

Radioactive Disequilibria in the Saturated Zone Transport Model and the Biosphere Model for the Yucca Mountain Repository — The Case of Radon-222

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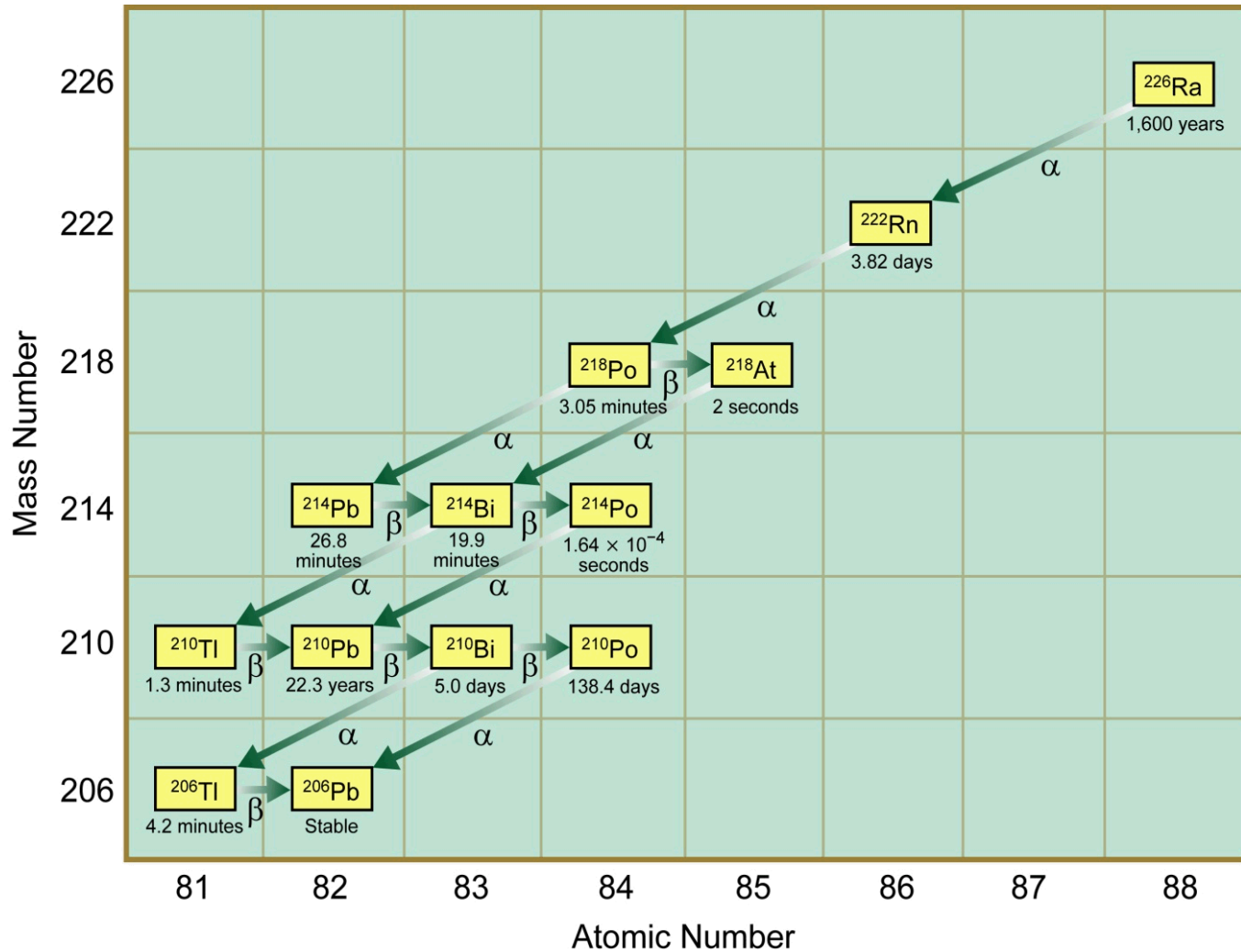




Take-Home Message

If the source of water in the assessment biosphere is a well, don't forget to consider a possibility of disequilibrium between ^{226}Ra and ^{222}Rn .

^{226}Ra and its Decay Products



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Secular Equilibrium in the Decay Chain

- **Activity of the decay product equal to that of a parent**

- **One-phase system**

$$\lambda_i N_i = \lambda_{i-1} N_{i-1}$$

λ = radioactive decay constant

N = number of atoms (moles) present.

- **Two-phase system (aqueous phase + solid sorbed phase)**

$$\lambda_i (N_{i,aq} + N_{i,s}) = \lambda_{i-1} (N_{i-1,aq} + N_{i-1,s})$$



Secular Equilibrium in the Decay Chain

$$C_{i,aq} = C_{i-1,aq} \frac{R_{f,i-1}}{R_{f,i}}$$

Under secular equilibrium conditions (in two-phase system), the activity concentration of the decay product (C_i) is equal to the activity concentration of the parent (C_{i-1}) multiplied by the ratio of the parent retardation factor ($R_{f,i-1}$) to the decay product retardation factor ($R_{f,i}$).

However, for radon...

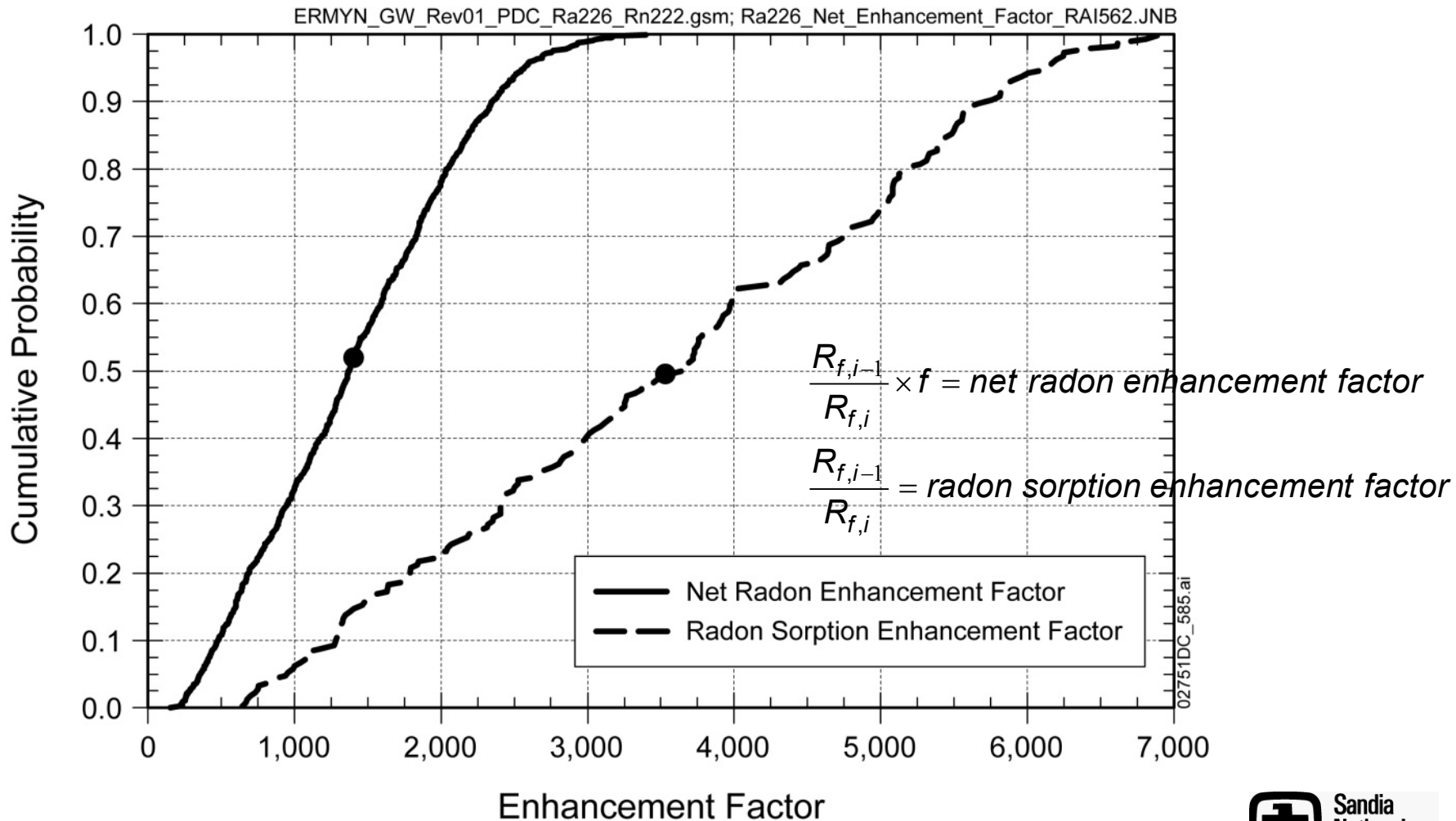


Secular Equilibrium in the Decay Chain

... for radon, we need to include the emanation factor (f), which accounts for fractional release of radon produced in the solid phase into the aqueous phase.

$$C_{i,aq} = C_{i-1,aq} \frac{R_{f,i-1}}{R_{f,i}} \times f$$

Enhancement Factor for Radon





Radon at the Geosphere-Biosphere Interface

- Average concentration of ^{222}Rn in water is, on average, 1,400 times greater than concentration of ^{226}Ra in that water.
- Peak dose ^{226}Ra concentration in groundwater is about 0.7 Bq/m^3 ; ^{222}Rn concentration would then be $\sim 1,000 \text{ Bq/m}^3$
- From Henry's Law, equilibrium concentration of ^{222}Rn in water exposed to 10 Bq/m^3 of ^{222}Rn in air (ambient level) is about 6 Bq/m^3 .
- Even though the concentration of radon can be high in the groundwater, upon entering the biosphere, most of that radon will be outgassed.



Radon at the Geosphere-Biosphere Interface

- Radon gas largely escapes from the groundwater when the water is used outdoors, e.g., for crop irrigation.
- Radon decay products are left behind in the water and continue to decay through the remainder of the decay chain, effectively ending with ^{210}Pb .
- If ^{222}Rn did not escape, there would be about 5×10^{-4} Bq of ^{210}Pb produced for every Bq of ^{222}Rn in the water.



Concentration of ^{210}Pb in the Soil

^{210}Pb in the irrigation water:

$$C_{W_{\text{Pb-210}}} = C_{W_{\text{Pb-210}}(\text{supported})} + C_{W_{\text{Pb-210}}(\text{from excess } ^{222}\text{Rn})}$$

^{210}Pb in the soil:

$$\begin{aligned} C_{S_{\text{Pb-210}}} = & C_{S_{\text{Pb-210}}(\text{from } ^{226}\text{Ra built up in soil})} \\ & + C_{S_{\text{Pb-210}}(\text{from } ^{210}\text{Pb originally in water})} \\ & + C_{S_{\text{Pb-210}}(\text{from decay of excess } ^{222}\text{Rn})} \end{aligned}$$

^{210}Pb concentration from ^{226}Ra built up in the soil dominates.



^{214}Pb and ^{214}Bi in the Surface Soil

- **^{214}Pb and ^{214}Bi – short-lived ^{222}Rn decay products; important external dose contributors.**
- **Short-term increase in ^{214}Pb and ^{214}Bi activity in the soil following irrigation.**
- **The long-term, averaged effects are almost two orders of magnitude less than those from the ^{226}Ra -supported ^{214}Pb and ^{214}Bi .**
- **The short-term effects can be comparable to those from the ^{226}Ra -supported ^{214}Pb and ^{214}Bi .**



^{222}Rn Transfer from Groundwater to Outdoor Air

- **Occurring primarily during irrigation.**
- **Rapid ^{222}Rn release from irrigation water.**
- **For field crops (e.g., alfalfa), ^{222}Rn averaged flux density from the water used for irrigation is $\sim 2.5 \times 10^3 \text{ Bq/m}^2/\text{y}$.**
- **^{222}Rn flux density from decay of ^{226}Rn in soil is $4.1 \times 10^4 \text{ Bq/m}^2/\text{y}$.**
- **Local, short-term fluxes may be much higher because irrigation water is applied only during the growing season and for a fraction of a day.**



^{222}Rn Transfer from Groundwater to Indoor Air

Indoor water use:

- **Release of ^{222}Rn into indoor air during household water use (showering, doing laundry, washing dishes, cooking, and flushing toilets).**
- **Different water use rates, frequencies, durations, and fractions of ^{222}Rn released from the water for each activity.**
- **Effect of air exchange rate (home ventilation rate higher when evaporative coolers are used).**



^{222}Rn Transfer from Groundwater to Indoor Air

Indoor water use:

- **On average, for normal ventilation, the indoor use of water containing unsupported ^{222}Rn doubles the indoor ^{222}Rn concentration in indoor air (compared with that from radon entry from soil).**
- **With evaporative coolers running, the increase is about an order of magnitude less, ~10%.**



^{222}Rn Transfer from Groundwater to Indoor Air

Evaporative cooling use:

- **Evaporative cooler operation results in an incremental addition of radon into the indoor air.**
- **High air exchange rate (on average ~15/h, compared to 1/h for typical ventilation).**
- **Indoor ^{222}Rn concentration from soil gas is more than an order of magnitude higher than that from the unsupported radon from the evaporative cooler water.**



Drinking Water

- Consumption of 2 L of water per day
- For 1 Bq/m³ of ²²⁶Ra, the dose from drinking water containing excess unsupported ²²²Rn is about 3.6×10^{-6} Sv/y.
- Drinking water dose from ²²⁶Ra and its decay products is 2.1×10^{-7} Sv/y.
- All-pathway dose for a unit concentration of ²²⁶Ra in the groundwater, when the effect of unsupported ²²²Rn is not included is $\sim 2.7 \times 10^{-6}$ Sv/y.



Other Pathways

- **Inhalation of resuspended soil contaminated with radon decay products.**
- **Increased concentration of radon decay products in plants, animal products and fish.**
- **Increased external exposure to soil caused primarily by the gamma radiation from ^{214}Bi and ^{214}Pb .**



Effect of Radionuclide Enhancement on Doses from ^{226}Ra and ^{210}Pb

- ^{222}Rn enhancement not included:
 - 3.8×10^{-6} Sv/yr per Bq/m³ for ^{226}Ra
 - 2.7×10^{-6} Sv/yr per Bq/m³ for ^{210}Pb
 - ^{222}Rn enhancement included:
 - 8.7×10^{-6} Sv/yr per Bq/m³ for ^{226}Ra (accounting for enhanced ^{222}Rn groundwater concentrations).
 - 3.2×10^{-6} Sv/yr per Bq/m³ for ^{210}Pb (accounting for enhanced ^{210}Pb and ^{210}Pb from unsupported ^{222}Rn)
- (For mean net radon enhancement factor of 1,400.)



Conclusion

Neglecting to include unsupported ^{222}Rn can result in underestimating the dose from ^{226}Ra and ^{210}Pb .