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**Radiological Survey of the
Inactive Uranium-Mill Tailings
at Slick Rock, Colorado**

F. F. Haywood
P. T. Perdue
K. D. Chou
B. S. Ellis

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL-5452
Dist. Category UC-41

Contract No. W-7405-eng-26

Health and Safety Research Division

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TAILINGS AT SLICK ROCK, COLORADO**

F. F. Haywood, P. T. Perdue, K. D. Chou,
and B. S. Ellis

Appendix I in this document is a direct reproduction of a previously unpublished report of the Phase I interagency site visit prepared by Lucius Pitkin, Inc., under AEC Contract AT(05-1)912.

Date Published: June 1980

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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3	Assessment of the Radiological Impact of the Inactive Uranium-Mill Tailings at Mexican Hat, Utah	ORNL-5448
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ACKNOWLEDGEMENTS

The authors of this series of reports wish to express their deep appreciation to the following persons: to L. J. Deal and R. H. Kennedy, Department of Energy, Washington, D. C., for their encouragement and support during the field operations phase of this project; to Dr. Charles J. Barton of Science Applications, Inc. (SAI), Oak Ridge, for his diligent work in preparing, under subcontract, the drafts of this series, and to Wilma Minor, also of SAI, for typing the manuscripts; to the many members of the Health and Safety Research Division who provided technical reviews of the individual reports; to Jenny Vinson, Health and Safety Research Division Technical Editor, special thanks is extended for her careful review of each manuscript, especially for helping ensure that a uniform format was followed; to Dr. Barry Berven for his assistance in organizing the final drafts. Appreciation is extended to John G. Themelis and Frank McGinley, Department of Energy, Grand Junction Operations Office, for their support and advice during the conduct of this project; to Charles Brunner, Bendix Field Engineering Company, Grand Junction, Colorado, for his assistance in arranging for the grinding of approximately 1600 soil samples which were collected during the project; also to Dr. Vern Rogers and his staff, Ford, Bacon and Davis Utah Inc., for assistance during the field operations phase of this project. Finally, the authors wish to acknowledge the efforts of Mr. Ev Haldane, Department of Energy, Grand Junction, who was associated with the uranium mill tailings program from its earliest days. Ev passed away suddenly on June 30, 1979, and it is to his memory that this series of reports is dedicated.

RADIOLOGICAL SURVEY OF THE INACTIVE URANIUM-MILL
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ABSTRACT

Results of a radiological survey of two inactive mill sites near Slick Rock, Colorado, in April 1976 are presented. One mill, referred to in this report as North Continent (NC), was operated primarily for recovery of radium and vanadium and, only briefly, uranium. The Union Carbide Corporation (UCC) mill produced a uranium concentrate for processing elsewhere and, although low-level contamination with ^{226}Ra was widespread at this site, the concentration of this nuclide in tailings was much lower than at the NC site. The latter site also has an area with a high above-ground gamma dose rate (2700 $\mu\text{R/hr}$) and a high-surface ^{226}Ra concentration (5800 pCi/g). This area, which is believed to have been a liquid disposal location during plant operations, is contained within a fence. A solid disposal area outside the present fence contains miscellaneous contaminated debris. The estimated concentration of ^{226}Ra as a function of depth, based on gamma hole-logging data, is presented for 27 holes drilled at the two sites.

1. INTRODUCTION

This is the seventh of a series of reports on results of radiological surveys of uranium-mill tailings at inactive mill sites in the western United States. The first four reports and report No. 12 include attempts to assess potential health effects of radiation and radionuclides from the sites. The first report also contains a discussion of modes of radiation exposure to individuals and to population groups resulting from the radionuclides in tailings at uranium-mill sites and a survey of the pertinent literature. A complete list of the reports in this series is found at the front of this report. This report on two inactive mill sites near Slick Rock, Colorado, like the previous reports on the Tuba City and Durango sites, presents only the results of a radiological survey conducted by an ORNL survey team in April 1976. The survey was conducted in cooperation with an engineering team from Ford, Bacon and Davis Utah Inc., the architect-engineering company responsible for the Phase II engineering assessment of the sites considered in this series. Their report on this site has been published.¹ Results of a gamma radiation survey of these sites [by the Environmental Protection Agency (EPA)] have also been published.² The previously unpublished Phase I reports on the Slick Rock sites by Mayer et al. are included in Appendix I. Several publications³⁻⁷ include discussions of the uranium-mill tailings problem and of the assessment of their radiological impact.

2. SITE DESCRIPTIONS

Descriptions of the two inactive uranium-mill sites near Slick Rock, Colorado, and a history of the operations at these sites are included in the Phase I reports (Appendix I), and only a brief summary of this information is presented here.

Both of the uranium-mill sites near Slick Rock are presently owned by Union Carbide Corporation. The larger of the two sites is referred to in this report as the Union Carbide Corporation (UCC) site and the

other as the North Continent (NC) site. These two sites are 0.9 km apart and are located approximately 5 km northwest of the Slick Rock post office. An aerial photograph of the area is displayed in Fig. 1.

2.1 Union Carbide Corporation Site

The UCC mill site was operated from 1957 to 1961 as a uranium and vanadium upgrader plant. That is, a physical mineral separation process was performed, followed by acid treatment of part of the material, and the uranium and vanadium concentrate was sent to the Rifle plant for chemical processing. Consequently, a large fraction of the ^{226}Ra delivered to the mill was transported to the Rifle plant along with the uranium concentrate containing 90 to 95% of the uranium content of the original ore.

The tailings pile contains an estimated 320,000 metric tons with approximately 140 pCi $^{226}\text{Ra}/\text{g}$ and a ^{226}Ra inventory of 70 Ci. The convex-shaped pile covers an area of 6.3 hectares extending, at the northeast corner, to within 11 m of the Dolores River. The tailings have been stabilized in accordance with Colorado regulations. Grading of the tailings and settling pond areas was performed followed by application of 15 cm of topsoil which was then seeded. Also, a dike was constructed, using mine waste materials, between the tailings pile and the Dolores River; and a drainage ditch was provided to divert area drainage around the tailings. Mill buildings were dismantled, but concrete foundations remain. The property is fenced, with locked gates, and is posted in accordance with state regulations. Of the 146 hectares at this site originally owned by Union Carbide Corporation approximately 2 hectares were sold to the Rocky Mountain Gas Company (RMGC), which operates a gas sweetener plant at this location. Several houses and trailers in the former townsite area are occupied by RMGC employees (ref. 1 and Appendix I).

ORNL-Photo 0528-79

Fig. 1. Aerial photograph of the Slick Rock sites. Source: EG&G, Inc.

2.2 North Continent Site

The NC mill was operated from 1931 to 1943 for production of radium and vanadium. Uranium recovery operations also were conducted briefly at this site. The mill was built by the Shattuck Chemical Company in 1931, but ownership or control was acquired by North Continent Mines in 1934; Union Mines Development Corporation in 1945; U. S. Government in 1949; and Union Carbide Corporation in 1957. The area owned by Union Carbide includes the townsite, mill site, and tailings pile covering a total area of 65 hectares.

An estimated 33,600 metric tons of ore, averaging 0.28% of U_3O_8 , was processed at the NC mill. The convex-shaped tailings pile covers an area of 1.5 hectares, and it extends to within a few meters of the Dolores River. The estimated ^{226}Ra concentration in the tailings is 784 pCi/g resulting in a calculated inventory of 30 Ci of ^{226}Ra . The tailings pile was stabilized according to Colorado regulations. The pile was contoured, covered with 15 cm of top soil, seeded, and fertilized. Growth on the pile is sparse because of the semi-arid climate of the area.

All buildings formerly on the site have been removed, including most foundations, and the property was fenced and posted.

3. SAMPLING TECHNIQUES AND RADIOLOGICAL MEASUREMENTS

Sampling techniques as well as equipment and methods used for radiochemical analyses of soil samples and radiological monitoring are described in Appendix II, and a description of the technique used to analyze water samples is contained in Appendix III.

4. RESULTS OF MEASUREMENTS

Measurements were made at the Slick Rock sites to determine: (1) background external gamma exposure rates and background radionuclide concentrations in surface soil samples; (2) external gamma exposure rates 1 m above the ground both at the sites and in the area immediately surrounding the sites; (3) the radionuclide concentration in

water samples and in surface or near-surface soil samples; (4) the distribution of ^{226}Ra in tailings piles and other contaminated areas as a function of depth; and (5) particulate radionuclide concentrations in air samples. Direct alpha measurements were made on the surface of the concrete floor of one of the former mill buildings at the UCC site. Because of the short term of the survey and the absence of buildings on the sites, no attempts were made to measure the concentration of radon or radon daughters. Results of the various types of measurements are discussed in separate sections below.

4.1 Background Radioactivity

Knowledge of background external gamma exposure rates and of background concentrations of radionuclides in the surface soil is needed in order to evaluate the extent of spread of tailings from the site and to provide data needed in implementing clean-up procedures.

Locations are shown in Fig. 2 where background measurements were made of external gamma-ray exposure rates 1 m above the ground and surface soil samples were obtained for analysis. Details of the sample sites and the results obtained are displayed in Table 1. These are the same locations used to determine background levels for the Durango site.

The data in Table 1 show a variation in measured values of the background gamma exposure rate 1 m above the ground from 7 to 22 $\mu\text{R/hr}$. The average value of 14 $\mu\text{R/hr}$ corresponds to an annual background dose equivalent of 123 millirems. The average ^{226}Ra concentration in surface soil is 1.5 pCi/g. There is not a good correlation between the direct gamma exposure rate and the ^{226}Ra concentration in surface soil, possibly due to the presence of other terrestrial radionuclides, failure to obtain representative soil samples, and poor measurement statistics resulting from the small amount of activity present.

• BACKGROUND SAMPLE LOCATION AND IDENTIFICATION

Fig. 2. Locations of background external gamma measurements and background soil samples.

Table 1. Background gamma exposure rates and background concentrations of radionuclides in surface soil near Slick Rock, Colorado

Sample location	Description of sample location	External γ exposure rate ^a (μ R/hr)	Nuclide concentration (pCi/g)		
			²²⁶ Ra	²³² Th	²³⁸ U
C01	E side of Hwy 550, 1.6 km N of Colo.-N. Mex. border	15	1.1	1.1	0.4
C02	~8 km S of Montrose, E Side of Hwy 550	14	1.5	1.2	0.5
C03	W side of Hwy 141, ~1.6 km S of Gateway	11	3.4	b	0.9
C04	Junction Hwys 666 & 141, NW side Hwy 141	7	1.9	0.1	0.5
C05	S of I-70 at Colo.-Utah border	7	1.0	b	0.3
C06	S side of Hwy Colo. 41, 2 km E Colo.-Utah border	7	0.5	0.6	0.3
C07	Junction Colo. 172 & County 309, W side 309	10	1.2	b	0.5
C08	Near Hwy 666 at Pleasant View	12	1.2	b	0.5
C09	~45 km S of intersection of Hwys 141 & 145	14	1.6	1.2	0.7
C010	Beside road at Erikson Springs, between Crested Butte and Paonia	13	1.5	b	0.5
C011	W side of Hwy 0.4 km S of Crested Butte	22	1.2	b	0.5
C012	SE side intersection of road at Spur Guest Ranch	19	1.2	b	0.4
C013	S side of Hwy 50 in Sargent Colo.	19	2.2	b	1.2
C014	S side of road at summit of N. Cochetope Pass	17	1.3	b	0.5

Table 1. (Continued)

Sample location	Description of sample location	External γ exposure rate ^a ($\mu\text{R/hr}$)	Nuclide concentration (pCi/g)		
			²²⁶ Ra	²³² Th	²³⁸ U
C015	S side intersection, roads to Powderhorn & Lake City	13	1.3	<i>b</i>	0.5
C016	Hwy between Powderhorn & Lake City, Big Blue turnoff	14	1.4	<i>b</i>	0.6
C017	~450 m above Big Blue Mesa Dam Reservoir	18	0.9	1.5	0.5
C018	SW side Hwy 145 at Placerville 300 m west of intersection	15	0.85	<i>b</i>	0.4
C019	N side Hwy 90 at Utah-Colo. border	15	1.6	<i>b</i>	0.7
Average		14	1.5	1.0	0.6

^aOne meter above the ground.

^bBelow detection limits.

4.2 Direct Gamma Exposure Rates

Measurements were made of direct gamma-ray exposure rates 1 m above the ground using the "Phil" gamma-ray dosimeter described in Appendix II. These measurements at both Slick Rock sites were made, in general, at 23-m (25-yd), 46-m (50-yd), or 91-m (100-yd) intervals; but topographic features and natural boundaries, such as the Dolores River, resulted in irregular measurement intervals in some places. Measurements were also made above locations where dry-wash sediment samples were obtained.

Gamma exposure rates measured at the UCC site are displayed in Fig. 3, while results of measurements at the NC site are shown in Fig. 4. The UCC data in Fig. 3 indicate moderately low gamma exposure rates throughout the area with a maximum of 97 $\mu\text{R/hr}$. The average for the tailings area is 31 $\mu\text{R/hr}$. There is little difference in the general level of gamma exposure above the tailings area and in the other areas covered by the survey. The lowest gamma exposure rate observed was 8 $\mu\text{R/hr}$. While the measurements in Fig. 3 reflect widespread, low-level contamination, the maximum gamma exposure rate (14 $\mu\text{R/hr}$) in the vicinity of the gas sweetener plant and the housing area is equal to the average area background value (14 $\mu\text{R/hr}$) in Table 1.

The gamma exposure rates observed at the NC site (Fig. 4) are markedly higher than at the UCC site. Although the average gamma exposure rate above the tailings pile (52 $\mu\text{R/hr}$) is low compared to that observed at many other inactive uranium mill sites, other parts of the site show exceptionally high exposure rates. Especially notable was the area southwest of the tailings pile, between the toe of the bluff and the Dolores River, where a maximum gamma exposure rate of 2700 $\mu\text{R/hr}$ was observed. There appeared to be a dry wash leading into the area from the former mill area, but the authors believe that liquid plant wastes may have been discharged here. The soil in this vicinity exhibited coloration characteristic of vanadate salts. For continuous occupancy, the maximum exposure rate of 2700 $\mu\text{R/hr}$ corresponds to an annual dose equivalent of 23 rem but, as noted in Sect. 2, access to

Fig. 3. External gamma exposure rates 1 m above the ground at the Slick Rock, Union Carbide site. Original photo by EG&G, Inc.

Fig. 4. External gamma exposure rates 1 m above the ground at the Slick Rock, North Continent site. Original photo by EG&G, Inc.

this area was restricted. Measurements made along the river bank near the tailings pile were only slightly above the minimum readings, showing little if any transport of tailings to the river.

The average gamma exposure rate on the NC tailings pile was 52 $\mu\text{R/hr}$ with a maximum of 190 $\mu\text{R/hr}$. The rates measured outside the fence surrounding the tailings pile were significantly above background levels, especially along drainage areas. In the far southwest corner in Fig. 4, miscellaneous debris from plant operations were observed. This presumably was the source of the two high exposure rates seen in this area (730 and 270 $\mu\text{R/hr}$).

As was true in the case of background measurements discussed previously, there was not a good correlation between above-ground gamma measurements and the ^{226}Ra concentration in dry-wash sediment samples discussed below. This may possibly be due to the discrepancy between the depth at which the samples were taken and the depth at which the contamination was located. Other gamma measurements made by FE&DU personnel in the vicinity of the Slick Rock sites have been reported.¹

4.3 Radionuclide Concentrations in Surface Soil and Sediment Samples

Analysis of soil and sediment samples for ^{226}Ra and its daughters supplements measurements of above-ground gamma exposure rates in detecting the spread of uranium tailings or uranium ore particles. Surface and near-surface soil and sediment samples were analyzed for ^{226}Ra by use of the technique and equipment described in Appendix II. Results are displayed in Table 2 for the UCC site and in Table 3 for the NC site. Locations of samples are shown in Figs. 5 and 6 for the UCC and NC sites, respectively.

The data in Table 2 confirm the belief, based on the gamma measurements described in Sect. 4.2, that contamination at the UCC site is widespread but the level of radioactivity in the tailings and area soil was moderately low. The maximum observed ^{226}Ra concentration in surface soil was 52 pCi/g at a location near the northwest edge of the

Table 2. Concentration of ^{226}Ra in soil and sediment samples at the Slick Rock, Union Carbide site

Sample designation	Sample description and location	Concentration of ^{226}Ra (pCi/g)
KCWS6 ^a	Water sediment sample upstream at bridge crossing Dolores River near UCC tailings site	1.7
KCWS7	Water sediment sample 320 m (350 yd) downstream from bridge (site of KCWS6)	1.7
KCWS8	Water sediment 228 m (250 yd) downstream from sample KCWS7	1.5
KCWS9	320 m (350 yd) downstream from sample KCWS8	1.4
KCWS10	411 m (450 yd) downstream from sample KCWS9	1.2
KCWS11	229 m (250 yd) from sample KCWS10	0.8
KCCrE	Traverse west to east with Standard Oil sign at entrance to trailer park, the central point east (CPE)	2.0
KC100E	91 m (100 yd) east from CP	40
KC200E	183 m (200 yd) east from CP	7.3
KC375E	343 m (375 yd) east from CP	36
KCCPW	Traverse west from and starting at hole 15A in a northwest direction past RMNGC plant	3.3
KC250W	229 m (250 yd) west of CPW	1.3
KC400W	366 m (400 yd) west of CPW	1.5
KCCPN	Traverse north away from pile outside fence; wood gate on north slope of TP serves as control point (CPN)	52

Table 2. (Continued)

Sample designation	Sample description and location	Concentration of ^{226}Ra (pCi/g)
KC150N	137 m (150 yd) north of CPN	3.1
KCCP1S	North to south traverse starting at hole-16A	21
KC100S	Near old foundation just across paved road next to old road	2.8
KCCP2S	North to south traverse starting at base of 1st large concrete footing	41
KC150S	Traverse north to south 137 m (150 yd) starting at base of 1st large concrete footing	17
KC250S	Traverse north to south 228 m (250 yd) south starting at base of 1st large concrete footing	10

^aWater sediment (WS) samples were collected from the Dolores River bed at points shown in Fig. 5.

Table 3. Concentration of ^{226}Ra in soil and sediment samples at the Slick Rock, North Continent site

Sample designation	Sample description and location	Concentration of ^{226}Ra (pCi/g)
KNWS1 ^a	At bridge on Hwy 141 which crosses Dolores River	1.3
KNWS2	46 m (50 yd) upstream from Dolores River bridge on road into NC site	1.1
KNWS3	At bridge on road into NC site	1.0
KNWS4	At AEC marker northwest of fanned out area over tailings	1.6
KNWS5	At end of fence which encloses the west end of tailings pile (TP)	1.6
KN50W	46 m (50 yd) E of river and 46 m (50 yd) S of fence line below TP	2.6
KN125W	114 m (125 yd) west traverse in a washed out area	2.4
KN200W	183 m (200 yd) west traverse along side fence	1.4
KN200S	South traverse 183 m (200 yd) south outside fence along AEC marker line	1.8
KN275S	South traverse 252 m (275 yd) south toward rock cliff	2.4
KNEO	Intersection of 2 dirt roads on site near west end of fence	30
KNE200	183 m (200 yd) east of road intersection	1.6
KNE340	Edge of cliff above river flood plain, 311 m (340 yd) east of road intersection	19
KNDWO	In area with colored soil southeast of TP, between bluff and Dolores River	5800

Table 3. (Continued)

Sample designation	Sample description and location	Concentration of ^{226}Ra (pCi/g)
KNDW1	Surface sediment 4.6 m (5 yd) downstream of AEC marker 1 m from river	2.2
KNDW2	15 cm below surface at same point as KNDW1	0.9
KNDW3	Surface sediment 5 m AEC marker and 10 m from river	3.6
KNDW4	15 cm below surface at same point as KNDW3	0.8
KNDW5	Surface sediment at west end of site near fence and 3 m from river	3.0
KNDW6	15 cm below surface at same point as KNDW5	0.9
KNDW7	Surface sediment 10 m from river at west end of fence	1.1,
KNDW8	15 cm below surface at same point as KNDW7	1.20

^aWater sediment (WS) samples were collected from the Dolores River bed at points shown in Fig. 6.

Fig. 5. Locations and identifications of environmental samples at the Slick Rock, Union Carbide site. Original photo by EG&G, Inc.

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tailings pile, and several samples from the vicinity of the former mill site contained approximately 40 pCi/g. The river bank sediment samples each contained a near-background level of ^{226}Ra . The sediment sample results show little evidence of movement of tailings to the river.

Most of the soil and sediment samples obtained at the NC site contained a low concentration of ^{226}Ra . There was one notable exception to this: one sample from a high radiation area presumably used to dispose of liquid wastes during plant operations contained 5800 pCi/g. This was the highest ^{226}Ra concentration observed at any of the mill tailings sites. The elevated concentration of radium in this area may be related to the fact that early work at this site involved the recovery of radium and vanadium rather than uranium.

4.4 Radiochemical Analysis of Water Samples

Water samples obtained at locations shown in Fig. 5 for the UCC site and in Fig. 6 for the NC site were analyzed by use of the technique described in Appendix III. Results for both sites given in Table 4 show a rather small range of ^{226}Ra concentrations (0.9 to 2.2 pCi/liter). All values are well below the concentration guide⁸ for drinking water (5.0 pCi/liter for $^{226}\text{Ra} + ^{228}\text{Ra}$).

4.5 Surface Alpha Contamination

Direct measurements of surface alpha contamination were made on the concrete surface of one of the former mill building foundations, using the portable detector described in Appendix II. The range of measured values was 800 to 3000 dpm/100 cm². The average for the nine measurements, 1700 dpm/100 cm², is well below the NRC guideline⁹ for directly measured surface alpha contamination if, as seems likely for this site, the alpha contamination is primarily natural uranium. On the other hand, this alpha activity level is significantly higher than the guideline for ^{226}Ra on surfaces. No measurements were made of removable surface alpha contamination, and unfortunately, it was not possible to determine whether the source was uranium or radium.

Table 4. Concentration of ^{226}Ra in water samples
from both Slick Rock sites

Sample designation	Sample location	Concentration of ^{226}Ra (pCi/liter)
KKW1	At Dolores River bridge on Hwy 141 approximately 1 mi south of entrance to NC site (upstream)	2.7
KKW2	46 m (50 yd) upstream from Dolores River bridge on road into NC site	1.6
KKW3	At bridge into NC site	1.8
KKW4	At AEC marker northwest of fanned out area over tailings	1.7
KKW5	At end of fence which encloses west end of tailings pile (TP)	1.9
KKW6	Edge of tailings on UCC site upstream at county road bridge crossing Dolores River	2.2
KKW7	320 m (350 yd) downstream from bridge	0.9
KKW8	229 m (250 yd) downstream from sample KKW7	2.2
KKW9	320 m (350 yd) downstream from sample KKW8	1.6
KKW10	412 m (~450 yd) downstream from sample KKW9	2.0

4.6 Distribution of ^{226}Ra in Subsurface Soil and Tailings

Holes were drilled, or attempted, at 21 locations at the UCC site, but gamma monitoring data were obtained only at the 16 locations shown in Fig. 7. Similar information for the 11 locations monitored at the NC site is shown in Fig. 8.

Measurements of gamma-rays in these holes as a function of depth were made by FB&OU and ORNL personnel using the apparatus described in Appendix II. Since the subsurface gamma-rays are due primarily to ^{226}Ra and several of its daughters, it is possible to calibrate the instrument and, thus, to convert the gamma-ray measurements to concentration of ^{226}Ra by the method described in Appendix II. The conversion was accomplished and the data were plotted by use of a 9815A Hewlett-Packard desk calculator and a 9871A Hewlett-Packard printer. The available analytical data for samples taken from several holes at known depths were plotted using the same equipment.

The calculated distribution of ^{226}Ra in subsurface soil and tailings at the UCC site is displayed in Figs. 9-12, inclusive, while similar information for the NC site is shown in Figs. 13-15, inclusive. Similar graphs for holes UC5, UC18, NC9, and NC12 are included in another report.¹

Fair agreement is observed between calculated and measured values for ^{226}Ra concentration for holes 5, 6, and 18 at the UCC site and for hole 9 at the NC site. As has been observed in similar comparisons at other sites, the calculated ^{226}Ra concentration in sections of holes where the concentration is low may be too high due to the scattering of gamma radiation from adjacent sections of the hole and, possibly, due to smearing of contaminated soil on walls of the holes through the action of the auger bit.

The data plotted for holes 4, 5, 6, 9, 11, and 18 at the UCC site, which are all located in the tailings area (Fig. 7), show maximum ^{226}Ra concentrations above 100 pCi/g, while hole 10, located between 9 and 11, shows very low concentrations at all depths where gamma measurements were made (0-5 ft). Holes 16 and 19, adjacent to a former set-

ORNL-Photo 3912-79A

Fig. 7. Locations of holes drilled at the Slick Rock, Union Carbide site. Original photo by EG&G, Inc.

ORNL-Photo 4024-79A

Fig. 8. Locations of holes drilled at the Slick Rock, North Continent site.
Original photo by EG&G, Inc.

Fig. 9. Calculated concentration of ^{226}Ra in holes 2, 4, 5, and 6 at the Slick Rock, Union Carbide site. Values noted by circles in holes 5 and 6 represent data from the analysis of individual soil samples.

Fig. 10. Calculated concentration of ^{226}Ra in holes 7, 8, 9, and 10 at the Slick Rock, Union Carbide site.

Fig. 11. Calculated concentration of ^{226}Ra in holes 11, 15, 16, and 17 at the Slick Rock, Union Carbide site.

Fig. 12. Calculated concentration of ^{226}Ra in holes 18, 19, 20, and 21 at the Slick Rock, Union Carbide site. Values noted by circles in hole 18 represent data from the analysis of individual soil samples.

Fig. 13. Calculated concentration of ^{226}Ra in holes 2, 3, 4, and 5 at the Slick Rock, North Continent site.

Fig. 14. Calculated concentration of ^{226}Ra in holes 6, 7, 8, and 9 at the Slick Rock, North Continent site. Values noted by circles in hole 9 represent data from the analysis of individual soil samples.

Fig. 15. Calculated concentration of ^{226}Ra in holes 10, 11, and 12 at the Slick Rock, North Continent site.

ling pond, as well as holes 20 and 21 south of this settling pond, are the only off-tailings locations showing significant subsurface concentrations of ^{226}Ra .

The plots also show that some holes (e.g., 6, 9, and 20) were not drilled deeply enough to reach the background ^{226}Ra concentration.

The data for the NC site (Figs. 13-15, inclusive) show much higher ^{226}Ra concentrations in the tailings pile than at the UCC site, with a maximum in hole 11 of 760 pCi/g. One off-tailings pile location, hole 12, near the toe of the bluff in an area showing high gamma levels, showed a high ^{226}Ra concentration (650 pCi/g) at the surface. The concentration dropped rapidly below the surface and then leveled off at approximately 60 to 80 pCi/g at depths of 0.6 to 2.3 m (2 to 7.5 ft). Hole 4, just south of the tailings pile, also shows a significant level of contamination with a maximum ^{226}Ra concentration of 30 pCi/g at the 0.6 m (2 ft) depth.

4.7 Radionuclide Concentrations in Air Samples

Air particulates were collected on an asbestos fiber filter having a collection efficiency of greater than 99% for particles of 0.3 μm or larger. Air was drawn through the filter by a Staplex high-volume pump.

Three air particulate samples were collected at the UCC site over a period of approximately 250 min. The samples were taken at those locations indicated in Fig. 16, and the results are listed in Table 5. Concentrations of ^{238}U , ^{226}Ra , ^{210}Pb , and ^{230}Th were one to several orders of magnitude lower than their maximum permissible concentration in air (MPC)_a as listed in 10 CFR 20.¹⁰ These values are not assumed by the authors to reflect annual average concentrations due to the relatively short sampling period on a single day.

Although the concentration of radionuclides in air are higher than background concentration,¹¹ they are lower than concentrations observed at other uranium tailings piles.¹² The tailings in Slick Rock (UCC) have been stabilized with a thin, seeded topsoil cover, which probably

Fig. 16. Location of Staplex high-volume air samples at the Slick Rock, Union Carbide site. Original photo by EG&G, Inc.

Table 5. Concentration of radionuclides in airborne particles at the Slick Rock, Union Carbide site

Sample ^a	Date	Sampling time (min)	Radionuclide concentration (fCi/m ³) ^b			
			²²⁶ Ra	²¹⁰ Pb	²³⁰ Th	²³⁸ U
KC-3HV	4-10-76	250	13 ± 2.4	27 ± 27	16 ± 1.4	16 ± 1.5
KC-4HV	4-10-76	243	16 ± 2.3	87 ± 52	19 ± 1.0	20 ± 5.2
KC-5HV	4-10-76	250	27 ± 3.1	51 ± 25	34 ± 1.2	26 ± 3.4
MPC _a ^c			2000	4000	80	3000

^aLocation of sample shown in Fig. 16.

^bIndicated errors associated with these concentrations are two sigma (95% confidence).

^cMaximum permissible concentrations in air (MPC) for unrestricted areas, 10 CFR 20, Appendix B, Table 2, Column 1. Limiting concentrations for the given radionuclides are for the soluble state excepting ²²⁶Ra which is for the insoluble state.

accounts for the near background concentrations of airborne radionuclides.

5. SUMMARY

Results of a radiological survey conducted at the two sites near Slick Rock, Colorado, in April 1976, are presented. Although only a relatively small amount of ore (33 600 metric tons) was processed at the NC site for radium and vanadium recovery, the nature of the operations here resulted in higher concentrations of ^{226}Ra in the tailings than at the UCC site where the mill was operated to produce a concentrate of uranium for chemical processing at another plant and a large fraction of the ^{226}Ra in the raw ore accompanied the uranium concentrate. In addition to the tailings area, an area between a bluff on which the former mill was located and the Dolores River exhibited a high above-ground radiation level (maximum 2700 $\mu\text{R/hr}$) and a high surface-soil ^{226}Ra concentration (5800 pCi/g). This area is believed to have been a liquid disposal location during or following mill operations. The contaminated areas described above are within a restricted access area but an area outside the fence was located that contained contaminated debris from mill operations.

In contrast to the NC site, which exhibited small areas with high levels of ^{226}Ra contamination, the UCC site displayed widespread, low-level contamination. The average gamma exposure rate 1 m above the tailings pile was 31 $\mu\text{R/hr}$, about three times the background rate. A maximum exposure rate of 97 $\mu\text{R/hr}$ was observed outside the fenced area. Low gamma exposure rates were observed in the vicinity of occupied houses and trailers and near the gas sweetener plant operated by the Rocky Mountain Natural Gas Company near the west end of the tailings pile.

Plots are provided showing the calculated concentration of ^{226}Ra in drilled holes as a function of depth below the surface, based on gamma-ray measurements made by FB&DU and ORNL personnel, for 27 holes drilled at the two sites. The data, in general, support the indica-

tions of the extent of ^{226}Ra contamination provided by above-ground gamma measurements and surface-soil analyses. In addition, the data presented graphically show the subsurface distribution of this nuclide. This information is useful in planning remedial action or in the estimation of the cost of removing tailings and contaminated soil.

Concentrations of ^{226}Ra , ^{210}Pb , ^{230}Th , and ^{238}U in airborne particles were above background concentrations reported in the literature; however, they were lower than those concentrations observed at other uranium tailings piles. This was probably due to the vegetated, top-soil cover placed over the tailings to provide stability.

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APPENDIX I

PHASE I

**Report on Conditions of the Uranium Mill Site and Tailings
at Union Carbide Upgrader Site and of the Old North
Continent Site and Tailings near Slick Rock, Colorado**

Site visited May 7, 1974 by

**Stanley A. Mayer, Lucius Pitkin, Inc., (Contractor to USAEC),
Grand Junction, Colorado
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**This Phase I site investigation was conducted
under a cooperative agreement among the Atomic
Energy Commission, the Environmental Protection
Agency and the State of Colorado. The report,
prepared by Lucius Pitkin, Inc., under AEC Con-
tract AT(05-1)912, is reproduced directly from
the best available copy with color photographs
attached to the original report changed to black
and white.**

REPORT ON CONDITIONS OF UNION CARBIDE URANIUM UPGRADER SITE AND TAILINGS
NEAR SLICK ROCK, COLORADO

Introduction

Pertinent information has been accumulated from available records of the AEC, EPA, the States and companies involved. An on-site visit was made to note current conditions, including the millsite and the tailings disposal area, proximity to populated and industrialized areas, present ownership, and whether a need for corrective action exists. It is intended that this report will serve as a basis for determining the necessity of a detailed engineering assessment (Phase II).

This report on the site near Slick Rock, Colorado, was prepared jointly by the AEC, EPA, and the State of Colorado's Department of Health, Division of Occupational and Radiological Health (CDH).

Summary and Conclusions

Union Carbide Corporation operated a uranium-vanadium upgrader in Slick Rock, Colorado, from September 1957 through December 1961. During that time 600,000 tons of ore were processed and approximately 350,000 tons of sand tailings having low level radioactivity, as a result of the upgrading process, remain at the site. This is a sparsely settled semi-arid part of Western, Colorado. The tailings were impounded on a 15.5 acre area adjacent to the Dolores River. After the upgrader was shut down in December 1961 Union Carbide dismantled it, decontaminated equipment, and stabilized the tailings in accordance with Colorado regulations. Additionally, Union Carbide fenced and posted the tailings area as required by the State.

Of the original 360 acres owned by Union Carbide, five acres were disposed of to the Rocky Mountain Gas Company for a gas sweetener plant.

The main concern at this location is the possible contamination of the Dolores River by erosion of the pile through migration of the tailings into the river.

As a result of the site visit and review of available information, it is concluded that the public health and economic impacts of the following actions should be investigated in a further study of this Slick Rock site.

- I. Improve in-place pile stabilization against wind and surface water erosion.
- II. Construct a compacted earthen dike with riprap to more effectively separate the tailings pile from the river.

- III. Examine the millsite and its vicinity to determine the extent of radioactive contamination and arrive at recommendations for decontamination if necessary.

The continued surveillance and maintenance responsibility for the tailings rests with Union Carbide Corporation under a State of Colorado source material license and in accordance with the State's Rules and Regulations Pertaining to Radiation Control, Part VIII.

Location

The Union Carbide Corporation's upgrader site is located near Slick Rock, San Miguel County, Colorado. The site is in Section 25, Township 44 North; Range 19 West, New Mexico Principal Meridian, at 38°02'43" North latitude and 108°54'30" West longitude.

Slick Rock and the upgrader site are located in a small mountain valley approximately nine miles east of the Colorado-Utah border and 25 miles north of Dove Creek, Colorado, on the Dolores River and on the west slope of the Rocky Mountains. The valley floor is at an elevation of 5,440 feet and the surrounding mesas rise to elevations of about 7,000 feet. Aerial Photograph 1.

Ownership

Union Carbide Corporation was the operational owner of the mill, and the site has continued under its surveillance and ownership, with the exception of the five acre tract sold to the Rocky Mountain Gas Company.

History of Operations

The Slick Rock upgrader became operational in September 1957 with a design capacity of 350 tons of ore per day which was later expanded to 500 tons per day. The operation shut down in December of 1961. Ore averaging 0.245 percent U_3O_8 and 1.35 percent V_2O_5 was delivered to the Slick Rock upgrader from the Deremo mine and the mines in the Slick Rock area. All of the ore was trucked to the upgrader and the resultant upgraded material was trucked to the Rifle mill for further beneficiation.

Process Description

Dry grinding and air sizing were used as an initial step to produce a coarse and a slime fraction. The slime fraction constituted the first concentrate. The ground coarse ore fraction was combined with recirculated acid solution and a sand-slime separation then made on the slurry. The sand product was further acid leached, washed and discharged to tailings. The slimes from this step were dewatered and dried as a second

concentrate. A third product resulted from ammonium neutralization of part of the pregnant solution. All three products were shipped to Union Carbide's Rifle mill for further processing. About 60 percent of the uranium was contained in the initial dry fine product and an additional 30 to 35 percent in the other two products. 1/ The sand tailings remaining at the site contained only a small portion of the residual radioactivity.

Present Millsite

Union Carbide owned the surface rights to 360 acres in the Slick Rock area, but sold five acres to the Rocky Mountain Gas Company which has built a gas sweetener plant. This plant is just north of the upgrader site and northwest from the tailings pile, in the Northwest Quarter of the Southeast Quarter, Section 25, Township 44 North, Range 19 West, New Mexico Principal Meridian.

The tailings pile lies on a gentle slope rising towards the west. The base of the pile is on a bench about four feet above the normal water level of the Dolores River. The greater portion of the toe of the tailings pile is approximately 300 feet from the river, however, at the northeast corner, the river and the toe of the pile are separated by only about 35 feet. The pile is cone shaped and rises to a height of 40 feet at the peak with a 5 to 1 slope and covers approximately 15.5 acres.

Further west of the mill is Carbide's commissary, now used as a storage warehouse, the trailer park and superintendent housing which are being used by employees of the gas sweetener plant and Union Carbide. See Figure 1.

The property is fenced with locked gates and is posted in compliance with State regulations. The tailings, estimated at 350,000 tons by Union Carbide personnel, have been stabilized in accordance with plans approved by the State of Colorado. After grading to consolidate and contour tailings (Pre-stabilization Aerial Photograph) and the settling ponds shown in Figure 1, the pile was covered with about 6 inches of soil and seeded. A dike utilizing mine waste material was constructed between the tailings pile and the Dolores River (Photograph 2). A drainage ditch above the upper part of the tailings pile was constructed so that the area drainage does not flow over the pile. The mill buildings have been dismantled, and only the concrete foundations are in evidence (Photograph 3). The vegetation is moderate to sparse as a result of the semi-arid conditions prevailing in Slick Rock (Photograph 4), but it is sufficient to prevent wind and surface water erosion.

Figure 1. Town - and Millsite Layout. Tailings area below settling pond.

Environmental Considerations

On July 12, 1971, a gamma radiation survey utilizing an AEC mobile detection unit under contract to the EPA and in cooperation with the Colorado Department of Health, was made of the Slick Rock upgrader tailings pile and surrounding area. No use of tailings was identified. However, a few locations were found where various radioactive materials were present, including radioactive fire bricks used as walkways in the trailer park. 2/

The surveillance station on the Dolores River at Bedrock, Colorado, below Slick Rock was established in 1961 and data collected on the water quality through June 1972. 3/ During this period the average concentration of Ra-226 was 0.48 pCi per liter. This is well below the protection guideline of 3.0 pCi per liter in drinking water for the general population.

AEC records indicate that 590,000 tons of ore averaging 0.25 percent U_3O_8 were fed to process and 350,000 tons of sand tailings remain at the Slick Rock site. These sand tailings are estimated to contain about one-fifth of the total amount or 140 pCi Ra-226 per gram of sand tailings. On this basis the total Ra-226 content of the tailings pile is estimated to be 70 curies. Had all the Ra-226 reported to the sand tailings, the estimated content would be 370 curies.

Three houses and eight trailers are occupied at the old townsite by employees of the Rocky Mountain Natural Gas Company and Union Carbide. There are two ranches within a half-mile of the tailings pile. The potable water supply is derived from a well in the trailer park. There have been no known removal of tailings for construction or road repair purposes.

At the present time there are approximately 50 people residing in the Slick Rock area. Nearly all are within a half-mile radius. This might increase to 100 with the reactivation of uranium mines in the area. No other industrial development is foreseen.

Meteorology

The climate of the Slick Rock district is semi-arid. Annual precipitation averages 15 to 20 inches at altitudes of 6,500 to 7,000 feet but local measurements indicate that Slick Rock receives 6 to 7 inches.

The prevailing wind direction is from the southwest and would have no influence on the residents of the area.

Hydrology

The tailings pile is located on the present-day flood plain of the northward-flowing Dolores River, whereas the upgrader was located

immediately westward on a gravel terrace which is a remnant of a former flood plain. Maps show that the modern flood plain on the southwest side of the river is about 275 feet wide. At the upstream end of the tailings pile, the river is approximately 750 feet distant from the pile, but when the river swings westward and northwestward again it is laterally and vertically within 100 feet and 10 feet respectively, of the pile. The toe of the tailings pile is subject to inundation and probably erosion at peak flood stages.

The wells supplying potable water to the district are hydraulically upgradient from both this tailings pile and the upstream North Continent pile, referred to in a separate report, and are not likely to contain other than background levels of radioactivity.

Natural seepage of ground-water or precipitation into the tailings is unlikely. The static ground-water level is either at the level of the river or below it. Significant inflow to the river in the reach between Dolores and Redrock is absent, a further indication that the river is either neutral or losing with respect to the ground-water reservoir.

Site Visit

The Slick Rock upgrader site was visited on May 7, 1974, by the following personnel (team) in the company of Robert G. Beverly, Director, Environmental Control, Mining and Metals Division, Union Carbide Corporation and Fred Dedrickson, Operations Superintendent, Mining and Metals Division, Union Carbide Corporation:

Stanley A. Mayer, Lucius Pitkin, Inc., (Contractor to USAEC),
Grand Junction, Colorado
Jon Yeagley, Environmental Protection Agency, Region VIII,
Denver, Colorado,
Don Lambdin, Environmental Protection Agency, Las Vegas, Nevada,
Bert Crist, Colorado Department of Health, Denver, Colorado.

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1. The two Click Rock Sites - July 1974
Approximate Scale - One Inch equals 1,250'

2. Dike formed by mine waste material between tailings pile and Dolores River.

3. Lower right, Dolores River; lower center, Union Carbide Slick Rock tailings pile; right center, Rocky Mountain Gas Sweetener plant; center, millsite; left center, store building, Superintendent's housing.

4. Tailings pile showing sparse vegetation.

REPORT ON CONDITIONS OF URANIUM MILLSITE AND TAILINGS
AT OLD NORTH CONTINENT SITE, SLICK ROCK, COLORADO

Introduction

Pertinent information has been accumulated from available records of the AEC, EPA, the States and companies involved. An on-site visit was made to note current conditions, including the millsite and the tailings disposal area, proximity to populated and industrialized areas, present ownership, and whether a need for corrective action exists. It is intended that this report will serve as a basis for determining the necessity of a detailed engineering assessment (Phase II).

This report on the site near Slick Rock, Colorado, was prepared jointly by the AEC, the EPA, and the State of Colorado's Department of Health, Division of Occupational and Radiological Health (CDH).

Summary and Conclusions

The North Continent mill operated from 1931 to 1943 for production of radium and vanadium from an estimated 37,000 tons of ore processed.

This mill operated very briefly as a uranium recovery facility but the site was included in this study because the site and tailings are radioactive and similar in character to those studied at other locations. It is now controlled by Union Carbide Corporation. All of the mill buildings and buildings related to the mill have been removed from the property and in April 1971 the tailings were stabilized in accordance with Colorado regulations. Additionally, Union Carbide fenced and posted the tailings area as required by the State.

Regarding the site the main concern relates to erosion of the pile and its proximity to the river.

As a result of the site visit and review of available information it is concluded that the public health and economic impacts of the following actions should be investigated in a further study of this Slick Rock site:

- I. Reestablish a six inch soil cover over the areas where this cover is lacking.
- II. Construct a compacted earthen dike with riprap to more effectively separate the tailings pile from the river.

The continued surveillance and maintenance rests with Union Carbide Corporation on the property under the State of Colorado source material license No. SUA-925.

Location

The North Continent Mines, Inc., mill and tailings site is located near Slick Rock, San Miguel County, Colorado. The site is in Section 30, Township 44 North, Range 19 West, New Mexico Principal Meridian, precisely 38°02'30" North latitude and 108°53'30" West longitude. The millsite is located in a small mountain valley approximately 9.5 miles east of the Colorado-Utah border and 25 miles north of Dove Creek, Colorado, on the Dolores River and on the west slope of the Rocky Mountains. The valley floor is at an elevation of 5,440 feet and the surrounding mesas rise to elevations of about 7,000 feet.

Ownership

The property is presently owned by Union Carbide Corporation.

History of Operations

The mill was designed and built in 1931 by the Shattuck Chemical Company of Denver, Colorado, for the extraction of vanadium and radium salts. In 1934 North Continent Mines, Inc., absorbed the interests of Shattuck Chemical Company and continued operations of the plant until early in 1943 when the mill was shut down. An estimated 37,000 tons of ore were fed to process producing about the same amount of tailings. The initial capacity was 10 to 15 tons per day; in the summer of 1942 a rotary kiln roaster was installed and the capacity was increased to 30 tons per day. 1/ Figure 1 shows the millsite as it appeared in 1944.

Ore averaging 0.28 percent U_3O_8 and $\pm$ 3.00 percent V_2O_5 was delivered by truck and mules to the North Continent Mines mill from their company controlled mines within a 10 mile radius.

On the 24th day of February 1945 North Continent Mines deeded the property to Union Mines Development Corporation, a corporation set up by the government for the production of uranium and vanadium ores for the Manhattan Project during World War II. On the 28th day of February 1949 Union Mines Development Corporation deeded this property to the U. S. Government and on the 27th day of November 1957 the U. S. Government deeded to Union Carbide 160 acres which included the North Continent Mines, Inc., townsite, millsite and tailings pile.

Figure 1

Process Description

From 1931 until 1942 a method of acid leaching was used on ore averaging ± 3.00 percent V_2O_5 . In 1942 a rotary kiln roaster was installed and the mill converted to a salt roast process along with the acid leach for the recovery of a V_2O_5 , U_3O_8 and a radium concentrate.

Present Millsite

The site is about a half-mile upstream from Union Carbide's upgrader tailings pile which is covered in another report. The Slick Rock, Colorado, post office is a half-mile to the east.

The radium slimes were stockpiled on the grounds in the area marked "tailings" in Figure 1, and the uranium-vanadium tailings were deposited on the slope between there and the Dolores River.

The tailings cover an area of approximately four acres in a cone shape that rises at a 5 to 1 slope to the level of valley bench from almost river level. (Photograph 1). The toe of the pile is approximately 15 to 75 feet from the edge of the normal river flow.

At the time of the visit, some small localized erosion had occurred and some tailings had been exposed, but none had reached the river. Union Carbide was in the process of making repairs.

Approximately 350 to 400 tons of tailings were removed from the tailings pile, a portion of which was sent to the Slick Rock upgrader and the balance to the Uravan mill for reprocessing. There is no known removal for construction or other purposes.

The property is fenced and posted. The tailings pile was stabilized in accordance with Colorado regulations. The pile was contoured, covered with six inches of top soil, seeded and fertilized; however, the growth is sparse as a result of the semi-arid climate. (Photograph 2). There are no utility lines buried within the tailings pile though the bricks that were removed from the roaster were buried there. The mill foundations, including the foundations of houses, have all been dismantled and the material removed from the site. The site remains under the ownership and surveillance of Union Carbide.

Environmental Considerations

On July 12, 1971, a gamma radiation survey utilizing an AEC mobile detection unit under contract to the EPA and in cooperation with the Colorado Department of Health was performed at the North Continent Mines, Inc., tailings pile and surrounding area. No positive identification of tailings use was made. However, there are a few locations where radioactive contamination

from various materials was found. In Union Carbide's trailer park the anomalies were caused by contaminated fire bricks used as walkways. 2/

One surveillance station on the Dolores River at Bedrock, Colorado, below Slick Rock was established during the period 1961 through June 1972 and data collected on water quality, 3/ and during this period the average concentration of Ra-226 was 0.48 pCi per liter well below the 3.0 pCi per liter the maximum permissible concentration in drinking water for the general population.

Based on an estimated 37,000 tons of ore with an average grade of 0.28 percent U_{308} fed to process and assuming secular equilibrium, the theoretical concentration of Ra-226 is approximately 784 pCi per gram of ore for an estimated total of 30 curies.

There is one ranch house within a quarter of a mile of this site towards the northwest and within 1,000 feet is the adit to Union Carbide's operating Burro mine. At the present time there are approximately 50 people residing in the Slick Rock area, and about 40 live a mile away from the tailings pile. This might increase to about 100 people in the immediate area within the next two years due to reactivated uranium mining. No other industrial development is foreseen.

Meteorology

The climate of the Slick Rock district is semi-arid. Annual precipitation averages 15 to 20 inches at altitudes of 6,500 to 7,000 feet but local measurements indicate that Slick Rock at 5,440 feet only receives 6 to 7 inches.

The prevailing wind direction is from the southwest and blows away from the population.

Hydrology

The North Continent tailings pile is located in approximately the center of the ancestral flood plain of the Dolores River. The flood plain is 0.2 mile wide on the southeast bank of the river and essentially absent on the northwest side, where the edge of the river channel is a cut bank developed in the Salt Wash sandstone member of the Morrison formation (Jurassic). Peak flood stages of the river are expected to cause inundation of the toe of the tailings pile.

The domestic water supply for the Slick Rock area is obtained from two water wells 200 feet deep in the Entrada sandstone (Jurassic). Both wells are hydraulically upgradient from this tailings pile and the Union Carbide upgrader tailings pile located about one-half mile downstream and are therefore not likely to contain other than background levels of radioactivity.

Natural seepage of ground water or precipitation into the tailings is unlikely. The static ground water level is either at the level of the river or below it. Significant inflow to the river in the reach between Dolores and Bedrock is absent, a further indication that the river is either neutral or losing with respect to the ground water reservoir.

Site Visit

The North Continent Mines, Inc. millsite was visited on May 7, 1974, by the following personnel (team) in the company of Robert G. Beverly, Director, Environmental Control, Mining and Metals Division, Union Carbide Corporation and Fred Dedrickson, Operations Superintendent, Mining and Metals Division, Union Carbide Corporation:

Stanley A. Mayer, Lucius Pitkin, Inc., (Contractor to USAEC),
Grand Junction, Colorado,
Jon Yeagley, Environmental Protection Agency, Region VIII,
Denver, Colorado,
Don Lambdin, Environmental Protection Agency, Las Vegas, Nevada,
Bert Crist, Colorado Department of Health, Denver, Colorado.

References

1. Unpublished Supplementary Report on the Property of North Continent Mines, Incorporated, Slick Rock, Colorado, by W. E. Haldane, July 1944.
2. The unpublished results of the community mobile scanning unit by the U. S. Environmental Protection Agency in conjunction with the Colorado Department of Health.
3. Radium-226, Uranium, and Other Radiological Data Collected From Quality Surveillance Stations Located in the Colorado River Basin of Colorado, Utah, New Mexico, and Arizona - January 1961 through June 1972.

AERIAL PHOTOGRAPH OF THE SLICK ROCK NORTH CONTINENT
SITE INCLUDED AS PHOTOGRAPH 1 IN THE SLICK ROCK
UNION CARBIDE CORPORATION SECTION.

1. View looking south, Dolores River in foreground, showing North Continent covered tailings pile.

2. View looking south, North Continent tailings pile, showing erosion and sparsity of vegetation.

APPENDIX II

Soil Sampling Techniques and Radiological Measurements

Soil Sampling and Measurement of Radionuclide Concentration as a Function of Depth in Soil

A monitoring and sampling procedure was established for this project in conjunction with FB&DU to measure the radionuclide concentration in soil as a function of depth. At each site, a set of 15-cm (6-in.) diameter holes was drilled through the tailings and into the subsoil. A polyvinyl chloride (PVC) pipe (7.6 cm o.d.), sealed on one end, was lowered into each hole, and measurements were made of gamma-ray intensities as a function of depth. A 15-cm-long Geiger-Mueller tube shielded with a lead cover containing collimating slits was used for this purpose by lowering it inside the PVC pipe for measurements. Signals from this detector were counted using a portable scaler.¹

After gamma-ray vs depth profiles were determined, the position of the interface between tailings and subsoil was estimated. Once completed, the drilling rig was moved approximately 1.2 m (4 ft), and another hole was drilled to the interface level. Samples of soil core were then collected as a function of depth using a split-spoon sampler (each core section was 0.6 m long).

Most of the penetrating gamma radiation monitored is attributable to ^{226}Ra and its daughters. Therefore, a calibration factor for ^{226}Ra concentration was determined for the collimated gamma-ray probe by comparing the response of this unit (counts per unit time) with a measured value for the radium concentration (picocuries per gram) in several soil samples determined by a gamma-ray spectrometry technique. A least-squares fit of FB&DU data (first probe) from this comparison yields the equation

$$R = 0.528(C - 16)$$

For this case, R is the ^{226}Ra activity in picocuries per gram and C is the observed response of the collimated gamma-ray detector in counts per minute; there were 16 background counts per minute for the gamma-ray detector.

The above expression was useful in estimating the overall distribution of radioactivity in the tailings as well as the total quantity of radium in the tailings area. Surface soil samples were obtained normally by removal of an approximately 3-cm-deep layer of soil from an area of about 25 x 25 cm. The same procedure was used to obtain samples 15 cm (6 in.) below the surface except that the top 15-cm layer of soil was discarded and the sample was removed from the next 3-cm layer.

Each sample was dried for 24 hr at 110°C in order to remove moisture. The samples were then pulverized in a high speed rotary crusher having plates adjusted to provide particles no larger than 500 μm . The soil was dispensed into 25-ml polyethylene vials of the type used for liquid scintillation counting and sealed tightly. A soil sample normally consists of 12 of these vials. The net weight of the group of vials was measured to the nearest tenth of a gram.

The sealed sample vials were stored for a period sufficient to allow attainment of equilibrium between ^{226}Ra and its short-lived daughters. Radon-222, which has a radioactive half-life of 3.8 days, will reach the same activity as its long-lived parent, ^{226}Ra , in about 30 days. The short-lived progeny of ^{222}Rn will have reached equilibrium within the same time. Determination of the activity of any of the daughters in the sample will reflect ^{226}Ra activity. After equilibration of radon daughters, the 12 sample vials (or smaller number) were inserted into a sample carousel or holder (Fig. II-1) that was placed on a Ge(Li) detector for counting as described in the section on gamma-ray spectrometry below.

Field Laboratory Facilities and Equipment

A 20-ft mobile laboratory van was used as a field office and for transporting instruments. This van contained an alpha spectrometry counting system for air samples along with air sampling equipment; a Johnston Laboratory radon monitor complete with Lucas-type flasks and an evacuation manifold; gamma-ray detectors; miscellaneous electronic testing equipment; and standard calibration sources. A trailer-mounted, gasoline-powered 12 kW motor generator, pulled by the van, was used to

ORNL-Photo 2171-75

Fig. II-1. Horizontal mounted Ge(Li) detector system used for counting soil samples (carousel-type sample holder is shown in its counting position).

supply electrical power in remote locations. A voltage stabilizer was used to provide regulated power for instruments.

A second field laboratory used in the project was an 8 x 35 ft air-conditioned semitrailer with running water, tools, and miscellaneous supplies. It served as an instrument calibration facility, office, and workshop. This trailer required electrical power from an external source. During most of this project, the trailer was parked in Grand Junction and was used as a temporary field office.

Gamma-Ray Spectrometry Systems

A Harshaw integral 3 x 3 in. NaI (TI) crystal, a high sensitivity detector, was used to scan all samples for a preliminary estimate of ^{226}Ra activity. This detector was used in a "pickle barrel" type shield, lined with copper and cadmium to shield x-rays. Signals from the crystal were sorted by a computer-based (PDP-11) pulse-height analyzer. The computer was programmed to control all functions of the analyzer and counter, to analyze the data, and to print out a statistically weighted average of the ^{226}Ra activity per unit mass. One advantage of this counting arrangement is that it permits quick sorting; samples can be scanned at the rate of about six per hour (minimum counting period is 5 min).^{*} An energy calibration of the NaI crystal and analyzer was obtained by standardizing with ^{57}Co , ^{137}Cs , and ^{60}Co . An efficiency calibration was obtained through daily counting of a uranium standard[†] (0.05% uranium mixed with dunite, particle size = 500 μm). Radium-226 is in equilibrium with the uranium, and this isotope and its daughters provide a source of gamma-ray lines for calibration.

^{*}The principal reason for using this scanning system was to estimate how much time would be required to count the samples with one of three high resolutions Ge(Li) gamma-ray spectrometers.

[†]Standard uranium sample obtained from the former Atomic Energy Commission New Brunswick Laboratory.

Final data on the concentration of radionuclides in soil samples were determined by counting all samples with one of three high resolution Ge(Li) spectrometers. These high resolution counting systems consist of one horizontally mounted 50-cm³ Ge(Li) crystal positioned on a platform for movement into and out of a lead shield (Fig. II-1), and two vertically mounted detectors (Fig. II-2). The detector systems were used to obtain complete photon spectra of the soil samples. Signals from the horizontal Ge(Li) crystal were routed to a 4096-channel pulse height analyzer and signals from the other two Ge(Li) crystals were routed to two 2688 channel regions of a computer based pulse height analysis system. Samples were counted for periods long enough to evaluate the ²²⁶Ra concentration to a statistical accuracy of $\pm 5\%$ or better. Spectra from the horizontally mounted Ge(Li) detector were recorded on magnetic tape and stored for later analysis using the ORNL IBM computer system.*

The computers were programmed to sort out peaks from ²³²Th daughters including the 909 and 967 keV peaks from ²²⁸Ac, the 239 keV from ²¹²Pb, and the 2614 and 583 keV peaks from ²⁰⁸Tl. These data permitted measurements of the ²³²Th concentration and data are reported for many of the samples.

Energy calibration of the Ge(Li) detectors was controlled through the use of isotopic sources of ⁵⁷Co, ²²Na, ¹³⁷Cs, ⁶⁰Co, ⁸⁸Y, and ⁴⁰K. A calibration check was completed each day prior to beginning sample counting. In order to maintain linearity of the ADC's, a spectrum stabilizer was utilized. This instrument can be adjusted so that two individual photon energies are detected and maintained in two channels at separate ends of the scale. These two calibration points helped maintain an energy span of 1 keV per channel. Efficiency calibration was obtained through the use of the same uranium ore standard samples as for the NaI crystal. An analysis of the counting data was accomplished

*Spectra from the two vertically mounted Ge(Li) detectors were stored on magnetic tape for record purposes, but were analyzed immediately using a Tencomp Model TP-5/11 computer-based analyzer.

ORNL-Photo 6719-76

Fig. II-2. Computer based multichannel analyzer and one of three Ge(Li) counting systems.

through a linear least-squares fitting routine. Net adjusted areas under photo peaks of interest were compared with an extensive radio-nuclide library.² Data from the computer were presented for each radio-nuclide as a weighted mean with standard deviation.

External Gamma-Ray Detector

A gamma radiation survey was made on and around the mill site and tailings pile. The instrument used for these measurements was a "Phil" gamma-ray dosimeter.³ The basic unit was a 15-cm- (6-in.) long 30-mg/cm² glass-walled organic-filled Geiger-Mueller (G-M) tube with an energy compensation shield made of tin and lead. Pulses from this unit were counted with a battery-powered portable scaler. Typically, G-M counters are not used for dosimeters because of a peaked response at low photon energies. However, perforated layers of tin (1.0 mm), and lead (0.1 mm), were used as an energy compensation filter to flatten this peaked response at photon energies below about 200 keV. Sealed sources of ¹³⁷Cs and ²²⁶Ra were used for calibration. It was found that the response of this detector was: 1 mR/hr = 3400 counts/min.

For each gamma-ray-exposure rate measurement, at least three 1-min counts were recorded. The mean of these readings (less instrument background) was used to determine the exposure rate to external gamma rays.

Radon Daughter Sampler*

Radon daughter concentrations were measured with a sampling and counting instrument which has been in use at ORNL for several years,⁴ and it was also used to make some comparative measurements in the remedial action program in Grand Junction.⁵ The filter counter for this sampling device, shown in Fig. 11-3, utilized a modified gas flow alpha

*This section and the following section contain descriptions of devices and methodologies typically used in the radiological surveys of milling facilities. They are included in each report in this series. However, in some instances, the measurements were not possible.

Fig. II-3. System used for measurement of radon daughter concentrations.

counter for housing a 450-mm² silicon diode. Normally, this type detector is operated in a vacuum chamber. However, in this case, it was found that by flowing helium at atmospheric pressure through the assembly, absorption of alpha particles is small relative to absorption in air. Alpha particle pulses were recorded with a 100-channel analyzer. A small ²²⁸Th alpha source standard was used for standardizing the energy scale. Air that was monitored for radon daughters was sampled at a rate of 12 to 14 liters/min. An absolute calibration of the airflow was provided through a comparison of the sampler's mass flow meter and a wet test meter. Samples were normally collected for 10 min, and the first count of the filter was started at 2 min after removal of the sample and continued for 10 min. For this case, a determination was made of the number of counts due to the decay of ²¹⁸Po (RaA) and ²¹⁴Po (RaC'). A second count was started 15 min after removal of the sample and continued for 15 min. In this case, counts were recorded from the decay of ²¹⁴Po. Data from the counter were stored in a pulse height analyzer and reduced by computer. The code for this analysis is explained in detail elsewhere.⁶ Results of the analysis of data using this code were presented as concentrations of RaA, RaB, and RaC'. In addition, a value for the working level concentration was also provided along with an estimate of the error associated with each reported value.

Radon Monitor

The instrument used by ORNL to measure radon concentrations in air consisted of 95-ml Lucas chambers and a readout unit.* Each chamber was evacuated to approximately 1 mm Hg and then opened to atmospheric pressure in the area where a radon measurement was required. No filtration was used for sampled air. The short-lived daughters of radon drawn into the chamber were allowed to decay for 3 to 4 hr prior to counting the flask. Comparison of the results from this instrument and the radon

*LLRC-2 Low Level Radon Counting System manufactured by Johnston Laboratories, Inc., Baltimore, Md.

progeny monitor provided an estimate of the degree of equilibrium between radon and its daughters in the selected locations where air samples were taken.

APPENDIX II REFERENCES

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APPENDIX III

Water Sampling and Analysis

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Water samples are obtained at appropriate points on and around the mill site, labeled and stored for later analysis. Each sample is centrifuged and filtered through a 0.45- μ m filter to remove suspended solids. The samples are then analyzed by radiochemical techniques as described in this appendix.

Procedure for the Sequential Determination of ^{226}Ra , ^{230}Th ,
and ^{210}Pb in Water from Uranium Mill Tailings Sites

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1.0 Radium-226

- 1.1 Filter the ~1.0 liter water sample using a vacuum flask and #42 Whatman filter paper to remove suspended particles.
- 1.2 Reduce the volume of the water sample, to which 10 ml of concentrated HNO_3 has been added, to less than 250 ml by evaporation.
- 1.3 Transfer the solution to a 250-ml, long-neck, tapered-joint, flat-bottom Pyrex boiling flask. Insert a Teflon-coated magnetic stirring bar. Add 37 ml of concentrated HNO_3 to make the final concentration 3M. Insert the modified, female, tapered joint with gas diffuser and side arm with stopcock. Seal off the gas inlet and close the stopcock to assure containment of ^{222}Rn in the flask. Store for at least 30 days to await attainment of ^{226}Ra - ^{222}Rn equilibrium.
- 1.4 Next, connect the 250-ml de-emanation flask to a helium source and the radon trapping system. Attach an evacuated Lucas chamber. Flush the system with helium gas while bypassing the flask. Stop the gas flow. Immerse the unfired Vycor radon concentrator in a liquid nitrogen bath. Be sure the upstream exit for helium gas is open. Start the magnetic stirrer. Open the flask side arm stopcock to the system and start helium gas flowing through the liquid at a rate not to exceed 2.8 liters/hr. The radon-helium stream is dried and stripped of organic condensable components by KOH and ascarite traps. Radon is condensed on the Vycor at liquid nitrogen temperature and thus separated from the helium gas carrier.

- 1.5 Stop the de-emanation process after 30 min. Having shut off the gas flow, close the helium exit. Isolate the radon trap and the evacuated Lucas chamber from the remainder of the system via stopcocks.
 - 1.6 Open the Lucas chamber stopcock and remove the liquid nitrogen from the radon trap to allow the gaseous radon to diffuse into the chamber. To hasten the diffusion, the trap may be gently flamed.
 - 1.7 Bypassing the flask, use a controlled stream of helium to flush residual radon into the Lucas chamber until near atmospheric pressure has been reached. Stop the gas flow and close the stopcock on the Lucas chamber.
 - 1.8 After a delay of 3.0 to 3.5 hr to permit the ^{222}Rn to reach equilibrium with its daughters, place the Lucas chamber over a photomultiplier tube and count the gross alpha for 30 min.
 - 1.9 Subtract the Lucas chamber background, counted under the same conditions, from the gross count. Divide the net count by three to obtain the ^{222}Rn count at that time. Correct the count for time elapsed since de-emanation was terminated and the efficiency of the Lucas chamber for converting alpha discharges to scintillations (~85%). Report the ^{226}Ra in equilibrium with ^{222}Rn as picocuries per liter.
-
- 2.0 Thorium-230
 - 2.1 Transfer one-half of the water sample remaining from the radon de-emanation process (3M HNO_3) to a Pyrex beaker for volume reduction on a magnetic stirrer hot plate.
 - 2.2 Add 0.7 g $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, 2.0 ml (20 mg) Pb carrier, 1.0 ml (20.9 mg) Bi carrier and 5,000 to 10,000 cpm of ^{234}Th tracer to the water sample before reducing the volume to approximately 20 ml.
 - 2.3 Should the sample solution contain undissolved salts, separate liquid and solids by use of centrifuge. Dissolve the

solids by heating with a minimum volume of distilled water or dilute HNO_3 . Combine the dissolved solid with the original supernate. Should silicic acid form in the solution during volume reduction, as evidenced by its deposition on the beaker walls, cool the solution to room temperature and centrifuge. Add an equal volume of concentrated HNO_3 to the supernate. Wash the solids with a small volume (5.0 ml) of 8 M HNO_3 and centrifuge. Combine the wash with the adjusted supernate. Discard the solids. Keep the solution cool in an ice bath during precipitation of hydroxides with an excess of ammonium hydroxide to minimize the formation of silicic acid from dissolved silicates. Let stand 5 to 10 min. Centrifuge, pour off the supernatant liquid, and wash the precipitate with dilute ammonium hydroxide. Discard the supernatant and wash liquids. Dissolve the solids in 10-20 ml of 8 M HNO_3 . Should the solution contain suspended silicic acid, centrifuge, wash the solids with 5 ml of 8 M HNO_3 and combine the supernatant liquids. Discard the solids.

- 2.4 Transfer the 8 M HNO_3 solution to a conditioned Dowex 4 x 1 anion exchange column 5 mm i.d. x 10 cm long (~2.0 ml vol.). The column is conditioned by passing through it at least 5 column volumes (10 ml) of 8 M HNO_3 . The anion-complexed thorium adsorbs on the resin column to the exclusion of the cations. Wash the column with 10 ml of 8 M HNO_3 to remove residual bismuth. Combine the effluent and wash solutions, and save them for lead and bismuth recovery.
- 2.5 Strip the thorium from the column with 5.0 ml of distilled water followed by 10 ml of 6 M HCl .
- 2.6 Convert the chloride to the nitrate by adding an excess of HNO_3 and reducing the solution to near dryness on a hot plate. Dissolve the solids in 5.0 ml of 0.1 M HNO_3 .
- 2.7 Transfer the 0.1 M HNO_3 solution to a conditioned Dowex 50 x 1 mm cation exchange 2.5 mm i.d. x 7 cm long (~0.4 ml vol.). The column is conditioned by passing 5.0 ml 8 M HNO_3 through

- it and then washing it free of excess acid with distilled water as indicated by litmus paper.
- 2.8 Wash the column with 5.0 ml of 2M HCl to remove traces of bismuth and other weakly bound cations.
 - 2.9 Strip the thorium with 5.0 ml of 8M HNO₃ and reduce the volume of the solution to a few drops by evaporation.
 - 2.10 Transfer the solution with a suitable pipette onto a 2-in. stainless-steel disc supported on a hot plate by a steel washer 0.75 in. i.d. x 1.5 in. o.d. Dry slowly to minimize the deposit area at the center of the disc. Fire the disc to red heat with a gas torch to remove carbonaceous materials.
 - 2.11 Determine the thorium yield by counting the ²³⁴Th beta with an end window counter and compare it with a mounting of like count of the ²³⁴Th tracer used in the analysis.
 - 2.12 Determine the ²³⁰Th alpha disintegrations per minute (dpm) by pulse-height analysis using a diode pickup in a helium atmosphere. Compare the counts of ²³⁰Th alpha in the sample with those in a ²³⁰Th standard mounting whose dpm is known.
 - 2.13 To correct for the contribution of ²³⁰Th which may be in the ²³⁴Th tracer, pulse analyze the ²³⁴Th mounting. Subtract the contribution from the tracer after correcting for yield to obtain the net ²³⁰Th content of the water sample.
 - 2.15 Calculations

$$^{230}\text{Th}(\text{pCi/liter}) = \frac{AB}{CDEF},$$

where

- A = Water sample net alpha (cpm)
 B = ²³⁰Th standard (dpm)
 C = ²³⁰Th standard (cpm)
 D = Fraction of ²³⁴Th tracer recovered
 E = Volume of sample (liter)
 F = 2.22 d/(m·pCi)

3.0 Lead-210

- 3.1 Evaporate the Dowex 4 x 1 effluent and wash from Step 2.4 to ~20 ml. Cool and slowly add ammonium hydroxide, while stirring in an ice bath, until hydroxide precipitation barely starts. Add 1 to 2 drops of concentrated HNO_3 to each 10 ml of solution to give an acidity of 0.2 to 0.4 M .
- 3.2 Slowly bubble H_2S through the chilled solution to precipitate metal sulfides. Let the mixture stand 10 to 15 min and centrifuge. Discard the supernate. Wash the sulfides with 5 to 10 ml of H_2S -saturated 0.2 M HNO_3 solution. Centrifuge and discard the wash.
- 3.3 Dissolve the sulfide precipitate in a minimum of concentrated HNO_3 by heating in a hot water bath. Dilute with 5 to 10 ml of distilled water and filter out the suspended sulfur on #42 Whatman filter paper. Wash out the centrifuge tube and filter with 5 to 10 ml of distilled water.
- 3.4 Transfer the solution to a centrifuge tube and precipitate the hydroxides with an excess of ammonium hydroxide. Digest 10 min in a hot water bath. Cool, centrifuge, and wash the precipitate with 5 to 10 ml of dilute NH_4OH . Discard the supernatant and wash liquids.
- 3.5 Dissolve the hydroxides in a minimum of concentrated HNO_3 and dilute to 10 ml. Add 0.5 ml of concentrated H_2SO_4 to precipitate PbSO_4 . Digest 15 min in a hot water bath, cool, centrifuge, and wash the PbSO_4 with distilled water. Save the supernatant and wash liquids for bismuth recovery.
- 3.6 Transfer the PbSO_4 slurry onto a tared #42 Whatman filter paper disc which is supported by the perforated fixed plate of a Hirsch funnel. Dry the PbSO_4 and paper with ethyl alcohol followed by ethyl ether.
- 3.7 Weigh the filter paper and PbSO_4 to determine the yield of ^{210}Pb . Store the $^{210}\text{PbSO}_4$ sample for 30 days to allow the ^{210}Pb to reach equilibrium with its ^{210}Bi daughter. The ^{210}Bi beta is counted in a low-level gas-proportional counter with a

1-mil-thick polystyrene cover to shield out any stray alpha emissions.

- 3.8 Add pellets of NaOH to the bismuth solution from Step 3.5 to precipitate bismuth hydroxide. Digest for 10 min in a hot water bath, cool, and centrifuge. Wash the precipitate with 10 ml of distilled water. Discard supernatant and wash liquids.
- 3.9 Dissolve the solids in a minimum of HNO_3 . Add 3-4 drops of concentrated HCl and dilute to ~40 ml with hot distilled water to precipitate BiOCl . Digest for ~45 min in a hot water bath or until the precipitate has settled.
- 3.10 Pour the hot supernatant liquid through a tared #42 Whatman filter paper supported by a perforated, fixed-plate, Hirsch funnel. Slurry the BiOCl onto the filter paper disc with small portions of hot distilled water. By means of a stirring rod, guide the deposit to the center of the disc. Dry with ethyl alcohol and ethyl ether.
- 3.11 Weigh the BiOCl and filter paper in order to determine yield.
- 3.12 Count the 5.01 day ^{210}Bi beta, which is in equilibrium with ^{210}Pb , in a low-level, gas-proportional counter. The counting efficiency of the counter is determined by counting several similar mountings having known ^{210}Bi disintegration rates, with varying weights of BiOCl from which a calibration curve is constructed.
- 3.13 Refer to the calibration curve and convert cpm to dpm by means of an efficiency factor for the weight of sample in question.
- 3.14 Calculation

$$^{210}\text{Pb} \rightarrow ^{210}\text{Bi}(\text{pCi/liter}) = \frac{AB}{CDEF},$$

where

A = Beta count minus background (cpm)

B = Correction for decay from Pb separation time
to counting time

C = Counter efficiency
D = Fraction of Bi recovered
E = Volume of sample (liter)
F = 2.22 d/(m·pCi)

4.0 Reagents

- 4.1 Aluminum nitrate.
- 4.2 Lead carrier, 10 mg/ml. Dissolved 8.0 g $\text{Pb}(\text{NO}_3)_2$ in dilute HNO_3 and dilute to 500 ml with water.
- 4.3 Bismuth carrier, 20.9 mg/ml. Dissolve 5.225 g bismuth metal in concentrated HNO_3 and dilute to 250 ml with water.
- 4.4 Thorium tracer, ^{234}Th . Pretreat a 30% Adogen 364-Xylene solution by extracting it with an equal volume portion of 2 M HNO_3 for 2 min. Dissolve 5.0 g of recently depleted ^{238}U (as U_3O_8) in 2 M HNO_3 . Extract the thorium and uranium with an equal volume of pretreated 30% Adogen 364-Xylene in a separator flask by hand shaking at least 2 min. Separate phases and strip thorium from the solvent with 10 ml of 10 M HCl . Convert the chloride solution to 2 M HNO_3 solution for a repeat extraction with solvent to remove traces of uranium. The second 10 M HCl strip is again converted to the nitrate for counting the ^{234}Th beta on a stainless steel disc. The mounting should be examined in a pulse-height alpha analyzer for the presence of ^{230}Th . Should the ^{230}Th level be significant, then another source of depleted ^{238}U should be sought, or alternatively extract the ^{234}Th from a batch of ^{238}U from which the thorium had been extracted 1 to 2 months previously.
- 4.5 Ammonium hydroxide, concentrated.
- 4.6 Nitric acid, concentrated.
- 4.7 Hydrochloric acid, concentrated.
- 4.8 Sodium hydroxide pellets.
- 4.9 Sulfuric acid, concentrated.

4.10 Hydrogen sulfide gas.

4.11 Dowex 4 x 1 and Dowex 50 x 1 exchange resins.

5.0 Apparatus

5.1 Radon de-emanation train with radon concentrator* and Lucas chamber.

5.2 Radon photomultiplier counter.

5.3 Modified[†] 250-ml, flat-bottom, boiling flasks.

5.4 Other counting equipment--G-M beta counter; low-level, gas-proportional beta counter; pulse-height spectral alpha analyzer.

5.5 Stainless-steel alpha counting discs.

5.6 Laboratory centrifuge.

5.7 Pyrex centrifuge tubes, 50 ml.

5.8 Beakers, assorted.

5.9 Ion exchange columns.

5.10 Dowex 4 x 1 and Dowex 50 x 1 exchange resins.

5.11 Hirsch fixed plate funnel.

*The radon concentrator consists of a 20-cm-long U-tube constructed from 6 mm o.d. Pyrex glass tubing. Ten centimeters of the U-section is filled with 20 to 40 in. unfired Vycor which has a large surface to volume ratio. When the tube is immersed in liquid nitrogen and radon-laden helium gas passes through the tube, the condensable radon adheres to the Vycor surface. The stripped helium gas exits the system. Upon removal of the coolant the radon vapor diffuses through 10 to 15 cm of capillary tubing to the evacuated Lucas chamber. Flushing the U-tube and attached capillary tubing with 20 to 30 ml of helium transfers essentially 100% of the radon to the Lucas chamber. Since the efficiency of Lucas chambers for counting alphas may vary from 75 to 85%, it is necessary to calibrate each chamber with an equilibrated ^{226}Ra standard solution.

[†]The radium-radon equilibrating flask consists of a flat-bottom 250-ml boiling flask with a female 24/40 tapered joint. A saber-type sintered glass gas diffuser is sealed into a male 24/40 taper joint section so that when it is inserted in the flask it will extend well into the equilibrating solution. A suitable inlet gas connection is provided on the opposite end of the diffuser tube. Onto the shoulder of the male 24/40 joint is sealed a short length of small bore (5 mm i.d.) glass tubing with a glass stopcock terminating with a connector suitable for hooking up with the radon trapping system.