Appendix B - Radionuclide Risk Assessment and Analysis Report

Colorado Department of Public Health and Environment

Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS)

Final Report Radionuclide Risk Assessment Analysis Report

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Report Prepared By:

Malcolm Pirnie, Inc.

100 Fillmore St.
Suite 200
Denver, CO 80206
Phone: 303.316.6500

5322009

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1. Introduction

1.1. CO-RADS Background

The Water Quality Control Division (WQCD) of the Colorado Department of Public Health and Environment (CDPHE) regulates public water systems (PWSs) under the Colorado Primary Drinking Water Regulations (CPDWR). The maximum contaminant levels (MCLs) the U.S. Environmental Protection Agency (EPA) has established for radionuclides have been adopted by WQCD as part of the CPDWRs. The regulated radionuclides and the corresponding MCL values are as follows:

- Gross alpha particle activity: 15 picoCuries per liter (pCi/L)
- Combined radium 226/228: 5 pCi/L
- Uranium: 30 micrograms per liter (μg/L)
- Beta and photon particle activity: 4 millirems per year (mrem/yr)

Radionuclides are naturally present in the environment, including groundwater sources. Typically, the levels of naturally occurring radioactive material (NORM) are not a significant health concern in drinking water; however, Colorado has over 40 water systems that are currently or expected to be in violation of one or more of the radionuclide MCLs. This presents a health concern for nearly 40,000 consumers.

Treatment techniques are available for the removal of these contaminants from water supplies, but for small drinking water systems, the cost of treatment and disposal may be substantial. Additionally, environmental and worker safety concerns arise from the removal of radionuclides from drinking water. NORM accumulates in treatment residuals and is classified as Technologically Enhanced Naturally Occurring Radioactive Material (TENORM). Worker exposure and disposal of these residuals is also a potential issue.

The systems affected by radionuclides in Colorado are small groundwater systems with limited resources that may struggle to find feasible compliance options. WQCD has initiated the Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) to address the issues associated with removal of radionuclides from drinking water and offer compliance and technical assistance to the communities affected by these contaminants. The ultimate goal of this project is to resolve drinking water radionuclide violations. The project has been structured to include 5 distinct phases, as outlined below:

- Phase 1 – Review existing data and identify affected systems
- Phase 2 – Sample affected sources to characterize water quality
- Phase 3 – Perform engineering analyses and pilot-studies of treatment and disposal options
- Phase 4 – Offer financial and compliance assistance to affected systems
- Phase 5 – Provide recommendations and implementation assistance for affected systems

Malcolm Pirnie, Inc. in conjunction with the Colorado School of Mines (CSM) has been contracted by WQCD to perform Phases 2 and 3. This report is one of the deliverables for Task 1 Policy Development Assistance.

1.2. CO-RADS Task 1 Objectives

As part of the CO-RADS project, CDPHE is developing policy for the following:

- The necessary degree of protection that water systems must provide, on an interim basis, before a long-term compliance option is successfully implemented; including the identification and evaluation of appropriate interim compliance measures and associated requirements.

- The ability of water systems to implement point-of-use (POU) or point-of-entry (POE) treatment technologies for long-term compliance with the Radionuclide Rule.

The goal of this radionuclide risk assessment analysis is to provide CDPHE with background information to support interim treatment policy development activities for water systems that are planning to implement longer-term solutions to address the Radionuclides Rule requirements. More information on Task 1 can be found in the Memorandum of Understanding (MOU #CD-2007-208) dated August 24, 2007. This report summarizes the methodology, results, and observations of Malcolm Pirnie's risk assessment analysis for the CO-RADS project.

2. Radionuclides Risk Assessment

2.1. Methodology

The intent of this document is to provide CDPHE with information about the incremental risk associated with radionuclides exposure that could be expected over various time periods. The intent is not to evaluate the radionuclide maximum contaminant limits (MCLs) or the methodology used to create the MCLs. However, in order to maintain consistency of techniques for this CO-RADS risk evaluation, Malcolm Pirnie applied the same general risk assessment methodology and assumptions used by the EPA to establish the Radionuclides Rule MCLs.

For this analysis, Malcolm Pirnie evaluated various exposure scenarios for radionuclides at concentrations greater than or equal to MCLs over varying time periods to determine the additional or incremental risk of developing cancer above the naturally expected cancer rate. Per the EPA's Radionuclides Rule development methodology, natural cancer incidents for the two types of risk of cancer conditions (mortality and morbidity) considered in this evaluation include:

- Development of fatal cancer (mortality): one in five (1:5) or 20%
- Development of fatal or non-fatal cancer at some time during ones lifetime (morbidity): 1:2 (50%) in men, 1:3 (33%) in women (USEPA, 2000a)

This risk evaluation included exposure of radionuclides via ingestion of drinking water, inhalation from potable water use, and consumption of vegetables irrigated with water containing radionuclides in excess of MCL.

A more detailed discussion of risks, their basis, the models used, and uncertainty in the models considered in this assessment is provided in "Cancer Risk Coefficients for Environmental Exposure to Radionuclides-Federal Guidance Report No. 13" (FGR-13) (USEPA, 1999).

As noted, the types of risk are the mortality risk (fatal cancer) or morbidity risk (fatal and non-fatal cancers), which are calculated using risk coefficients that are dependent on the type of radionuclide. These are defined as follows:

- Mortality risk coefficient - an estimate of the additional risk to an average member of the U.S. population (per unit of [radio] activity inhaled or ingested) of dying from cancer as a result of the intake of the radionuclide

- Morbidity risk coefficient - an estimate of the additional risk to an average member of the U.S. population (per unit of [radio] activity inhaled or ingested) of experiencing a radiogenic cancer, whether or not the cancer is fatal

FGR-13 contains a compilation of mortality and morbidity risk coefficients, allowing calculation of the risk associated with a given exposure time and concentration of a radionuclide. The risk calculations provided in this report assume water ingestion of two (2) liters/day (L/d) for 365.4 days/year (d/y), resulting in the following equation:

$$Risk = Rad.Conc.(pCi/L) \times 2\ L/d \times 365.4\ d/y \times ingestion\ \ period\ (y) \times risk\ coefficient\ (risk/pCi)$$

That is, the additional cancer risk associated with a radionuclide intake or external exposure is calculated as the product of the appropriate cancer risk coefficient and the corresponding radionuclide intake or exposure. EPA used the coefficients in FGR-13 to set the MCLs for radionuclides in drinking water.

The risk coefficients in FGR-13 were based on state-of-the-art methods and models that take into account age and gender dependence of intake, metabolism, dosimetry, and radiogenic risk for internal exposures to radionuclides. Therefore, they reflect average risks in large populations from low doses or exposures over long periods of time and should not be applied to high doses over short periods (acute doses). For purposes of this work, exposures periods of greater than six months to radionuclides at concentrations less than or equal to10 times MCL were considered.

EPA considers an incremental or additional risk range of 10^{-6} to 10^{-4} when establishing national primary drinking water regulations, where EPA's "target ceiling" additional risk for radionuclides is 10^{-4}. The decision to set an MCL at this level that is based on available and affordable treatment or compliance options to reduce the contaminant and the associated risk. Ultimately, the MCL is based on maximizing health risk reduction benefits at a cost that is justified by the benefits (cost benefit analysis). Numerically, this would increase the normal mortality cancer risk from 20 percent to 20.0001 percent (20 plus 10^{-4}), a number which manifests itself when multiplying by large aggregates of people and can be used in the determination of cost benefit for the nation.

To set the MCLs for gross alpha and combined radium, the EPA used combinations of the mortality and morbidity risk coefficients for various radionuclides. For the gross alpha MCL, EPA used an averaged weighted risk coefficient from FGR-13 composed of the risk coefficients for Ra-226 and Ra-224. That average was weighted by the relative prevalence of Ra-224 and Ra-226 (USEPA, 2000b and 2000c) in drinking water supplies as compiled through EPA's National Inorganics and Radionuclides Survey (NIRS) carried out in the 1990's. The selection of Ra-224 and Ra-226 for gross alpha is discussed in the latter reference. To establish the combined radium MCL (Ra-226 and Ra-228), EPA again used a weighted average of the risk coefficients of these two radionuclides based on NIRS data.

The averaged risk coefficients used for gross alpha and combined radium, and the risk coefficients for uranium are provided in Table 1 below.

Table 1. Radionuclide risk coefficients

Radionuclide	Mortality Risk Coefficient (per pCi)	Morbidity Risk Coefficient (per pCi)
Gross Alpha	1.14×10^{-10}	1.83×10^{-10}
Combined Radium	5.66×10^{-10}	8.03×10^{-10}
Uranium	4.40×10^{-11}	6.81×10^{-11}

Ingestion risks were calculated at the MCL, 2×MCL, and 10×MCL for exposure periods ranging from 6 months to 70 years, assuming consumption of 2 liters of water per day.

Malcolm Pirnie evaluated the exposure to radionuclides via ingestion of vegetables raised with water contaminated with radionuclides. It was assumed an individual has a garden and consumes all of the vegetables from the garden. Using the methodology presented in the Department of Energy's Risk Assessment Information System (), Malcolm Pirnie estimated that the radium ingestion rate due to vegetation consumption from home gardens irrigated with tap water is less than 3% of that from drinking the same tap water; therefore, incremental associated with ingestion of vegetables was not further evaluated.

Finally, Malcolm Pirnie evaluated the inhalation of radon from tap water contaminated with radionuclides. In 1999 EPA conducted a review of exposure to radon (Federal Register Vol 64, 38, February 26 1999 pg 9560) and concluded that tap water contributes about 2% of the radon in homes and that the lifetime mortality risk is 6.25×10^{-7} per pCi/L of radon in tap water. In general, the amount of radon in water varies considerably and is composed of radon from radium in the soil and radium dissolved in the water. For this report, Malcolm Pirnie only considered radium at equilibrium with radon in water. Thus, 5 pCi/L of radium-226 would provide 5 pCi/L of radon-222. The resulting lifetime risk is then 3.2×10^{-6}, two orders of magnitude lower than ingestion of radium at 5 pCi/L for a lifetime (1.45×10^{-4}). Thus, the contribution of radon due to radionuclide contaminated water is minimal and was not further evaluated. It is noted that EPA did not promulgate any concentration limits for radon. Radon from the thorium chain (radon-220 from the decay of radium-228) was considered insignificant in this evaluation, as its half-life is 55 seconds and would quickly decay.

2.2. Risk Evaluation Results

Risks associated with ingestion of combined radium, gross alpha, and uranium for the concentrations and exposure periods discussed above are provided in Tables 2-4. The gray area represents concentrations which result in risks that exceed the EPA's target ceiling risk for ingestion. EPA's risk for ingestion of a radionuclide is calculated as described above, assuming ingestion of the MCL (at 2 liters per day) for 70 years. It is noted that the resulting risks are the same order of magnitude as the EPA's target ceiling risk (10^{-4}); however, the actual value is different for each radionuclide.

Table 2 Incremental risk of developing cancer from ingestion of combined radium in drinking water*

Ingestion Period (years)	Liters Ingested liters	pCi of Rad Ingested at 1*MCL (5 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])	pCi of Rad Ingested at 2*MCL (10 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])	pCi of Rad Ingested at 10*MCL (50 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])
0.5	365	1,825	1.03E-06	1.47E-06	3,650	2.07E-06	2.93E-06	18,250	1.03E-05	1.47E-05
1	730	3,650	2.07E-06	2.93E-06	7,300	4.13E-06	5.86E-06	36,500	2.07E-05	2.93E-05
2	1,460	7,300	4.13E-06	5.86E-06	14,600	8.26E-06	1.17E-05	73,000	4.13E-05	5.86E-05
3	2,190	10,950	6.20E-06	8.79E-06	21,900	1.24E-05	1.76E-05	109,500	6.20E-05	8.79E-05
4	2,920	14,600	8.26E-06	1.17E-05	29,200	1.65E-05	2.34E-05	146,000	8.26E-05	1.17E-04
5	3,650	18,250	1.03E-05	1.47E-05	36,500	2.07E-05	2.93E-05	182,500	1.03E-04	1.47E-04
6	4,380	21,900	1.24E-05	1.76E-05	43,800	2.48E-05	3.52E-05	219,000	1.24E-04	1.76E-04
7	5,110	25,550	1.45E-05	2.05E-05	51,100	2.89E-05	4.10E-05	255,500	1.45E-04	2.05E-04
8	5,840	29,200	1.65E-05	2.34E-05	58,400	3.31E-05	4.69E-05	292,000	1.65E-04	2.34E-04
9	6,570	32,850	1.86E-05	2.64E-05	65,700	3.72E-05	5.28E-05	328,500	1.86E-04	2.64E-04
10	7,300	36,500	2.07E-05	2.93E-05	73,000	4.13E-05	5.86E-05	365,000	2.07E-04	2.93E-04
11	8,030	40,150	2.27E-05	3.22E-05	80,300	4.54E-05	6.45E-05	401,500	2.27E-04	3.22E-04
12	8,760	43,800	2.48E-05	3.52E-05	87,600	4.96E-05	7.03E-05	438,000	2.48E-04	3.52E-04
13	9,490	47,450	2.69E-05	3.81E-05	94,900	5.37E-05	7.62E-05	474,500	2.69E-04	3.81E-04
14	10,220	51,100	2.89E-05	4.10E-05	102,200	5.78E-05	8.21E-05	511,000	2.89E-04	4.10E-04
15	10,950	54,750	3.10E-05	4.40E-05	109,500	6.20E-05	8.79E-05	547,500	3.10E-04	4.40E-04
35	25550	127750	7.23E-05	1.03E-04	255500	1.45E-04	2.05E-04	1277500	7.23E-04	1.03E-03
70	51100	255500	1.45E-04	2.05E-04	511000	2.89E-04	4.10E-04	2555000	1.45E-03	2.05E-03

*Shaded gray cells represent concentrations and ingestion periods which result in risks that exceed the EPA's "ceiling" mortality risk of 1.45e-04 and morbidity risk of 2.05e-04 that are based on ingesting the MCL for 70 years.

[1] Mortality refers to the incremental additional risk of developing a fatal cancer, above the average rate, as a result of the intake of radionuclides

[2] Morbidity refers to the incremental risk of developing a cancer ,fatal or non-fatal, above the average rate, from the intake of radionuclides

Table 3 Incremental risk of developing cancer from ingestion of gross alpha in drinking water*

Ingestion Period (years)	Liters Ingested liters	pCi of Rad Ingested at 1*MCL (15 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])	pCi of Rad Ingested: 2*MCL (30 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])	Rad Ingested at 10*MCL (150 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])
0.5	365	5,475	6.24E-07	4.40E-06	10,950	1.25E-06	8.79E-06	54,750	6.24E-06	4.40E-05
1	730	10,950	1.25E-06	8.79E-06	21,900	2.50E-06	1.76E-05	109,500	1.25E-05	8.79E-05
2	1,460	21,900	2.50E-06	1.76E-05	43,800	4.99E-06	3.52E-05	219,000	2.50E-05	1.76E-04
3	2,190	32,850	3.74E-06	2.64E-05	65,700	7.49E-06	5.28E-05	328,500	3.74E-05	2.64E-04
4	2,920	43,800	4.99E-06	3.52E-05	87,600	9.99E-06	7.03E-05	438,000	4.99E-05	3.52E-04
5	3,650	54,750	6.24E-06	4.40E-05	109,500	1.25E-05	8.79E-05	547,500	6.24E-05	4.40E-04
6	4,380	65,700	7.49E-06	5.28E-05	131,400	1.50E-05	1.06E-04	657,000	7.49E-05	5.28E-04
7	5,110	76,650	8.74E-06	6.15E-05	153,300	1.75E-05	1.23E-04	766,500	8.74E-05	6.15E-04
8	5,840	87,600	9.99E-06	7.03E-05	175,200	2.00E-05	1.41E-04	876,000	9.99E-05	7.03E-04
9	6,570	98,550	1.12E-05	7.91E-05	197,100	2.25E-05	1.58E-04	985,500	1.12E-04	7.91E-04
10	7,300	109,500	1.25E-05	8.79E-05	219,000	2.50E-05	1.76E-04	1,095,000	1.25E-04	8.79E-04
11	8,030	120,450	1.37E-05	9.67E-05	240,900	2.75E-05	1.93E-04	1,204,500	1.37E-04	9.67E-04
12	8,760	131,400	1.50E-05	1.06E-04	262,800	3.00E-05	2.11E-04	1,314,000	1.50E-04	1.06E-03
13	9,490	142,350	1.62E-05	1.14E-04	284,700	3.25E-05	2.29E-04	1,423,500	1.62E-04	1.14E-03
14	10,220	153,300	1.75E-05	1.23E-04	306,600	3.50E-05	2.46E-04	1,533,000	1.75E-04	1.23E-03
15	10,950	164,250	1.87E-05	1.32E-04	328,500	3.74E-05	2.64E-04	1,642,500	1.87E-04	1.32E-03
35	25550	383250	4.37E-05	3.08E-04	766500	8.74E-05	6.15E-04	3832500	4.37E-04	3.08E-03
70	51100	766500	8.74E-05	6.15E-04	1533000	1.75E-04	1.23E-03	7665000	8.74E-04	6.15E-03

*Shaded gray cells represent concentrations and ingestion periods which result in risks that exceed the EPA's "ceiling" mortality risk of 8.74e-05 and morbidity risk of 6.15e-04 that are based on ingesting the MCL for 70 years.

[1] Mortality refers to the incremental additional risk of developing a fatal cancer, above the average rate, as a result of the intake of radionuclides

[2] Morbidity refers to the incremental risk of developing a cancer ,fatal or non-fatal, above the average rate, from the intake of radionuclides

Table 4 Incremental risk of developing or cancer from ingestion of uranium in drinking water*

Ingestion Period (years)	Liters Ingested liters	pCi of Rad Ingested at 1*MCL (27 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])	pCi of Rad Ingested at 2*MCL (54 pCi/L)	Risk (mortality[1])	Risk (morbidity[2])	pCi of Rad Ingested at 10*MCL 270 pCi/L	Risk (mortality[1])	Risk (morbidity[2])
0.5	365	9,855	4.34E-07	6.71E-07	19,710	8.67E-07	1.34E-06	98,550	4.34E-06	6.71E-06
1	730	19,710	8.67E-07	1.34E-06	39,420	1.73E-06	2.68E-06	197,100	8.67E-06	1.34E-05
2	1,460	39,420	1.73E-06	2.68E-06	78,840	3.47E-06	5.37E-06	394,200	1.73E-05	2.68E-05
3	2,190	59,130	2.60E-06	4.03E-06	118,260	5.20E-06	8.05E-06	591,300	2.60E-05	4.03E-05
4	2,920	78,840	3.47E-06	5.37E-06	157,680	6.94E-06	1.07E-05	788,400	3.47E-05	5.37E-05
5	3,650	98,550	4.34E-06	6.71E-06	197,100	8.67E-06	1.34E-05	985,500	4.34E-05	6.71E-05
6	4,380	118,260	5.20E-06	8.05E-06	236,520	1.04E-05	1.61E-05	1,182,600	5.20E-05	8.05E-05
7	5,110	137,970	6.07E-06	9.40E-06	275,940	1.21E-05	1.88E-05	1,379,700	6.07E-05	9.40E-05
8	5,840	157,680	6.94E-06	1.07E-05	315,360	1.39E-05	2.15E-05	1,576,800	6.94E-05	1.07E-04
9	6,570	177,390	7.81E-06	1.21E-05	354,780	1.56E-05	2.42E-05	1,773,900	7.81E-05	1.21E-04
10	7,300	197,100	8.67E-06	1.34E-05	394,200	1.73E-05	2.68E-05	1,971,000	8.67E-05	1.34E-04
11	8,030	216,810	9.54E-06	1.48E-05	433,620	1.91E-05	2.95E-05	2,168,100	9.54E-05	1.48E-04
12	8,760	236,520	1.04E-05	1.61E-05	473,040	2.08E-05	3.22E-05	2,365,200	1.04E-04	1.61E-04
13	9,490	256,230	1.13E-05	1.74E-05	512,460	2.25E-05	3.49E-05	2,562,300	1.13E-04	1.74E-04
14	10,220	275,940	1.21E-05	1.88E-05	551,880	2.43E-05	3.76E-05	2,759,400	1.21E-04	1.88E-04
15	10,950	295,650	1.30E-05	2.01E-05	591,300	2.60E-05	4.03E-05	2,956,500	1.30E-04	2.01E-04
35	25550	689850	3.04E-05	4.70E-05	1379700	6.07E-05	9.40E-05	6898500	3.04E-04	4.70E-04
70	51100	1379700	6.07E-05	9.40E-05	2759400	1.21E-04	1.88E-04	13797000	6.07E-04	9.40E-04

*Shaded gray cells represent concentrations and ingestion periods which result in risks that exceed the EPA's "ceiling" mortality risk of 6.07e-05 and morbidity risk of 9.40e-05 that are based on ingesting the MCL for 70 years.

[1] Mortality refers to the incremental additional risk of developing a fatal cancer, above the average rate, as a result of the intake of radionuclides

[2] Morbidity refers to the incremental risk of developing a cancer ,fatal or non-fatal, above the average rate, from the intake of radionuclides

A summary of the exposure times that result in the EPA's "target ceiling risk" for ingestion of combined radium, gross alpha, and uranium at their respective MCLs, 2×MCL, and 10×MCL are provided in Table 5.

Table 5. Ingestion periods at various radionuclide concentrations that result in the EPA's target ceiling risk

Radionucliude	Exposure Time, years		
	MCL	2×MCL	10×MCL
Combined Radium	70	35	7
Gross Alpha	70	35	7
Uranium	70	35	7

2.3. Observations

Some observations from the radionuclides risk assessment include:

- Any exposure to radionuclides in water is associated with an increased risk of cancer. EPA has determined that the concentrations at the MCL over 70 years results in an additional risk which is below their "target ceiling." Once a person reaches the "target ceiling" exposure (from all sources of radionuclides), then their exposure to radionuclides for the remainder of their life would have to be limited to zero to stay below the EPA's "target ceiling" risk.

- Risk of cancer associated with ingestion of vegetables watered with water contaminated with radionuclides is, on average, 2 orders of magnitude lower than risk associated with ingestion of radionuclides from drinking water. As a result, ingestion of water is the exposure route that WQCD should be most concerned with in regards to the interim health protection measures.

- Risk of cancer associated with inhalation of radionuclides was considered by EPA and determined to be minimal in comparison to ingestion. Consequently, radon was not incorporated into the Radionuclides Rule.

- The concentration of radionuclides in water directly correlates to the increased health risk to the consumer. As such, water systems that provide water with higher concentrations of contaminants will have customers at a proportionally higher risk than water systems with lower concentrations for the same type of contamination. In addition to concentration, time is a critical component of the risk calculation. The amount of time consumers drink water with elevated radionuclides concentrations is directly proportional to their health risk. It is also evident that these risks are small incremental increases to the natural risk of developing a cancer.

- The risk assessment methodology used by the EPA to establish drinking water MCLs (and subsequently used for this evaluation) uses several assumptions, including volume of water consumed per day, standard man, and lifespan. In the case of water systems that serve populations that do not match those assumptions, consumers may have higher or lower risks associated with interim exposure to concentrations of radionuclides that are above the MCLs. However these variations are expected to be less than an order of magnitude.

- The EPA established the Radionuclide Rule MCLs by evaluating the risks associated with each separate contaminant and did not account for potential increased public health risks associated with having more than one contaminant at a time.

3. References

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