Effluent and Environmental Monitoring Techniques

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Module Objectives

- **Describe potential source terms from uranium recovery operations.**

- **Describe airborne effluent monitoring programs.**

- **Describe liquid effluent monitoring programs.**

- **Describe estimating of radon source terms.**

- **Discuss computer codes used for environmental dose modeling.**

Effluent and Environmental Monitoring

- All uranium recovery sites must conduct effluent and environmental monitoring to demonstrate compliance with both NRC and EPA regulations.

- Monitoring programs must take into account possible source terms and background conditions.

- The main source terms are airborne and liquid emissions from processing activities.

Airborne Particulate and Radon Source Term Estimations

Airborne Source Terms

- **Estimations of the location and extent of effluent source terms is essential to creating an effective environmental monitoring program.**

- **The main source terms for airborne radioactive material are:**

  - **Uranium particulate emissions from yellowcake drying at ISR mills and ore crushing operations at conventional uranium mills.**

  - **Radon gas emissions from tailings piles and dry ore operations at conventional mills and from lixiviant circulation and evaporation ponds for ISL mills.**

Airborne Particulate Source Terms

- **Processes that release airborne particles at conventional mills include:**

    - ore handling

    - grinding

    - crushing

    - conveying

    - yellowcake drying.

- **For ISR facilities yellowcake drying is the main particulate airborne source term.**

Estimating Airborne Particulate Source Terms

- The general method for estimating source terms is to multiply together the normalized emission rate, contaminant content, emission control factor, and processing rate for each process being evaluated.

- Regulatory Guide 3.59 "Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations" provides the general equations to use for source term estimation.

- Similar source term calculations can be found in Appendix D of NUREG 1569 "Standard Review Plan for In Situ Leach uranium Extraction License Applications."

- The follow section considers some selected source term calculations from Reg Guide 3.59.

General Source Term Equation

$$S = M \, C \, E \, N \, (1 - R)$$

S = source term (kg U-238/hr or Ci U-238/yr)

M = process rate (metric ton / yr)

C = contaminant concentration (pCi/g uranium)

E = emission factor for process (dust released per metric ton of material)

N = enrichment ratio (amount of uranium in dust as compared to ore)

R = emission control factor (amount of reduction in dust caused by emission control devices)

Notes on the General Source Term Equation

- This is a general equation some parts of the equation may not be used or may be modified.

- Conversion factors for units are needed when using the equation.

- N can be changed to any type of ratio which calculates the amount of radioactive material released from the source. The NRC default is 2.5.

- Values for E are found in Appendix B of Reg Guide 3.59.

- Values for R can be found in Appendix C of Reg Guide 3.59

- If using weight of U_3O_8 must account for oxygen content when determining uranium concentration use 0.85 g U / g U_3O_8.

Example Calculation: Particulate Release for Yellowcake Dryer

Estimate the release from the stack of a yellowcake dryer with a production of 200 Metric tons/year of which 90 percent is U_3O_8

- M = 200 MT/yr

- C = 3.33 x 10^{-7} Ci/g U-238

- E = 0.1% based on EPA measurements at six mills

- N, the enrichment ratio, is not used

- R, the emission control factor, is taken into account in E

S = M C E N (1 – R)

= 200 (MT/y) x 0.9 x 10^6 (g/MT) x 3.33 x 10^{-7} (Ci/g) x 0.85 (g of U per g of U_3O_8) 0.001

= 0.051 Ci/y of U-238

Radon Release at Conventional Mills

- **Major pathways for radon release at conventional uranium mills:**

    - Ore storage

    - Ore crushing and grinding

    - Mill tailings disposal

Example Calculation: Radon Release for Ore Storage at Conventional Mill

The equation to calculate radon source term (S) from ore stockpiled on storage pads is:

$$S = C \ F \ A$$

C is the Ra-226 concentration in the ore (e.g., pCi/g)

F is the flux factor (e.g., pCi of Rn-222/m^2-s per pCi/g of Ra-226)

A is the area of the ore stockpile (e.g., m^2)

Example Calculation: Radon Release for Ore Storage at Conventional Mill

In this example, the average Ra-226 concentration in the ore is 300 pCi/g and the storage pad area is 3 hectares. An acceptable flux factor is considered to be 1 pCi of Rn-222/m^2-s per pCi/g of Ra-226.

S = C F A

$\quad$ = 300 (pCi of Ra-226/g) x 1 (pCi of Rn-222/m^2-s per pCi of Ra-226/g) x 3 (ha) x 10^4 (m^2/ha) x 3.156 x 10^7 (s/y)

$\quad$ = 2.84 x 10^{14} pCi of Rn-222 per year

$\quad$ = 284 Ci of Rn-222 per year

Example Calculation: Radon Release for Ore Crushing and Grinding at Conventional Mill

It is estimated that less than 10% of the radon in the ore is released during crushing and grinding.

$$S = M C E$$

$$= 135,000 \text{ (MT/y)} \times 10^6 \text{ (g/MT)} \ 350 \text{ (pCi/g)} \times 10^{-12} \text{ (Ci/pCi)} \times 0.1$$

$$= 4.73 \text{ Ci of Rn-222 per year}$$

Example Calculation: Radon Release from Active Mill Tailings

Although the situation with mill tailings is far more complicated, Regulatory Guide 3.59 uses the same equation that was used for ore storage. In this example, the average Ra-226 concentration in the tailings is 300 pCi/g and the tailings area is 50 hectares. An acceptable flux factor is considered to be 1 pCi of Rn-222/m^2-s per pCi/g of Ra-226.

S = C F A

= 300 (pCi of Ra-226/g) x 1 (pCi of Rn-222/m^2-s per pCi of Ra-226/g) x 50 (ha) x 10^4 (m^2/ha) x 3.156 x 10^7 (s/y)

= 4.734 x 10^{15} pCi of Rn-222 per year

= 4,734 Ci of Rn-222 per year

Radon Release From ISR Operations

- **Major pathways for radon release at ISR facilities:**

    - leaching (production)

    - soaking and startup

    - restoration of the groundwater

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Radon Release From ISR Operations

- **The major source of radon release is the lixiviant which, when exposed to the atmosphere, will release radon.**

- **The release will occur when the lixiviant arrives at the process recovery surge tanks, ion exchange tanks, or columns, or settling ponds.**

- **Aquifer restoration is also a source of radon that must be considered.**

Radon Release From ISR Operations

- **The key parameters used to determine the average annual radon release are:**

  - **Ore grade (% U_3O_8)**

  - **Mined area per year (e.g., m^2)**

  - **Average lixiviant flow rate (e.g., L/min)**

  - **Average restoration flow rate (e.g., L/min)**

  - **Duration of operation (e.g., days)**

  - **Formation thickness (e.g., m)**

Radon Release From ISR Operations

- Formation porosity

- Rock density (e.g., g/cm^2)

- Residence time for lixiviant (e.g., days)

- Residence time for restoration solution (e.g., days)

- Emanating power of the ore

Radon Release From ISR Operations

- **If the Ra-226 content of the ore has not been measured, it is assumed that the U-238 is in equilibrium with all of its daughters.**

- **The Ra-226 and Rn-222 concentration present in the ore would therefore be 2820 pCi/g per % U_3O_8.**

- **The radon emanating power is assumed to average 0.2 unless otherwise determined.**

Radon Release From ISR Operations

- **To determine the annual radon release at an ISR facility, it might be assumed that:**

  one mining unit is leached

  one unit soaked

  one unit restored

- **We will now perform an example calculation of the radon release at an ISR facility for all three source terms.**

- **Release during startup will also be factored in to the calculation.**

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Example Calculation: Radon Release From an In Situ Recovery Facility

Assumptions:

- Ore Grade $\quad\quad\quad\quad\quad\quad$ 0.1% U_3O_8
- Average area to be mined $\quad$ 10 acres
- Average lixiviant flow $\quad\quad$ 4000 L/min
- Average restoration flow $\quad$ 400 L/min
- Operating days per year $\quad$ 365
- Formation thickness $\quad\quad$ 3 m
- Formation porosity $\quad\quad\quad$ 0.3
- Rock Density $\quad\quad\quad\quad\quad$ 1.8 g/cm^3
- Residence time for lixiviant $\quad$ 5 days
- Residence time for restoration $\quad$ 10 days
- Emanating power $\quad\quad\quad\quad$ 0.2

Example Calculation: Radon Release From an In Situ Recovery Facility

First we must calculate the equilibrium radon concentration in the soil pores.

$$G = \frac{R\rho E(1-p)}{p \times 10^6}$$

G = radon release (e.g., Ci/m$^{3)}$

R = radium content (e.g., pCi/g)

ρ = rock density (e.g., g/cm^3)

E = emanating power

p = formation porosity

10^6 is a conversion factor in cm^3/m^3 and pCi/Ci

Example Calculation: Radon Release From an In Situ Recovery Facility

To calculate the equilibrium radon concentration in the ore, we need the radium concentration in the ore (R):

R = 3.33 x 10^5 (pCi of U-238/g of uranium) x 0.001 (g of U_3O_8/g of ore)
  x 0.85 (g of uranium/g of U_3O_8)

  = 28.3 pCi of Ra-226 per gram of ore

Example Calculation: Radon Release From an In Situ Recovery Facility

Now we can calculate the equilibrium radon concentration in the ore:

$$G = \frac{R\,\rho\,E\,(1-p)}{p}$$

$$= \frac{28.3\,pCi/g\ x\ 10^{-12}\,Ci/pCi\ x\ 1.8\,g/cm^2\ x\ 10^6\,cm^3/m^3\ x\ 0.2(1-0.3)}{0.3}$$

$$= 2.4\,x10^{-5}\,Ci/m^3$$

Note that the example in Reg Guide 3.59 is off by an order of magnitude. They incorrectly multiplied by 0.1%.

Example Calculation: Radon Release From an In Situ Recovery Facility

Now we will calculate the annual radon release due to:

one field (mining unit) being leached

one field (mining unit) being soaked

one field (mining unit) being restored

Radon release during startup, which must be accounted for, is assumed to be the same as the release due to soaking.

These source terms will then be summed.

Example Calculation: Radon Release From Leaching Operations

The yearly radon release Y (Ci/yr) is calculated by:

$$Y = G\,M\,\varepsilon\,D \times 1.44$$

G = radon release at equilibrium (Ci/m^3 of rock)

M = lixiviant production rate (e.g., L/min)

ε = equilibrium factor for radon ($1 - e^{-\lambda t}$) where λ is the radon decay constant and t is the residence time.

D = production days per year

1.44 is a conversion factor in m^3/L and min/day.

Example Calculation: Radon Release From Leaching Operations

To calculate the yearly release of radon due to leaching operations we need to calculate the equilibrium factor:

$$\varepsilon = 1 - e^{-\lambda t}$$

$$= 1 - e^{-0.181\,d^{-1}\,x\,5\,d}$$

$$= 1 - 0.4$$

$$= 0.6$$

Example Calculation: Radon Release From Leaching Operations

The yearly release of radon due to leaching operations (i.e., production) is:

Y $=$ $1.44\ G\ M\ \varepsilon\ D$

       $=$ $1.44 \times 2.4 \times 10^{-5}\ Ci/m^3 \times 4000\ L\ /min\ \times 0.6\ \times\ 365\ d/y$

       $=$ $30.0\ Ci/y$

Example Calculation: Radon Release From Soaking and Startup

- It is estimated that one pore volume of nonproduction solution will be removed as each mining unit is soaked.

- The radon release (S) is calculated as:

$$S = G\,A\,T\,\rho$$

G = radon release at equilibrium (Ci/m^3 of rock)

A = area of mining unit (m^2)

T = thickness of ore (m)

ρ = formation porosity

Example Calculation: Radon Release From Soaking and Startup

The Rn-222 release during soaking and startup is calculated as follows:

$$S = G\,A\,T\,p$$

$$= 2.4 \times 10^{-5} \text{ Ci/m}^3 \times 10 \text{ acres} \times 4074 \text{ m}^2/\text{acre} \times 3 \text{ m} \times 0.3$$

$$= 0.9 \text{ Ci/y for soaking and } 0.9 \text{ Ci/y during startup}$$

Example Calculation: Radon Release During Restoration

The equation used to calculate the annual radon released during restoration(r) in Ci/y is the same as for leaching:

$$r = 1.44 \; G \; N \; \varepsilon \; D$$

G = radon release at equilibrium (Ci/m^3 of rock)

N = restoration solution rate (L/min)

ε = equilibrium factor

D = restoration days per year

1.44 is a conversion factor in m^3/L and min/day

As with startup it is assumed that one pore volume of solution is removed before restoration begins.

Example Calculation: Radon Release During Restoration

To calculate the yearly release of radon due to restoration operations we need to calculate the equilibrium factor:

$$\varepsilon = 1 - e^{-\lambda t}$$

$$= 1 - e^{-0.181\, d^{-1}\, x 10\, d}$$

$$= 1 - 0.16$$

$$= 0.84$$

Example Calculation: Radon Release During Restoration

The radon release from restoration activities is:

r = 1.44 G M ε D

= 1.44 x 2.4 x 10^{-5} Ci/m^3 x 400 L /min x 0.84 x 365 d/y

= 4.2 Ci/y

This is adjusted upward to account for a small release similar in magnitude to the release during startup (0.9 Ci/y)

Total release during restoration = 4.2 Ci/y + 0.9 Ci/y

= 5.1 Ci/y

Example Calculation: Radon Release From an In Situ Recovery Facility

The total release of radon from startup solution, production lixiviant, and soaking is:

Leaching (production)	30.0 Ci/y
Soaking	0.9 Ci/y
Startup	0.9 Ci/yr
Restoration	5.1 Ci/yr
Total	**36.9 Ci/yr**

Liquid Effluents

Liquid Effluents

- The liquid effluents from uranium recovery are predominately production bleed (1% to 3% of the process flow rate) and aquifer restoration water for ISR facilities and raffinate for conventional mills.

- The liquid effluents from ISR facilities can be handled by a waste water treatment facility, placed in an evaporation pond, or deep well injected.

- At conventional mills the liquid effluents are placed with the mill tailings pile.

Evaporation Ponds

- **Evaporation ponds are used to retain the process related liquid effluents that cannot be discharged directly to the environment.**

- **The sludge from the settling (evaporation) ponds is usually left in place until the facility is decommissioned.**

- **Settling ponds are designed with leak detection systems to detect liner failures.**

- **Licensees must maintain sufficient pond capacity that the contents of one pond can be transferred to another in the event of a liner leak.**

Waste Water Treatment

- **Liquid effluents can be treated in a waste water treatment facility to reduce the amounts of radioactive material to meet release standards.**

- **The water can then be discharged to surface water if the facility has a National Pollution Discharge Elimination System (NPDES) permit**

Deep Well Injection

- Deep well injection involves pumping the waste fluids into a deep confined aquifer at depths typically greater than 5000 ft below ground surface.

- The most common liquid approved for this method is the brine from the reverse osmosis system.

- This also requires a NPDES permit.

Computer Codes for Compliance

Computer Codes for Compliance

- Computer codes can be used for dose modeling due to environmental releases.

- Some examples are:
  - RESRAD has been used to determine cleanup standards by estimating doses based on several inputs.

  - CAP88PC or COMPLY can be used to demonstrate compliance with air emission regulations when the facility discharges via a stack.

  - MILDOSE can be used to evaluate radiological impacts of uranium processing facilities.

MILDOSE

- **Current version of MILDOSE is MILDOSE-AREA which incorporated the ICRP 30 recommendations for dose calculations due to airborne emissions of U-238 and daughter products.**

- **MILDOSE-AREA also takes into account operations at a ISL mine and mill for dose calculations.**

- **MILDOSE dose calculations similar to what was presented above for radon release.**

- **MILDOSE also calculates the amount of U-238 released up a stack by assuming that 0.1% of yellowcake in a dryer is released.**

MILDOSE

- Once the source term is calculated MILDOSE uses a Gaussian plume model to calculate the dose to a downwind receptor.

- The location of activities and the location of the receptor is input into the software.

- This code does not appear to have been validated.

Environmental Monitoring Programs

Environmental Monitoring Programs

- An environmental sampling and monitoring program has two phases:

    - Preoperational

    - Operational

- Preoperational data is submitted to the NRC as part of the application process.

- Operational data is reported as required by 10CFR40.65 and the facilities license.

- The following guidance is from NRC Regulatory Guide 4.14 "Radiological Effluent and Environmental Monitoring at Uranium Mills."

Preoperational Monitoring

- At least 12 months of data should be submitted before beginning milling operations. Might begin before building construction.

- Must not do beyond what is permitted.

- A preoperational program should consists of:

    - Air Samples

    - Water Samples

    - Vegetation, food, and fish samples

    - Soil and sediment samples

    - Direct radiation

    - Radon flux samples

Preoperational Air Monitoring

- Air samples should be collected at a minimum of three locations near the site boundary.

- If there are residences or occupiable structures within 10 km a continuous outdoor air sample should be collected at or near the structure with the highest predicted airborne radionuclide concentration due to activities.

- A continuous air sample should be collected at a remote location that represents background conditions.

- Normally filters are changed on a weekly basis dependent on filter loading.

- Rn-222 samples should be collected at least one week per month

Preoperational Air Monitoring

- **Meteorological data should be obtained (ca. 1 year)**

- **Met data should be obtained onsite if at all possible.**

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Preoperational Air Monitoring

Preoperational Air Monitoring

Inside of environmental air sampling station

Preoperational Water Samples

- Sample of ground water should be collected quarterly from at least three sampling wells located down gradient from operations.

- Ground water samples should also be collected quarterly from each well within 2 km from operations that is or could be used as a water source for humans, livestock, or irrigation.

- Samples from surface water should be collected quarterly from each onsite or offsite water impoundment that may be affected by leaks from operations.

- Samples should be collected at least monthly from streams, rivers, and any other water source that may be affected by operations

Preoperational Water Samples

Sampling surface water

Preoperational Water Samples

Sampling groundwater

Preoperational Vegetation, Food, and Fish Samples

- Forage vegetation should be sampled at least three times during grazing season in grazing areas in three different sectors having the highest predicted airborne radionuclide concentrations due to operations.

- At three samples should be collected at time of harvest, slaughter, or removal of animals from grazing for each type of crop or livestock raised within 3 km of the mill site.

- Fish (if any) samples should be collected semiannually from any bodies of water that may be subject to seepage or surface drainage from potentially contaminated areas.

Preoperational Soil and Sediment Samples

- **Surface soil samples (to a depth of 5 cm) should be collected using a consistent technique at 300 m intervals in each of the eight compass directions out to a distance of 1500 m from the center of the milling area.**

- **Surface soil samples should also be collected at each of the locations chosen for air samplers.**

- **Subsurface samples (to a depth of 1 m) should be collected at the center of the milling area and at a distance of 750 m in each of the four compass directions.**

- **Sediment should be collected from surface water sampling locations.**

Preoperational Direct Radiation Measurements

- Gamma exposure rate measurements should be conducted before mill construction at 150 meter intervals in each of the eight compass directions out to a distance of 1500 meters from the center of the mill area.

- Measurements should be made with a passive integrating device such at a TLD or OSL, pressurized ion chambers, or properly calibrated survey instruments.

- Direct radiation measurements should be made at air sampling locations

- Measurements should be made in dry weather.

Preoperational Direct Radiation Measurements

- **Environmental dosimeters (TLD) in plastic bag attached to one side of pole.**

- **Should consider potential for photon attenuation by pole.**

- **White chamber on right side of pole houses radon monitor**

Preoperational Direct Radiation Measurements

- Use of GPS based data logging and plotting software desirable.

Preoperational Radon Flux Measurements

- **Rn-222 flux measurements should be made in three separate months during normal weather conditions in the spring through fall when the ground is thawed.**

- **The measurements should be made at the center of the milling area and at locations 750 and 1500 meters from the center in each of the four compass directions.**

Operational Monitoring

- Operational monitoring are similar to the preoperational monitoring program.

- The results of operational monitoring programs should be summarized quarterly and reported semiannually in accordance with 10CFR40.65

Operational Stack Sampling

- **Effluents from yellowcake dryer and packaging stacks should be sampled at least quarterly during normal operations.**

- **The sampling should be isokinetic, representative, and adequate for determination of the release rates and concentrations of radionuclides**

- **Other stacks should be sampled semiannually, the sampling has to be representative (not isokinetic) and adequate to determine the release rates and concentrations of radionuclides.**

- **All stack flows should be measured at the time of sampling.**

Operational Water Samples

- Sample of ground water should be collected monthly for the first year then quarterly from at least three sampling wells located down gradient from operations.

- Ground water samples should also be collected quarterly from each well within 2 km from operations that is or could be used as a water source for humans, livestock, or irrigation.

- Samples from surface water should be collected quarterly from each onsite or offsite water impoundment that may be affected by leaks from operations.

- Samples should be collected at least monthly from streams, rivers, and any other water source that may be affected by operations

Operational Vegetation, Food, and Fish Samples

- **Forage vegetation should be sampled at least three times during grazing season in grazing areas in three different sectors having the highest predicted airborne radionuclide concentrations due to operations.**

- **At three samples should be collected at time of harvest, slaughter, or removal of animals from grazing for each type of crop or livestock raised within 3 km of the mill site.**

- **Fish (if any) samples should be collected semiannually from any bodies of water that may be subject to seepage or surface drainage from potentially contaminated areas.**

Operational Soil and Sediment Samples

- **Surface soil samples should be collected at each of the locations chosen for air samplers annually.**

- **Sediment should be collected from surface water sampling locations annually.**

Operational Direct Radiation Measurements

- Direct radiation measurements should be made at air sampling locations

- Measurements should be made with a passive integrating device such at a TLD or OSL, pressurized ion chambers, or properly calibrated survey instruments.

- Measurements should be made in dry weather.

Analysis of Operational Samples

- Air samples should be analyzed for natural U, Th-230, Ra-226, and Pb-210.

- Radon samples should be analyzed for Rn-222.

- Water samples should be analyzed for natural U, Th-230, Ra-226, Po-210, and Pb-210.

- Vegetation, food, and fish should be analyzed for Ra-226 and Pb-210.

- Soil samples should be analyzed for natural U, Ra-226, and Pb-210.

- All sediment samples should be analyzed for natural U, Th-230, Ra-226, and Pb-210.

Radon Measurement Methods

Measurement of Radon

1. Regulatory Guidance

The following contain guidance regarding the assessment of radon and its decay products at mill tailings and ISR sites.

- Regulatory Guide 4.14. *Radiological Effluent and Environmental Monitoring at Uranium Mills.*

- Regulatory Guide 8.30. *Health Physics Surveys in Uranium Recovery Facilities.*

Measurement of Radon

1. Regulatory Guidance

Regulatory Guide 4.14 states that:

- Samples should be collected continuously, or for at least one week per month, for analysis of radon-222.

- Sampling locations for radon should be the same as those for the continuous air particulate samples.

- Sampling locations should be the same for preoperational and operational monitoring.

- Sampling locations should be "at a remote location that represents background conditions at the mill site; in general, a suitable location would be in the least prevalent wind direction from the site."

Measurement of Radon

1. Regulatory Guidance

Regulatory Guide 4.14 states that:

- Sampling locations should be "at a minimum of three locations at or near the site boundary."

- "If there are residences or occupiable structures within 10 kilometers of the site, a continuous outdoor air sample should be collected at or near the structure with the highest predicted airborne radionuclide concentration due to milling operations and at or near at least one structure in any area where predicted doses exceed 5 percent of the standards in 40 CFR Part 190."

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

- The Lucas Chamber, and its multiple variants collectively known as scintillation cells, are grab sampling devices for measuring radon concentrations.

- In essence, they are empty chambers coated on the inside with ZnS. One end of the chamber, usually transparent, is coupled to a photomultiplier tube (PMT).

- The air being sampled is introduced into the chamber. Alpha particles emitted by the radon and its decay products in the sampled air produce scintillations in the ZnS and these scintillations are converted into electronic pulses by the PMT.

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

- The pulse rate from the PMT is related to the radon concentration via a calibration factor:

$$Radon\,Concentration\,(pCi/l) = \frac{R\,e^{\lambda t}}{E}$$

R is the net count rate (e.g., counts per hour)

λ is the decay constant for radon (7.6×10^{-3} hr^{-1})

t is the time (hours) between collection and counting

E is the calibration factor (e.g., counts per hour per pCi/l)

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

- If long count times are employed (e.g., several hours), the net count rate (R) should be corrected for decay during the count.

- The time between collection and counting (t) must be greater than three hours so that the radon decay products will be in secular equilibrium with the radon.

- The calibration factor (E) is determined by deploying the Lucas chamber/scintillation cell in a radon calibration chamber and relating the count rate to the known radon concentration.

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

- The original Lucas cell is solid glass with a single valve on top. It has a volume of 125-170 mls. The end of the cell that is coupled to the PMT is clear and colorless, i.e., not coated with ZnS.

- Variations of the Lucas cell referred to as scintillation cells might be made of plastic, glass or some combination of metal and glass. They night be as small as 50 mls or as large as 500 mls. The end couple to the PMT might or might not be coated with ZnS. Coating the window end increases the detector efficiency but it reduces the intensity of the scintillations.

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

The image to the right shows the standard Lucas cell.

Before use, a vacuum is generated in the chamber.

The evacuated cell is taken to the area where the sample is to be collected. The valve is opened up so that the ambient air is pulled inside - the air might or might not be pulled through a filter. The valve is then closed.

Measurement of Radon

2. Lucas Chamber or Scintillation Cell

- Some scintillation cells employ two valves. With one valve connected to a pump and the other valve open to the ambient air, the latter is pulled through the cell for several minutes. The pump is turned then off and both valves are closed. There is no need to generate a vacuum in the cell prior to sampling!

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Measurement of Radon

2. **Lucas Chamber or Scintillation Cell**

Advantages:

- They are very sensitive, able to measure very low environmental levels of radon.

- The results can be obtained quickly.

Disadvantages:

- The chambers can easily become contaminated so that the background goes up

- If it employs a single valve, air might leak into the chamber prior to sampling.

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Measurement of Radon

3. **Passive Environmental Radon Monitor (PERM)**

- The PERM is an integrating device for determining radon concentrations.

- The bulk of the device consists of a conical (funnel-shaped) chamber. There is an electrode positioned at the narrow end of the chamber and a bed of silica gel supported by a filter covering the opening at the large end.

- The electrode is given a 900 volt potential (produced by three 300 volt batteries).

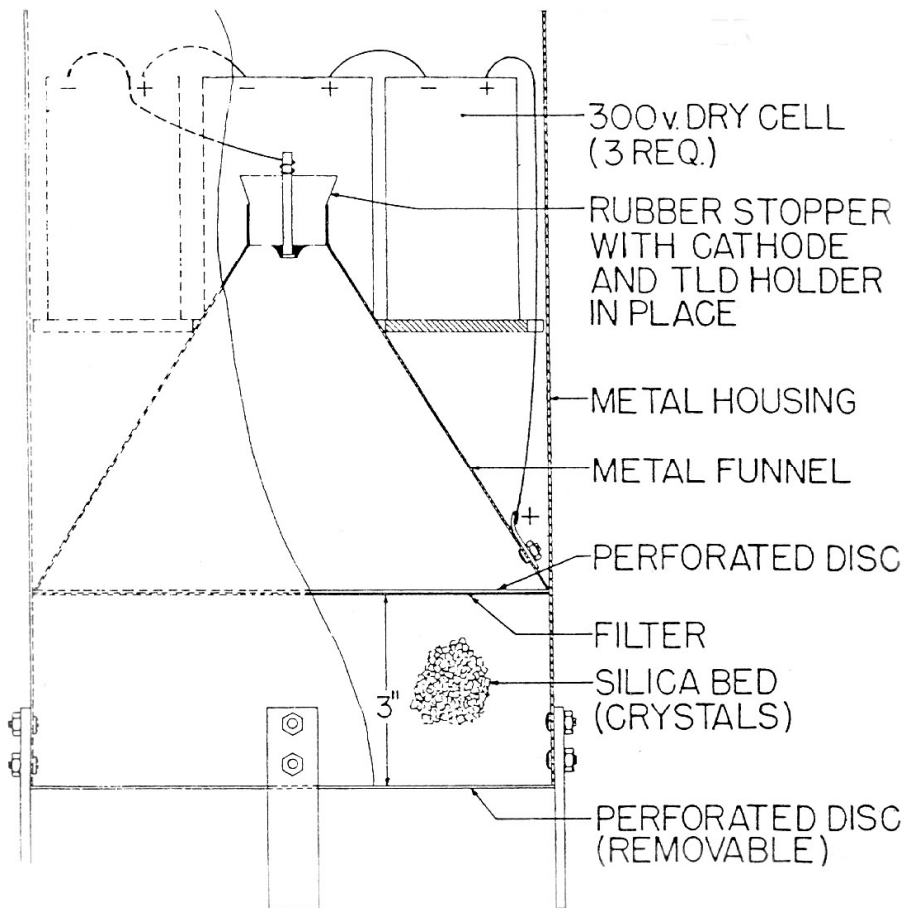- One TLD is located next to the electrode.

Measurement of Radon

3. **Passive Environmental Radon Monitor (PERM)**

- Air passively diffuses through the filter and silica gel. This dries the air and removes the ambient radon decay products.

- Inside the chamber, the radon decays to Po-218 (RaA). Since it has a positive charge, the Po-218 is drawn to the negative electrode at far end of the chamber. The TLD near this electrode is exposed to the alpha particles emitted by the radon decay products.

- A second "background" TLD chip is housed in the unit but shielded from the electrode and the radon decay products.

Measurement of Radon

3. Passive Environmental Radon Monitor (PERM)

300 v. DRY CELL (3 REQ.)

RUBBER STOPPER WITH CATHODE AND TLD HOLDER IN PLACE

METAL HOUSING

METAL FUNNEL

PERFORATED DISC

FILTER

SILICA BED (CRYSTALS)

3"

PERFORATED DISC (REMOVABLE)

Measurement of Radon

3. Passive Environmental Radon Monitor (PERM)

The radon concentration is calculated with the following formula:

$$Radon\,Concentration\,(pCi/l) = \frac{S - B}{E\,t}$$

S   is the response of the sample (exposed) TLD

B   is the response of the background TLD

E   is the calibration factor

t   is the exposure time

Measurement of Radon

3. Passive Environmental Radon Monitor (PERM)

Advantages

- It is sensitive and capable of measuring environmental levels

- It is passive with no external power source required

Disadvantage

- Labor intensive – regular silica gel replacement required

Measurement of Radon

4. Charcoal

- In 1981 A. George described a simple method employing charcoal canisters to measure indoor radon. Prior to then, charcoal canisters had only been used to measure radon flux rates.

    The charcoal might be in a metal can or even a bag. For convenience we will refer to all of them as charcoal canisters.

    Fifty to several hundred grams of charcoal was typical.

Measurement of Radon

4. Charcoal

Measurement of Radon

4. Charcoal

- In brief, the method requires that the canister be deployed (opened and exposed to the atmosphere) for the specific number of days (usually 2-6) and then sealed. After a minimum of a four hour wait, the activity of the radon decay products (Pb-214 and Bi-214) in the charcoal is assayed via gamma spectrometry.

- Finally, the atmospheric radon concentration is calculated with the aid of a calibration factor. The latter is determined by deploying the canister in a radon calibration chamber.

Measurement of Radon

4. Charcoal

- The charcoal not only collects radon, it also collects atmospheric moisture. The higher the humidity, the more water collected and the lower the collection efficiency for radon. In other words, the calibration factor depends on the amount of moisture collected as well as the duration of the deployment.

- To account for the effect of moisture pick up, the canister is weighed before and after deployment. The increase in weight (e..g., a few grams) is then used to select the appropriate calibration factor.
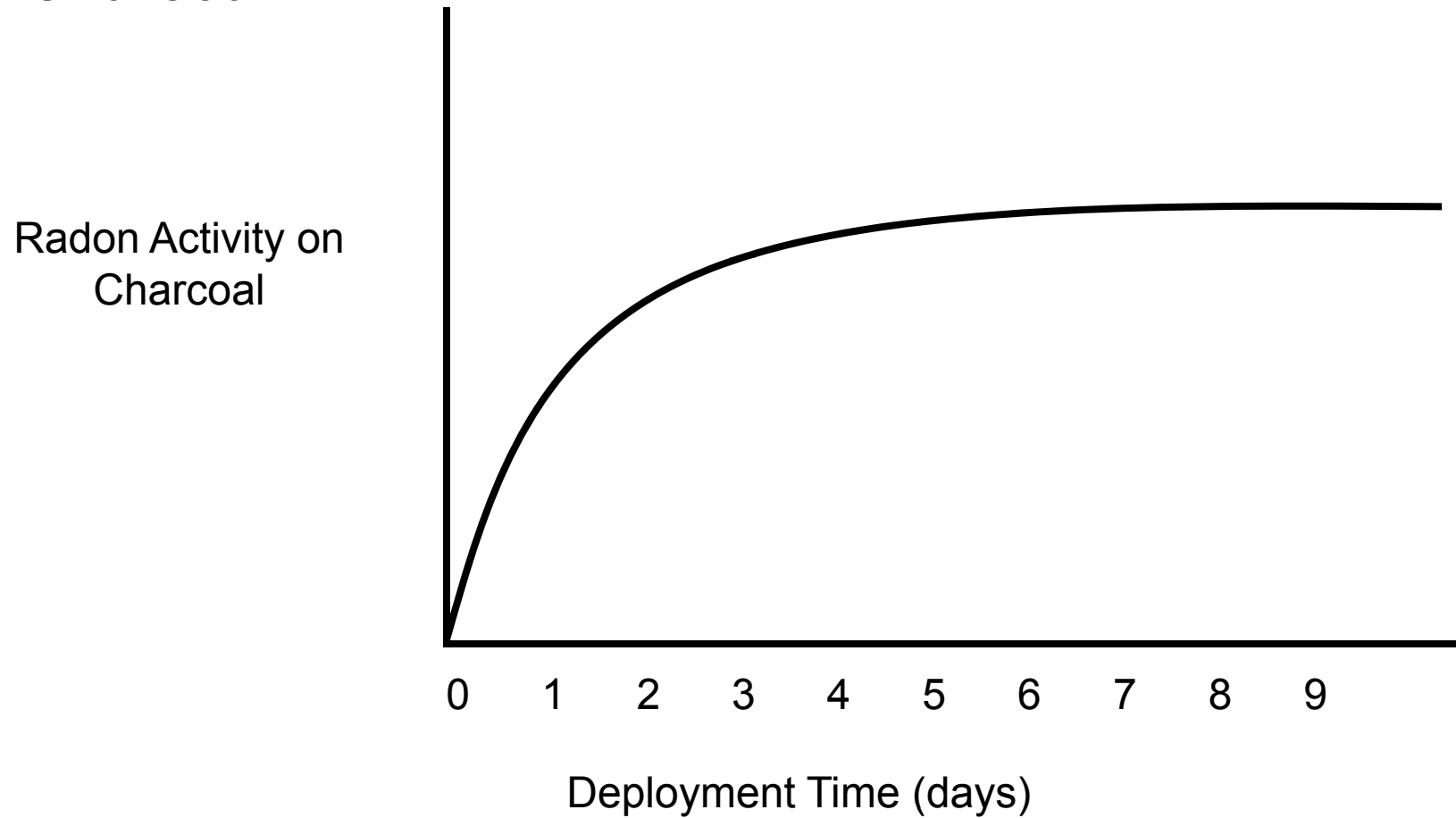
Measurement of Radon

4. **Charcoal**

   - During deployment, radon is passively adsorbed onto the surface of the charcoal granules. At the same time, the adsorbed radon is decaying as well as desorbing back to the atmosphere.

   - If the exposure period is long enough, the adsorption and desorption/decay rates become equal. When this happens, extending the duration of the deployment will not increase the total amount of adsorbed radon. As such, charcoal canisters are rarely deployed for more than six days. The EPA standard protocol employs as 2 day deployment.

Measurement of Radon

4. Charcoal

Radon Activity on Charcoal

Deployment Time (days)

Measurement of Radon

4. Charcoal

- Some charcoal canisters employ a diffusion barrier design that reduces moisture pick up by the charcoal and extends the integration period. Diffusion barrier devices are normally deployed for 4 to 7 days.

- In some cases, the diffusion barrier consists of a filter paper covering a 0.75" diameter hole in the top of the canister. Radon passively diffuses into the canister through the filter. When the canister is not deployed, the hole is covered with tape.
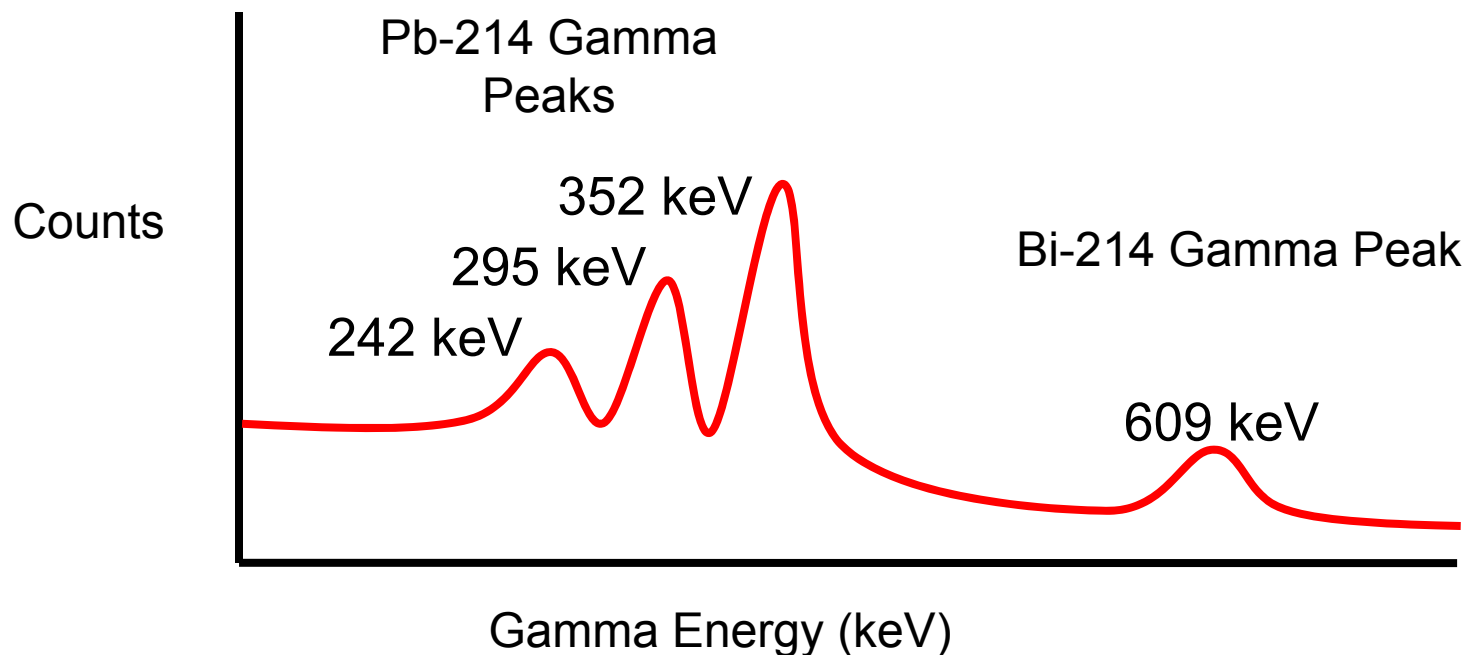
Measurement of Radon

4. Charcoal

- The analysis of the collected radon (usually with a NaI detector) can be performed in a variety of ways.

- For example, the gamma spec analysis might determine the counts in the 242, 294, and 352 keV peaks of Pb-214 and the 609 keV peak of Bi-214. Or, the 242 keV peak might be ignored to eliminate possible interference from Pb-212 gammas due to the presence of thoron (the EPA's standard protocol determines the total counts in a region of interest from 270-720 keV). A common variation on the standard protocol is to use two regions of interest: one for the Pb-214 gammas and the other for the Bi-209

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Measurement of Radon

4. Charcoal

The count rate for the region(s) of interest is determined for a background canister and subtracted from the count rate for the deployed canister.

Pb-214 Gamma Peaks

Counts

352 keV

295 keV

Bi-214 Gamma Peak

242 keV

609 keV

Gamma Energy (keV)

Measurement of Radon

4. Charcoal

Advantages:

- Simple enough that a homeowner can deploy the device and mail it off for analysis

- Quick

- Inexpensive

Disadvantages:

- Sufficiently sensitive for measuring concentrations at or above the EPA guideline of 4 pCi/l, but large errors are associated with measurements below 1 pCi/l.

- Calibration is sensitive to humidity and air currents

Measurement of Radon

4. Charcoal Analyzed by LSC

The deployment device is a liquid scintillation counting vial with a few grams of fine charcoal inside. The vial may or may not include a diffusion barrier and/or desiccant.

After the vial has been deployed (opened) for the appropriate period, usually a few days, it is analyzed by liquid scintillation counting.

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Measurement of Radon

4. Charcoal Analyzed by LSC

- The analysis involves adding the cocktail directly into the vial and counting.

- Instead of counting gamma rays this approach measures total alpha and beta activity. The advantages of LSC are lower background and higher detection efficiency than with gamma spectroscopy. The result is a technique of superior sensitivity.

- Another advantage is that liquid scintillation counters employ automatic sample changers and can analyze large numbers of samples without the need for a system operator.

Measurement of Radon

5. Wrenn Chamber and Modern Variants

- The Wrenn Chamber was a continuous monitor for measuring radon.

- Radon diffused into a hemispherical chamber (ca. 10" diameter). The walls of the chamber consisted of foam rubber supported by a wire screen (a colander). The foam filtered out the radon decay products only allowing the radon inside. In the center of the chamber was a small hemispherical Plexiglas dome coated with ZnS and covered with aluminized Mylar. A negative charge on the latter attracted the positively charged radon decay products produced by the decay of the radon.

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Measurement of Radon

5. Wrenn Chamber and Modern Variants

- The Po-218 and Po-214 alpha particles produced scintillations in the ZnS which were converted to electronic pulses by a photomultiplier. The pulse rate was used to provide hourly determinations of radon concentrations.

- Although the Wrenn chamber is no longer in use, some more modern variations shown on one of the following slides.

- The major difference between the Wrenn Chamber and the modern variants is that the latter employ a semiconductor detector instead of a ZnS scintillator.

Measurement of Radon

5. Wrenn Chamber and Modern Variants
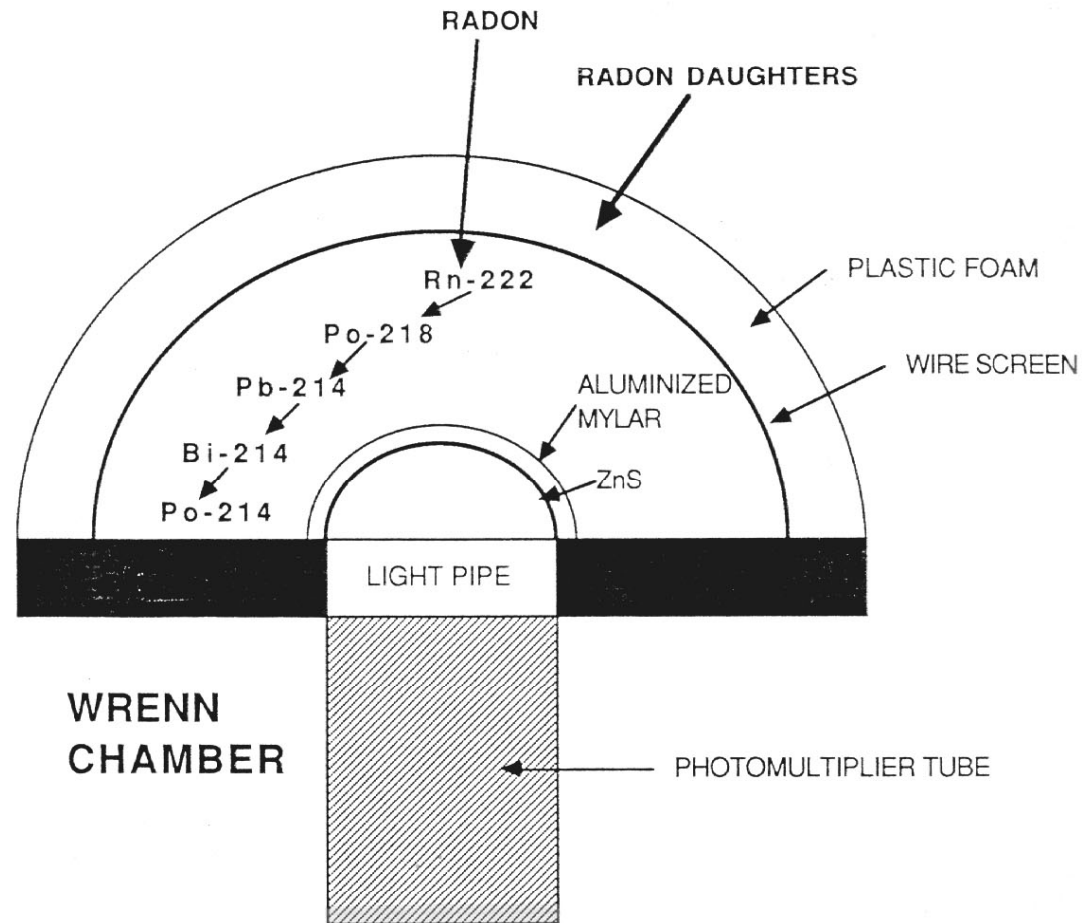
Measurement of Radon

5. Wrenn Chamber and Modern Variants

The latest incarnation of the At-Ease monitor, Sun Nuclear Corp.'s Model 1029


At-Ease monitor

Measurement of Radon

6. Alpha Track

- Alpha track (aka track etch) devices employ a passive integrating technique for the evaluation of radon (or radon daughter) concentrations.

- The detector is a small piece of clear plastic inside a plastic container. If the device is designed to measure radon, the opening of the container is covered with a filter that is permeable to radon but not its decay products.

- During use, radon passively enters the unit. When the radon decays, the decay products plate out on the container walls. Alphas emitted by radon and its decay products produce invisible damage tracks in the detector.

Measurement of Radon
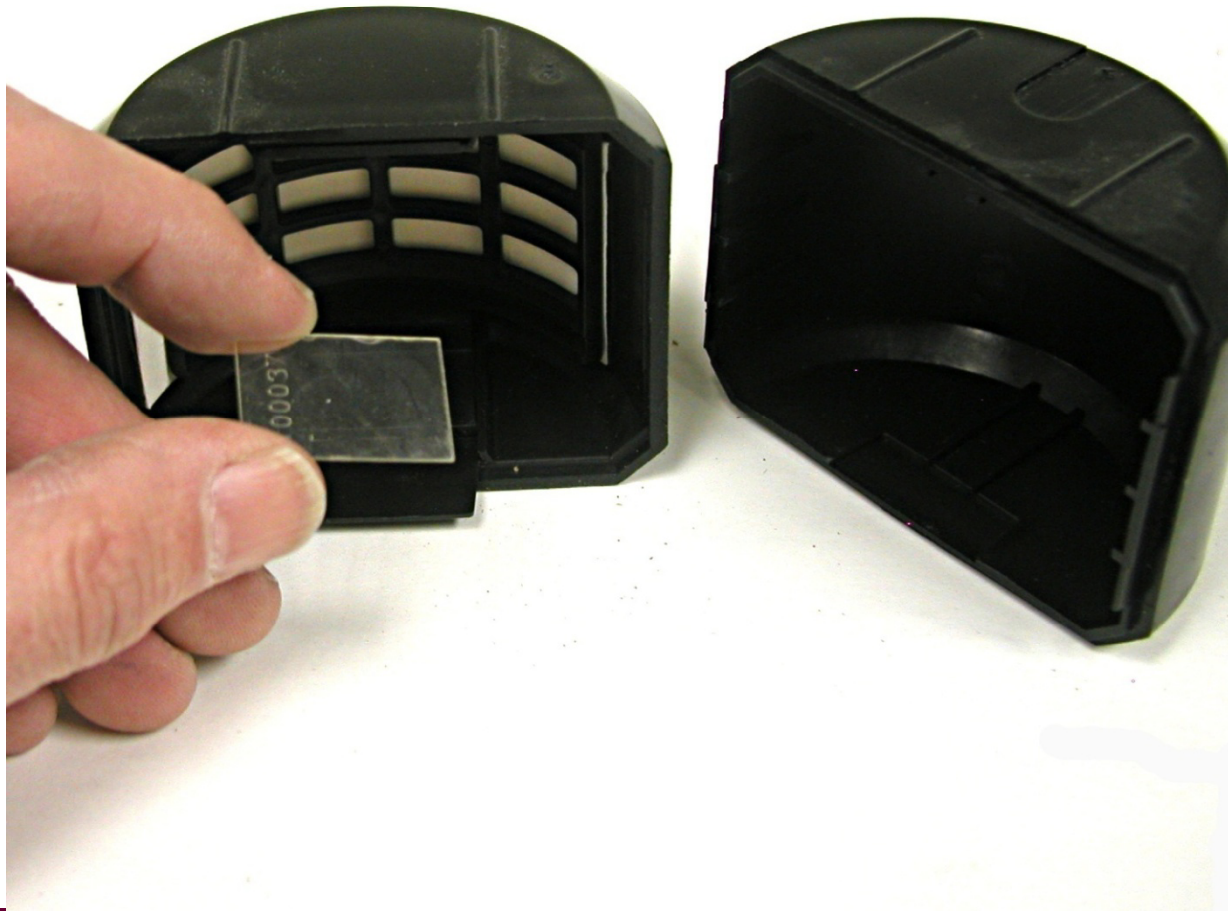
6. Alpha Track

Measurement of Radon

6. Alpha Track

After deployment (from 1-12 months), the damage tracks are chemically enhanced (made visible) by etching in a solution of KOH or NaOH, or by an electrochemical treatment.

The now visible tracks over a specified area of the detector are counted manually with a light microscope or, more commonly, with an automatic system employing a computer.

Since relatively few tracks are produced, the devices are usually deployed for periods greater than one month.

Measurement of Radon

6. Alpha Track

- The precision can always be improved by counting the tracks over a larger area of the detector.

- Since the track etch material is insensitive to beta or gamma radiation, background measurements do not have to be subtracted.

- The device should be deployed soon after receipt in order to minimize any exposure to radon that might leak through the detector package during storage. Some facilities store these devices inside charcoal "shields".

Measurement of Radon

6. Alpha Track

- The precision can always be improved by counting the tracks over a larger area of the detector.

- Since the track etch material is insensitive to beta or gamma radiation, background measurements do not have to be subtracted.

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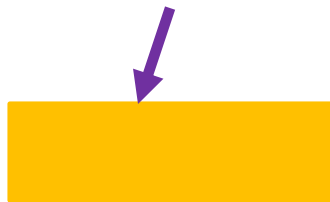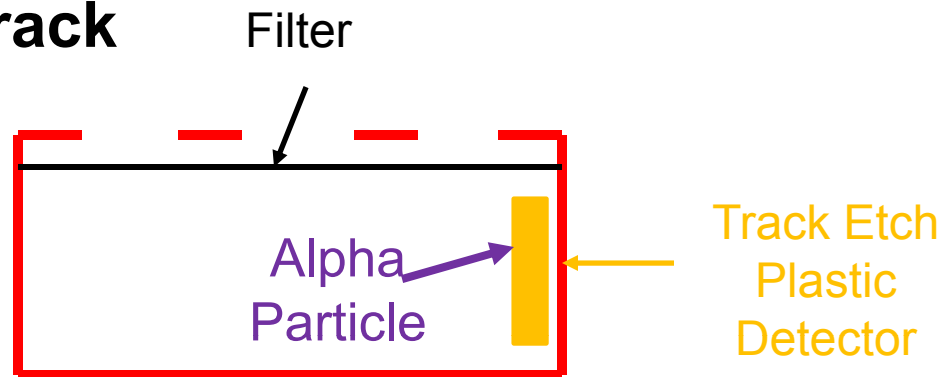
Measurement of Radon

6. Alpha Track

- Devices for measuring radon decay product concentrations (in working levels) do not employ a membrane/filter barrier over the opening.

- Since open alpha track devices respond to both ambient radon and its decay products, a second unit might be used to estimate the number of tracks produced by radon. Rather than using a second device it is also possible to assume a certain equilibrium and have the calibration factor take the radon contribution into account.
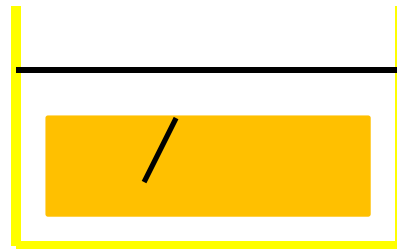
Measurement of Radon

6. Alpha Track

Filter

Alpha Particle

Track Etch Plastic Detector

Alpha strikes plastic detector

Damage track produced

Plastic detector etched in KOH

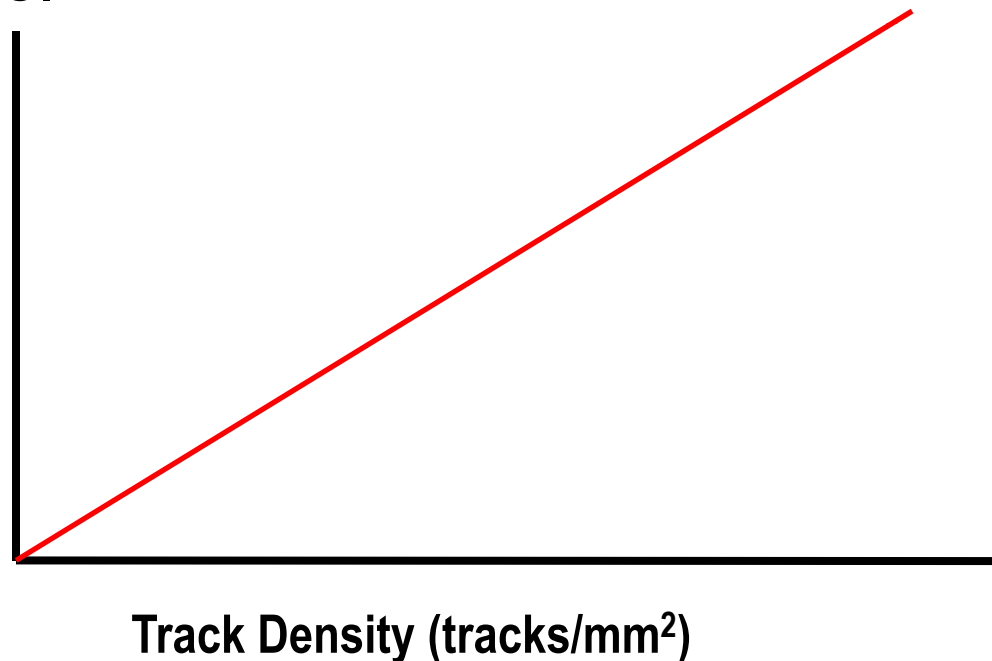Damage track visible under microscope

Measurement of Radon

6. Alpha Track

The track density (tracks per mm^2) is related to the radon concentration or decay product concentration with a calibration curve.

Radon or Radon Decay Product Concentration (e.g., pCi/l, Bq/m^3, WL)

Track Density (tracks/mm^2)

Measurement of Radon

6. **Alpha Track**

    Advantages

    - Passive
    - Simple
    - Long term deployment possible

    Disadvantages

    - There has been some indications of excessive variability in the results. As such, it might be wise to deploy more than one at a given location.

Measurement of Radon

7. Electret

- Operates much like an electroscope: the intensity of the radiation is measured by the decrease in a stored electric charge.

- The electret itself is a dielectric material (e.g. Teflon) that is given an electric charge and sealed in a chamber made from a low Z material (e.g., plastic). During deployment, the chamber is opened so that air can passively enter it through a filter (thus removing the radon daughters). Air inside the chamber is ionized by the decay of radon as the decay of its decay products. The ions created are attracted to the electret thus reducing the charge.

Measurement of Radon

7. Electret

Electret Chamber

Electret Reader

Measurement of Radon

7. Electret

Electrets are available in one of two versions:

- Short term electrets
    - usually deployed for 1 – 7 days
    - measure radon at 200 Bq/m^3 in 48 hours.

- Long term electrets
    - usually deployed for 1 – 12 months
    - measure radon at 200 Bq/m^3 in 28 days.

Measurement of Radon

7. Electret

- The charge, or more commonly the potential in volts, of the electret is measured before and after deployment.

- The greater the radon concentration, the greater the voltage drop.

- For a typical unit, a one day exposure to 1 ρCi/liter of radon results in a drop of 2 volts.

- Even in the absence of radon, the ionization due to background gamma rays results in a voltage drop. This can be accounted for in several ways. For example, a second device could be deployed that is kept sealed – it would indicate the decrease due to background.

Measurement of Radon

7. Electret

- Avoid doing anything that might cause the electret to lose its charge, e.g. it should be handled carefully, the surface of the electret should not be touched, air jets should not be used to clean the surface, etc.

Measurement of Radon

7. Electret

Advantages

- easy to use
- rapid analysis
- relatively inexpensive
- can be analyzed in the field

Disadvantages

- must be careful to achieve reproducible measurements

Measurement of Radon

Environmental air sampling station

Measurement of Radon

Environmental air sampling station for particulates and radon

Measurement of Radon

Radon monitor on outside of shelter

Measurement of Radon

Alpha track
radon monitor
seen from below

Radon Decay Product Measurement Methods

Measurement of Radon Decay Products

1. Regulatory Guidance

Regulatory Guide 4.14 states that:

"Monthly measurements of radon daughter concentrations should be made where radon daughters routinely exceed 10% of the limit or 0.03 working level above background. If radon daughter concentrations are normally greater than 0.08 working level (25% of limit) or radon concentrations are above 3×10^{-8} uCi/ml, the sampling frequency should be increased to weekly. Sampling should continue to be performed weekly until four consecutive weekly samples indicate concentrations of radon daughters below 0.08 working level or radon below 3×10^{-8} µCi/ml. After that, radon daughter surveys may be resumed on a monthly basis."

Measurement of Radon Decay Products

1. Regulatory Guidance

Regulatory Guide 4.14 states that:

"Quarterly sampling for radon daughters should be made where previous measurements have shown the daughters are not generally present in concentrations exceeding 0.03 working level (10% of the limit) but where proximity to sources of radon daughters might allow them to be present. For example, quarterly measurements might be appropriate for a shop area attached to the crushing and grinding circuit building."

"Radon daughter samples should be representative of worker exposures. Samples should be taken from locations where workers are most often present. The state of operation of major equipment during sampling and the time of day the sample was taken should be recorded."

Measurement of Radon Decay Products

2. Kusnetz Method

The first two measurement methods for radon decay products that are described here are very similar: the Kusnetz and the Tsivoglou techniques.

They are not particularly sensitive, that is they would not be used for environmental measurements.

Both methods were developed for use in the uranium industry about 50 years ago.

They share one important advantage: there is no need calibrate the instrumentation in an atmosphere with a known decay product concentration.

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Measurement of Radon Decay Products

2. Kusnetz Method

An air sample is collected on a surface loading (membrane) filter over a 5 minute sampling time. Sampling flow rates typically range from 2 to 25 liters/min.

Between 40 and 90 minutes after sampling, the total alpha activity on the filter is measured. Count times might range from 1 to 10 minutes.

It is the most common method employed to measure the PAEC (working levels).

Measurement of Radon Decay Products

2. Kusnetz Method

The working level concentration is determined with the following formula:

$$PAEC = \frac{R}{K\,V\,E}$$

PAEC is the potential alpha energy concentration in working levels

R is the net count rate in cpm

E is the alpha counting efficiency (cpm/dpm)

V is the volume of air in liters

K is a correction factor taken from the table in the next slide

Measurement of Radon Decay Products

2. Kusnetz Method

Time (min)	K		Time (min)	K		Time (min)	K
40	150		58	114		76	82
42	146		60	110		78	78
44	142		62	106		80	75
46	138		64	102		82	73
48	134		66	98		84	69
50	130		68	94		86	66
52	126		70	90		88	63
54	122		72	87		90	60
56	118		74	84			

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Measurement of Radon Decay Products

2. Kusnetz Method

Advantages:

- It is simple

- The long time between sampling and counting allows analysis to be performed some distance away from sampling location

- It is not necessary to calibrate this system in a radon/radon daughter chamber. All that is needed is a counting efficiency for the alpha detector.

Measurement of Radon Decay Products

2. Kusnetz Method

Disadvantages:

- The long wait time before counting reduces the method's sensitivity - after 40 minutes, all the Po-218 has decayed away. This is sometimes exacerbated by low sampling flow rates (2 lpm is very common) and short count times.

- The method's accuracy depends on the equilibrium between the decay products. Usually this error is low (e.g., < 10%), but in "young air" where Po-218 is the major contributor to the PAEC, the error might be 25%.

- It is a short term grab sample

Measurement of Radon Decay Products

3. Tsivoglou Method

An air sample is collected over a five minute sampling period. Typical flow rates range from 2 to 25 lpm.

In most cases, a membrane filter is used to avoid the need to correct for alpha burial losses.

Three alpha counts are performed:

- from 2-5 minutes after sampling (3 minute count)
- from 6-20 minutes after sampling (14 minute count)
- from 21-30 minutes after sampling (9 minute count)

The formulae on the next slide are used to calculate the concentrations of the individual radon daughters:

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Measurement of Radon Decay Products

3. Tsivoglou Method

$Concentration\,of\,Po-218\,in\,pCi/l:$

$$C_{Po-218} = \frac{1}{F\,E}(0.16746G_1 - 0.0813G_2 + 0.0769G_3 - 0.0566R)$$

$Concentration\,of\,Pb-214\,in\,pCi/l:$

$$C_{Pb-214} = \frac{1}{F\,E}(0.00184G_1 - 0.0209G_2 + 0.0494G_3 - 0.1575R)$$

$Concentration\,of\,Bi-214\,in\,pCi/l:$

$$C_{Bi-214} = \frac{1}{F\,E}(-0.0235G_1 + 0.0337G_2 - 0.0382G_3 - 0.0576R)$$

Measurement of Radon Decay Products

3. Tsivoglou Method

F   is the flow rate in lpm

E   is the counting efficiency in cpm/dpm

R   is the background count rate in cpm

G_1 is the gross count from 2-5 minutes after sampling
(a three minute count)

G_2 is the gross count from 6-20 minutes after sampling
(a 14 minute count)

G_3 is the gross count from 21-30 minutes after sampling
(a 9 minute count)

Measurement of Radon Decay Products

3. Tsivoglou Method

The Potential Alpha Energy Concentration (in working levels) is then determined with the following formula:

$$\text{PAEC (WL)} = 0.00105\ C_{\text{Po-218}} + 0.00508\ C_{\text{Pb-214}} + 0.00373\ C_{\text{Bi-214}}$$

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Measurement of Radon Decay Products

3. Tsivoglou Method

Advantages:

- It is a more sensitive technique than the Kusnetz method since the time between sampling and counting is much shorter and the count time(s) is longer.

- It provides information about the concentrations of the individual radon daughters.

- Its accuracy is not impacted by the equilibrium between the decay products (i.e., the age of the air).

Measurement of Radon Decay Products

3. Tsivoglou Method

Disadvantages:

- The need to begin counting two minutes after sampling can be a problem in many situations

- The counting protocol and the math are more complicated than for the Kusnetz method.

- It is a short term grab sample

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Measurement of Radon Decay Products

4. Radon Progeny Integrating Sampling Unit (RPISU)

RPISUs, pronounced "rip i sues," were widely used during the 1970s in the UMTRA program. They are not used today.

A RPISU (or MOD) is an integrating device typically operated over a period of 3-7 days. In its most basic form, it employs a filter (a 0.8 µm membrane filter is commonly used), a sampling head holding one or more detectors, a pump, a flow meter and an elapsed timer.

The original RPISU, as described in the following text, utilized two TLDs to assess the collected decay products. Later versions have employed alpha track devices and electrets.

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Measurement of Radon Decay Products

4. Radon Progeny Integrating Sampling Unit (RPISU)

The pump, running at 0.1 - 4 lpm for one to two weeks, collects radon daughters on the filter.

As the collected daughters decay, alpha energy is deposited in a TLD placed near the filter in the sampling head. One or two other TLDs are also located in the sampling head but shielded from the alphas. Their function is to account for the TLD response to gamma ray background.

The response of the TLDs is related to the time averaged radon daughter concentration by the formula on the next slide:

Measurement of Radon Decay Products

4. Radon Progeny Integrating Sampling Unit (RPISU)

$$PAEC = \frac{S - B}{V\,E}$$

S is the response of the exposed TLD chip

B is the response of the background TLD chip

V is the volume of air sampled in liters

E is the calibration factor giving the net TLD response per WL per liter sampled

Measurement of Radon Decay Products

4. Radon Progeny Integrating Sampling Unit (RPISU)

The E-RPISU
employing electrets as the
sensing devices

By using three electrets simultaneously, one with a filter (decay products and radon background), one without a filter (radon background only) and one with a screen, the E-RPISU can assess the decay products, the radon concentration and the unattached fraction.

Measurement of Radon Decay Products

4. Radon Progeny Integrating Sampling Unit (RPISU)

Advantages:

- RPISUs are very sensitive devices.

- It is an integrating device rather than a grab sample

Disadvantages:

- There are no radon decay product calibration chambers. Historically, the calibration factor was determined by comparison with Kusnetz measurements.

- RPISUs require electrical power

- They can be noisy

Measurement of Radon Decay Products

5. Alpha Spectrometry

Semiconductor diode detectors are used to count and measure the energy of the alpha particles emitted by material collected on a membrane filter.

Several different alpha spectrometry methods have been employed for determining radon daughter (working level) concentrations.

Some involve the analysis of a single grab sample, while others operate as continuous monitors.

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Measurement of Radon Decay Products

5. Alpha Spectrometry

At one time, the following method, which incorporates elements of the Tsivoglou method, was employed by Oak Ridge National Laboratory.

Radon decay products were collected on a membrane filter by sampling for 10 minutes at 15 lpm. Two minutes after collection, the filter was analyzed with a surface barrier or diffused junction detector in two consecutive counts. The first count was from 2 to 12 minutes and the second from 15 to 30 minutes after collection.

Not only did this method provide measure the alpha particle energies, it also obtained information about the half-life of the collected material.

Measurement of Radon Decay Products

5. Alpha Spectrometry

Advantages:

- Alpha spectrometry provides the ability to eliminate interference from any collected thoron decay products

Disadvantages:

- a rather sophisticated detection system needs to be located at or near the point of sampling

- electrical power is required

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Measurement of Radon Decay Products

6. Alpha Track

This method equates the radon decay product concentration to the number of damage tracks in plastic caused by the alpha particles emitted by these decay products.

The alpha track (aka track etch) technique is more often used to assess the radon concentration than the decay product concentration. As such, it is discussed in more detail in the section dealing with radon measurements.

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Measurement of Radon Decay Products

6. Alpha Track

The design of the device used to hold the alpha track plastic determines whether the radon decay product or radon concentration will be measured.

Unfiltered alpha track devices are used to measure the working level while filtered devices are used to measure the radon decay product concentrations.

There is some disagreement as to the ability of alpha track systems to accurately assess the decay products.

Measurement of Radon Decay Products

7. Lower Limit of Detection – Regulatory Guide 8.30

Regulatory Guide 8.30 states the following:

"The LLD for radon daughter measurements should be 0.03 working level. Appendix B to this guide shows how to calculate the LLD for a radon daughter measurement. Measured values less than the LLD, including negative values, should still be recorded on data sheets."

The equation given in Appendix B is presented on the next slide.

Unfortunately, the equation is incorrect. Note that the numerator contains the standard deviation of the background count rate rather than the standard deviation of the count.

Measurement of Radon Decay Products

7. Lower Limit of Detection – Regulatory Guide 8.30

$$LLD = \frac{3 + 4.65\, S_b}{3.7\, x10^4\; E\, V\, Y\, e^{-\lambda t}}$$

where:

LLD = the lower limit of detection (µCi/ml)

S_b = the standard deviation of background count rate (counts per second)

3.7 x10^4 = the number of disintegrations/sec/µCi (this term is omitted if Sb is given in terms of microcuries)

E = the counting efficiency (counts per disintegration)

V = the sample volume (ml)

Y = the fractional radiochemical yield (if applicable)

λ = the decay constant for the particular radionuclide

t = the elapsed time between sample collection and counting

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Measurement of Radon Decay Products

7. Lower Limit of Detection – Regulatory Guide 8.30

NUREG 1507 gives the following correct equations for the minimum detectable concentration:

$$MDC = \frac{3 + 4.65\, s_B}{K\,T} \qquad (equation\ 3-9)$$

$$MDC = \frac{3 + 4.65\, \sqrt{C_B}}{K\,T} \qquad (equation\ 3-10)$$

where:

s_b = the standard deviation of the background count (not count rate) in time T

C_B = the background count (not count rate)

K = a proportionality constant that relates detector response to the activity level in a sample for a given set of measurement conditions and T is the counting time. This factor typically encompasses detector efficiency, self-absorption factors, etc.

Radon Flux Measurements

Measurement of Radon Flux

1. Regulatory Guidance

Regulatory Guide 4.14 *Radiological Effluent and Environmental Monitoring at Uranium Mills* states that radon flux measurements:

"should be made in three separate months during normal weather conditions in the spring through the fall when the ground is thawed."

"the measurements should be made at the center of the milling area and at locations 750 and 1500 meters from the center in each of the four compass directions."

"Measurements should not be taken when the ground is frozen or covered with ice or snow or following periods of rain."

Measurement of Radon Flux

1. Regulatory Guidance

10 CFR 40 Appendix A. Criterion 6:

"the licensee shall verify through appropriate testing and analysis that the design and construction of the final radon barrier is effective in limiting releases of radon-222 to a level not exceeding 20 pCi/m^{2}s averaged over the entire pile or impoundment using the procedures described in 40 CFR part 61, appendix B, Method 115, or another method of verification approved by the Commission . ."

Measurement of Radon Flux

2. Charcoal Canisters

Method 115 specifies a "large area collector" "placed on the surface of the pile area to be measured and allowed to collect radon for a time period of 24 hours." "The collector shall be carefully positioned on a flat surface with soil or tailings used to seal the edge."

The radon is to be "measured by gamma ray spectroscopy."

Method 115 states that the detailed procedure is found in Appendix A of EPA 520/5-85-0029 (should actually refer to EPA 520/5-85-029).

Measurement of Radon Flux

2. Charcoal Canisters

This method specifies that the canister be made from a 10" diameter PVC end cap containing a bed of 180 grams of dried activated charcoal. The charcoal is distributed within a plastic support grid that is sandwiched between two ½" thick scrubber pads (with fiberglass screens). There is an additional 1" scrub pad above the charcoal.
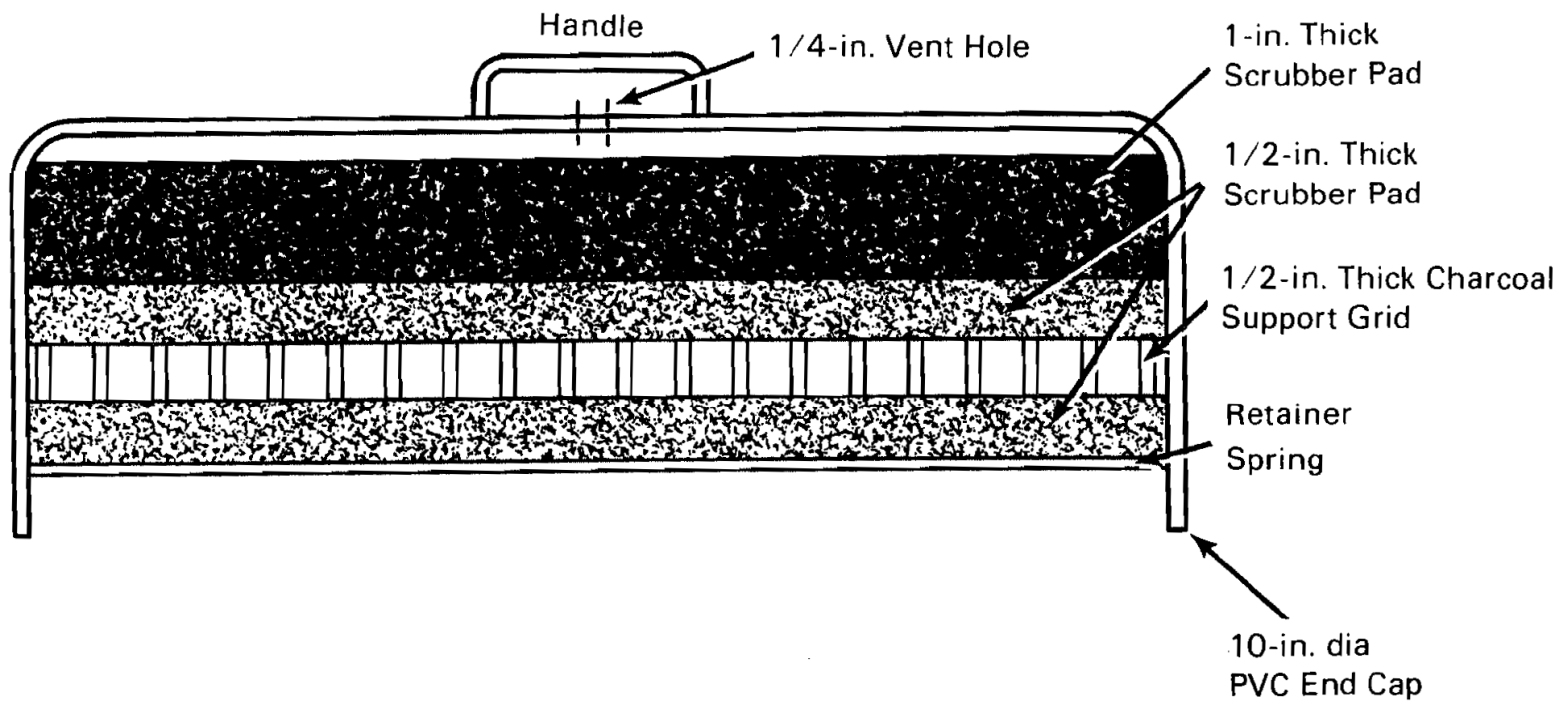
The top of the canister has a ¼" vent hole and a handle.

Radon emanating from the soil passively diffuses through the foam rubber and is adsorbed on the charcoal.

Measurement of Radon Flux

2. Charcoal Canisters

Handle
1/4-in. Vent Hole
1-in. Thick Scrubber Pad
1/2-in. Thick Scrubber Pad
1/2-in. Thick Charcoal Support Grid
Retainer Spring
10-in. dia PVC End Cap

EPA 520/5-85-029

Measurement of Radon Flux

2. Charcoal Canisters

Measurement of Radon Flux

2. Charcoal Canisters

Method 115 contains the following three restrictions regarding deployment:

"Measurements shall not be initiated within 24 hours of a rainfall."

"If a rainfall occurs during the 24 hour measurements period, the measurement is invalid if the seal around the lip of the collector has washed away or if the collector is surrounded by water."

"Measurements shall not be performed if the ambient temperature is below 35 F or if the ground is frozen."

Measurement of Radon Flux

2. Charcoal Canisters

After collection, the charcoal is transferred to a sealed container and counted on a shielded NaI detector or a high purity germanium detector.

Which peaks on the spectrum are used is left up to you, although the EPA document states that the 609 keV peak of Bi-214 is usually used.

At one facility where NaI detectors are employed, the net counts are obtained for a region of interest covering 220 to 662 keV. The net count is obtained by subtracting out the counts obtained from unexposed charcoal.

Measurement of Radon Flux

2. Charcoal Canisters

At least one gamma spectroscopy standards, used to determine the detector efficiency for Rn-222, are constructed by adding a NIST traceable Ra-226 solution to 180 grams of activated charcoal contained in a collector.

These standards are to be counted at the beginning and end of each day counting as part of a performance check.

In addition, a background count employing a collector containing unexposed charcoal is performed at the beginning and end of each day's counting.

Measurement of Radon Flux

2. Charcoal Canisters

An equation similar to the following is given in EPA 520/5-85-029 to calculate flux, except that EPA 520/5-85-029 incorrectly squares λ in the numerator.

$$J(pCi/m^2\,s) = \frac{C\lambda}{K\,A\,E\,(1-e^{-\lambda t_1})(e^{-\lambda(t_2-t_1)} - e^{-\lambda(t_3-t_1)})}$$

J is the radon flux (pCi/m^2 s)
C is the net count
λ Is the radon decay constant (2.097×10^{-6} s^{-1})
A is the collector area (m^2)
E is the detector efficiency (c/d)
K is a conversion factor of 0.037 dps per pCi
t_1 is the canister deployment time (s)
t_2 is the time from the start of deployment to start of count (s)
t_3 is the time from the start of deployment to end of count (s)

Measurement of Radon Flux

2. Charcoal Canisters

The following equation, or a modification, has also been used to calculate the radon flux:

$$Radon\ flux\,(pCi/m^2\,s) = \frac{R_n}{t\,A\,E\,e^{-0.0076d}}$$

R_n is the net count rate (cpm)

t is the canister deployment time (s)

A is the area of the collector (m^2)

E is the detector efficiency (cpm/pCi)

d is the decay time from the middle of deployment to the middle of the count (hr)

Measurement of Radon Flux

3. Electret Flux Monitor

This device has the electret positioned at the top of a large hemispherical chamber (ca. 7" diameter at the base) with a Tyvek diffusion barrier across the bottom.

The bottom of the device is placed in contact with the surface to be measured. Radon emanating from the surface passively enters the chamber through the barrier. It then exits through one of four filtered vent holes.

The discharge rate of the electret is a measure of the radon flux. The calibration factor was established using the CANMET radon flux beds in Elliot Lake, Canada.
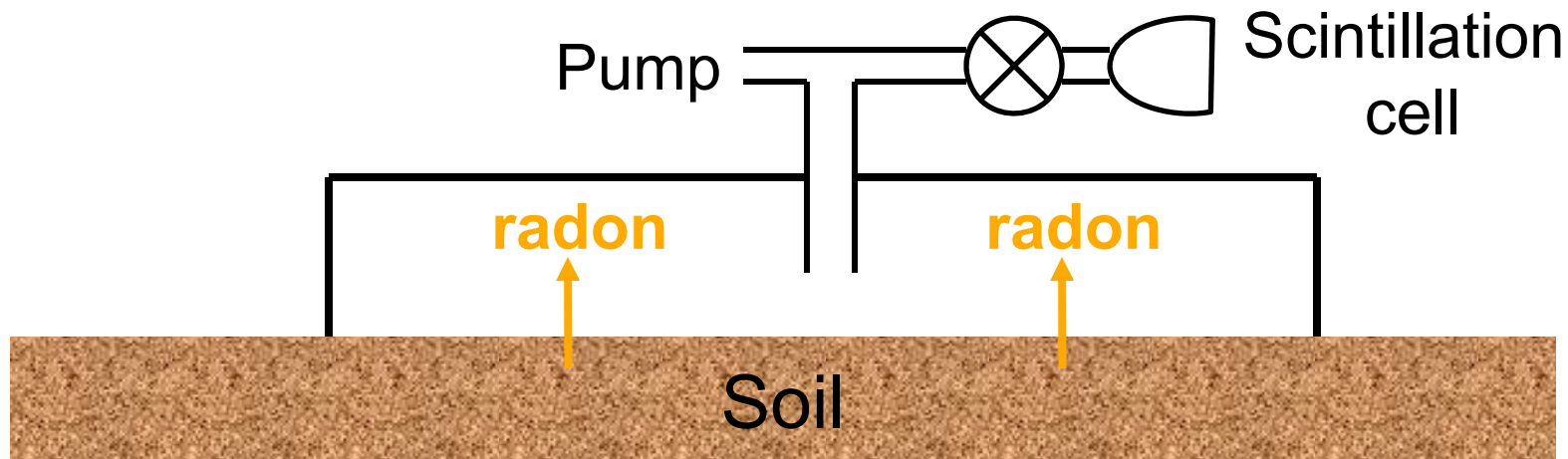
Measurement of Radon Flux

3. Electret Flux Monitor
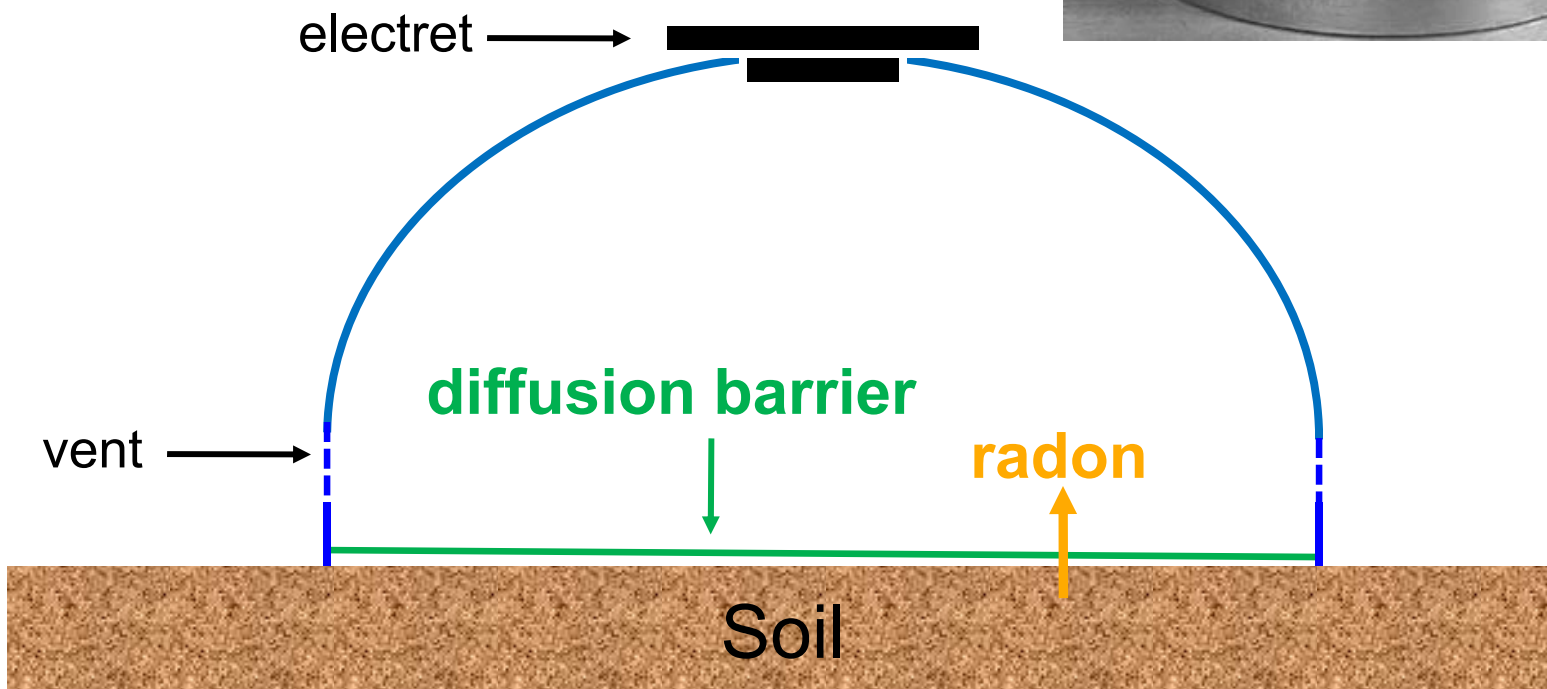
Measurement of Radon Flux

4. Accumulation Method

The open end of a container/vessel (e.g., a 55 gallon drum) is sealed to the surface being measured and the air inside the vessel is sampled and analyzed.

The air would typically be analyzed using a scintillation cell.

These devices would be employed for a relatively short period, e.g., one day.

Measurement of Radon Flux

5. Flow Method

As with the accumulation method, the open end of a container/vessel is sealed to the surface being measured. The air inside the chamber is continuously circulated through a measurement device (e.g., an ion chamber) or though a collector that is later analyzed (e.g., charcoal).

6. Soil Concentration Gradient Method

The increase in the radon concentration with depth in soil can be used to calculate flux. One method that has been used to determine the concentration gradient is to measure the Pb-210 concentration profile.

The Challenge of Demonstrating Compliance with 10 CFR 20.1301

Challenge of Demonstrating Compliance

1. The Challenge of Demonstrating Compliance

Demonstrating compliance with 10 CFR 20.1301 can be a challenge due to:

- Temporal variability in radon concentrations

- Spatial variability in concentrations of radon from a localized source

- Decrease in the concentration of radon downwind from a localized source

- Disequilibrium between radon and the decay products

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Challenge of Demonstrating Compliance

1. The Challenge of Demonstrating Compliance

- The low regulatory limits relative to background

- The issue of the "boundary of the unrestricted area" when certain operations (e.g., well installation) might be conducted on public land.

Challenge of Demonstrating Compliance

2. Temporal Variations

Complex Terrain

Local meteorological conditions can contribute to temporal (and spatial) variability in radon concentrations. In general, the more complex the terrain, the more complicated the meteorological conditions and the greater the variability.

All other things being equal, air (and radon) tends to move down a slope at night and up a slope during the day.

Air tends to flow up a slope in areas exposed to the sun and down on slopes in the shade.

Challenge of Demonstrating Compliance

2. Temporal Variations

Diurnal Variation

Radon concentrations tend to be highest at night and in the early morning when the atmosphere is stable and lowest in the afternoon when the atmosphere is unstable.

Large Bodies of Water

During the day, the tendency is for the wind to move air from the water towards the land. At night, the air tends to move from the land towards the water. Since bodies of water (e.g., the ocean) are not sources of radon, radon concentrations measured on land near the shore might be lower during the day than at night.

Challenge of Demonstrating Compliance

2. Temporal Variations

Rainfall and Snow

Precipitation can remove particulate material from the air and the radon decay products associated with the particulates, but they should not remove the radon. Nevertheless, moisture and snow can reduce the emanation from the ground and thereby lower ambient radon concentrations. This effect can persist for as long as the soil is moist or covered with snow.

Challenge of Demonstrating Compliance

2. Temporal Variations

Technological Enhancement

When radon monitoring is performed in areas with high levels of uranium in the soil, local activities (e.g., construction) could temporarily increase the background levels of radon and its decay products.

Challenge of Demonstrating Compliance

3. Spatial Variability in Radon from Localized Source

What is Downwind?

Radon concentrations are higher downwind than upwind from a localized source, but determining what is downwind can be tricky. What is downwind one day can be upwind the next.

Challenge of Demonstrating Compliance

3. Spatial Variability in Radon from Localized Source

Ridges and Valleys

While the predominant wind direction in a given region is of primary importance, ridges and valleys near the source can change the local wind direction and speed.

Challenge of Demonstrating Compliance

4. Low Concentrations Downwind

Close to a localized source (e.g., mill tailings) the elevated radon concentrations might be distinguished from background.

Nevertheless, these concentrations decrease rapidly with downwind distance. Measurements around mill tailings indicate that any local increase in radon due to the source becomes undetectable at distances greater than 0.5 to 1.0 miles downwind.

Such localized sources might have higher emanation rates that the local soils, nevertheless even a large tailings pile represents a small fraction of the land area in a given region that is contributing to the ambient radon.

Challenge of Demonstrating Compliance

4. Low Concentrations Downwind

Using a Gaussian plume model, one study estimated a radon concentration of 3×10^{-6} Bq m^{-3} (ca. 8×10^{-8} pCi/l) one kilometer downwind from a mill tailings pile for every Bq/s (27 pCi/s) emanating from the tailings.

Downwind of one kilometer, the concentration decreased according to $1/d^{1.5}$.

When modeling the decreasing concentrations in a plume downwind, it might be important to account for radon decay as well as the dispersion.

Challenge of Environmental Radon

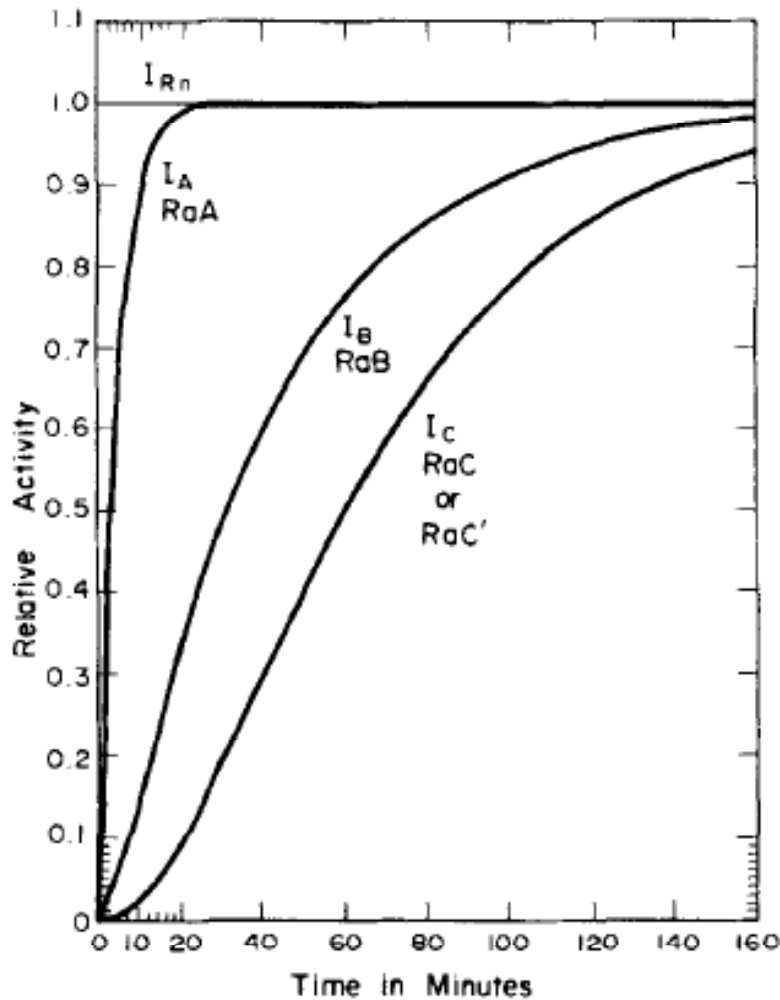## 5. Disequilibrium Downwind from Localized

The radon-222 emanating from a given source (e.g., mill tailings) is almost completely devoid of its decay products.

As the radon travels downwind, the decay products grow in and eventually reach some sort of equilibrium. As such, the PAEC above background due to the source increases with downwind distance until it reaches some maximum value. Beyond this point, the PAEC decreases due to dispersion.

The first decay product to grow in is the alpha emitter Po-218 (RaA). Within ten or so minutes of the radon release, the Po-218 activity nearly equals that of the radon-222.

Challenge of Environmental Radon

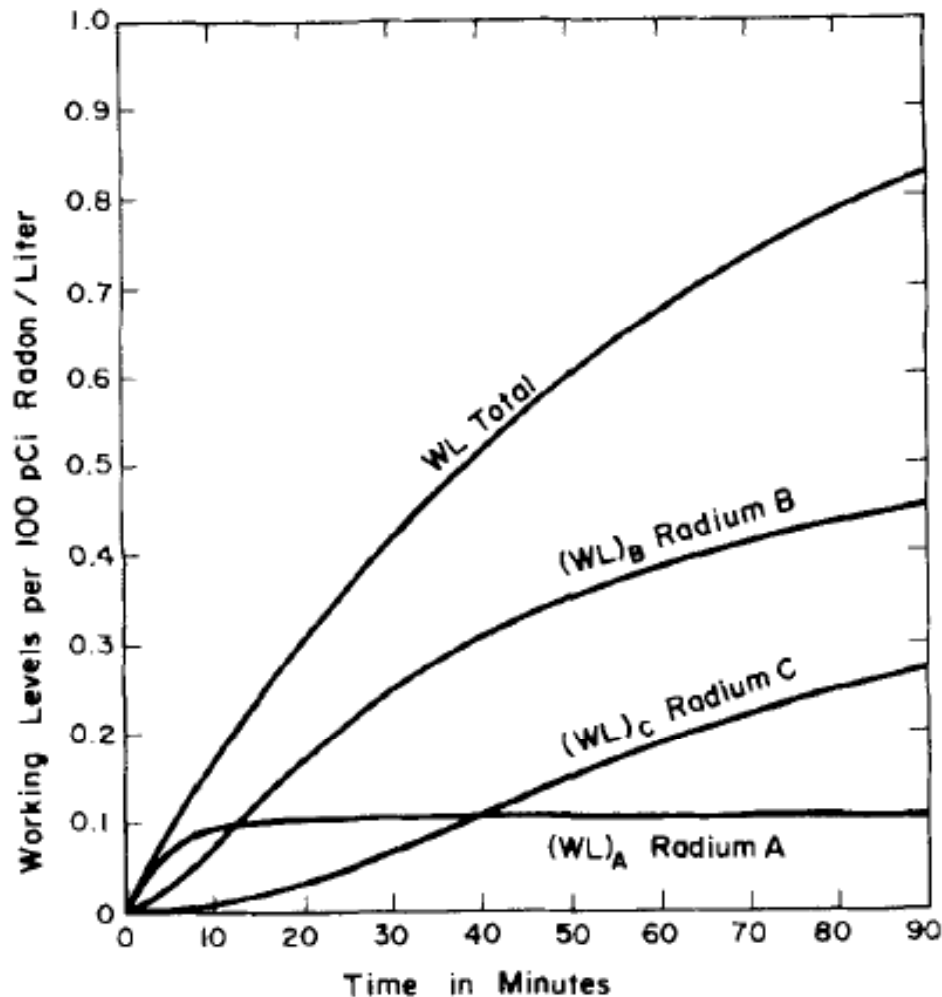## 5. Disequilibrium Downwind from Localized Source

Relative activities and ingrowth of radon decay products as a function of time (Evans 1969).
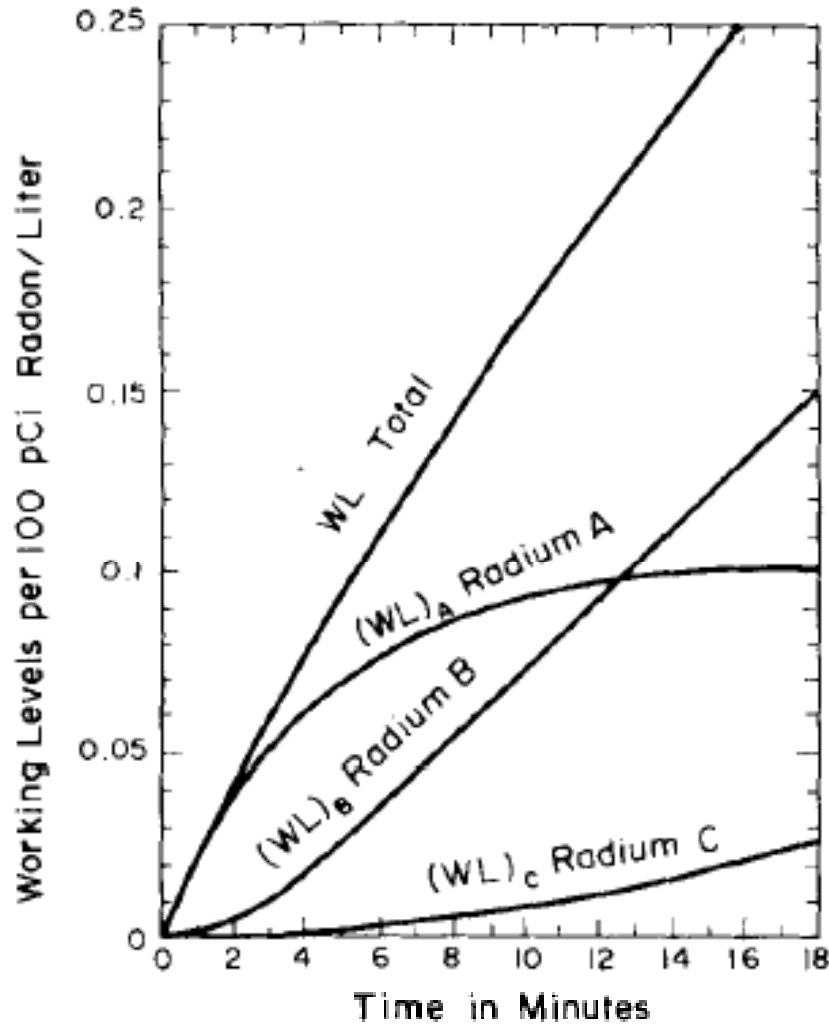
Challenge of Environmental Radon

5. Disequilibrium Downwind from Localized Source

Growth of working level as a function of time given initially pure radon-222. (Figure 4. Evans 1969).

Challenge of Environmental Radon

5. Disequilibrium Downwind from Localized Source

Growth of working level as a function of time given initially pure radon-222.
(Figure 6. Evans 1969).

Challenge of Environmental Radon

5. Disequilibrium Downwind from Localized Source

Starting with a given Rn-222 concentration (C_{Rn}) and none of the decay products, the equations on the next slide give the concentrations of RaA, RaB, RaC and RaC' as a function of time.

The ingrowth time (t) is in minutes.

These equations are modified versions of those given by Evans (1969). The modifications account for slight changes in the assumed half-lives of the decay products.

The equations do not account for any plating out of the decay products.

Challenge of Environmental Radon

5. Disequilibrium Downwind from Localized Source

$$C_{RaA} = C_{Rn}(1 - e^{-\frac{t}{4.47}})$$

$$C_{RaB} = C_{Rn}(1 + 0.13\, e^{-\frac{t}{4.47}} - 1.130\, e^{-\frac{t}{38.95}})$$

$$C_{RaC} = C_{Rn}(1 - 0.0239\, e^{-\frac{t}{4.47}} - 4.297\, e^{-\frac{t}{38.95}} + 3.32\, e^{-\frac{t}{28.71}})$$

$$C_{RaC'} = C_{RaC}$$

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Challenge of Environmental Radon

5. Disequilibrium Downwind from Localized Source

Assuming a wind speed of 2.5 m/s, the equilibrium factor one kilometer downwind from a mill tailings would be approximately 0.1 (due to the source and excluding background).

The higher the wind speed, the lower the equilibrium factor at a given distance downwind from the tailings.

The highest radon concentrations are greatest close to the tailings, but the equilibrium factors are the lowest. Further downwind, the radon concentration decreases, but the equilibrium factor increases until a final equilibrium is reached.

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Facility Property | **Increasing Distance Offsite**

Licensed Radon Source
Rn conc. high (20 pCi/l)
Equil. factor v. low (0.05)

Licensed Radon Source
Rn conc. mod (1 pCi/l)
Equil. factor low (0.1)

Licensed Radon Source
Rn conc. low (0.05 pCi/l)
Equil. factor mod (0.3)

Natural Radon Source
Rn conc. low (0.4 pCi/l)
Equil. factor high (0.6)

Natural Radon Source
Rn conc. low (0.4 pCi/l)
Equil. factor high (0.6)

Natural Radon Source
Rn conc. low (0.4 pCi/l)
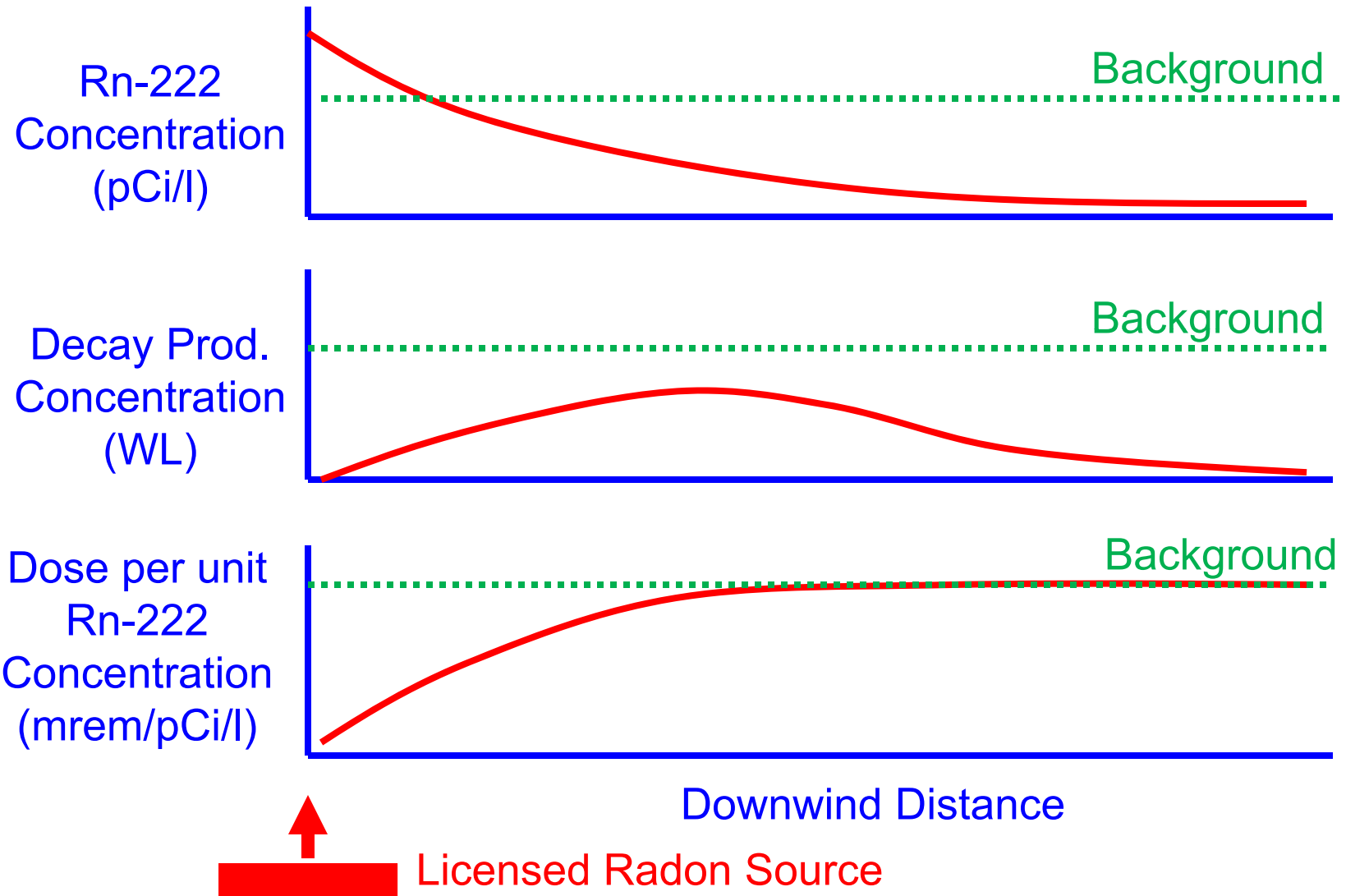Equil. factor high (0.6)

Natural Radon Sources

Licensed Radon Source

Natural Radon Sources

Worker Exposure | **Public Exposure**

Challenge of Environmental Radon

Rn-222 Concentration (pCi/l)

Background

Decay Prod. Concentration (WL)

Background

Dose per unit Rn-222 Concentration (mrem/pCi/l)

Background

Downwind Distance

Licensed Radon Source

Challenge of Environmental Radon

6. Low Regulatory Limits

The simplest way to demonstrate compliance with the regulatory limits in 10 CFR 20.1301 is to show that the radon concentration (above background) due to the licensed source is below the effluent concentration in 10 CFR 20 Appendix B Table II:

Radon with daughters 1×10^{-10} uCi/ml (0.1 pCi/l)

Radon without daughters 1×10^{-8} uCi/ml (10 pCi/l)

At almost any distance from a licensed source, some decay products (particularly RaA) are present. Hence, it would seem that the appropriate effluent limit is 0.1 pCi/l

Effluent Concentrations at Boundary

10 CFR 20 Appendix B Table 2

Rn-222 with daughters: $\quad$ **1 x 10^{-10} uCi/ml**
$$\text{(0.1 pCi/l)}$$

Rn-222 daughters removed: $\quad$ **1 x 10^{-8} uCi/ml**
$$\text{(10 pCi/l)}$$

40 CFR 192.02

Licensed Radon
Source

Rn-222: $\qquad$ **0.5 pCi/l**

Facility Property $\qquad$ **Offsite**

Challenge of Environmental Radon

6. Low Regulatory Limits

a. The average background concentration of radon in the U.S. (0.3 – 0.4 pCi/l) is three to four times this limit. In areas with uranium deposits, the area background might be as high as 1 pCi/l, i.e., ten times the effluent limit.

Complicating any comparison with the limit is the spatial and temporal variability in the concentrations of radon from the licensed source as well as background.

In addition, the limit assumes that the radon decay products are in secular equilibrium with the 0.1 pCi/l limit, a conservative assumption that is very unlikely.

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Challenge of Environmental Radon

6. Low Regulatory Limits

A more complicated way to show compliance is to demonstrate through measurements or calculation that the dose due to the facility operations does not exceed 100 mrem in a year.

Even assuming that the only contribution to the public dose is from radon, this calculation is not straightforward.

We either have the same problem as before (i.e., measuring the radon concentration above background at the facility boundary), or we must determine the release rate from the source (e.g., pCi/s).

Challenge of Environmental Radon

6. Low Regulatory Limits

b. Measuring the release rate from simple sources (e.g., an inactive tailings pile), is doable.

   Measuring or calculating the release rate from a complex site (e.g., an operating in situ leach uranium recovery facility) might border on the impossible or fall into the not worth the effort category.

Challenge of Environmental Radon

7. Some Ideas for Demonstrating Compliance

- Measure the radon concentration at the property boundary

- Use long term measurements to account for temporal variability

- Use a large number of measurement locations to account for spatial variability

- Make similar measurements in a sufficient number of background locations to fully access background near the property

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Challenge of Environmental Radon

7. Some Ideas for Demonstrating Compliance

- Calculate the equilibrium between radon and its decay products that exists at the property boundary or at the location of the individual likely to receive the highest dose from licensed operations.

- Obtain regulatory approval to account for the existing disequilibrium between radon and its decay products.

  This would be for the purpose of adjusting the effluent limit in Appendix B Table 2 or for the purpose of calculating the public dose for comparison with the annual dose limit of 100 mrem.

Deriving the
Radon Effluent Concentration in
10 CFR 20 Appendix B Table 2
and
Calculating the Resulting Dose

Effluent Concentration in 10 CFR 20

1. General

This section begins by deriving the effluent concentration specified in App. B Table 2 for radon plus its decay products.

Then we perform three calculations of the dose associated with this concentration.

The calculations are similar but employ different equilibrium factors and dose conversion factors.

The purpose of this exercise is to show the range of doses that might be calculated using different but "reasonable" input terms.

Effluent Concentration in 10 CFR 20

2. Derivation of App. B. Table 2 Effluent Concentration

The effluent concentration of 1×10^{-10} uCi/ml (0.1 pCi/l) is derived from the occupational limit of 4 WLM. The latter is assumed to result in an exposure of 5,000 mrem to workers.

The primary standard of 4 WLM per year roughly translates to an ALI of 100 uCi for radon with daughters:

4 WLM/year also equates to a PAEC of 0.333 WL (4 WLM/y divided by 12 months per year).

0.333 WL is the same as 3.33×10^{-8} uCi/ml (33.3 pCi/l) of Rn-222 with daughters in equilibrium. Since workers inhale 2.4×10^9 mls/year, 0.333 WL translates to 80 uCi (3.33×10^{-8} uCi/ml x 2.4×10^9 mls/year). Not quite 100 uCi, but close.

Effluent Concentration in 10 CFR 20

2. Derivation of App. B. Table 2 Effluent Concentration

For a breathing rate of 1.2 x 10^6 mls/hr over 2000 hours (2.4 x 10^9 mls/year), the 100 uCi ALI given in Table 2 equates to 4.17 x 10^{-8} uCi/ml.

To account for the fact that the public exposure limit is 100 mrem, we divide by 50. As such, 8.33 x 10^{-10} uCi/ml would result in an exposure of 100 mrem over 2000 hours.

Since the duration of the public's annual exposure is approximately three times that of a worker, we divide by three. In other words inhaling 2.78 x 10^{-10} uCi/ml for an entire year is assumed to result in an exposure of 100 mrem.

Finally, we reduce this by a safety factor of two since we are dealing with the public. Rounded down, this becomes 1 x10^{-10} uCi/ml and it equates roughly to 50 mrem.

Effluent Concentration in 10 CFR 20

2.   Derivation of App. B. Table 2 Effluent Concentration

$$Effluent\ concentration\ (App.B\ Table\ 2) = \frac{ALI}{2.4\ x\ 10^9\ x\ 3\ x\ 50\ x\ 2}$$

$$= \frac{100\ uCi}{7.2\ x\ 10^{11}}$$

$$= 1.39\ x\ 10^{-10}\ uCi/ml$$

$$= 1\ x\ 10^{-10}\ uCi/ml\ (rounded\ down)$$

As indicated previously, a concentration of 0.1 pCi (with daughters in secular equilibrium) is assumed to equate to 50 mrem, i.e., 500 mrem per pCi/l.

Effluent Concentration in 10 CFR 20

3. Calculating the Dose

We will use three approaches to calculate the dose equivalent to a member of the public exposed for an entire year at the effluent concentration specified in 10 CFR 20 Appendix B Table 2 for radon with its daughters, i.e., 1×10^{-10} uCi/ml (0.1 pCi/l).

1. The first method employs a conservative equilibrium factor and a conservative dose conversion factor.

2. The second method uses a "more realistic" equilibrium factor and the ICRP 65 dose conversion factor.

3. The third approach uses the factors employed in NRCP 160.

Effluent Concentration in 10 CFR 20

4. Dose Calculated Using Conservative Assumptions

- We employ a conservative outdoor equilibrium factor of 0.8.

- We employ a dose factor of 9 nSv/Bq h/m^3 (UNSCEAR)

First, we convert the concentration of 1 x 10^{-10} uCi/ml into Bq/m^3:

$$1 \times 10^{-10} \text{ uCi/ml} = 1 \times 10^{-4} \text{ uCi/m}^3 = 3.7 \text{ Bq/m}^3$$

Assume the exposure is for an entire year (8760 hours) .

Effluent Concentration in 10 CFR 20

4. Dose Calculated Using Conservative Assumptions

Cumulative exposure = concentration x equilibrium factor x time

$$= \text{3.7 Bq/m}^3 \text{ x 0.8 x 8760 hrs}$$

$$= \text{2.59 x 10}^4 \text{ Bq h/m}^3$$

Annual Effective Dose   = cumulative exposure x dose factor

$$= \text{2.59 x 10}^4 \text{ Bq h/m}^3 \text{ x 9 nSv/Bq h/m}^3$$

$$= \text{2.33 x 10}^5 \text{ nSv}$$

$$= \text{0.233 mSv}$$

$$= \text{23.3 mrem}$$

Effluent Concentration in 10 CFR 20

5. Dose Calculated Using Less Conservative Assumptions

Now we use two less conservative assumptions:

- The ICRP 65 (1993) dose factor for the public of 4 mSv/WLM equates to 6.4 nSv/Bq h/m^3. This is substantially lower than UNSCEAR's value of 9.

- We will use what might be a more realistic outdoor equilibrium factor of 0.6 than the value of 0.8 used in the previous calculation.

    Note: this is still conservative! As mentioned earlier, an equilibrium factor of 0.1 might be expected at one kilometer from a tailings pile for a wind speed of 2.5 m/s.

Effluent Concentration in 10 CFR 20

5. Dose Calculated Using Less Conservative Assumptions

Cumulative exposure = concentration x equilibrium factor x time

$$= 3.7 \text{ Bq/m}^3 \text{ x } 0.6 \text{ x } 8760 \text{ hrs}$$

$$= 1.94 \text{ x } 10^4 \text{ Bq h/m}^3$$

Annual Effective Dose = cumulative exposure x dose factor

$$= 1.94 \text{ x } 10^4 \text{ Bq h/m}^3 \text{ x } 6.4 \text{ nSv/Bq h/m}^3$$

$$= 1.24 \text{ x } 10^5 \text{ nSv}$$

$$= 0.124 \text{ mSv}$$

$$= 12.4 \text{ mrem}$$

Effluent Concentration in 10 CFR 20

6. Dose Calculated Using NCRP 160 Factors

$$PAEC = \frac{C\ F}{3,740}$$

$$= \frac{3.7\ x\ 0.6}{3,740}$$

$$= 5.94\ x\ 10^{-4}\ WL$$

C is the Rn-222 concentration (Bq/m^3)

F is the assumed outdoor equilibrium factor

1 WL = 3,740 Bq/m^3 (EEC)

Effluent Concentration in 10 CFR 20

6. Dose Calculated Using NCRP 160 Factors

$$Cumulative\ exposure = \frac{PAEC\ t}{170}$$

$$= \frac{5.94\ x\ 10^{-4}\ WL\ x\ 8{,}760\,hrs}{170}$$

$$= 0.031\ WLM$$

PAEC is the potential alpha energy concentration (WL)

t is the exposure time (1 year = 8,760 hrs)

one working month = 170 hrs

Effluent Concentration in 10 CFR 20

6. Dose Calculated Using NCRP 160 Factors

Annual dose equivalent = 0.031 WLM/year x 10 mSv/WLM

$$= 0.31 \text{ mSv}$$

$$= 31 \text{ mrem}$$

Example Calculation
of
Offsite Dose

Example Calculation of Offsite Dose

1. **General**

Dose calculations are performed for a measured Rn-222 concentration of 1 pCi/l at a property boundary.

The fundamental issue is how to estimate the EEC (pCi/l), the PAEC (WL) and the resulting dose due to the decay products.

The Rn-222 concentration measured at the property boundary is 1 pCi/l (37 Bq/m^3) above background.

Distance from source of radon to the property boundary = 1 km

Average wind speed = 2.5 m/s

Example Calculation of Offsite Dose

1. General

The time it takes the radon to travel from the source to the facility boundary is 400 seconds (1000 m/2.5 m/s) or 6.67 minutes. No decay products are initially present.

First. We will calculate the EEC in pCi/l and compare it with the effluent concentration of 0.1 pCi/l specified in Table 2.

Second. We convert the EEC into a PAEC and use the NCRP 160 methodology to estimate the dose.

Third. We use a graph showing the Working Level as a function of the age of the air and compare it with our earlier calculation.

Example Calculation of Offsite Dose

2. Calculation of EEC

The RaA (Po-218) concentration is calculated as follows:

$$C_{RaA} = C_{Rn}(1 - e^{-\frac{t}{4.47}})$$

$$= 1\,pCi/l\,(1 - e^{-\frac{6.67}{4.47}})$$

$$= 0.78\,pCi/l$$

Example Calculation of Offsite Dose

2. Calculation of EEC

The RaB (Pb-214) concentration is calculated as follows:

$$C_{RaB} = C_{Rn}(1 + 0.13\, e^{-\frac{t}{4.47}} - 1.130\, e^{-\frac{t}{38.95}})$$

$$= 1\, pCi/l\,(1 + 0.13\, e^{-\frac{6.67}{4.47}} - 1.130\, e^{-\frac{6.67}{38.95}})$$

$$= 1\, pCi/l\,(1 + 0.0293 - 0.952)$$

$$= 0.077\, pCi/l$$

Example Calculation of Offsite Dose

2. Calculation of EEC

The RaC (Bi-214) concentration is:

$$C_{RaC} = C_{Rn}\left(1 - 0.0239\, e^{-\frac{t}{4.47}} - 4.297\, e^{-\frac{t}{38.95}} + 3.32\, e^{-\frac{t}{28.71}}\right)$$

$$= 1\, pCi/l\left(1 - 0.0239\, e^{-\frac{6.67}{4.47}} - 4.297\, e^{-\frac{6.67}{38.95}} + 3.32\, e^{-\frac{6.67}{28.71}}\right)$$

$$= 1\, pCi/l\,(1 - 0.00537 - 3.6207 + 2.6317)$$

$$= 0.0056\, pCi/l$$

Example Calculation of Offsite Dose

2. Calculation of EEC

The equilibrium equivalent concentration (EEC) of the decay products is calculated as follows:

$$EEC = 0.105[Po - 218] + 0.516[Pb - 214] + 0.379[Bi - 214]$$
$$= 0.105[0.78] + 0.516[0.077] + 0.379[0.0056]$$
$$= 0.12 \, pCi/l$$

Unfortunately, this exceeds the effluent concentration for Rn-222 in Appendix B of 0.1 pCi/l (1×10^{-10} uCi/ml). We have failed to demonstrate compliance

Example Calculation of Offsite Dose

3. Estimate the Dose via NCRP 160 Method

First, we will convert the EEC into a PAEC

$$PAEC = \frac{EEC\,(pCi/l)}{100}$$

$$= \frac{0.12}{100}$$

$$= 0.0012\,WL$$

Example Calculation of Offsite Dose

3. Estimate the Dose via NCRP 160 Method

Now we calculate the cumulative exposure:

$$Cumulative \; exposure \; (WL) \; = \; \frac{PAEC \; x \; t}{170}$$

$$= \; \frac{0.0012 \; x \; 8760 \; hrs}{170}$$

$$= \; 0.062 \; WLM$$

Annual effective dose = 0.062 WLM x 10 mSv/WLM

= 0.6 mSv/year

= 60 mrem/year

Example Calculation of Offsite Dose

4. Using Figure 6 from Evans (1969)

Fig. 6 from Evan's *Engineer's Guide to the Elementary Behavior of Radon Daughters* (1969), indicates a working level concentration of 0.12 to 0.13 per 100 pCi/l Rn-222 for 6.7 minute air.

This equates to 0.0012 to 0.0013 WL for a radon concentration of 1 pCi/l - the same result we determined earlier using more labor intensive calculations!

References

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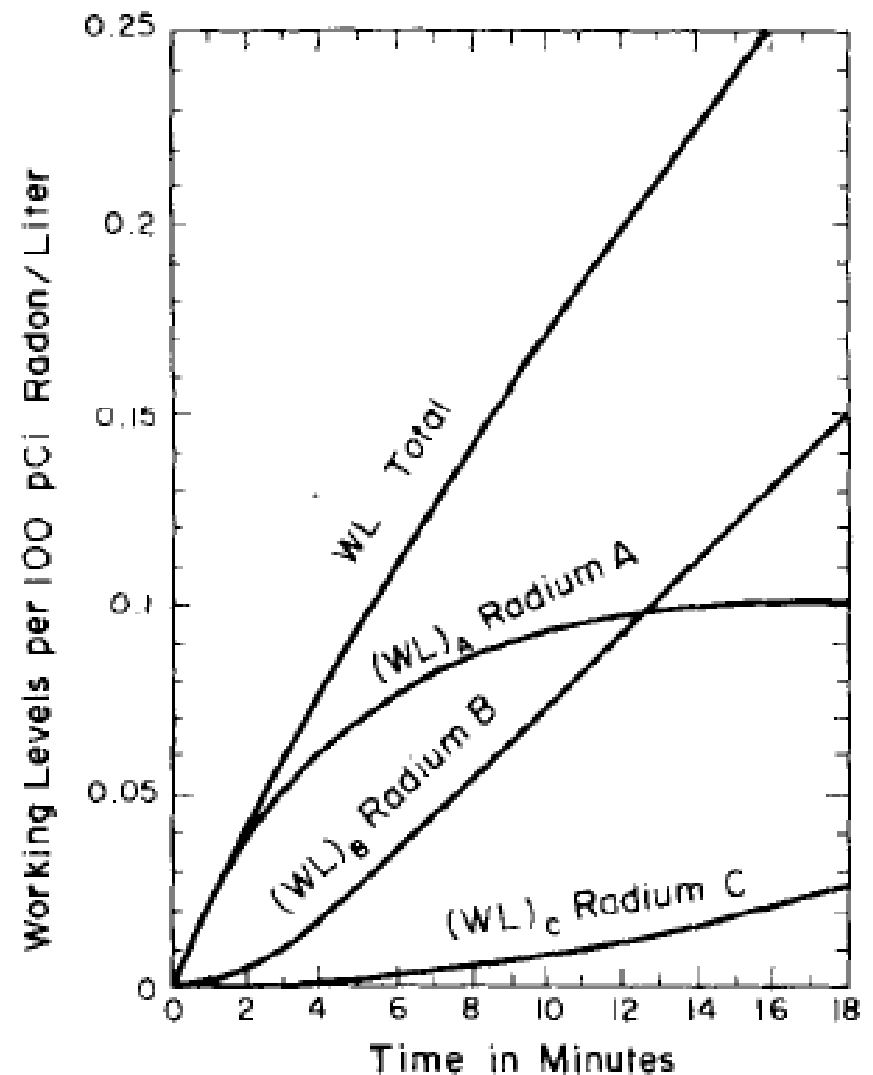
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Regulatory Guide 8.30. *Health Physics Surveys in Uranium Recovery Facilities.*

Appendix A

Conversion Factors

Conversion Factors

Radon Concentrations

$$1 \text{ pCi/l} = 0.037 \text{ Bq/l} = 37 \text{ Bq/m}^3$$

$$1 \text{ Bq/m}^3 = 0.027 \text{ pCi/l}$$

Radon Decay Product Concentrations

$$1 \text{ WL} = 2.08 \times 10^{-5} \text{ J/m}^3 = 3.74 \times 10^3 \text{ Bq/m}^3$$

$$1 \text{ J/m}^3 = 1.80 \times 10^8 \text{ Bq/m}^3 = 4.81 \times 10^4 \text{ WL}$$

Cumulative Exposures

$$1 \text{ WLM} = 3.54 \times 10^{-3} \text{ J h m}^{-3}$$

$$1 \text{ WLM} = 6.38 \times 10^5 \text{ Bq h m}^{-3}$$

$$1 \text{ J h m}^{-3} = 282 \text{ WLM} = 1.8 \times 10^8 \text{ Bq h m}^{-3}$$

Conversion Factors

Equilibrium Equivalent Concentration (EEC)

Converting potential alpha energy concentration (in WL) into the equilibrium equivalent concentration (in Bq/m^3)

Rn-222

$$\text{EEC (in Bq/m}^3) = 3740 \times \text{PAEC (in WL)}$$

$$\text{EEC (in pCi/l)} = 100 \times \text{PAEC (in WL)}$$

$$\text{PAEC (in WL)} = 2.7 \times 10^{-4} \times \text{EEC (in Bq/m}^3)$$

Rn-220

$$\text{EEC (in Bq/m}^3) = 275 \times \text{PAEC (in WL)}$$

$$\text{PAEC (in WL)} = 3.64 \times 10^{-3} \times \text{EEC (in Bq/m}^3)$$

Conversion Factors

UNSCEAR Conversion Factors

Equilibrium Equivalent Exposure

$$1 \text{ Bq h m}^{-3} = 1.57 \times 10^{-6} \text{ WLM} = 5.56 \times 10^{-9} \text{ J h m}^{-3}$$

$$1 \text{ WLM} = 6.38 \times 10^{5} \text{ Bq h m}^{-3} = 3.54 \times 10^{-3} \text{ J h m}^{-3}$$

Dose Conversion Factor for Radon-222 Decay Products

$$1 \text{ Bq h m}^{-3} = 9 \text{ nSv} = 0.9 \text{ urem}$$

Dose Conversion Factor for Radon-220 Decay Products

$$1 \text{ Bq h m}^{-3} = 40 \text{ nSv} = 4 \text{ urem}$$

Conversion Factors

ICRP 65 Conversion Factors for Rn-222 Decay Products

Public Exposures

1 WLM	= 4 mSv	= 400 mrem
1 Bq h m^{-3}	= 6.1 nSv	= 0.61 urem
1 J h m^{-3}	= 1,100 mSv	= 110 rem

Worker Exposures

1 WLM	= 5 mSv	= 500 mrem
1 Bq h m^{-3}	= 8 nSv	= 0.8 urem
1 J h m^{-3}	= 1,400 mSv	= 140 rem

Conversion Factors

NRCP 160 Conversion Factors and assumptions

1 WLM = 10 mSv

Indoor Equilibrium factor = 0.4

Outdoor equilibrium factor = 0.6

Appendix B

EPA Method 115

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

1. Radon-222 Emissions from Underground Uranium Mine Vents

1.1.1 Continuous Measurement. These measurements shall be made and the emissions calculated as follows:

(a) The radon-222 concentration shall be continuously measured at each mine vent whenever the mine ventilation system is operational.

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

1. Radon-222 Emissions from Underground Uranium Mine Vents

1.1.2 Periodic Measurement. This method is applicable only to mines that continuously operate their ventilation system except for extended shutdowns. Mines which start up and shut down their ventilation system frequently must use the continuous measurement method describe in Section 1.1.1 above. Emission rates determined using periodic measurements shall be measured and calculated as follows:

(a) The radon-222 shall be continuously measured at each mine vent for at least one week every three months.

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

1. Radon-222 Emissions from Underground Uranium Mine Vents

1.2.3 Test Methods A–6 or A–7 of Appendix B, Method 114 to part 61 shall be used for the analysis of radon–222. Use of Method A–7 requires prior approval of EPA based on conditions described in Appendix B.

Note: Methods A-6 and A-7 of Appendix B can be found in Appendix C of this presentation.

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

2. Radon-222 Emissions from Uranium Mill Tailings Piles

Water covered area—no measurements required as radon flux is assumed to be zero,

(b) Water saturated beaches—100 radon flux measurements,

(c) Loose and dry top surface—100 radon flux measurements,

(d) Sides—100 radon flux measurements, except where earthen material is used in dam construction. [a, b, c, d subpart W]

For a mill tailings pile after disposal which consists of only one region a minimum of 100 measurements are required [subpart T]

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

2.1.4 Restrictions to Radon Flux Measurements.

The following restrictions are placed on making radon flux measurements:

(a) Measurements shall not be initiated within 24 hours of a rainfall.

(b) If a rainfall occurs during the 24 hour measurements period, the measurement is invalid if the seal around the lip of the collector has washed away or if the collector is surrounded by water.

(c) Measurements shall not be performed if the ambient temperature is below 35 °F or if the ground is frozen.

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

2.1.6 Radon Flux Measurement.

Measuring radon flux involves the adsorption of radon on activated charcoal in a large-area collector.

The radon collector is placed on the surface of the pile area to be measured and allowed to collect radon for a time period of 24 hours.

The radon collected on the charcoal is measured by gamma-ray spectroscopy.

The detailed measurement procedure provided in Appendix A of EPA 520/5–85–0029(1)

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

2.1.7 Calculations

(b) The mean radon flux for the total uranium mill tailings pile shall be calculated as follows.

$$J_s = \frac{J_1 A_1 + J_2 A_2 + \dots J_i A_i}{A_t}$$

Where: J_s = Mean flux for the total pile (pCi/m^2-s)
$\quad\quad\quad$ J_i = Mean flux measured in region i (pCi/m^2-s)
$\quad\quad\quad$ A_i = Area of region i (m^2)
$\quad\quad\quad$ A_t = Total area of the pile (m^2)

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

4.0 Quality Assurance Procedures for Measuring Rn–222 Flux

C. Calibration Procedures and Frequency

The radioactivity of two standard charcoal sources, each containing a carefully determined quantity of radium-226 uniformly distributed through 180g of activated charcoal, shall be measured.

An efficiency factor is computed by dividing the average measured radioactivity of the two standard charcoal sources, minus the background, in cpm by the known radioactivity of the charcoal sources in dpm.

EPA's Method 115

40 CFR 61 Appendix B. Method 115 - Monitoring for Radon-222 Emissions

C. Calibration Procedures and Frequency [continued]

The same two standard charcoal sources shall be counted at the beginning and at the end of each day's counting as a check of the radioactivity counting equipment.

A background count using unexposed charcoal should also be made at the beginning and at the end of each counting day to check for inadvertent contamination of the detector or other changes affecting the background.

The unexposed charcoal comprising the blank is changed with each new batch of charcoal used.

Appendix C

EPA's Method 114

EPA's Method 114

40 CFR 61 Appendix B. Method 114 – Test Methods for Measuring Radionuclide Emissions from Stationary Sources

3.1.6 Method A–6, Radon-222—Continuous Gas Monitor.

Principle: Radon-222 is measured directly in a continuously extracted sample stream by passing the air stream through a calibrated scintillation cell. Prior to the scintillation cell, the air stream is treated to remove particulates and excess moisture. The alpha particles from radon-222 and its decay products strike a zinc sulfide coating on the inside of the scintillation cell producing light pulses. The light pulses are detected by a photomultiplier tube which generates electrical pulses. These pulses are processed by the system electronics and the read out is in pCi/l of radon-222.

EPA's Method 114

40 CFR 61 Appendix B. Method 114 – Test Methods for Measuring Radionuclide Emissions from Stationary Sources

3.1.6 Method A–6, Radon-222—Continuous Gas Monitor.

Applicability: This method is applicable to the measurement of radon-222 in effluent streams which do not contain significant quantities of radon-220. Users of this method should calibrate the monitor in a radon calibration chamber at least twice per year. The background of the monitor should also be checked periodically by operating the instrument in a low radon environment. EPA 520/1–89–009(24).

EPA's Method 114

40 CFR 61 Appendix B. Method 114 – Test Methods for Measuring Radionuclide Emissions from Stationary Sources

3.1.7 Method A–7, Radon-222-Alpha Track Detectors
Principle: Radon-222 is measured directly in the effluent stream using alpha track detectors (ATD). . . The number of tracks per unit area is correlated to the radon concentration in air using a conversion factor derived from data generated in a radon calibration facility.

Applicability: Prior approval from EPA is required for use of this method. This method is only applicable to effluent streams which do not contain significant quantities of radon-220, unless special detectors are used to discriminate against radon-220. This method may be used only when ATDs have been demonstrated to produce data comparable to data obtained with Method A–6.