

Engineering Encyclopedia

Saudi Aramco DeskTop Standards

Radioactive Scales

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SOURCE OF RADIOACTIVITY

So far, we have discussed the cations Mg^{++} , Ca^{++} , Sr^{++} , and Ba^{++} in connection with oil field scales. These cations are part of a group of the periodic table called the alkaline earth metals. Each of these ions has similar chemical properties. They all form doubly-charged ions and have roughly the same solubility of their carbonate and sulfate salts. There is another member of this group, element number 88, or radium, that is also found in some oil field scales. Radium, or Ra, differs from the other alkaline earth ions because it is **radioactive**.

All elements having an **atomic number** higher than 83 are radioactive. Elements having atomic numbers less than 83 might have radioactive **isotopes**, but they all have at least one isotope that is stable. Isotopes are atoms that have the same atomic number but different **mass numbers**. All the isotopes of a given element have identical chemical properties. Many radioactive isotopes that exist in nature are formed by cosmic radiation or are man-made (**anthropogenic**). Radium, however, occurs naturally and is part of one of earth's three naturally-occurring radioactive decay chains.

Radium occurs in oil field scales because it coprecipitates with the other alkaline earth cations in sulfate and carbonate scales. It is most prevalent in barium scales because the physical size of the Ra^{++} ions most closely resemble Ba^{++} ions. Radium sulfate is less soluble than is $BaSO_4$. However, it is found only as a coprecipitated constituent of other scales. Radium is rare, and its concentration in produced waters is far too low to form a scale by itself. The radium concentrations found in oil field waters are usually too low to be hazardous to human health. Some deposits of oil field scales, however, have been found to have potential hazards. Therefore, we have included this module so you will be informed about their existence and their properties.

Atoms consist of a dense nucleus surrounded by a cloud of electrons in definite orbital configuration. The nucleus contains heavy **neutrons** and protons. Protons can be considered to be positively-charged neutrons. The number of neutrons plus the number of protons is the mass number of that isotope (Figure 1). The number of protons equals the number of electrons and is the atomic number of the isotope. Radium has 23 known isotopes. They differ in mass number, but all have the same atomic number. All the radium isotopes are unstable. Some exist for only a second, or less. The three radium isotopes that we are concerned with, however, may exist for thousands of years.

$^{226}_{88}\text{Ra}$

- Mass number, $A = 226 = \text{neutrons (N)} + \text{protons (P)}$
- Atomic number, $Z = 88 = \text{protons (P)} = \text{electrons (e-)}$

So, for Ra226

- Protons = electrons = 88
- Neutrons = $226 - 88 = 138$

FIGURE 1. The Mass Number and the Atomic Number

Mass numbers of single isotopes are always whole integers. For naturally-occurring elements, the atomic mass is usually not a whole number because the elements consist of several isotopes. Also, the mass of a nucleus is less than the sum of the masses of the neutrons and protons. This is because part of the mass is present as binding energy between the neutrons and protons. If an atom is split in two (fissioned), a tremendous amount of energy is released because part of the mass is converted to binding energy for the fission products. Neutrons and protons are equal in mass and are about 1,800 times as heavy as an electron.

The amount of hydrochloric acid required to dissolve a given amount of CaCO_3 can be readily calculated from the equation for the reaction given above.

Radioactive isotopes emit ionizing radiation. It is called ionizing radiation because ions are created in matter through which the radiation passes. We will be discussing three kinds of radiation: alpha (α), beta (β), and gamma (γ). Alpha and beta consist of particles ejected from the isotope. **Gamma rays** consist of electromagnetic radiation similar to X-rays. **Alpha particles** have a double positive charge, a mass of 4 and contain two neutrons and two protons. An alpha particle is essentially a helium nucleus (Figure 2). **Beta particles** are electrons, and they weigh only 1/7200 as much as an alpha particle. Gamma rays have no mass.

Radiation	Composition	Charge	Mass
Alpha (α)	2 N + 2 P	2 +	4
Beta (β)	1 e ⁻	1 -	0.00056
Gamma (γ)	electromagnetic	0	0

FIGURE 2. Forms Of Radiation

Alpha particles have velocities of 2,000-10,000 miles/sec when emitted but cannot penetrate a sheet of paper. They travel only a few centimeters in air. Beta particles have velocities up to the speed of light and travel several meters in air. They can penetrate several inches into the human body. Gamma rays travel at the speed of light and can penetrate steel and the human body.

The emission of gamma radiation does not change the mass or charge of an isotope. Hence, it accompanies the particulate forms of radiation, α and β . When an isotope emits an alpha particle, its mass number decreases by 4, and its atomic number decreases by 2. When $^{226}_{88}\text{Ra}$ disintegrates by α -emission, it becomes $^{222}_{86}\text{Rn}$, or radon-222. Beta emission does not change the mass number, but it increases the atomic number by 1. When an α - or β -particle is emitted, the resulting isotope has an imbalance of binding energy. The excess energy is emitted as γ -radiation. The energy, or wavelength of the γ -emission, is characteristic of the isotope from which it was emitted. Gamma **spectral analysis** is used to identify radioactive isotopes.

Unstable isotopes decay at different rates. The rate at which an isotope decays is usually expressed as its **half-life**. The half-life is the time required for half of any amount of a given isotope to decay. Radium-226 has a half-life of 1,620 years. It will require 1,620 years for the radioactivity of a given quantity of radium to decrease to 1/2 its original **activity**. The shorter the half-life, the greater is the intensity of radiation from a given amount of isotope. Radium-228 has a half-life of 5.76 years so the radiation from one gram of Ra228 will be 1,620/5.76, or 281, times as intense as the radiation from one gram of Ra226.

The decay rate for isotope disintegration is given in Figure 3. Actually, the decay rate of a radioisotope is not steady. It occurs in bursts or uneven pulses. The decay rate can only be established by counting the emissions for a statistically valid period of time. Isotopes that decay slowly must be counted for long periods of time, perhaps for months, to obtain the decay rate. Every unstable isotope has its own decay rate, and there is no way to change it.

$$A = A_0 e^{-\lambda t}$$

A = activity after time t
 A_0 = activity at time 0.
 λ = decay constant.

$$\text{Half-life} = T = \frac{0.693}{\lambda}$$

So $A = A_0 e^{-(0.693t/T)}$

FIGURE 3. Equation for the Decay Rate

Radium and, to a lesser extent, other radioactive elements occur in produced water because of the presence of uranium-238 and thorium-232 in the producing reservoir. U238 and Th232 are the sources of two of the earth's natural decay series. A third series, called the actinide series, also exists but it is very rare and does not contribute significantly to the radioactivity of produced waters.

The uranium and thorium series are given in Figure 4. The **uranium series** begins with $^{238}_{92}\text{U}$ and the **thorium series** begins with $^{232}_{90}\text{Th}$. These isotopes have very long half-lives and were part of the earth's matter when it was formed billions of years ago. The half-life of U238 is 4.47×10^9 years. About half of the U238 present when the earth was formed still remains. From Figure 4, it is seen that U238 decays by α -emission to form its **daughter** product, Th234, which has a half-life of 24.1 days. The Th234, in turn, decays to Pa234, and so on, until the last remaining isotope is lead-206, which is a stable isotope and decays no further.

Uranium Series			Thorium Series		
Nuclide	Mode of Decay	Half-Life	Nuclide	Mode of Decay	Half-Life
$^{238}_{92}\text{U}$	α	4.47×10^9 y	$^{232}_{90}\text{Th}$	α	1.4×10^{10} y
$^{234}_{90}\text{Th}$	β	24.1 d	$^{228}_{88}\text{Ra}$	β	5.76 y
$^{234}_{91}\text{Pa}$	β	1.17 m	$^{228}_{89}\text{Ac}$	β	6.13 h
$^{234}_{92}\text{U}$	α	2.45×10^5 y	$^{228}_{90}\text{Th}$	α	1.91 y
$^{230}_{90}\text{Th}$	α	7.54×10^4 y	$^{224}_{88}\text{Ra}$	α	3.65 d
$^{226}_{88}\text{Ra}$	α	1600 y	$^{220}_{86}\text{Rn}$	α	55.6 s
$^{222}_{86}\text{Rn}$	α	3.82 d	$^{216}_{84}\text{Po}$	α	0.15 s
$^{218}_{84}\text{Po}$	α, β	3.11 m	$^{212}_{82}\text{Pb}$	β	10.46 h
$^{214}_{82}\text{Pb}$	β	26.8 m	$^{212}_{83}\text{Bi}$	α, β	60.6 m
$^{214}_{83}\text{Bi}$	α, β	19.8 m	$^{212}_{84}\text{Po}$	α	0.3 μs
$^{214}_{84}\text{Po}$	α	163.7 μs	$^{208}_{81}\text{Tl}$	β	3.05 m
$^{210}_{82}\text{Pb}$	β	22.3 y	$^{208}_{82}\text{Pb}$	stable	—
$^{210}_{83}\text{Bi}$	α, β	5.01 d			
$^{210}_{84}\text{Po}$	α	138.4 d			
$^{206}_{82}\text{Pb}$	stable	—			

FIGURE 4. The Uranium and Thorium Decay Series

If some U238 could be contained in a sealed container so that nothing could escape, all the isotopes listed in Figure 4 would eventually be contained in it. After roughly 160,000 years, the isotopes would reach secular equilibrium. That means every isotope would have the same activity as the parent U238. When a daughter does not have the same activity as its parent, it is said to be in disequilibrium.

U238 and Th232 are widely distributed in the earth's crust. They are present in sandstones up to 0.6 ppm for uranium and 200 ppm for thorium (Figure 5). Some oil shales contain 500 ppm of uranium and 200 ppm of thorium. The variability of the concentration of uranium and thorium, their daughter products, and other **nuclides** in underground formations is the basis for γ -ray logging of oil wells.

Mineral	K (%)	U (ppm)	Th (ppm)
Basalt	0.61 - 1.7	0.25 - 1.7	0.05 - 6.8
Carbonates	0 - 2.0 (0.3)	0.1 - 9.0 (2.2)	0.1 - 7.0 (1.7)
Clays	0.16 - 9.8	1.5 - 30	0.01 - 130
Feldspars	0.54 - 10.9	—	0.01
Granite	2 - 6	3.6 - 16	14 - 62
Oil shales (Colorado)	4.0	up to 500	1 - 30
Sandstones (average)	0.7 - 3.8 (1.1)	0.2 - 0.6 (0.5)	0.7 - 200 (1.7)
Silica, quartz (pure)	0.15	0.4	0.2
Beach sands:			
Gulf of Mexico	1.2	0.84	2.8
Atlantic (Florida, North Carolina)	0.37	3.97	11.27
Atlantic (New Jersey, Massachusetts)	0.3	0.8	2.07
Shales (average)	1.6 - 4.2 (2.7)	1.5 - 5.5 (3.7)	8 - 18 (12.0)

FIGURE 5. Concentration of Radioelements in Various Minerals

The uranium and thorium present in sandstones or other rock in the oil-bearing formation decay to their respective daughter products. Examination of uranium- and thorium-bearing sands reveals that the uranium and thorium are part of the sand grain itself. How, then, does the radium escape from the sand grains to the formation water? The currently accepted explanation is that the sand grains are damaged by α -recoil. When a nuclide ejects a heavy α -particle, there is a recoil similar to a cannon firing a projectile. The calculated force of this recoil is sufficient to rupture crystalline bonds in silica, causing fissures in the sand grains. Radium cations, being soluble in water, are extracted from the sand grains by formation water.

Illustrations of the processes described above are given in Figure 6. In the uranium series, the first soluble daughter produced by U238 is Ra226. In the water phase, Ra226 decays to Rn222, which is a noble gas and is only slightly soluble in water. The Rn222 distributes between the gas phase and water phase according to the conditions prevailing in the reservoir. Almost all of the Rn222 is liberated from the water phase when the pressure is dropped to atmospheric at the surface. We will discuss Rn222 and its fate in a later section.

The thorium series (Figure 6) behaves similarly to the uranium series in that radium isotopes are the only soluble daughter products formed. However, thorium has two radium daughter products, Ra228 (half-life 5.76 yr) and Ra224 (half-life 3.65 days).

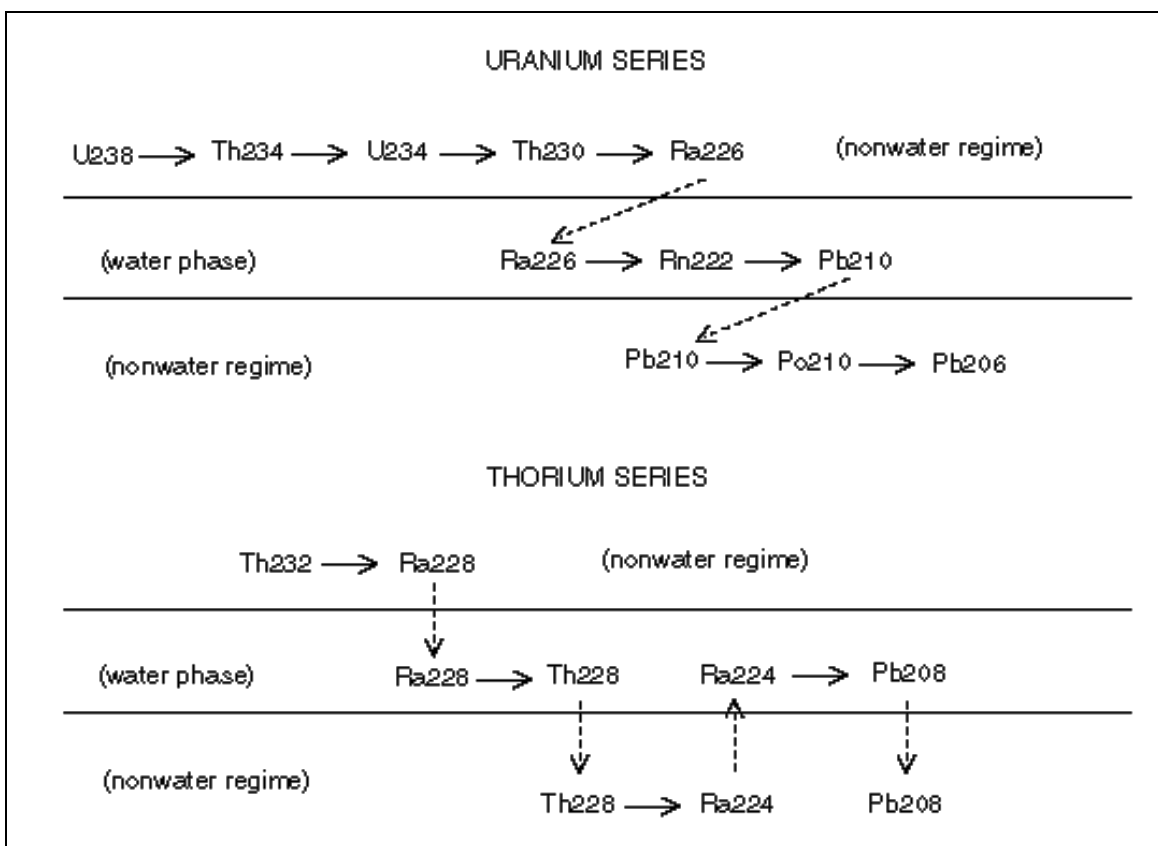


FIGURE 6. Phase Behavior of the Uranium and Thorium Natural Decay Series

All three isotopes of Ra (226, 228, and 224) are found in produced water. Most data are for Ra226 only because it is the most convenient to measure by trapping the Rn222 daughter emitted. Available data indicate that Ra228 is present in produced waters in activities as high, or more than, the Ra226. The actual ratio of Ra228 to Ra226 in produced water depends on the ratio of the parents, Th232 to U238, in the reservoir rock. Ra224 is rarely measured because of its short half-life. Based on equilibrium considerations, Ra228 and Ra224 should have equal activities since Ra224 is a daughter of Ra228.

Complete radiological analyses of produced waters are rare. However, they report that radium isotopes are the major source of produced-water radioactivity. One such analysis is given in Figure 7. Activities of the nuclides in Figure 7 are given in picocuries per liter (pCi/l). A picocurie is 10^{-12} curies (Figure 8). A **curie** was originally defined as the number of disintegrations per second occurring in 1 gram of radium, or 3.7×10^{10} disintegrations per second. The picocurie then is 3.7×10^{-2} disintegrations per second, or one disintegration every 27.03 seconds. The picocurie has been replaced by the SI unit **becquerel**, or Bq, which is one disintegration per second. One Bq is equal to 27.03 pCi. Much of the data reported in this module was measured before the Bq was adopted so we are using pCis in some places because the two units are easily converted.

Isotope	Half-life	Activity (pCi/l)	% of Total Activity
U238	4.7×10^9 y	0.054	0.01
Th234	24.1 d	3.63	0.79
U234	2.44×10^5 y	0.082	0.02
Th 230	7.5×10^6 y	0.10	0.02
Ra226	1620 y	227	49.2
Rn222	3.82 d	182	39.4
Pb210	23.3 y	1.4	0.30
Bi210	5.0 d	4.1	0.89
Po210	138.4 d	0.5	0.11
Th232	1.4×10^{10} y	0.009	0.002
Ra228	5.76 y	21.4	4.64
Th228	1.91 y	0.59	0.13
Ra224	3.66 d	20.4	4.42

FIGURE 7. Concentration of Radionuclides in Brine Water from Zone 2 (4638-4514 ft) of Mansfield Well No. 1 (Palo Duro Basin)

Note: From Laul, et al, 1987

picocurie, pCi	=	10^{-12} curies
curie	=	3.7×10^{10} disintegrations/sec
1 pCi	=	3.7×10^{-2} disintegrations/sec
1 Bq	=	1 disintegration/sec
1 Bq	=	27.03 pCi
1000 pCi/l	=	158,760 pCi/bbl
100,000 BWPD, 1000 pCi/l	=	1 curie/63 days

FIGURE 8. Units of Decay Activity

From Figure 7, radium isotopes are 58.3% of the total activity found in the formation water. Excluding Rn222, which is released to the atmosphere, the radium isotopes are 96.2% of the total activity. Note from Figure 7 that the activities of Ra228 and Ra224 are nearly equal as expected. For this particular water, the activity of Ra226 is about 10 times that of Ra228. In some formation waters, Ra228 is higher than Ra226.

The concentration of an isotope can be estimated from its activity (Figure 9). For example, one gram atomic weight of Ra226 is 226 grams, and it contains 6.023×10^{23} atoms (Avogadro's number). Half of the Ra226, or 3.012×10^{23} atoms, will disintegrate in 1,620 years, which is equivalent to an average of 3.6×10^{10} disintegrations per second per gram, or 1×10^{10} pCi/g. The Ra226 activity in Figure 7 is 227 pCi/l so the concentration of Ra226 is only 2.27×10^{-7} mg/l. From the K_{sp} for RaSO₄ (Figure 10), even the highest concentrations of Ra⁺⁺ ever found in formation waters are far too low to precipitate as RaSO₄ by themselves.

$$\begin{aligned} \text{Activity of Ra226} &= \frac{6.023 \times 10^{23} (0.693)}{(2)(1,620)(365.25)(24)(3,600)} \\ &= 3.61 \times 10^{10} \text{ disintegrations/sec/g} \\ \text{Activity in pCi} &= \frac{3.6 \times 10^{10}}{3.7 \times 10^{-2}} \\ &= 1 \times 10^{12} \text{ pCi/g} \\ \text{Concentration of Ra226} &= \frac{(227)(1000)}{1.0 \times 10^{12}} \\ &= 2.27 \times 10^{-7} \text{ mg/l} \\ \text{or, } \frac{2.27 \times 10^{-7}}{226 \times 10^3} &= 1 \times 10^{-12} \text{ M/l} \end{aligned}$$

FIGURE 9. Calculating Concentration from Activity

Salt	K _{sp} at 25 °C
CaSO ₄	3.75 × 10 ⁻⁵
SrSO ₄	3.42 × 10 ⁻⁷
BaSO ₄	1.05 × 10 ⁻¹⁰
RaSO ₄	4.3 × 10 ⁻¹¹

FIGURE 10. Solubility Product Constants of Alkaline Earth Sulfates

We conclude from the foregoing that formation waters, whose radium content is leached from sand, will contain the radium isotopes 226, 228, and 224. In addition, barium is also leached from these sands. The water, therefore, is likely to contain barium and will be low in sulfate.

Another possible source of radium in produced water has been shown to exist in at least one location. This is the formation of Ra226 from concentrated deposits of uranium in the reservoir. Uranium is known to occur in concentrated deposits associated with asphalts. Asphalts containing up to 13% by weight of uranium are known. The mechanism of formation of these deposits is not known for certain. It is assumed to be due to the insolubility of the reduced, or +4, form of uranium and the high solubility of the oxidized, or +6, form of uranium. Aerated ground waters leach uranium from rock by oxidizing it to U^{+6} (Figure 11). If the ground water encounters a reducing condition, such as a vent of hydrocarbon gases, the U^{+6} is reduced to U^{+4} , and it precipitates. The resulting localized radioactivity polymerizes lighter hydrocarbons to asphalts. Uranium is mined by leaching such deposits with oxidizing agents.

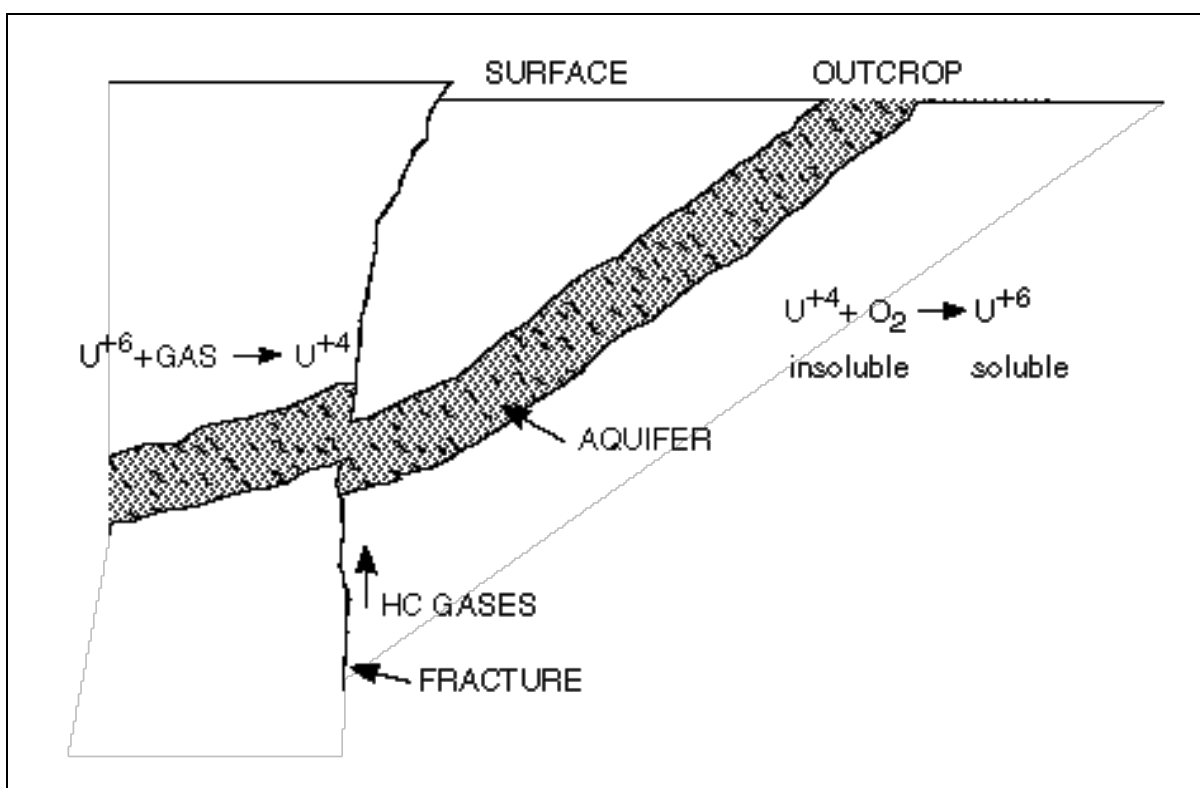


FIGURE 11. Mechanism of Uranium Deposition

When concentrated deposits of U^{+4} are the source of radium in produced water, Ba^{++} , Ra228, and Ra224 do not necessarily accompany Ra226. Also, SO_4^{-} can be present in high concentrations since Ba^{++} is low or absent.

The characteristics of produced water for the two sources of nuclides are shown in Figure 12. Barium, Ra226, and Ra228 are prevalent if the radium is leached from sand grains (Figure 12-A). Ra226 is high and barium and Ra228 are low if the radium is leached from concentrated deposits of U^{+4} . Some other characteristics will be noted as we move along.

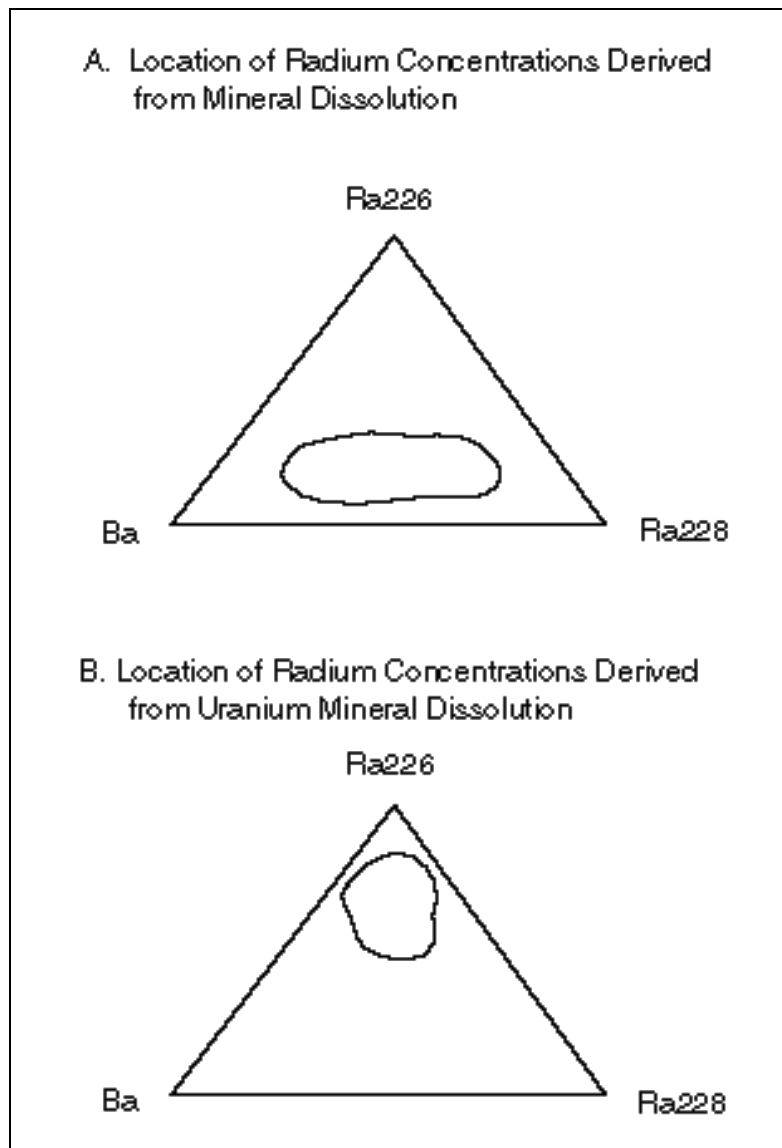


FIGURE 12. Characteristics of Produced Water When Radium Is Leached From Two Sources

NOTE: © 1980 American Association of Petroleum Geologists. From Bloch and Key, *Bulletin* 65 (1) (January 1980), 154-159, reprinted by permission.

Several investigators have noted that the higher the TDS of a produced water, the higher the activity of radium isotopes can be (Figure 13). This does not mean that every produced water having a high TDS also has a high radium content. There must be a source of radium in the producing formation. The data in Figure 13 are from a region where uranium-bearing sands are prevalent in most of the producing oil and gas fields. Data from other parts of the world also fit the curve in Figure 13 if radium is present in produced water.

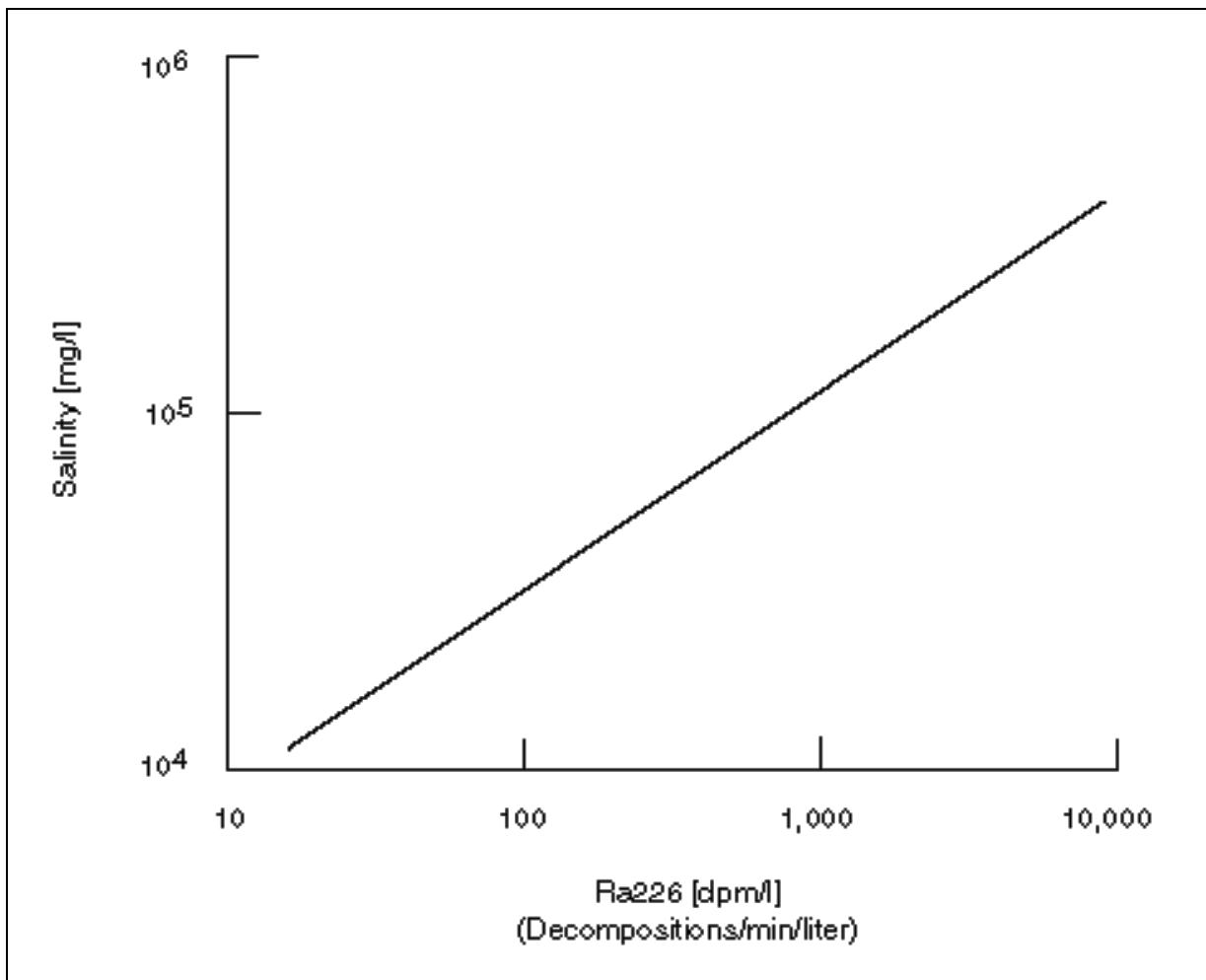


FIGURE 13. Salinity Versus Ra226 Activity in Louisiana-produced Waters

Note: From Kraemer and Reid

The reason that radium increases with TDS is that there are more ions to compete with the Ra⁺⁺ for adsorption sites. Ra⁺⁺ adsorbs very readily on solid surfaces. However, if the water in contact with those surfaces contains high concentrations of Ca⁺⁺, Mg⁺⁺, and Na⁺, the adsorption of Ra⁺⁺ is decreased, and its concentration in the water is higher.

The effect of TDS on adsorption of Ra⁺⁺ on solids is also shown in Figure 14, which gives the **distribution coefficients** (K_D) of Ra⁺⁺ between solution and sediments for various TDS concentrations. The distribution coefficient (Figure 15) is the ratio of the concentration of Ra⁺⁺ in a sediment to the concentration in the solution with which it is in equilibrium. The units of K_D , as expressed here, are l/g. Therefore, K_D expresses the number of liters of solution whose total radium content is equal to the radium adsorbed by one gram of solid.

Ra226				
TDS (mg/l)	Water (pCi/l)	Sediment (pCi/g)	K_D (l/g)	Reference
90,000 ^a	133	0.47	0.0035	1
30,000 ^b	8.0	0.12	0.015	1
9,000 ^b	0.33	0.015	0.045	1
3,800 ^c	0.024	0.14	5.6	2
500 ^d	0.58	1.45	2.5	3
200 ^e	0.007	8.8	120	2

Notes:

- a. Produced water
- b. Produced water diluted with distilled water
- c. Estuary
- d. Marsh
- e. Hudson River, New York, USA

References:

- 1. Landa and Reid (1983)
- 2. Li et al (1977)
- 3. Hanan (1981)

FIGURE 14. Distribution Coefficients of Sediments for Waters of Various Total Dissolved Solids

Ra⁺⁺ (solution) ↔ Ra⁺⁺ (adsorbed)

$$K_D = \frac{C_S}{C_L}$$

Where C_S = concentration on the solid, pCi/g
 C_L = concentration in the solution, pCi/l

$$\text{So } K_D = \frac{\frac{\text{pCi}}{\text{g}}}{\frac{\text{pCi}}{\text{l}}} = \frac{\text{l}}{\text{g}}$$

FIGURE 15. Definition of the Distribution Coefficient

In Figure 14, for example, K_D for sediments in water that contains 90,000 mg/l of TDS is 0.0035 l/g. This can be interpreted to mean that sediments in this water will adsorb the amount of Ra^{++} contained in only 0.0035 l of water. When TDS is low, for example, the last water in Figure 14 that contains 200 mg/l TDS, K_D is 120. These data clearly demonstrate that briny waters retain Ra^{++} because it is adsorbed very little by sediments. Fresh waters, such as rivers and lakes, contain very little Ra^{++} because it is adsorbed strongly by sediments.

The data on which Figure 13 is based are given in Figure 16. These data are for analyses of brines from various oil and gas fields on the Louisiana Gulf Coast where Ra^{++} is common in produced waters. In these waters, SO_4^{--4} is low or absent, Ba^{++} is high, and Ra^{226} , Ra^{228} , and Ra^{224} are also present. These characteristics indicate that the Ra^{++} is leached from uranium-bearing sandstones. Note that the ratio of Ra^{228} to Ra^{226} varies from 0.55 to 2.25 for the analyses reported in Figure 16.

Depth(m)	Production	Salinity(mg/l)	Ra226(pCi/l)	Ra228(pCi/l)	Ra228/Ra226
4,275	Oil	235,000	437	432	0.98
4,275	Oil	127,000	330	430	1.30
4,275	Oil	98,000	300	331	1.10
4,275	Oil	98,000	145	204	1.40
4,275	Oil	110,000	397	575	1.45
4,275	Oil	120,000	316	411	1.30
4,275	Oil	81,000	182	—	—
3,368	Gas/oil	20,300	1.3	—	—
3,257	Gas/oil	21,200	1.8	—	—
3,622	Gas/oil	36,300	15.8	—	—
3,216	Gas	17,500	0.11	—	—
2,903	Gas	7,500	< 0.05	—	—
3,694	Gas	32,400	8.3	18.6	2.25
5,732	Gas	185,000	1,235	1,087	0.88
3,777	Gas	29,600	45.4	80.0	1.76
3,574	Gas	78,300	186	340	1.83
3,424	Gas	80,800	165	353	2.14
4,320	Gas	134,000	339	484	1.43
3,891	Gas	149,600	1,256	1,507	1.2
3,000	Gas	66,000	212	308	1.45
5,930	Gas	74,800	369	612	1.66
4,860	Gas	76,500	207	406	1.96
6,238	Gas	51,000	127	—	—
6,154	Gas	37,500	88.6	129	1.45
1,140	Gas	11,500	< 0.05	—	—
4,555	Gas	147,500	300	183	0.61
4,935	Gas	200,000	1,580	1,248	0.79
4,733	Gas	105,000	523	831	1.59
4,842	Brine	274,000	995	922	0.93
4,694	Brine	165,000	458	431	0.94
4,834	Brine	190,000	> 92	434	0.55
5,105	Brine	36,000	56.4	99.5	1.77
4,450	Brine	100,000	268	376	1.41
4,511	Brine	23,750	32.7	7.3	1.75
2,984	Brine	13,500	31.8	46.4	1.46
4,511	Brine	42,600	102	132	1.30
4,473	Brine	132,000	699	618	0.88
3,567	Brine	15,300	10.3	8.3	0.81
3,932	Brine	113,500	575	500	0.87
4,077	Brine	95,000	192	269	1.4
5,035	Brine	44,000	86.4	99.1	1.15

FIGURE 16. Radium Contents of Waters From Louisiana Oil, Gas, and Geopressed Brine Wells.

The data in Figure 17 are analyses from a carbonate reservoir where it is believed that uranium exists in a concentrated asphaltic deposit. Note that SO_4^- is high in most cases, and Ra226 varies considerably from well to well. Ra228 is very low in this field. Also, there is not a good correlation between TDS and Ra226 activity. The field produces high concentrations of helium, which is believed to be **radiogenic** in origin. Asphaltic deposits of U^{+4} have been found in cores taken from the field.

Well	mg/l					pCi/l
	TDS	Ca^{++}	Mg^{++}	Cl^-	SO_4^-	Ra226
Cator 1	181,904	9,490	2,032	112,084	120	1,060
Bivins F-1	145,033	5,176	956	87,140	1,996	206
Lee	228,607	4,900	1,600	138,000	1,920	720
Lee 11	154,111	4,640	1,470	93,500	2,240	435
Lee 1	161,178	3,440	4,220	96,900	2,490	565
Flyr 1	205,190	5,860	1,370	140,000	2,080	575
Jessie 1	154,189	5,110	1,270	90,700	1,850	218
Arlene 1	151,202	8,647	3,798	93,200	1,369	318
Idell 1	106,533	2,261	1,116	61,867	3,827	289
Drury 1	103,773	5,262	1,788	62,395	2,096	483
Ola 1	140,965	6,703	2,263	86,084	1,290	350
Fuqua B-1	125,973	6,205	1,863	76,247	1,731	1,560
Taylor 1-G	113,585	5,160	2,470	69,300	845	224
Bivins G-G	171,156	4,810	1,600	104,000	1,300	1,170
Berneta 1	195,151	8,704	2,634	117,000	1,743	724
Cobb 1-G	247,708	1,670	863	151,000	2,800	227
Dill Morrow 1	152,114	7,823	1,844	92,658	1,396	288
Brilton A-1	135,355	7,963	2,227	82,270	1,421	550

FIGURE 17. Composition of Some Brines From the Panhandle Gas Field

Note: From Pierce, Gott, and Mytton (1955)

The radium contents of produced waters are too low to be hazardous to humans from external exposure. A radium-bearing produced water would be hazardous if ingested. However, produced waters are not ingested by humans. We will examine possible pathways of radium from produced waters to humans in a later part of this module.

The main hazard of radium in produced waters arises from the coprecipitation of radium with scales formed from the water, especially BaSO_4 scales. Other scales also coprecipitate radium but not to the extent that BaSO_4 does. If BaSO_4 is precipitated from a solution that contains Ra^{++} , about 98% of the Ra^{++} will be included in the BaSO_4 crystals even though RaSO_4 is far below saturation.

Practical Example

This example illustrates how radium forms part of a barium scale.

A produced water contains 980 pCi/l of total radium. The water also contains sufficient Ba^{++} that it forms 20 mg of BaSO_4 scale per liter of solution. What will be the concentration of radium in the BaSO_4 ?

Solution

98% of the radium will be included in the BaSO_4 .

$C =$ _____

$C =$ _____ pCi/g

The concentration of radium in some mixed $\text{BaSO}_4 \cdot \text{SrSO}_4$ scales from some oil wells in Kansas are given in Figure 18. The scales were analyzed several years after they were formed. Most of the activity is expected to be from the long-lived Ra^{226} . Scales containing over 100,000 pCi/g of radium have been observed on some North Sea platforms. The first column in Figure 18 is the concentration of natural uranium that would be equivalent to the radioactivity measured for the scales. The second column is the amount of uranium actually measured in the scales, and the third column is the concentration of radium measured in the scales. The last column is the concentration of uranium that is equivalent to the concentration of radium found.

Serial Number	Equivalent Uranium (%)	Chemical Uranium (%)	Radium Content (pCi/g)	Calculated Equivalent Uranium (%)
15539	1.17	0.003	9,400	1.6
15543	1.14	0.003	7,500	1.3
18377	1.20	0.000	11,000	2.0
18446	8.11	0.001	46,000	7.8
18448	7.10	0.000	32,000	5.5
18452	4.37	0.001	25,000	4.3

FIGURE 18. Radium Concentrations in Precipitates From Southeastern Kansas Oil Field Brines

Note: From Gott and Hill, 1953

DETECTION AND MEASUREMENT

Radiation is harmful if absorbed by humans in sufficient quantity. Low levels of radiation do no harm. In fact, we spend our lives exposed to low levels of radiation from natural and man-made sources. Human senses cannot detect harmful levels of radiation since it is invisible, colorless, odorless, tasteless, and makes no sound. Even lethal doses of radiation have no immediate effect on the body's senses. Therefore, some instrumented means must be employed to detect and measure levels of radiation to ensure human safety.

Radiation cannot be measured directly, but we can measure the effects it produces. Radioactive emissions are called ionizing radiation because they produce ions in matter with which they interact. The most common effect of α , β , and γ radiation is to produce **ion-pairs** (Figure 19).

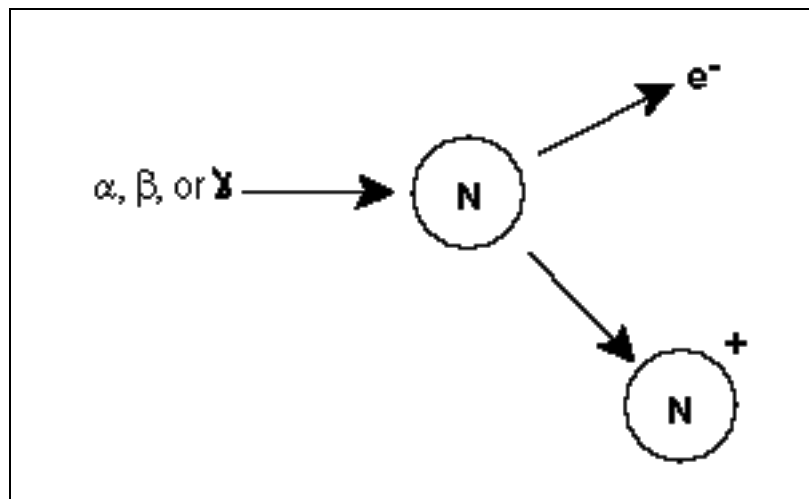


FIGURE 19. Production of an Ion-pair

When an α - or β -particle, or a γ -**photon**, strikes an atom in air, such as a nitrogen atom, an electron is knocked loose from the outer shell of the nitrogen atom. This leaves the nitrogen atom deficient by one electron. Therefore, it has a positive charge. The ions that are produced can be measured by sensitive instruments in various ways. The nucleus is never affected by α -, β -, or γ -radiation so these do not induce radioactivity in other atoms. Neutrons are required to affect the nucleus of other atoms. Since neutrons are not emitted by any naturally-occurring decay series, we are not concerned with them here.

Personal Monitors

People who work with or near radioactive material wear a personal radiation monitor that measures accumulated dose over a period of time. These **dosimeters** were film badges originally. They consisted of a small plastic badge that contained a piece of photographic film. Radiation exposes the film. The longer the exposure or the greater the intensity of radiation, the darker is the developed film. After a period of time, the film was developed, and the dose was determined from the amount of light that could pass through the film from a standard source.

Another type of personal monitor, and the one preferred nowadays, is the direct-reading dosimeter. Capacitative and electrometer types are available. Capacitative dosimeters have a capacitor with plates separated by a gas-filled gap that is charged by high voltage. Radiation creates ions in the gas, causing charge to leak from the capacitor. The total dose is determined by simply measuring the charge remaining on the capacitor. The electrometer type uses thin metal sheets or fibers suspended in an inert gas. When charged by high voltage, the sheets or fibers repel each other because they have the same charge. Radiation causes the charge to leak off so the sheets or fibers approach one another. The total dose is determined by measuring the distance between the sheets or fibers. The direct-reading personal dosimeters are in the form of a cylinder with a clip similar to a pen or pencil so they are very convenient to use.

Oil field personnel are not expected to work with radioactive materials for any length of time. The removal and disposal of radioactive scales are done by qualified contractors who have means of protecting their personnel and the public from excessive exposure. Therefore, we will not discuss personal monitors any further.

Survey Meters

The presence of radioactivity can be detected and measured immediately by use of a **survey meter**. These meters are small, rugged, portable, and inexpensive. They cost US\$500-\$1500 depending on the sensitivity and accessories. They announce the presence of radioactivity by an audible clicking or buzzing. As the frequency of the clicking or buzzing increases, so does the intensity of the radiation. A sensitive survey meter is always clicking when turned on because of **background** radiation from **cosmic rays**, building materials, and minerals. This background must always be subtracted from readings obtained on a possible source of radiation. The meters indicate intensity of the radiation on a meter calibrated in units of roentgens per hour (R/hr) or **milliroentgens** per hour (mR/hr). The **roentgen** is a measure of the energy delivered to matter by X-rays and γ -rays. It is the amount of X-ray or γ -ray radiation that produces 2.083×10^9 ion-pairs in 1 cubic centimeter of air (Figure 20). The production of this many ion-pairs is equivalent to the dissipation of 1 esu, or 83 ergs. One gram of radium produces 1 R at a distance of about 1 meter. The usual limit of exposure allowed for the general public is 2 milliroentgens per hour (2 mR/hr).

roentgen (R)	=	production of 2.083×10^9 ion-pairs in 1 cc of air.
	=	1 esu
	=	83 ergs
	=	1 gram of radium at 1 meter.
milliroentgen (mR) = 0.001 R		
Limit for general public = 2 mR/hr		

FIGURE 20. Definition and Magnitude of a Roentgen

The intensity of radioactivity, or the dose received, decreases as the square of the distance from the source. Thus, if the intensity of radiation at 1 meter from the source is 1 R, it is 1/4 R at 2 meters, 1/9 R at 3 meters, etc. (Figure 21).

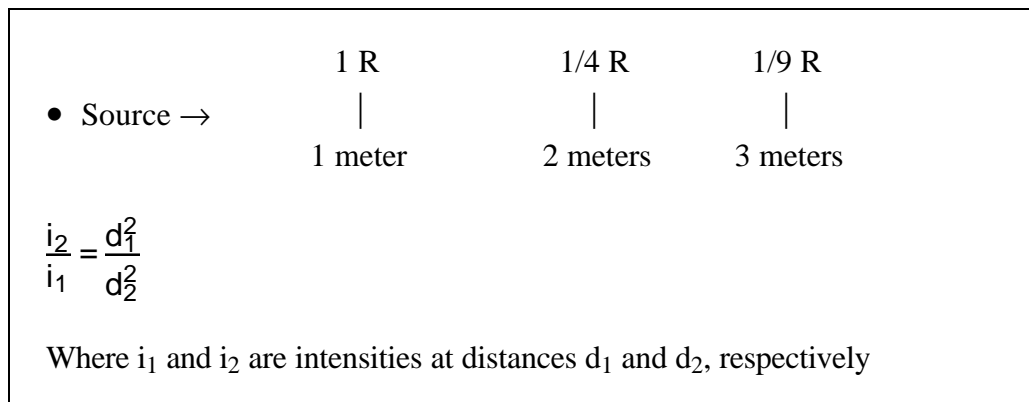


FIGURE 21. The Inverse Square Law

Surveys of radiation intensity are made at the distance from a source where humans will be exposed. In the case of radioactive oil field scales, the survey contacts the outside of scaled pipe. For scaled vessels that humans will enter, the survey contacts the scale in the vessel because humans would contact it.

Survey meters use an **ion chamber** to measure radiation (Figure 22). An ion chamber is a gas-filled cylinder made of thin walls lined with an electrical conductor such as a metallic coating. There are two types of ion chamber meters. The ion chamber type uses air at atmospheric pressure. The other type, called a Geiger-Muller (GM) tube, uses low-pressure argon or helium. Both have accuracies of about 15%, but the GM type is more sensitive and can measure much lower levels of radiation than can the ion chamber type.

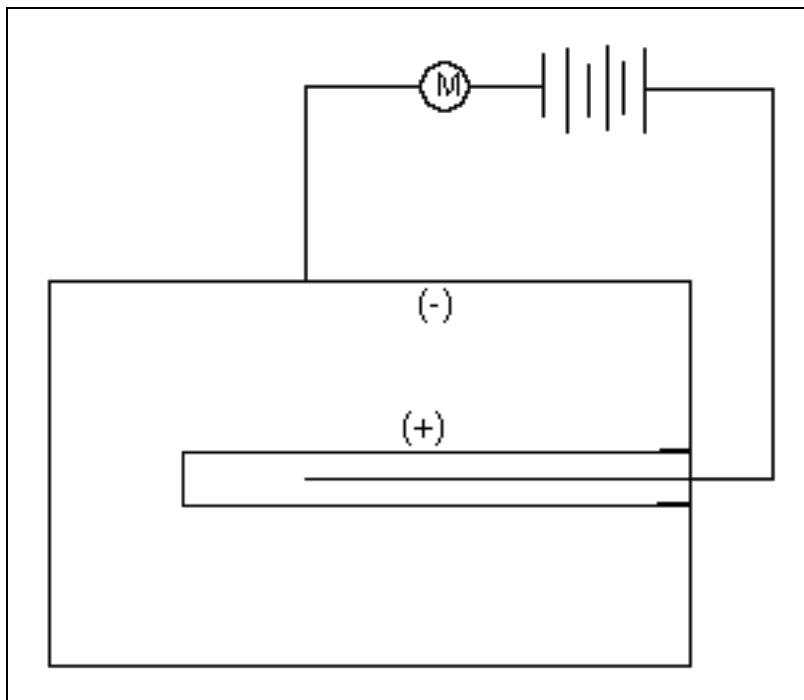


FIGURE 22. An Ion Chamber

The ion chamber instruments read from about 0.1 to 5000 mR/hr. The chamber is filled with dry air that is vented to the atmosphere through a desiccant to exclude moisture. When a particle or photon of X-rays or γ -rays enters the ion chamber, it collides with atoms in the air, creating ion-pairs. These ion-pairs migrate to the electrodes, which are charged to about 12 volts. The ion-pairs neutralize charges on the electrodes, giving rise to pulses of electric current. The current is analyzed by circuits in the meter to produce an audible sound and a reading on the meter.

The GM tube is more sensitive because the GM tube itself amplifies the intensity of the radiation. The gas in the GM tube is at low pressure so the ion-pairs that are produced last longer. The electrodes are charged with a high voltage. This voltage accelerates the ion-pairs toward the electrodes at high velocities, creating additional ion-pairs by subsequent collisions. For each ion-pair created by radiation, many more will be created as these ions are accelerated toward the electrodes. The GM instruments can measure X-rays, γ -rays, β -radiation, and under some conditions, α -radiation.

COPRECIPITATION

Radium coprecipitates with all the alkaline earth ions. Therefore, any scale formed from an oil field brine can contain radium. The largest concentration of radium is found in barium scales because Ra^{++} resembles Ba^{++} more closely than the other alkaline earth ions. The radius of the Ra^{++} ion is 1.2 Å compared to 1.35 Å for Ba^{++} (Figure 23). The Ra^{++} ion is able to fit nicely into the crystal lattice of barium salts such as BaSO_4 .

Ion	Crystal (Å)	Hydrated (Å)	Ratio, Charge to Crystal Radius
Be^{++}	0.31	4.59	6.45
Mg^{++}	0.65	4.28	3.01
Ca^{++}	0.99	4.12	2.02
Sr^{++}	1.13	4.12	1.77
Ba^{++}	1.35	4.04	1.48
Ra^{++}	1.52	3.98	1.32

1 Å = 10^{-8} cm or 10^{-10} m

FIGURE 23. Ionic Radii of Alkaline Earth Cations

Note: From Nightingale, 1954

Radium is separated quantitatively from solutions for analysis by coprecipitation with BaSO_4 . Usually, BaCl_2 is added to the solution if Ba^{++} is not already present. Then H_2SO_4 or Na_2SO_4 is added to the solution to form the BaSO_4 precipitate. The treatment is also used to remove radium from uranium mining tailings ponds. The amount of radium removed by coprecipitation decreases as the TDS of the water increases.

The amount of radium removed by coprecipitation increases as the amount of BaSO_4 precipitated increases. For example, in a water having a TDS of 40,000 mg/l and containing 1000 pCi/l of Ra^{++} , the Ra^{++} was lowered to 10 pCi/l by precipitating 30 mg of BaSO_4 (35,000 pCi/g) and to 1 pCi/l when 200 mg of BaSO_4 was precipitated (5000 pCi/g) (Figure 24).

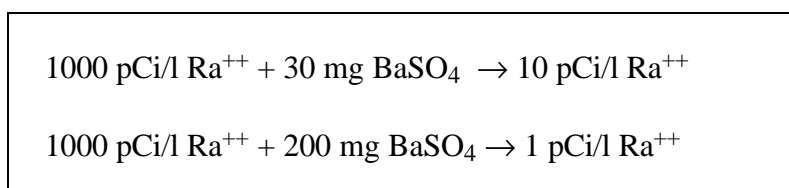


FIGURE 24. Coprecipitation of Ra^{++} by BaSO_4 From a 40,000 mg/l TDS Brine

PRECAUTIONS

Introduction

We live our lives in constant contact with small amounts of radium. It is in the air we breathe, the water we drink, and the food we eat. The earth's crust averages 2 pCi/g of radium. One cubic yard of soil from almost anybody's back yard contains 3,000,000 pCi of Ra226. We are not so much concerned that radium is present in some oil field waters. The concern is to be sure that there is no pathway to man. Most countries have adopted standards for the maximum concentration of radium to which one should be exposed. Some adopt the principle of **ALARA** or, "As Low As Reasonably Attainable". In other words, ALARA essentially means to avoid any unnecessary exposure to radium or ingestion of radium-containing substances. Of course, for a given situation, local regulations prevail and must be implemented.

In this section, we will discuss general precautions to observe in the presence of radioactive oil field waters and scales. We will see, from surveys to be presented, there is little chance of overexposure to the external surfaces of equipment containing water having a radium content or radium-containing scales. The hazards we must avoid are ingestion or inhalation of dusts of radium-containing scales.

Some idea of the ubiquitous nature of radium can be seen in Figure 25, which gives our "normal" intake of radium and other radioactive substances. The maximum average of Ra226 + Ra228 is about 6.8 pCi/day. The ratio of Ra/Ca in the human body to the ratio of Ra/Ca in our food sources is 0.015. Since the ratio is less than 1, man has the ability to reject Ra in favor of Ca. The radium that is metabolized is distributed 87% to the skeleton and 13% to other parts of the body. The normal burden of radium in the human skeleton is 0.1 μg , or 10^5 pCi. Since Ra226 has a half-life of 1,620 years and is largely found in the skeleton where cell replacement is low, it is in the human body for a long time. Ra226 is an α -emitter. It affects tissue in a highly localized area because α emissions are not very penetrating. Since α -particles effects are expended totally on a small amount of tissue, it is more damaging than β - or γ -particles, which are more penetrating and are absorbed by a larger amount of tissue. The reverse is true for external exposure to the three types of ionizing radiation. Specifically, γ is more damaging than β which is more damaging than α (Figure 26).

Radionuclide	Source	pCi/d
Ra226	Air	0.007
	Food	1.1-1.7
	Drinking water	0.6-2
Ra228	Air	0.007
	Food	1.1
	Drinking water	0.6-2
U234, U238	Air	0.0007
	Food	0.37-0.9
	Drinking water	0.6-4
Pb210	Air	0.3
	Food	1.2-3
	Drinking water	Less than 0.02
Po210	Air	0.06
	Food	1.2-3
	Drinking water	Less than 0.02
Th230	Air	0.0007
	Food	Negligible
	Drinking water	Less than 0.06
Th232	Air	0.0007
	Food	Negligible
	Drinking water	Less than 0.02
Rn222	Air, out doors (1.8 Bq/m ³)	970
	Air, indoors (15 Bq/m ³)	8,100
	Drinking water	100-800

FIGURE 25. Average Relative Source Contribution to Daily Intake of Natural Radionuclides (Cothorn, 1987)

$\alpha > \beta > \gamma$ Inside the body $\gamma > \beta > \alpha$ Outside the body

FIGURE 26. Biological Effectiveness of Radiation

Figure 27 gives the natural distribution of radium from different sources. Produced waters, geothermal waters, and mineral springs have the highest radium content because of their high TDS. There is a continuous input of Ra226 and Ra228 from U238 and Th232 in ocean sediments. The statutory limit for Ra226 + Ra228 in U.S. water supplies is 5 pCi/l. It is estimated that lifetime consumption of water containing 5 pCi/l of Ra226 + Ra228 would result in 20 deaths per 106 people. Municipal water sources that exceed 5 pCi/l are treated to lower the radium content.

Source	Ra226 (pCi/l)	Ra228 (pCi/l)	Total Radium Range or (Average)	Reference
Produced water	0.1-1620	8.3-1507	0.1-2800 pCi/l	1, 2, 3
Mineral springs			0.08-420 pCi/l	4
Precipitates			145-2830 pCi/g	4
Earth's crust			(2) pCi/g	5
Oceans			(0.07) pCi/l	6
Ocean sediments			1-17 pCi/g	5
U.S. water supplies*	0.3-0.8	0.4-1.0	0-over 10 pCi/l	7
Potable ground waters	0-81	0.3-32		8
Surface fresh waters			(0.1) pCi/l	9
Geothermal waters			0.041-1500 pCi/l	10

*Population-weighted average

References:

1. Armbrust and Kuroda (1955)
2. Pierce, Gott, and Mytton (1964)
3. Kraemer and Reid (1984)
4. Felmlee and Cadigan (1978)
5. Piggot (1933)
6. Foyn et al (1939)
7. Aieta et al (1987)
8. Lucas (1985)
9. Cothorn and Lappenbusch (1984)
10. O'Connell and Kaufmann (1976)

FIGURE 27. Activity of Naturally-occurring Radium

In most cases, sand filters will remove sufficient Ra⁺⁺ if the TDS of the water is low. The sand filter is regenerated by a dilute acid rinse. Where sand filtration is impractical or uneconomical, Ra⁺⁺ is removed by ion exchange with Ca⁺⁺-laden weak acid or strong acid resins. Acrylic fibers impregnated with manganese dioxide are also used to remove Ra⁺⁺ from potable waters. All softening processes are effective in removing Ra⁺⁺ in addition to Ca⁺⁺ and Mg⁺⁺. Surface waters usually do not require treatment to remove Ra⁺⁺, but any ground water source of potable water should be suspect.

Safety

It is beyond the scope of this course to teach the proper handling and disposal of radioisotopes and radiation sources. This requires special training and licensing. Our intention is to teach the means for self-protection from possible random exposure to radioactive sources in the oil field. These sources mainly include radioactive scales and Rn222. There does not appear to be a need for protection from produced waters that contain radium because emissivity is very low, the water is not ingested, and normal personal hygiene prevents most absorption.

Radiation exposure is expressed in **rems** which stands for roentgen equivalent man. It is the biological effect produced by the absorption of one roentgen of radiation. For exposure to γ -radiation, one roentgen equals one rem so we will use the terms interchangeably. Exposure levels are measured in terms of mR/hr (milliroentgens per hour) or mrem/hr (**millirems** per hour). One roentgen is 1000 mR, and one rem is 1000 mrem. The limit of exposure for the general population from all sources is 500 mrem/yr. Areas where emissions are more than 5 mrem/hr are required to be posted with the radiation symbol and the words “CAUTION RADIATION AREA”. If emissions are greater than 100 mrem/hr, posting must have the radiation symbol and the words “CAUTION HIGH RADIATION AREA” (Figure 28). The SI unit that replaces the rem is called the **sievert** (Sv) and one sievert equals 100 rem.

1 roentgen	=	1000 milliroentgens (1000 mR)
1 rem	=	1000 millirem (1000 mrem)
1 sievert	=	100 rem

Limit of exposure = 500 mrem/yr

Maximum exposure rate in unrestricted areas = 2 mrem/hr

>5 mrem/hr → posting required: CAUTION RADIATION AREA

>100 mrem/hr → posting required: CAUTION HIGH RADIATION AREA

FIGURE 28. Some Limits on External Exposure to Radiation

The limits imposed on radiation exposure in Figure 28 are necessarily conservative. The annual exposure of persons in the United States from natural and man-made sources of radiation is 267 mrem/yr (Figure 29).

Source	Millirems
Cosmic rays	28.0
Terrestrial	47.0
Building materials	3.0
Air	2.0
Body accumulation	21.0
Man-made:	
X-rays	150.0
Therapy	11.0
Others (fall-out, watches, TV, etc.)	5.1
Total	267.1

FIGURE 29. Annual Radiation Exposure in the U.S.

External radioactivity emission levels were recently measured for many production facilities in the U.S. In this survey, the survey meter readings were taken in contact with the external surfaces of equipment. A summary of the results is shown in Figure 30. The highest medians were 245 microrem/hr, or 0.245 mrem/hr, which is well below the 2 mrem/hr allowed for exposure of the general population.

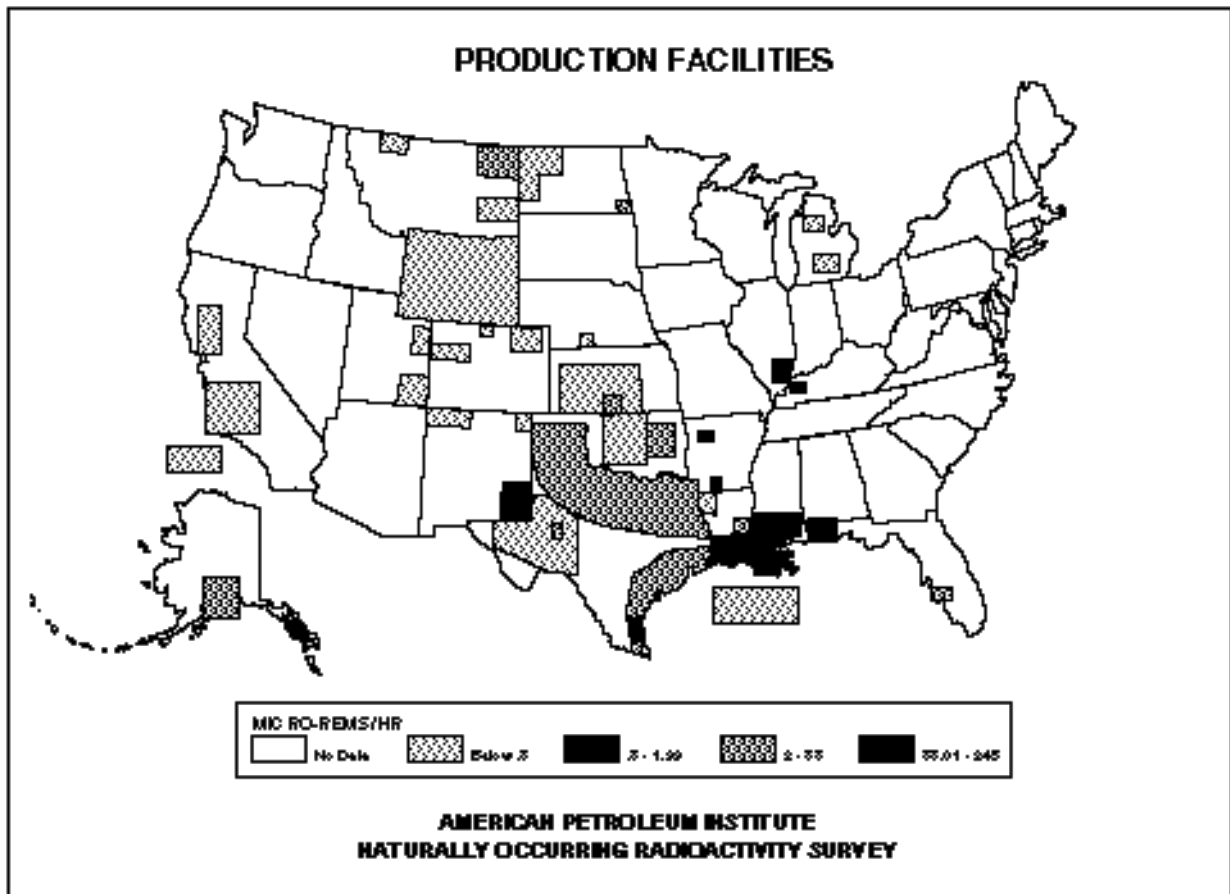


FIGURE 30. Median of Difference of Radiation Levels Over Background for Production Facilities. (API, 1989)

For individual equipment in production facilities, the highest emissions were found on flow lines (Figure 31) where the median readings over background were 42 $\mu\text{rem/hr}$. Water lines were next with median readings of 42 $\mu\text{rem/hr}$.

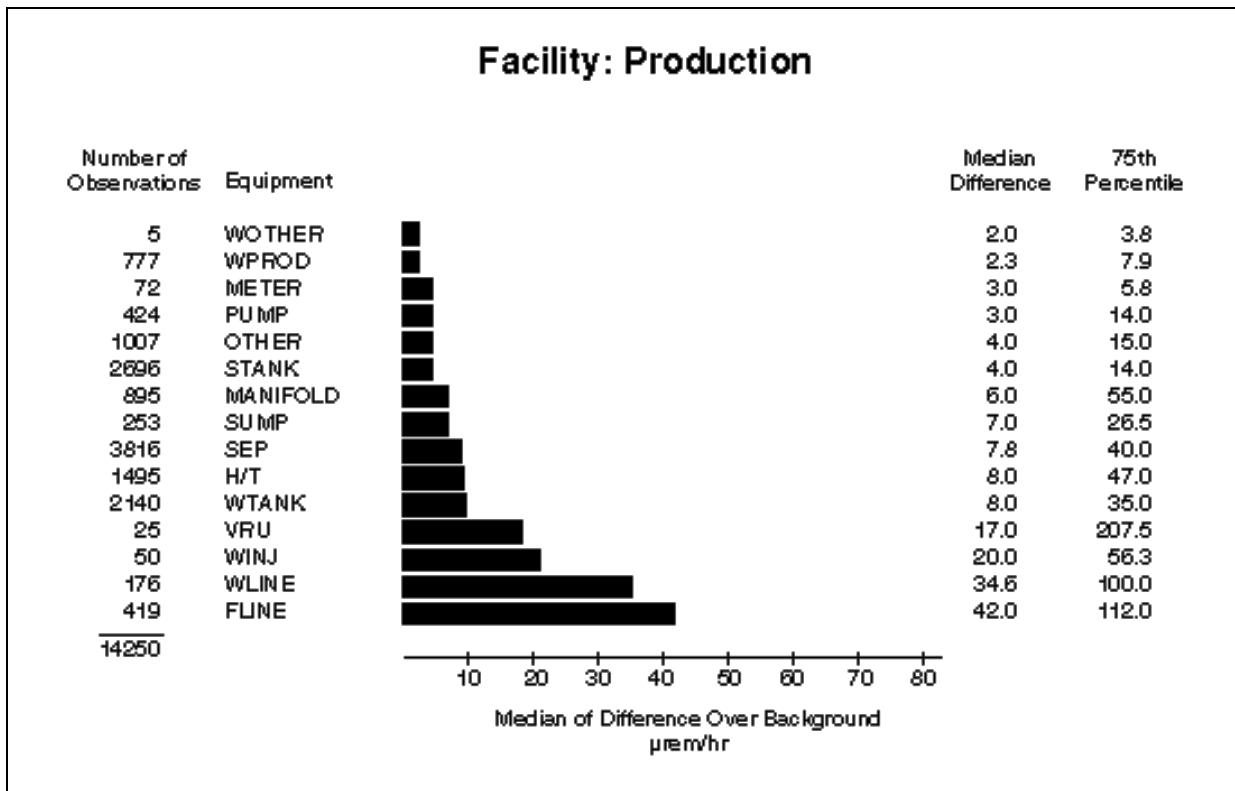


FIGURE 31. Median of Difference of Radiation Levels Over Background for Equipment in Production Facilities (μrem/hr). (API, 1989)

For gas processing facilities (Figure 32), the highest medians were found on reflux pumps in gas fractionators. This median was 76 μrem/hr with a 75th percentile of 291 μrem/hr.

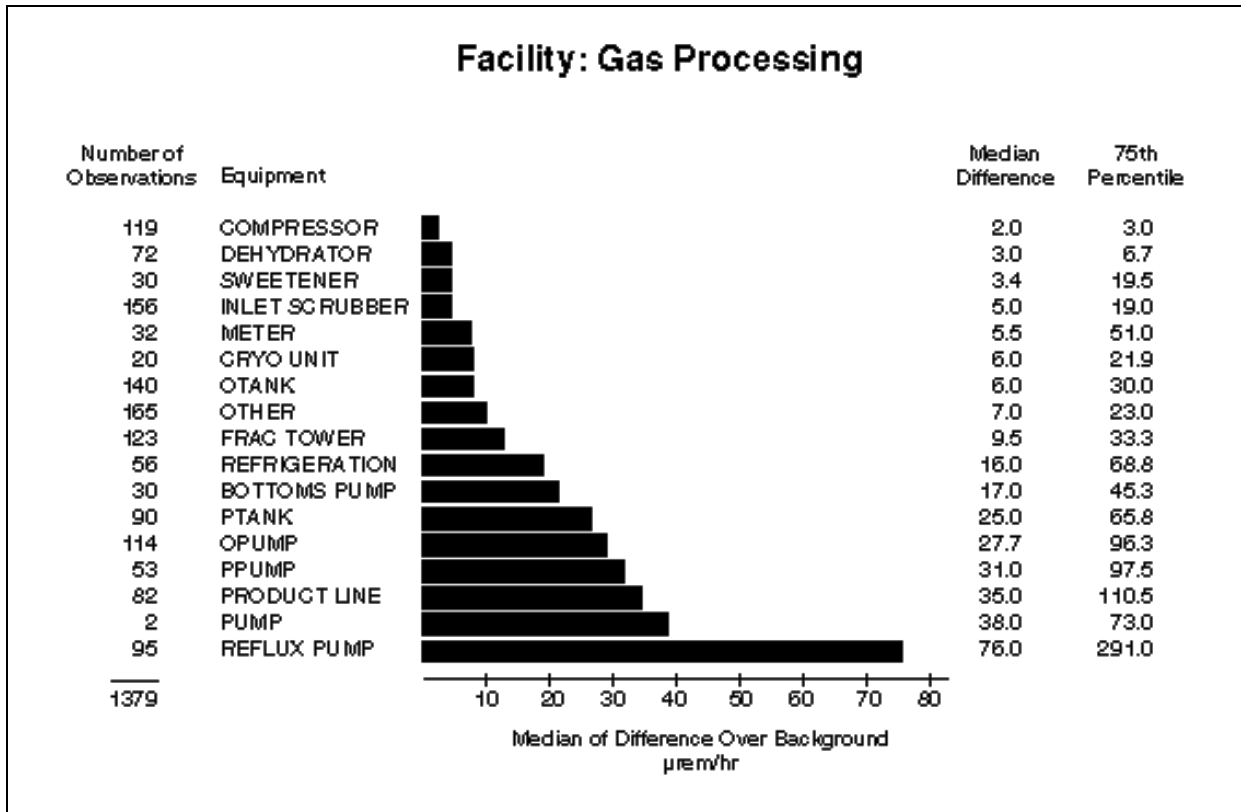


FIGURE 32. Median of Difference of Radiation Levels Over Background for Gas Facility Equipment (µrem/hr). (API, 1989)

From the foregoing, it is apparent that external exposure is not a problem with oil field equipment. Some precautions must be observed, however, when exposure to radioactive scales is possible.

Waters and solids contaminated with naturally-occurring radioisotopes are called **NORM** (Naturally-Occurring Radioactive Materials), **NARM** (Natural and Accelerator-produced Radioactive Materials) or **LSA** (Low Specific Activity) materials. We will use the term **NORM** because we do not encounter man-made radioisotopes.

Radium-containing scales were discovered on North Sea offshore platforms in 1981. Regulations and procedures were adopted for insuring the safety of personnel. The regulations are in compliance with international standards issued by the International Commission for Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA). Where no regulations exist, it is advisable to adopt the ICRP/IAEA recommendations. The basic rules that should be applied in operations involving radiation or radioactive materials are given in ICRP Publication 26 (Figure 33).

1. No practice shall be adopted unless its introduction produces a positive net benefit.
2. All exposure shall be as low as reasonably achievable (ALARA), economic and social factors being taken into account.
3. The dose-equivalent to individuals shall not exceed the recommended limits.

FIGURE 33. Basic Rules for Operations Involving Radiation or Radioactive Materials

Note: From ICRP Publication 26

The ICRP-recommended radiation dose limit for the whole body is 50 mSv/yr (5 rem/yr) for persons that work with radioactive materials. The U.S. Occupational Safety and Health Act (1970) and the UK Ionizing Radiation Regulations (1985) both adopt the limit. A reference level, or short-term dose limit, is calculated by the UK as 3/10 of the hourly rate. This is calculated as shown in Figure 34. These limits would probably be exceeded by entering or by dismantling some oil field equipment that is scaled with compounds containing NORM. Warning signs should be posted on such equipment so it is entered or decontaminated by trained and protected personnel.

ICRP limit	=	50 mSv/yr (5 rem/yr)
UK reference level	=	3/10 of hourly rate
For a 40-hr work week, 50 weeks/yr:		
Reference level	=	$3/10 \times 50\text{mSv} \times 1/50 \times 1/40$
	=	7.5 $\mu\text{Sv/hr}$ (0.75 mrem/hr)
2nd reference level	=	$1/3 (7.5) = 2.5 \mu\text{Sv/hr}$ (0.25 mrem/hr)
	=	requirement for designation as a specially supervised area.

FIGURE 34. UK Limits for External Radiation Exposure

Scales that contain NORM are not a large problem from the standpoint of ingestion, but inhalation of dusts from the scales must be avoided. Radioactive dusts deposited in the lungs might stay there for a long time where the α -emissions of Ra226 can do considerable damage. Since α -emissions are blocked by the scales themselves, survey meters cannot count them. A reading of γ -emissions only can be misleading. For this reason, the limits of radioactivity are expressed in terms of the radioactive content of the scale or surface expressed in Bq/cm². Recall that 1 Bq (becquerel) is one disintegration per second. It is equal to 27.03 pCi. The measurement of surface contamination requires a Geiger counter that can measure β -radiation and low-energy γ -rays when held close to the surface being monitored.

The possibility that different isotopes are present in a scale makes the setting of exposure limits very difficult because of varying effects when in the body. For this reason, different limits are used by the various regulating authorities. For example, the UK uses 4 Bq/cm² (108 pCi/cm²) as a hazardous dust (inhalation) level. Norway considers any component that has a reading above background as radioactive. Louisiana has adopted 1 Bq/g (27.03 pCi/g) as the minimum level above which a scale is classed as radioactive (Figure 35).

Regulatory	Limit
UK	4 Bq/cm ² (108 pCi/cm ²)
Norway	> background
Louisiana	1 Bq/g (27.03 pCi/g)

FIGURE 35. Various Limits for Classifying Substances as Hazardous Dusts

It is not reasonable or practical to analyze every scale for all the isotopes that might be present. The UK and other authorities have agreed to measure one isotope (Ra226) from the U238 radioactive series and one (Ac228) from the Th232 series. They assume that other isotopes will contribute 6 times the Ra226 activity and 8 times the Ac228 activity (Figure 36).

$\text{Total activity} = 6 \times \text{Ra226} + 8 \times \text{Ac228}$ <p>Suppose a sample contains 100 Bq/g of Ra226 and 50 Bq/g of Ac228:</p> $\begin{aligned} \text{Total activity} &= 6 \times 100 + 8 \times 50 \\ &= 1,000 \text{ Bq/g or } 27,030 \text{ pCi/g} \end{aligned}$
--

FIGURE 36. Calculating the Total Activity of a Scale Sample

Not all oil field scales are radioactive, and protection is generally not needed. Where the potential for hazard exists, the first step is to survey the area and equipment with a survey meter.

If activity approaches the limits described above, the area should be posted and access limited to informed personnel. The internal activity of equipment will be about five times that measured through a steel wall. If such equipment is to be opened or dismantled, it should be checked with a Geiger counter to determine if surface activities exceed limits for inhalation. If activity exceeds established limits, the equipment should be entered only by trained personnel wearing protective clothing. The process equipment will require decontamination prior to reassembly by mechanics. This is accomplished in place for large equipment by high pressure jets of water operated by protected personnel under the supervision of a radiation health specialist. Personnel should be protected by washable or disposable outerwear including coveralls, breathing apparatus, gloves, shoe coverings, and head coverings. Outerwear should be disposed in an approved manner, or personnel should shower in their protective clothing until decontaminated.

Brushing or grinding or any cleaning method that creates dusts should be avoided. If this not possible, personnel must wear breathing apparatus when performing these operations. Unprotected personnel must be denied access to the area.

Small equipment can be transported to a processing site for decontamination. In transit, the equipment should be sealed so radioactive dusts are not spread. Decontamination areas should be protected to avoid the spreading of radioactivity. Sludges can be disposed in the sea or injected in abandoned wells. Water can be injected.

If decontamination is not practical, the equipment can be stored in a remote, protected area with suitable posting. In some areas, contaminated pipe and equipment can be scrapped by licensed companies that have access to approved decontamination and dump sites.

The most desirable form of decontamination is by solvents where possible. Exposure to radioactive dusts is avoided, and it is usually not necessary for anyone to enter the equipment. Spent solvents can be injected in a well for disposal.

The casual handling of radioactive scales, such as for sampling, requires some simple precautions. Disposable plastic gloves should be worn, and the scale should be wet, if possible, to avoid dusts. The hands and other exposed parts of the body should be washed before eating or smoking. Bottles containing radioactive scale samples should be so labeled. The small amount of total activity in a scale sample presents no transport problems.

Radon-222 is a noble, radioactive gas produced as a daughter product of the decay of Ra226. Rn222 has a half-life of 3.82 days (refer to Figure 4). It is carried from production facilities in natural gas where it presents little hazard except for isolated instances. Rn222 has a boiling point of 211 K at 1 atmosphere or roughly half-way between that of ethane (186 K) and propane (231 K). Thus, in a fractionating gas plant, Rn222 is concentrated in the deethanizer and depropanizer. The Rn222 itself presents no health hazards. However, its daughter products, Pb210 and Po210, are solids. They accumulate on the inside of equipment associated with C₂ and C₃ production. Reflux pumps internally coated with Pb210 and Po210 have been found to be hazardous to mechanics that remove the deposits by wire-brushing. These items in gas plants should be examined for contamination. If it is present, provision should be made for the protection of mechanics.

GLOSSARY

activity	An expression for the intensity of radioactivity.
ALARA	As Low As Reasonably Achievable.
alpha particle	A positively-charged composite particle consisting of 2 neutrons and 2 protons, such as, a helium nucleus.
anthropogenic	Created or caused by man.
atomic number	The number of protons in a nucleus.
background	The natural level of radioactivity caused by cosmic and terrestrial sources.
becquerel	A unit of activity equal to one disintegration per second.
beta particle	An electron.
cosmic rays	A stream of ionizing radiation of extraterrestrial origin.
curie	A unit of activity equal to 3.7×10^{10} disintegrations per second.
daughter	The product of a radioactive decay.
distribution coefficient	The ratio of the concentration of adsorbed isotope to its concentration in a solution with which the adsorbing surface is in equilibrium.
dosimeter	An integrating device that measures the total radiation dose received by an individual over a period of time.
gamma rays	Electromagnetic radiation of very short wavelength associated with radioactive decay.
Geiger tube	A form of ion chamber that uses low pressure gas and a high electrode voltage.
half-life	The time required for any amount of radioactivity to decrease to 1/2 its initial value.
inverse square law	The principle that the intensity of radiation decreases as the square of the distance from the source.
ion chamber	A closed chamber in which ion-pairs produced by radioactive emissions can be measured by the resulting increase in electrical conductance of the gas in the chamber.

ion-pair	The combination of electron and positive ion produced when ionizing radiation interacts with matter.
isotope	Atoms having the same atomic number but different mass numbers.
mass number	The sum of the number of neutrons and protons in a nucleus.
millirem	0.001 rem, mrem.
milliroentgen	0.001 roentgen, mR.
NARM	Naturally-occurring and Accelerator-produced Radioactive Material.
neutrons	Electrically neutral subatomic particle having a mass of one and no charge. Neutrons and protons make up the entire mass of a nucleus.
NORM	Naturally Occurring Radioactive Material.
nuclide	Any atomic nucleus specified by its atomic number, mass, and energy state.
photon	A quantum of electromagnetic energy, generally regarded as a discrete particle having no mass or charge.
picocurie	10^{-12} curies or 3.7×10^{-2} disintegrations per second.
proton	A positively-charged subatomic particle whose mass is 1,836 times that of an electron.
radioactive	Exhibiting radioactivity, the spontaneous emission of radiation.
radiogenic	Formed by radioactive decay.
radionuclide	An unstable or radioactive nuclide.
rem	Abbreviation for “roentgen equivalent man”. It is the biological effect of absorbing one roentgen.
roentgen	The amount of X-rays or γ -rays that produces 2.083×10^9 ion-pairs in 1 cubic centimeter of air. It is a level of energy equal to 1 esu or 83 ergs.
sievert	A unit of radiation dose equal to 100 rem.

spectral analysis	Identifying substances by the characteristic energy or wave length of the γ -rays they emit.
survey meter	Small, portable meters, usually of the ion chamber type, used to detect and measure higher levels of radiation.
thorium series	The natural radioactive decay series whose source is Th232.
uranium series	The natural radioactive decay series whose source is U238.