15		30.0	15		-40.0
16		-40.0	16		-130.0
17		60.0	17		-50.0
18		53.3	18		-65.7
19		96.7	19		-80.0
20		80.0	20		106.7
21		353.3	21		73.3
22		660.0	22		180.0
23		603.3	23		483.3
24		1330.0	24		856.7
AVERAGE		521.9	AVERAGE		113.7
STD. ERROR		112.9	STD. ERROR		48.9

Table 9. Concentration of Radon-222 in Air at the Elkins Background Station

Season/Month	<u>Concentration (pCi/m³)</u>				Modal- Concen- tration Frequency (%)	No. of Hours of Data
	Avg	<u>Daily Average</u>				
		Max	Min	Modal		
<u>Winter 77-78:</u>						
Dec	271	898	a	a	21.2	259
Jan	349	726	51.9	100	19.0	415
Feb	286	623	28.9	100	29.6	658
Mar	229	533	a	a	30.4	635
Avg	284	695	20.2	50	25.1	
<u>Spring 78:</u>						
Apr	197	562	a	a	31.5	718
May	183	523	a	a	33.4	647
Avg	190	543	a	a	32.5	
<u>Summer 78:</u>						
Jun	232	616	a	a	23.7	630
Jul	307	784	45.5	100	22.2	270
Avg	270	700	22.8	50	23.0	
<u>Fall 78:</u>						
Sep	331	755	75.5	100	24.4	262
Oct	505	1090	127	200	15.0	638
Nov	389	920	43.8	200	22.9	157
Avg	408	922	82.1	167	20.8	

^a Not detectable, i.e. count rate is equal to or less than detector background.

Table 10. Concentration of Radon-222 in Air at the McBride Background Station

Season/Month	<u>Concentration (pCi/m³)</u>				Modal- Concen- tration Frequency (%)	No. of Hours of Data
	Avg	Max	Min	Modal		
<u>Winter 77-78:</u>						
Dec	1690	4220	784	900	18.4	316
Jan	907	2070	148	200	14.1	305
Feb	770	2090	74.1	100	14.6	638
Mar	524	1610	a	a	16.0	431
Avg	973	2500	252	300	15.8	
<u>Spring 78:</u>						
Apr	330	1080	a	a	28.4	718
May	358	1250	a	a	24.0	724
Avg	344	1165	a	a	26.2	
<u>Summer 78:</u>						
Jun	242	926	a	a	20.2	563
Jul	312	1050	a	a	20.3	266
Avg	277	988	a	a	20.3	
<u>Fall 78:</u>						
Sep	570	1510	34.2	200	18.1	83
Oct	549	1750	a	a	18.9	525
Avg	560	1630	17.1	100	18.5	

^a Not detectable, i.e. count rate is equal to or less than detector background.

Table 11. Concentration of Radon-222 in Air
Measured Adjacent to the Ore Stockpile at
the Anaconda Mill in 1978 Using 24-Hour
Integrated Air Samples (pCi/m³)

<i>Location^a and Date</i>	<i>Concen- tration</i>	<i>Location^a and Date</i>	<i>Concen- tration</i>
<u>Location 1:</u>		<u>Location 4:</u>	
15 May	600	8 Feb	1200
16 May	1000	13 Feb	1300
Avg	800	20 Feb	3300
		22 Feb	3600
		2 Mar	1900
		7 Mar	2800
<u>Location 2:</u>		13 Mar	900
8 Feb	300	15 Mar	2800
13 Feb	400	23 Mar	2400
20 Feb	600	Avg	2200
22 Feb	4200		
1 Mar	1300		
6 Mar	2200		
7 Mar	2200	<u>Location 5:</u>	
19 Mar	3200	13 Feb	500
22 Mar	900	1 Mar	500
23 Mar	2400	2 Mar	800
17 May	600	6 Mar	200
22 May	800	13 Mar	500
Avg	1600	23 Mar	800
		28 Mar	600
		Avg	600
<u>Location 3:</u>			
20 Feb	2400		
1 Mar	600		
6 Mar	900		
13 Mar	900		
Avg	1200		

^aFive locations selected to surround the ore pile.

Table 12. Monthly Averaged Concentration of Radon-222 in Air Measured Adjacent to the Ore Stockpile and Ore-Grinding and Ore-Feeding Systems at the Anaconda Mill in 1978 Using Continuous Radon Monitors

<i>System</i>	<i>Month</i>	<i>Number of Hourly Observations</i>	<i>Concentration of Radon (pCi/m³)</i>	
			<i>Mean</i>	<i>Standard Deviation</i>
CRM-1	Jan	21	3120	415
CRM-2	Jan	21	2770	354
CRM-1	Feb	194	2640	162
CRM-2	Feb	194	2350	149
CRM-1	Mar	498	2560	105
CRM-2	Mar	498	2280	97.2
CRM-1	Apr	211	2370	166
CRM-2	Apr	211	2200	166

Table 13. Concentration of Radon-222 in Air
 Measured over the Anaconda MAIN Tailings
 from December 1977 to October 1978
 Using 24-Hour Integrated
 Air Samples (pCi/m³)

<i>Location^a and Date</i>	<i>Concen- tration</i>	<i>Location^a and Date</i>	<i>Concen- tration</i>
<u>Location 1:</u>		<u>Location 7:</u>	
14 Dec	12 400	18 Jan	12 200
Avg	12 400	Avg	12 200
<u>Location 2:</u>		<u>Location 9:</u>	
14 Dec	9 000	20 Sep	9 800
Avg	9 000	21 Sep	2 200
<u>Location 3:</u>		25 Sep	8 900
14 Dec	8 100	26 Sep	8 600
17 Jan	8 600	27 Sep	21 300
18 Jan	6 500	3 Oct	7 900
Avg	7 700	4 Oct	14 600
<u>Location 5:</u>		5 Oct	2 500
17 Jan	10 300	10 Oct	16 500
18 Jan	11 500	11 Oct	17 200
Avg	10 900	Avg	11 000

^a Six locations selected to surround the ore pile.

Table 14. Concentration of Radon-222 in Air Measured at
Various Distances South of the MAIN Tailings in 1977
Using 24-Hour Integrated Air Samples (pCi/m³)

<i>Distance and Date</i>	<i>Concen- tration</i>	<i>Distance and Date</i>	<i>Concen- tration</i>
<u>Distance, 0 m:</u>		<u>Distance, 525 m:</u>	
28 Nov	2 400	28 Nov	900
30 Nov	400	30 Nov	300
5 Dec	600	9 Dec	1 400
7 Dec	10 900	Avg	900
Avg	3 600		
<u>Distance, 100 m:</u>		<u>Distance, 600 m:</u>	
30 Nov	1 400	5 Dec	300
4 Dec	200	6 Dec	1 500
5 Dec	800	7 Dec	300
Avg	800	Avg	700
<u>Distance, 250 m:</u>		<u>Distance, 705 m:</u>	
5 Dec	600	28 Nov	400
6 Dec	900	30 Nov	100
7 Dec	2 600	4 Dec	300
Avg	1 400	5 Dec	700
		6 Dec	1 700
		7 Dec	700
		8 Dec	700
		Avg	700
<u>Distance, 375 m:</u>		<u>Distance, 825 m:</u>	
29 Nov	300	28 Nov	900
4 Dec	1 100	29 Nov	700
6 Dec	1 000	5 Dec	500
8 Dec	1 100	6 Dec	400
Avg	900	7 Dec	1 400
		8 Dec	900
		Avg	800

Table 15. Concentration of Radon-222 in Air Measured at Various Distances Southwest of the MAIN Tailings in 1977 Using 24-Hour Integrated Air Samples (pCi/m³)

<i>Distance and Date</i>	<i>Concen- tration</i>	<i>Distance and Date</i>	<i>Concen- tration</i>
<u>Distance, 10 m:</u>		<u>Distance, 125 m:</u>	
19 Oct	5600	19 Oct	1900
24 Oct	3000	24 Oct	500
25 Oct	5600	25 Oct	1900
26 Oct	4900	26 Oct	2000
27 Oct	4200	27 Oct	1900
1 Nov	2400	31 Oct	600
3 Nov	4800	1 Nov	1500
Avg	4400	3 Nov	2200
		Avg	1600
<u>Distance, 75 m:</u>		<u>Distance, 325 m:</u>	
19 Oct	2300	19 Oct	700
24 Oct	700	24 Oct	300
25 Oct	2400	25 Oct	700
26 Oct	3500	Avg	600
27 Oct	3300		
1 Nov	200		
2 Nov	200		
3 Nov	4200		
Avg	2100		

Table 16. Concentration of Radon-222 in Air Measured at
Various Distances East of the MAIN Tailings in 1978
Using 24-Hour Integrated Air Samples (pCi/m³)

<i>Distance and Date</i>	<i>Concen- tration</i>	<i>Distance and Date</i>	<i>Concen- tration</i>
<u>Distance, 200 m:</u>		<u>Distance, 2970 m:</u>	
26 Sep	4000	26 Sep	1300
27 Sep	4500	27 Sep	400
3 Oct	3800	3 Oct	1400
4 Oct	5400	4 Oct	300
5 Oct	4100	5 Oct	800
8 Oct	4400	8 Oct	1600
10 Oct	3300	11 Oct	600
11 Oct	4200	11 Oct	500
16 Oct	6800	12 Oct	900
18 Oct	1400	16 Oct	1400
24 Oct	1700	18 Oct	400
Avg	4000	24 Oct	200
		Avg	800
<u>Distance, 400 m:</u>		<u>Distance, 3170 m:</u>	
3 Oct	2200	20 Sep	600
5 Oct	2700	21 Sep	600
6 Oct	1900	26 Sep	300
8 Oct	1600	27 Sep	1500
11 Oct	2300	3 Oct	1900
12 Oct	2300	4 Oct	2000
16 Oct	3500	6 Oct	1900
18 Oct	600	9 Oct	1400
24 Oct	1100	10 Oct	1500
Avg	2000	12 Oct	600
		16 Oct	1700
<u>Distance, 1120 m:</u>		18 Oct	400
11 Oct	1900	24 Oct	300
12 Oct	2200	Avg	1100
18 Oct	1900		
Avg	2000		
<u>Distance, 1630 m:</u>			
11 Oct	600		
12 Oct	1600		
16 Oct	2000		
Avg	1400		

Table 17. Atmospheric Concentration of Radon-222 Determined from Grab Air Samples on the ALKO Site (pCi/m³)

<i>Date</i>	<i>Time</i>	<i>Concen- tration</i>	<i>Date</i>	<i>Time</i>	<i>Concen- tration</i>
<u>1977:</u>			<u>1977-78:</u>		
13 Sep	0900	12 200	26 Jan	1217	1 300
15 Sep	1110	4 400	27 Jan	1308	5 000
20 Sep	1205	9 700	30 Jan	1209	5 500
22 Sep	1000	4 700	1 Feb	1120	600
27 Sep	1110	9 800	2 Feb	1228	4 500
29 Sep	1050	4 600	21 Feb	1127	400
5 Oct	1416	9 700	22 Feb	1117	8 100
10 Oct	1043	4 200	23 Feb	1146	4 900
12 Oct	1050	9 700	27 Feb	1126	4 100
17 Oct	1520	7 800	6 Mar	1117	1 700
19 Oct	1025	9 100	7 Mar	1149	3 600
Avg		7 800	14 Mar	1117	400
<u>1977-78:</u>			15 Mar	1416	1 900
24 Oct	1103	1 000	21 Mar	1301	4 000
25 Oct	1118	3 000	23 Mar	1248	2 100
26 Oct	1535	1 200	28 Mar	1339	2 500
30 Nov	1630	1 700	30 Mar	1221	1 400
5 Dec	1141	7 500	4 Apr	1229	1 700
7 Dec	1245	1 800	6 Apr		3 200
8 Dec	1535	2 200	3 Oct	1200	3 000
12 Dec	1414	1 300	9 Oct	1325	700
13 Dec	1640	1 200	10 Oct	1435	600
14 Dec	1227	2 100	16 Oct	1150	2 200
16 Dec	1335	3 400	18 Oct		2 000
20 Jan	1315	2 300	23 Oct		2 200
23 Jan	1257	400	24 Oct	1300	2 400
25 Jan	1100	900	27 Oct	1100	1 800
			Avg		2 500

Table 18. Atmospheric Concentration of Radon-222 Determined from Grab Air Samples on the ACID Site (pCi/m³)

<i>Date</i>	<i>Time</i>	<i>Concen- tration</i>	<i>Date</i>	<i>Time</i>	<i>Concen- tration</i>
<u>1977:</u>			<u>1977-78:</u>		
14 Sep	1150	2 800	26 Jan	1153	1 500
19 Sep	1110	2 200	27 Jan	1233	1 100
21 Sep	1525	5 700	30 Jan	1120	1 600
26 Sep	1040	12 500	1 Feb	1145	2 100
28 Sep	1110	4 700	2 Feb	1153	2 900
3 Oct	1057	800	21 Feb	1112	600
4 Oct	1025	2 900	22 Feb	1042	1 200
7 Oct	1110	800	23 Feb	1115	1 400
11 Oct	1110	7 500	27 Feb	1101	4 500
13 Oct	1124	11 700	6 Mar	1048	400
18 Oct	1118	7 900	7 Mar	1058	2 000
Avg		5 400	10 Mar	1439	1 200
<u>1977-78:</u>			14 Mar	1032	400
19 Oct	1730	1 700	15 Mar	1349	1 400
24 Oct	1150	1 500	21 Mar	1232	2 200
25 Oct	1150	3 800	23 Mar	1207	1 100
26 Oct	1449	2 800	28 Mar	1259	2 900
30 Nov	1603	700	30 Mar	1259	2 900
5 Dec	1216	5 300	4 Apr	1146	1 400
7 Dec	1200	1 100	6 Apr	1108	1 700
8 Dec	1227	800	3 Oct	1120	1 000
13 Dec	1200	4 700	9 Oct	1250	1 500
14 Dec	1130	2 400	10 Oct	1505	1 100
14 Dec	1147	2 400	16 Oct	1110	2 600
16 Dec	1350	5 700	18 Oct	1112	1 800
20 Jan	1518	2 000	23 Oct	1210	1 200
23 Jan	1233	1 200	24 Oct	1225	900
25 Jan	1031	1 200	27 Oct	1015	800
			Avg		1 900

Table 19. Concentration of Radon-222 in Air Measured at Station 100 in 1978 Using the Grab-Sampling Technique (pCi/m³)

<i>Date</i>	<i>Concentration</i>
8 May	500
9 May	700
10 May	300
15 May	600
17 May	100
22 May	1700
24 May	800
31 May	600
7 Jun	200
8 Jun	300
8 Jun	700
Avg	600

Table 20. Concentration of Radon-222 in Air Measured at Station 101 in 1978 Using the Grab-Sampling Technique (pCi/m³)

<i>Date</i>	<i>Concentration</i>
8 May	900
9 May	700
10 May	1100
15 May	600
17 May	900
22 May	400
31 May	600
7 Jun	700
Avg	700

Table 21. Concentration of Radon-222 in Air Measured at Station 105 in 1978 Using the Grab-Sampling Technique (pCi/m³)

<i>Date</i>	<i>Concentration</i>
8 May	200
9 May	400
10 May	400
15 May	300
17 May	500
22 May	400
31 May	400
7 Jun	200
8 Jun	100
Avg	300

Table 22. Average Concentration of Radon-222 in Air Measured at Station 102 in 1977 Using 24-Hour Integrated Air Samples (pCi/m³)

<i>Date Started</i>	<i>Concentration</i>
20 Sep	600
29 Sep	1210
5 Oct	1330
13 Oct	1400
Avg	1135

Table 23. Average Concentration of Radon-222 in Air Measured at Station 104 in 1977 Using 24-Hour Integrated Air Samples (pCi/m³)

<i>Date Started</i>	<i>Concentration</i>
20 Sep	880
29 Sep	730
5 Oct	818
13 Oct	900
Avg	832

Table 24. Average Concentration of Radon-222 in Air Measured at the ANL Field Lab in 1977 Using 24-Hour Integrated Air Samples (pCi/m³)

<i>Date Started</i>	<i>Concentration</i>
20 Sep	500
29 Sep	5400
5 Oct	1500
13 Oct	750
Avg	2037.5

Table 25. Working Level and Radon Concentration at Station 102

NORTH BOUNDARY STATION ANACONDA			NORTH BOUNDARY STATION ANACONDA		
STATION 102 29/ 9/77			STATION 102 29/ 9/77		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	2.18E-03	890.0	1	9.73E-03	2060.0
2	1.99E-03	720.0	2	9.27E-03	1590.0
3	1.89E-03	630.0	3	6.52E-03	1093.3
4	1.74E-03	656.7	4	6.01E-03	1233.3
5	1.83E-03	763.3	5	7.48E-03	1696.7
6	2.34E-03	1030.0	6	8.92E-03	1303.3
7	3.20E-03	1236.7	7	9.89E-03	1400.0
8	3.81E-03	1133.3	8	1.14E-02	1540.0
9	3.27E-03	850.0	9	1.33E-02	1670.0
10	2.37E-03	733.3	10	1.20E-02	1003.3
11	1.69E-03	626.7	11	1.01E-02	940.0
12	1.50E-03	626.7	12	1.05E-02	1173.3
13	1.24E-03	516.7	13	1.05E-02	1030.0
14	1.24E-03	550.0	14	6.94E-03	676.7
15	1.09E-03	643.3	15	4.39E-03	506.7
16	1.04E-03	353.3	16	3.03E-03	463.3
17	1.02E-03	430.0	17	2.37E-03	453.3
18	9.49E-04	476.7	18	2.15E-03	516.7
19	8.75E-04	480.0	19	2.15E-03	433.3
20	9.09E-04	600.0	20	2.00E-03	643.3
21	9.39E-04	716.7	21	1.90E-03	756.7
22	9.24E-04	686.7	22	2.34E-03	1193.3
23	9.60E-04	803.3	23	3.83E-03	1246.7
24	1.25E-03	1346.7	24	6.91E-03	1500.0
AVERAGE	1.67E-03	732.1	AVERAGE	6.84E-03	1090.6
STD. ERROR	1.70E-04	50.7	STD. ERROR	7.62E-04	94.2

NORTH BOUNDARY STATION ANACONDA			NORTH BOUNDARY STATION ANACONDA		
STATION 102 5/10/77			STATION 102 13/10/77		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	5.45E-03	1790.0	1	4.92E-03	1913.3
2	6.84E-03	1456.7	2	9.40E-03	2646.7
3	6.87E-03	1416.7	3	1.22E-02	2510.0
4	6.50E-03	1746.7	4	1.00E-02	2036.7
5	7.65E-03	2173.3	5	9.41E-03	2000.0
6	1.47E-02	2780.0	6	1.07E-02	2343.3
7	2.24E-02	3316.7	7	1.22E-02	2350.0
8	2.73E-02	3426.7	8	1.21E-02	1986.7
9	9.27E-03	3213.3	9	1.46E-02	2853.3
10	1.53E-02	2196.7	10	1.70E-02	2543.3
11	9.58E-03	1550.0	11	1.16E-02	1566.7
12	4.49E-03	840.0	12	8.13E-03	1373.3
13	1.99E-03	606.7	13	7.22E-03	1043.3
14	1.20E-03	630.0	14	6.32E-03	1040.0
15	1.04E-03	520.0	15	5.13E-03	796.7
16	9.06E-04	550.0	16	3.90E-03	596.7
17	8.57E-04	633.3	17	3.42E-03	526.7
18	8.52E-04	760.0	18	3.26E-03	696.7
19	8.25E-04	836.7	19	3.13E-03	676.7
20	1.13E-03	1030.0	20	3.10E-03	866.7
21	2.71E-03	1320.0	21	3.27E-03	1023.3
22	6.36E-03	1826.7	22	3.60E-03	1023.3
23	6.10E-03	1510.0	23	4.24E-03	1140.0
24	5.61E-03	1593.3	24	4.69E-03	1140.0
AVERAGE	6.92E-03	1573.9	AVERAGE	7.65E-03	1531.0
STD. ERROR	1.41E-03	182.7	STD. ERROR	8.47E-04	152.3

Table 26. Working Level and Radon Concentration at Station 103

TEN METER TOWER ANACONDA

STATION 103 1/10/77

HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	6.27E-03	3430.0
2	9.51E-03	3273.3
3	8.14E-03	2393.3
4	7.37E-03	2566.7
5	7.17E-03	2370.0
6	8.27E-03	2670.0
7	8.71E-03	2400.0
8	9.11E-03	2043.3
9	8.40E-03	1743.3
10	6.60E-03	1230.0
11	5.31E-03	1243.3
12	5.22E-03	1340.0
13	4.14E-03	1376.7
14	3.68E-03	1375.7
15	3.63E-03	1333.3
16	3.26E-03	1173.3
17	2.88E-03	1470.0
18	2.68E-03	1450.0
19	2.79E-03	2033.3
20	3.23E-03	1750.0
21	7.69E-03	3496.7
22	1.32E-02	3486.7
23	1.47E-02	4780.0
24	1.67E-02	4580.0
AVERAGE	7.03E-03	2297.1
STD. ERROR	7.73E-04	216.1

TEN METER TOWER ANACONDA

STATION 103 28/11/77

HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	4.61E-03	1473.3
2	4.62E-03	1440.0
3	4.27E-03	1303.3
4	4.34E-03	1723.3
5	5.17E-03	1226.7
6	5.57E-03	1413.3
7	5.49E-03	1643.3
8	7.20E-03	1960.0
9	8.03E-03	1386.7
10	5.45E-03	1470.0
11	4.44E-04	1510.0
12	6.42E-04	1566.7
13	5.34E-04	1503.3
14	6.03E-04	1590.0
15	7.05E-04	1433.3
16	8.29E-04	1486.7
17	8.88E-04	1653.3
18	9.97E-04	1550.0
19	1.18E-03	1350.0
20	1.62E-03	1110.0
21	1.97E-03	1426.7
22	1.93E-03	1343.3
23	2.22E-03	1433.3
24	2.62E-03	1340.0
AVERAGE	3.00E-03	1472.4
STD. ERROR	4.77E-04	35.1

TEN METER TOWER ANACONDA

STATION 103 6/ 2/78

HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	4.23E-03	456.7
2	4.61E-03	640.0
3	5.65E-03	936.7
4	6.81E-03	836.7
5	8.02E-03	1066.7
6	1.24E-02	2003.3
7	2.35E-02	2230.0
8	1.30E-02	1086.7
9	6.80E-03	690.0
10	4.46E-03	526.7
11	3.74E-03	286.7
12	3.25E-03	343.3
13	3.04E-03	333.3
14	2.83E-03	386.7
15	2.91E-03	466.7
16	2.71E-03	416.7
17	2.77E-03	463.3
18	2.92E-03	530.0
19	2.86E-03	820.0
20	2.42E-03	520.0
21	2.35E-03	660.0
22	3.13E-03	476.7
23	3.65E-03	950.0
24	3.54E-03	706.7
AVERAGE	5.45E-03	743.1
STD. ERROR	9.82E-04	98.5

TEN METER TOWER ANACONDA

STATION 103 26/ 3/78

HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	1.20E-02	1373.3
2	1.25E-02	1336.7
3	1.33E-02	1290.0
4	1.69E-02	1676.7
5	2.33E-02	1890.0
6	2.60E-02	1283.3
7	1.65E-02	736.7
8	1.16E-02	510.0
9	8.37E-03	353.3
10	6.46E-03	233.3
11	5.44E-03	350.0
12	4.70E-03	326.7
13	4.32E-03	303.3
14	4.19E-03	370.0
15	3.95E-03	503.3
16	3.93E-03	516.7
17	3.92E-03	626.7
18	5.40E-03	1210.0
19	1.12E-02	1933.3
20	2.15E-02	2940.0
21	3.05E-02	2690.0
22	3.24E-02	2983.3
23	3.35E-02	3470.0
24	2.63E-02	2553.3
AVERAGE	1.41E-02	1310.8
STD. ERROR	2.04E-03	204.2

Table 27. Working Level and Radon Concentration at Station 104

SEWAGE PLANT ANACONDA			SEWAGE PLANT ANACONDA		
STATION 104 20/ 9/77			STATION 104 29/ 9/77		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	3.01E-03	143.3	1	5.02E-03	683.3
2	2.96E-03	460.0	2	7.03E-03	1080.0
3	3.44E-03	446.7	3	9.97E-03	1230.0
4	3.55E-03	543.3	4	1.17E-02	1146.7
5	4.12E-03	436.7	5	1.24E-02	1043.3
6	3.99E-03	400.0	6	1.23E-02	1116.7
7	5.05E-03	690.0	7	1.40E-02	1290.0
8	5.47E-03	643.3	8	1.53E-02	1340.0
9	6.47E-03	663.3	9	1.52E-02	1203.3
10	5.35E-03	436.7	10	1.24E-02	936.7
11	2.86E-03	166.7	11	1.18E-02	830.0
12	2.16E-03	63.3	12	1.24E-02	896.7
13	1.87E-03	56.7	13	8.11E-03	446.7
14	1.76E-03	73.3	14	5.21E-03	233.3
15	1.57E-03	176.7	15	3.67E-03	160.0
16	1.46E-03	86.7	16	3.18E-03	-50.0
17	1.45E-03	213.3	17	2.74E-03	163.3
18	1.46E-03	170.0	18	2.61E-03	53.3
19	1.92E-02	12490.0	19	3.05E-03	-20.0
20	1.75E-03	296.7	20	3.01E-03	173.3
21	1.66E-03	320.0	21	3.34E-03	490.0
22	1.65E-03	443.3	22	3.63E-03	516.7
23	1.68E-03	596.7	23	4.27E-03	576.7
24	1.78E-03	730.0	24	6.98E-03	1260.0
AVERAGE	3.57E-03	864.4	AVERAGE	7.89E-03	700.0
STD. ERROR	7.45E-04	507.4	STD. ERROR	9.24E-04	96.0

SEWAGE PLANT ANACONDA			SEWAGE PLANT ANACONDA		
STATION 104 5/10/77			STATION 104 13/10/77		
HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)	HOUR OF THE DAY	WORKING LEVEL	RADON CONCENTRATION (PCI/M3)
1	4.83E-03	346.7	1	7.01E-03	646.7
2	6.57E-03	600.0	2	1.95E-02	1806.7
3	7.68E-03	753.3	3	2.39E-02	1630.0
4	8.57E-03	1015.7	4	1.93E-02	1716.7
5	1.48E-02	1803.3	5	2.43E-02	2006.7
6	1.61E-02	1596.7	6	2.19E-02	1233.3
7	1.53E-02	1463.3	7	1.80E-02	896.7
8	1.84E-02	1766.7	8	1.74E-02	1193.3
9	1.13E-02	2030.0	9	1.82E-02	1266.7
10	1.70E-02	1900.0	10	1.92E-02	1250.0
11	1.25E-02	1000.0	11	1.52E-02	580.0
12	9.60E-03	793.3	12	1.12E-02	513.3
13	2.55E-03	143.3	13	9.30E-03	246.7
14	1.45E-03	66.7	14	1.06E-02	456.7
15	1.18E-03	90.0	15	9.12E-03	210.0
16	1.05E-03	103.3	16	4.63E-03	6.7
17	9.15E-04	60.0	17	4.77E-03	53.3
18	8.45E-04	110.0	18	7.18E-03	283.3
19	5.02E-03	303.3	19	6.98E-03	643.3
20	5.10E-03	533.3	20	8.87E-03	1053.3
21	6.35E-03	396.7	21	8.36E-03	570.0
22	5.38E-03	343.3	22	7.72E-03	386.7
23	7.97E-03	1016.7	23	8.03E-03	530.0
24	1.43E-02	2463.3	24	1.21E-02	1296.7
AVERAGE	8.11E-03	862.5	AVERAGE	1.30E-02	855.3
STD. ERROR	1.15E-03	150.3	STD. ERROR	1.27E-03	118.0

Table 28. Concentration of Radon-222 in Air at Station 102

Season/Month	<u>Concentration (pCi/m³)</u>				Modal- Concen- tration Frequency (%)	No. of Hours of Data
	Avg	Max	Min	Modal		
<u>Summer 77:</u>						
Jul	779	1770	267	400	11.9	717
Aug	117	2450	497	700	8.9	652
Avg	448	2110	382	550	10.4	
<u>Fall 77:</u>						
Sep	1080	2320	406	600	8.6	674
Oct	1000	2170	361	400	9.0	742
Nov	794	2050	184	200	8.8	679
Avg	958	2180	317	400	8.8	
<u>Winter 77-78:</u>						
Dec	791	1840	237	200	11.5	741
Jan	582	1540	110	300	10.1	739
Feb	217	789	a	a	17.1	670
Mar	217	922	a	a	18.6	742
Avg	452	1273	85	125	14.3	
<u>Spring 78:</u>						
Apr	274	952	a	a	23.2	582
May	211	696	a	a	16.2	420
Jun	238	1270	a	a	26.2	130
Avg	241	973	a	a	21.8	

^a Not detectable, i.e. count rate is equal to or less than detector background.

Table 29. Concentration of Radon-222 in Air at Station 103

Season/Month	Concentration (pCi/m ³)				Modal- Concen- tration Frequency (%)	No. of Hours of Data
	Daily Average					
	Avg	Max	Min	Modal		
<u>Summer 77:</u>						
Jul	2160	4710	866	1400	8.0	623
Aug	2390	5710	1030	1300	7.0	740
Avg	2275	5210	948	1350	7.5	
<u>Fall 77:</u>						
Sep	2210	5500	1070	1400	7.6	680
Oct	2210	4680	1070	1200	8.5	740
Nov	1940	3780	953	1400	7.4	677
Avg	2120	4653	1031	1333	7.8	
<u>Winter 77-78:</u>						
Dec	2470	6110	1090	1300	9.0	741
Jan	1370	3160	200	200	7.1	737
Feb	895	2290	188	300	13.5	650
Mar	1050	2980	205	300	14.1	739
Avg	1446	3635	421	450	10.9	
<u>Spring 78:</u>						
Apr	838	2550	150	200	16.4	718
May	891	2760	213	300	14.8	721
Avg	865	2655	182	250	15.6	
<u>Summer 78:</u>						
Jun	902	2900	161	200	14.1	710
Jul	1070	3740	134	200	18.2	606
Avg	986	3320	148	200	16.2	

Table 30. Concentration of Radon-222 in Air at Station 104

Season/Month	<u>Concentration (pCi/m³)</u>				Modal- Concen- tration Frequency (%)	No. of Hours of Data
	Avg	Max	Min	Modal		
<u>Summer 77:</u>						
Jul	712	2710	98.1	200	15.0	678
Aug	589	2010	44.1	200	17.4	724
Avg	651	2360	71.1	200	16.2	
<u>Fall 77:</u>						
Sep	820	3450	90.9	100	11.0	643
Oct	732	2130	41.3	a	9.4	735
Nov	595	1970	77.5	200	18.1	72
Avg	716	2517	69.9	100	12.8	
<u>Winter 77-78:</u>						
Dec	772	2680	a	a	8.0	639
Jan	624	1570	a	a	8.9	743
Feb	565	1730	3.57	200	10.7	664
Mar	1550	4950	a	a	5.7	558
Avg	876	2733	0.9	50	8.3

WORKING LEVEL

Working levels (WLs) for radon-222 daughters in free (outdoor) atmosphere have seldom been measured. Shiager (1974) found radon progeny concentrations in outdoor air, measured in Colorado, limited to the range of 1×10^{-3} to 1×10^{-2} WL, with a mean of about 4×10^{-3} WL. Momeni et al. (1978) report a value of 1.5×10^{-3} WL from selected measurements during late mornings and late afternoons in areas of New Mexico remote from uranium mills. WLs at the Anaconda Uranium Mill were measured using both an American National Standards Institute (ANSI) technique and a continuous-measurement technique.

WORKING LEVEL DETERMINED BY THE ANSI TECHNIQUE

The ANSI technique was used to measure WL at stations 100 through 105 (Fig. 3). The WLs measured at station 100 are given in Table 31; the average value is 1.7×10^{-3} (range 2.2×10^{-4} to 9.8×10^{-3}). The WLs measured at station 101 are given in Table 32. The average is 2.0×10^{-3} (range 1.2×10^{-4} to 9.2×10^{-3}). At station 102 (adjacent to station 101) the average value, as shown in Table 33, is 2.4×10^{-3} (range 3.1×10^{-4} to 9.5×10^{-3}). The average WLs at stations 101 and 102 are in close agreement.

Station 103 is located 0.5 km downwind of the MAIN tailings and the average measured WL, given in Table 34, is 2.7×10^{-3} (range 2.6×10^{-4} to 1.4×10^{-2}). Because of the proximity of station 103 to the tailings, the transit times are generally too small for ingrowth of radon progeny other than polonium-218. Stations 104 and 105, which are farther from the tailings, have average WLs of 1.7×10^{-3} and 3.3×10^{-3} , respectively (Tables 35 and 36).

The average net contribution from the mill, for all stations except station 105, is 5.5×10^{-4} . Station 105 is downwind and farther from the mill tailings and ore pads than are the other stations, allowing nearly optimum ingrowth and dispersion of the radon daughters. The net WL measured at station 105 is 1.8×10^{-3} . Station 105 is adjacent to mesas enclosing the station and affecting dispersion. It seems that topography could have affected the WL at this station, resulting in higher levels of WL-to-radon ratios.

CONTINUOUS MEASUREMENT OF WORKING LEVEL

Outdoor WLs were measured continuously using the Continuous Radon and Working Level Monitor (CRWM-100 system) at stations 102, 103, and 104; hourly averaged WLs for selected days are given in Tables 25 to 27. These WLs are combined values obtained from background and mill operations. The WL on 19 August 1977 at station 102 shows diurnal variations similar to those of radon concentration. WL is maximum at 6 a.m., whereas the radon concentration is maximum at 5 a.m.; this delay is due to ingrowth of radon daughters. The ratio of WL at its maximum value at 6 a.m. to radon concentration at the same time is 8.42×10^{-3} WL/(pCi/L). At the secular radioactive equilibrium each

pCi/L of radon generates 1×10^{-2} WL; thus, radon-daughter concentration is 84.2% of the equilibrium value. In contrast, at the minimum WL the ratio is 9.9×10^{-4} WL/(pCi/L), or only 9.9% of secular equilibrium. The daily average ratio of WL to radon concentration is 4.1×10^{-3} , or 41% of equilibrium.

Variations in WL, by month, at stations 102, 103, and 104 are shown in Figures 25 to 27 (see also App., Figs. A11 to A13). The principal characteristics of these data are incidences of large WLs at night and the appearance of doublets (two closely spaced peaks) in the distributions, similar to those observed for radon. The magnitude of maximum WLs relative to the preceding minimum WLs are not similar for the three stations, suggesting influences of local wind fields and topography on dispersion. The highest WLs observed in July 1977 are about 2.0×10^{-2} on 15 July at station 102, about 5.5×10^{-2} on 26 July at station 103, and about 5.2×10^{-2} on 12 July at station 104.

Frequencies of occurrence of given WLs are given in Figures 28 to 30 (see also App., Figs. A14 to A16). During July 1977 at station 102, WLs of less than 3×10^{-3} are predominant (frequency about 35%). The maximum observed value is about 2×10^{-2} . At station 103 during the same month the most probable WL is about 5×10^{-3} (frequency about 20%). The highest observed WL is about 5.6×10^{-2} . At station 104, the distribution is similar to those at the other two stations, with a maximum frequency of about 25% at 3×10^{-3} WL. The maximum observed value at station 104 is about 5×10^{-2} WL.

The daily-average maximum and minimum WLs measured at station 102 from July 1977 to March 1978 are presented in Table 37. The average WL for each month varies from 3.63×10^{-3} in July to 7.97×10^{-3} in January. The daily-average maximum ranges from 1.0×10^{-2} to 2.0×10^{-2} , and the daily-average minimum ranges from 1.0×10^{-3} to 2.27×10^{-3} . The daily-average minimum range is comparable to that measured using the ANSI technique. The modal WL, i.e. the most frequently observed WL during the month, ranges from 1.3×10^{-3} in July to 3.0×10^{-3} in September and October. The frequency of observation of the modal WL ranges from 14.2% to 34.6%. Comparison of the average seasonal WLs shows the lowest value during the summer and the highest during the winter. The largest variations in daily-average minimum and maximum values were observed during the summer (14 times), and the smallest variations during the fall (8 times).

Average WLs for July 1977 to July 1978 at station 103 are given in Table 38. The average value ranges between 6.9×10^{-3} in July 1977 and 8.0×10^{-2} in December. The daily-average maximum WL ranges from 2.0×10^{-2} to 5.4×10^{-2} , and the daily-average minimum from less than 3.0×10^{-4} to 7.0×10^{-3} . The modal WL varies from less than 3.0×10^{-4} to 7.5×10^{-3} .

Table 39 shows the average WL at station 104 to be between 4.7×10^{-3} in September 1977 and 1.8×10^{-2} in December 1977. The daily-average maximum WL ranges between 1.3×10^{-2} and 4.0×10^{-2} ; daily-average minimum ranges between 1.0×10^{-3} and 4.0×10^{-3} . Modal WL varies from 1.4×10^{-3} to 3.0×10^{-2} . The minimum seasonal-average WL was during the summer and the maximum during the winter.

The lowest seasonal-average WL observed at station 103, a station only 0.5 km from the MAIN tailings, was during the spring (Table 40). At the other

two stations the lowest values were in the summer. Among stations 102, 103, and 104, comparison of seasonal-average WLs indicates that, in contrast to radon concentration, WL does not steadily decrease from summer to spring. Lowest WL at each station was observed in the summer and the highest in the winter, except at station 103 where the highest level occurred in the fall. The differences between fall and winter seasonal-average WLs are small and may not be statistically significant.

STATION 102, JANUARY 1978

STATION 102, FEBRUARY 1978

Figure 25. Working Level by Hour at Station 102.

STATION 103, JANUARY 1978

STATION 103, FEBRUARY 1978

Figure 26. Working Level by Hour at Station 103.

STATION 104, DECEMBER 1977

STATION 104, JANUARY 1978

Figure 27. Working Level by Hour at Station 104.

STATION 102, JANUARY 1978

STATION 102, FEBRUARY 1978

Figure 28. Working-Level Frequency at Station 102.

STATION 103, JANUARY 1978

STATION 103, FEBUARY 1978

Figure 29. Working-Level Frequency at Station 103.

STATION 104, FEBUARY 1978

STATION 104, MARCH 1978

Figure 30. Working-Level Frequency at Station 104.

Table 31. Working Level Measured
at Station 100 in 1977 Using
the ANSI Technique

<i>Date</i>	<i>Time</i>	<i>Working Level</i>
4 Jul	1413	5.4E-04
5 Jul	0923	1.4E-03
7 Jul	1428	4.7E-04
11 Jul	1254	5.8E-04
13 Jul	0804	9.4E-03
16 Jul	0818	9.8E-03
19 Jul	1250	4.2E-04
20 Jul	0820	1.2E-03
22 Jul	1318	5.6E-04
25 Jul	0858	4.9E-03
3 Aug	1409	4.3E-04
4 Aug	0800	5.9E-03
9 Aug	1109	5.2E-04
10 Aug	1018	5.8E-04
15 Aug	1106	8.4E-04
16 Aug	1040	8.4E-04
17 Aug	0840	1.8E-03
19 Aug	0820	4.0E-03
25 Aug	1825	3.0E-04
26 Aug	1425	4.6E-04
29 Aug	1417	5.3E-04
30 Aug	1330	4.5E-04
1 Sep	1355	4.0E-04
2 Sep	1500	5.5E-04
6 Sep	1248	9.3E-04
7 Sep	1425	9.2E-04
8 Sep	1440	5.8E-04
23 Sep	1415	3.2E-04
29 Sep	1435	2.2E-04
Avg		1.7E-03

Table 32. Working Level Measured
at Station 101 in 1977 Using
the ANSI Technique

<i>Date</i>	<i>Time</i>	<i>Working Level</i>
4 Jul	1129	9.1E-04
6 Jul	1503	2.8E-04
7 Jul	0918	3.3E-03
12 Jul	1226	7.3E-04
13 Jul	0917	2.6E-03
16 Jul	1027	6.0E-04
18 Jul	0836	2.2E-03
20 Jul	1342	4.6E-04
21 Jul	1024	1.4E-03
25 Jul	1247	1.4E-03
1 Aug	0825	5.6E-03
2 Aug	0940	9.2E-03
4 Aug	1353	3.4E-04
8 Aug	1044	1.2E-03
10 Aug	1249	6.3E-04
11 Aug	0808	3.8E-03
15 Aug	1313	8.7E-04
16 Aug	0841	1.1E-03
25 Aug	1130	3.9E-04
29 Aug	0940	2.8E-03
31 Aug	0930	4.2E-03
28 Sep	1405	1.2E-04
3 Oct	1355	8.7E-04
Avg		2.0E-03

Table 33. Working Level Measured
at Station 102 in 1977-78
Using the ANSI Technique

<i>Date</i>	<i>Time</i>	<i>Working Level</i>
4 Jul	1106	1.2E-03
6 Jul	1523	3.2E-04
7 Jul	0938	1.5E-03
12 Jul	1244	1.2E-03
13 Jul	0858	3.6E-03
16 Jul	1046	5.9E-04
18 Jul	0856	1.8E-03
20 Jul	1401	3.1E-04
21 Jul	1042	1.9E-03
25 Jul	1306	1.1E-03
1 Aug	0845	5.2E-03
2 Aug	0959	9.0E-03
8 Aug	1044	7.7E-04
10 Aug	1307	6.3E-04
11 Aug	0826	4.3E-03
15 Aug	1333	8.3E-04
16 Aug	0901	9.6E-04
25 Aug	1109	5.7E-04
29 Aug	0920	4.9E-03
31 Aug	0911	9.5E-03
1 Sep	1335	3.7E-04
2 Sep	1000	1.1E-03
7 Sep	0935	6.8E-03
8 Sep	1030	3.3E-03
16 Sep	1055	3.3E-04
23 Sep	0950	7.6E-04
27 Sep	1415	6.1E-04
30 Sep	1435	3.2E-04
26 Jun	0800	3.7E-04
27 Jun	0830	2.4E-03
29 Jun	0830	1.1E-03
5 Jul	0830	7.1E-03
10 Jul	0830	1.1E-03
11 Jul	0830	2.6E-03
Avg		2.4E-03

Table 34. Working Level Measured
at Station 103 in 1977-78
Using the ANSI Technique

<i>Date</i>	<i>Time</i>	<i>Working Level</i>
5 Jul	1533	7.6E-04
6 Jul	0918	9.9E-03
11 Jul	1014	1.3E-03
13 Jul	1308	6.7E-04
15 Jul	1306	7.7E-04
18 Jul	1305	9.5E-04
19 Jul	0859	1.0E-02
21 Jul	1415	5.4E-04
22 Jul	1132	8.6E-04
1 Aug	1005	3.5E-04
2 Aug	1354	6.3E-04
3 Aug	0656	1.4E-02
8 Aug	1319	7.3E-04
9 Aug	0914	4.4E-03
11 Aug	1035	1.3E-03
12 Aug	1002	1.0E-03
17 Aug	1123	1.5E-03
19 Aug	1158	7.7E-04
22 Aug	1125	3.8E-03
24 Aug	1612	5.4E-04
26 Aug	1045	5.8E-04
30 Aug	1001	2.3E-03
1 Sep	0912	1.5E-03
7 Sep	1005	8.3E-03
8 Sep	1045	2.5E-03
9 Sep	0805	2.3E-02
16 Sep	1120	5.6E-04
23 Sep	1030	1.0E-03
28 Sep	1430	2.6E-04
26 Jun	0800	3.3E-04
28 Jun	0830	7.6E-04
29 Jun	0830	1.3E-03
6 Jul	0830	5.3E-04
10 Jul	0830	1.1E-03
Avg		2.7E-03

Table 35. Working Level Measured
at Station 104 in 1977-78
Using the ANSI Technique

<i>Date</i>	<i>Time</i>	<i>Working Level</i>
4 Jul	1353	9.3E-04
5 Jul	0903	1.7E-03
7 Jul	1448	4.8E-04
11 Jul	1317	4.4E-04
13 Jul	0823	6.3E-03
16 Jul	0839	3.5E-03
19 Jul	1310	4.5E-04
20 Jul	0840	1.5E-03
22 Jul	1338	4.4E-04
25 Jul	0918	3.5E-03
3 Aug	0349	5.9E-04
4 Aug	0741	5.6E-03
9 Aug	1050	1.0E-03
10 Aug	0959	9.6E-04
12 Aug	1212	9.4E-04
15 Aug	1042	1.0E-03
16 Aug	1018	7.8E-04
17 Aug	0820	2.5E-03
19 Aug	0800	6.8E-03
25 Aug	1005	3.0E-04
26 Aug	1404	3.7E-04
29 Aug	1355	6.5E-04
30 Aug	1312	4.8E-04
31 Aug	1400	5.5E-04
2 Sep	1438	5.1E-04
6 Sep	1230	9.7E-04
7 Sep	1405	6.8E-04
8 Sep	1420	8.5E-04
23 Sep	1355	3.4E-04
29 Sep	1405	7.4E-04
30 Sep	1510	3.2E-04
27 Jun	0830	5.0E-03
28 Jun	0800	7.7E-04
2 Jul	0830	4.6E-03
6 Jul	0830	1.0E-03
11 Jul	0830	3.5E-03
Avg		1.7E-03

Table 36. Working Level Measured
at Station 105 in 1977
Using the ANSI Technique

<i>Date</i>	<i>Time</i>	<i>Working Level</i>
5 Jul	1508	4.0E-04
6 Jul	0853	1.3E-02
11 Jul	0953	8.1E-04
13 Jul	1247	4.1E-04
15 Jul	1245	7.2E-04
18 Jul	1243	8.4E-04
19 Jul	0836	2.3E-02
21 Jul	1352	7.3E-04
22 Jul	1109	1.0E-03
1 Aug	1445	5.9E-04
2 Aug	1338	5.1E-04
3 Aug	0635	9.1E-03
8 Aug	1259	5.7E-04
9 Aug	0853	6.1E-03
11 Aug	1014	1.7E-03
12 Aug	0938	1.0E-03
17 Aug	1103	2.0E-03
19 Aug	1135	8.4E-04
22 Aug	1035	5.3E-03
24 Aug	1641	2.2E-04
26 Aug	1000	1.3E-03
30 Aug	0940	2.1E-03
31 Aug	1420	3.9E-04
1 Sep	0850	2.4E-03
2 Sep	1025	9.0E-04
9 Sep	0740	1.6E-02
27 Sep	1440	4.6E-04
3 Oct	1425	8.9E-04
Avg		3.3E-03

Table 37. Working-Level Analysis, Continuous Measurements, Station 102

Season/ Month	Working Level				Modal- Working- Level Frequency (%)	No. of Samples
	Daily Average			Modal		
	Avg	Max	Min			
<u>Summer 77:</u>						
Jul	3.63E-03	1.04E-02	1.00E-03	1.30E-03	34.6	717
Aug	4.43E-03	1.30E-02	1.00E-03	1.58E-03	24.7	652
Avg	4.03E-03	1.17E-02	1.00E-03	1.44E-03	29.6	
<u>Fall 77:</u>						
Sep	4.25E-03	1.12E-02	1.00E-03	3.00E-03	24.2	674
Oct	6.43E-03	1.57E-02	2.27E-03	3.00E-03	16.4	742
Nov	6.48E-03	1.66E-02	2.19E-03	2.94E-03	14.6	679
Avg	5.72E-03	1.45E-02	1.82E-03	2.98E-03	18.4	
<u>Winter 77-78:</u>						
Dec	6.16E-03	1.59E-02	1.00E-03	1.96E-03	18.6	741
Jan	7.87E-03	1.95E-02	2.00E-03	2.98E-03	14.2	739
Feb	7.16E-03	1.74E-02	2.00E-03	2.56E-03	16.9	670
Mar	6.96E-03	1.80E-02	1.00E-03	2.39E-03	17.3	742
Avg	7.04E-03	1.77E-02	1.50E-03	2.47E-03	16.8	
<u>Spring 78:</u>						
Apr	5.97E-03	1.93E-02	1.77E-03	2.00E-03	20.2	243
Avg	5.97E-03	1.93E-02	1.77E-03	2.00E-03	20.2	
<u>Summer 78:</u>						
Jun	4.38E-03	1.40E-02	1.00E-03	1.87E-03	27.7	130
Avg	4.38E-03	1.40E-02	1.00E-03	1.87E-03	27.7	

Table 38. Working-Level Analysis, Continuous Measurements, Station 103

Season/ Month	Working Level				Modal- Working- Level Frequency (%)	No. of Samples
	Daily Average					
	Avg	Max	Min	Modal		
<u>Summer 77:</u>						
Jul	6.85E-03	2.09E-02	1.66E-03	2.00E-03	20.5	623
Aug	7.81E-03	2.79E-02	1.77E-03	2.00E-03	15.1	740
Avg	7.33E-03	2.44E-02	1.72E-03	2.00E-03	17.8	
<u>Fall 77:</u>						
Sep	8.49E-03	2.59E-02	2.00E-03	2.56E-03	18.1	680
Oct	1.16E-02	3.12E-02	3.16E-03	4.00E-03	12.8	740
Nov	7.73E-02	1.98E-02	a	a	24.8	677
Avg	3.26E-02	2.56E-02	1.72E-03	2.19E-03	18.6	
<u>Winter 77-78:</u>						
Dec	8.04E-02	2.05E-02	a	a	25.9	741
Jan	1.20E-02	3.12E-02	3.00E-03	4.05E-03	12.7	734
Feb	1.06E-02	2.74E-02	3.00E-03	3.10E-03	13.3	661
Mar	1.08E-02	3.31E-02	1.00E-03	2.85E-03	16.5	738
Avg	2.84E-02	2.81E-02	1.89E-03	2.50E-03	17.1	
<u>Spring 78:</u>						
Apr	9.46E-03	2.97E-02	3.00E-03	3.17E-03	13.4	717
May	1.05E-02	3.35E-02	3.00E-03	3.29E-03	15.9	722
Avg	1.00E-02	3.16E-02	3.00E-03	3.23E-03	14.7	
<u>Summer 78:</u>						
Jun	1.50E-02	4.64E-02	4.00E-03	4.54E-03	10.7	637
Jul	1.83E-02	5.41E-02	7.00E-03	7.49E-03	7.9	558
Avg	1.67E-02	5.03E-02	5.50E-03	6.02E-03	9.3	

^aNot detectable (less than or equal to 5.00E-04 at a 95% confidence level).

Table 39. Working-Level Analysis, Continuous Measurements, Station 104

Season/ Month	Working Level				Modal- Working- Level Frequency (%)	No. of Samples
	Daily Average			Modal		
	Avg	Max	Min			
<u>Summer 77:</u>						
Jul	5.17E-03	1.64E-02	1.00E-03	1.50E-03	26.4	678
Aug	4.88E-03	1.40E-02	1.00E-03	1.41E-03	27.1	724
Avg	5.03E-03	1.52E-02	1.00E-03	1.46E-03	26.7	
<u>Fall 77:</u>						
Sep	4.72E-03	1.29E-02	1.00E-03	1.69E-03	22.0	660
Oct	8.95E-03	2.01E-02	3.00E-03	3.28E-03	13.1	728
Avg	6.84E-03	1.65E-02	2.00E-03	2.49E-03	17.6	
<u>Winter 77-78:</u>						
Dec	1.76E-02	4.04E-02	2.00E-03	5.70E-03	10.5	637
Jan	1.58E-02	3.38E-02	4.00E-03	6.67E-03	8.8	742
Feb	1.20E-02	2.66E-02	3.00E-03	4.95E-03	9.3	664
Mar	1.13E-02	2.60E-02	4.84E-03	3.00E-02	13.0	562
Avg	1.42E-02	3.17E-02	3.46E-03	1.18E-02	10.4	

Table 40. Seasonal-Average Working Levels

<i>Season</i>	<i>Station</i>		
	<i>102</i>	<i>103</i>	<i>104</i>
Summer 77	4.0E-03	7.3E-03	5.0E-03
Summer 78	4.4E-03	1.7E-02	
Summer avg	4.2E-03	1.2E-02	5.0E-03
Fall	5.7E-03	3.3E-02	6.8E-03
Winter	6.4E-03	2.8E-02	1.4E-02
Spring	6.0E-03	1.0E-02	

DISCUSSION

Previously reported data have been based on short-duration air samples or integrated air samples (about 48 hours). Concentrations of radon and its short-lived daughters show both diurnal and seasonal variations, variations with climate, and dependence on regional air-mass movements associated with continental air circulation. Estimation of radon concentration based on short-duration air samples results in erroneous conclusions due to high variability between sampling periods. The practice of obtaining air samples primarily during daylight hours results in underestimation of the average concentration. Diurnal variation of radon concentration indicates a much larger concentration between sunset and sunrise than after sunrise. This higher concentration at night is due to lower wind velocities and shallow mixing heights as a result of thermal inversion. The variability of maximum concentrations of radon and its daughters observed at night at any location depends partially on air-mass winds breaking the inversion condition, thereby changing atmospheric stability and resulting in more mixing of radon into the air space. Concentrations of radon and its daughters are not constant even at equal distances from a mill or at equal wind velocities, and change in magnitude with changing wind direction.

Theoretical estimation of radon concentration and working level has been utilized for prediction of potential exposures from milling and mining operations, e.g. in our use of the UDAD Code (Momeni et al. 1979a) in the radiological assessment of Bear Creek (U.S. Nuclear Regulatory Commission 1977a), Morton Ranch (U.S. Nuclear Regulatory Commission 1978), and Lucky Mc (U.S. Nuclear Regulatory Commission 1977b). For radon, the usefulness of these assessments is related to the soundness of predictions of radon concentration, which depends in turn on the validity of input data such as meteorology, radon source terms, and effects of topography. Unless valid data are utilized, resultant predictions are of little worth.

The objectives of this study were to obtain:

1. Site-specific meteorology over a period of one year or longer and
2. Measurement of radon concentration and working level at several stations over a one-year period.

These items were examined in this report. Comparison of predicted concentrations using UDAD and site-specific parameters with measurements obtained during 1977 has been discussed previously (Momeni et al. 1978). Further comparisons using all the data, obtained from 1977-1978, will be reported later.

During the period of this study starting in June 1977, the Anaconda milling-operation conditions were changed several times. Among these changes were the covering with local soil of two small inactive tailings piles, located northeast and south of the main active tailings, during the fall of

1977 (Momeni et al. 1979b); expansion of the tailings dam; reconstruction of the tailings structure; addition of evaporation ponds; and alteration of tailings discharge, in an attempt to increase moisture in the beach areas, using a technique similar to that described by Momeni et al. (1979b). The amount of stockpiled ore was increased several times in anticipation of labor management disputes resulting in a strike. However, these alterations have affected estimation of radon concentration and impaired a realistic assessment of climatic and seasonal parameters. Milling is a dynamic operation whereby alterations in protocol, similar to those described, are to be expected.

RADON CONCENTRATION

Inhalation of radon-222 may be the most significant exposure pathway for the population in the immediate vicinity of uranium mines and mills. Concentrations of radon in air have been reported previously for Mexican Hat, Utah (Snelling 1971), for other mills (U.S. Environmental Protection Agency 1973), and summarized for inactive uranium tailings in areas near Durango, Grand Junction, and Vitro by Swift et al. (1976). The average radon concentration measured by grab samples directly over the Mexican Hat tailings is reported to be between 3200 and 14 000 pCi/m³. Radon concentration measured directly on the Grand Junction tailings is reported as 7800 pCi/m³ (ranging from 1100 to 28 000 pCi/m³), on the Durango tailings as 16 000 pCi/m³ (ranging from 480 to 34 000 pCi/m³), on the Monticello tailings as 3500 pCi/m³ (ranging from 120 to 12 000 pCi/m³), and on the Vitro tailings as 10 000 pCi/m³ (ranging from 1600 to 22 000 pCi/m³). The average radium-226 activity for the Grand Junction tailings is 784 pCi/g (Biles 1967, Liverman 1974, McGinley 1974).

Normalization of radon concentration in air (χ) measured on tailings to the rate of release of radon ($\dot{Q}$) may provide a parameter for comparison between different tailings. The rate of release of radon $\dot{Q}$ is given by:

$$\dot{Q} = \Phi \cdot A$$

where Φ is the flux [(pCi/(m²·s))] and A is the area of the tailings. Because Φ is proportional to the radium concentration [Ra] in the tailings, then:

$$\dot{Q} \propto [Ra] \cdot A$$

Thus, radon concentration normalized to the area of tailings and the radium concentration in tailings (χ_s) may allow comparison between different operations:

$$\chi_s = \frac{\chi}{[Ra] \cdot A}$$

The contribution of the area A to the measured concentration χ may not be significant beyond a certain size of the tailings-retention area. Normalization of the average radon concentration to the activity of radium and to the area of the tailings (specific concentration, χ_s) at Grand Junction is:

$$\begin{aligned} \chi_s &= (780 \text{ pCi radon/m}^3) / [(784 \text{ pCi radium/g of tailings})(2.22 \times 10^5 \text{ m}^2)] \\ &= 4.5 \times 10^{-5} \text{ (pCi radon/m}^3) / [(pCi \text{ radium/g of tailings}) (\text{m}^2)] \end{aligned}$$

Similarly, the radium-226 activity is 840 pCi/g for the Durango tailings (Foote Mineral Corp.) with an area of $1.01 \times 10^5 \text{ m}^2$ (Biles 1967, Liverman 1974, McGinley 1974); specific radon concentration is:

$$\chi_s = 1.9 \times 10^{-4} \text{ (pCi radon/m}^3\text{)/[(pCi radium/g) (m}^2\text{)]}$$

The similarly specific radon concentrations in air for the Monticello tailings (USAEC) and the Vitro tailings are: 8.1×10^{-5} and 2.6×10^{-5} (pCi radon/m³)/[(pCi radium/g of tailings)(m²)], respectively.

Radon concentration over the Anaconda MAIN tailings averaged 11 000 pCi/m³ radon-222, with a range of 2200 to 21 000 pCi/m³ (Table 13). The area of the beach tailings was estimated at $3 \times 10^5 \text{ m}^2$, and a total release rate was estimated at 4700 Ci/yr radon-222 (Momeni et al. 1979b). The average radium-226 concentration for the Anaconda tailings was estimated at 500 pCi/g, with average measured activities of 616.6 pCi/g and 604.4 pCi/g for the two inactive ACID and ALKO tailings, respectively (Momeni et al. 1979b). Specific radon concentration in air over the Anaconda tailings is:

$$\begin{aligned}\chi_s &= (11\,000 \text{ pCi radon/m}^3)/[(500 \text{ pCi radium/g})(3 \times 10^5 \text{ m}^2)] \\ &= 7.3 \times 10^{-5}\end{aligned}$$

The probable range for the specific radon concentration is 5.5×10^{-5} to 9.1×10^{-5} (pCi radon/m³)/[pCi radium/g) (m²)].

The average of the specific radon concentrations for the Durango, Vitro, Monticello, and Grand Junction tailings is 8.6×10^{-5} . Our estimated value, 7.3×10^{-5} , is in close agreement. The Anaconda MAIN tailings is an active pile and the radon concentration measured directly over its beach is lower than over an inactive pile due to higher moisture (Momeni et al. 1979b). The estimated 11 000 pCi/m³ radon-222 concentration over the Anaconda MAIN tailings may increase after drying.

The radon concentration decreases with distance from the tailings and is a function of climatic and meteorological factors as well. These factors influence both radon flux and dilution by mixing in the atmosphere. At present, our quantitative knowledge of processes effecting release and diffusion of gases and aerosols in the atmosphere is limited. In general, the concentration of radon in air (χ) is dependent on the release rate: $\dot{Q} = \Phi[\text{pCi}/(\text{m}^2 \cdot \text{s})] \times (\text{area})$; and dilution rate $\dot{V}$ is proportional to U_x (m/s) U_y (m/s) U_z (m/s); where Φ is the flux, and U_x , U_y , and U_z are windspeeds in the space directions $\hat{x}$, $\hat{y}$, and $\hat{z}$. The parameters $U_{x,y,z}$ are complex site-specific parameters with both diurnal and seasonal components. Under near-stable conditions and small vertical mixing (low U_z), the concentration of radon is perceptibly larger in the downwind direction.

Snelling (1971) reports a concentration of about 14 000 pCi/m³ just at the edge of tailings of the Mexican Hat uranium mill, decreasing to about 1000 pCi/m³ at a distance of about 1 km. The background at this mill is estimated to be 300 pCi/m³. Shearer and Sill (1969) measured background radon concentrations at selected mills and reported concentrations of 380 pCi/m³ for Vitro, 800 pCi/m³ for Grand Junction, 510 pCi/m³ for Durango, and 340 pCi/m³

for Monticello. Radon concentration at about 0.5 km from the Grand Junction tailings is between 780 and 1100 pCi/m³, decreasing to about 800 pCi/m³ at 1.5 km (Shearer and Sill 1969). At Durango, concentration of radon in air is about 500 pCi/m³ at 0.5 km and remains nearly the same to 4 km, but the concentration on the tailings is 12 000 to 19 000 pCi/m³. At Vitro, the radon concentration is 400 pCi/m³ at 0.5 km. The concentration at these three mills varies with direction from the tailings.

Radon concentration in the Grants Mineral Belt of New Mexico has been measured by Eadie et al. (1976) using 48-hour integrated air samples. The average ambient outdoor radon concentration in Bluewater Village, 5 km southwest of the Anaconda mill, is reported to be 790 pCi/m³, with a range of 210 to 2800 pCi/m³. The concentration in residential areas about 1 km to the southeast of the mill (Bluewater) is 1120 pCi/m³ (range, 320 to 1800 pCi/m³). Concentration of radon at Broadview Acres, about 1 km south of the United Nuclear Homestake Partners Mill, is reported to be 2100 pCi/m³ (range, 240 to 3600 pCi/m³). The concentration about 1.5 km east of the Homestake Partners Mill is 220 pCi/m³ (range, 460 to 4900 pCi/m³). Farther south, 10 km from the Homestake Partners Mill in the town of Milan, the average concentration is 1200 pCi/m³ (range, 130 to 2700 pCi/m³). This last value is larger than background and cannot be attributed to either the Anaconda or Homestake Partners mills. We surmise that it is a local anomaly not unrelated to the lava-bed geological formation. The lowest radon concentration measured by Eadie et al. (1976) is 110 pCi/m³ (range, 70 to 140 pCi/m³) at Thoreau. The sampling station at Thoreau, topographically and stratigraphically, is not located on the Westwater Canyon member of the Morrison formation, which in general bears the Grants Mineral Belt area. Eadie et al. (1976) suggest a background of 720 pCi/m³ (standard error, 210 pCi/m³) for the mean radon concentration measured at the Milan, Bluewater Village, and Grants areas.

Background radon concentration in air was measured at the Mesita and Laguna areas, New Mexico, using an integrated air-sampling technique, also (Eadie et al. 1979). The average concentration at Mesita and Laguna is reported to be between 420 and 630 pCi/m³, with a range of 120 to 1600 pCi/m³.

For the Anaconda mill, the concentration of radon-222 in air at 0.5 km is between 600 pCi/m³ and 3600 pCi/m³ (Fig. 18) depending on direction. At 1 km from the tailings the radon concentration is about 300 pCi/m³, 700 pCi/m³, and 2500 pCi/m³ to the southwest, south, and east, respectively. This increased concentration in the east is not due solely to prevailing winds, but is also caused by adjacent sources of radon, wind-blown tailings, and local topography. Extrapolation of the radon concentration to long distances from the mill, specifically to the south and southwest, suggests a background concentration between 200 and 300 pCi/m³.

The averages of radon concentration in air, for each month of data collected and analyzed, are given in Table 9 for the Elkins station. The range of the averages, from December 1977 to November 1978, is 183 to 505 pCi/m³. The lowest average observed was during May, and the highest during October. The fall of 1978 showed the highest average radon concentration (408 pCi/m³), and spring showed the lowest (190 pCi/m³). The daily-average maximum concentration was highest during fall (922 pCi/m³) and lowest during spring (543 pCi/m³). The minimum concentration was observed during the spring (undetectable).

The frequency of observation of the modal radon concentration (50 pCi/m^3) at the Elkins station during the winter of 1978 was 25.1%, whereas at the McBride station (300 pCi/m^3) at that time it was 15.8%. Comparison of the modal concentrations for each month and season reveals distinct site characteristics, not only with respect to background concentrations but also in dispersion patterns.

The combined concentrations at the two stations, shown in Table 41, may represent a better radon-background value for the Anaconda Uranium Mill than could be obtained by local sampling. This annual-average concentration of radon for the areas of Bluewater and Grants, New Mexico, is 408 pCi/m^3 , compared to the previous estimate of 300 pCi/m^3 (Momeni et al. 1978). These values compare well with the radon background obtained from extrapolation to long distances from the mill (Fig. 18). Because of the extent of the Anaconda site, which has diverse geophysical structures, its radon background may differ from that at the Elkins and McBride stations as well as vary from point to point within the site.

The seasonal-average radon concentrations are lower during the spring and summer. This may indicate that conditions pertaining to atmospheric dispersion, such as higher mean wind velocity and vertical mixing, are then more prevalent.

The net radon concentrations due to the Anaconda operations are given in Table 42. The average radon concentration at station 102 due to mill operation is 162 pCi/m^3 . At this station, the concentration of radon decreases significantly from fall to winter, and a similar decrease is also evident at station 103. This behavior may not be due solely to atmospheric dispersion, but may have resulted partially from reduction of radon releases from inactive and MAIN tailings by a change in the tailings management (Momeni et al. 1979b). Because of this change in management protocol, seasonal variations of radon concentration are not directly discernible from the data. Further study at this mill, under relatively stable milling and tailings-storage conditions, will be necessary to supplement the present data and to permit estimation of the magnitude of seasonal variations of radon concentrations. Use of the measured meteorological data and radon concentrations for comparison with theoretical predictions of radon concentrations using the UDAD code are the subject of a separate report.

WORKING LEVEL

Even though the WL unit was applied initially to quantify exposures from underground mining, it can also be used to describe both ambient indoor and outdoor conditions (Momeni et al. 1979a). In general, radioactive equilibrium distribution of radon daughters in outdoor atmospheres is less than under indoor conditions. Seasonal variations in radioactive equilibrium of radon daughters have not been reported, but in indoor air variations are generally due to isolation of air during cold and hot seasons and ventilation during spring and fall.

Tsivoglou et al. (1953) made measurements of radon-daughter concentration in a naturally ventilated mine atmosphere and suggested that lead-214 concentration exceeds 70% of polonium-218 concentration and is generally near the

equilibrium value. For bismuth-214 and polonium-214, concentrations as low as 50% and as high as 93% of the equilibrium value were measured. Ventilation of the mine atmosphere results in exchange of mine air (containing as much as 1×10^7 pCi/m³) with outdoor air (less than 5000 pCi/m³) and, in addition, discharges radon daughters into the atmosphere before substantial radon-daughter growth has taken place. Toth (1972) and Holmgren (1974) summarize radon-daughter ratios in indoor air relative to polonium-218 concentration and report values of 86% (lead-214 to polonium-218) and 82% (bismuth-214 to polonium-218).

Eadie et al. (1976) estimated the average equilibrium ratio w , defined as $WL \times 10^2 / (\text{pCi/L radon-222})$, at 57% and 70% for indoor air at Bluewater Village and Bluewater, respectively. The highest values reported for the Milan City Hall and Broadview Acres are at equilibrium ($w = 1$). The corresponding indoor WLs are 1.29×10^{-2} and 2.71×10^{-2} . The lowest indoor WLs are for Bluewater Village and Bluewater at 4.5×10^{-3} and 7.7×10^{-3} , respectively. Eadie et al. (1976) suggest a background indoor WL of 6.8×10^{-3} , with a standard error of 4.6×10^{-3} . Eadie et al. (1979) report an average indoor WL of 4.9×10^{-3} with $w = 0.96$ for Laguna, New Mexico. The natural-background WL for the Grand Junction area has been estimated at 4×10^{-3} (Joint Committee on Atomic Energy 1971).

Outdoor WL has not been reported for areas adjacent to uranium mines and mills. Schiager (1974) suggested that outdoor radon-progeny concentrations in Colorado are in the range of 1×10^{-3} to 1×10^{-2} , with a mean of 4×10^{-3} . Based on this suggested mean value and the assumption that radon concentration is within 0.5 to 2 pCi/L, w is 0.2 to 0.8. Average outdoor equilibrium ratios close to a mill are significantly smaller than the equilibrium value. From the point of view of radiological protection this is a fortunate situation as long as the radon, at higher concentrations near a mill, is not trapped within housing enclosures or otherwise allowed to build to high radon-daughter concentrations.

The average background outdoor WL has been reported as 1.5×10^{-3} during late morning and early afternoon for areas remote from the Anaconda Uranium Mill and the Homestake Partners Mill (Momeni et al. 1978). Background WLs for each season, with an annual average of 3.6×10^{-3} , are presented in Table 43. The larger annual-average background WL is for the entire diurnal cycle, whereas the previously reported value (1.5×10^{-3} WL) represented only a fraction of a day when the WL is low. Net seasonal-average WLs, i.e. those attributable to the Anaconda milling operations, are also given in Table 43. The value is lowest at station 102 during the fall (8.2×10^{-4}) and highest in spring (3.5×10^{-3}), a factor of 4.2. At station 103 the minimum is during the spring (7.5×10^{-3}) and the maximum during the fall (2.8×10^{-2}), a factor of 3.7. At station 104 the minimum is during the fall (1.9×10^{-3}) and the maximum during the winter (9.8×10^{-3}), a factor of 5.2. Data for spring are not available for station 104; thus, the interseasonal comparison may not be valid here. Minimums at stations 102, 103, and 104 occur in the fall, spring, and fall, respectively, and maximums occur in the spring, fall, and winter, respectively. The annual-average net WL is highest at station 103, corresponding to the highest annual-average radon concentration (Table 42).

Radon concentration and WL show a significant decrease in concentration with increasing distance from the mill. Radon concentration is about 10 000 pCi/m³ directly over tailings, in agreement with our previous estimation using a different technique (Momeni et al. 1979b), decreasing to background level at 10 km from the mill. Radon concentration corresponding to a suggested maximum of 3000 pCi/m³ occurs between 0.15 km and 0.5 km from the mill, depending on wind direction. WL is between 1×10^{-3} and 1×10^{-2} , increasing slightly at 0.1 km, but decreasing at greater distances (Momeni et al. 1979b). The background outdoor WL is estimated at 3.6×10^{-3} .

Table 41. Suggested Radon Background Concentrations for the Bluewater and Grants Areas (pCi/m³)

Season	Station		Avg
	Elkins	McBride	
Winter	284	973	629
Spring	190	344	247 ^a
Summer	270	277	272
Fall	408	560	485
Annual avg			408

^a Estimated value - differs slightly from the average of the two stations.

Table 42. Background Levels and Net Radon Concentrations Due to Anaconda Operations Alone (pCi/m³)

Season	Background	Station		
		102	103	104
Summer 77	272	176	2003	379
Summer 78			714	
Summer avg	272	176	1359	379
Fall	485	473	1635	231
Winter	629	a	817	247
Spring	247	a	618	
Avg	408	162	1107	286

^aThe contribution from the Anaconda operations cannot be readily estimated because the concentrations measured at the two background stations differ significantly in these seasons (Table 41).

Table 43. Net Seasonal-Average Working Levels

Season	Station			Background ^a
	102	103	104	
Summer	1.5E-03	9.3E-03	2.3E-03	2.7E-03
Fall	8.2E-04	2.8E-02	1.9E-03	4.9E-03
Winter	2.2E-03	2.4E-02	9.8E-03	4.2E-03
Spring	3.5E-03	7.5E-03		2.5E-03
Avg	2.0E-03	1.7E-02	4.7E-03	3.6E-03

^aSuggested, tentative data.

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