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**Radiological Survey of the
Inactive Uranium-Mill Tailings at
Green River, Utah**

F. F. Haywood
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B. S. Ellis
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**RADIOLOGICAL SURVEY OF THE INACTIVE URANIUM-MILL
TAILINGS AT GREEN RIVER, UTAH**

F. F. Haywood, D. J. Christian, B. S. Ellis,
H. M. Hubbard, Jr., D. Lorenzo, and W. H. Shinpaugh

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RADIOLOGICAL SURVEYS AT INACTIVE URANIUM-MILL SITES

<u>Number</u>	<u>Title</u>	<u>Report No.</u>
1	Assessment of Radiological Impact of the Inactive Uranium-Mill Tailings Pile at Salt Lake City, Utah	ORNL/TM-5251
2	Assessment of the Radiological Impact of the Inactive Uranium-Mill Tailings at Shiprock, New Mexico	ORNL-5447
3	Assessment of the Radiological Impact of the Inactive Uranium-Mill Tailings at Mexican Hat, Utah	ORNL-5448
4	Assessment of the Radiological Impact of the Inactive Uranium-Mill Tailings Piles at Monument Valley, Arizona	ORNL-5449
5	Radiological Survey of the Inactive Uranium-Mill Tailings at Tuba City, Arizona	ORNL-5450
6	Radiological Survey of the Inactive Uranium-Mill Tailings at Durango, Colorado	ORNL-5451
7	Radiological Survey of the Inactive Uranium-Mill Tailings at Slick Rock, Colorado	ORNL-5452
8	Radiological Survey of the Inactive Uranium-Mill Tailings at Gunnison, Colorado	ORNL-5453
9	Radiological Survey of the Inactive Uranium-Mill Tailings at Naturita, Colorado	ORNL-5454
10	Radiological Survey of the Inactive Uranium-Mill Tailings at Rifle, Colorado	ORNL-5455
11	Radiological Survey of the Inactive Uranium-Mill Tailings at Maybell, Colorado	ORNL-5456
12	Assessment of the Radiological Impact of the Inactive Uranium-Mill Tailings at Grand Junction, Colorado	ORNL-5457
13	Radiological Survey of the Inactive Uranium-Mill Tailings at Ambrosia Lake, New Mexico	ORNL-5458
14	Radiological Survey of the Inactive Uranium-Mill Tailings at Green River, Utah	ORNL-5459
15	Radiological Survey of the Inactive Uranium-Mill Tailings at the Spook Site, Converse County, Wyoming	ORNL-5460
16	Radiological Survey of the Inactive Uranium-Mill Tailings at Riverton, Wyoming	ORNL-5461
17	Radiological Survey of the Inactive Uranium-Mill Tailings at Falls City, Texas	ORNL-5462
18	Radiological Survey of the Inactive Uranium-Mill Tailings at Ray Point, Texas	ORNL-5463
19	Radiological Survey of the Inactive Uranium-Mill Tailings at Lakeview, Oregon	ORNL-5464
20	Radiological Survey of the Radioactive Sands and Residues at Lowman, Idaho	ORNL-5465

CONTENTS

	<u>Page</u>
LIST OF FIGURES	iv
LIST OF TABLES	v
ACKNOWLEDGEMENTS	vii
ABSTRACT	ix
1. INTRODUCTION	1
2. SITE DESCRIPTION	1
3. SAMPLING TECHNIQUES AND RADIOLOGICAL MEASUREMENTS	2
4. RESULTS OF MEASUREMENTS	2
4.1 Background Radioactivity	4
4.2 Direct Gamma-Ray Exposure Rates	4
4.3 Radionuclide Concentrations in Surface Soil and Sediment Samples	7
4.4 Radiochemical Analysis of Water Samples	12
4.5 Distribution of ^{226}Ra in Subsurface Soil and Tailings	12
5. SUMMARY	18
REFERENCES	20
APPENDIX I, PHASE I, Report on Conditions of Uranium Mill Site and Tailings at Green River, Utah	21
APPENDIX II, Soil Sampling Techniques and Radiological Measurements	37
APPENDIX III, Water Sampling and Analysis	51

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Aerial view of the Green River site and surrounding area	3
2	Locations of background external gamma measurements and background surface soil samples	5
3	External gamma exposure rates 1 m above the ground	8
4	Locations and identifications of environmental samples	9
5	Locations of holes drilled at the Green River site	14
6	Calculated concentration of ^{226}Ra in holes 1, 3, 4, and 5	15
7	Calculated concentration of ^{226}Ra in holes 2, 6, 7, and 9	16
8	Calculated concentration of ^{226}Ra in holes 10, 11, 12, and 13	17

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Background gamma-ray exposure rates and concentration of nuclides in surface soil samples around Green River, Utah	6
2	Concentration of ^{226}Ra in surface soil and sediment samples at the Green River, Utah, site	10
3	Concentration of ^{226}Ra in water and water sediment samples	13

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RADIOLOGICAL SURVEY OF THE INACTIVE URANIUM-MILL
TAILINGS AT GREEN RIVER, UTAH

F. F. Haywood, D. J. Christian, B. S. Ellis,
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ABSTRACT

The uranium-mill tailings at Green River, Utah, are relatively low in ^{226}Ra content and concentration (20 Ci and 140 pCi/g, respectively) because the mill was used to upgrade the uranium ore by separating the sand and slime fractions; most of the radium was transported along with the slimes to another mill site. Spread of tailings was observed in all directions, but near-background gamma exposure rates were reached at distances of 40 to 90 m from the edge of the pile. Water erosion of the tailings is evident and, since a significant fraction of the tailings pile lies in Brown's Wash, the potential exists for repetition of the loss of a large quantity of tailings such as occurred during a flood in 1959. In general, the level of surface contamination was low at this site, but some areas in the mill site, which were being used for non-uranium work, have gamma-ray exposure rates up to 143 $\mu\text{R/hr}$.

1. INTRODUCTION

This is one of a series of reports on results of radiological surveys of uranium-mill tailings at inactive mill sites in the western United States. A list of all the reports in this series is found at the front of this report. The first four reports and report No. 12 include assessments of potential health effects resulting from radiation and radionuclides from the tailings. The first report 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. The present report on the inactive mill site near Green River, Utah, presents the results of a radiological survey conducted in July 1976 in cooperation with an engineering team from Ford, Bacon and Davis Utah Inc. (FB&DU), 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 this site [by the Environmental Protection Agency (EPA)] have also been published.² The previously unpublished Phase I engineering report on the Green River site by Brown et al. is included in Appendix I. Several publications³⁻⁸ include discussions of the uranium-mill tailings problem and of the assessment of the radiological impact of these tailings.

2. SITE DESCRIPTION

A description of the inactive uranium-mill site near Green River, Utah, and a history of the operations at this site is included in the Phase I report (Appendix I); similar information is furnished in the report by FB&DU.¹ Only a brief summary of this information is included here.

The Green River mill was built in 1958 by Union Carbide Corporation (UCC) and operated by this company until the mill was shut down in 1961. During this operating period, the mill processed 166,000 metric tons of ore with an average U_3O_8 content of 0.29% (Appendix I). The mill product, an "ore concentrate," was shipped to UCC's Rifle, Colorado, plant

for further treatment. Consequently, a large fraction of the radium shipped with raw ore to the Green River plant left with the concentrate. The tailings consist of the acid leached sand fraction, and they cover an area of approximately 3.2 ha (8 acres). The tailings (112,000 metric tons) contain approximately 20 Ci of ^{226}Ra with an average ^{226}Ra concentration of 140 pCi/g. The tailings pile has been graded and covered with soil averaging 15 cm (6 in.) in depth. Dikes have been constructed around the north and east edges of the pile to protect it from run-off water in Brown's Wash. According to a drawing of the plant and mill site layout (Appendix I), a large part of the tailings pile is located in Brown's Wash. In August 1959, a flood washed away approximately 10% of the original tailings pile (Appendix I). An aerial view of the Green River site and surrounding area is shown in Fig. 1.

The tailings are surrounded by a barbed wire fence, and about 15% of the area is reported¹ to be covered with weeds. The uranium-mill equipment was dismantled after production ceased; but the buildings are intact, and the area has been leased by UCC to Celesco, a contractor providing missile testing and assembly services to the U. S. Department of Defense.

3. SAMPLING TECHNIQUES AND RADIOLOGICAL MEASUREMENTS

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

4. RESULTS OF MEASUREMENTS

Measurements were made at the Green River site to determine: (1) background gamma radiation levels and background radionuclide concentrations in surface soil samples; (2) external gamma-ray exposure rates 1 m above the ground both at the site and in the area immediately around the site; (3) radionuclide concentrations in surface soil, sediment, and water samples; and (4) the subsurface distribution of ^{226}Ra in

Fig. 1. Aerial view of the Green River site and surrounding area.
Source: EG&G, Inc.

tailings and contaminated soil. Because of the short term of the survey, no attempts were made at this site by the authors to measure the concentration of radon, radon daughters, or other airborne particulate matter. Results of the various types of measurements are discussed in separate sections below.

4.1 Background Radioactivity

Knowledge of background external gamma radiation levels and of background concentrations of radionuclides in the area 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 exposure rates 1 m above the ground and where surface soil samples were obtained for analysis. Details of the sample sites and the results obtained are displayed in Table 1.

The data in Table 1 show a variation in measured values of the background gamma exposure rates 1 m above ground from 5 to 9 $\mu\text{R/hr}$. The average value of 7 $\mu\text{R/hr}$ corresponds to an annual background dose equivalent of 61 millirems. The average ^{226}Ra concentration in surface soil is 0.7 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.

4.2 Direct Gamma-Ray 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 were made, in general, at 23-m (25-yd), 46-m (50-yd), or 91-m (100-yd) intervals; but man-made features such as fences and buildings resulted in irregular measurement intervals in some places.

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

Table 1. Background gamma-ray exposure rates and concentration of nuclides in surface soil samples around Green River, Utah

Sample point	Description of sample location	External γ exposure rate ^a (μ R/hr)	Nuclide concentration (pCi/g)		
			²²⁶ Ra	²³² Th	²³⁸ U
UT25	Junction of Rt 24S and I-70 ~19 km west of Green River	5	1.0	<i>b</i>	0.3
UT26	On Rt 24S ~21 km south of I-70	7	0.5	0.3	0.2
UT27	End of Twist Gap Road ~16 km east of UT-26	6	0.5	0.6	0.3
UT28	Along Green River ~19 km north of I-70	7	0.8	0.8	0.4
UT29	Entrance of Devils Garden, Arches National Monument	9	0.9	<i>b</i>	0.7
Average		7	0.7	0.6	0.4

^aOne meter above the ground.

^bThis nuclide not measured.

Data obtained at this site are displayed in Fig. 3. The data in Fig. 3 indicate moderately low gamma-ray exposure rates throughout the area with a maximum of 143 $\mu\text{R/hr}$ at the mill site. The average for both the tailings area and the fenced mill site is 25 $\mu\text{R/hr}$. There is little difference in the general level of gamma exposure rate above the tailings area and in the other parts of the site. Off-site measurements of the above-ground gamma exposure rates in Fig. 3 show that 6 $\mu\text{R/hr}$ was reached at approximately 90 m from the edge of the pile toward the east and south. Toward the north, the lowest measurement observed was 12 $\mu\text{R/hr}$ at 60 m from the tailings, the end of the traverse in this direction. In the western direction, the 6 $\mu\text{R/hr}$ exposure rate was reached at 38 m from the edge of the tailings pile while even lower measurements were obtained further west.

The data in Fig. 2 show that there are several locations outside the fenced area (e. g., east and north of the tailings pile and east of the mill site) where exposure rates in the range 90 to 210 $\mu\text{R/hr}$ were measured. Exposure at the higher rate for 2000 hr, a working year, would result in a dose equivalent of 420 millirem. This is below the 10CFR20 guide value for individuals in the general public, but it is higher than other proposed EPA and NRC standards for exposure of members of the public to low level radiation from nuclear fuel cycle activities.

4.3 Radionuclide Concentrations in Surface Soil and Sediment Samples

Analysis of soil and sediment samples for ^{226}Ra supplements the measurement of above-ground gamma intensity in detecting the spread of uranium tailings or uranium ore particles. Surface and near-surface soil and sediment samples obtained at locations shown in Fig. 4 were analyzed for ^{226}Ra by use of the technique and equipment described in Appendix II. Results are displayed in Table 2.

The data in Table 2 confirm the belief, based on the external gamma measurements described in the previous section, that contamination at the Green River site is moderately low. The maximum observed ^{226}Ra concentration in surface soil is 97 pCi/g at a point 366 m south of the

ORNL-Photo 4688-79A

Fig. 3. External gamma exposure rates 1 m above the ground. Original photo by EG&G, Inc.

ORNL-Photo 4688-79B

Fig. 4. Locations and identifications of environmental samples. Original photo by EG&G, Inc.

Table 2. Concentration of ^{226}Ra in surface soil and sediment samples at the Green River, Utah, site

Sample designation	Sample location and description	Concentration of ^{226}Ra (pCi/g)
E200E	Surface soil 183 m east from base of Tailings Pile (TP)	6.5
E400E	Surface soil 366 m east from base of TP	4.6
E600E	Surface soil 549 m east from base of TP	3.2
E200W	Surface soil 183 m west from base of TP	12
E400W	Surface soil 366 m west from base of TP	0.9
E600W	Surface soil 549 m west from base of TP	1.1
E200N	Surface soil 183 m north from base of TP	12
E400N	Surface soil 366 m north from base of TP	4.5
E200S	Surface soil 183 m south from base of TP	32
E400S	Surface soil 366 m south from base of TP	97
E600S	Surface soil 549 m south from base of TP	5.6
E800S	Surface soil 732 m south from base of TP	2.2
EDW1	Surface sediment from dry wash at north-east corner of fence around mill complex	25
EDW2	15 cm below surface at EDW1	15
EDW3	Surface soil from flat dry wash area 23 m west of fence corner around TP	82
EDW4	15 cm below surface at EDW3	9.2
EDW5	Surface sediment from dry wash 46 m west of north fence of bunker area SE of TP	14
EDW6	15 cm below surface at EDW5	3.2
EDW7	Surface sediment from dry pond 27 m east of TP fence	110

Table 2 (Continued)

Sample designation	Sample location and description	Concentration of ^{226}Ra (pCi/g)
EDW8	15 cm below surface at EDW7	48
EDW9	Surface sediment from 300 m NE of pile in dry wash under railroad	0.90
EDW10	15 cm below surface at EDW9	0.94
EDW11	Surface sediment from dry wash at NE corner of TP about 32 m from Hole 6	0.85
EDW12	15 cm below surface at EDW11	1.1
EDW13	Surface sediment from dry wash midway of TP on north side	1.0
EDW14	15 cm below surface at EDW13	1.1
EDW15	Surface sediment from dry wash at NW corner of TP	0.9
EDW16	15 cm below surface at EDW15	1.0
EDW17	Surface sediment from dry wash ~914 m west of pile and due south of sewage pond	0.8
EDW18	15 cm below surface at EDW17	0.9
EDW19	Surface sediment from dry wash 3 m before confluence with Green River	1.2
EDW20	15 cm below surface at EDW19	1.2
EDW21	Surface sediment from dry wash west side of road across from NW corner of fence around mill site below drainage tile	11
EDW22	15 cm below surface at EDW21	9.9
EDW23	Surface sediment from ditch east side of road at NW corner of fence around mill site	11

edge of the tailings pile, indicating that some tailings material has been moved by wind. There are a number of dry-wash gullies around the tailings pile. Surface water run-off into these dry-washes represents one mechanism for tailings migration on the surface. Soil samples labelled EDW-1 through EDW-23 were collected in the dry-washes. Odd-numbered samples represent surface samples and the immediately following even numbered sample was collected at a depth of 15 cm. In most cases, the dry-wash samples were near the area average background concentration. However, most all of the elevated ^{226}Ra concentrations were found in samples within about 50 m from the edge of the tailings. One dry-wash sediment sample from near the east end of the tailings pile (EDW7) contained 110 pCi/g. Two of the river bank sediment samples contained a near-background level of ^{226}Ra , but one contained approximately twice the background concentration. The sediment sample results show little evidence of current movement of tailings to the river.

4.4 Radiochemical Analysis of Water Samples

Water samples from locations shown in Fig. 4 were filtered, and the sediment samples were analyzed using the equipment and techniques described in Appendix II. The filtrate was analyzed by use of the technique described in Appendix III. Results are displayed in Table 3, along with details of the sample locations which are all in the Green River.

The data in Table 3 show that all the samples meet the EPA interim standard⁹ for radium in drinking water (5.0 pCi/liter for ^{226}Ra + ^{228}Ra).

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

Holes were drilled at the 13 locations shown in Fig. 5. Measurements of gamma rays in these holes as a function of depth were made by FB&DU and ORNL personnel using the apparatus described in Appendix II. Since subsurface gamma exposure is primarily due to ^{226}Ra and several of its daughters, it is possible to calibrate the instrument and, thus,

Table 3. Concentration of ^{226}Ra in water and water sediment samples

Sample designation	Sample location	Concentration of ^{226}Ra	
		Soluble (pCi/liter)	Suspended (pCi/g)
EW1	Green River under road bridge west of tailings pile	0.26	1.2
EW2	Green River 46 m upstream from mouth of dry wash	0.24	1.1
EW3	Green River 140 m downstream from mouth of dry wash	0.28	1.8
EW4	Green River 1.6 km downstream from mouth of dry wash	a	1.1

^a No data available.

ORNL-Photo 4688-79C

Fig. 5. Locations of holes drilled at the Green River site. Original photo by EG&G, Inc.

Fig. 6. Calculated concentration of ^{226}Ra (pCi/g) in holes 1, 3, 4, and 5. Values noted by circles in holes 3 and 5 represent data from the analysis of individual soil samples.

Fig. 7. Calculated concentration of ^{226}Ra (pCi/g) in holes 2, 6, 7, and 9.

Fig. 8. Calculated concentration of ^{226}Ra (pCi/g) in holes 10, 11, 12, and 13.

to convert the gamma-ray measurements to concentration of ^{226}Ra by direct comparison between ^{226}Ra concentration and gamma-ray measurements at locations where both quantities have been determined. 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 (excluding hole composite samples) were plotted using the same equipment.

The calculated distribution of ^{226}Ra in subsurface soil and tailings at this site is displayed in Figs. 6-8, inclusive, omitting the plot for hole 8 where none of the measurements exceeded background. Similar graphs for holes 3 and 5 are included in another report.¹

Satisfactory agreement is observed between calculated and measured values for ^{226}Ra concentration for holes 3 and 5, the only holes for which analytical data are available. As has been observed in similar plots of data from other sites, the calculated ^{226}Ra concentration in sections of holes where the concentration is low may be too high due to gamma-ray "shine" from an adjacent section of the hole and, possibly, due to smearing of contaminated soil on walls of the holes through the action of the auger bit, or due to contaminated soil that drops to the bottom of the hole.

5. SUMMARY

The uranium mill at the Green River site was operated for three years to produce an "ore concentrate" that was transported to Rifle, Colorado, for further processing. Consequently, a large fraction of the ^{226}Ra brought to the plant in ore was removed in the plant product leaving sand fraction tailings with a low average ^{226}Ra concentration (140 pCi/g) and a small inventory of this isotope (20 Ci). This material was deposited in a tailings pile covering 3.2 ha (8 acres). The tailings pile has been stabilized, but only a small fraction of it is covered with vegetation. A significant fraction of the tailings pile is located in a dry wash area, but the pile is presently protected by dikes on the

north and east sides. The original mill buildings are intact; they are leased by the owner, Union Carbide Corporation, to Celesco, a government contractor.

Measurements of the external gamma exposure rate 1 m above ground showed moderately low levels throughout the area with an average of 25 $\mu\text{R/hr}$ above the tailings and at the mill site. A maximum measurement of 143 $\mu\text{R/hr}$, in the former mill area, was obtained. The off-site measurements indicate spread of tailings in all directions with near-background levels being reached at distances from approximately 10 to 90 m. Some of the spots showing exposure rates in the range 90 to 210 $\mu\text{R/hr}$ are outside the fenced areas. Analysis of surface soil samples supports the conclusion of limited spread of tailings and data from analysis of dry wash sediment samples helps to define the spread of tailings through water erosion. There is little evidence that, under normal rainfall conditions, significant quantities of tailings currently reach the Green River. However, a flood in 1959 transported approximately 14,000 tons of the tailings.

Gamma monitoring data furnished by FB&DU personnel were used to show the subsurface distribution of ^{226}Ra in the holes drilled in the tailings and other parts of the site. The holes drilled in the tailings pile showed maximum ^{226}Ra concentrations of over 100 pCi/g, but most of the other holes exhibited low levels of near-surface contamination.

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APPENDIX I

PHASE I

Report on Conditions of Uranium Mill Site and Tailings at Green River, Utah

Site visited May 15, 1974 by

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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 Utah. The report, prepared by Lucius Pitkin, Inc., under AEC Contract 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 URANIUM MILLSITE AND TAILINGS
AT GREEN RIVER, UTAH**

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 at Green River, Utah, was prepared jointly by the AEC, the EPA, and the State of Utah's Division of Health, Environmental Health Administration.

Summary and Conclusions

The Green River, Utah, plant was operated by Union Carbide Corporation from March 1958 to January 1961 for the upgrading of ore from the uranium mines at Temple Mountain. The upgraded "ore concentrate" was shipped by rail to Rifle, Colorado, for further processing.

The upgrading plant has been dismantled, but the buildings remain and are leased by Union Carbide Corporation to Celesco, a company which performs some missile assembly and testing functions under contract with the U. S. Department of Defense.

The tailings pile on a lower bench about 200 feet from the plant site is estimated to contain 123,000 tons with an average grade of 0.03 percent U_3O_8 . Because of the nature of the upgrading process, the tailings are almost all sand and the radium content is much lower than in ordinary uranium mill tailings. Union Carbide graded and covered the tailings and natural vegetation is becoming established.

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 the Green River site:

- I. Remove radioactive material from surrounding areas, return it to the tailings pile, and stabilize it.
Evaluate need to decontaminate the millsite.

- II. Increase the stabilizing covering on the pile and contour it across the slope to minimize erosion.
- III. Improve the riprap along Brown's Wash on the north side of the tailings pile and evaluate other steps to reduce possibility of erosion and flood damage.
- IV. Evaluate radioactivity levels in the occupied buildings and millsite enclosure. Recommend corrective actions if indicated.

Location

The site of the Green River uranium ore upgrading plant is at 38°59' North latitude and 110°08'20" West longitude, in Section 15, Township 21 South, Range 16 East, Salt Lake Meridian, about a half mile east of the Green River and a mile east of the town of Green River, Utah, just south of the D&RGW Railroad and nearly a mile south of U. S. Highway 6 and 50. The elevation is about 4,100 feet above sea level.

Ownership

The Green River upgrading plant was built and operated by Union Carbide Corporation and the site and buildings are still owned by Union Carbide.

History of Operations

The Green River plant was operated from March 1958 to January 1961 for the upgrading of ore from the uranium mines at Temple Mountain. During its three years of operation, 183,000 tons of ore averaging 0.29 percent U_3O_8 were fed to process in the Green River plant. The upgraded "ore concentrate" was shipped by rail to Rifle, Colorado, for further processing.

Figure 1 shows the layout of the plant and tailings area.

Process Description

The ore was sandstone loosely cemented with clay and asphaltic material, with part of the uranium intimately associated with the carbonaceous minerals. After crushing and grinding, the ore was screened, with minus 35 mesh material going to flotation and the plus 35 mesh material joining the flotation concentration to form a carbonaceous concentrate. The flotation tailings were separated into sand and slime fractions, the sands were leached with acid, the leached slurry washed, and the spent sands discarded to the tailings area. The recovered slimes and pregnant solution then joined with a portion of the initial slime fraction. Any excess acid was neutralized with ammonia. This mixed product plus the remainder of the primary slimes were then dewatered and dried for shipment to the Rifle plant. 1/

Plant & Mill Site
Layout
UCC GREEN RIVER,
UTAH PROPERTY

Present Millsite

Photograph 1 shows the site as it is now.

The upgrading plant has been dismantled, but the buildings remain and are leased by Union Carbide Corporation to Celesco, a company which performs some missile assembly and testing functions under contract with the U. S. Department of Defense.

The tailings cover an area of about eight acres on a lower bench about 200 feet north of the plant site. (Photograph 2). The quantity of tailings generated by the upgrading plant was estimated to be 137,000 tons, but since some of the material was lost down Brown's Wash toward the Green River during a flash flood the quantity remaining is now estimated at 123,000 tons. Because of the nature of the upgrading process, the tailings are almost all sand, with an average U_3O_8 content estimated to be 0.03 percent.

Environmental Considerations

There are apparently no published radiation surveys of the Green River area. A very cursory survey by this team and preliminary results from a current EPA gamma radiation survey indicate general contamination in the millsite area (roughly 1 mR/hr around the ore weighing station and the ore bin ramp) and across the railroad track, which is about 400 feet north of the tailings pile.

No intentional removals of tailings from the pile are known to have occurred. Past reports of the Federal Water Pollution Control Administration indicate that tailings have been carried both by wind erosion and flood waters (August 1959) into Brown's Wash, which flows to the Green River. Results of samples from the river apparently indicate that Ra-226 concentrations are well within the guidelines. Because of the nature of the upgrading process used here, the Ra-226 concentration in the remaining sand tailings is quite low, about 140 pCi per gram. On this basis the Ra-226 contained in the tailings is about 20 curies.

Celesco has about 25 people working 40 hours per week in the building on the former upgrading plant site. There are storage facilities east of the site which are essentially unmanned and are visited only occasionally. The nearest dwellings are about a quarter mile north of the tailings pile where the White Sands Missile Range has administrative offices and some on-base housing. The village of Elgin is about a half mile northwest of the pile.

Union Carbide Corporation constructed dikes on the east, north and west sides of the tailings pile and it is contained by higher ground on the south. Large rocks were placed on the east dike and part of the north dike to prevent further flood erosion. A diversion pond at the northwest corner is to prevent runoff from the pile from going into Brown's Wash.

The tailings pile was graded and covered with dirt taken from the hillside on the southeast and compacted to a depth of six inches. Some vegetation is becoming established on the soil cover. It was observed that many of the machine tracks on the surface do not parallel the contours but run up and down the slope forming natural erosion channels. (Photograph 2). The pile slopes north toward Brown's Wash and some runoff water erosion has occurred. (Photograph 5). There also appears to be some wind erosion.

The pile is well fenced (Photographs 4 and 7) and adequately posted, though the gates are not locked.

Meteorology

The average annual precipitation is about six inches and the average annual temperature is about 52°F. The prevailing winds are from westerly directions ranging from north-northwest to south-southwest.

Hydrology

Flooding in Brown's Wash has been a problem in the past. Channel improvements to handle floods in excess of 5,600 cubic feet per second would be needed to provide sufficient channel capacity to accommodate runoff without erosion of the tailings. Extensive riprap and possibly channel deepening may be necessary. (Photographs 6 and 7).

Ground water in the area is not expected to be a problem. It is fairly deep and of poor quality and its widespread development is unlikely.

Diversions of potable water from the Green River are upstream from the tailings and not likely to be affected now or in the future.

Site Visit

The Green River site was visited on May 15, 1974, by the following personnel (team) guided by Bernie Lasson of Celesco and Joe Hopkins of Union Carbide Corporation:

Corden T. Brown, Lucius Pitkin, Inc., (Contractor to USAREC),
Grand Junction, Colorado,
Jon Yeagley, Environmental Protection Agency, Region VIII, Denver,
Colorado,
David E. Bernhardt, Environmental Protection Agency, Las Vegas,
Nevada,
Blaine Howard, Utah Division of Health, Salt Lake City, Utah.

References

1. Merritt, Robert C., The Extractive Metallurgy of Uranium, Colorado School of Mines Research Inst., USABC Contract, 1971, pp. 271-273.

2. Aerial view of Green River Site during plant operation.

GREEN RIVER - Union Carbide Corporation

Approximate Scale - one inch equals 360 feet

3. Green River tailings pile, beyond the fence. Brown's Wash and D&RGW railroad in the background. Looking north.

4. Looking southeast from Brown's Wash to northwest corner of fenced tailings area.

5. Brown's Wash. Looking southeast.

Fig. 1. The bank of the river. The top of the bank is on the left.

7. Brown's Wash. Looking west.

1. Riprap in Brown's Wash. Looking N. 100° W.

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

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 (Tl) 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 Tennecomp Model TP-5/11 computer-based analyzer.

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 filler counter for this sampling device, shown in Fig. II-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.

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APPENDIX III

Water Sampling and Analysis

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 3 M. 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 (3 *N* 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 *N* 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 2 M HCl to remove traces of bismuth and other weakly bound cations.
- 2.9 Strip the thorium with 5.0 ml of 8 M 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

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

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 ²²⁶Ra 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.