MICHIGAN DEPARTMENT OF ENVIRONMENTAL QUALITY
WASTE MANAGEMENT AND RADIOLOGICAL PROTECTION DIVISION
RADIOLOGICAL PROTECTION SECTION

FLOW LINE ABANDONMENT TENORM WHITE PAPER

SECTION 1 - ISSUE

The purpose of this white paper is to inform the Supervisor of Wells (SOW) in the matter of oil and gas flow line abandonment with respect to technologically enhanced naturally occurring radioactive material (TENORM). The SOW Instruction 1-2002 provides existing instruction requirements for abandonment of oil and gas flow lines in Michigan, including that the abandoned flow line must have at least 30 inches of cover. It clarifies Part 615, Supervisor of Wells, of the Natural Resources and Environmental Protection Act, PA 451 of 1994, as amended (Part 615), administrative rule R 324.1011 that requires “A permittee of a well shall purge all flow lines and vessels, including tanks, if the flow lines or vessels are not used for 1 year and shall provide notification of the purging operation to the supervisor or authorized representative of the supervisor. The supervisor may require the line to be removed or abandoned.” SOW Instruction 1-2002 addresses the environmental concerns that may be associated with removal or abandonment in place but does not address potential issues associated with the TENORM containing scale. SOW Order 3-6-92 has been the guiding document for TENORM issues at oil and gas facilities in Michigan but it does not specifically address the issue of TENORM containing scale in abandoned flow lines. Since there is no regulatory requirement to remove buried flow lines, they are often abandoned in place.

This white paper addresses the radiological hazards associated with both abandonment in place and removal of oil and gas flow lines with respect to TENORM, specifically radium-226 (Ra-226) and radium-228 (Ra-228). Ra-226 and Ra-228 are radioactive isotopes that occur naturally in rock formation as a product of radioactive decay of minerals containing uranium and thorium. During oil and gas production, fluids flowing through pipelines may deposit scale, often in the form of barium sulfate that may contain some radium sulfate with Ra-226 and Ra-228. The radium is radioactive, but the barium is not radioactive.

This white paper does not address any other considerations (e.g., the costs of restoring disturbed land to its original state, future liability, or the affect to property value) of abandonment in place or removal of flow lines.

SECTION 2 - BACKGROUND

Rock formations commonly contain uranium and thorium in small quantity; these are naturally occurring radioactive materials (NORM). These radioactive elements have decay chains whereby daughter radioactive isotopes are created over time through the process of radioactive decay. The geochemistry of rock formations and the fluids contained within them have direct bearing on the presence and concentration of each isotope present in produced water. Daughter nuclides of uranium and thorium include radium, radon, polonium and lead. Because of the long half-life of radium-226 (1,602 years) it is the primary isotope of concern in oil and gas production. The ratios of Ra-228 to Ra-226 in material filtered at Central Production Facilities are the best representation of what is coming out of the ground since the filters are cleaned periodically. The soil and scale samples represent years of accumulation where some of the original Ra-228 has decayed. Because TENORM predominantly contains Ra-226, we will only be using the gamma radiation due to Ra-226 for calculations in this paper.

The decay product of radium is radon gas which may be a potential exposure risk if entrapped inside a structure. Radon-222 has a very short half-life at 3.8 days and is not a concern if flow lines are removed, primarily because radon disperses quickly in the open-air environment. Radon is a consideration for corrodible flow lines abandoned in place because the decay of radium-containing pipe scale continues to produce radon over time and, if structures are built over them, the potential exists for migration and entrapment of radon gas within those structures. While the decay of Ra-226 and Ra-228 to radon gas is a concern, Ra-226 and Ra-228, and Rn-222 and Rn-224, are also naturally present in most soils in Michigan and throughout the United States. Assessing the amount of leakage and entrapment of radon because of TENORM in flow lines is problematic due to varying concentration levels of naturally occurring sources, its release or permeability in the scale in the flow pipe, the small area footprint of buried flow lines, and the radon entrapment capabilities of a variety of edifices. Consequently, its impact beyond existing sources of radon will not be addressed. The U.S. Environmental Protection Agency (USEPA) recommends that all homes be tested for radon. If the indoor air concentration of radon equals or exceeds 4 picocuries per liter, the home should have a radon mitigation system installed.

The final decay products of concern following radon are lead-210 and polonium-210. Lead and polonium are of concern to public health; however, their relatively short half-lives make them a very low risk and would have to accumulate somewhere accessible from the decay of radon.

The TENORM in the scale found in flow lines is principally comprised of radium and barium sulfates. Both sulfate forms are very insoluble in water. At 20º C, 0.0021 grams of radium sulfate will dissolve in a liter of water. Barium sulfate is slightly more soluble as 0.0024 grams of it will dissolve in a liter of water. Scale can be physically moved by rainfall, water currents, or groundwater movement. People could receive a radiation dose by water consumption, plant consumption (from uptake of water), or meat consumption (from water or plants). However, an organism’s ability to absorb a compound is dependent upon the solubility of that compound and radium sulfate is the most insoluble of all alkaline earth sulfates and one of the most insoluble radium compounds known. Because of this insolubility, radium sulfate is less dangerous biologically than most radium compounds (USAEC, 1964) meaning that the radium would not be absorbed by plants. Should drinking water be contaminated, the radium sulfate may result in slight increases in exposure while the products are inside the body, but the products will not be readily absorbed into the body and will be expelled quickly. As such, the biological impact is considered to be of minimal risk on organics from ingestion/absorption of TENORM found in flow lines.

2.1 RADIOACTIVITY MEASUREMENT

A person with a radiation survey meter can measure the exposure rate near a radiation source. The readings are usually in units of Roentgens per hour (R/h), or milli- or micro- Roentgens per hour (mR/h or μR/h). The Roentgen is a measure of the ionization produced in air and is 2.58×10^{-4} coulombs per kilogram (C/kg) (i.e., 1 C/kg = 3,876 R). When discussing dose rates, the unit for radiation dose is the roentgen equivalent man (rem) which is the equivalent biological risk of Roentgens per hour. For gamma radiation, a person exposed to 1 mR/h for one hour, as read on a survey meter, would receive a radiation dose of approximately 1 mrem. Radiation survey meter readings can be used to approximate radioactive concentrations when the area being measured, or the volume of a container are considered.

A sample of radioactive material can be sent to a radiological laboratory to determine what elements are radioactive and how much there is. Many radionuclides emit gamma radiation, so gamma spectroscopy can be used. The results are usually reported in picocuries per gram (pCi/g) or picocuries per liter (pCi/l). A picocurie is 2.2 transformations per minute. A gram of material with a radioactive concentration of 10 pCi/g has 22 atoms transforming into something else each minute.

2.2 EXISTING GUIDELINES FOR RADIUM-226

The Michigan Department of Environmental Quality (DEQ), under the authority of the Public Health Code and the Ionizing Radiation Rules, has issued guidelines to address the remediation of Michigan sites contaminated with radium-226 and its associated decay series (DEQ, 2007). They are:

1) 10 microroentgens per hour (μR/h) above local background as measured with a properly calibrated exposure rate meter at a 1-meter height above any surface averaged over 100 square meters in outside areas and over 10 square meters in structure interiors.
2) 5 picocuries per gram (pCi/g) of radium-226 above the natural background concentration of any 15-cm thick layer that is 100 square meters in area.

The following is a calculation of the amount of Ra-226 allowed by number 2 above and the Ra-226 concentration if all that activity were in a 3-inch pipe. Assuming a soil density of 1.5 g/cm^3 and a Ra-226 concentration of 5 pCi/g, the 15 cubic meters of soil would contain 112,500,000 pCi (0.1 millicurie) of Ra-226. The volume of a 3-inch (7.62 cm) interior diameter pipe 10 meters long is 45,600 cm^3. Since scale is primarily barium sulfate with a mass of 4.5 g/cm^3, scale filling this pipe would weigh 205,200 grams. The 0.1 mCi Ra-226 distributed throughout this mass would have a concentration of 548 pCi/g.

The previous calculation assumes the pipe was completely clogged with scale. This is rarely the case. If the 0.1 mCi of Ra-226 was contained in a thinner layer of scale on the inside of the pipe, the concentration would be greater than 548 pCi/g. However, since the amount of Ra-226 per linear foot would be the same, a gamma radiation meter would measure basically the same exposure rates from the two pipes.

Table 2 in Scenario A shows that an unburied 3-inch pipe filled with scale at 50 pCi/g Ra-226 would have gamma radiation readings at contact of 0.034 mR/h for iron/steel pipe and 0.049 mR/h for PVC pipe. The exposure rates are proportional for greater or lesser concentrations of Ra-226. The expected exposure rates at contact for 548 pCi/g of Ra-226 would be 0.37 mR/h for iron/steel pipe and 0.54 mR/h for PVC pipe.

When applying guidelines and protecting the public from the risks of radiation exposure, the principle is that exposures of individuals and populations should be maintained As Low As Reasonably Achievable (ALARA) with economic and social factors considered. An additional factor that is important in developing guidelines for TENORM is a judgement about the applicability of existing guidelines that can be transferred to other situations. The physical and chemical properties of the type of TENORM in question, as well as projected exposure pathways, may be similar or drastically different to those considered when developing existing precautions or guidelines for each situation.

2.3 AVAILABLE DATA

Oil, gas, and brine production can produce TENORM-contaminated scales. Michigan has had procedures in place for proper handling of scale in removed pipe from wellbores and equipment, specifically Supervisor of Wells Orders 3-6-92 and (M) 1-6-92. A national report mentions production scale containing up to 100,000 pCi/g of Ra-226 (CRCPD 2015, page 19). The highest scale sample analyzed by the DEQ radiological laboratory had 197,000 pCi/g of Ra-226 and 14,000 pCi/g of Ra-228.

> **Note:** In Michigan NORM does vary by formation and is not always present within oil and gas produced water and infrastructure.

Table 1 shows the highest Ra-226 concentrations of TENORM filtered at Central Production Facilities or in pipe scale, the Ra-228 results, and the ratio of Ra-228 to Ra-226. If noted in the investigation file, exposure rates taken of the material before sampling are shown.

Table 1: Radium Levels

Ra-226 (pCi/g)	Ra-228 (pCi/g)	Ratio 228/226	Material	Exposure Rate (mR/h)
197,000 ± 8000	14,000 ± 1000	0.071	Material filtered at CPF	55
184,000 ± 2000	5,000 ± 300	0.027	Pipe Scale	nmt
137,000 ± 3000	3,400 ± 500	0.024	Pipe Scale	5
120,000 ± 2000	4,900 ± 400	0.041	Pipe Scale	5.3
105,000 ± 3000	4,200 ± 100	0.040	Pipe Scale	3.5
100,000 ± 2000	4,200 ± 400	0.042	Pipe Scale	nmt
89,000 ± 2000	1,200 ± 300	0.013	Pipe Scale	0.3
78,000 ± 2000	3,500 ± 300	0.045	Pipe Scale	5
76,000 ± 2000	2,700 ± 300	0.036	Pipe Scale	4.6
70,000 ± 1000	1,300 ± 300	0.019	Pipe scale	4.6
68,000 ± 2000	4,300 ± 100	0.063	Material filtered at CPF	3.2
50,000 ± 3000	3,100 ± 100	0.062	Material filtered at CPF	3.2

CPF = Central Production Facility for gas production
nmt = no measurement taken

The ratios of Ra-228 to Ra-226 in material filtered at Central Production Facilities are the best representation of what is coming out of the ground. The soil and scale samples represent years of accumulation where some of the original Ra-228 has decayed. As stated previously, because TENORM predominantly contains Ra-226, we will only be using the gamma radiation due to Ra-226 for calculations in this paper.

SECTION 3 – DISCUSSION

There are three possible scenarios where a risk of radiation exposure exists. They are:

A. The risk of radiation exposure to individuals if the flow lines contain TENORM, are abandoned in place, and remain undisturbed.
B. The risk of radiation exposures to workers during the removal process.

C. The risk to individuals if an abandoned flow line containing TENORM is uncovered sometime in the future.

Scenario A: Abandonment in-place

Part 615 rules and SOW Instruction 1-2002 allow abandonment in place of flow lines buried 30 inches or deeper. The 30-inch burial depth requirement is intended to ensure that the flow line is below the frost line and below the depth likely to be affected by other surface disturbances.

In Michigan, typical background gamma exposure rates range from 0.007 to 0.010 mR/h. During radiation walkover surveys, a gamma rate less than 0.020 mR/h is indistinguishable from background due to fluctuations in meter readings.

Soil provides good shielding for radioactive material. Table 2 shows the expected gamma exposure rates near ground level for various burial depths for a 3-inch flow line clogged with radium sulfate at a concentration of 50 pCi/g Ra-226.[1] The exposure rates are proportional for greater or lesser concentrations of Ra-226. At ground level the dose rate for a pipe buried at 30 inches would be, depending on the type of pipe material, 0.00001 to 0.00002 mR/h. Therefore, if a person occupied a tent for 24 hours a day, seven days a week above such a flow line buried at 30 inches for one year, they would receive a total dose of approximately 0.175 millirem. This dose rate is a minor fraction of the public dose limit in Michigan of 500 millirems per year.

Table 2: Ground Level Exposure Rates of a 3-inch Pipe* Containing 50 pCi/g Ra-226

Burial Depth (inches)	Iron (mR/h)	PVC (mR/h)	No Flow line (mR/h)
30	0.00001	0.00002	0.00002
25	0.00004	0.00005	0.00005
20	0.0001	0.0001	0.0001
15	0.0003	0.0004	0.0004
10	0.0011	0.0014	0.0015
5	0.0046	0.0059	0.0063
0	0.034	0.049	0.048

The maximum concentration of Ra-226 in TENORM that has been measured in Michigan was almost 200,000 pCi/g. Table 3 shows the expected gamma exposure rates near ground level, as well as 1m above ground level, for various burial depths for a 3-inch flow line clogged with radium sulfate at a concentration of 200,000 pCi/g Ra-226.[1] In this case, the expected exposure rate at the surface for a clogged flow line, buried at 30 inches would be 0.05-0.07 mR/h (depending on type of pipe material). A person occupying a tent, 24 hours a day, above this flow line for a week would receive a radiation dose of approximately 10 mrem and would need to stay in the tent continuously for 50 weeks to reach the public dose limit of 500 mrem (See Appendix Section 1.4.1). Agricultural workers would spend much less time above a flow line and could be riding mechanized equipment; therefore, their exposure would be extremely low. For public access over the buried flow lines it is expected that individuals traversing the area would not remain long enough, or close enough, to the buried flow lines to present any risk due to radiation exposure.

[1] MicroShield Version 11.01 was used for this modeling.

Table 3: Exposure Rates of a 3-inch Pipe* Containing 200,000 pCi/g Ra-226

	Iron Pipe (mR/hr)		PVC Pipe (mR/hr)	
Burial Depth (inches)	Ground Level	1 Meter Above Ground Level	Ground Level	1 Meter Above Ground Level
30	0.05	0.02	0.07	0.03
25	0.14	0.06	0.18	0.08
20	0.42	0.15	0.53	0.19
15	1.29	0.39	1.66	0.50
10	4.44	1.04	5.72	1.34
5	18.5	2.81	23.8	3.62
0 (uncovered)	136	6.79	196	9.37

*Pipes with 3.5-inch outer diameter and 3-inch inner diameter.

Should the abandoned flow pipe become disturbed or deteriorated to the point where the scale was no longer contained, then some of the radium and barium sulfate scale could combine with the ground materials. Radium and barium sulfates are very insoluble in water and scale can be physically moved by rainfall, water currents, or groundwater movement with a very low migration rate. People could receive a radiation dose by water consumption, plant consumption (from uptake of water), or meat consumption (from water or plants). However, an organism's ability to absorb a compound is dependent upon the solubility of that compound and radium sulfate is the least soluble of all alkaline earth sulfates and one of the least soluble radium compounds known. Because of this insolubility, radium sulfate is less dangerous biologically than most radium compounds (USAEC, 1964) meaning that the scale would not be absorbed by plants. Should drinking water be contaminated, the radium sulfate may result in slight increases in exposure while the products are inside the body, but the products will not be readily absorbed into the body and will be expelled quickly. Consequently, it is likely that ingesting TENORM at these levels would not pose a health risk.

Scenario B: Removal of flow lines

Not all geologic formations will produce water with elevated levels of radium. Flow lines are too small in diameter to use smart pig type devices to detect scale from inside the flow line. When a formation does happen to contain elevated radium levels, only the most radioactive TENORM-containing scale can be detected when buried, so the radioactivity can only be measured by excavating and measuring right against the flow line. This excavation may create surface impacts unnecessarily for flow line lengths that do not contain TENORM in the form of scale. If the flow line is made of a ferrous material and in an area with a large amount of water, the flow line may have degraded after decades of abandonment and, upon excavation, the pipe may break releasing some TENORM to the environment.

Steel or iron pipe can be removed by digging pits along the flow line, cutting the pipe, and pulling out the segment of pipe. Because of their poor tensile strength, flow lines of PVC or other materials can be removed by digging along the length of the flow line and removing it. The flow line must be cut into manageable lengths for transportation and disposal. When the flow lines are cut, TENORM scale will also be cut and enter the breathing zone of the worker. If water is used to contain the TENORM dust, the water must be collected and disposed appropriately. Removal of flow lines can create numerous areas along the removal path where potential TENORM-containing scale may be released to the environment and exposure of workers can occur.

If dust containing TENORM is not contained, workers can inhale the radioactive material. Outdoors, radon quickly diffuses in the atmosphere and should not result in significant worker lung exposures. If proper engineering controls and personal protective equipment are not used, workers could also ingest small amounts of TENORM. However, because of this insolubility, radium sulfate is less dangerous biologically since it will not be readily absorbed into the body and will be expelled quickly.

Radiological surveys must be conducted in pits and trenches before they are filled and on surface areas that may have been contaminated during operational and closure activities. Contamination exceeding limits must be remediated.

Michigan allows soils and scale containing 50 pCi/g or less of Ra-226 to be disposed in a Michigan Type II solid waste landfill or in a Michigan hazardous waste landfill. Pipe containing Ra-226 and Ra-228 may be disposed in these landfills if the maximum gamma exposure rate at contact with the pipe does not exceed 0.05 mR/h. Pipe exceeding this limit can be sent out of state to a disposal facility or to an authorized descaling facility to remove the scale and then be disposed in a landfill if it meets the 0.05 mR/h criterion, or the pipe can be sent out of state to a processing or disposal facility. Metal recycling facilities will not accept any material with measurable radioactive material. Their radiation portal monitors are much more sensitive than a handheld radiation meter. Flow lines made of PVC or other material could be disposed with the soil if it met the 50 pCi/g criterion.

Transportation of radium must meet the requirements of the US Department of Transportation in Title 49 of the Code of Federal Regulations.

Scenario C: Inadvertent Intrusion

Events could occur that uncover the abandoned flow line and possibly damage it. This could be during logging operations, road grading, or construction. Discovery of an abandoned flow line should cause the prudent person to consider what they have uncovered and how to deal with the flow line. The Oil, Gas, and Minerals Division (OGMD) should work with state and local governmental units, industry organizations, contractors, and MISS DIG to make them aware of actions to take if flow lines are uncovered. If the person removes the flow line, the considerations in the removal scenario (Scenario B) would apply to them.

SECTION 4: CONCLUSIONS

Based on existing data, some flow lines contain more radioactive material than others while some contain no radioactive material at all. Based on modelling, radioactive material in flow lines buried 30 or more inches do not cause any significant radiation exposures to people walking or living on the land. However, flow lines may become uncovered due to various events.

A strict interpretation of Michigan's "Cleanup and Disposal Guidelines for Sites Contaminated with Radium-226" would require flow lines be removed if gamma exposure rates measured in contact with the flow line exceed 0.37 mR/h for iron/steel pipe and 0.54 mR/h for PVC pipe. See Section 2.2 for the calculation of these exposure rates.

Because the flow lines are not typically on the surface but usually buried 30 inches deep, a reasonable criterion is to remove a flow line, or a portion of a flow line, if a calibrated gamma radiation survey meter in contact with the flow line has an exposure rate of 1.00 mR/h or greater. If measurements taken at both ends of the flow line are less than 1.00 mR/h, the flow line can remain in place. In cases where the beginning of a flow line exceeds the criterion, but the end does not, the flow line can be removed until measurements along the remaining portion are less than the criterion.

For a flow line that was 1.0 mR/h at contact buried 30 inches underground, the expected exposure rate at the surface would be 0.0004 mR/h. Typical background exposure rates in Michigan vary between and 0.008 and 0.010 mR/h. The 0.0004 mR/h increase due to the buried flow line would not be distinguishable from the normal variation in background exposure rates and therefore wouldn’t pose any risk to public safety.

APPENDIX

SECTION 1: BACKGROUND

1.1 Natural Radioactive Material

Uranium and thorium are found throughout the Earth's crust. Figure 1 shows the decay chains of uranium-238 (U-238) and thorium-232 (Th-232). The uranium, thorium, and their decay products are naturally occurring radioactive material (NORM).

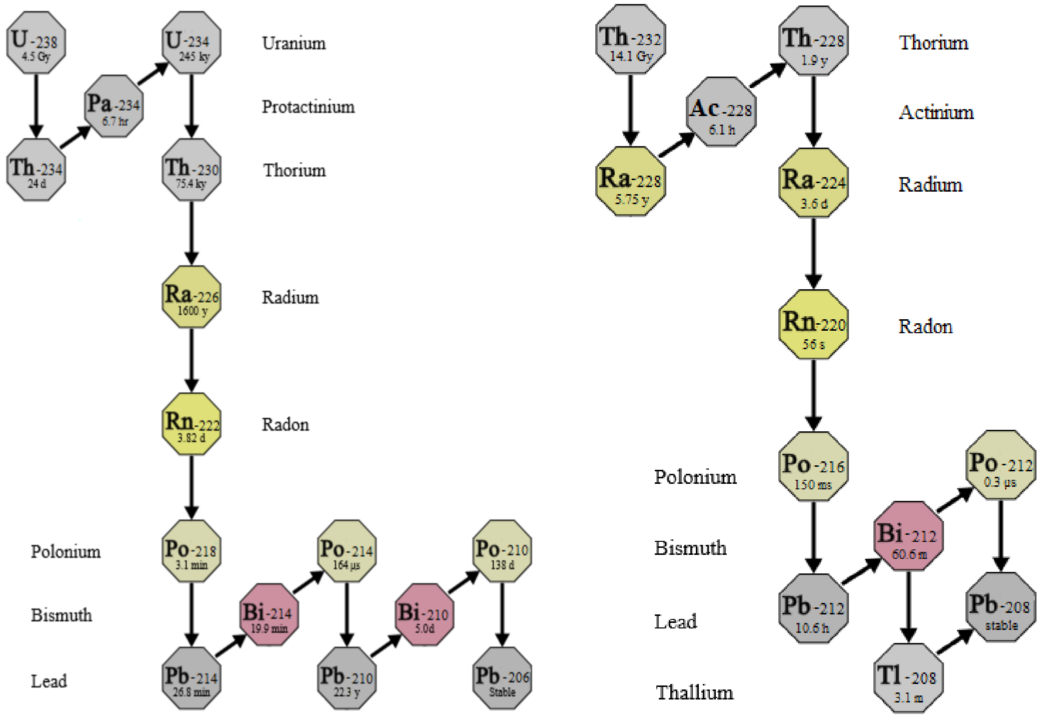


Figure 1: Left - Uranium-238 Decay Chain
Right - Thorium-232 Decay Chain.

The geochemistry of rock formations and the fluids contained within them have direct bearing on the presence and concentration of each radionuclide present in fluids from the wells.

In general, radium has a much higher solubility in produced water than uranium and thorium. Ra-226 is part of the U-238 chain and Ra-228 is part of the Th-232 chain. Underground, fluids are under higher temperature and pressure than they are at the surface. As the fluids rise to the surface, precipitate forms on downhole tubulars, inside surface processing equipment, and inside flow lines. Fluids with high concentrations of radium may precipitate out as radium sulfate ($RaSO_4$) along with non-radioactive barium sulfate ($BaSO_4$).

Fluids can also contain dissolved radon-222 from the U-238/Ra-226 decay chain and radon-220 from the Th-232/Ra-228 decay chain. Since radon is a noble gas, filtration and treatment does not remove it. Rn-220 and its progeny have half-lives from microseconds to hours, so the material quickly becomes non-radioactive lead-208. Rn-222 has a 3.8-day half-life so it can travel a long distance before it decays through several progeny until it reaches lead-210 (Pb-210) with a 22-year half-life. The Pb-210 eventually decays and becomes non-radioactive Pb-206. Pb-210 is found in gas transmission lines and storage tanks.

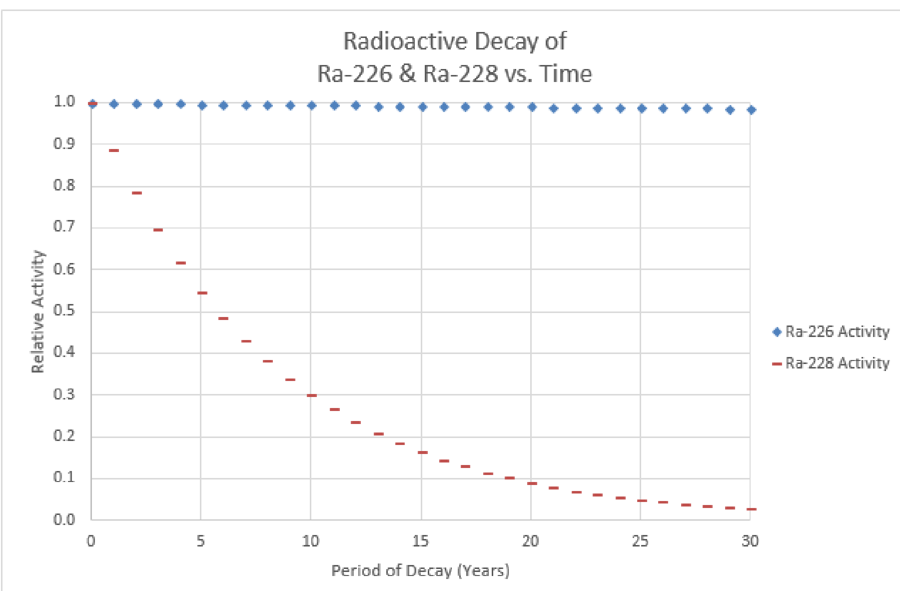
The Ra-226, Ra-228, and Rn-222 that accompany the produced water during oil, gas, and brine operations and their decay products are classified as technologically enhanced naturally occurring radioactive material (TENORM). TENORM is regulated by the Michigan Department of Environmental Quality.

1.2 Alpha, Beta, and Gamma Radiation

There are three primary types of radioactive decay: alpha, beta, and gamma. Alpha particles are large particles that are stopped by a sheet of paper or the dead skin layer on humans. Alpha-emitting radioactive material is a concern if the radioactive material is ingested or inhaled. An alpha particle attracts electrons and becomes a helium atom. Beta particles are identical to electrons and are stopped by approximately ½-inch of water. Beta particles are a concern if they are ingested or inhaled, or if very high-activity beta emitters stay on the skin for a long time. Gamma radiation is like radiation from the sun or a light bulb, but of much higher energy. Because of its high energy, gamma rays can penetrate matter such as the human body. Alpha, beta, and gamma radiation are considered "ionizing radiation" because they can knock electrons away from atoms and sever molecular bonds.

1.3 Measuring Radiation and Radioactive Material

Each radionuclide has a unique half-life. One half-life is the amount of time for the material to become half as radioactive as it originally was. For example, Ra-228 has a half-life of 5.7 years. If the original concentration of Ra-228 was 50 pCi/g, it would be 25 pCi/g after 5.7 years had elapsed. The half-life of Ra-226 is 1,602 years. The following graph shows the relative decay of Ra-226 and Ra-228 over time.



1.4 Radiation Dose Limits

Different radiation dose limits exist for members of the public and for occupational workers.

1.4.1 Dose to Members of the Public

The national standard for the annual radiation dose allowed to a member of the public is 100 millirem while a facility is in operation. The U.S. Nuclear Regulatory Commission (USNRC) has this dose limit in 10 CFR 20.1301 (https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/). A facility being decommissioned is required to show that the residual activity above background does not result in a dose to an average member of the public exceeding 25 millirem per year (10 CFR 20.1402).

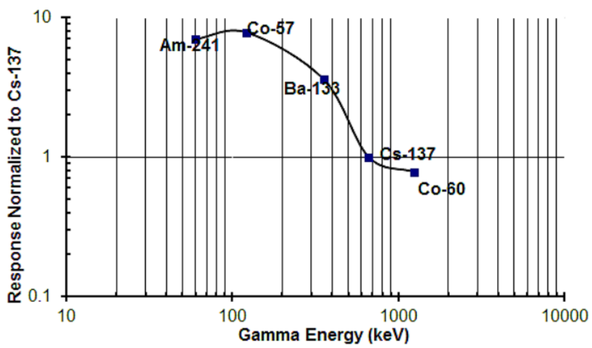
1.4.2 Dose to Workers

The USNRC (10 CFR 20.1201) and many states have a 5,000 millirem per year dose limit for occupationally exposed workers.

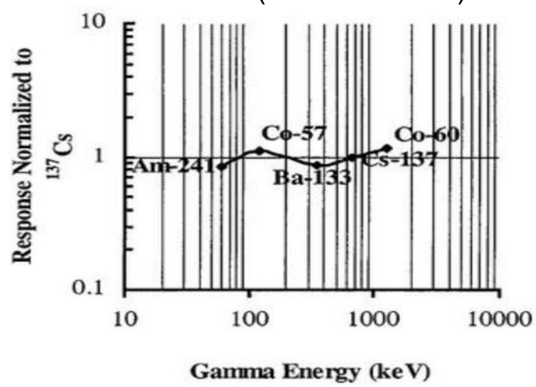
1.5 Radiation Survey Meters

Two types of survey meters are commonly used to detect gamma radiation. These use either a sodium iodide scintillation crystal or a Geiger-Müller probe. These meters are calibrated using a cesium-137 source. Meters with thin window probes can be used for detecting surface contamination but should not be used for gamma measurements. The sodium iodide detector can obtain low μR/h exposure rates but the energy response curve for the detector overresponds by up to a factor of 8 for low gamma energies. A Geiger-Müller probe has a relatively flat energy response curve, but readings fluctuate at intensities less than 0.1 mR/h.

Sodium Iodide Scintillator



GM Detector (window closed)



The gamma emissions for the Ra-226 and Ra-228 decay chains having greater than a 5% probability of occurring with energies greater than 50 kilo-electron volts (keV) are:

Ra-226

keV	Probability	Nuclide
75	.06	Pb-214
77	.11	Pb-214
242	.08	Pb-214
295	.19	Pb-214
352	.37	Pb-214
609	.46	Bi-214
768	.05	Bi-214
1,120	.15	Bi-214
1,238	.06	Bi-214
1,765	.16	Bi-214

Ra-228

keV	Probability	Nuclide
75	.11	Pb-212
77	.18	Pb-212
87	.08	Pb-212
239	.45	Pb-212
338	.11	Ac-228
511	.08	Tl-208
583	.30	Tl-208
727	.12	Bi-212
911	.28	Ac-228
965	.05	Ac-228
969	.17	Ac-228
2,615	.36	Tl-208

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