Appendix F – Worker Exposure Memorandum

Technical Memorandum

Date:	June 27, 2008
To:	Jon Erickson - CDPHE
From:	Les Skoski, Jason Kerstiens, Ben Johnson - Malcolm Pirnie, Inc.
Re:	Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) Analysis of Worker Exposure
Project No.:	5322-009

1. INTRODUCTION

The use of ion exchange resins for removal of uranium, radium-226 and radium-228, and other gross alpha emitters is being evaluated as a potential Radionuclides Rule compliance solution for small drinking water systems that are participating in the Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) project. As with all ion exchange treatment systems, build-up of contaminants on the ion exchange resin occurs prior to regeneration. Unlike chemical contamination, the build-up of certain types of radionuclides can lead to radiation exposures for people in the proximity of the treatment system. The magnitude of an exposure can vary and is primarily based on the following three health physics variables:

- *Time* - amount of time that the person is exposed to the radiation.
- *Distance* - amount of space between the worker and the source of radiation.
- *Shielding* - different materials that separate the worker from the source of radiation can reduce the amount of exposure.

In other words, to minimize an exposure, one can minimize the time in the radiation field, maximize the distance from the source of radiation, and/or place a shield between the source and the exposed individual. To better understand the risk of exposure and identify, if necessary, potential strategies to minimize those risks, it is first necessary to calculate the exposure rate at a point from a source of radioactivity. Once the exposure rate is known at a point, the allowed hours of exposure and possible requirement for shielding can be determined. The following presents the methodology and findings of such an analysis to help evaluate the potential risks for CO-RADS systems that may install ion exchange.

2. METHODOLOGY

Malcolm Pirnie developed a representative, but conservative, design of an ion exchange system for purposes of this analysis. Assumptions regarding the number of vessels, size of vessels, amount of resin, and concentrations of contaminants on the resin were developed based on a few representative systems participating in CO-RADS and typical industry standards.

It was assumed that the treatment system consisted of four ion exchange columns in four steel/iron vessels. Each vessel was assumed to be six foot high, four feet in diameter, and approximately half full of resin. Each vessel was assumed to be supported on a two foot high base (legs) so the vessel's midpoint would be at a height of five feet and the center of the resin column would be at a height of three and a half feet (the approximate height of a human's midsection). Attachment A presents a schematic view of the system and a single vessel cut away.

The design parameters of each of the vessels are as follows:

- Vessel volume = 75.4 cubic feet (cf)
- Resin volume = 35.4 cf
- Free water volume in the resin area = 4.6 cf
- Resin density = 79.2 lb/cf (1.20 g/cc)
- Steel casing is 0.25 inches (0.64 cm) thick

Figure 1 presents a plan view of the system and three exposure points A, B, and C. That configuration served as the starting point for the exposure analysis. The vessels are labeled I, II, III, and IV. The distances from the center of each vessel to each of the points A, B, C is the effective distance for the exposure rate from that vessel. In other words, a person standing at point A would be five feet from the origin (the centerline bisecting the system), 12.62 feet from vessel I, and 7.83 feet from vessel II. The figure also shows the symmetry of the system. As the configuration in the computer code in MicroShield allows only one cylinder at a time (a model run) this symmetry indicates that calculations for only vessel I and vessel II need be run and the results doubled.

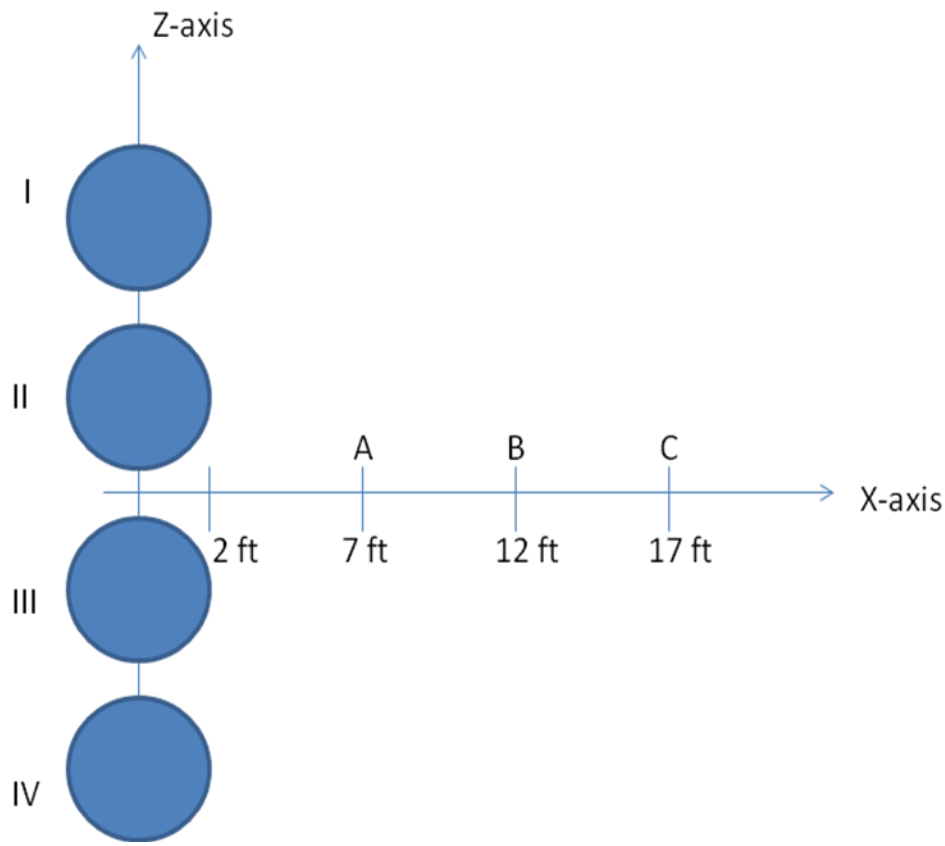

Figure 1: Schematic of Ion Exchange Configuration for Exposure Analysis – Plan View (not to scale)

Malcolm Pirnie focused the analysis on gamma emitting radionuclides (primarily radium) and not alpha and beta emitters. This was done because alpha and beta emitters are easily shielded and do not travel far (approximately 20 feet or so in air). They are also charged and, as a result, they are also easily shielded. For example, beta particles can be shielded by 1 cm of Lucite or water. Similarly, gross alphas are self shielded by the water and ion exchange vessel.

Model and Code

The computer model used to calculate the exposures from the vessels was MicroShield Version 5. MicroShield calculates the exposure from gamma radiation from up to 16 different geometries or configurations. The configuration used herein is an annular cylinder filled with ion exchange resin and water in an iron casing with the dose point at different distance from the center of the vessel (see Attachment B for examples of how MicroShield was configured). In terms of shields (matter that interacts with the gamma rays between the source and the exposure point) the first shield is the vessel casing. The casing is a cylindrical shield, followed by a transition shield (a hypothetical shield indicating the point where the cylinder shield stops and the slab shield starts) and a slab shield that is, the air gap to the exposure point.

Each vessel is treated separately and, given the symmetry of the problem, exposures from vessel I and vessel II were calculated and doubled. That is, the exposure from vessel IV is equivalent to the exposure from vessel I while the exposure from vessel II is equivalent to vessel III. Thus the total exposure at any point along a line which bisects the configuration such as point A, B or C is twice that from vessel I and vessel II.

The geometry of each case is defined by MicroShield, as described above and presented in Attachment A and Figure 1. MicroShield has number of inputs in addition to the dimensions of the system, including the following:

a. *Point of exposure* - As discussed above, points of exposure were selected along the centerline bisecting the four vessel configuration.

b. *Materials* - MicroShield provides 12 standard materials which can be used to define the source and each shield. The material determines the attenuation and buildup characteristics of gamma rays interacting with the source and shields. Attenuation is the reduction in the energy of a gamma ray by interactions with the source and shield material while buildup is the increase of secondary gamma rays of lesser energies due to the interaction of higher energy gammas with the materials.

   MicroShied also allows the use of custom materials as is the case here for the resin. The representative resin selected was DOWEX® 50Wx8, 100-200 Mesh, H Cation Exchange Resin with a chemical formulation of (C10H12.C10H10.C8H8)x. Using that chemical formulation, a custom material was composed by assuming three composite materials e.g.C10H10, C10H10 etc. each material contributing a weight percent to the total. The weight percent was the atomic weight of the material (C10H10=120+10=130) divided by the total atomic weight. Once the weight percent was calculated, the atoms making up each material were selected; in this case it was carbon and hydrogen. The final density was 1.2 grams per cubic centimeter (g/cc). Given that most resins are composed primarily of long string polymers, their nuclear characteristics and interactions with gamma radiation should be approximately the same.

   Iron was used for the cylinder walls (density 7.86 g/cc) while the air gap and transition shield had a density of 0.00122 g/cc.

c. *Radioactive Source* - Two sources were assumed: the first was radium-226 with most of its daughters, the second radium-228 with one daughter. In the case of radium -226 all the daughters are short lived, half lives of days or less through lead-210 with a 22.3 year half life.

   In the case of radium-228, it and the next daughter, actinium-228, have short half lives. The next daughter, however, is thorium-228 with a half life of 1.9 years

and would take some time to build up to equilibrium. However, after Th-228 is Ra 224 with a short half life as do all its subsequent daughters. As the influent water would have Ra-228 in equilibrium with Ra-224, all its daughters would be included in the calculation. Lastly, Th-228 was included as conservative as the actual amount ingrown is depends on how long the resin is used which can vary. Also Th-228's gamma ray contribution is nearly negligible, as 99% of the time it is an alpha emitter.

One run was performed for a uranium removal system to confirm that it would provide a significantly smaller dose and would be less of a concern than for radium treatment systems (see below for further discussion).

d. *Sensitivity* - MicroShield allows the user to conduct "sensitivity" analysis on some of the parameters. Specifically, one parameter is varied and the others are fixed to see the effect of that parameter. The sensitivity analysis run for this problem was the distance along the centerline.

e. *Concentration of radium* – In a cation exchange system, radium is readily exchanged with sodium ions bound to the ion exchange resin. When the capacity of the resin is reached, radium ions will break through into the finished water. Prior to breakthrough, the resin is regenerated with a sodium solution that will replace a portion of the radium ions. The resin concentrations used in the model are based on the exchange capacity of the resin (maximum value of 44 pCi/g), the efficiency of the regeneration process (literature has shown that due to the affinity of the resin for radium, only 30% of the radium is removed in the regeneration process, yielding the minimum value of 30 pCi/g), and the average concentration during the production cycle (assuming a constant raw water concentration of radium, the buildup will be proportional to the raw water flow, 37 pCi/g).

Radon

Radium decays into radon which is a gas. As a gas, radon can dissolve into the surrounding water and be removed in the ion exchange treated water. This is the case for radium nuclei dissolved in the water, but is not the case for radium removed from the water by the resins. Industry research and Malcolm Pirnie's experience working with a few CO-RADS systems has shown that that after a period of time that ion exchange systems operate (days to weeks) the resin vessels become a source of gamma radiation. As neither radium nor radon are gamma emitters (decaying by alpha emission more than 96% of the time and low energy gammas < 4%), the observed gamma radiation is from the radon daughters. As their half lives are short they quickly build up to secular equilibrium with the parent. The question becomes how much radon may be released back into the water and how much is "trapped" in the resin.

Radium removed by the cation exchange forms an ionic bond to the resin. On decay the ionic bond could be broken and the radon nucleus propelled either into the water or further into the cation exchange resins. Once in the cation exchange resin the radon

would decay and give rise to charged daughters which would tend to "plate out" to the surface of the resin. If in the water, the radon nucleus could leave the system or decay to a charged daughter which again could "plate out" on the resin. The question of how much radon is removed from the system is beyond the scope of this study. For conservatism it is assumed all the radon and radon daughter contribute to the dose.

As a check, the MicroShield was run for a case with just radium and radon on the resin (no daughters) versus the case with all the daughters. The dose from only radium and radon was 1000 times less than that from radium, radon and the daughters (2 E-6 mR/hr versus 2 E-3 mR/hr).

Uranium

Uranium -238 and uranium-234 are alpha emitters. Their daughters, (Th-234, Pa-234m, Pa-234 IT) are primarily beta emitters and will be self shielded by the water in the ion exchange resin. There is one gamma emitting daughter, Pa-234, which emits gammas about 65% of the time. The energy of these gammas is about the same as that from the radium-226 case daughters. The latter, however, has about three times as many gammas. A MicroShield run for the same configuration shows the dose is about 2 ½ times less than that for Radium 226 at the same concentration.

3. RESULTS

MicroShield code was run separately for each vessel. That is (see Figure 1) for vessel I the dose was calculated for points on the line bisecting the four vessels for a specific resin loading of Ra-226 or Ra-228 (30 pCi/g, 37 pCi/g or 44 pCi/g) – as indicated above, these values were selected. This was repeated for vessel II. Because of symmetry, the dose from vessel IV is equivalent to that from vessel I while that from vessel III is the same as vessel II.

The output of each run for vessel I and vessel II was input into an excel file. The doses from vessel I and vessel II were added and doubled for vessel III and vessel IV to give the final dose. Using the sensitivity analysis the dose at various points along the x axis was determined and a graph of the final dose prepared. The power curve was fitted to each graph. This power curve may be useful to estimate doses at various x distances however it must be cautioned that this is a mathematical construct and is not useful for configurations other than that discussed herein. In addition, the power curve serves as a check for the calculation. If the resin column was a "point source" the exposure would be the inverse radius squared ($1/r^2$). The cylindrical sources at different distances give a power curve of $1/x^{1.6}$ which is not too far from the inverse square.

The following summarizes the results from three primary cases evaluated as part of this effort.

Case 1: Dose from Ra-226 and Ra-228 (Points A, B, and C)

The purpose of this first case was to set-up the model, validate results, and identify the primary causes of exposure that needed to be further evaluated. Malcolm Pirnie ran the model for radium-226 and radium-228.

The first case was the calculations of the dose for radium-226 at concentrations of 30 pCi/g, 37pCi/g and 44 pCi/g. As discussed previously, the model was run for vessel I and vessel II and by symmetry the results are also for vessel III and vessel IV. The total dose at a point is the sum of the doses from all the vessels

The results are presented in Figure 2 below. One important note is that the ratios between the assumed concentrations of radium-226 are the same as the ratios of the doses, irrespective of the distance. This allows a quick calculation for a different loading for the same configuration. For example, the dose from a resin loading of 50 pCi/g of Ra-226 is just 50/44 times the dose from 44 pCi/g.

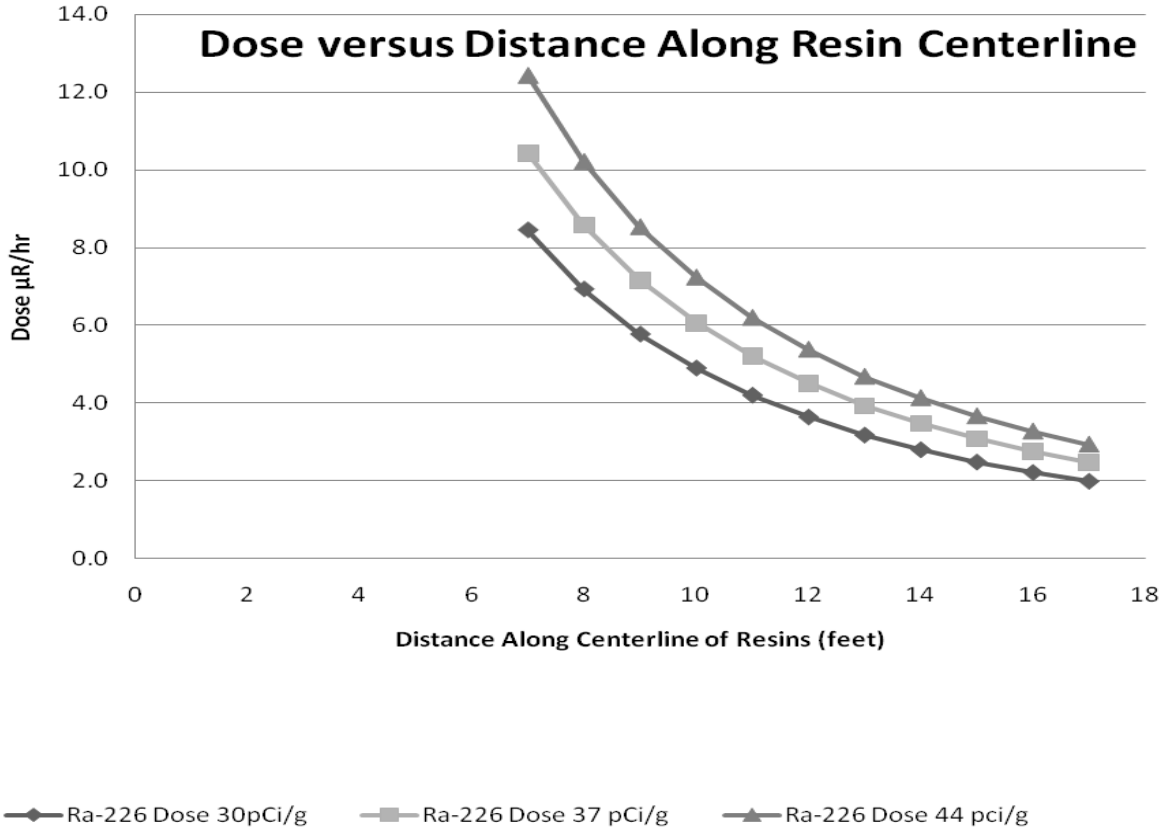

Figure 2: Case 1 Results

The maximum dose (12.4 µR/h) is at 7-feet along the centerline for a loading of 44 pCi/g of radium-226. This results in a dose of 24.8 mRem per year for a 2000 hour exposure (an unrealistic scenario).

The same geometry and radium loadings were run for radium-228. The maximum dose at was slightly higher 14.2 µR/hr. This dose would exceed 25 mrem/year for a 2000 hour exposure. The higher dose from radium-228 is due to the higher energy gammas from the daughters in this chain versus the radiun-226 chain.

It was decided to focus attention on the radium-228 chain in further calculations as the doses from the same configurations would "bracket" the doses from Ra-226.

Case 2: Radium-228 at Closer Doses

Under the same physical configuration as Case 1, Malcolm Pirnie calculated the dose change from 3 feet to 17 feet along the centerline bisecting the vessels (see Figure 1). This was done to better understand doses to workers who may spend limited time in close proximity of the ion exchange vessels. These were calculated for radium-228 at 30 pCi/g and 44 pCi/g. As indicated above, this analysis only included radium-228 because it was a more conservative assumption than using radium-226.

As expected, the doses increase considerably closer to the vessels. Figures 3, 4, and 5 present these results for Ra-228. These results indicate:

- Figure 3: doses along the line bisecting the vessels from 3 to 17 feet for Ra-228 with a loading of 30 pCi/g. One series in the plot indicates the dose from vessel I, another line indicates the dose from vessel II, and the third line indicates the sum of those multiplied by 2 (which provides the total dose from all 4 vessels – see Figure 1).
- Figure 4: doses along the line bisecting the vessels from 3 to 17 feet for Ra-228 with a loading 44 pCi/g. This figure presents the same type of information as described for Figure 3.
- Figure 5: comparative doses at loadings of 30 and 44 pCi/g radium-228 for 3 to 17 feet. This presents the total doses from all four vessels at those two different concentrations.

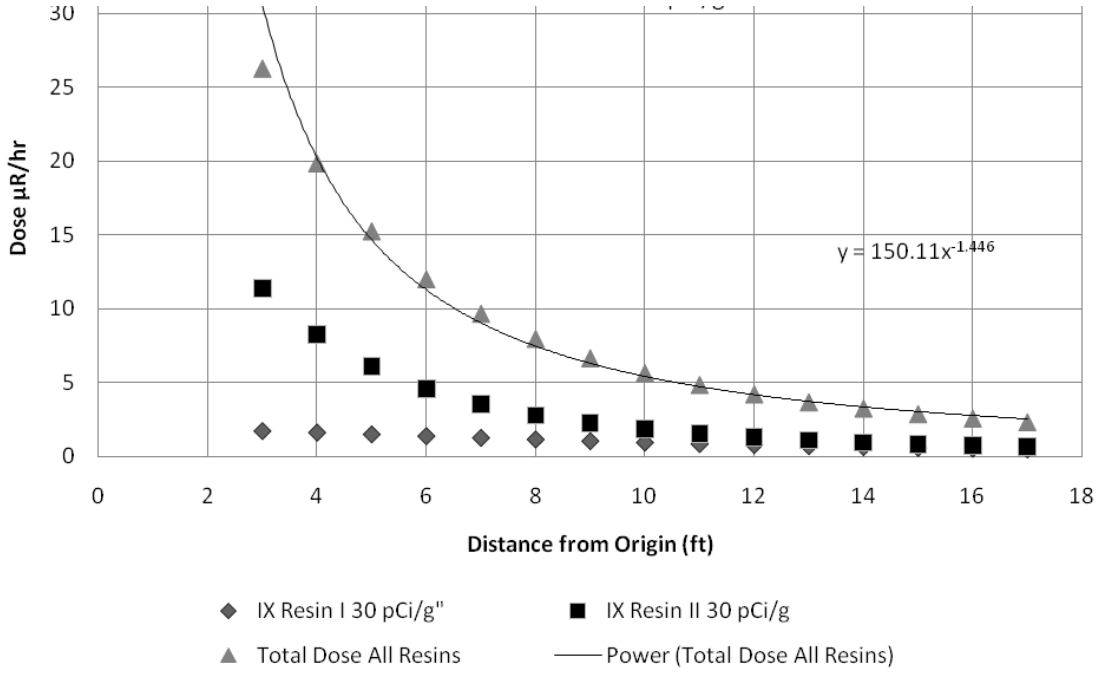

Figure 3: Case 2 Results for the 30 pCi/g of Radium-228 Scenario

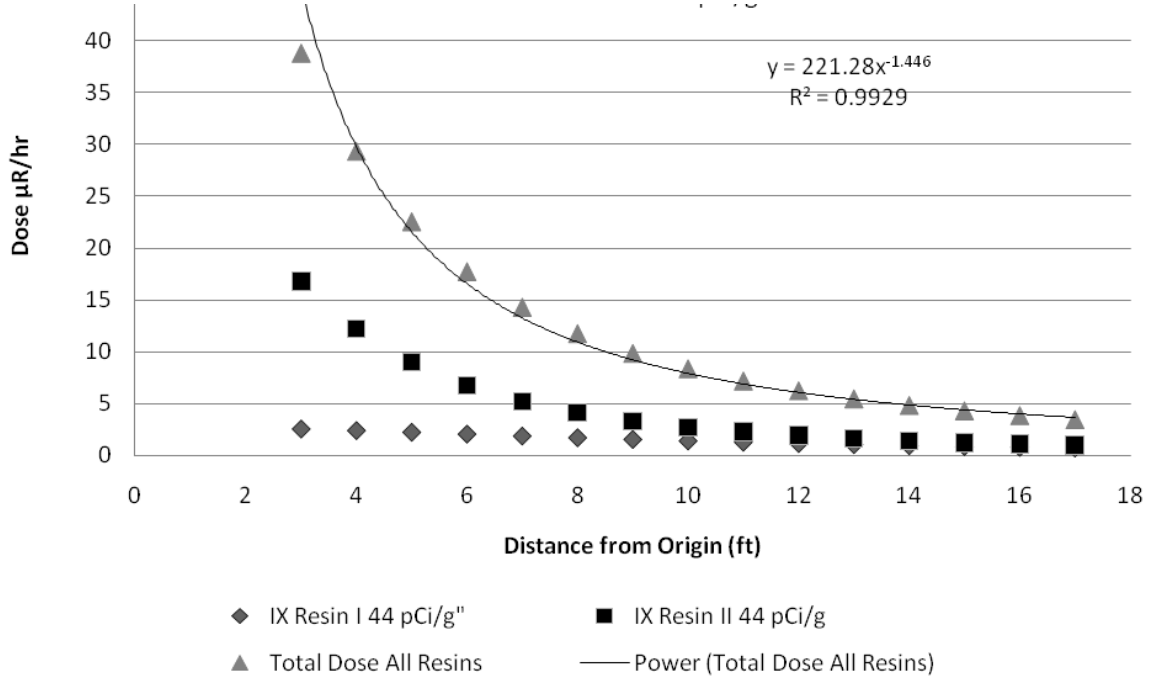

Figure 4: Case 2 Results for the 44 pCi/g of Radium-228 Scenario

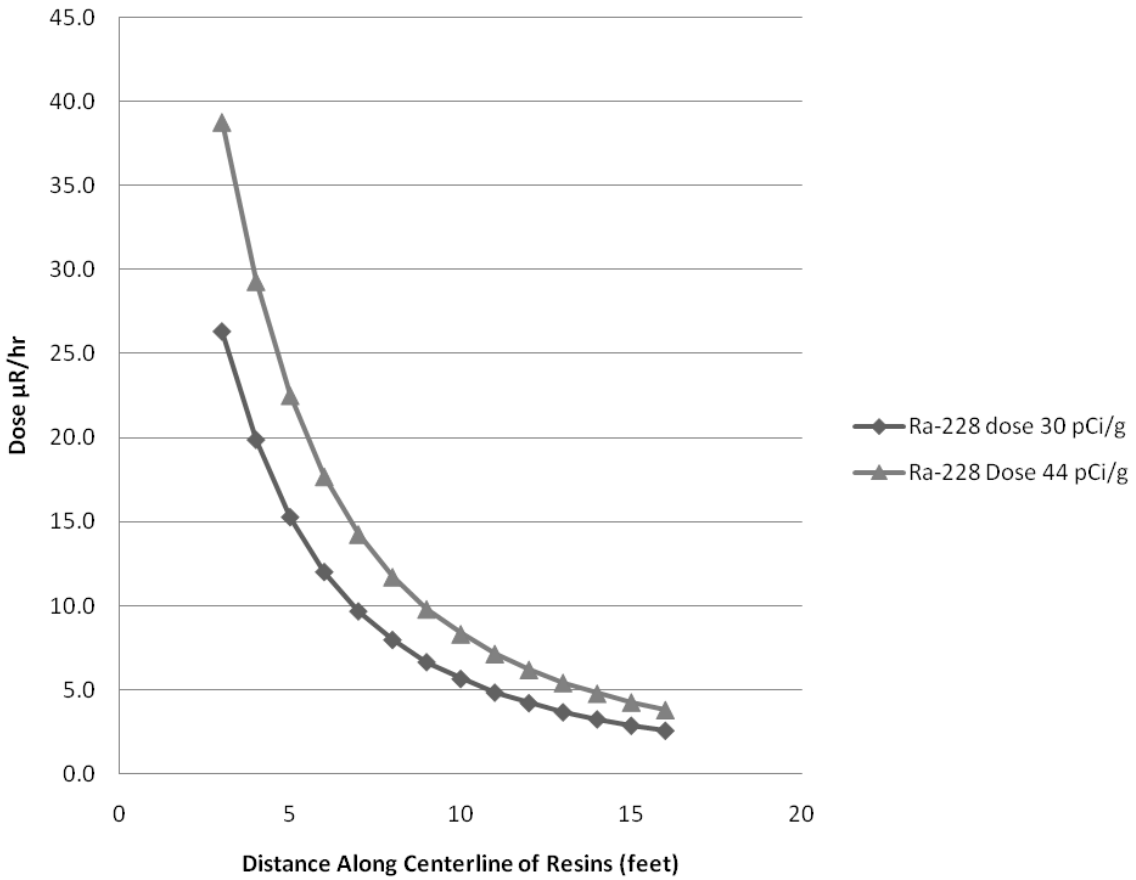

Figure 5: Case 2 Results for Both the 30 and 44 pCi/g of Radium-228 Scenarios

The dose increases significantly at closer distances to the vessels. This is expected as for point sources the dose is proportional to the inverse square of the distance from the source. In this case (with four vessels), the power is -1.4 times the distance. This graph can be used to limit the time spent at any point along the line bisecting the vessels to meet the 25 mrem/year limit. For example, at the 3 foot distance the time limit is 25 mrem/yr divided by 38.8 E-03 mR/hr or 644 hours per year.

Note again that the ratio of the doses is the same as the ratio of the concentrations. At any distance along x, the ratio of doses is the same as the ratio of concentrations. Therefore if you change the concentration, the dose changes proportionally.

Table 1: Comparison of Ratio of Dose to the Ratio of Concentration for Radium-228

Example Distances on x-axis (feet)	Radium-228 concentration = 30 pCi/g	Radium-228 concentration = 44 pCi/g	Ratio of concentration = 44/30 = 1.47
	Total Dose mR/hr*E-3	Total Dose mR/hr*E-3	Ratio of Total Dose (no units)
3	26.3	38.8	1.47
5	15.3	22.5	1.47
6	12.0	17.7	1.47
7	9.7	14.2	1.47
8	8.0	11.7	1.47
9	6.6	9.8	1.47
10	5.6	8.3	1.47
12	4.2	6.2	1.47

Case 3: Centerline Doses

The next series of calculations have been named the "centerline doses." That is, the dose from the center of each vessel was calculated. The configuration for this analysis is a little different and is presented in Figure 6. In this case, the dose from vessel IV was calculated along the centerline from vessel IV (points A, B and C) and at z values from the center line which coincide with the center lines of the other vessels (z=7, 14 and 21 ft) from points A, B, and C. For example, the dose was calculated at the point in the graph (5, 7), which is the dose from vessel IV along the centerline of vessel III.

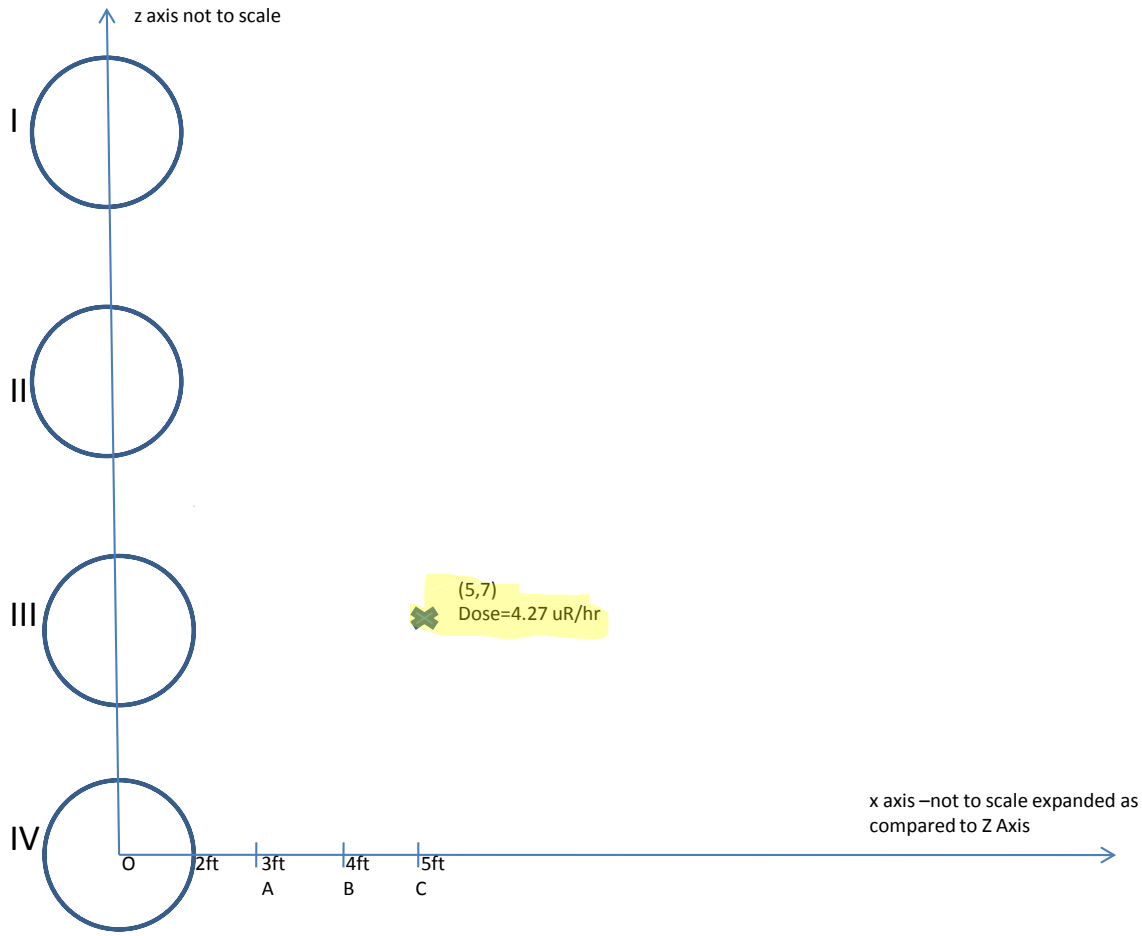

Figure 6: Configuration for Case 3 Centerline Doses (not to scale)

Table 2 below presents these doses for vessel IV as an example. To determine the final dose it was necessary to repeat the above calculation of each vessel and then add the doses at the points of interest. The final results are presented in Table 2 and Figure 7.

Table 2: Doses from Vessel IV: Radium-228 Concentration of 44 pCi/g

Point A	Point Z	Distance	Dose
ft	ft	from 0	mR/hr*E-3
3	0	3.00	44.76
3	7	7.62	5.54
3	14	14.32	1.45
3	21	21.21	0.639
PointB	Point Z	Distance	Dose
ft	ft	from 0	mR/hr*E-3
4	0	4.00	23.24
4	7	8.06	4.9
4	14	14.56	1.4
4	21	21.38	0.629
Point C	Point Z	Distance	Dose
ft	ft	from 0	mR/hr*E-3
5	0	5.00	14.01
5	7	8.60	4.27
5	14	14.87	1.34
5	21	21.59	0.617

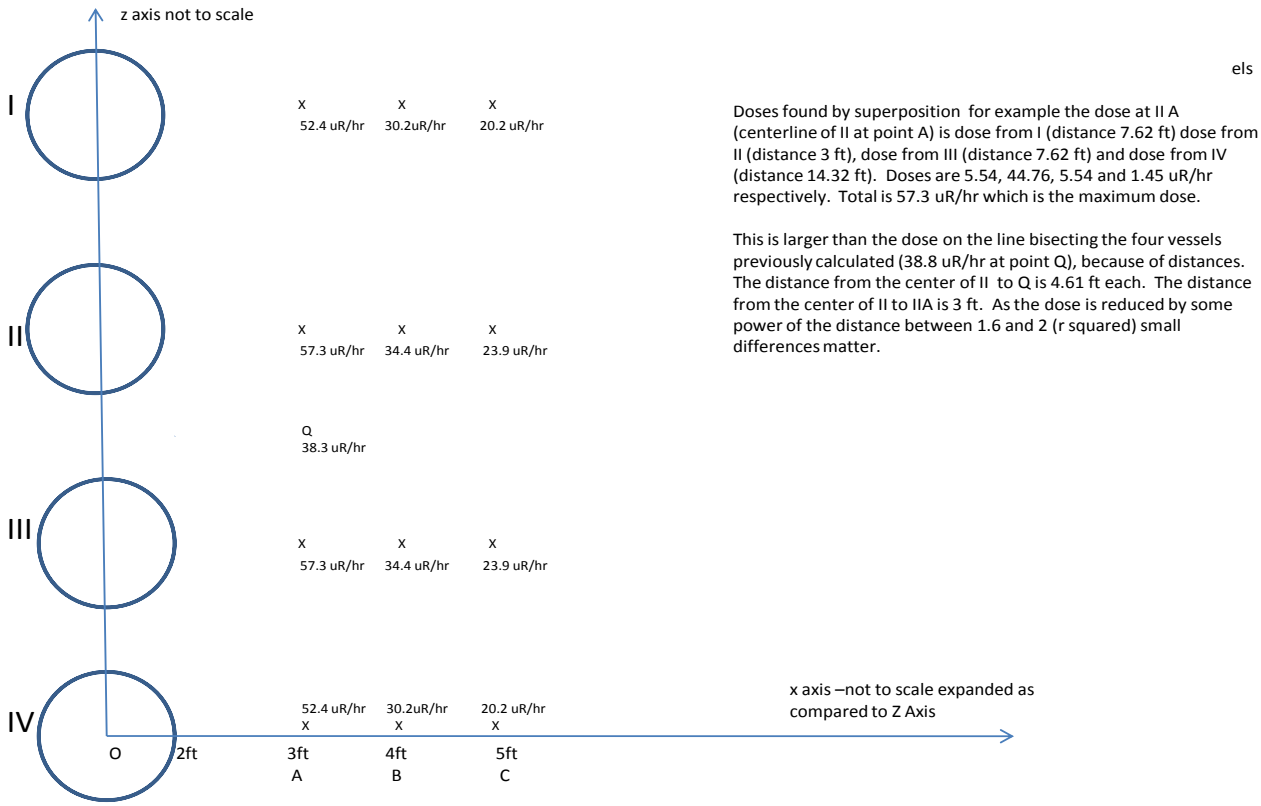

Figure 7: Configuration for Case 3 Centerline Doses (not to scale)

As discussed on the figure, the doses on the center lines are larger than the doses on the line bisecting the vessels. This is a consequence of the inverse 'power" law for distances from the sources. The dose from the closest vessel is much greater than that from other vessels whose doses fall off rapidly. Importantly, the dose in all cases drops off quickly along the centerlines - for example, the dose drops from 57.3 µR/hr to 34.4 µR/hr in one foot along the centerline of vessel III.

It should be noted that all these calculations have an inherent amount of error. This error is from numerous sources and assumptions (system configuration, interactions of the gammas from adjacent vessels, type of radionuclides, amount of radionuclides and daughters that remain in vessels, and so forth). Many of these items are too complex for the model used herein and require a Monte Carlo analysis which is very expensive, albeit very sophisticated. Monte Carlo analysis is typically used in nuclear power plants for design.

Given the above a factor of safety of two is suggested, that is reduce the time of exposure by half until measurements at actual resins are conducted. For example the exposure time at 3 feet from the centerline of vessel III is 25 mrem/yr divided by 57.3 E-3 mrem/hr or 436 hours. For conservatism, reduce the exposure to 218 hours.

Shielding is yet another factor. The shield used in a further calculation was a one foot thick concrete wall. The reduction in the dose for concrete was about a factor of ten.

4. CONCLUSIONS AND RECOMMENDATIONS

The following summarizes key conclusions from this effort:

- At concentrations that were evaluated (30, 37, and 44 pCi/g) and using the system configuration that was assumed, there will need to be limits on the amount of time spent in close proximity to the vessels (three to four feet away) to meet the standard of 25 mrem/yr identified by CDPHE.
- Dose decreases very quickly with distance from the source – approximately $1/x^{1.6}$. So, if someone does need to work in vicinity of vessels, they should generally stay 6 to 8 feet from the vessels (or further) as much as possible, and exposure should be less than the 25 mrem/yr.
- The calculations in this memo were based on conservative assumptions about configuration of vessels, size of system, and concentration of radionuclides in the resin. The calculated doses presented in this memo would likely be greater than measured in real world scenarios. One of the most conservative assumptions is that all of the gamma emitting daughters of radon were assumed to stay in the vessels (instead of some portion flowing out with the treated water stream).
- Systems that are participating in CO-RADS that have uranium treatment systems indicated that they have historically performed infrequent regeneration (if any at all). As a result, there may be significant doses to operators from one daughter product, Pa-234. Note that there is no reduction in the daughter concentration after transformation because the Pa-234 is a solid and would not travel through the liquid treated stream under routine operations (which is different than radon, for example).

Recommendations moving forward include:

- Measure the concentrations of radium in the resin of some representative existing ion exchange water treatment systems. This information can be used to confirm some of the assumptions in this analysis.
- Measure the doses (exposure) at different distances from existing ion exchange water treatment systems to evaluate the accuracy of the assumptions in this analysis.
- Additional analysis should be performed to evaluate doses from resins used to remove uranium. Specifically, doses should be measured on-site at representative systems.
- Additional information should be provided to CO-RADS systems to help system operators establish strategies to reduce worker exposure. Specifically, the information in Section 5 of this memo should be included in each system's preliminary engineering report and a discussion of the general risks associated with radionuclide treatment systems.

5. STRATEGIES TO REDUCE WORKER EXPOSURE

The following summaries some potential strategies that could be implemented to reduce worker exposure for water systems that are implementing ion exchange for the removal of radionuclides in drinking water. These items will be general considerations provided to water systems as a result of CO-RADS.

Work Practices

Minimizing the dose to workers in the vicinity of the vessels can be achieved through the three health physics variables discussed in Section 1. Again these are:

- Time
- Distance
- Shielding

Reducing the time spent has already been discussed, however, the simple practice of measuring the hourly exposure at different areas in the vicinity of the vessels when they are close to being removed would provide a check of the calculation and a template for exposure. The room could be gridded and exposures at each grid point known prior to any work in the area. A work order which limited the exposure would be created before any work in the area. The work order limits would need to be strictly adhered to.

Distance is the second item. As seen previously in all the cases considered the dose is at a point is a function of the distance from the vessels being the distance to the 1.6 power ($x^{1.6}$ where x is the distance). As seen, doses fall off quickly the further away a person would be from the vessels. For example, in the case of the resins having a concentration of 44 pCi/g of radium-226 the dose on the line bisecting the vessels is reduced from 12.4 µR/hr to 10.2 µR/hr in going from 7 to 8 feet.

The last variable is shielding. As discussed in Section 3, a one foot thick concrete wall will reduce the dose by an order of magnitude. So, one option is to separate the vessels in their own room and only have access to the vessels when specific operation/maintenance activities are necessary for the ion exchange system. Another option is to install a portable shield made of iron or steel on wheels could be used. The shield would have to be wide enough to shield gamma rays from all of the vessels. An alternative would have a smaller shield with shielding on three sides for each vessel. Given the doses calculated, the use of a shield would only be practical for situations where workers are close to the vessels for hundreds of hours, an unlikely event.

Monitoring

Monitoring is highly recommended for any situation where exposures may be above background radiation levels, both for the protection of the worker and protection of the facility operator from future litigation should the worker develop an illness. Monitoring can be done by using portable instruments such a “micro R meters” which will provide an immediate reading of the dose. These instruments are easy to use and fairly inexpensive perhaps a few hundred dollars to purchase or long term rental.

Individual exposure badges are highly recommended for those individuals expected to receive a dose above background. The most common of these are the TLDs (thermoluminescent dosimeters) or OSLDs (optically stimulated luminescent dosimeters). These are badges which are worn in the radiation area (inside the building) and provide a quarterly integrated dose. They are inexpensive, for OSLDs the more sensitive type and the one recommended for this work, the cost is about $140 per year per badge.

Exposures Outside the Building

Exposures outside the building may be estimated by assuming the wall between the vessels is a one foot concrete wall. The dose close to the wall is the same as that on the far side of a concrete shield. This dose is of the order of μR/hr or about background. It would be prudent to fence in the area to keep the public away from the area. Instead of a fence, the planting of a few bushes would increase the distance a few feet which would eliminate the dose from the vessels for all practical purposes.