POOR ORIGINAL

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING APPEAL BOARDS

In the Matters of	
PHILADELPHIA ELECTRIC COMPANY *et al*. (Peach Bottom Atomic Power Station, Units 2 and 3)	Docket Nos. 50-277 50-278
METROPOLITAN EDISON COMPANY *et al*. (Three Mile Island Nuclear Station, Unit 2)	Docket No. 50-320
PUBLIC SERVICE ELECTRIC AND GAS CO. (Hope Creek Generating Station, Units 1 and 2)	Docket Nos. 50-354 50-355
ROCHESTER GAS AND ELECTRIC CORPORATION *et al*. (Sterling Power Project, Nuclear Unit 1)	Docket No. STN 50-485

TESTIMONY OF MORTON I. GOLDMAN

I. Introduction.

In a Decision dated September 10, 1979 (ALAB-562), the Appeal Boards in this proceeding granted summary disposition of a number of the alleged deficiencies claimed by the intervenors to exist in the *Perkins* record regarding radon-222 emissions attributable to the mining and milling of uranium fuel. The Appeal Boards, however, declined to grant summary disposition with respect to twelve of the alleged deficiencies and set them for an evidentiary hearing. My testimony[1] will address these

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[1] I was a witness in the *Perkins* proceeding and submitted

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twelve alleged deficiencies; since the Appeal Boards grouped them in five general areas (emissions from mill tailings piles, from underground mines, from open-pit mines, from water pathways, and from phosphate residue processing), I will follow the same format in the sections that follow.

II. Emissions from Tailings Piles.

The Appeal Boards have identified a number of issues relating to emissions from mill tailings piles. The issues fall into three general areas, the first of which includes the accuracy of the value assigned by the Staff to the emissions from uncovered tailings piles (Alleged Deficiency No. 10), as well as the effect that the area of the tailings piles and the ore grade would have on radon released per annual fuel requirement ("AFR"), including the effect of ore grade on the fraction of uranium recovered in the milling process (Alleged Deficiency Nos. 14 and 17). The second area deals with the question of stability of the tailings piles, considering erosion and tails migration (Alleged Deficiency Nos. 13, 14 and 21); the third area deals with the ability to verify the degree of compliance with the guideline values for radon emission rates (Cf. Alleged Deficiency Nos. 13, 16).

(continued)
an affidavit herein in support of the Licensees' Joint Motion for Summary Disposition of Radon Issues. A statement of my professional qualifications was attached as Exhibit "A" to that affidavit.

A. Emissions from uncovered (unstabilized) piles.

1. Radon diffusion through a tailings pile.

In dealing with the first general area, that is, the rate of radon emissions from uncovered tailings, I have performed a series of calculations to examine (over a broad range of variables) the radon exhalation from uncovered tailings in order to provide a perspective on past and current estimates of such exhalation from mill tailings piles. There are a number of variables that enter into this calculation. They include:

a. the radium concentration, which is related to the ore grade;

b. the porosity and bulk density of the tails;

c. the diffusion coefficient for radon through the mass of tailings which, in turn, is related to porosity and moisture content;

d. the emanating power of the tailings particles;

e. the volume of tailings per unit of U_3O_8 recovered, which is related to ore grade and milling recovery fraction; and

f. the area-depth relationship for the tailings pile.

Depending upon the particular choice of variables, exhalation rates per annual fuel requirement can be calculated to vary over more than one order of magnitude.

The basic relationship for radon diffusion through a tailings pile is given in equation (1), which is derived from Reference [1]:[2]

$$J = \left(\frac{D}{v}\right)\sqrt{\frac{\lambda}{D/v}} \quad R\varepsilon\rho\left[1 - e^{-\left(\sqrt{\frac{\lambda}{D/v}}\right)t}\right] \times 10^4 \qquad (1)$$

where J = radon flux, pCi/m^2-sec

D = pore diffusion coefficient, cm^2/sec

D/v = bulk diffusion coefficient, cm^2/sec

v = porosity

λ = Radon-222 decay constant, 2.1×10^{-6}/sec

ε = emanating power, 0.2

ρ = bulk density, g/cm^3

t = tailings depth

R = Ra-226 concentration in tails, pCi/g

10^4 = cm^2/m^2 conversion.

It can be noted that the flux will vary directly with the radium concentration and, in a somewhat more complex fashion, with the bulk diffusion coefficient and the tailings depth. The radium concentration, in turn, is directly related to the grade of the uranium processed. Average values for the porosity and bulk density of the tailings are well established, as is the value for the emanating power of the tailings

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[2] References cited are listed at the end of my testimony.

particles. Thus, the major variables in this equation are the concentration of radium (which is proportional to the ore grade), the bulk diffusion coefficient, and the depth of the tailings pile. The effect of each of these variables will be examined separately below and then the results will be combined parametrically.

2. Tailings area per AFR.

Equation (1) provides the exhalation rate of radon per unit tailings area; it does not include consideration of the area of tailings exposed per AFR. The tailings area is a function of the volume of the tails and the average depth to which they are placed. The volume of the tails, in turn, is an inverse function of the ore grade, increasing as the ore grade decreases. If the fraction of the U_3O_8 recovered from the ore and the tailings depth were constant, then the change in ore grade would have no net effect on exhalation per AFR. To the extent the ore grade decreased, the radium concentration (which determines the flux) would decrease; the surface area per annual fuel requirement would increase in the same ratio, thus exactly cancelling.

However, the recovery efficiency does change somewhat as a function of ore grade. To determine the significance of this effect, data on uranium ore grade processed and the percent of contained U_3O_8 recovered from the ore were examined, as presented in Reference [2]. These data, covering the period from 1966 to 1978, are plotted in Figure 1; the linear equation best fitting those points was calculated using the method of least-squares and is also presented in Figure 1. Based on this equation, the recovery fraction for an ore grade of 0.10% can be seen to be 90.2%, or 0.2% higher than that used by the NRC Staff for their model 0.1% ore grade. While no data have been published on the recovery fraction for ore grades below 0.1%, I believe the linear equation would provide a reasonable approximation of the recovery fraction for grades down to at least .07% (the average grade of ore currently included in the Department of Energy's "$50 uranium reserve" category). [2] At the .07% grade, the percentage recovery rate would be about 89%.

The relationship of tailings area per AFR to ore grade and tailings depth is presented in equation (2):

$$\text{tailings area/AFR} = \frac{\text{vol. of ore}}{\text{AFR}} \times \frac{1}{\text{depth}}$$

$$= 245\left(\frac{\text{MT } U_3O_8}{\text{AFR}}\right) \times \frac{1}{.01g} \left(\frac{\text{MT ore}}{\text{MT } U_3O_8}\right) \times \frac{1}{r} \times \frac{m^3}{1.6 \text{ MT}} \times \frac{1}{t} \left(\frac{100 \text{ cm}}{m}\right)$$

$$= \frac{1.531 \times 10^6}{(g)(r)(t)} \quad \frac{m^2}{\text{AFR}} \quad ; \text{ or } \quad \frac{378.4}{(g)(r)(t)} \quad \frac{\text{acres}}{\text{AFR}} \qquad (2)$$

where g = ore grade, %

r = milling recovery fraction

= $.8633 + .3863g$ (from Figure 1)

t = depth, cm.

Equation 2 utilizes the generally accepted value of 1.6 g/cm^3 for the bulk density of the mill tailings [3], as well as the value of 245 metric tons U_3O_8 per AFR which has been used consistently in this proceeding.[3] From the equation, the tailings surface area per annual fuel requirement can be calculated as a function of ore grade and depth of the tailings pile. These results are presented in Figure 2, from which it can be seen that, for a given tailings depth, halving the ore grade increases the area by a factor only slightly greater than 2. In other words, the difference in the recovery percentage over the range from 0.2% U_3O_8 ore to 0.07% U_3O_8 ore is not a significant factor in the volume of tailings or, consequently, in the surface area per AFR for a given depth of tails.

It must be noted at this point that the value of 2.9 acres per AFR adopted by Mr. Magno at page 4 of his affidavit in the Perkins proceeding for a tailings depth of 38 feet (11.6 meters) was not consistent with the bulk density value used elsewhere in his affidavit. As Figure 2 indicates, the correct value is about 3.6 acres per AFR for that depth of tailings. A

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[3] It should be noted, however, that other (lower) figures have been postulated, depending among other things on the definition of AFR that is adopted. For instance, a letter dated November 15, 1979 from L.C. Schwendiman of Battelle Pacific Northwest Laboratories to the NRC regarding radon releases from underground uranium mines (which letter was forwarded to the Appeal Boards and the parties herein on December 21, 1979) assumes 182 MT U_3O_8 per AFR. Use of such a definition would, of course, result in decreased radon emissions per AFR.

review of the source which Mr. Magno referenced as his basis for tailings area and volume (ORNL-TM-4903, Vol. 1, Table 4.13), revealed a footnote which indicates the density of tails used therein to be 120 pounds per cubic foot, or 1.92 g/cm^3, which is higher than that generally accepted for dry tailings[4] of 100 pounds per cubic foot, or 1.6 g/cm^3 [3], which Mr. Magno used everywhere else in his affidavit.

3. Radon exhalation per AFR.

The product of equations (1) and (2) yields the radon exhalation per annual fuel requirement. This equation has been used to calculate the radon exhalation rate per AFR as a function of ore grade and depth of tails for three different bulk diffusion coefficients. The first diffusion coefficient, 0.0776 cm^2/sec, was calculated to match the effective surface flux of approximately 1.3 (pCi/m^2-sec)/(pCi Ra-226/g) presented by EPA in Reference [4]. The second diffusion coefficient, 0.054 cm^2/sec, was that used by Mr. Magno in his affidavit in the *Perkins* proceeding. This is equivalent to a surface flux of 1.08 (pCi/m^2-sec)/(pCi Ra-226/g). Both of these values were developed theoretically without reference to measured data on tailings.

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[4] The 1.92 g/cm^3 density used in ORNL-TM-4903 is appropriate for wet tailings, which were the type of tailings considered in Table 4.13 of that document.

The third diffusion coefficient used, 0.019 cm^2/sec, is that based on the experimental measurement of radon flux from acid-leached tailings by Argonne National Laboratory [5] which provided an average flux value of 0.64 (pCi/m^2-sec)/(pCi Ra-226/g). The Argonne National Laboratory also measured an average flux value from carbonate-leached tailings of 0.30 (pCi/m^2-sec)/(pCi Ra-226/g), less than half that for the acid leached tails. The carbonate-leached tailings diffusion coefficient was not used in my calculations because it is less conservative and because only a minority of mills (about 20%) utilize such a process.

The results of my calculations for the three bulk diffusion coefficients reported (.0776, .054 and .019 cm^2/sec), are presented in Figure 3 as a function of tailings depth for two ore grades, 0.07% and 0.2%. As noted above, the .07% value was chosen as the average ore grade included in current $50 uranium reserves. From these results it can be noted, first, that the effect of ore grade on exhalation rate per AFR is minor, as also reflected in the earlier surface area per AFR computations. Second, both the EPA and the NRC diffusion coefficient values provide similar results (within about 20%), and both are considerably higher than the diffusion coefficient values obtained from experimentally measured diffusion rates by the Argonne National Laboratory.[5] The EPA values are approximately double those of the experimental values; those of the NRC, approximately 60% greater than those experimentally measured.

On Figure 3, I have also plotted the original Staff value of 110 Ci Rn-222/yr per AFR as calculated by Mr. Magno, and the corrected value of 140 Ci Rn-222/yr per AFR based on the accepted bulk density of the tailings for a depth of 11.6 meters (38 feet). I have also plotted for Dr. Pohl's "average existing inactive tailings pile" (cited in his affidavit dated July 6, 1979 in response to the Licensees' Joint Motion for Summary Disposition) my computed value of about 310 Ci/yr per AFR for a tailings pile of an average depth of 4.8 meters. My computed value is somewhat less than the 330 Ci/yr per AFR cited on page 1 of Dr. Pohl's affidavit, since for the average tailings pile he cited the ore grade is approximately 0.22%; the recovery percentage, therefore, approximates 95% rather than the 90% assumed in his analysis. The higher recovery rate produces a larger number of AFRs (9.2) than the 8.8 AFRs used by Dr. Pohl, and hence a smaller exhalation rate per annual fuel requirement.

Finally, I have also plotted on Figure 3 the calculated yearly radon exhalation rate per AFR for the model tailings pile presented in the Staff's Generic Environmental Impact Statement on Uranium Milling (NUREG-0511). In Chapter 5 of this document, the radon exhalation per year from the dry portion (50 hectares) of an 8 meter deep tailings pile is calculated to be 7,000 curies. The model mill is said to produce 920 metric tons U_3O_8 per year from 1800 MT per day of 0.15% ore. The volume of the dry portion of the tails is $(50 \times 10^4 \times 8) = 4 \times 10^6\ m^3$, which would accommodate

$$\frac{4 \times 10^6\ m^3 \times 1.6\ MT/m^3 \times 920\ MT\ U_3O_8/yr}{1800\ MT/d \times 365\ d/yr \times 245\ MT\ U_3O_8/AFR} = 36.6\ AFR.$$

Thus, for a dry tailings pile with a depth of 8 meters, the radon exhalation per annual fuel requirement is calculated to be about 191 Ci/yr per AFR. This value falls slightly below the curve for the NRC diffusion coefficient in Figure 3 because in the Generic Environmental Impact Statement (Appendix G, p.G-13), the Staff has used a slightly lower bulk diffusion coefficient (0.047 cm^2/sec) than that used in the Perkins analysis.

4. Effect of tailings depth.

As indicated in Dr. Pohl's affidavit, the average depth of existing inactive tailings piles as reported in Reference [4] is about 4.8 m. On the other hand, while the Staff cites in the Uranium Milling GEIS (Appendix S, p.S-2) an effective tailings thickness of 6 meters, the GEIS appears to have used an 8 meter deep pile in its model, and Appendix S notes that "the effective depth of existing active piles is between about 12 and 13 m" (emphasis added), and "effective thickness could reasonably be expected to go as high as 15 m". Therefore, the estimated depth of an active tailings pile is currently around 12-13 m. and the lower value adopted by Dr. Pohl from Reference [3] only applies to inactive piles not relevant to this proceeding because they do not represent current practice and are not and will not be the source of fuel for any of the reactors involved here.

A limited survey performed by members of my staff of active mills which were operating prior to January 1, 1975 obtained data for 14 mills which indicate an average pile depth of about 42 feet, or 13 meters, with a maximum depth in the range of about 43 meters. This result is consistent with the estimate by the Staff in the GEIS of about 12-13 meters. If the median depth value of 12.5 meters is used as appropriate for current active mills, I would expect the actual radon exhalation rate per AFR from dry uncovered tailings to be about 75-80 Ci/yr, and a conservatively calculated rate to be in the range of 135-160 Ci/yr.

On the basis of the foregoing analysis, I conclude that 1) differences in ore grade make an almost negligible incremental contribution to radon exhalation per AFR; 2) assumptions as to the bulk diffusion coefficient may change the estimate of radon exhalation by a factor of about two for a given depth of tails; 3) the major determinant of radon exhalation per AFR is the surface area-to-volume relationship, or the average depth to which the tailings are accumulated; and 4) a conservative estimate of the radon exhalation rate, which takes into account current practice in tailings depth and the most conservative estimates of bulk diffusion coefficient, is 135-160 Ci Rn-222/yr per AFR (See Figure 3).

B. Stabilization of tailings piles.

The Appeal Boards have solicited evidence on the degree to which tailings piles can be covered or stabilized successfully and on the possible effect of erosion followed by migration of the tailings. At the outset, there should be no question about the existing capability for moving and placing large volumes of earth. With respect to the integrity of stabilized piles over long periods of time, there is evidence that earth structures erected by primitive peoples have remained largely intact for thousands of years. Finally, existing unstabilized tailings piles provide at least a measure of the migration and radon emission potential for these materials assuming the disappearance of the stabilizing cover. These three areas are discussed in the following subsections.

1. Technical capability for stabilizing tailings piles.

There is no technical difficulty in moving and placing large volumes of soil or similar materials. These tasks have been accomplished for many years in large construction projects such as earth-filled dams and in the stripping and reclamation of large open-pit mines for coal and other minerals. Current reclamation requirements in Wyoming, for example, have resulted in the movement of huge quantities of soil and overburden at mine sites to temporary sites where they are stabilized and revegetated to prevent erosion pending their return to the mined out pit. I have personally observed stabilized overburden and topsoil volumes in Wyoming having dimensions in the order of 300-400 acres in area by 120 feet in depth, larger than the largest mill tailings piles of which I have knowledge and certainly larger in volume than the cover needed for such tailings piles.

For example, an exhalation rate of about 160 Ci/yr per AFR from a 12.5 m deep pile (see p.12 above) is associated with an area of about 4.85 acres per AFR (Figure 2), yielding a flux of about 260 pCi/m^2-sec from the uncovered tailings. To meet the proposed criterion of 2 pCi/m^2-sec [6] would require cover capable of reducing exhalation by a factor of 130. This could be accomplished by a cover of about 26 feet of sand similar in radon diffusion characteristics to those assumed by the NRC Staff for the tailings themselves, or by less than 3 feet of clay, or by some intermediate thicknesses of clay and other local soils.

It is therefore my opinion that mill tailings piles can be covered using the same earth-moving techniques which are now in use, for example, in reclaiming open pit mines for other minerals.

It should also be noted that dry (or moist) piles of earth (or other granular materials) are inherently limited by their internal friction in the degree to which they will spread out, or slump, from their own weight. Thus, the sheer mass of a material alone will not induce spreading out beyond the natural angle or slope of repose for that material. For wet sand and clay, the slope of repose is about 3 h (horizontal) to 1 v (vertical); for dry sand and clay, the slope of repose is steeper, about 1.33 h to 1 v.[7] The current Staff position on mill tailings piles[6] calls for slopes no steeper than 5 h to 1 v, and preferably 10 h to 1 v, which provide ample protection against migration due to slope instability.

2. Ability to maintain piles over long periods of time.

In considering the potential for maintaining a cover for tailings over long periods of time under conditions in which erosion is a factor, the earth structures, or mounds, built by Pre-Columbian Indians in North America serve as a useful frame of reference.[8, 9] These mounds generally served one of two purposes in these early cultures, either as burial mounds or as foundations for elevated structures such as temples or ceremonial centers. One of the earliest earth mound systems, the Poverty Point Mound, was built between 1500 and 1000 B.C., at least 3,000 years ago, beside Bayou Maçon in Louisiana, and includes one mound 70 feet tall.

The Adena Mounds, numbering in the hundreds in the Ohio Valley, were predominantly burial sites built between 1000 B.C. and 300 B.C., over 2,000 years ago. One of the larger is the 70 foot tall Grave Creek Mound, now in downtown Moundsville, West Virginia. At the 30 foot high Seip Mound, Ross County, Ohio, "Surveyor's instruments show an accumulation adjacent to the margin of the mound as a result of erosion of less than five inches, despite the fact that the elements for centuries have beaten upon it."[8]

In East St. Louis, Illinois, the Cohokia Mounds State Park, located in the American Bottoms area of the Mississippi River flood plain, contains forty mounds, one of which, Monks Mound, covers 16 acres and rises in terraces to a height of 100 feet. This mound was raised between 900 and 1100 A.D. Other lower mounds on the site are burial mounds which have provided protection of their contents against natural forces for a thousand years.

Other mounds exist in Wisconsin, Minnesota, the Dakotas and Iowa, in the southeastern part of the United States and in Canada, as well as in California, Oregon and Washington, Europe and Asia, under a wide range of climatic conditions. The climatic conditions in the regions of the United States where mounds are most prevalent are significantly wetter than those of the more arid western regions, particularly in the southeast and along the Ohio and Mississippi River valleys. These areas have undoubtedly been subject to the severe erosive forces of rainfall and flooding which are not uncommon in those regions from tropical and continental storms, yet the mounds have survived the effects of these erosive forces.

The potential for wind erosion is higher in many parts of the uranium producing areas in the West than it is for the eastern half of the United States. Nevertheless, recognition of a potential for wind erosion permits its control by providing rip-rap (large blocks of rock), flat slopes and/or asphaltic layers as protection on upwind faces for those instances where revegetation alone is not sufficiently effective. Considering the limited technology available to the early mound-builders, the fact that their structures have survived natural forces for many centuries indicates that contemporary engineers, recognizing potential erosion problems and with substantially greater resources available, should be able to do at least as well. The survival of these ancient structures also indicates that mill tailings piles can be maintained in stabilized condition with a minimum amount of administrative control by the public authorities.

3. Effect of failure of stabilizing cover.

I have attempted to estimate the radon emissions for a scenario in which erosion eventually removes all the stabilizing cover from a tailings pile. To do so, I have studied the extent of tails migration that has taken place on existing inactive tailings piles, and evaluated the radon emissions resulting from such migration.

To determine the spread of radioactive materials for this testimony, I examined a report by EPA [10], which presents the results of surveys at 20 inactive sites in the western United States. The results of these surveys are presented in the EPA report on maps delineating plant areas as contour lines of gamma exposure rates which are related to surface contamination by Ra-226.

For each of the 20 sites, the EPA report presents contours which define areas of contamination extending down to background levels. For 15 out of the 20 sites, the contours were closed within the confines of the surveyed area. For four of the remaining five sites, contours were not constructed or were not closed for lack of sufficient data (Monument Valley, Arizona; Grand Junction, and Durango, Colorado), or due to extensive downwind contamination by a roaster (calciner) plume (Naturita, Colorado). For the fifth site (Lowman, Idaho) no source information (i.e., tailings quantity or radioactivity content) was presented. Because of these reasons, I did not use the remaining five sites in my calculations. In a number of the other 15 sites the contours enclose the inactive mill area, haul roads and evaporation pond sites as well as the tailings pile. Measured contamination levels reflect, in these instances, sources other than dispersed tailings and therefore provide a conservative (high) estimate of tailings dispersion. In two cases (Maybell, Colorado and Converse Co., Wyoming), the sites include extensive mine waste dumps and overburden piles in addition to an open pit mine, hence the emissions at those sites are not representative of those from a tailings pile and were not used in my analysis of tailings dispersion.

My analysis method assumed tailings piles and the respective contaminated zones to be represented by circles of area equal to that given by EPA for each of the zones. Contamination per unit area was assumed to decrease exponentially with distance, the rate of decrease being computed from the known contamination level at the tailings pile and the levels corresponding to each of the survey contours.

Dispersed contamination was calculated by a series of integrations: first, between the tailings pile equivalent radius and the equivalent radius of the first survey contour; successive integrations were made between the first and second survey contour radii, and between the second and third (background) contour radii.

The results of my calculations are presented in Table 1 for each of the 13 piles evaluated, and the totals of pile inventory and dispersed Ra-226 for all of those piles. A total of 56.1 curies of Ra-226 are calculated to have been dispersed out of a total inventory of about 10,140 curies estimated to be in the piles, or about 0.55% of the inventory on average. These 56.1 dispersed curies of Ra-226 are calculated to release 743 Ci Rn-222 per year.

The EPA [4] has estimated that all inactive mill tailings piles in the United States contain a total of 15,450 Ci of Ra-226. Assuming that all inactive piles disperse at the average rate found for the 13 piles evaluated, the total radon-222 emanated by dispersed tailings would be (15,450 x 743)/10,140 = 1,130 Ci Rn-222/yr. Since the EPA estimates that the total radon emission from these inactive tailings piles is 6 x 10^4 Ci Rn-222/yr, it follows that the total amount of radon emitted by the dispersed tailings is about 1.9% of the radon released by the piles themselves.

In considering the rate at which dispersion occurred at these inactive sites, I examined the data covering the period of operation of each of them. Assuming the dispersion occurred between the mid-life of each facility and the measurement period (1974) for the data in Reference [10], I have calculated the mean dispersion period for these 13 facilities to have been

15.3 years. Thus, the mean fraction dispersed per year would be (0.0055/15.3), or 0.00036 per year. This would imply complete dispersal in about 2700 years if the erosion rates were to remain the same. However, I would expect erosion rates to decrease with time as the more readily eroded material (i.e., finer particles, more steeply sloped material) is removed.

On the basis of these calculations, the dispersion of unstabilized tailings would not appear to result in a significant addition to tailings radon exhalation over any reasonable near term period. For example, assuming erosion to continue at the same rate for 200 years would increase the current estimate of 60,000 Ci/year from the inactive tailings piles by only 25%. This very slow rate of dispersion indicates that there should be ample opportunity for taking remedial action to correct the effects of erosion or other destabilizing agents.

4. Verification of compliance with regulatory guidelines.

The Appeal Boards have identified as an issue in this proceeding the capability of verifying compliance with guideline values for radon emission rates by direct measurement. As will be seen, the Boards are correct in their assumption of the inability to confirm compliance by direct measurement, although not because of limited instrument sensitivity, but due to the inability to differentiate between radon releases from the tailings and those from the cover material (and to a lesser degree from the soil beneath the tailings).

The guideline value for emission rate presented during the Perkins hearing (Tr. 2399), which was at that time a Branch Technical Position, was "about twice the emanation rate in the surrounding environs". This guideline has now been superseded by the August, 1979 proposed amendments to 10 C.F.R. Part 40[6] in which Criterion 6 of proposed Appendix A calls for "sufficient earth cover...to result in a calculated reduction in surface exhalation of radon from the tailings...to less than two picocuries per square meter per second above natural background levels" (emphasis in original). Instrument sensitivities are currently in the range of 1-2 pCi/m^2-min (0.017 - 0.033 pCi/m^2-sec), well below the proposed criterion.

Any radon exhalation measured for compliance with the guidelines would be the sum of those residual contributions from the tailings which diffuse through the cover material, from the cover material itself, and to a lesser degree from the soil underlying the tailings. It is not possible to distinguish by confirmatory measurements alone the contribution from each of these sources, hence the emphasis by the Staff on calculated reductions of radon from tailings. This emphasis on calculation could be alleviated if cover materials free of radium could be found. However, radium is found quite widely in soils, and radium-free cover materials are not readily available.

It should be noted that the limiting factor of total exhalation rates from covered tailings may be the available cover material, which could emit substantially greater amounts of radon than the guideline value of 2 pCi/m^2-sec proposed by the Staff. For example, topsoil samples in the Gas Hills, Wyoming region average 8.9 pCi Ra-226/g (range: 2.8 to 33.5).[11] If no tailings were present, the radon exhalation rate from this soil would be, on average, 8.9 pCi/m^2-sec (assuming 1.0 pCi/m^2-sec per pCi Ra-226/g, which is approximately the specific surface flux used by the Staff in Perkins, see p. 8 above). Exhalation rates from tailings piles covered with this topsoil in accordance with the proposed guideline would thus total about 10.9 pCi Rn-222/m^2-sec, 8.9 from the topsoil and 2 from the tailings.

C. Summary.

In response to the questions raised by the Appeal Boards in this first general area of emissions from mill tailings piles, I have shown that:

1) The radon emissions per AFR are not significantly affected by the ore grade.

2) The major factor affecting radon emissions per AFR is the depth of the tailings pile.

3) The currently active mills have tailings piles which average 12-13 meters in depth, and I know of no reason for current tailings depth practices to change in the future.

4) The resulting uncovered pile emissions of radon are realistically expected to be in the range of 75 - 80 Ci/yr per AFR, and conservatively in the 135 - 160 Ci/yr per AFR range.

5) Technology for covering tailings piles consists primarily of moving and placing earth materials on a lesser scale than currently applied elsewhere.

6) Earth structures built by Pre-Columbian native cultures which are still in existence strongly suggest that long-term stability is achievable by contemporarily engineered stabilized tailings piles.

7) Estimates based on data for inactive tailings piles indicate that, should contemporary tailings piles become uncovered, tailings dispersal will be slow requiring several centuries for a significant increase in radon emissions over those from the uncovered piles alone, and thus providing ample time to take remedial action.

8) Verification of compliance with radon emission rate guidelines cannot be made directly, but only because almost all earth materials available for covering tailings naturally contain Ra-226 which will emit Rn-222 and hence contribute to any flux measured atop the covered tailings piles.

III. Emissions From Underground Mines.

The Appeal Boards have requested information on the extent to which underground mines can be sealed as well as the extent of radon exhalation from unsealed mines through natural convection (Alleged Deficiency No. 3).

On the first question, shaft openings of underground mines can be and have been sealed using earth and/or concrete plugs.[12] The decision to seal a mine in this fashion depends upon the requirements of the State, and the judgment as to the potential for future extension of mining activities as the value of residual lower ore grades increases. In an informal survey conducted by members of my staff of five mining companies in Colorado, Wyoming and New Mexico, it was learned that none of them has closed underground mines recently; several have committed to their State agencies to seal shafts with concrete and/or earth plugs, or plan to do so in future mine closures.

As to the second question, during normal operation of an underground mine, the radon removed by the mechanical ventilation system balances that emanated from the mine walls, thus maintaining a reasonably constant concentration of radon in the mine air. When the mine is closed and mechanical ventilation ceases, radon continues to emanate from the mine walls; without the removal by ventilation radon concentrations in the mine air build up to a value which is usually much greater than that existing during the active mining period.

The only mechanism for the removal of the radon from the mine air to the outside atmosphere is by means of whatever natural circulation air flow may be established. The driving force for this flow is primarily determined by the temperature difference between the mine air and the outside air, and secondarily by the difference in elevation between the mine and the surface. Resistance to the flow is created by the nature of the mine drifts, bulkheads, dead-end rooms, flooding, the size of and the distance between vents, possible blockages due to collapses, etc.

A draft report by EPA describes monitoring at several inactive mines in the Grants, New Mexico, area.[13] One of these was small, with five 30 cm diameter vents and a shaft, from which a maximum radon emission of 2.8 mCi/day (or 1 Ci/yr) was estimated; the low value was attributed to partial blockage of the vents and water in the mine. At another inactive mine connected to three other inactive and two active mines, measurements were made over a weekend when ventilation fans were shut down. Assuming all six mines contributed equally, the draft report estimates a daily emission of 0.18 Ci/day-mine (66 Ci/yr). However, no data are provided which would relate the emission rate to mine production.

The EPA report has also considered Rn-222 exhalation from inactive underground uranium mines, using as a model the average of some 2,100 inactive underground mines. The model mine was assumed to have ended operation by 1977 and to have produced 3.02 x 10^4 MT of ore and 9.68 x 10^3 MT of waste. As a "first approximation," the analysis assumed that all Rn-222 released into mine air would be exhausted by natural ventilation before significant decay occurred and calculated a release of 12.3 Ci/yr. No ore grade is specified. If it is assumed for this small model mine that the ore grade was midway between the average grade bought by the AEC in 1960 (0.43%), and that processed by uranium mills in 1977 (0.15%)[2] the mine ore grade would be 0.29%. At this ore grade, the model mine would have produced 87.6 MT U_3O_8. Further assuming an average recovery of 95% for this ore grade (see Figure 1 above) would result in the mine having produced 87.6 x 0.95/245 = 0.34 AFR, and a Rn-222 emission rate of 36.2 Ci/yr per AFR.

Considering the relatively small amount of information in this area, the conservative approach would be to assume, as did EPA, that the radon emitted by an abandoned, unsealed underground mine would equal that removed by the ventilation system during normal operation; that is, the radon emanated by the mine walls would be released to the atmosphere whether or not the fans were in operation. I would however expect that this value would be greatly in excess of that actually released. Such factors as blockages of the vents, collapses of mine drifts, flooding, etc. would significantly reduce radon emissions.

IV. Emissions From Open-Pit Mines.

The Appeal Boards have noted an uncertainty in estimates of emissions from both unreclaimed and reclaimed open-pit mines (Alleged Deficiency Nos. 4 and 5). As to the former, Ecology Action, in its response of June 25, 1979, to the Licensees' Joint Motion, for Summary Disposition has indicated (p.6) uncertainty as to whether my estimate of such emissions in *Perkins* (Tr.2640) included only the contribution from overburden.

My estimate of Rn-222 emission from unreclaimed open-pit mines (in the bounding range of 100-200 Ci/yr per AFR) included the exhalation from both the overburden and the walls and floor of a pit enclosing the volume of overburden plus ore for one AFR, and encompassed overburden-to-ore ratios of up to 10 (*i.e.*, within the range of 8 to 35 cited by the intervenors in Alleged Deficiency No. 5). It did not consider sub-ore stockpiles, that is, accumulations of ores of lower grade than economically recoverable at the time of mining. However, I used in my estimate the radon exhalation rate corresponding to mill tailings which have been processed by grinding; this assumption yielded a larger exhalation rate per unit volume than I would expect to exist for the much larger fragments of uncrushed overburden. Thus, I compensated in my estimate for any sub-ore stockpile that might have been left at the mine.

In the past year, two assessments of open pit uranium mining activities have been performed: one by Pacific Northwest Laboratory-Battelle Memorial Institute (PNL)[14] and the other by EPA.[13] The PNL study was based on a model derived from average statistics for eight major open pit uranium mines in the Casper, Wyoming area and included measurements of radon flux in an open pit mine. The model recognized the current practice of sequential development of individual pits, with worked out pits being backfilled using overburden from new pits. Radon emission was calculated assuming the final pit, overburden and sub-ore piles were not reclaimed, and that overburden is so mixed with sub-ore in the relocation and backfilling operation as to raise the effective uranium content of the backfill material by a factor of five (from 4 ppm to 20 ppm U_3O_8). The resulting radon emission is calculated to be 33 ± 25 Ci/yr per AFR.

In the EPA evaluation of an inactive surface mine [13], a model mine was established based on annual ore and waste production statistics for an estimated 944 surface mines. The model mine was assumed to end operations in 1977. The total waste and ore removed from the pit would be 1.18×10^6 MT and 4.75×10^5 MT, respectively, with an amount of sub-ore equal to that of the ore. The sub-ore was assumed to be placed in a uniform layer on top of the overburden pile, which would maximize the radon emissions from that source. The pit and waste pile were calculated to emit about 145 mCi/day, or about 53 Ci/yr. The ore grade was not specified.

To determine an estimate of the radon emitted per AFR for the EPA model mine, I again assumed the ore grade to be midway between the average grade bought by the AEC in 1960 (0.43%) and that processed by uranium mills in 1977 (0.15%).[2] At this average ore grade (0.29%), the model mine would have produced 138 MT U_3O_8. Further, assuming an average recovery of 95% for this ore grade (see Figure 1) would result in the mine having produced 138 x .95/245 = 0.53 AFR, and the Rn-222 emission would equal 100 Ci/yr per AFR.

In summary, two recent evaluations of emissions from abandoned open-pit mines, one based on current large scale methods and the other based on the average of more than 900 small surface mines reflecting no reclamation whatsoever, have yielded radon emissions per AFR which are equal to or less than, and therefore validate, the estimates provided to the Board in the Perkins record by myself and the Staff.

V. Water Pathways to Radiation.

This set of issues calls for a more complete assessment of the potential exposure to radon which may reach humans through water pathways, and particularly the potential for groundwater transport of radon or its precursors from abandoned mines or tailings piles (Alleged Deficiency Nos. 7 and 18).

A. Groundwater transport.

Unlike the direct airborne release of radon from mining and milling operations, the indirect release of radon following transport in groundwater has not been modeled on a generic basis. This is due to the highly localized, site specific nature of groundwater movement patterns, the local relationships between precipitation, evaporation and runoff, and the variable physical and chemical effects of specific compositions of local soils and rocks on the chemical precipitation or sorption of the radon precursors uranium, thorium and radium. The following discussion, therefore, attempts to provide an estimated upper bound to the releases associated with water pathways.

In the case of mining, the extent of potential groundwater transport of radon precursors is initially established by the location of the groundwater table with respect to the abandoned workings. Although many of the early, shallow mines were essentially dry, most current and planned mines are located at or below the local groundwater table and require dewatering by pumping during mine development and operation. When the mine ceases operation, the groundwater returns to its normal elevation at a rate determined by the local soil/rock permeability. To the extent such mining operations as drilling and blasting have increased the local permeability of the aquifer, groundwater will flow more readily through the affected zones. Depending upon the particular chemistry of the groundwater and of the mineralized zones, radon precursors may be dissolved in the groundwater, as well as radon itself.

In general, of the radon progenitors, uranium is most readily dissolved and transported, thorium is least mobile, and radium lies roughly in between in mobility.[13] Using mine drainage water as indicative of groundwater, analytical data from 14 underground mines in Wyoming, Utah, Colorado and New Mexico [13] indicate Ra-226 to be present on average in concentrations less than 0.4% of those expected if Ra-226 were in equilibrium with measured concentrations of uranium in the same samples. Radium-226 concentrations ranged from 0.1 to 89 pCi/liter (geometric mean = 3.8 pCi/liter; arithmetic mean = 11.8 pCi/liter) in the mine drainage water. Similar data for 6 open-pit mines in Wyoming show Ra-226 concentrations to be less than 0.9% of equilibrium values, with a range of 0.67 to 10 pCi/liter (geometric mean = 3.1 pCi/liter; arithmetic mean = 4.1 pCi/liter).

While the concentration of Ra-226 in groundwater is thus rather low, the concentration of its daughter Rn-222 in groundwater has been found to be substantially greater than would be expected assuming secular equilibrium with the dissolved Ra-226. This is due to the solution in the groundwater of Rn-222 resulting, not only from Ra-226 in the groundwater, but also from decay of Ra-226 fixed in the rock materials through which groundwater flows.

Concentrations of Rn-222 measured in public groundwater supplies in the United States have been reported in excess of 100,000 pCi/liter [15], substantially greater than the typical

Ra-226 concentrations which as seen above rarely exceed a few tens of pCi/liter even in uranium mining areas.

To determine an appropriate ratio of Rn-222 to Ra-226 in groundwater, I have reviewed data recently reported by EPA for Rn-222 in a number of public groundwater supplies in Iowa.[18] Ra-226 concentrations were also reported for eleven of the same towns (although not necessarily from the same wells or sampled at the same time).[19] For these eleven towns, Ra-226 concentrations ranged from 0.6 to 46.2 pCi/liter; Rn-222 concentrations ranged from 56 to 1700 pCi/liter. The Rn-222/Ra-226 concentration ratios ranged from 7 to 212 (arithmetic mean: 100; geometric mean: 63).

Based on the maxima of the measured figures, if one assumes that a community of 1,000 draws groundwater containing 90 pCi Ra-226 per liter and 212 times as much Rn-222 (18,900 pCi Rn-222 per liter) from an abandoned mine area at a rate of 500 liters (132 gallons) per capita-day, the annual Rn-222 emission from release of all of the contained gas would amount to 3.45 Ci, hardly a significant addition to the uranium mining source term.

With the cessation of mining, less uranium and radium are available for dissolution than was the case before the mining operation. Thus, groundwater concentrations of these substances should be somewhat lower in the mined-out area and, because of the chemical interactions with the mineral constituents of the aquifer, should decrease with distance from the mineralized zone at a rate dependent upon site-specific aquifer characteristics.

Groundwater transport of mill tailings would not differ significantly from that of mine drainage because the same physical/chemical factors retarding Ra-226 migration in mine waters are also applicable to mill tailings seepage.[1]

B. Surface water transport.

In considering transport of radium from mine wastes or mill tailings by surface waters, it should be noted at the outset that in uranium mining/milling areas, annual evaporation exceeds annual precipitation. Most surface streams are normally dry except for periods during and after precipitation. To the extent that, over a short time period, precipitation exceeds evaporation, uncovered inactive tailings impoundments will have a temporary excess of moisture which may temporarily increase seepage into the ground; however, over the long term, no significant movement of radium into groundwater is anticipated [1, 13].

Short period, high intensity rainfall can erode unstabilized sub-ore, or waste rock piles, again in a highly site-specific manner. Investigations of a limited nature by EPA [13] have indicated relatively short transport distances for such material. To provide an upper estimate of the significance of such erosion to emissions of Rn-222, I have assumed the complete erosion and dispersal of the sub-ore pile in the EPA model inactive surface mine described in Section IV above. In that model, the 47,500 metric tons of sub-ore containing 87 pCi Ra-226/gm (total 4.13 Ci) were assumed to be placed in a layer 0.36 m thick on top of the overburden pile, and to emit 128 mCi Rn-222/day (46.7 Ci/year)[13]. Assuming the 4.13 Ci of Ra-226 contained in the sub-ore to be completely dispersed in a thin layer by erosion, the resulting Rn-222 emission would be 54.7 Ci/yr (assuming an emanation fraction of 0.2), 7 Ci/yr more than the value calculated by EPA for the pile in-place, or an increase in the emission per AFR per year from 100 Ci to 113 Ci Rn-222.

Applying a similar approach to the large mine PNL model[15], I calculate that during the 17 year mine life, 8.78 x 10^6 MT of sub-ore averaging 0.0155% U_3O_8 would have been accumulated with a total Ra-226 content of 384.3 Ci, emitting 300 Ci/yr of Rn-222. In this model, the sub-ore pile is 100 feet in height and 1150 feet in base diameter; its complete erosion in any reasonable time frame seems highly unlikely. Nevertheless, assuming this pile to be completely dispersed, the resulting Rn-222 emission would be about 5100 Ci/yr, 4800 Ci/yr more than that calculated by PNL for the sub-ore pile, or an increase in the emission per AFR-year from 33 Ci to 139 Ci Rn-222.

In summary, surface water transport in uranium mining regions is ephemeral; short period-high intensity precipitation does not yield continuously flowing streams. Such precipitation may cause erosion of unstabilized waste rock from mines.

Calculations of Rn-222 emission from complete dispersal of unstabilized sub-ore piles at two model mines yield maximum values of 113 and 139 Ci/yr per AFR, considering all sources of Rn-222. These values are still within the range of 100-200 Ci/yr per AFR given in my earlier testimony in Perkins and here for abandoned open-pit mines.

VI. Emissions from Phosphate Residues.

The last issue in this proceeding is the amount of radon released from recovery of uranium associated with phosphate during processing of the latter, as well as a comparison of this quantity of radon with that released from the direct mining and milling of an equivalent amount of uranium (Alleged Deficiency No. 26). In brief, the answer is that no radon is released beyond that attendant upon the phosphate production itself.

Current and planned plants for the recovery of uranium from phosphate slag extract uranium from a phosphoric acid intermediate product. This product contains less than one percent of the amount of Ra-226 in secular equilibrium with its parent uranium, the remainder of the radium having been removed, together with calcium, in a precipitation process during production of the phosphoric acid. Thus, the effective absence of the Ra-226 parent of radon precludes the formation of significant quantities of radon during the solvent extraction of uranium from the phosphoric acid.[18]

Nevertheless, I have made a calculation to provide the Board with an upper limit value for radon release during the uranium recovery process. This would be the radon produced by the Ra-226 remaining in the phosphoric acid during the period of solvent extraction of the uranium prior to return of the phosphoric acid (and radium) to the phosphate processing plant. Since an average uranium recovery plant processes 158 MT of uranium per year [18], the average total process residence time is about 2.3 days/MTU (assuming 365 operating days per year) and includes a number of operations beyond the solvent extraction process. However, I have assumed a Ra-226 concentration at 1% of the equilibrium value, and a 100 hour residence time per MTU during which Rn-222 formed by Ra-226 decay is produced. This would result in the generation of 2.5 mCi Rn-222 per MTU or 0.52 Ci per AFR (as compared to the 1,100 Ci/AFR for milling estimated to occur during the active phase of these operations by the Staff in <u>Perkins</u>). It should be further noted that this radon would be produced whether or not the uranium is recovered from the phosphoric acid and should therefore be attributed to the phosphate production process and not the uranium recovery process.

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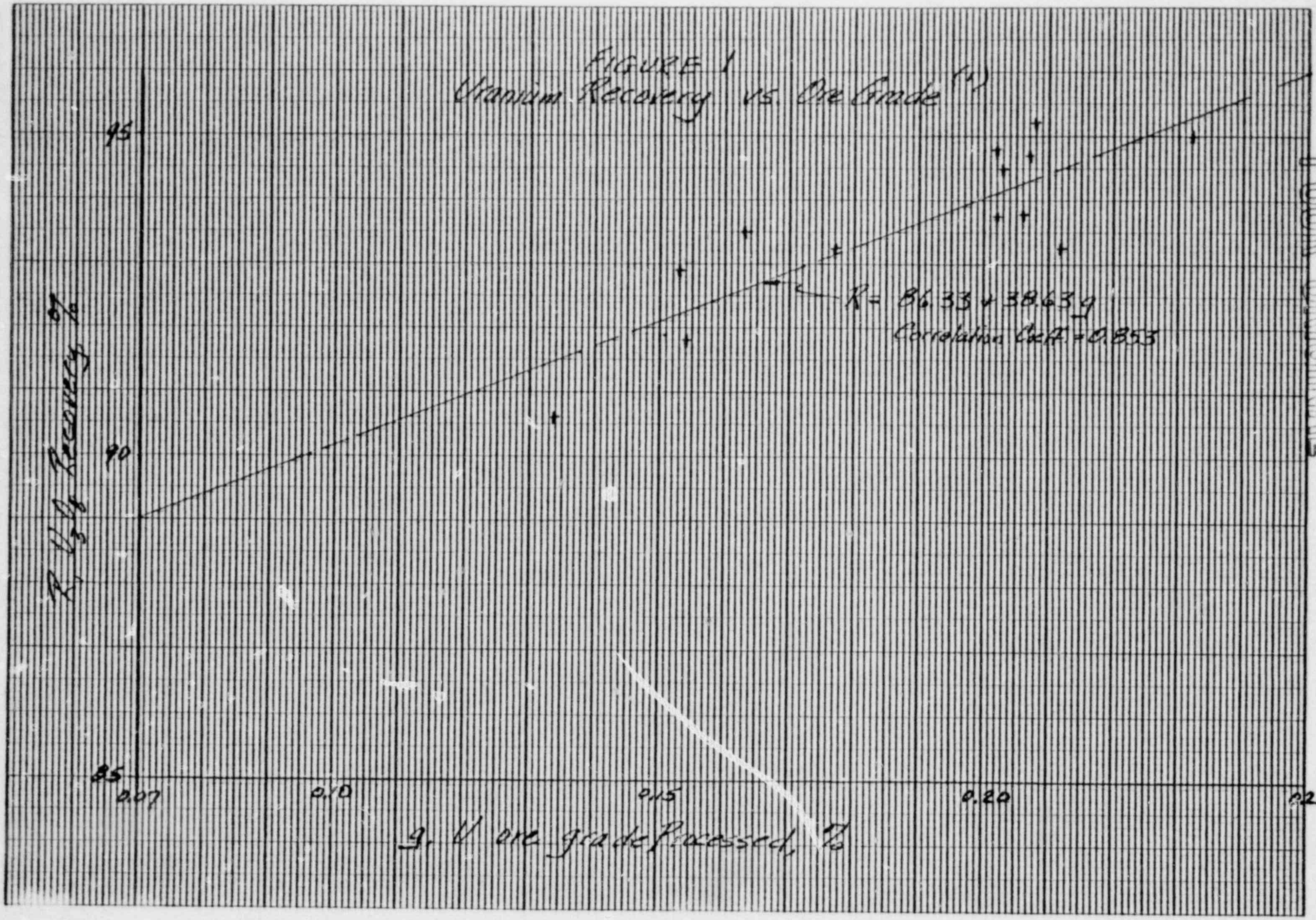

FIGURE 1
Uranium Recovery vs. Ore Grade(1)

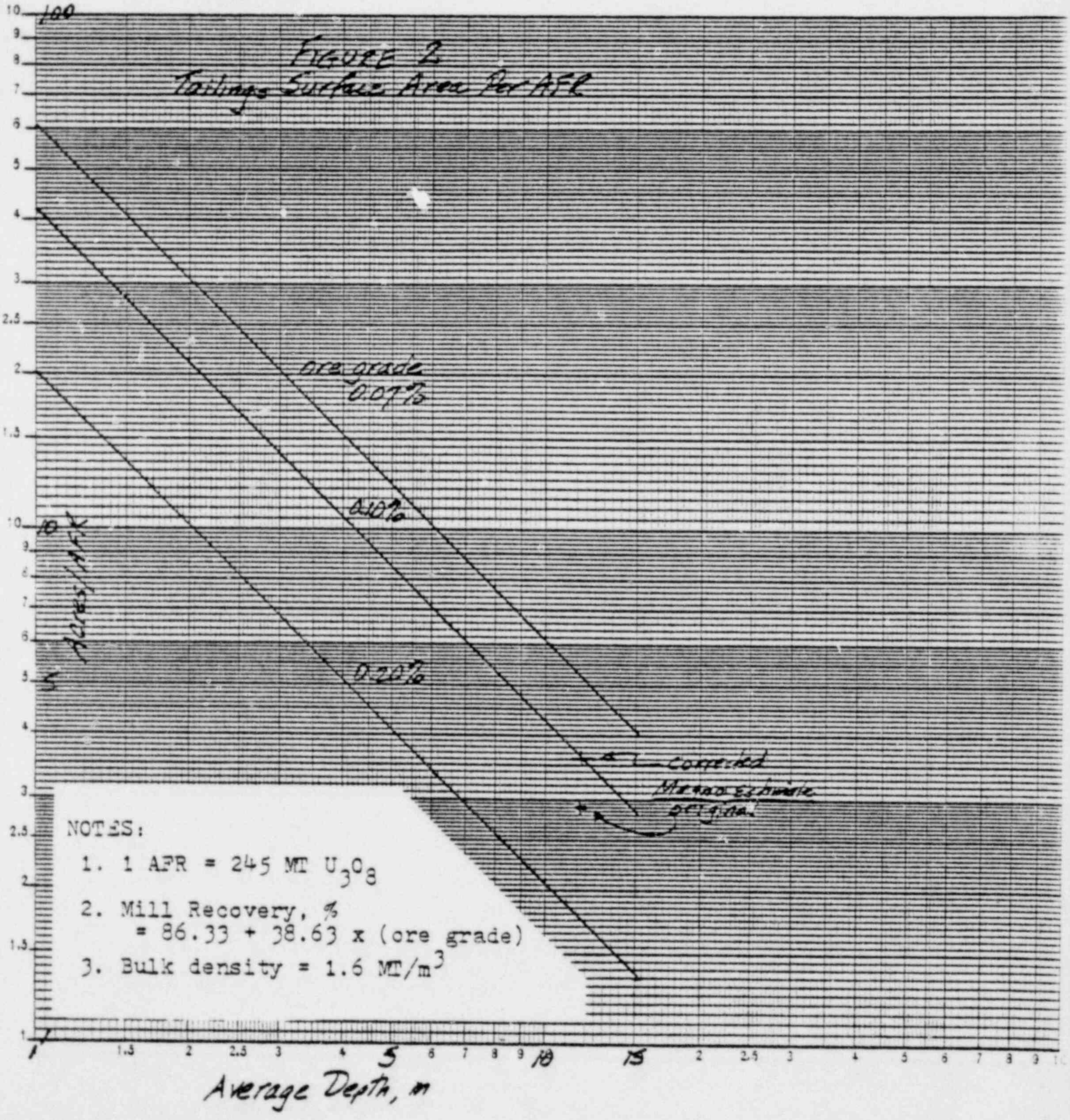

FIGURE 2
Tailings Surface Area Per AFR

NOTES:

1. 1 AFR = 245 MT U_3O_8
2. Mill Recovery, %
   = 86.33 + 38.63 x (ore grade)
3. Bulk density = 1.6 MT/m^3

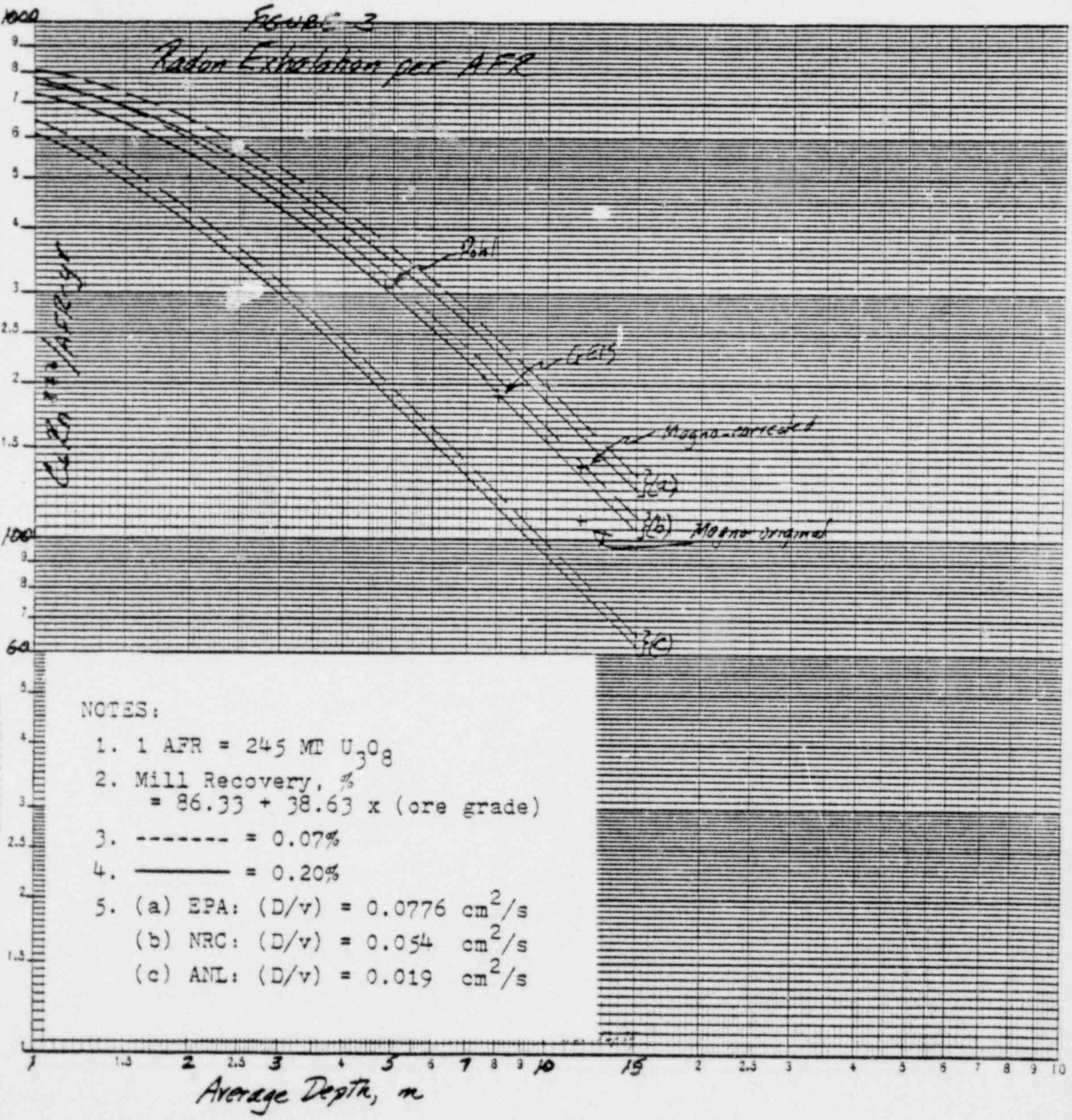

Figure 3

Radon Exhalation per AFR

NOTES:

1. 1 AFR = 245 MT U_3O_8
2. Mill Recovery, % = 86.33 + 38.63 x (ore grade)
3. ------- = 0.07%
4. ——— = 0.20%
5. (a) EPA: (D/v) = 0.0776 cm^2/s
   (b) NRC: (D/v) = 0.054 cm^2/s
   (c) ANL: (D/v) = 0.019 cm^2/s

TABLE 1

TAILINGS DISPERSION FROM INACTIVE PILES(1)

Site	Tailings Pile		Dispersed Ra-226						Fraction of Activity Dispersed
			R_t to R_1		R_t to R_2		R_t to Background		
	Area, ac.	Ci	Area, ac.	Ci	Area, ac.	Ci	Area, ac.	Ci	
Arizona									
Tuba City	27	670	128	14.7	169	15.0	202	15.0	0.0224
Colorado									
Gunnison	30	206	12	0.12	26	0.23	68	0.26	0.00126
Slick Rock (UC)	19	70	3	0.045	41	0.33	81	0.36	0.00514
Slick Rock (NC)	7	30	--	--	12	0.13	33	0.19	0.00633
Rifle (Old)	20	320	17	0.32	44	0.52	243	0.66	0.00206
Rifle (New)	21	2130	114	17.4	169	17.8	312	17.9	0.0084
New Mexico									
Ambrosia Lake	104	1520	210	7.41	390	8.78	617	8.97	0.00590
Shiprock	118	984(2)	--	--	126	0.75	229	1.03	0.00105
Texas									
Falls City	142	1020	139	2.45	256	3.34	411	3.47	0.00340
Ray Point	48	230	19	0.19	39	0.34	94	0.38	0.00165
Utah									
Salt Lake City	94	1380	114	2.36	198	3.00	510	3.24	0.00235
Green River	9	20	--	--	44	2.06	153	2.32	0.116
Mexican Hat	77	1560	--	--	127	1.53	457	2.35	0.00151
TOTAL		10,140						56.1	0.00553

(1) from ORP/LV-75-5
(2) from EPA-520/1-76-001

R_t = Equivalent Radius of Tailings Pile
R_1 = Equivalent Radius to 40 μr/hr contour
R_2 = Equivalent Radius to 10 μr/hr contour