# The Effect of Mining and Land Reclamation on the Radiological Characteristics of the Terrestrial Environment of Florida's Phosphate Regions

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## ABSTRACT

Studies were performed to evaluate the extent and nature of the redistribution of uranium-series radioactivity in phosphate mining, reclamation, and land development. Radium-226 was measured in waste materials that enter into land reclamation. Radium-226 surface soil concentrations and depth profile, soil surface radon flux, and gamma radiation above the surface were reported for unmined and mined, reclaimed, and otherwise altered lands. Mining, land reclamation, and construction site preparation can increase the near-surface soil radium and related characteristics. There is a general pattern with land type. The impact was evaluated in terms of effect on actual and potential indoor radon progeny concentrations in structures. It was concluded that debris lands, resulting from a former mining practice, represent the greatest impact on existing structures. However, a fraction of the lands produced by current practices may exceed criteria for unrestricted use if such criteria are based on limiting predicted indoor radon progeny concentrations in future structures to the lower limit of the Surgeon General's guidelines. Procedural modifications were identified for producing lands likely to meet criteria for unrestricted use.

Uranium and its decay series are associated with phosphate deposits. Recently, considerable attention has been focused on this naturally occurring radioactivity and the possible environmental effects of phosphate mining and processing, land reclamation and development, and product, by-product, and waste-product distribution, use, or disposal. In 1975 the U. S. Environmental Protection Agency (EPA) reported that the data from preliminary sampling suggested elevated levels of airborne radon progeny and a possible increased risk of lung cancer to residents in structures built on reclaimed Florida phosphate land (U. S. Environmental Protection Agency, 1975). Other impacts, including possible effects on radioactivity in ambient air, the food chain, and surface and ground water, have been raised in the press and in private discussions. The purpose of this study was to develop basic data for (1) assessing the radiological impact on the environment of mining, beneficiation, and land reclamation and (2) devising recommendations for modification of procedures to minimize such impact if indicated.

## DESCRIPTION OF PHOSPHATE LANDS AND MINING

### Location and Nature of Florida Phosphate Deposits

Present-day phosphate mining in Florida is carried out in the two districts shown in Fig. 1, the North Florida land-pebble district of

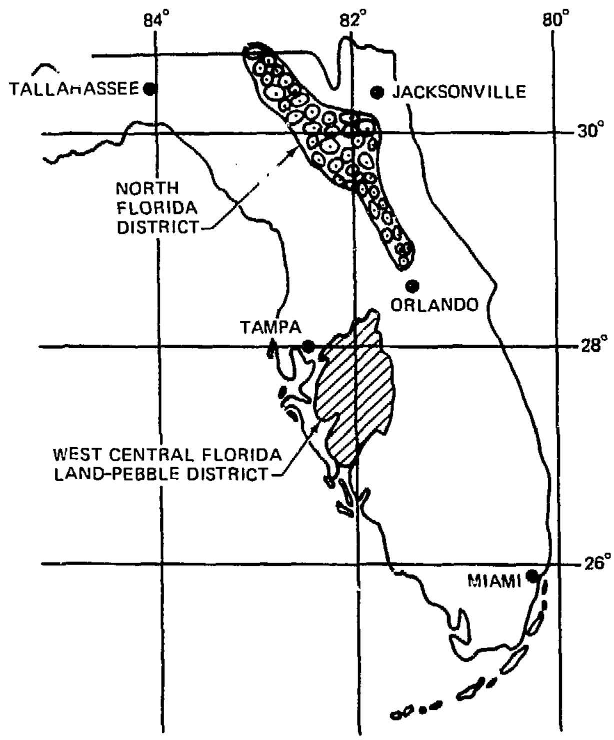


**Fig. 1 Map of Florida showing location of phosphate districts (adapted from Cathcart, 1970).**

Columbia and Hamilton counties and the Central Florida land-pebble district of Polk, Hillsborough, Manatee, Hardee, and De Soto counties (also referred to as West Central Florida and as the Bone Valley formation). The commercially recovered calcium phosphate-bearing ore or matrix ranges from <1 to 15 m thick and averages 4 m; it lies under a sand and clay overburden that varies from ~1 to 20 m thick. Much of the Central Florida matrix and some of the North Florida matrix is overlain by an irregular aluminum phosphate leached zone which may be as thick as 15 m but which is typically <1 to 5 m thick. Uranium is reported to be concentrated in the lower portion of the leached zone (Altschuler, Cathcart, and Young, 1964; Cathcart, 1970).

### Phosphate Mining and Beneficiation

The flow of the major solid materials in phosphate mining and rock beneficiation is shown in Fig. 2. The overburden is removed and cast aside so as to expose and remove the matrix. The leached zone, when present, may be designated as part of the overburden or as part

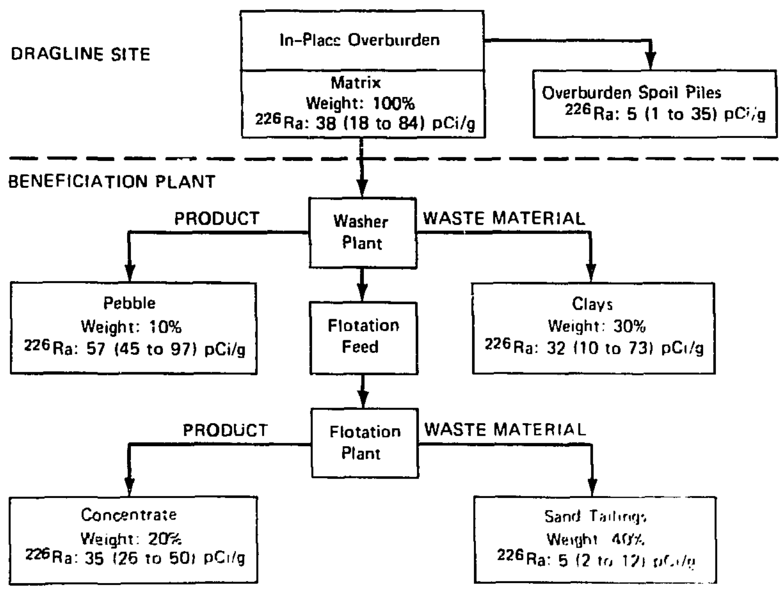


**Fig. 2 Flow diagram for major products and mineral waste products of phosphate rock mining and beneficiation. Geometric means and ranges of $^{226}$Ra are shown for Central Florida materials.**

of the matrix, depending upon the practice of the mining company; in actuality it is probably distributed between the two. In subsequent steps the matrix is slurried with water and pumped to the beneficiation plant where it undergoes washing, screening, flotation, and other sizing and separation processes. Two phosphate rock products, a coarse "pebble" fraction and a fine "rock concentrate," then become input for other steps in phosphate processing such as drying, grinding, phosphorus production, phosphoric acid manufacture, and production of fertilizer ingredients and other products, either nearby or at a remote location.

Typically, the matrix contains about ⅓ recoverable phosphate rock, about ⅓ sand, and about ⅓ nonrecoverable fine (−0.1 mm) material referred to as "clays." The sand tailings fraction is usually pumped onto the land where it rapidly dewaters. The clay suspension, often called "slimes," traditionally has been pumped to impoundments where dewatering takes place slowly. Since this conventional method of clay dewatering ties up considerable quantities of water and withholds substantial acreages of land from reclamation and productive use for many years, the industry is striving to develop alternative methods of clay dewatering and disposal. Methods under development include various schemes of mixing with sand tailings.

Prior to the 1940s, technology was not available to recover the fine phosphatic fraction (−1 mm) from the sand and, accordingly, this fraction (with its phosphate and radioactivity) also was left behind in so-called debris.

## Land Reclamation

Overburden, sand tailings, dewatered clays, and debris are returned to the land in various mixes and combinations of layering. Types of land resulting are summarized in Table 1; they are grouped into major categories according to the material judged to be most significant in determining radiological characteristics at the surface.

Very old mined lands are likely to contain overburden and debris. Reclaimed lands mined between 1940 and 1970 are likely to contain overburden spoil banks and tailings piles which have been submitted to some degree of leveling and may include dewatered clay settling areas which have been capped with overburden and/or tailings. Recently mined and reclaimed lands are likely to contain various combinations of sand tailings and overburden, with a deliberate attempt at contouring to simulate natural features of rolling terrain and lakes. In the future reclaimed lands will likely continue to have these features and increasing quantities of clays.

TABLE 1

Definition of Land Types as Used in This Study

| Land type | Description |
|---|---|
| Unaltered land | Unmined land either inside or outside of the phosphate district which has not received radioactive fill or cover. |
| Land with radioactive fill | Unmined land that has received fill or cover containing debris, leached-zone overburden, matrix-bearing material, or other materials of enhanced radioactivity. |
| Tailings reclaimed | Lands where sand tailings only were used in reclamation and no cap of overburden materials is present. |
| Overburden lands | |
| Overburden reclaimed land | Land reclaimed only by redistribution of overburden materials; frequently includes lakes in former mine cuts (also referred to as "land and lakes" reclamation). |
| Sand-fill reclamation | Sand tailings are pumped into old mine cuts to near original grade and are then capped with 1 or 2 ft of overburden from adjacent spoil piles. |
| Clays lands | |
| Reclaimed clays settling area | Former clays settling area in which the crust has been allowed to dry; may or may not be capped with overburden or tailings. |
| Sand-spray clays reclamation | Clays are pumped into an old mine cut and allowed to settle after which sand tailings are sprayed over the clays and intermixing occurs; the settling and spraying processes are repeated until the mixture fills the cut to near original grade. The mixture is allowed to dewater and is capped with overburden from surrounding spoil piles. |
| Sand—clays mix | Clays and tailings are pumped into a mine cut simultaneously until grade is reached; then the mixture is capped with overburden. This technique has largely been abandoned because of the failure of the clays and tailings to mix, but a few experimental parcels do exist. |
| Debris land | Lands upon which the fine- (<1 mm) sized fraction of the matrix was deposited. These lands originated prior to the widespread use of the flotation process to separate the 0.1- to 1-mm-sized phosphate fraction from the sand (prior to the 1940s). This material is high in phosphate and uranium-series nuclides. |

## METHODS

Approximately 100 sites, both unmined and mined, were studied in Polk County in the Central Florida phosphate mining region. In addition, a small number of unmined and reclaimed land sites were studied in the North Florida mining region.

Three principal radiological characteristics were measured: soil and other mineral radioactivity, gamma-radiation exposure rate above the surface, and land-surface radon exhalation rate or flux.

### Radioactivity Sampling and Analysis

Four types of samples were collected for radioactivity analysis. Samples to determine depth profile were collected at 13 mining and five reclaimed-land sites. These samples were collected either by drilling 6 m or more or by removing samples from the face of mine cuts. Shallow 1.8-m cores were collected with a hand auger in 0.3-m increments at the remaining sites. In addition, composite surface samples were collected at a number of sites. The first 10- to 15-cm depth was removed with a shovel; grass, roots, and twigs were discarded and several portions of soil from the vicinity were mixed to constitute a composite for the site. Finally, process materials were collected at beneficiation plants.

All samples were analyzed by high-resolution gamma-ray spectroscopy (Bolch et al., 1976).

In the analysis of the soil data, two particular depth increments were emphasized: the surface soil layer and the average layer over a 1.8-m depth. The surface soil represents the medium in which crops are grown and the zone whose radon has the greatest probability of reaching the surface. The 1.8-m layer represents the major contributor to surface radon flux (80% of the total from a typical uniform medium).

### Gamma-Radiation Levels

Gamma radiation was measured with scintillation survey meters held 1 m above the ground. These meters were intercalibrated in extended natural radiation fields with a pressurized ionization chamber. A number of readings were recorded for each site, and site means were calculated.

### Radon Flux

Radon exhalation rate, or flux, at the soil surface was measured by the flux can technique (Breslin, 1977) or by the charcoal cannister technique (Countess, 1976). Radon flux values for individual parcels of land were based on the average of from one to three replicate measurements per sampling and from one to seven samplings (at different times) per site. During the course of this study, it was determined that radon flux measurements are characterized by substantial variation in time and space and thus considerable replication is necessary to predict a site's long-term average radon flux with an acceptable degree of confidence. For detecting anomalous values and for measuring long-term average flux within a factor of two at the 95% confidence level with the techniques employed, at least three collectors should be deployed at a time and the measurement should be repeated six to eight times.

## RESULTS

### Radioactivity Profile of Unmined Lands

The radioactivity profile with depth in unmined lands indicates the baseline situation prior to mining and provides an insight as to the origin, distribution, and magnitude of the source of radioactivity potentially appearing in mined and reclaimed lands. Individual profiles of radioactivity with depth at a number of unmined sites were presented previously by Roessler, Bolch, and Groome (1976). Although considerable variation is observed from site to site, there is a general pattern of radioactivity with depth. Figure 3 shows a normalized general profile of radium concentration from the surface to the top of the matrix in unmined lands; the shaded portion of the figure represents the range of values that might be expected at any

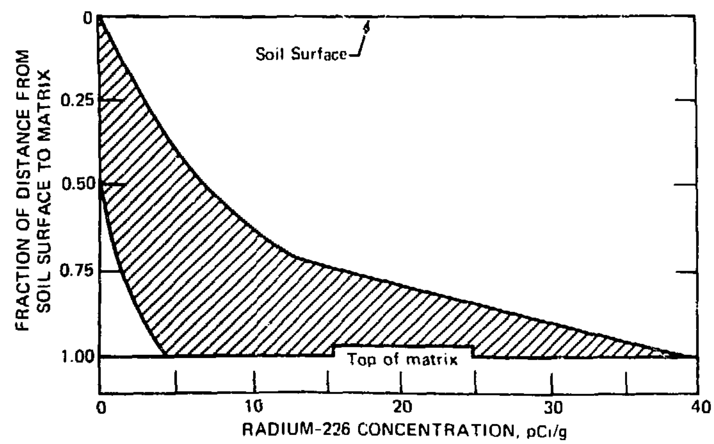


**Fig. 3 Normalized radium profile for unmined phosphate lands.**

fractional depth from the surface. In general, radioactivity is low at the surface, increases with depth, and is most concentrated in or just above the matrix.

### Inputs to Altered Land Radioactivity

Table 2 indicates the mean* and range of soil radium concentrations that were found in various layers from mining. The ranges of values for individual samples are also presented to indicate the variation that might be associated with a collection of small, discrete random samples, rather than mixing, compositing, or weighting proportionally with depth throughout the indicated layer.

The values for the upper overburden layer (0 to 1.8 m) indicate that, except where the matrix is very near the surface, mixed upper layer overburden will have relatively low radioactivity if selectively removed and placed. The other two overburden layers indicate the increased level of radioactivity likely to result from thorough mixing of the entire overburden (1) down to the leached zone and (2) down to the matrix, respectively. In practice disturbed overburden may include matrix since stripping with a dragline bucket does not achieve perfect separation at the interface. The radioactivity concentrations in the leached zone and in the matrix listed in the table indicate localized soil radium concentrations that might result from indiscriminate or adventitious placement of either of these two materials at the surface.

By-products from beneficiation represent the remaining major source of materials found in mined lands and in mining-derived fill. Table 3 summarizes the results of sampling inputs, products, and waste products of phosphate rock beneficiation. The waste-product sand tailings have lower radioactivity than the matrix but have higher concentrations than the original surface soil. Settled clays, on the other hand, represent radium concentrations similar to those of the original matrix. The majority of the radioactivity appears in the phosphate rock products which have concentrations exceeding that of the input matrix. These products are not land-reclamation materials in present-day practice; however, the material now represented by the rock concentrate was originally returned to the land without separation from the sand fraction in the debris of the preflotation mining era. If surplus or wasted phosphate rock were to be present near the land surface, this also would cause a considerable localized radiation and radioactivity enhancement.

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*The various measurements tended to be log normally distributed; hence, the geometric mean was chosen as the most representative parameter for averaging in data summaries.

TABLE 2

## Radium-226 Concentrations in Topsoil, Overburden, Leached Zone, and Matrix of Mining Lands

| Material type | $^{226}Ra$ concentration, pCi/g | |
|---|---|---|
| | North Florida | Central Florida |
| Surface soil (depth, 0 to 30 cm) | | |
| Average* | 0.4 | 0.5 |
| Range of site means | 0.2 to 0.8 | 0.2 to 3.8 |
| Range of individual samples | 0.2 to 0.8 | 0.2 to 3.8 |
| Number of sites | 3 | 5 |
| Upper layer overburden (depth, 0 to 1.8 m) | | |
| Average* | 1.3 | 0.6 |
| Range of site means | 0.6 to 4.4 | 0.3 to 2.1 |
| Range of individual samples | 0.6 to 10.6 | 0.2 to 3.8 |
| Number of sites | 3 | 6 |
| Overburden (surface to top of leached zone) | | |
| Average* | † | 1.6 |
| Range of site means | | 0.5 to 7.2 |
| Range of individual samples | | 0.2 to 7.2 |
| Number of sites | | 7 |
| Leached zone | | |
| Average* | † | 9.4 |
| Range of site means | | 2.0 to 45.6 |
| Range of individual samples | | 1.2 to 45.6 |
| Number of sites | | 7 |
| Overburden (surface to matrix) | | |
| Average* | 2.5 | 2.5 |
| Range of site means | 1.5 to 5.3 | 0.5 to 7.2 |
| Range of individual samples | 0.6 to 10.6 | 0.2 to 30.6 |
| Number of sites | 3 | 8 |
| Matrix | | |
| Average‡ | 10.9 | 25.9 |
| Range of site means | 5.1 to 31.6 | 13.2 to 84.2 |
| Range of individual samples | 2.6 to 58.8 | 6.0 to 136.5 |
| Number of sites | 6 | 13 |

*Average is the geometric mean of the site means.

†Leached zone is not present in typical North Florida profile.

‡Site means are calculated from mixed matrix samples and from depth-weighted average of cores.

TABLE 3

**Radium-226 Concentration* of Materials in Phosphate Rock Beneficiation**

| | $^{226}$Ra concentration,* pCi/g | | | | | |
|---|---|---|---|---|---|---|
| | North Florida | | | Central Florida | | |
| Material | N† | Mean | Range | N† | Mean | Range |
| Input | | | | | | |
| Matrix | 4 | 8.6 | 5.1—13.3 | 6 | 37.6 | 18.1—84.2 |
| Phosphate rock products | | | | | | |
| Pebble | 1 | 25.8 | | 13 | 57.4 | 44.5—96.5 |
| Rock concentrate | 4 | 16.6 | 16.1—16.9 | 12 | 34.9 | 26.0—50.4 |
| Waste products | | | | | | |
| Sand tailings | 4 | 2.7 | 2.0—3.3 | 24 | 5.2 | 1.7—12.2 |
| Clays | | Not sampled | | 10 | 32.4 | 9.8—72.6‡ |

*All concentrations reported on a dry-weight basis.

†N denotes number of samples in summary.

‡Based on pooling University of Florida data and data from Guimond and Windham (1975).

## Radiological Characteristics by Land Type

The results of actually measuring soil radium, gamma radiation, and soil-surface radon flux on various land types in the Central Florida mining region are summarized in Table 4 and Fig. 4. These data indicate that

(1) Mining and reclamation can cause an increase in radiation and radioactivity levels.

(2) The characteristics have a wide range of values within land types, and, thus, there is an overlap between land types. (Much of what appears to be a high site-to-site radon flux variation within land types can be attributed to inadequate replication.)

(3) A general ranking is based on radiological characteristics: unaltered land $<$ tailings $\leqslant$ overburden $<$ debris.

(4) Settled clays have a high radium content, but, since the data represent a composite of a few samples from each of a variety of different practices, it is difficult to draw conclusions.

(5) The greatest radiation and radioactivity values are associated with debris lands and thus not with present or future mining practices.

(6) The indiscriminate choice of fill materials also can result in increases in the radiological parameters measured.

TABLE 4

**Summary of Radiological Characteristics of Various Land Types**

| | $^{226}$Ra content, pCi/g | | | | | | Gamma level, μR/hr | | | Radon flux, pCi $m^{-2}$ $sec^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Surface soil (0—0.3 m) | | | Soil core (0—1.8 m) | | | | | | | | |
| Land type | N* | Mean† | Range | N* | Mean† | Range | N* | Mean† | Range | N* | Mean† | Range |
| Unaltered land | 20 | 0.6 | 0.1—3.8 | 18 | 0.4 | 0.2—3.1 | 9 | 5 | 4—7 | 17 | 0.2 | <0.1—1.7 |
| Unmined radioactive fill | 2 | 3.2 | 2.5—4.1 | 2 | 2.2 | 1.1—4.4 | 1 | 9 | | 2 | 1.3 | 0.6—2.8 |
| Tailings | 20 | 3.2 | 0.4—9.2 | 16 | 3.1 | 0.5—8.7 | 11 | 11 | 6—16 | 19 | 0.7 | <0.1—2.7 |
| All overburden‡ | 28 | 5.0 | 0.8—35.3 | 24 | 5.3 | 1.0—23.1 | 16 | 13 | 7—33 | 27 | 1.5 | <0.1—12.8 |
| Capped and mixed clays§ | 6 | 6.8 | 3.3—14.6 | 6 | 7.4 | 2.8—18.3 | 6 | 17 | 11—24 | 6 | 1.6 | 0.3—7.2 |
| Debris | 18 | 9.5 | 3.4—23.3 | 18 | 7.3 | 3.1—24.7 | 8 | 22 | 11—54 | 15 | 4.2 | 1.7—13.7 |

*N denotes number of sites in summary.

†Means are geometric means of average values for N sites of indicated land type.

‡Overburden category includes (1) reclaimed overburden piles and (2) sand-fill reclamations capped with overburden.

§Clays category includes (1) settled clays areas capped with overburden and/or tailings and (2) clays—sand mixtures capped with overburden.

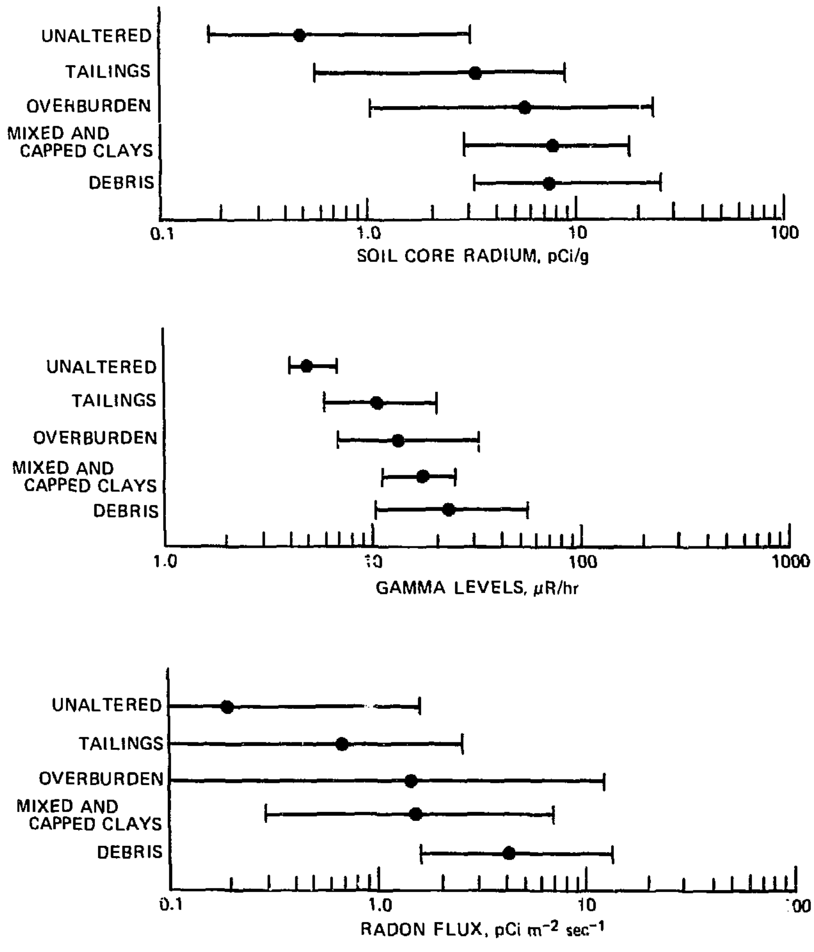


**Fig. 4 Radiological characteristics of Polk County lands. Geometric means and ranges are shown by land type.**

Samples at nine unaltered land sites in North Florida indicated surface soil radium concentrations and gamma-radiation levels essentially the same as those reported in Table 4. The average 1.8-m soil-core radium concentration, 1.0 pCi/g, and the radon flux value, 0.7 pCi $m^{-2}$ $sec^{-1}$, were slightly higher than the unaltered-land values in Table 4; thus a thinner overburden is reflected at the North Florida sampling sites. Sampling one parcel each of tailings and overburden reclaimed land in the North Florida mining region gave respective soil radium concentrations of 4.8 and 8.1 pCi/g, gamma-radiation levels of 9.8 and 7.9 $\mu$R/hr, and radon flux values of 1.2 and 3.0 pCi $m^{-2}$ $sec^{-1}$. These values fall about midrange in the data for similar land types in Table 4. This very limited sampling suggests that radiological characteristics of mined lands in the North Florida mining region do not differ greatly from those reported for the Central Florida mining region.

## DISCUSSION

The impact of the redistribution of natural radioactivity by phosphate mining and land reclamation can be assessed in terms of radiation exposure routes through the environment to man. Such potential routes encompass exposure to direct gamma-radiation and radionuclide transfer routes, including those involving (1) airborne radon and progeny in structures, (2) radionuclide uptake by plants and transfer through the food chain, (3) radionuclides in surface and ground water, and (4) ambient airborne radioactivity.

It is not the intent of this paper to relate a detailed environmental impact analysis. However, the scope of some of the potential impacts can be defined rather easily without elaborate analysis.

### Direct Gamma Radiation

For persons continuously present with no attenuation from structures or vehicles, the observed average increments of gamma-radiation exposure above the average unaltered-lands background represent annual whole-body dose equivalents of 50, 70, 100, and 150 mrems for tailings, overburden, clays, and debris lands, respectively. These values are all less than 170 mrems/annum, the guideline recommended by the Federal Radiation Council (1960) for average exposure to a population group.

The maximum gamma-radiation exposure rates represent increments above background of about 100, 250, 150, and 425 mrems/annum for tailings, overburden, clays, and debris lands, respectively. These values are all less than the Federal Radiation Council guideline of 500 mrems/annum above background for any individual of the general population.

Structures built over these lands are likely to attenuate these radiation levels. If adjustments were made for the effects of time spent indoors and of time spent away from these lands, then both the average and the maximum doses would be less than those cited, and the number of individuals receiving the maximum would be small.

**Impact via Indoor Radon Progeny**

Although all the radionuclide transfer routes previously cited should be considered, the greatest efforts to date have been directed toward studying indoor radon progeny concentrations and their interrelationships with Florida phosphate lands. Assessment of impact via this route is limited by the facts that a consensus has not yet emerged on appropriate standards for indoor radon progeny concentrations, satisfactory models relating characteristics of Florida lands to human exposure by various routes are lacking, and there are insufficient predictive standards for application to undeveloped lands.

One point of reference on which to base evaluation criteria is the guidance issued by the Surgeon General for use in the state of Colorado for assessing dwellings constructed over uranium mill tailings (Surgeon General, 1970). According to these guidelines, no remedial action is indicated for structures where indoor airborne radon progeny levels are less than 0.01 WL above background, remedial action is indicated for concentrations exceeding 0.05 WL above background, and remedial action may be indicated for concentrations between these two values.*

*Impact on Existing Structures*

After reviewing the available data, the Florida Department of Health and Rehabilitative Services (HRS) in 1978 adopted a control level of 0.029 WL (0.025 WL above an average indoor background of 0.004 WL) for existing structures in Florida. The HRS has estimated that, of the approximately 4000 structures on reclaimed land in the Central Florida mining region, 6 to 10% will require some kind of corrective action to achieve the control level of 0.029 WL.

Analysis of the HRS findings and of additional University of Florida data leads to the conclusion that most of the structures exceeding the HRS control level were on debris lands. Furthermore, for lands with more than about 10 pCi/g of radium-226, indoor radon progeny levels in conventional slab-on-grade buildings constructed without incorporation of land cover or other remedial measures are likely to exceed the HRS control level. On the other

*WL represents "working level," a unit defined for expressing concentrations of short-lived radon progeny in air. One WL is any combination of radon progeny in 1 liter of air whose ultimate decay through polonium-214 will deliver $1.3 \times 10^5$ MeV of alpha-particle energy. This is the same quantity of energy as that delivered by the alpha particles from the complete decay of the radon progeny in secular equilibrium with 100 pCi of radon-222 in 1 liter of air.

hand, tailings lands and overburden lands without leached-zone material or adventitious matrix are not likely to have this level of soil radium, and relatively few structures on such lands are likely to have indoor radon progeny levels exceeding the HRS control level. No slab-on-grade structures currently exist on clays.

*Impact on Future Structures*

Of particular importance is the impact with respect to future structures on currently undeveloped lands and on lands mined and reclaimed in the future. When the lower range of the Surgeon General's guidelines (0.01 WL above background) is used as a basis for discussion and when the HRS estimate of 0.004 WL is adopted as the average indoor background, 0.014 WL becomes the reference indoor radon progeny concentration upon which to base lands criteria for unrestricted construction.

Modeling work still in progress indicates that, for limiting indoor radon progeny levels in conventionally constructed slab-on-grade structures to no more than 0.014 WL without remedial action measures, the appropriate lands criteria are approximately 10 $\mu$R/hr of gamma radiation, 4 pCi/g of soil radium, or 3 pCi $m^{-2}$ $sec^{-1}$ of radon flux. From the data presented in Table 4 and Fig. 4, it is concluded that, in addition to the lands cited above, about one-half the tailings and overburden lands reclaimed according to current practices would exceed these criteria.

Soil radium can also be expected to exceed 4 pCi/g in future clays reclamations. Preliminary information suggests that radon exhalation from clays lands will be comparable to that from other soils of similar radium content, but at present there is insufficient information on radon emanating and transport properties of such mixtures.

## Measures to Moderate the Impact of Radioactivity in Phosphate Lands

The major impacts demonstrated to date from the redistribution of natural radioactivity in the course of phosphate mining, reclamation, and land development have been the existing and the projected contributions to airborne radon progeny in structures. Fortunately, in many cases land and materials management techniques can be used to obviate the need for imposing land-use restrictions or requiring the incorporation of remedial measures into new structures.

Three areas in which to apply such techniques are

1. Site preparation and building construction avoiding the use of fill materials containing radium-226 in concentrations greater than several picocuries per gram.

2. Utilization of existing lands where possible, covering or replacing high-radioactivity or high-radon-flux land with a sufficient depth of low-radioactivity material.

3. Future mining and land reclamation with simulation of the natural situation by selectively placing higher radioactivity material under a lower radioactivity cover.

The high-radioactivity materials to avoid as fill and upper-layer materials include debris, lower-layer overburden containing leached-zone material and adventitious matrix, waste phosphate rock, and sand tailings. The data in Table 2 and Fig. 3 indicate that, with the possible exception of locations with thin overburden, sufficient low-radioactivity overburden should be available for use as fill or cover.

Suggested modifications in mining and land-reclamation procedures include placing clays, lower-layer overburden, and sand tailings in the bottom of empty cuts and covering these materials with the lower-activity upper-layer overburden from another cut. Engineering methods, based on radon-flux prediction, are currently being developed for use in designing and evaluating specific materials placement strategies.

## CONCLUSIONS

In the natural state the uranium-series radioactivity associated with phosphate deposits is buried under sufficient low-radioactivity cover (Fig. 3) to substantially moderate any effects at the land surface. In the process of mining and land reclamation, this naturally occurring radioactivity is redistributed with a likely increase of near-surface soil radium and a resultant increase in soil surface radon flux and above-surface gamma-radiation levels. Although there are wide ranges of values within and considerable overlapping between land types, there is a general pattern of radiological characteristics with land type as shown in Fig. 4.

This redistribution of radioactivity has a significant impact in that several hundred structures were reported to exceed the Florida Department of Health and Rehabilitative Services 0.029 WL control level for existing structures. Interestingly, these structures are believed to be primarily on debris lands; such lands are the result of pre-1940s mining techniques and are not produced by present mining practices. If lands criteria traceable to the lower-level Surgeon General's guideline of 0.01 WL above background are applied for lands to be used for new construction, it is concluded that some of the overburden and tailings reclaimed lands produced by current and proposed mining and reclamation techniques would exceed criteria for construction of slab-on-grade structures without remedial action.

The impact on future construction, however, can be substantially moderated by avoiding the use of materials of designated high radium content for fill, by covering or replacing soil of high radioactivity in the development of existing lands, and by modifying mining and land-reclamation techniques to selectively place designated high-radioactivity materials under a cover of materials selected for low radioactivity.

The indoor airborne radon progeny pathway is probably the most significant exposure route associated with this radioactivity source; however, other routes through the environment to man should be evaluated as well.

## ACKNOWLEDGMENTS

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## DISCUSSION

**Tanner:** Were you able to discriminate between radon and thoron in your measurements of flux in northern Florida? An aeroradiometric survey in 1954 by the U. S. Geological Service of potential phosphate areas in Florida yielded a weak, factor-of-2 anomaly that I studied subsequently by measuring soil-gas samples and then by drilling and measuring the radon in shallow groundwater. The anomaly was related primarily to thoron. The water samples did not support the idea of upward movement of radon.

**Roessler:** We did not attempt to distinguish $^{220}Rn$ from $^{222}Rn$ or to quantitate $^{220}Rn$ flux. We are aware of the heavy mineral deposits to the east of the area identified in Fig. 1 as North Florida Phosphate Region. My initial reaction is that the thoron you observed was related to similar deposits. I do not think a significant amount of thoron was involved in our measurements. We would like to have a copy of your report so we can follow through on this.