Management of Airborne Risks

in the Landfarming of High-Radium Petroleum Scale

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This discussion examines the concept of landfarming high-radium scale that arises in certain areas of the US during petroleum exploration and production, but generalized, most of the ideas discussed are also applicable to landfarming radium from a whole variety of sources classified as "Naturally Occurring Radioactive Materials (NORM)." Regulation of most NORM is largely nonexistent at the federal level. The states have been slow and to some extent inconsistent in promulgating regulations, partially because many states appear to be unaffected due to where these radioactive materials happen to be found in nature. Of the states that have chosen to regulate NORM at all, not all permit its landfarming, but some do.

A large fraction of the areas with radium oil field scale in the US have scale concentrations that are very low in radium, so it would seem that a state without significant radiation exposures from unregulated NORM would not need any NORM regulations. Eleven years ago the National Academy of Sciences in evaluating EPA's guidance pointed out that "federal regulation of TENORM is fragmentary, and many potentially important sources of public exposure to TENORM are not regulated by any federal agency (EPA 2000)." States that have no petroleum production at all still may have treatment of groundwater that produces similar materials, although the concentrations of radium may be lower, or may not.

Table 1 compares the highest "high" range values for ^{226}Ra in some industrial dry wastes (EPA 2000). EPA and some state agencies embrace the term "Technologically Enhanced" added before the traditional "NORM," with the peculiar choice of term "enhanced" meaning that the processes and activities of humans have resulted in increased concentrations of naturally occurring materials, displacement of materials to new locations, or both. This creates the reference initialism TENORM which due to the almost humorous obfuscation provided by the terminology "technological enhancement" has not gained universal acceptance among all the regulatory agencies. As shown in Table 1, the petroleum industry is not the only source of technological enhancement, but the higher range radium concentrations found in petroleum scale seem to occupy a special position in terms of relative hazard among a spectrum of industries that enhance their NORM.

Table 1: High Range Radium-226 Concentrations in Some Wastes

Radium-226 Source	**High Range pCi/g**
Soils of the United States	4.2
Uranium Mining In-Situ Leach Evaporation Pond Solids	3,000
Petroleum Industry **Pipe/Tank Scale****	**Over 100,000**
Water Treatment Plant Filter Media*	40,000
Zircon Wastes	1,300

* Average shown for water filters because "high" range was not reported. Additional data and references to each original data source are available from EPA (EPA 2000). Whether some water treatment filter wastes might be higher in radium than petroleum scale wastes could not be determined by EPA's summary reporting.

** USGS and others report concentrations to 400,000 pCi/g resulting in an industry median of 0.2 µCi/g for high-radium barium sulfate scale.

For spent water treatment plant media, EPA suggested to the state regulatory agencies that *landfills* are the single preferred disposal option (EPA 2005), saying

> "US EPA is aware that some states allow land spreading or soil mixing as an alternative to landfill disposal for water treatment residuals (for example, as a soil amendment on farm fields). One central concern with land spreading is the potential for build-up or movement of radionuclides to create contaminated sites that would require remediation and/or use of institutional and engineering controls. Other factors to take into account include the physical and chemical attributes of the material, the amount of radiation introduced into the soil over time, the mobility of radionuclides and their decay products along multiple pathways of exposure, and the consideration of future controls and future land use. Programs would need to be designed to provide adequate risk protection to human health and the environment."

Since the focus here is petroleum scale, the extent of landfarming high-radium water plant media was not investigated, yet much of the subsequent discussion will apply, especially where chemical processes in water treatment have separated radium from its parents. The extent to which high-radium scale has been or will be landfarmed by any particular industry was not addressed here, but the eligibility for landfarming definitely remains.

As an example of a state that *does* allow landfarming of petroleum industry scale, the state of Texas under Texas Administrative Code Title 16 Part 1 Chapter 4 Subchapter F Rule §4.614 allows:

> (d) Landfarming. A person may dispose of oil and gas NORM waste at the same site where the oil and gas NORM waste was generated by applying it to and mixing it with the land surface, provided that after such application and mixing the radioactivity concentration in the area where the oil and gas NORM waste was applied and mixed does not exceed 30 pCi/g Radium-226 combined with Radium-228 or 150 pCi/g of any other radionuclide.

An oil lease holder does not have to contact the landowner for approval before electing on-site disposal of NORM on the land-owner's property according to the Texas Railroad Commission (RRCT 2012). Subsequent use of the land for food crops or other purposes appears to be unrestricted. How the 30 pCi/g or complete mixing can ever be achieved during landfarming without pulverizing hard scale into powder is not addressed. Without pulverizing this material sufficiently to permit homogeneous mixing with the local soil, sampling would tend to have a kind of Easter egg hunt aspect, making it difficult or impossible to ever reach a scientifically defensible overall conclusion that 30 pCi/g has been met.

In some cases, drilling mud and cuttings from formations above the reservoir cap rock that tend to be very low in NORM may also be landfarmed as a means of bulk waste disposal, and that process is not the subject here. The acceptability of landfarming high-radium scale could be rationalized based on also landfarming large quantities of drilling mud from formations above the caprock that probably have vastly lower radium concentrations than typical scale. How dense hard pipe and equipment scale would be uniformly distributed into either natural soil or introduced waste mud with cuttings, and what extent of mixing would take place is not really clear.

In Texas, the disposal of petroleum industry NORM is regulated by the Railroad Commission, while handling NORM in the workplace is regulated by the Department of State Health Services under Chapter 25 of the Texas Administrative Code at 289.202 (f)-(o), (ww)-(zz) and .203. These Chapter 25 TAC regulations emulate the NRC federal

10CFR20, while curiously omitting the NRC regulations in 10CFR20 that relate to bioassay, respiratory protection, airborne radioactivity, and so forth, giving the NORM regulations a kind of "don't look, don't tell" honor system feel while preserving the same dose limits as applied to the nuclear industry. This leaves companies handling radium from NORM with a kind of self-regulating responsibility in comparison to companies handling the same radium derived from source material.

Presumably Texas Health Services has determined that no airborne exposure potential is involved in landfarming or in scale removal from tubing or other activities involving loose high-radium scale. The state has self-protected if things go South, in that a licensee is still required to comply with the restrictive internal exposure limits, but measuring compliance via bioassay and the means of achieving compliance are left to the industrial hygiene program of the licensee, which also places greater responsibility on company safety personnel to determine how to protect the company from legal liability. Unlike radium regulated under the full code, when radium from NORM sources is regulated, the state is not responsible for the means by which the dose limits are achieved.

The radiation regulators conference, in their draft "model" TENORM state regulations provided 5 pCi/g above background for the free release of sites (CRCPD 2004):

> "The concentration of residual TENORM ^{226}Ra and ^{228}Ra, on land averaged over 100 square meters, is less than 185 becquerel per kilogram (5 pCi/g) above the background concentration, averaged over any 15 cm layer of soil. The 15 cm layers are contiguous depth increments from the surface down. Each of the progeny radionuclides of the residual TENORM ^{226}Ra and ^{228}Ra may also be present in concentrations similar to the residual TENORM ^{226}Ra and ^{228}Ra concentration.."

At first the CRCPD model regulation seems much more restrictive, but the difference isn't all that significant. The Texas regulation is actually probably the better choice because it does not require establishing a background for an area, which in itself can be subjective, and the 30 pCi/g is typical of high natural ^{40}K in many sand outcroppings, so it is still a very low exposure level. Critics who point out that different state limits jump all over the map should keep in mind that all the numbers represent low levels of radioactivity, and that many states have no NORM limits at all. Regulation of NORM in the state of Texas is an exemplary proactive effort propelled forward by confrontation with the scale and sludge issue while many other states lagged behind hoping nothing similar would ever be discovered in their back yard.

Given that less regulation is always good, the petroleum industry appears to have benefited from special exemptions and omissions during historical development of environmental regulation in some instances, like the "petroleum exemption" of CERCLA

(EPA 1987) or the omission of the issue of NORM (and thereby TENORM) from the Atomic Energy Act of 1954, as amended (AEA 42 USC §2011 et seq.). Nevertheless, in regulating NORM, the states often turn to regulations promulgated pursuant to these inapplicable federal statues for consistency, realizing that exposure to identical material causes identical harm regardless of which law is applied.

Exempting or inapplicable regulations also provide standards under which toxic tort claimants may point to in alleging harm based on the human right to equal protection from harm by others under the law and implementing regulations. Under toxic torts, a person or class (when the class definition can be judicially satisfied) claiming harm could always point as a reference to the reasonableness of protection they *would have* otherwise been provided as a member of the public deserving equal protection through laws and regulations, had an omission of identical material not been made or a special industry exemption not been granted by lawmakers. After all, there is zero difference in the *harm* caused by a set of atoms of radium regulated under the Atomic Energy Act and a set of atoms of radium that are regulated by a state or atoms that remain unregulated. The biological impact is always the same.

Therefore to minimize torts risk, the burden of responsibility for a corporation is to apply reasonable standards that will prevent harm and show evidence of concern for workers and the public in addition to compliance with standards that may seem almost randomly imposed through various regulatory authorities over time as a result of agency and political policy decisions. The safety, health, and environmental goals of the corporation and regulatory agency are in the end always the same. A responsible corporate environmental advocate must keep in mind legal liability as well as regulatory compliance, since toxic tort claims may be brought to court whenever an argument can be made that a company has unfairly caused suffering of loss or harm through negligence, without regard to whether noncompliance with any environmental statute, or regulation promulgated pursuant to that statute, can be proven. Civil law essentially allows anyone harmed to recover their loss. Compliance with applicable environmental regulations, while always a positive and imperative objective of companies, is not always unilaterally sufficient to intelligently manage toxic tort risks.

To appropriately manage the risk of potential litigation arising from waste management, the owners of petroleum scale waste should anticipate the likely nature of potential hard evidence that might be made available supporting claims. In the case of scale, examples of evidence that could be faced in civil court include:

(1) bioassay results showing elevated radium on post mortem bone surfaces and teeth of deceased exposed residents or workers (radium is a "bone seeker") or

(2) bioassay results such as urinalysis or fecal sample analyses showing elevated radium in living exposed persons.

Most sources agree that the highest risk route of exposure to radium salts is through inhalation. A primary reason is that while radium can be ingested in food or water, about 80% of all radium ingested will promptly exit in feces. Some particles that enter the nose but are too large to be inhaled will be swallowed and ingested. Ingested radium from all sources that is not excreted will enter the bloodstream, and along with calcium, a large fraction will be deposited in the bones and teeth. Inhaled radium can remain in the lungs for several months and will gradually enter the bloodstream following along the routes of calcium internally (ANL 2005).

The expected chemical form of radium in petroleum piping and equipment scale is $(Ba,Ra)SO_4$, and its poor solubility under the applicable parameters is how the radium ended up in the scale to begin with (Crabtree 1999). Poor solubility exaggerates its lung retention in humans. The primary component of common hard barium sulfate scale is the natural mineral barite, which in the mined natural form can contain crystalline silica, making it an acute and chronic inhalation hazard that is sometimes reported as carcinogenic (EM 2012).

The characteristic ^{228}Ra to ^{226}Ra ratio is preserved as a fingerprint during incorporation of radium into human bone surface and teeth as well as during biological elimination, since only the electron shells of atoms participate in these nonnuclear electrochemically-driven metabolic transfer processes between the organs. The ^{228}Ra to ^{226}Ra ratio varies widely in nature and varies in patterns that can point to its origin in specific petroleum reservoirs (Wilson 2012). This traceability cannot be universally guaranteed because the isotopic ratios of radium in the local soil profile could coincidentally align well with those of the reservoir rock, but while these *could* coincidentally align, it is much more likely that radium traceability will be possible.

In addition, the shorter lived ^{224}Ra and ^{223}Ra that are generally present in samples of natural soil radium whenever the parents of the chain are present have long vanished from aged petroleum production scale (Wilson 2012). In some cases this age-dating provides some more evidence that can be employed to distinguish between radium sampled from the earth's surface nearby locally and radium sampled from areas where farmed scale aged at a production facility includes reservoir NORM, that may also have a distinctive isotopic signature.

While the cause of death by cancer in a specific individual cannot be linked to radium alone with any absolute certainty, these isotopic ratios, when they happen to be conclusive in bioassay results, could nevertheless provide the appearance of a "smoking gun" that it seems could have powerful psychological influence in court. Results could likewise prove for the company that radium shown in bioassay results was not likely to be radium that originated from a specific reservoir rock or its scale.

Even when considering landfarming in a state that explicitly permits it or has no NORM regulations restricting it, hopefully the basis has been established above for looking at what protection *would be* afforded a worker or member of the public without regard to direct applicability of a regulation or of special exemptions.

First, let's consider how much scale could be ground or pulverized and landfarmed without the need for an air permit simply by virtue of the small quantity of material on hand. That can illustrate whether there is any airborne potential of radium to be concerned about, even if the air regulations do not apply to landfarming. Table 2 indicates that quantity if we assume 0.1 μCi/g for both of the longer lived radium isotopes (that is, a ^{228}Ra to ^{226}Ra activity per mass ratio of 1) so all values on which Table 1 is based, while strictly hypothetical, are well within the published values for petroleum scale. This is an idealized "median" scale whose 0.2 μCi/g Ra-total is half the maxiumum 0.4 μCi/g reported by USGS (USGS 1999). What we realize from this calculation is that the total amount (204 lbs of scale) that would be exempted from air permitting based on quantity alone could be obtained from one single gas oil water separator with a heavy scale deposit.

The 204 lb. quantity applies of course to powdery material capable of airborne dispersion, not to large solid chunks of hard scale. This would be like the fines portion of the material created by removal from oil field equipment through the mechanical abrasive action of pipe reaming, grit blasting, pipe sawing, water blasting, hammer rattling, sustained vibration, drilling, or otherwise made dispersible subsequently by repeated disk harrowing of land. It could also be material removed at remote equipment refurbishment sites or material brought up during descaling workovers. The primary point here is that 204 lb. of dense scale that would be exempt from air permitting is not really a large volume and is so little that it could come from just one piece of equipment.

Table 2: Pounds of Dust From Median Scale That Would Not be Exempt *by Quantity* From Air Permitting under NESHAPS

Isotope	Curies of Isotope	Pounds of Scale Per Year
Ra-226	2.8E-03	61
Ra-228	6.5E-03	143
	Total pounds in a year:	**204**

The increased lifetime cancer mortality risk of inhalation of ^{226}Ra has been estimated to be 2.4E-08 chances of cancer death per pCi inhaled, with ^{228}Ra risk at 9.0E-08 per pCi inhaled (ANL 2005). Material accidentally scattered on roadways by poor transportation packaging can pose an airborne hazard because of the action of traffic on the dropped material. This potential airborne road hazard has led some investigators to suggest wrapping tubulars in duct-taped plastic for transport between workover sites (Swan 2010).

Photo 1: Truck Traffic and Heavy Equipment

Can Pulverize Material on a Roadway Making it More Dispersible

Assuming radium inhalation is the only source of their exposure, the NRC allows nuclear industry workers to inhale up to 0.6 µCi per year of ^{226}Ra or 1.0 µCi per year of ^{228}Ra (the "Allowable Limits of Intake," or ALI's) or a combination where the prorating "sum of fractions" of those two isotopes does not exceed unity. Prorating for equal concentrations of the two would allow you 0.8 µCi of total Ra annually, for example. A sum of fractions of unity produces a committed effective dose of 5 Rem, or 5,000 millirem allowed for a nuclear worker. We will ignore direct external exposure for simplification. Members of the public are only allowed 100 millirem when NRC is regulating through their authority provided through the Atomic Energy Act of 1954, which does not apply to NORM. State agencies that have any NORM regulations at all have tended to adopt this 100 millirem standard to protect the exposed public. This is a very low limit to meet.

A 36-year-old chemist worked with radium for 14 years and then suddenly developed acute leukopenia and died of bronchopneumonia within a month after the onset. It was suspected, but not known, that radium could have been associated with the fatality. The autopsy showed 1 µci of Ra-total as ^{226}Ra plus ^{228}Ra in the lungs of the corpse as compared to no radium detected in the liver, gastrointestinal tract, heart, and kidneys, so inhalation was thought to be the primary mode of exposure. Most radioactivity was found in the skeleton, the target organ for radium. The ^{228}Ra:^{226}Ra ratio is available from the data.

Leukopenia is a condition of low white blood cell count, not generally associated with radium per se, nor is pneumomia conventionally linked to radium, but the autopsy was nevertheless convincing to some that radium exposure was the cause of death. (ATSDR 1990). Given the high incidence of cancer deaths, consider how a jury would view a cancer death that could have resulted from totally unrelated causes, when the jury is faced with a similar autopsy report. Consider that in civil law the standard of proof will be the preponderance of evidence, or at the very most, clear and convincing evidence, and some people are likely to find bioassay evidence from a corpse with an isotopic ratio and separation age that point to a specific radium source as clear and convincing evidence.

Photo 2: Farming Activities Can Act as a Moving Source of Airborne Material

Air Sampling for Landfarming High Radium Scale

In looking at whether the tractor driver or other workers present during land application should be protected by respirators or whether samples should be taken, we can ask merely as an inapplicable reference point what might the rule be if these individuals received equal protection to that which would be provided for identical radium found at an NRC-licensed facility. NRC uses 10,000 ALI in total possession to trigger when a nonreactor licensee should evaluate the need for air sampling (NRC 1992). The evaluation would consider the form of the radium. Evaluation is the appropriate action because "special" form material like sealed well logging sources could not be made airborne so air sampling would not be necessary.

If we assume 0.1μCi for each of ^{228}Ra and ^{226}Ra in a gram of scale and no other Ra is present aged "median" scale that has 0.2μCi/g Ra-total, then we see our median scale has

4 grams mass per each ALI. In this median case for the industry, 10,000 ALI is contained in 88 lbs of scale. What we conclude is that to landfarm 88 lbs of scale in an NRC-licensed nonreactor facility licensed under the Atomic Energy Act that possesses identical radium scale not technically classified as NORM, an evaluation would probably be made to determine whether air sampling would be needed, and the result would be that air sampling would be needed unless dust control is effective. The need for air sampling may not even be considered under most NORM regulations, but keep in mind that the same dose limits are generally imposed without telling you how to get there.

While air sampling for a process facility can be complicated, assuming the applicable state NORM regulations, if any exist, do not trigger an entire air sampling program, then the short answer here is that it might be a good idea for liability purposes to consider continuous lapel sampling the tractor driver and any workers who might stand in a dust plume when dry landfarming 10,000 ALI of high-radium scale in a year, even if the agencies regulating NORM in the state where the landfarming occurs do not require sampling. Of course this depends on dust control measures. Dust control and/or air sampling during landfarming of high-radium scale would provide a semblance of equal protection to that which workers and the public would have received under the Atomic Energy Act without regard to the omission of NORM in the 1954 statute. Dust control during landfarming can also reduce complaints from the site neighbors.

Bioassay for Landfarming of High Radium Scale

Assuming the flow rate and counting results are recorded from lapel sampling of the tractor driver (and any worker exposed in the plume), it will be easy to determine whether a worker is likely to have inhaled 0.02 ALI of radium. If the worker received equal protection under the law and regulations to that which would otherwise have been provided had NORM not been omitted from regulation under the Atomic Energy Act, then bioassay would be required prior to exposure to airborne radioactive material and upon termination and would be repeated each time the worker appears to have inhaled another 0.02 ALI, the "Evaluation Level" as described by NRC (NRC 1993). 0.02 ALI also lines up with the 100 millirem allowed annually for a member of the public.

Intakes would be *investigated* by NRC licensees each time the worker has inhaled another 0.1 ALI (NRC 1993). It would be prudent liability-wise to consult a health physicist to help if the need for investigation appears to be triggered, whether or not this was required by state NORM regulations. The ALI quantity is based on an NRC-approved model for the "Reference Man." The Reference Man breathes at a rate of 2E+04 ml/min while performing light work like driving a tractor to landfarm radium scale. Flow rate for a typical lapel sampler might be 2E+03 ml/min, or only 10% of the reference man's breathing rate, in which case ten times the activity on the sample paper that was collected in the breathing zone would have been inhaled by the Reference Man breathing for the same period of time.

If the sample paper has collected 0.008 g of our median scale, then bioassay is required, and if it has collected 0.04 g of scale then investigation is needed. The mass of *scale* on the paper can't be determined even with a highly sensitive balance, since most of the mass collected is presumably dust from plowing the land rather than from the scale. A sample of dense scale that weighs 0.08 g (the amount of our industry-median scale a member of the public is allowed to inhale in a year) would make a very good show-and-tell training illustration. Visualize 0.08 g while examining Photo 2 above. Gross counting could be used for screening purposes, but laboratory high resolution gamma spectroscopy is what can easily differentiate things like the ^{40}K component contributed by the local soil.

A radiochemical lab can report all four radium isotopes in the radium fingerprint. Certified laboratory results can protect the company in case any legal actions arise in the future. The laboratory can also advise on aging the samples to account for decay of the short lived daughters. Since landfarming is outside and presumably would be done during at least some slight wind, radon exposure should not be significant. Use of large industrial misters would be a very positive step toward controlling airborne material as long as plowing can still be accomplished under damp conditions.

Of course if high-radium scale was planted within a large volume of drilling mud and cuttings to be landfarmed, then the odds that regulators could ever find the high-radium lumps of scale without an intense sampling campaign would be extremely low, and it is difficult to conceive of state regulatory agencies ever being budgeted for such extensive oversight. State sampling of landfarmed areas is likely to be very budget-limited. With low radium concentrations in drilling mud and cuttings from low activity formations being farmed, "landfarming" could essentially amount to surface spreadings that could be accomplished by bulldozers without the need for disk harrows or other blending devices at all. The mixing could be done later by the public during unrestricted use.

If done in this manner, growing plants on the waste overburdened land would be difficult until a new soil horizon had time to develop. Since the petroleum industry is committed to responsible environmental stewardship it is unlikely that high-radium scale would ever be hidden in drilling mud and cuttings in this manner, and if it was, the result over time could be difficult to guess. So long as tort claimants were without incriminating evidence such as bioassay results that implied a specific reservoir source, then waste farming could appear to be a successful disposal path. The long term liability of this path should be considered. Contents of the 10CFR and agreement state regulations that emulate it are not a well-guarded secret. Well loggers and radiographers comply with these regulations every day at petroleum sites. A defense against toxic torts actions of “the state let me do it” or “I had no idea that I could have avoided this” could seem like conscious indifference or willful disregard for the public in the face of hard evidence and the easy access to national standards of practice.

Respiratory Protection Program for Landfarming High Radium Scale

Unless landfarming is done using directed misters or under wet conditions but not “too wet to plow” or radium scale is plowed in the form of large lumps, creating the bewildering Easter egg hunt aspect of determining what is truly an indeterminate overall post landfarming radium concentration, then respiratory protection may be prudent for the tractor driver and for any workers positioned in the dust plume, assuming there is a dust plume caused by soil blending without misting. To see what a respiratory protection progam would be like if required by NRC, scan the content of 10CFR20.1703. This scan should trigger considering the use of misters or alternative disposition paths where airborne exposure would not be an issue.

Liability for the Added Radium After Landfarming

Lumps of hard high-radium barite will not readily dissolve, and pose an interesting hurdle to any meaningful concentration determination. Finely divided barite dust in the soil may transfer radium to a form readily absorbed by plants. State NORM regulations may require blending as well as a concentration limit, neither or which could be easily achieved without pulverizing the scale. Depending on the specific plant type and soil, soil-plant transfer coefficients or concentration factors for radium salts have ranged from 1.1×10^{-3} to 6.5 (ATSDR 1990), meaning that on the high side, a 30 pCi/g soil could concentrate up to 200 pCi/g of radium in the food plant that is grown in it.

If the 30 pCi/g was not the true concentration then proportionate results should be anticipated. As pointed out previously, plowing and cultivation of the land for food crops or other purposes after landfarming radium scale is not always restricted and the landowner’s permission or notification to landfarm the NORM was not even required in Texas. Growing food apparently might commence immediately after landfarming NORM. If the original landfarming did not successfully blend the high-radium scale, then subsequent plowing by the public may pose an inappropriate corporate risk.

While barium radium sulfate is insoluble, bacteria in soil with a food source can reduce the sulfate to soluble sulfide (Krumholz 2000) so that the radium becomes soluble in vadose zone and shallow groundwater. In sulfate-containing soil water, precipitation and redissolution of calcium, strontium, and barium sulfates, rather than adsorption/ desorption, could control the concentrations of dissolved radium. All these electrochemically similar cations compete for charged sites in the soil matrix, which makes the behavior of radium more difficult to predict.

Any concentrated radium that has been buried in large particles during the initial landfarming can be distributed later in the farmed soil by these processes so that future dust-generating agricultural activities result in totally different, and possibly far higher airborne levels than during the initial plowing. Radium is strongly adsorbed on clay minerals and soil organics. It can be transported as a solid on colloids or an adsorbed cation on suspended solids. A spectrum of studies showed K_d values for Ra ranging all the way from single digits to almost a million ml/g (EPA 2004). K_d is the ratio of the contaminant concentration associated with the soil or rock solid media to the contaminant concentration in the groundwater at equilibrium. This wide range indicates land-farmed radium could leach, move, dilute, or concentrate, depending on the localized conditions.

With radium behavior in soil being subject to bacterial action and a host of chemical parameters, it would seem unlikely that the fate of landfarmed radium could easily be forecast without expensive complex site investigation fraught with uncertainty. Each outcome of landfarming will be strongly site specific. Future uncertainty adds more undesirable prospects in addition to the inhalation risk, further suggesting that landfarming of high radium scale may not be the most prudent disposition path when future toxic tort liability is fully considered. Superior options might include acid dissolution and reinjection in wells or burial in accepting landfills if available.

Protection of the Public

Protection of the public such as nearby residents, or the owner of the radium farmed land who did not need to be consulted prior to landfarming see (RRCT 2012), poses some interesting issues. Unless the radium scale is powderized to a fine easily dispersible particulate and mixed thoroughly and uniformly in the soil, which would make concentration determination possible upon landfarming, then the airborne levels during landfarming of radium scale could be insignificant in comparison to airborne levels when the land is plowed later by the landowner or other public during unrestricted use.

The standard for protection of the public from NORM adopted by some of the states that have any NORM standards at all, is 100 millirem per year--a value patterned after the NRC 10CFR20. An inhalation of a total of 0.08 g of our industry-median scale as defined previously will result in a 100 millirem dose. How inhalation is prevented during subsequent unrestricted use and unrestricted access of radium-farmed land by the public deserves additional consideration. At a minimum, landfarmers should consider what protection would be afforded under the accepted legal national standards governing otherwise identical material that benefits from no exemption or omission.

Conclusions

(1) The ^{228}Ra:^{226}Ra ratio can be used at times in a fingerprinting manner to show that radium in the human body was or was not likely to have originated from particular scale. Similarly, certain ^{224}Ra and ^{223}Ra results can age date radium and provide evidence that can support or contradict an alleged source of radiation dose. Bioassay evidence with an isotopic fingerprint pointing to a specific radium source might have strong psychological impact without regard to an actual link to the cause of death or illness. Companies should be conscious of this potential.

(2) If a company decision is made to landfarm high-radium scale, then while complying with all state regulations, it would be prudent to comply with some of the main standards of personnel and public protection inapplicable to NORM that are implemented through the federal law and regulations that apply to otherwise identical material of a different origin. Thereby workers and the public are provided equal protection to that which would have been achieved through broadly accepted national standards of health protection for these materials.

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