NUREG/CR-1549

Estimates of Uranium Content and Radon Flux for Uranium Mine Dumps Based on Borehole Radioactivity Logs

Prepared by D. W. Riedel

Kilborn/NUS, Incorporated

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FOREWORD

Table S-3 of the Commission's fuel cycle rule, 10 CFR 51.20(e) is being amended to provide a revised estimate of radon releases associated with the production of uranium fuel for a typical year's operation of a model 1000-MWe LWR nuclear power plant. As a part of the effort to develop new estimates of radon releases associated with uranium mining, Kilborn/NUS, Incorporated, under an NRC contract developed an alternate method of estimating radon releases from the data usually available from mining exploration activities without requiring special field samples and radon analyses. This report describes the method in sufficient detail for others to use it. William E. Thompson was Project Manager for the amendment of the radon value in Table S-3, and questions regarding this report may be addressed to him in care of the Division of Fuel Cycle and Material Safety, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, or at telephone number (301) 427-4211.

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I. SUMMARY

A. Introduction

NUS Corporation, on behalf of the Nuclear Regulatory Commission, recently authorized Kilborn/NUS Inc. to develop a rough estimate of the radon flux levels from uranium mine dumps as part of an effort to revise and update Table S-3, Title 10, Part 51 of the Code of Federal Regulations.

The method employed to obtain these estimates of radon flux makes use of natural gamma-ray borehole logs which are available before the uranium mines are developed. The technique is based on the empirical relationship between the uranium, thorium and potassium contents of the rock, the equilibrium between decay products and the resulting total gamma radiation. The calculations are derived directly from those used in uranium ore reserve estimation and in radon health physics.

The sixteen uranium mining companies who operate most of the mines or who have proposed to develop new mines in the seven major U.S. uranium districts were asked to cooperate in this study. Appreciation is expressed to the seven companies who chose to participate. The uranium districts, companies contacted and data furnished are shown in Table 1. Locations of the nine mines, in existence or proposed, whose dumps we studied are shown in Figure 1.

B. Conclusions

The methods used here have broad applicability in that suites of natural gamma-ray logs are generated during the development of nearly all uranium mines, and are available long before the mine is in operation. The equivalent uranium (eU) data presented here probably vary less than ± 20 percent from true values. The corrected eU data, however, may vary more due to our assumptions regarding average thorium and potassium content. Uranium content (U) was assumed to be equal to corrected eU, adding an additional possible small error factor into the calculations. Other data used, such as E (emanation coefficient) and De/v (effective diffusion coefficient) are less accurately known or more variable in nature. At best these calculations indicate the correct order of magnitude for radon flux; at worst, they may be in error by more than one order of magnitude. In these latter cases we believe that our calculations are conservative in that they tend to portray the higher radon flux conditions.

We conclude that:

1. The average eU content in the nine mine dumps studied is 26 ppm with a range from 16 to 40 ppm. These figures do not include a low-grade ore stockpile at the Schwartzwalder Mine which contains 190 ppm eU. These values are shown in Table 2.

2. The average U content in these mine dumps is 15 ppm with a range from 5 to 29 ppm. These data are calculated by deducting the gamma-ray contributions of the average ^{40}K and ^{232}Th contents in the crust of the earth from the eU data above.

3. The average ^{222}Rn flux calculated for these mine dumps is 4.5×10^{-10} uCi/cm^2-sec with a range from 1.2×10^{-10} uCi/cm^2-sec to 9.2×10^{-10} uCi/cm^2-sec. These figures do not include a low-grade ore stockpile at the Schwartzwalder Mine which yields 1.7×10^{-9} uCi/cm^2-sec.

4. Most important, this work indicates that a useful estimate of the radon emissions from a mine dump can be routinely developed on the basis of data from the natural gamma-ray logs of exploratory holes drilled in advance of the start of mining operations. The radon emission estimates, expressed as Ci ^{222}Rn/acre/year, allow the total radon emission from a dump of a given area to be estimated, ignoring the effects of depth, moisture content and inhomogeniety in the waste dump. The resultant estimates can be expected to be the correct order of magnitude when based on gamma-ray logs for which there is an accurately known conversion-factor (K-factor) to calculate parts per million uranium from the gamma-ray counts per minute.

C. Applicability

The technique we have developed provides a readily-calculated order-of-magnitude estimate of radon gas emissions from uranium mine waste dumps. Since the method utilizes down-hole gamma-ray logs from exploration and development drill holes, the radon emission estimates can be made prior to any actual mining. Estimates can then be incorporated into environmental and licensing applications and reports.

While at present our method provides only an order-of-magnitude estimate of radon emissions due to the several uncertainties involved, the recent commercial availability of down-hole gamma-ray spectrometer (KUT) probes will enable eU data to be obtained which does not have to be discounted for thorium-232 and potassium-40 gamma-ray contributions. Thus a more precise uranium value will be available for use in the radon flux calculations. Further research on the other variables involved (emanation coefficient, diffusion coefficient, etc.) will make it possible to further refine the estimates of radon flux.

At present, the technique suffers from decreasing precision as the calculated eU content (before thorium-232 and potassium-40 deductions) falls to 10 ppm or less. In our calculations, the deduction for thorium-232 and potassium-40 amounted to an equivalent of 11 ppm eU, thus at very low average eU levels, the correction reduces the corrected eU to zero or a negative number which is not valid. The use of spectral (KUT) gamma probes will eliminate the need for any correction of the eU values. The above limitation should be kept in mind when applying the technique, and for waste rock of very low uncorrected eU content, it will probably be necessary, lacking any other pertinent data, to use the uncorrected eU rather than corrected eU value in the radon flux calculations.

TABLE 1

WESTERN U.S. URANIUM PRODUCING DISTRICTS LISTING COMPANIES CONTACTED AND INVOLVEMENT IN THIS STUDY

District	Case	Company	Mine or Deposit	Status	Data Available		
					Gamma-Logs	Waste Dump Plan	Equilibrium Factor
South Texas							
	A	Continental Oil Co.	Unidentified	Operating	yes	yes	yes
	-	Chevron	Panna Maria	Developing	---	---	---
	-	Exxon	Unidentified	?	---	---	---
Wyoming Basins							
Powder River Basin							
	B	Continental Oil Co.	Moore Ranch	Developing	yes	yes	yes
	-	Exxon	Highland Mine	Operating	---	---	---
	-	Kerr-McGee	Smith Mine	Operating	---	---	---
	C	Rocky Mtn. Energy Co.	Bear Creek Mine	Operating	yes	yes	yes
Shirley Basin							
	-	Pathfinder Corporation	Lucky Mc	Operating	---	---	---
Gas Hills							
	D	Pathfinder Corporation	Unidentified	Completed	yes	yes	yes
	-	Western Nuclear	Jeffrey City	Operating	---	---	---
Washakie Basin	E	Urangesellschaft	Poison Basin	Proposed	yes	no	yes
San Juan Basin							
	-	Anaconda Corporation	Jackpile-Paguate	Operating	---	---	---
	F	Continental Oil Co.*	Bernabe	Proposed	yes	yes	yes
	-	Kerr-McGee			---	---	---
	G	Phillips Uranium Corp.	Nose Rock Mine	Developing	yes	no	yes
	-	Western Nuclear	Smith Lake Mine	Operating	---	---	---

TABLE 1 con't

WESTERN U.S. URANIUM PRODUCING DISTRICTS LISTING COMPANIES CONTACTED AND INVOLVEMENT IN THIS STUDY

District	Case	Company	Mine or Deposit	Status	Data Available		
					Gamma-Logs	Waste Dump Plan	Equilibrium Factor
Colorado Plateau							
	-	Atlas Corporation	Moab Area	Operating	---	---	---
	-	Pioneer Uravan	Uravan Area	Operating	---	---	---
	-	Union Carbide	Uravan Area	Operating	---	---	---
Eastern Washington							
	-	Dawn Mining	Midnight Mine	Operating	---	---	---
	-	Western Nuclear	Sherwood Project	Operating	---	---	---
Central Rocky Mountain							
	H	Cotter Corporation	Schwartzwalder Mine	Operating	no*	yes	yes
Other							
	I	Cyprus Mines	Hansen Mine	Proposed	yes	yes	yes

* Furnished production scan and ore-waste probe records

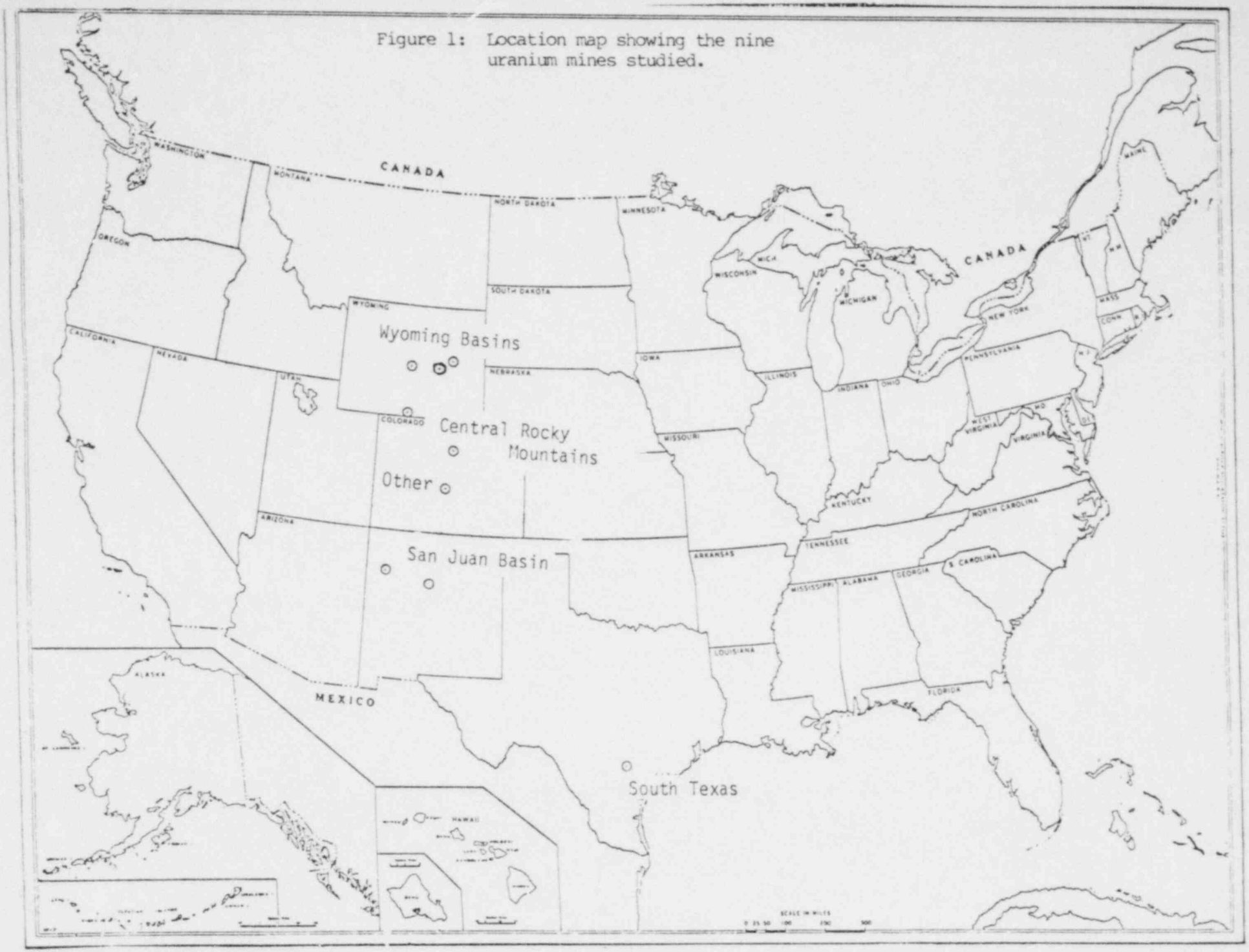


Figure 1: Location map showing the nine uranium mines studied.

TABLE 2

MINE DUMP DATA

Case	Mining method	Uranium Content Equivalent ppm	Uranium Content Corrected ppm[1]	Waste Dumped, tpd	Dump Area, Acres
A	Open Pit	31	20	NA[3]	10.0
B	Open Pit	27	16	16,166	42
C	Open Pit	20	9	45,280	272
D	Open Pit	33	22	101,250	106
E	Open Pit	40	29	NA	NA
F	Underground	18	7	300	2.1
G	Underground	16	5	NA	NA
H	Underground	190[2]	180	103	2.1
I	Open Pit	26	15	129,395	1066
		Ave. = 26	Ave. = 15		
	Open Pit	Ave. = 30	Ave. = 19		
	Underground	Ave. = 17	Ave. = 6		

Notes:

1) Estimated as eU - (^{40}K + ^{232}Th); See Discussion

2) Low grade ore; not included in calculation of mine dump average

3) Not Available

TABLE 3

SUMMARY OF CALCULATED RADON FLUX FROM MINE DUMPS

	Variables Used in Calculations				Calculated Radon Values		
Case	Uranium Content (U), ppm	Density, g/cm^3	Emanation Coefficient[1] (E)	Radon Concentration (uCi/cm^3)	uCi/cm^2-sec.	Ci/acre-year	Total Ci/year
A	20	2.0	0.2	1.3×10^{-5}	3.8×10^{-10}	0.49	4.9
B	16	2.0	0.6	1.1×10^{-5}	9.2×10^{-10}	1.17	49.1
C	9	2.0	0.6	5.9×10^{-6}	5.2×10^{-10}	0.66	179.5
D	22	2.0	0.2	1.5×10^{-5}	4.2×10^{-10}	0.54	68.0
E	29	2.0	0.3	1.9×10^{-5}	8.3×10^{-10}	1.06	NA[4]
F	7	1.7	0.3	3.9×10^{-6}	1.7×10^{-10}	0.22	0.5
G	5	1.7	0.3	2.8×10^{-6}	1.2×10^{-10}	0.16	NA
H^3	180	2.0	0.1	1.2×10^{-4}	1.7×10^{-9}	2.20	4.6
I	15	1.6	0.2	7.9×10^{-6}	2.3×10^{-10}	0.29	309.1
Ave.	15				Ave. 4.5×10^{-10}		

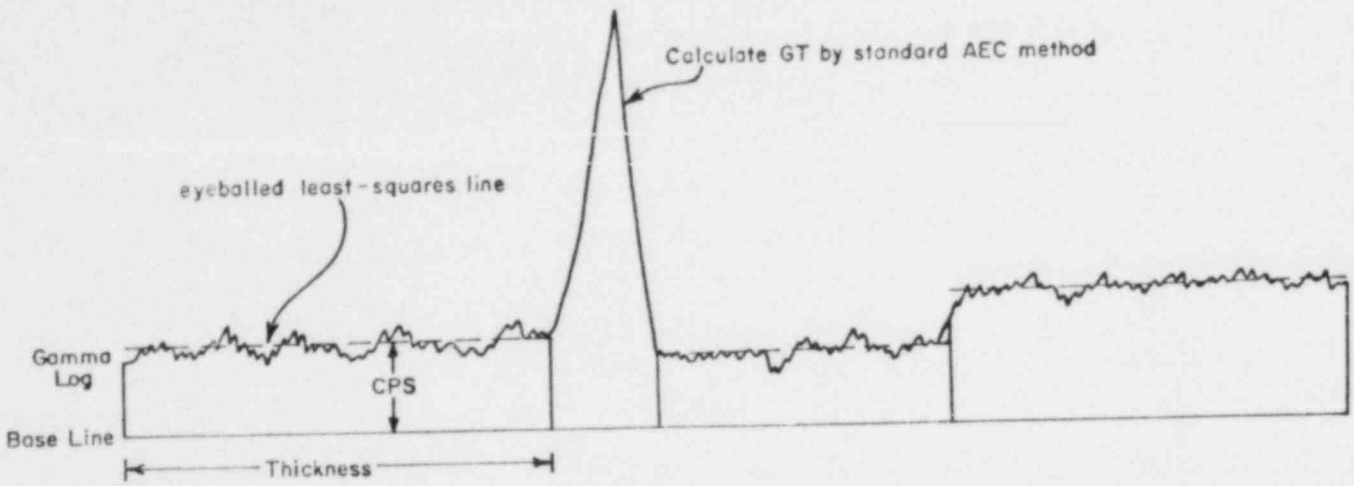
NOTES:

1) From Austin and Droullard, 1978
2) Assume U equals corrected eU
3) Low-grade ore; not included in calculation of mine dump average.
4) Not Available

II. DATA AND CALCULATIONS

A. Methodology

In this study we proposed to estimate the average uranium content in mine dumps from suites of natural gross gamma-ray logs obtained from cooperating mining companies. Uranium content of the waste rock was determined using modifications of the standard AEC method (Scott, et. al., 1960). The gamma-ray log for the waste rock is characterized by low amplitude, with weak peaks and lows. Additionally, a few, relatively thin, high amplitude peaks will usually be present through the waste rock zone. The low amplitude portions of the gamma-ray log can be approximated by least-squares straight lines through zones of relative uniformity. Generally, the least-squares lines will be of zero or near-zero slope, and can be "eyeballed" rather than be calculated. To calculate the equivalent uranium (eU_3O_8) content of the waste rock zone, first the grade-thicknesses (GT) for the low-amplitude zones are determined by calculating the area under the curve using the least-squares line and then multiplying by the probe K-factor and water or mud factor. High amplitude zones are calculated using the standard AEC method. All GT's are summed and then divided by the total thickness to obtain an average grade in percent eU_3O_8 for the waste-rock zone. The average grade, in eU_3O_8, is then converted to ppm and then multiplied by 0.85 to obtain the grade in ppm equivalent uranium (eU). The calculation procedure is illustrated in Figure 2.



Grade-Thickness = GT = kA

A = CPS X Thickness (rectangle)
k = Water (or mud) factor X K-factor

Calculate GT's for all segments, add together and divide by total thickness to obtain average grade (G) of eU_3O_8

FIGURE 2:

ILLUSTRATION OF PROCEDURE FOR CALCULATING AVERAGE URANIUM GRADE FROM GAMMA LOGS

Following the above procedure, several representative drill-hole gamma logs are calculated and averaged together to give an average waste-rock eU grade for the entire mine site. A typical ore zone and waste rock gamma log is given in Figure 3.

Since these eU data reflect gamma-ray contributions from naturally occurring ^{40}K and from ^{232}Th decay products, as well as from the ^{238}U decay products, it is necessary to calculate a "corrected eU" content by making appropriate deductions from the eU value. No down-hole gamma spectral data, which would give an eU content with potassium and thorium decay products already deducted, are available for the mines studied. While airborne gamma-spectrometer data are available for some of the studied areas, it is not likely that these data give a true picture of the uranium, thorium and potassium contents of mine overburden. Surface weathering, with resultant leaching of soluble uranium and concentration of thorium-rich resistate minerals, will alter the airborne gamma-spectrometer data, giving an eU content different from the unweathered rock. Therefore, lacking specific thorium and potassium contents of rocks at the sites studied, we have assumed that the average crustal abundances, 2.6 percent potassium and 10 ppm thorium pertain in all cases. Some areas of Wyoming are known to have on the order of 20 ppm thorium and 3 percent potassium in rocks similar to those overlying uranium deposits in the state but sufficient specific mine-site data is not available.

Data presented in Reference 6, giving relative scintillation crystal response to 1% K, 1 ppm U and 1 ppm Th, were used to estimate the amount of borehole

logging signal that would be equivalent to 2.6% K and 10 ppm Th. This was expressed in terms of ppm eU to be deducted from the uncorrected eU measurements. A detector discrimination threshold of 0.4 MeV was assumed. The results indicate that average crustal values of K and Th are equivalent to 11 ppm U in their borehole gamma signal.

Bore hole gamma probes differ in the sensitivity of their response to ^{40}K, ^{232}Th and ^{238}U decay-series gamma-rays because of differing discrimination thresholds. We do not know the specific threshold levels of gamma probes used to produce the logs used in this study. An optimum threshold is at 0.4 MeV (IAEA, 1976) and data for gamma-ray counting at this level has been used to determine the amount by which the eU values must be discounted to account for the ^{40}K and ^{232}Th decay products. If the probes used actually had a different threshold the correction could range from 8 to 12 ppm U as the discrimination threshold is varied from 0.15 to 0.5 MeV.

Actual calculations of radon flux have been made by methods provided and reviewed by NUS Corporation using data taken from the geologic literature or from our prior experience with uranium mining operations. These data are covered more fully in the DISCUSSION section following.

B. Assumptions

1. All gamma activity recorded on natural gamma logs from boreholes in waste rock comes from ^{40}K, ^{232}Th and ^{238}U

series and can be expressed as eU. From the gamma log, an eU_3O_8 content is first calculated. This number is then converted to eU content by the conversion factor,
1 ppm eU = 0.85 ppm eU_3O_8.

2. The content and radioactivity of ^{226}Ra in waste rock is proportional to its eU content. The appropriate formula to convert eU to Ra(pCi/g) is:

$$Ra(pCi/g) = eU_3O_8 \times 0.28 \ \frac{pCi/g}{ppm(U_3O_8)}$$

or $$Ra(pCi/g) = eU(ppm) \times 0.33 \ \frac{pCi/g}{ppm(U)}$$

3. The ratio U/eU, commonly called the equilibrium factor in the uranium industry, may be locally more or less than 1.0, but for the entirety of any uranium deposit, the average factor is 1.0.

4. The decay products, ^{226}Ra, ^{222}Rn, ^{214}Pb, ^{214}Bi in the ^{238}U decay series are immobile in the borehole in the undisturbed waste rock; i.e., there is no disequilibrium which need be considered when applying the conversion factors above. Borehole logging is generally performed immediately after drilling the hole, so effects of radon migration are minimal.

5. The emanation coefficient, E, for ^{222}Rn in each Uranium District is taken to be as shown by Austin and Droullard, 1978, rounded to the nearest tenth to reflect the scatter in the data. Thus radon emissions from a given uranium content may vary by a factor of 6 according to the E value (.1 to .6) for the particular mining district.

6. The porosities and swell factors for the waste rocks in the several districts are taken from our personal experience with waste rocks seen on dumps previously, or as stated by the mine operators.

7. The sedimentary waste rock in the mine dump is taken to have an average moisture content of 15 percent year-around. The metamorphic waste rock is taken to have no appreciable moisture content.

8. All the waste rock in the mine dumps is assumed here to have the same effective diffusion coefficient, De/v, of 1×10^{-2} cm^2/sec (Tanner, 1964, Blanco et al, 1975).

9. The geometry of all the mine dumps studied is such that the relationships derived from one-dimensional diffusion theory based on solids of infinite thickness are appropriate. Further, the dumps are taken to be homogeneous; internal layering is not considered as a significant factor, and the content of uranium and uranium decay products is assumed to be uniform throughout.

C. Radon Exhalation Rates

The rates of exhalation ^{222}Rn from the surfaces of the mine dumps are calculated by using the formula:

$$J_O = E\left[\frac{De}{v}\right] C_T \left[\frac{\lambda}{De/v}\right] 1/2$$

where J_O = ^{222}Rn flux at the surface

E = Emanation coefficient (fraction of radon escaping the crystal in which it was formed).

De/v = Effective diffusion coefficient = 1.0×10^{-2} cm^2/sec

v = Percent porosity

C_T = Concentration of ^{222}Rn in waste rock in uCi/cm^3

$$= \frac{(ppmU) \quad (.33\ pCi/g/ppm) \quad (density\ g/cm^3)}{1 \times 10^6\ pCi/uCi}$$

λ = Decay constant for $^{222}Rn = 2.1 \times 10^{-6}$ sec^{-1}

D. Sample Calculation

Case A: Continental Oil Co., unidentified mine in South Texas Uranium District.

U = 20 ppm (from Table 3)

Density = 2.0 g/cm^3 (waste rock)

E = 0.2

$$C_T = \frac{(U,ppm)\ (0.33\ pci/g/ppm)\ (density,\ g/cm^3)}{1 \times 10^6\ pCi/uCi}$$

$$= \frac{(20\ ppm)\ (0.33\ pCi/g/ppm)\ (2.0\ g/cm^3)}{1 \times 10^6\ pCi/uCi}$$

$$= \underline{1.3 \times 10^{-5}\ uCi/cm^3}$$

$$J_O = E \left[\frac{De}{v}\right] C_T \left[\frac{\lambda}{De/v}\right]^{1/2}$$

$$= 0.2(1.0 \times 10^{-2} cm^2/sec)\ (1.3 \times 10^{-5}\ uCi/cm^3)\left[\frac{(2.1 \times 10^{-6} sec^{-1})}{1.0 \times 10^{-2} cm^2/sec}\right]^{1/2}$$

$$= \underline{3.8 \times 10^{-10}\ uCi/cm^2\text{-sec}}$$

$$= \underline{0.49\ Ci/acre\text{-}year}$$

If the assumed thorium and potassium contents are increased from 10 ppm Th and 2.6% K to 20 ppm Th and 3% K, the resulting corrected U content would be 14 ppm. The calculated rate of

diffusion would then be:

$$J_o = 2.7 \times 10^{-10} \text{ uCi/cm}^2\text{-sec.}$$
$$= 0.34 \text{ Ci/acre-year.}$$

This is a 29 percent reduction in the calculated rate of emission of radon-222 from the surface, illustrating that the calculated rates of radon emission, based on our assumptions, may be near the maximum values to be expected.

III. DISCUSSION

A. Uranium Geology

Uranium is one of the geochemically scarce metals, making up about 0.00027 percent (2.7 ppm) of the entire crust of the earth and a somewhat smaller percentage of the rocks which can be readily reached by mining. About 99 percent of this crustal uranium is disseminated in the common silicate minerals, either as adsorbed ions on crystal boundaries or as single-atom substitutions for other metals like calcium. The remaining uranium occurs as some 160 uranium minerals, more or less concentrated by the mineralizing processes. Of all of these, the uranium oxides, uraninite, pitchblende and brannerite, and the uranium silicate coffinite make up most of the world's ore reserves.

The known mineable uranium deposits of the United States range widely in size; the largest may exceed 100,000,000 lb. of mineable U_3O_8 while the smallest are well below 100,000 lb. of mineable U_3O_8. The average today is barely above 500,000 lb. of mineable U_3O_8. All of these deposits formed where water removed the uranium from a large volume of rock and concentrated it in a small volume. Most of the processes involved a change in oxidation state of the uranium ions.

B. Uranium Mining

The methods employed in uranium mining are almost entirely dictated by the shape, tonnage, grade and depth of the deposit and the comparative costs of different mining technologies. Initially, in the 1940's and 1950's, most of the uranium mined came from deposits which were exposed in outcrops. If the outcrops were flat-lying or nearly so, open-pit mining methods were used; if the outcrops were in a canyon, underground methods were found to be cheaper. In either case, the realities of costs versus price dictated that much of the uranium deposit was unmined or went to the mine dump as waste rock. Ore grade cut-offs initially were as high as 0.40 percent U_3O_8. Since 1973 the increases in uranium prices have made it economically attractive to mine at much lower cut-off grades and to salvage some of the "waste rock" of earlier mining operations.

According to the Department of Energy (GJO-100, 1977), 289 mines produced uranium in 1976; 214 of these were underground, either conventional or in-situ leach operations. Seventy-five mines were open pit operations; these averaged much larger and produced 52 percent of the year's total uranium. We speculate that, in the future, underground operations will produce most of the uranium.

Open pit mining operations typically begin with a development drilling program which outlines in considerable detail the distribution of thicknesses and grades of the uranium ore, and from these, the total tonnage that can be mined at a profit. This program also develops related engineering data which permits the operator to design a stable, dry pit with haulage roads and mine dumps and stockpiles, and to complete the required environmental impact statements and mine reclamation plans.

Before mining begins the topsoil is stripped and stockpiled for future use in reclamation and the waste rock overlying the ore is stripped and dumped. This rock, called "overburden", may be geologically unrelated to the uranium ore; it may contain only the crustal average of uranium. Since stripping a large open pit mine may involve on the order of 100,000,000 tons of rock, economies of scale are critical: fleets of 100- or 120-ton trucks or self-loading scrapers, assisted by large bulldozer-rippers and power shovels, are commonly used. The waste rock is hauled to dumps and graded to the dump plan or hauled to mined-out open pits and used for back-fill. Additional waste rock, from 5 to 20 percent of the stripped tonnage, is mined at the same time as the ore and also dumped. This rock, called "internal waste", is geologically related to the uranium ore; it contains a variable quantity of uranium ranging from less than the crustal average up to the ore grade cut-off. Indeed, ore grade mineralization which is too thin or too discontinuous to mine efficiently may be dumped as waste but the quantities involved are relatively minute. Since mining of ore involves a smaller tonnage and a separation of the ore from waste rock, smaller equipment is more efficient: 30- or 40-ton trucks, assisted by front-end loaders or backhoes are commonly used. Again, the waste rock is hauled to dumps or mined-out pits; the ore, typically one to five percent of the total tonnage of rock stripped and mined is hauled to stockpiles near the mine or mill.

During the mining phase, maximum attention is given to defining and maintaining ore grades. Mixing of barren rock with the ore, called "dilution", is minimized by careful, repetitive sampling and assaying and by selecting the most appropriate mining methods to separate the rock at the ore-waste interface. Traditionally the ore has been piled in "high-grade ore" and "ore"

stockpiles for blending prior to milling. Current uranium economics dictate that "high-grade", "mid-grade" and "low-grade" ore be separated and stockpiled during mining. The "low-grade" ore consists of rock not rich enough in uranium to repay the total costs of stripping, mining and milling but rich enough to repay the costs of milling and return a profit if the costs of stripping and mining can be accounted for by other ore. Thus "low-grade" consists mostly of mineralized rock that must be moved just to reach other ore. The cut-off grade for "low-grade" ore is now as low as 0.02 percent U_3O_8 at some open pit mining operations and may go lower. The "low-grade" stockpiles may be used for blending for grade control prior to milling or, alternately, may be crushed, stacked on cement pads and heap-leached. In either case, the stockpiles are consumed during the normal life of the mining operations.

Underground mining operations begin with development drilling programs which closely resemble those for open pit operations. However, the mining costs are higher underground than in open pits and so the product of the grades and thicknesses of uranium mineralization which define ore must be higher, commonly by a factor of five or more. This results in a ratio of ore to waste rock that is as much as 100 times higher than for open pits. It also results in fewer tons of ore mined and fewer pounds of uranium produced from otherwise similar deposits. The drilling program also develops related engineering data, but these pertain to vertical and horizontal tunnels, haulage and hoisting facilities, rock support, ventilation, and pumping of groundwater to dry the mine. Haulage roads, mine dumps and stockpiles are of lesser concern because of the smaller quantities of rock involved. Environmental requirements are similarly of lesser concern because of the smaller surface impact.

Before mining begins a complex of vertical and horizontal tunnels must be driven through the rock to drain the groundwater from the ore, to provide ventilation, to provide working faces for the miners and to permit haulage and, commonly, hoisting of ore and waste rock out of the mine. In the early stages of underground development, most of the rock moved is waste; much but not all of this rock is geologically related to the uranium ore; it contains a variable quantity of uranium ranging from less than the crustal average up to the ore grade cut-off. Later, once ore production is established, the quantity of waste diminishes both relatively and absolutely. Only when underground development into new areas resumes does the quantity of waste rock increase again.

C. Calculations

The basis for our eU, U and ^{222}Rn flux estimates is the natural gamma radiation from undisturbed waste rock which is measured by a down-hole scintillometer probe. Radiation from the ^{238}U decay series, principally from ^{214}Pb and ^{214}Bi, is augmented by radiation from the ^{232}Th decay series and the ^{40}K in the rock. This total gamma-ray intensity is converted by empirical formulas to equivalent uranium (eU). The ^{232}Th content of rocks averages 10 ppm and ranges from nearly zero to above 17 ppm; the ^{40}K content averages 3 ppm and presumably varies similarly. Since the K and Th contents of some ores are higher than these average values, our calculations are probably conservative. The efficiency of the scintillometer varies with the energy level of the radiation and with the details of construction, principally the energy discrimination threshold. Calculations based on available data (IAEA, 1976) show that if our average waste rock contains the average amounts of ^{40}K

and ^{232}Th, our average eU content of 26 ppm is equivalent to 15 ppm U; the balance of the radiation is from the ^{232}Th decay series and from ^{40}K. These calculated U values, which are assumed to equal to the "corrected eU" values shown in Table 2, have been used in our radon flux calculations.

For our short-term considerations, the decay products ^{226}Ra, ^{222}Rn, ^{214}Pb and ^{214}Bi in the ^{238}U decay series have been assumed to be in equilibrium in the undisturbed waste rock. ^{226}Ra has such a long half-life (1622 years) relative to its daughter products (3.8 days, 3 minutes and 27 minutes, respectively) that this assumption seems reasonable as well as mathematically essential. However, the radon flux from an undisturbed ore body (and presumably from the surrounding waste rock) has commonly been detected at the surface and as much as 600 feet above. No satisfactory model for emanations from such depth has been published, but pragmatic explorationists continue to use this phenomenon successfully. We believe that some ^{226}Ra and ^{222}Rn may move in the undisturbed waste rock and that the calculated eU and U data may be accordingly too high or too low. There is probably no way of correcting our calculation for this movement since any attempt to measure the movement will probably change the movement. Fortunately, this movement is probably insignificant at the depths that are of concern here.

For our long-term considerations, all the decay products from ^{238}U to ^{214}Pb and ^{214}Bi have been assumed to be in equilibrium in the undisturbed waste rock. On any small scale within any uranium ore body this is not so: U/eU ratios om 0.95 to 1.05 are common; ratios of 0.80 and 2.00 are occasionally found d ratios as low as 0.33 and as high as 7.00 are known. However, these wilder errations probably reflect local and very recent solution and reprecipitation

of uranium within an ore body rather than a pervasive condition. Most company geologists who have studied entire ore bodies in detail have concluded that, overall, the U/eU ratio closely approached 1.0. Thus these local variations when blended on the mine dump, can probably be disregarded for our purposes.

It should be noted that the U/eU ratios mentioned above are commonly based on different measurements and calculations than we have made in our study. The measurements above are made on ore samples, often cores obtained by drilling through the ore zone. These samples are crushed and ground, then subjected to several kinds of analyses: gross gamma, "closed-can" gamma, beta-gamma and fluorimetric uranium analyses are commonly performed. The ratio of the fluorimetrically determined uranium assay to the gross gamma or "closed-can" gamma equivalent uranium yields these U/eU ratios. Calculations based on gross gamma and beta minus gamma measurements can yield a ratio which is roughly comparable to this U/eU ratio. The normal ^{40}K and ^{232}Th content of the ore-bearing rock is insignificant in comparison to the U content and is commonly ignored in these calculations.

Uranium deposits tend to have relatively sharp boundaries, especially in the vertical direction in sedimentary deposits. These deposits are controlled by stratigraphy and can be sharply cut-off above or below by barren rock (See Figure 3). Laterally, these same sedimentary deposits have gradational boundaries, with ore-waste cut-offs determined by assays. Only in the immediate proximity of the ore, therefore, will the overburden have much of a significant increase in uranium and/or decay product content. Boreholes through the overburden do not typically show an increase in uranium content with depth.

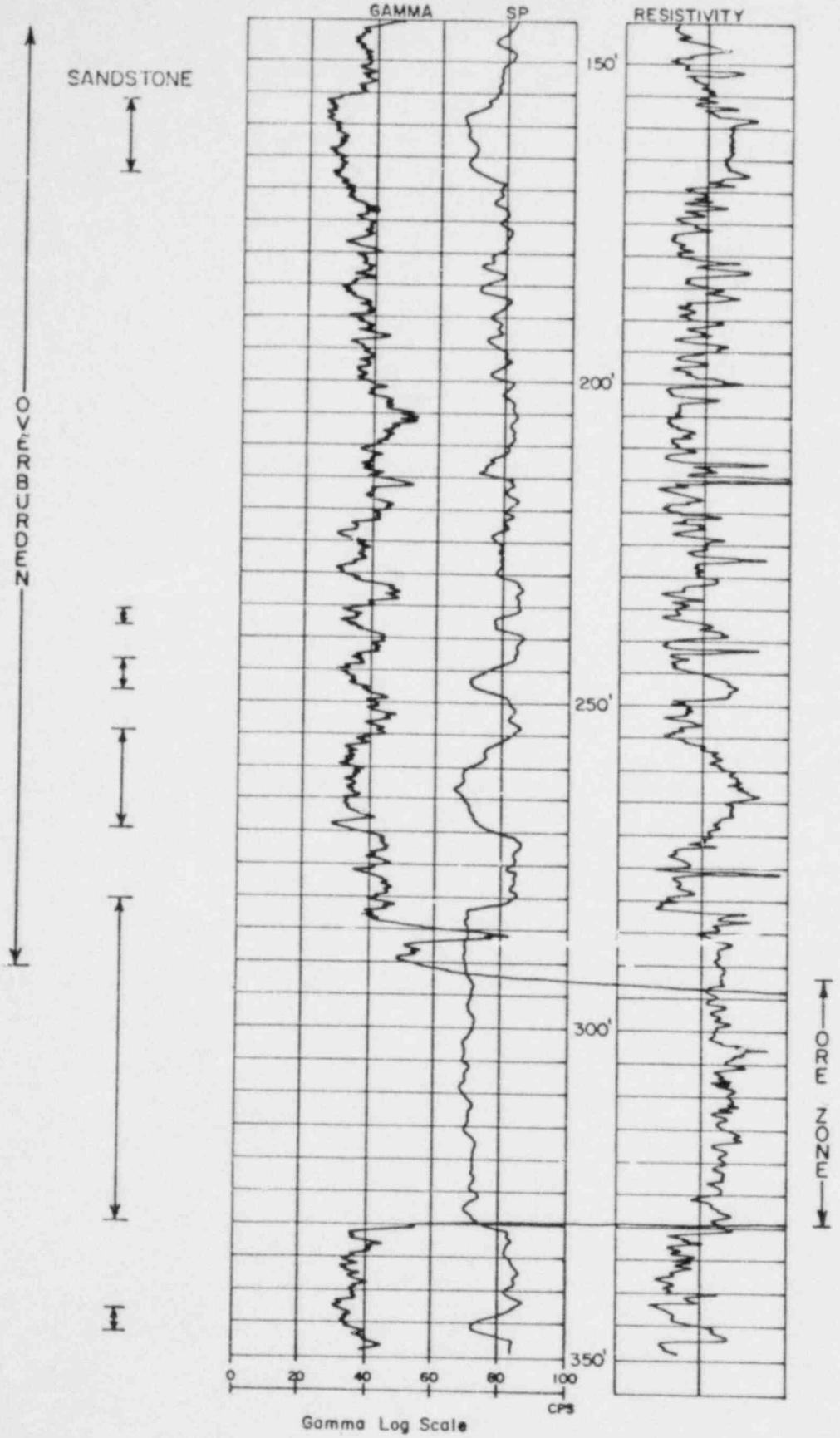


FIGURE 3:
PORTION OF TYPICAL POWDER RIVER BASIN
GAMMA AND ELECTRICAL BOREHOLE LOG

For the bulk of the stripped overburden, there will not be an "inverting of the overburden" problem in regards to uranium content. However, some sub-ore grade material will inevitably end up on the waste dump and internal waste can contain higher than background uranium values. An estimated 5 to 20 percent of stripped rock in an open pit mine can be internal waste, but it is difficult to estimate what percentage will actually have higher than background uranium content. This amount will be subject to specific site geology and mining methods.

The emanation coefficient, E, for ^{222}Rn measured by Austin and Droullard (1978) and used here ranged from .01 to .91 with considerable variation from district to district. We agree that the mode of mineralogic occurrence of the uranium in the samples significantly influences the emanation and speculate that similar variation occurs in the waste rock. Further, there is no assurance that the emanation coefficients from the waste rock in any district will closely resemble that for the ore since the relative abundance of uranium in each mineralogic mode may be substantially different. This variation is a probable source of error; however, the error is likely to be small relative to errors in estimating the effective diffusion coefficient.

The swell factor for broken rock in stopes as given by Peele (1941) is 30 to 50 percent. This is probably appropriate for igneous and metamorphic rocks but not for sedimentary rocks. We speculate that swell is substantially less in sedimentary rocks with high initial porosities; this is in agreement with the data furnished by the mine operators in the Wyoming Basins Districts. Whatever the swell factor may be in the mining process (drilling, blasting and mucking,

or ripping and stripping) it is probably increased by trucking and dumping. After this, however, the effective swell factor is substantially decreased by grading and by compaction by heavy equipment. We speculate that the final swell factor is relatively low, perhaps an average of 20 or 25 percent for all the sedimentary waste rocks. Such figures have been used in our calculations. Any errors introduced here are likely to be small relative to errors in estimating the effective diffusion coefficient.

The rock on the mine dump probably varies substantially in its moisture content, in part due to alternate precipitation and during, but also because of its clay content. Clays, particularly those in the montmorillonite group, adsorb and hold water efficiently. Since the mine dumps are commonly crudely stratified, layers of clay are probably common. If such a layer is at or near the bottom, a perched water table may be created within the dump; if such a layer is near the top, it may impede both downward percolation and upward capillary movement of water. In the one case examined, the metamorphic waste rock was notably lacking in fines; indeed, fragments below 2 inches average diameter were lacking because of the ore/waste sorting process. Such a dump should drain and dry immediately after a rain. We believe the average dump retains substantially more than 15 percent moisture year around. Thus our E values are likely to be conservative.

The effective diffusion coefficient, De/v, is probably the least reliable estimate in these data and calculations. This factor is probably sensitive to variations in several geologic factors, but we see no good way of evaluating these variations without a complete field study. In particular, we believe that polarized water molecules, oriented in layers around montmorillonite clay

particles may reduce the effective porosity substantially, and thus reduce the effective diffusion coefficient. On a larger scale these clays may form layered discontinuities in the mine dumps of sandstone uranium deposits. Such a layer should have low porosity and permeability and should substantially impede the upward diffusion of ^{222}Rn. We have not considered these reductions in De/v in our calculations since they are not known to apply to all cases. Thus we believe the value used here, 1×10^{-2} cm^2/sec, is conservative for most dumps.

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In exploratory drilling to locate uranium deposits, borehole logs of gamma radiation from naturally radioactive elements are utilized to indicate the presence of uranium and the concentrations in which it is found at various depths. This report describes a method of utilizing borehole log data to estimate uranium concentrations in the rock surrounding or overlying uranium deposits and to predict radon releases from waste rock brought to the ground surface in mining operations. The method can be used to predict radon releases before mining operations are started so that potential environmental impacts can be evaluated. The estimates of uranium concentration are generally within 20 percent of true values after correcting for concentrations of naturally radioactive thorium and potassium in the normal range; variations in emanation coefficients and diffusion rates for radon can introduce errors in radon flux estimates, but the estimates should be the correct order of magnitude in most mining regions.

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Radon, radon flux, uranium mining, open pit mining, underground mining, overburden, waste rock, dumps, environmental impacts, borehole logs, exploratory drilling.

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