Colorado Department of Public Health and Environment

4300 Cherry Creek Drive South • Building B-2 • Denver, CO 80202

Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) Phase 2 and 3 Summary Report

March 2009

Report Prepared By:

Malcolm Pirnie, Inc.

100 Fillmore Street
Suite 200
Denver, CO 80206
303-316-6500

MALCOLM PIRNIE

Contents

1. Executive Summary 1-1

2. Introduction and Background 2-1

2.1. CO-RADS Project Background 2-1
2.2. Radionuclides in Drinking Water 2-3
2.2.1. Health Effects 2-5
2.3. Characteristics of CO-RADS Systems 2-5

3. Project Purpose and Methodology 3-1

3.1. Task 1: Policy and Interim Measures 3-1
3.2. Task 2: Water Quality Sampling 3-3
3.3. Task 3: Radionuclides Rule Compliance Alternatives 3-5
3.4. Task 4: Worker Safety and Waste Handling 3-6
3.5. Task 5: Bench and Pilot Testing 3-8
3.6. Task 6: CO-RADS Reports 3-9
3.6.1. Utility Representatives Group – Forum for Systems to Provide Input 3-10
3.6.2. CO-RADS Compliance Alternatives Evaluation 3-10
3.6.3. Opinions of Probable Cost of Defined Alternatives 3-11

4. CO-RADS Results 4-1

4.1. Task 1: Policy and Interim Measures 4-1
4.2. Task 2: Water Quality Sampling 4-9
4.3. Task 3: Radionuclides Rule Compliance Alternatives 4-13
4.3.1. Treatment Alternatives 4-13
4.3.2. Liquid Residuals Disposal Options 4-19
4.3.3. Proprietary Solutions 4-21
4.3.4. Non-Treatment Alternatives 4-22
4.4. Task 4: Residuals Handling and Disposal and Worker Exposure 4-23
4.4.1. Monitoring and Mitigating Worker Exposure 4-24
4.5. Task 5: Bench and Pilot Testing 4-25
4.6. Task 6: CO-RADS Reports 4-29
4.6.1. Fundamental Assumptions and Summary of Defined Alternatives 4-30
4.6.2. CO-RADS Costs Compared to EPA Costs 4-34

5. CO-RADS Observations 5-1

5.1. Field Observations 5-1
5.2. Impact of CO-RADS Assumptions on Costs 5-4
5.3. Water Quality Challenges 5-4

6. Recommendations 6-1

7. References 7-1

List of Tables

Table 2-1. CO-RADS Systems – Population Served, Private/Non-Private, and Primary Contact 2-3
Table 3-1. List of Water Quality Parameters Measured in CO-RADS Sampling 3-4
Table 3-2. List of 20 Metals 3-5
Table 3-3. Characteristics of Source Water Tested in Bench and Pilot Testing 3-8
Table 3-4. Source Water and Technologies Tested in Bench and Pilot Tests............................ 3-9
Table 3-5. Description of CO-RADS Compliance Alternative Evaluation Criteria and Weights Used in Alternatives Analysis 3-11
Table 4-1 Detailed Comparison of Potential Interim Compliance Measures 4-2
Table 4-2. Selected Summary of States' POU/POE Policies as of October 2007 4-7
Table 4-3. Concentrations of Water Quality Parameters that Can Impact Water Treatment Determinations: Average, Minimum and Maximum Concentrations Measured in All CO-RADS Systems' Source Waters 4-12
Table 4-4. Radionuclides Treatment Alternatives 4-13
Table 4-5. Potential CO-RADS Treatment Technologies... 4-16
Table 4-6. Summary of Treatment Technologies Evaluated for CO-RADS.............................. 4-18
Table 4-7. Summary of Feasibility of Liquid Residuals Disposal Options 4-20
Table 4-8. Summary of CO-RADS Bench- and Pilot-Scale Testing Results 4-26
Table 4-9. Comparison of a PER and the CO-RADS Reports 4-29
Table 4-10. Summary of Defined Alternatives for CO-RADS Systems..................................... 4-31
Table 4-11. Primary Differences in EPA and CO-RADS Cost Development Assumptions 4-35
Table 4-12. Comparison of EPA and CO-RADS Cost Estimates for Complying with the Radionuclides Rule.. 4-37
Table 6-1. Recommendations Based on CO-RADS Work.. 6-1

List of Figures

Figure 2-1. CO-RADS System Locations and Type of Radionuclide Contamination.................. 2-2
Figure 2-2. Illustration of a Radioactive Atom 2-4
Figure 2-3. Distribution of CO-RADS Systems by Population Served 2-6
Figure 2-4. Portion of CO-RADS Systems that are Privately or Publicly Owned Utilities 2-7
Figure 2-5. Median Household Income in Counties Represented by CO-RADS Systems.......... 2-8
Figure 4-1. Number of CO-RADS Systems with One or More Sources Exceeding the Radionuclides Rule MCLs Based on One CO-RADS Water Quality Sampling Event at Each System.. 4-9
Figure 4-2. Combined Radium Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples 4-10
Figure 4-3. Uranium Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples 4-11
Figure 4-4. Adjusted GAA Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples 4-11
Figure 4-5. Radon-222 Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples 4-12
Figure 4-6. Relative capital cost of concentrate management options (AWWA, 2007) 4-19
Figure 4-7. Summary of Treatment Processes Defined for CO-RADS Systems 4-34
Figure 4-8. Comparison of Opinions of Probable Cost for Radionuclides Rule Compliance Developed through CO-RADS and by EPA (N=27) 4-38

Figure 5-1. Evaporation Basin where Liquid Residuals from Radionuclide Treatment are Discharged at one of the CO-RADS Systems 5-2
Figure 5-2. Picture of a CO-RADS System's Discharge of Spent Filter Backwash to the Ground5-3
Figure 5-3. Comparison of Estimated Costs for a Generic 100 gpm Cation Exchange Treatment System to Treat Water with Two Different Hardness Concentrations 5-5

Appendices

A. Contact Information for CO-RADS Systems
B. Radionuclide Risk Assessment and Analysis Report
C. Interim Measures and Point-of-Use and Point-of-Entry Treatment Evaluation Report
D. Water Sampling and Travel Plan
E. Treatment Technology Feasibility Evaluation Memorandum
F. Worker Exposure Memorandum
G. Bench and Pilot Testing Plan
H. Task 1 Policy Workshop Presentation Slides
I. Regionalization Matrix
J. Bench and Pilot Testing Report
K. Additional Information on Compliance Alternatives Included in CO-RADS Reports
L. EPA Estimates of Capital and O&M Costs for Defined Alternatives
M. Analysis of Impact of CO-RADS Costs on User Fees and Portion of Median Household Income
N. Portion of CO-RADS Costs for Evaporation Basin and Labor
O. Updated TENORM Liquid Residuals Flow Chart
P. Technical Memorandum: Results of Residuals Sampling at CO-RADS Systems

Definitions, Acronyms, and Abbreviations

AACE	Association for the Advancement of Cost Engineering
ABS	acrylonitrile butadiene styrene
BAT	best available technology
CDPHE	Colorado Department of Public Health and Environment
CHDT	Clean Harbors Deer Trail
CO-RADS	Colorado Radionuclide Abatement and Disposal Strategy
CPDWR	Colorado Primary Drinking Water Regulations
CSM	Colorado School of Mines
DO	dissolved oxygen
DWRF	Drinking Water Revolving Fund

gpm	gallons per minute
lbs	pounds
LLRW	low level radioactive waste
MCL	maximum contaminant level
mg/L	milligrams per liter
mg/L	micrograms per liter
mgd	million gallons per day
mrem/yr	millirems per year
NA	not available
NaCl	sodium chloride
NaOCl	sodium hypochlorite
NF	nanofiltration
NORM	naturally occurring radioactive material
NPV	net present value
NRC	nuclear regulatory commission
NTU	nephelometric turbidity units
ORC	operator in responsible charge
OSLD	optically stimulated luminescent dosimeters
pCi/L	picocuries per liter
POTW	publicly owned treatment works
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RMW	Residuals Management Workgroup
RO	reverse osmosis
SBA	strong base anion
SMCL	secondary maximum contaminant level
SSCT	small system compliance technology
TENORM	technologically enhanced naturally occurring radioactive material
TLD	thermoluminescent dosimeter
TMF	technical, managerial, and financial
URG	Utility's Representatives Group

USEPA	United States Environmental Protection Agency
WQCD	Water Quality Control Division

1. Executive Summary

The following executive summary has been developed as a standalone document, capable of being removed from the report for individual disposal.

Colorado Department of Public Health and Environment

Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS)

Executive Summary: CDPHE helps small water systems achieve Radionuclides Rule compliance

Background

In order to protect public health, the United States Environmental Protection Agency (USEPA) established drinking water standards for several radioactive contaminants as part of the Radionuclides Rule (established in 1976 and revised in 2000). The maximum contaminant levels (MCLs) include:

- Adjusted gross alpha activity (GAA): 15 pCi/L
- Combined radium 226/228: 5 pCi/L
- Uranium: 30 µg/L
- Beta and photon particle activity: 4 mrem/year

The Water Quality Control Division (WQCD) of the Colorado Department of Public Health and Environment (CDPHE) adopted these MCLs as part of the Colorado Primary Drinking Water Regulations (CPDWRs). Over 40 water systems in Colorado are affected by radionuclides and struggle to achieve one or more of those MCLs. Those systems all use groundwater and most of them serve small communities that are primarily located in rural areas of the State. The locations and sizes of the 33 systems participating in CO-RADS are illustrated in Figure 1.

In order to proactively assist those small, struggling communities, WQCD launched the Colorado Radionuclides Abatement and Disposal Strategy (CO-RADS) project to offer compliance and technical assistance at no charge. The ultimate goal of the CO-RADS project is to resolve drinking water radionuclide violations and further protect public health of Colorado residents. There are five phases to CO-RADS:

- **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 -** Build technical, managerial, and financial capacity
- **Phase 5 -** Provide assistance to systems during

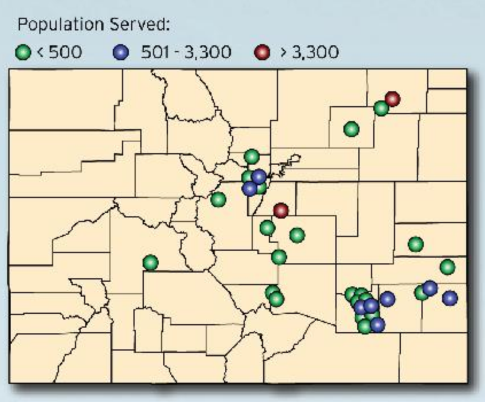


Figure 1: Locations and Sizes of CO-RADS Systems

Over the last two years, CDPHE contracted Malcolm Pirnie, Inc. (Pirnie) to assist with Phases 2 and 3. This Executive Summary presents an overview of the seven tasks performed through Phase 3 of CO-RADS. The progression of tasks is shown in Figure 2.

Figure 2: CO-RADS Tasks Performed by Malcolm Pirnie

Project Overview

Pirnie performed seven tasks as part of CO-RADS Phase 3. The following summarizes the primary activities performed for each task and the major outcomes from each task. Details of this project are included in the CO-RADS Final Project Report (March 2009).

Summary of CO-RADS Phase 3 Results

Description:	Major Outcome(s):
Task 1: Policy Development	
Pirnie assisted CDPHE with research to support policy related to interim RadionuclidesRule compliance and use of point-of-use/point-of-entry POU/POE (POU/POE) treatment for compliance.	• Using information provided by Pirnie, CDPHE is in the process of defining policy for POU/POE treatment and bottled water usage for long-term and interim compliance with the Radionclides Rule.
Task 2: Source Water Sampling	
Pirnie collected and analyzed water quality data for the CO-RADS systems to characterize their source waters to support compliance evaluations and treatment decisions.	• CO-RADS systems received a full analysis of their source waters, including radionuclides. Many systems had little or no analytical information to support decision making prior to CO-RADS.
Task 3: Treatment Evaluations	
Pirnie researched and analyzed treatment options for compliance with the Radionuclides Rule	• Each CO-RADS system received a defined treatment compliance alternative that will confidently provide water in compliance with the Radionuclides Rule. • CO-RADS systems also received substantial information on alternative radionuclides treatment options, including treatment efficacy, residuals, and operator certification requirements
Task 4: Worker Safety and Waste Disposal Evaluations	
Pirnie performed worker safety and disposal evaluations to characterize waste streams and determine the potential exposure of workers to radionuclides by working around radionuclide treatment systems and handling wastes from these systems.	• Pirnie and CDPHE developed a preferred method of treating liquid residuals. Liquid residuals from radionuclide treatment systems will be treated in a concrete-lined evaporation basin. • Pirnie conducted modeling to estimate and mitigate worker exposure around radionuclide treatment technologies. • CO-RADS systems received a residuals management plan template that was reviewed by CDPHE.

Task 5: Bench-top and Pilot-scale Studies	
Description:	**Major Outcomes:**
Pirnie worked with the Colorado School of Mines (CSM) to develop and conduct bench- and pilot-scale studies on treatment technologies for removing radionuclides from drinking water.	• Pirnie/CSM confirmed the ability of various EPA approved technologies to remove radionuclides from Colorado source waters. • Results of Pirnie/CSM bench-and pilot-testing can assist CO-RADS systems evaluate technologies and design treatment systems for compliance with the Radionuclides Rule.

Tasks 6 & 7: CO-RADS Reports and Project Report	
Description:	**Major Outcomes:**
Pirnie developed 33 system-specific CO-RADS reports - one for each participating system. Each report met the requirements of a Preliminary Engineering Report, as defined by the State Revolving Fund application requirements. Pirnie also developed a final project report.	• Each CO-RADS system received a CO-RADS Report with cost estimates and a preliminary design of a treatment system, as well as information on other treatment and non-treatment compliance alternatives. • This CO-RADS project report summarizes the work conducted through CO-RADS.

CO-RADS Compliance Alternatives

Pirnie defined a treatment compliance alternative for all CO-RADS systems, with the exception of those that already had treatment for radionuclides in place. The compliance alternative specified a treatment alternative that Pirnie and CDPHE are confident can help the water system comply with the Radionuclides Rule. However, due to the nature of the CO-RADS project, Pirnie could not evaluate every compliance option that a community may want to consider. As such, CO-RADS systems may elect to further evaluate compliance options and identify a preferred option. Total opinions of probable cost for the defined alternatives (capital, 20-year O&M, net present value (NPV)) as illustrated in Figure 3.

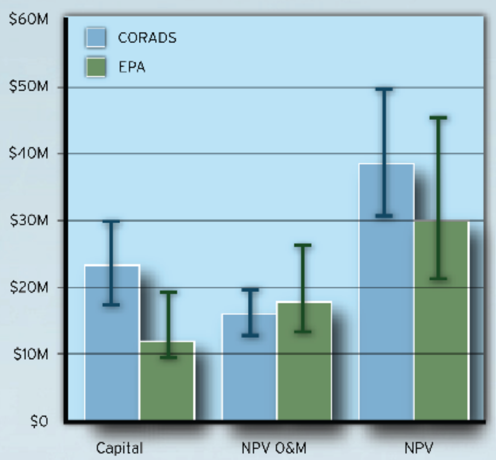


Figure 3: Opinion of Probable Costs for Radionuclide Treatment for 27 Systems

Pirnie also estimated the specific cost impact, per household, of the defined alternatives on each water system as a percentage of the median household incomes in each CO-RADS county. Results indicated the cost of the CO-RADS defined alternatives represent a cost increase of between 0.4% to 23.3% of median household incomes for each community, with an average of 4.7%.

The following are some items that CO-RADS systems were directed to further evaluate, if appropriate:

- Regionalization compliance options
- POU/POE treatment for very small communities
- Source water blending or development of a new source
- Proprietary solutions

In addition, several decisions made through CO-RADS impacted costs. Systems may find ways to reduce costs through the design phase of the project. Some specific examples include:

- Residuals disposal strategies
- Treatment redundancy
- O&M labor costs

Radionuclide Residuals

The primary challenge with treating waters containing radionuclides is handling and disposal of the solid and liquid residuals produced from the treatment processes. Because these residuals contain high levels of radionuclides, they must be carefully, handled and disposed of to avoid worker exposure and contamination issues. Several disposal options were researched as part of CO-RADS:

- Discharge to groundwater, surface water or sewer
- Evaporation basins or deep well injection
- Brine concentration (zero-liquid discharge (ZLD))
- Spray irrigation

With the exception of evaporation basins, disposal options could not be fully evaluated through CO-RADS due to the need for site-specific evaluations and permitting issues. Pirnie worked with CDPHE to devise a preferred process for treating the liquid residuals. It was assumed in the CO-RADS reports that liquid residuals would be treated in a concrete-lined evaporation basin constructed on-site (see details in project report). CO-RADS systems should evaluate alternative disposal options as they progress through the design phases of their projects.

Moving Forward

CO-RADS systems will need to work with CDPHE as they move forward to select and implement a compliance alternative. The CO-RADS reports provided to the systems provide a considerable amount of information on the defined compliance alternatives, as well as other potential compliance alternatives the systems may choose to further evaluate. Systems will need assistance selecting a compliance alternative and working towards implementing the alternative.

Building TMF Capacity

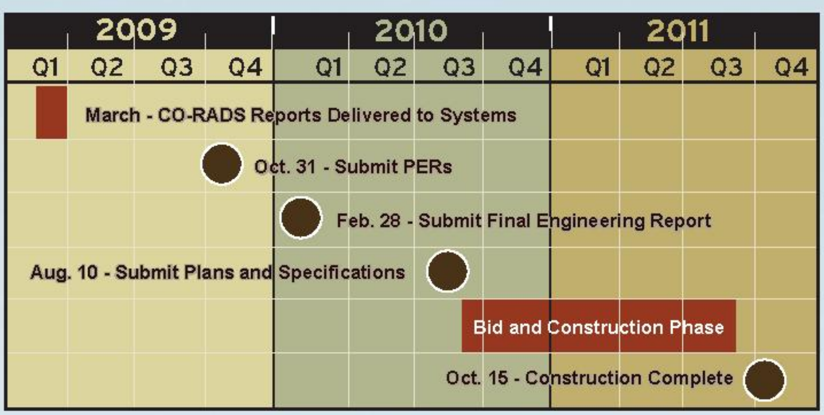
Cost of compliance is not the only challenge facing CO-RADS systems. Based on Pirnie's high-level technical, managerial, and financial, (TMF) evaluation conducted as part of CO-RADS, it appears many CO-RADS systems have significant TMF capacity challenges that need to be addressed in order to successfully comply with the Radionuclides Rule. Specifically, a majority of the systems lack the appropriate level of staffing, funding, and businesses processes to operate and manage their water systems.

CO-RADS systems will likely need some assistance building TMF capacity to select and implement a compliance alternative. In addition, demonstration of TMF capacity is required for funding from the State's Drinking Water Revolving Fund (DWRF). Pirnie recommends CO-RADS systems participate in CDPHE's TMF capacity development program to achieve TMF capacity and successfully achieve Radionuclides Rule compliance.

Technical, Managerial and Financial Issues are Interlocked

Compliance Schedule

Deadlines for submitting deliverables to CDPHE throughout the CO-RADS process are shown in the schedule below. Systems have approximately six months after they receive their CO-RADS Reports to select a compliance alternative, develop their preliminary engineering report (PER), and submit it to CDPHE. CDPHE's compliance schedule requires systems to achieve Radionuclides Rule compliance by October 2011.



MALCOLM PIRNIE
Solutions for Life™

2. Introduction and Background

2.1. CO-RADS Project Background

In order to protect public health, the United States Environmental Protection Agency (USEPA) established drinking water standards for several radioactive contaminants as part of the Radionuclides Rule. The original Radionuclides Rule was promulgated in 1976 and established the current Maximum Contaminant Levels (MCL) for combined radium and gross alpha particle activity. The Revised Rule took effect in December 2003 and created the MCL value for uranium and modified the sampling requirements for combined radium and gross alpha. The maximum contaminant levels (MCLs) established by the USEPA in the current rule are as follows:

- Adjusted gross alpha activity (GAA): 15 pCi/L
- Combined radium 226/228: 5 pCi/L
- Uranium: 30 µg/L
- Beta and photon particle activity: 4 mrem/year

The Water Quality Control Division (WQCD) of the Colorado Department of Public Health and Environment (CDPHE) adopted these MCLs as part of the Colorado Primary Drinking Water Regulations (CPDWRs).

WQCD launched the CO-RADS project to address issues associated with the 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 five 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 – Build technical, managerial, and financial capacity
- Phase 5 – Provide assistance to systems during

In order to perform Phases 2 and 3, WQCD contracted Malcolm Pirnie (Pirnie), in conjunction with the Colorado School of Mines (CSM). All of the source water sampling and engineering services provided by the Pirnie/CSM team were free of charge to the water systems participating in CO-RADS. The CO-RADS Report that each water system received through this project is intended to help fulfill the Preliminary Engineering

Report (PER) requirements of the WQCD Drinking Water State Revolving Fund (DWSRF) loan program, as well as many other funding agencies.

Approximately 40 water systems in Colorado are affected by radionuclides. These are primarily small ground water systems located in rural areas. The locations of the 33 systems participating in CO-RADS are illustrated in Figure 2-1, along with the type of radionuclide contamination in the systems' source water. In some cases, GAA was also measured in the systems' source waters at levels exceeding the MCL.

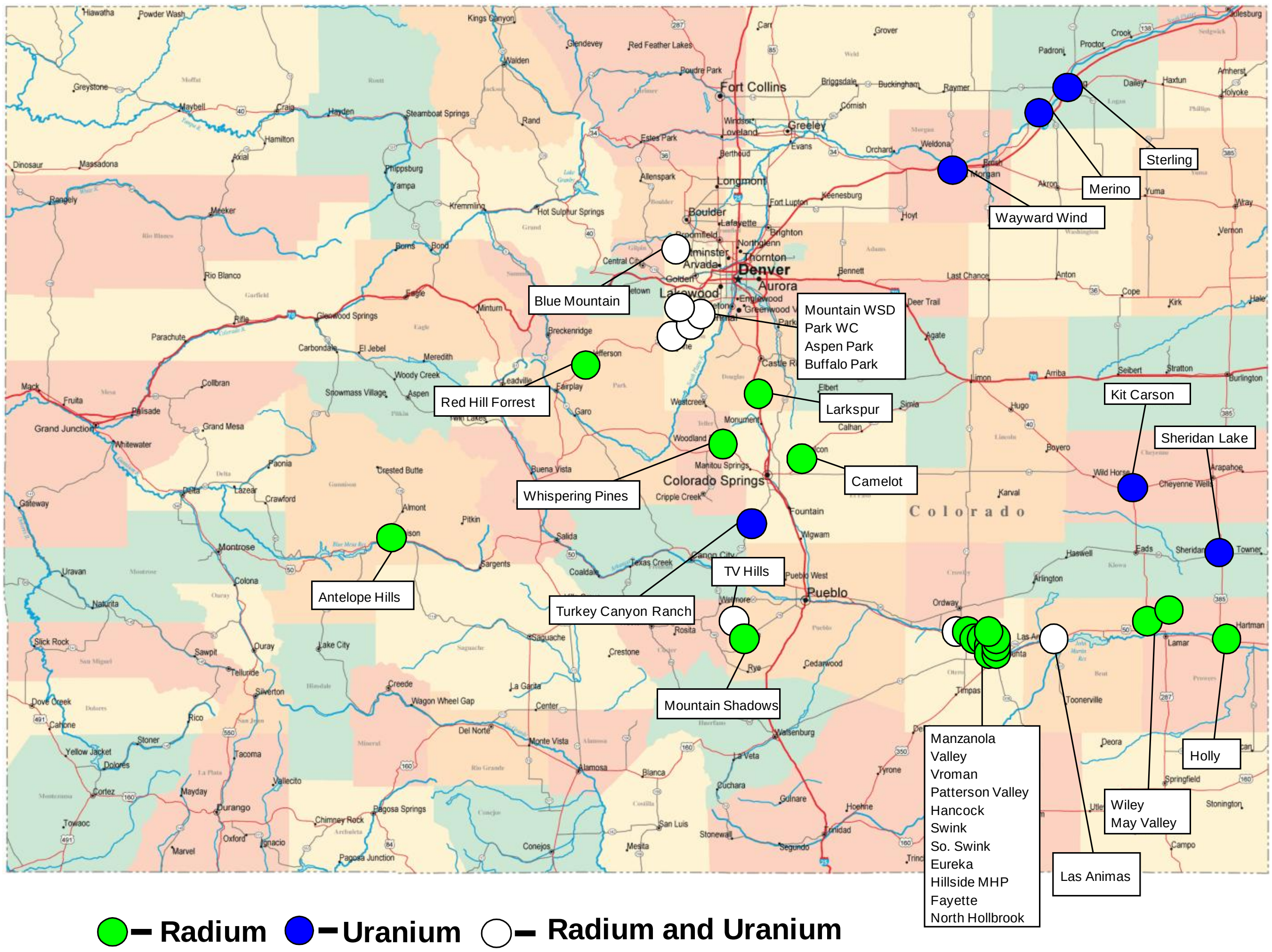


Figure 2-1.
CO-RADS System Locations and Type of Radionuclide Contamination

The list of CO-RADS systems is provided in Table 2-1, along with the population served, and whether or not it is a privately or publicly owned system. Contact information for the CO-RADS systems and additional background information (number of active wells and county) is included in Appendix A.

Table 2-1.
CO-RADS Systems – Population Served, Private/Non-Private, and Primary Contact

#	System Name	Approximate Population Served	Privately or Publicly Owned
1	Antelope Hills Homeowner's Association	350	Private
2	Aspen Park Metropolitan District	NA[1]	Private
3	Blue Mountain Water District	300	Public
4	Buffalo Park Development (aka Homestead Water)	700	Private
5	Camelot Subdivision	38	Private
6	Eureka Water Company	618	Private
7	Fayette Water Company	75	Private
8	Hancock Water Company	100	Private
9	Hillside Trailer Park	81	Private
10	Holly, Town of	900	Public
11	Kit Carson, Town of	300	Public
12	Larkspur, Town of	4,375[2]	Public
13	Las Animas, City of	3,035	Public
14	Manzanola, Town of	500	Public
15	May Valley Water Association	1,500	Private
16	Merino, Town of	275	Public
17	Mountain Shadows	100	Private
18	Mountain Water and Sanitation District	900	Public
19	North Holbrook Water Company	75	Private
20	Park Water Company Wonderview	100	Private
21	Patterson Valley Water Company	120	Private
22	Redhill Forest Property Owner's Mutual Water and Cattlemen's Association	125	Private
23	Sheridan Lake Water Company	80	Private
24	South Swink Water Company	600	Private
25	Sterling, City of	13,794	Public
26	Swink, Town of	696	Public
27	Turkey Canon Ranch Water District	75	Public
28	TV Hills Water, LLC	50	Private
29	Valley WC	270	Private
30	Vroman WC	125	Private
31	Wayward Wind Mobile Home Park	300	Private
32	Whispering Pines Mobile Home Park	40	Private
33	Wiley, Town of	468	Public

[1]NA – Not applicable (this system only serves commercial/retail customers)
[2]Estimate includes guests from the annual Renaissance Festival

2.2. Radionuclides in Drinking Water

Radionuclides are elements that decay, resulting in emissions of radiation energy. Decay refers to the transformation of an unstable isotope (or radionuclide) to a more stable configuration. Atoms tend to transform to more stable forms by electrons moving to lower orbits, such as an electron moving from orbit 2 to orbit 1 in Figure 2-2, or by a nucleus emitting radioactive particles or radiation (also illustrated in Figure 2-2). Radionuclides can decay into different isotopes or into the same isotope with a lower energy state. The primary types of radioactive decay are alpha particle emissions, beta particle emissions, and gamma ray emissions.

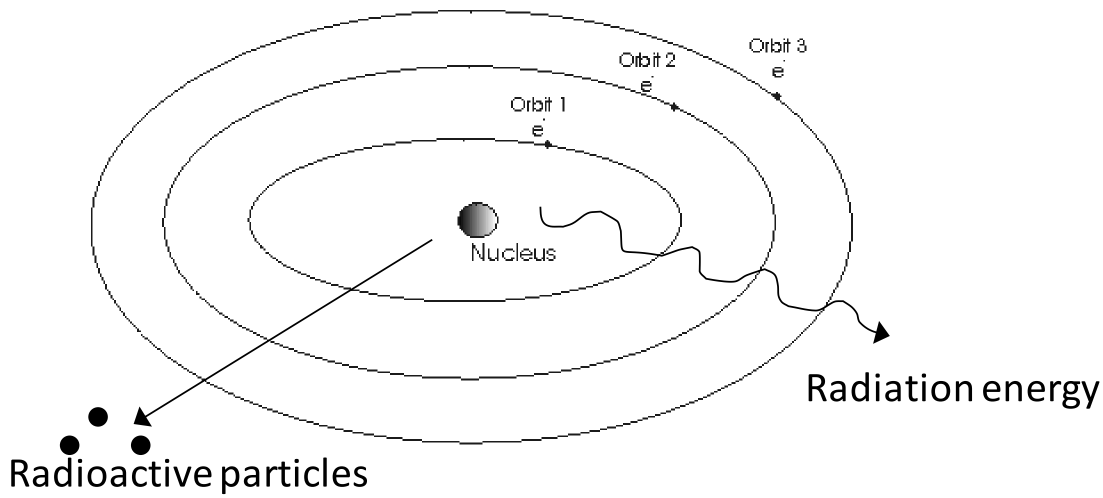


Figure 2-2.
Illustration of a Radioactive Atom

Radionuclides can be found in nature and are also man-made. Radionuclides are present in air, water, soil, and in living things; therefore, humans are exposed to background radiation all the time. Example sources of background radiation exposure include granite, cosmic radiation, and airborne radon. Radionuclides found in drinking water are usually present due to erosion and chemical weathering of naturally occurring mineral deposits, though they can also enter the water by anthropogenic activities (e.g., mining, military weapons testing, and industrial activities) however, in Colorado the radionuclide contaminants in drinking water sources are naturally occurring. Naturally occurring radionuclides, such as radium and uranium, are common in crystalline rocks and are usually present in ground water sources, though they can also be found in surface waters. In contrast, man-made radionuclides are most often found in surface waters.

Potential effects of radionuclides depend on the radiation (number of radioactive particles emitted) and not the mass of the radionuclides (USEPA, 1981); therefore, radionuclides are measured by their activity, which is different from most environmental contaminants that are measured in terms of mass (e.g., milligrams per liter (mg/L)). Common units of activity are curies (Ci) or picocuries (pCi). The curie is equal to a nuclear transformation rate of 3.7×10^{10} disintegrations per second. One gram of radium has 1 Ci of activity (by definition), and one gram of U-238 has an activity of 3.6×10^{-7} Ci. A picocurie is equivalent to 10^{-12} Ci. Radionuclide activities measured in water are most often reported in units of pCi per liter of water (pCi/L).

2.2.1. Health Effects

Exposure to radioactivity may be harmful to chemical reactions that are important to living cells in the body. Radiation pulls electrons off atoms in the cells (i.e., ionizes them) and can prevent the cell from functioning properly. This may result in the following:

- The cell may die
- The cell may not be able to repair itself
- The cell may grow uncontrollably (cancer)

For example, ionizing radiation can damage deoxyribonucleic acid (DNA), which carries a cell’s genetic information. Damage to DNA may change the cell’s genetic code, resulting in the mutation of one or more genes contained in the DNA. These mutations can cause cells to malfunction or lead to cancer (USEPA, 2002).

2.3. Characteristics of CO-RADS Systems

The distribution of the populations served by each of the CO-RADS systems is provided in Figure 2-3. Only 32 of the 33 systems are represented because one of the systems only serves commercial/retail customers.

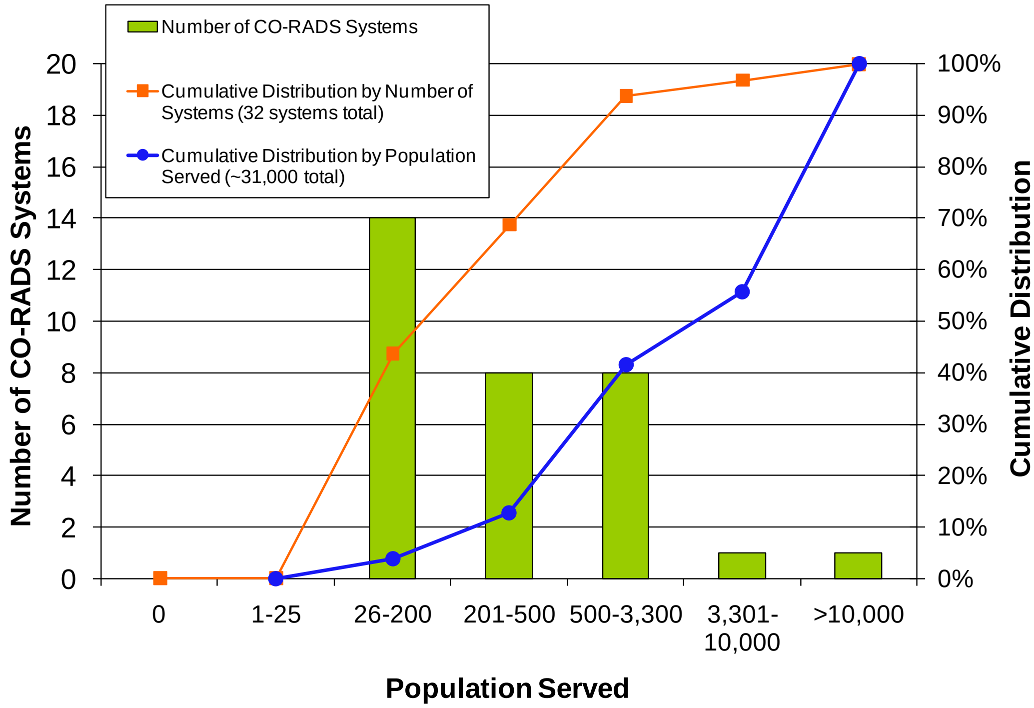


Figure 2-3.
Distribution of CO-RADS Systems by Population Served

Figure 2-3 demonstrates most of the CO-RADS systems are very small – of the 33 systems participating in CO-RADS, 31 systems serve 3,300 customers are fewer. In addition, the total population served by systems participating in CO-RADS is approximately 31,000, of which 45% is served by one water system.

Approximately 64% of the CO-RADS systems are considered privately owned, as illustrated in Figure 2-4. The remaining 36% of CO-RADS systems are governmental entities that are publicly owned. The number of private systems is of interest because privately owned systems (especially private, for profit systems) have limited funding opportunities compared to publicly owned systems.

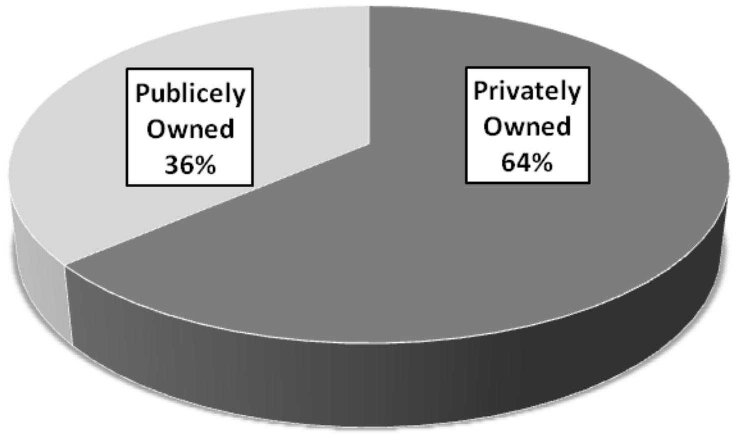


Figure 2-4.
Portion of CO-RADS Systems that are Privately or Publicly Owned Utilities

Most of the communities participating in CO-RADS are agricultural/farming communities. The 2007 median household income for the counties in which the CO-RADS systems are located and the number of CO-RADS systems in each county are illustrated in Figure 2-5. These data indicate 10 of the 15 counties where CO-RADS systems are located have median household incomes below the median for the State of Colorado ($55,212). The average median household income of these 15 counties is approximately $48,000, almost 15% less than the State median. One CO-RADS system is located in Douglas County, which has a median household income of almost twice the value of the State median.

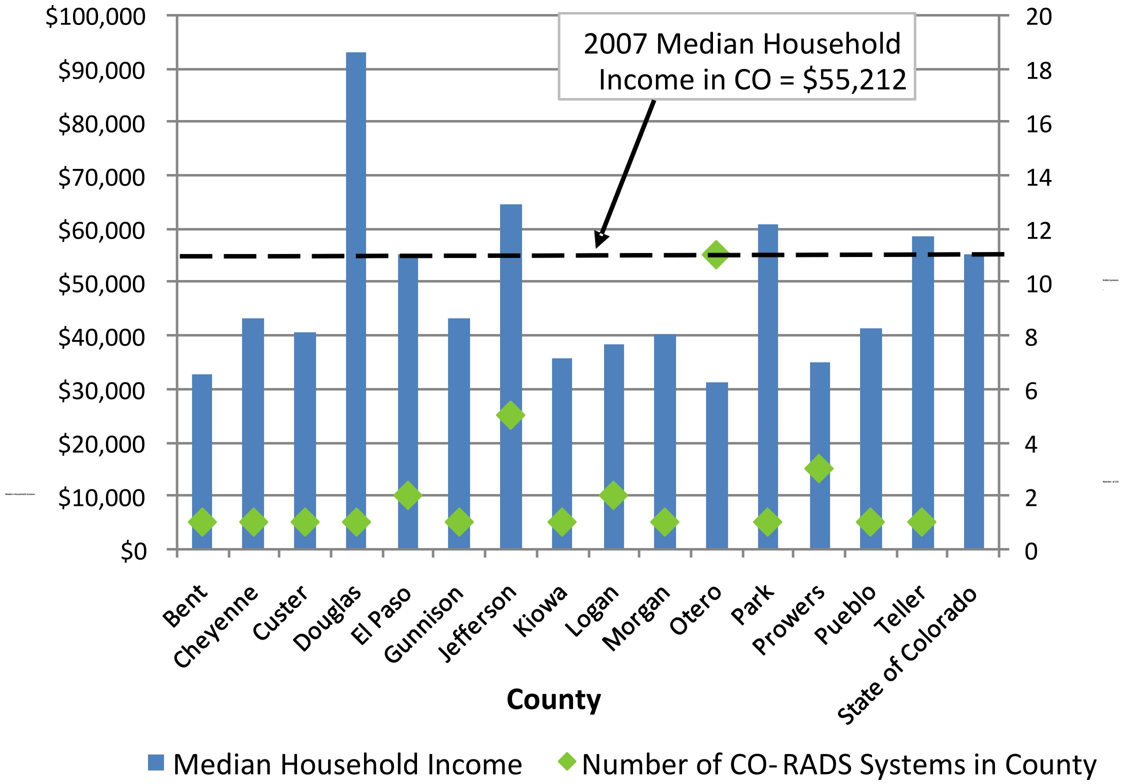


Figure 2-5.
Median Household Income in Counties Represented by CO-RADS Systems

Four of the 33 CO-RADS systems have treatment processes in place for radionuclides (three ion exchange systems and one reverse osmosis system). These systems participated in CO-RADS to obtain information on potential treatment and residuals handling improvements, as well as alternative compliance alternatives. The remaining systems participated in CO-RADS for assistance evaluating, selecting and implementing a Radionuclides Rule compliance alternative.

3. Project Purpose and Methodology

Pirnie and CSM assisted CDPHE with the following tasks as part of Phases 2 and 3 of CO-RADS (as described in Section 2.1):

- Task 1: Policy Development – Pirnie assisted CDPHE's WQCD with research and analysis to support policy directives related to interim health protection measures for systems to implement before they can implement a long-term Radionuclides Rule compliance alternative and the use of point-of-use/point-of-entry (POU/POE) treatment as a long-term compliance solution.
- Task 2: Source Water Sampling – Pirnie analyzed historical water quality data for the CO-RADS systems and conducted sampling to characterize the systems' water quality. Water quality data were used in treatment evaluations.
- Task 3: Treatment Evaluations – Pirnie conducted a desktop engineering analysis of treatment options for compliance with the Radionuclides Rule to identify the technologies that were feasible for CO-RADS systems.
- Task 4: Worker Safety and Waste Disposal Evaluations – Pirnie performed worker safety and disposal evaluations to characterize waste streams and determine the potential exposure of workers to radionuclides by working around radionuclide treatment systems and handling wastes from these systems. This task also included working with various CDPHE agencies to determine a preferred method for disposing of wastes from radionuclide treatment systems.
- Task 5: Bench-top and Pilot-scale Studies – Pirnie worked with CSM to develop and conduct bench- and pilot-scale studies on treatment technologies for removing radionuclides from drinking water.
- Task 6: CO-RADS Reports – Pirnie analyzed each water system and identified an option that could achieve compliance with the Radionuclides Rule. These options and associated costs and considerations were provided to each system as a CO-RADS Report.
- Task 7: Final Project Report – Pirnie summarized the results and recommendations from the project in this Report.

These tasks are described in more detail in the following sections.

3.1. Task 1: Policy and Interim Measures

As part of CO-RADS, CDPHE worked on policies for the following:

- The necessary degree of protection that water systems must provide, on an interim basis, before a long-term Radionuclides Rule compliance option is successfully implemented.

- The ability of water systems to implement POU or POE treatment technologies for long-term compliance with the Radionuclides Rule.

As part of this task, Pirnie investigated and summarized information that WQCD could use to support internal decision making processes. Pirnie facilitated a workshop with WQCD to present the results of the study and identify additional steps in the policy development process.

As described further in the Radionuclide Risk Assessment and Analysis Report included in Appendix B, Pirnie compiled information for CDPHE to understand the incremental risk associated with radionuclides exposure. This information was used to evaluate the increased risk associated with interim measures systems that might be implement before a compliance solution is implemented. The intent was not to evaluate the radionuclide MCLs or the methodology used to create the MCLs. However, in order to maintain consistency of techniques for this CO-RADS risk evaluation, Pirnie applied the same general risk assessment methodology and assumptions used by the EPA to establish the Radionuclides Rule MCLs.

For this analysis, 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. This 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.

Pirnie also identified and evaluated potential interim health protection measures (described in detail in Final Interim Measures and Point-of-Use and Point-of-Entry Treatment Evaluation Report included in Appendix C). Descriptions of the interim compliance measures considered in this evaluation include:

- *Public awareness and education* – educate consumers on water quality and the impacts/risks associated with water contaminated with radionuclides and let them determine whether or not to pursue an option to mitigate exposure. Public education will also be a component of the following interim measures.
- *Bottled water* – either the consumers purchase bottled water for consumption or the water system purchases the bottled water for the consumers.
- *Purchase and delivery of bottled water by the system* – the water system purchases and delivers drinking water to the consumer via a delivery service.
- *POU treatment* – the water system pays for a POU system to be installed on a tap (or taps) in consumers' homes. POU systems only treat water to one faucet and this evaluation assumed the POU treatment system would be installed under the kitchen sink to provide drinking water in the kitchen of a home.

- *POE treatment* – the water system pays for POE treatment for each consumer. POE treatment treats all water that enters an individual building and may be located in the garage, yard or other location at a residence or commercial site.

The interim measures were evaluated at a conceptual level for their effectiveness in reducing public health risks. Then, a more detailed analysis was conducted on potential interim measures selected by CDPHE – POU reverse osmosis, POU ion exchange, and bottled water. Although the feasibility assessment efforts were focused on these three interim measures, Pirnie also compiled less comprehensive information for the other potential options for comparative purposes. This evaluation included the following criteria:

- Public health protection
- O&M requirements for water systems
- Operator skill level required
- National Science Foundation (NSF)/American National Standards Institute (ANSI) certification
- SSCT
- Radionuclides removed
- Additional water quality parameters of interest
- Potential water quality issues
- Waste disposal
- Environmental impacts
- Other considerations

In addition, Pirnie performed the following activities to evaluate POU/POE treatment for long-term compliance:

- Evaluated costs to determine at what point POU or POE was more cost-effective than centralized treatment for a long-term compliance strategy.
- Conducted research on other States' policies regarding the use of POU or POE for long-term compliance. Specifically, Pirnie reviewed existing information and contacted four State regulators (November 2007) to determine their current situation regarding POU/POE treatment programs.

3.2. Task 2: Water Quality Sampling

Pirnie conducted a site visit to each CO-RADS system to collect water samples, conduct interviews, train staff on sample collection practices, and obtain information on the water system infrastructure and condition. Historical water quality data and results of water samples collected as part of CO-RADS were used to characterize the CO-RADS systems' source waters and evaluate treatment alternatives. WQCD determined that there were 132 unique source water locations (individual wells) associated with the 33 water systems that participated in CO-RADS. WQCD's budget for the CO-RADS source water sampling effort was not sufficient to sample all 132 locations; therefore, Pirnie worked with WQCD to consolidate the 132 independent sources to a representative subset of 55 sources. The methodology implemented for selecting the 55 sources at the 33 systems and the number of sources sampled at each system, including confirmation samples, is summarized in the Source Water Sampling and Travel Plan included in Appendix D. Each sampling location was sampled at least once, and nine locations were sampled a second time to assess potential temporal variations in water quality or to verify results.

Pirnie worked with CSM to develop a list of water quality analytes to measure in the source water samples to facilitate water treatment evaluations. Water quality parameters that are sensitive to hold times, pH, temperature, alkalinity, and dissolved oxygen (DO), were measured in the field. All other parameters were analyzed at the Laboratory Services Division of CDPHE. Confirmation samples were not analyzed for all parameters, but rather a subset of six "confirmation parameters" were analyzed to confirm the sources selected at a given system were representative of the system's other sources (wells). The analytes measured in representative samples, and justification for monitoring the analytes, are summarized in Table 3-1.

Table 3-1.
List of Water Quality Parameters Measured in CO-RADS Sampling

Category	**Analyte**	**Justification**
Radionuclides	Radionuclides (GAA[1], ^{226}Ra[2], ^{228}Ra[3] and U[4])	Characterize radionuclides concentrations
	Radon	Proposed USEPA regulation
General Water Quality Parameters	DO	For use in treatment evaluations
	pH	
	Temperature	
	Alkalinity	
	Turbidity	
	Iron	
	Manganese	
	TDS[5]	
	Sulfate	Can reduce capacity of anion exchange
	Silica	Can foul membranes
	Barium	
	Nitrate	Can reduce capacity of anion exchange
	Strontium	Can foul membranes
	20 metals (see Table 3-2)	Water quality characterization; includes parameters that may impact pretreatment requirements.
	TOC[6]	Pretreatment and treatment evaluation

1. GAA - Gross Alpha-particle Activity
2. ^{226}Ra – Radium 226
3. ^{228}Ra – Radium 228
4. U – Uranium
5. TDS – Total dissolved solids
6. TOC – Total organic carbon
7. RO – Reverse Osmosis
8. O_3 – Ozone

The 20 metals analysis referred to in Table 3-1 are a set of analytics available from the Laboratory Services Division of the CDPHE. The metals measured in this analysis are summarized in Table 3-2. While not every metal in Table 3-2was relevant to the source water sampling program, the cost for performing individual metals analyses is greater than ordering the package for all 20 metals.

Table 3-2.
List of 20 Metals

Aluminum	Chromium	Molybednum	Uranium
Arsenic	Copper	Nickel	Zinc
Barium	Iron	Potassium	
Berilium	Lead	Selenium	
Cadmium	Magnesium	Silver	
Calcium	Manganese	Sodium	

3.3. Task 3: Radionuclides Rule Compliance Alternatives

Pirnie identified and evaluated USEPA's accepted Radionuclides Rule compliance options in order to determine the alternatives that were most appropriate for CO-RADS systems. This evaluation included the following:

- Literature review of technologies
- Review of data collected from existing treatment systems
- Desktop evaluation of potential compliance options
- Bench and pilot testing of treatment alternatives(as part of Task 5)
- Interviews and discussions with technology manufacturers and vendors

Compliance alternatives for the Radionuclides Rule can be delineated into two categories:

- ***Treatment***: A drinking water treatment solution that, if designed, operated, and maintained correctly, will achieve regulatory compliance by treating existing water sources (assumes the system will not acquire a new water source).
- ***Non-treatment***: A compliance solution that does not include addition of centralized treatment to existing sources, including:
  - Blending water sources (combining well flows within a system or mixing with sources from a nearby system)
  - Obtaining new water sources (either surface water or groundwater)
  - Installing POU or POE treatment devices at each individual home
  - Regionalization/consolidation with a compliant system

Pirnie started the treatment evaluation by collecting information on EPA's best available technologies (BATs) and small system compliance technologies (SSCTs). BATs are defined by EPA as the best available technologies for meeting MCL requirements that are economically achievable. SSCTs are technologies examined specifically for small systems to affordably comply with MCLs. Both BATs and SSCTs are eligible for variances if, due to source water quality, the system cannot comply with the MCL with the selected technology.

An evaluation of the treatment alternatives was conducted to select technologies for radionuclides removal that should be further evaluated as compliance options for CO-RADS systems. The results are summarized in the Feasible Technology Evaluation Technical Memorandum, which is included in Appendix E. In some cases, alternatives could not be fully evaluated within the constraints of this CO-RADS project, as described in subsequent sections of this report.

Following the Feasible Technology Evaluation Technical Memorandum, feasible technologies were further evaluated to determine their applicability to CO-RADS systems. This investigation was done by contacting equipment vendors, researching residuals handling and disposal requirements, and visiting existing systems employing the technologies. The technologies were evaluated based on many criteria, including the following:

- Ability to consistently treat to at least 50% of the MCL
- Operational complexity and certification
- Worker exposure to radiation
- Industry experience with the technology
- Net Present Value
- Waste handling requirements

In addition, Task 3 included research and evaluation of options for disposing of liquid residuals produced by radionuclide treatment processes (this work was conducted in parallel with Task 4, described further below).

3.4. Task 4: Worker Safety and Waste Handling

Because radionuclides emit radiation, worker safety around treatment processes that accumulate radionuclides as part of the treatment process are a concern. The goal of Task 4 was to assess potential worker exposure to radiation and evaluate options for handling and disposal of wastes.

Of particular concern for radiation exposure are ion exchange and other treatment processes that accumulate radionuclides. As with all ion exchange treatment systems, build-up of contaminants on the ion exchange resin occurs prior to regeneration. This build-up of certain types of radionuclides can lead to radiation exposures for people in the proximity of the treatment system. Radioactive exposure is caused by gamma radiation waves emitted by radioactive material, which are capable of passing through media such as water, concrete, and steel. Alpha and beta emitters are easily shielded and can be shielded by the water and the ion exchange vessel.

The following activities were implemented to assess radiation from treatment processes:

- CDPHE measured radiation doses at existing treatment facilities that include processes that accumulate radionuclides.
- Pirnie held several workshops with representatives from CDPHE to identify an appropriate limit for radiation exposure in a water treatment plant. This Residuals Management Workgroup (RMW) is described below.
- Pirnie built a model to estimate the radiation exposure to a worker around model cation exchange water treatment plant equipment. A detailed description of the ion exchange treatment scenarios modeled is included in the CO-RADS Analysis of Worker Exposure Memorandum located in Appendix F.

An exposure limit of 25 mrem/year from the water treatment plant was indicated by CDPHE as the limit at which a radioactive materials license would likely be required if anticipated exposures were above that threshold. A radioactive materials license requires facilities to have more detailed procedures and training requirements associated with working in and around radioactive materials, in addition to periodic inspections and licensure fees.

The RMW was developed as part of Task 4 with the following objectives:

- Review the status of the Draft Interim Policy and Guidance Pending Rulemaking for Control and Disposition of Technologically-Enhanced Natural Occurring Radioactive Materials (TENORM) in Colorado manual
- Define a preferred radioactive residuals disposal strategy for CO-RADS systems
- Develop and review a Draft Residuals Management Plan (RMP) template
- Assess worker safety issues

Members of the RMW included representatives from Pirnie and WQCD, as wells as representatives of the following CDPHE agencies:

- Domestic Wastewater Permitting Unit, Water Quality Control Division
- Industrial Wastewater Permitting Unit, Water Quality Control Division
- Radiation Management Unit, Hazardous Materials and Waste Management Division

- Solid Waste Management Unit, Hazardous Materials and Waste Management Division

The RMW held two formal meetings to address the objectives described above. Several other less formal meetings were also held with members of the RMW to come to agreement about CO-RADS strategies and implications. The results of these meetings became the basis for determining feasible options for disposing of liquid and solid wastes generated in radionuclides treatment and defined the design criteria for those options.

3.5. Task 5: Bench and Pilot Testing

Bench and pilot scale studies were conducted on select radionuclide treatment technologies with the following objectives:

- Confirm ability of technologies to remove radionuclides from representative CO-RADS source waters to comply with the Radionuclides Rule
- Confirm approximate design criteria ranges for treatment technologies
- Characterize treatment residuals

Source waters from four CO-RADS systems were selected for testing. These systems were selected as representative of the remaining systems based on radionuclides concentrations and general water quality and are summarized in Table 3-3.

Table 3-3.
Characteristics of Source Water Tested in Bench and Pilot Testing

System	Population Served	Hardness Concentration (mg/L as $CaCO_3$)	Radium Concentration Above the MCL	Uranium Concentration Above the MCL	Gross Alpha Activity Above the MCL
Sterling	13,794	650 (Very High)		√	√
May Valley	1,500	350 (High)	√		√
Blue Mountain	300	170 (Moderate)	√	√	√
Redhill Forest	125	190 (Moderate)	√		√

Treatment technologies for the tests were selected from the list of BATs and SSCTs developed by EPA. Technologies were selected based on the following criteria:

- Ability to remove radionuclides based on literature
- Feasibility for small water systems
- Operation and maintenance requirements

The technologies selected for testing and the source waters they were tested on are summarized in Table 3-4.

Table 3-4.
Source Water and Technologies Tested in Bench and Pilot Tests

System	Cation Exchange (IX)	Hydrous Manganese Oxide (HMO)	Enhanced Coagulation	Bench-Scale Membrane (RO and NF)	Pilot-Scale Membrane (NF Only)
Sterling			√		√
May Valley	√	√		√	√
Blue Mountain	√	√			
Redhill Forest	√	√			

Details on how the source waters and technologies were selected and how the tests were conducted are included in the Task 5 Bench and Pilot Testing Plan located in Appendix G.

3.6. Task 6: CO-RADS Reports

Pirnie developed CO-RADS Reports for 33 systems, applying the results of tasks 2, 3, 4, and 5 to specific situations. These Reports summarize information collected through CO-RADS and provided systems with a compliance alternative and opinion of probable project cost for planning purposes. While the alternative defined in the Reports will safely achieve compliance with the Radionuclides Rule, systems may elect to evaluate other alternatives that could not be thoroughly examined through CO-RADS. Additional information to facilitate further evaluation of these alternatives was provided in the Reports.

The Reports provide a plan for the systems to follow to comply with the requirements of the Radionuclides Rule. They contain an examination of compliance alternatives, evaluations of those alternatives, and a preliminary design of a defined alternative. The preliminary design is approximately 15% complete and defines the following items:

- Plant capacity
- Preliminary layout
- Process equipment sizing
- Process flow diagrams
- Opinion of probable cost (further described below)

This level of project definition allowed for the completion of an Association for the Advancement of Cost Engineering (AACE) Class 4 estimate, which provides an accuracy of -20% to +30%, that could be used to define the project budget. Further, the CO-RADS Reports detailed operational requirements and provided estimates of costs for operating and maintaining the defined solution, allowing the calculation of the net present value (NPV), which is further defined later in the report. The CO-RADS Reports also provided an estimated schedule for implementing the process.

The intent of the Reports was to provide information to support the development of a Preliminary Engineering Report by the CO-RADS systems. The following subsections provide more detail on the information provided to the systems in the Reports and explains the process used for systems to provide feedback during the Report development process.

3.6.1. Utility Representatives Group – Forum for Systems to Provide Input

During the information collection and Report development process, the Utility Representatives Group (URG) served as a forum that allowed each system to provide input throughout CO-RADS and help Pirnie and CDPHE understand the participating water systems' perspective on issues that needed to be addressed in each CO-RADS Report. The URG was comprised of representatives of systems participating in the project. As the forum progressed through CO-RADS, it evolved and helped create an efficient and meaningful communication route amongst the group – primarily through e-mails and periodic workshops. During the Report development process, Pirnie and CDPHE continued to work with CO-RADS participants one-on-one to ensure the Reports met individual system needs and incorporated as much input as possible from system representatives.

CDPHE served as the communication hub for the URG, initiating email questionnaires, collecting responses, and facilitating working sessions. CDPHE included every CO-RADS participant that provided an e-mail address and was willing to participate in the URG.

3.6.2. CO-RADS Compliance Alternatives Evaluation

Pirnie worked with CDPHE to identify a preliminary list of criteria to evaluate potential compliance alternatives in the CO-RADS Reports. Using that list as a starting point, Pirnie and CDPHE solicited input from the URG to rank the top three criteria provided in the list and to identify any other outstanding criteria that they considered important for this evaluation. Ten system representatives representing ten different systems responded to the questionnaire. The results were compiled and used to create the final list of criteria used as evaluation criteria for CO-RADS compliance alternatives. A description of the criteria and the respective weightings applied in the alternatives analysis are summarized in Table 3-5.

Table 3-5.
Description of CO-RADS Compliance Alternative Evaluation Criteria and Weights Used in Alternatives Analysis

Criteria	Definition	Weight
Cost (Net Present Value (NPV))	NPV is the total present value of the project over the entire duration of the project (20 years), including: - Capital costs - Operation and maintenance costs - Residuals management and disposal	45%
Reliability of Solution to Meet Radionuclides Rule Requirements	The ability of the alternative to consistently produce water that meets regulatory requirements when properly operated and maintained	25%
Use of Existing Infrastructure	The ability to incorporate existing infrastructure (wells and filters, for example) into the compliance alternative	15%
Ability of Solution to Address Additional Water Quality and Compliance Issues	The ability of the alternative to address other regulatory requirements and improve aesthetic water quality (such as taste and odor)	5%
Operational Complexity	The level of operator certification required and the amount of knowledge and attention from a certified operator that is required to maintain compliance with the Radionuclides Rule	5%
Workplace Safety and Residuals Handling/Disposal	Radiation exposure due to the treatment of drinking water and disposal of residuals and complexities associated with residuals handling, treatment, and storage, as well as the required frequency of disposal	5%

The potential compliance alternatives for each system were evaluated and compared based on the evaluation criteria described in Table 3-5. Each alternative was given a relative score between 1 and 5 for each of the evaluation criterion, 5 being the best and 1 being the worst. In other words, a 5 was only "the best" when compared to alternatives evaluated in that specific CO-RADS Report. The score was multiplied by the weighting for the criterion (Table 3-5) to develop the weighted score. The sum of the weighted scores yielded the overall score for the alternative. The alternative with the highest score was the "defined alternative" for the system.

3.6.3. Opinions of Probable Cost of Defined Alternatives

Opinions of probable project costs for the defined alternatives (capital cost, operation and maintenance cost, and the net present value costs) were presented in each CO-RADS Report. The costs were provided for planning purposes only. The systems were encouraged to use the costs presented to begin preparing for the potential order of magnitude financial impact that Radionuclides Rule compliance would likely have on the water system if they implemented the defined alternative.

Capital cost in the CO-RADS Reports refers to the cost to implement the defined alternative, and includes engineering fees, administrative fees, costs to procure equipment, and costs to construct the project. The information provided in the CO-

RADS Reports was consistent with an AACE Class 4 estimate where project definition is between 1% and 15% and engineering is 1% to 5% complete. The typical purpose of this level of estimate is for concept study or feasibility evaluations. These estimates are primarily stochastic in nature (i.e., they are based on inferred or statistical relationships between similar projects and/or equipment quotes with additional factors applied rather than a deterministic estimate that relies on detailed quantity take-offs and unit costs). Class 4 estimates are generally prepared based on limited information and thus they have a wide accuracy range. Class 4 estimates are typically accurate on the low side between -15% to -30% and on the high side between +20% and +50%.

With awareness that the actual project cost may vary within the typical accuracy of the point or probable construction cost estimate (i.e., -20% to +30%) these estimates can successfully be used by owners for budget estimating purposes. AACE recommends that only after the project definition is advanced to 10% to 40%, and a Class 3 or higher cost estimate can be developed, should an authorization or project control budget be established.

The capital cost estimates provided in the CO-RADS Reports included the following line items:

- Miscellaneous for estimate accuracy - Consistent with the AACE Class 4 designation of this estimate, a 20% factor of safety was included. The intent of this line item is to cover items that are required for the construction of the project but are currently undefined in the cost estimate. As the project is better defined and the time to actual bidding nears, this line item would be reduced.
- General conditions - This line item refers to the overhead and profit of the general contractor performing the construction of the project. It includes items such as bonds, insurance, and temporary facilities. A factor of 15% was included in the estimate to account for these items.
- Engineering and administration - A factor of 25% was included to cover the costs of engineering work associated with preliminary design, final design, and construction assistance. This line item also covers any administrative costs incurred by the systems during the completion of the projects.

The estimate was performed in 2008 dollars. For budgeting purposes, it was recommended that the CO-RADS systems increase the cost of the project by at least 4% annually to the midpoint of construction to account for inflation.

O&M cost refers to the costs associated with successfully producing water that meets all regulatory requirements. Typically, O&M costs include electricity, labor, disposal of residuals, and replacement materials. For labor, an estimated burdened labor rate (which would include benefits) multiplied by the additional time expected to operated and maintain the alternative was used to derive labor costs. It is estimated that this role would be in addition to what the existing operator is currently performing. Chemicals included salt for regeneration of ion exchange systems and additional sodium hypochlorite required for iron oxidation (where applicable).

The level of accuracy of these estimates were similar to the capital cost estimate above (-20% to +30%). It should be used to budget for ongoing expenses, and further developed as the project is defined. These estimates were for the upgrades to the treatment and waste handling processes only, and were in addition to any operations and maintenance costs that the systems were already occurring.

In order to compare the O&M costs to the capital costs, the net present value was calculated. Net present value is defined as the cost in today's dollars of costs incurred at some point in the future that is if the net present value were invested today it would cover the cost of all future estimated O&M needs. In order to calculate the net present value, the estimated annual costs for the life of the project (20 years) were estimated and a discount rate of 6% was assumed.

.

4. CO-RADS Results

4.1. Task 1: Policy and Interim Measures

Conceptual level results of the evaluation of interim compliance measures are included in Appendix C. The results of the feasibility analysis, which focused on POU reverse osmosis, POU ion exchange, and bottled water as interim measures are summarized in Table 4-1. Pirnie included information in Table 4-1 on measures not included in the feasibility evaluation for comparative purposes.

Table 4-1
Detailed Comparison of Potential Interim Compliance Measures
(per CDPHE guidance, shaded items were not included in the feasibility evaluation, but information is included in the table for comparative purposes)

	Potential Public Health Protection	O&M Requirements for Water System	Operator Skill Level Required	NSF/ANSI Certified Units?	Small Systems Compliance Technology (SSCT)?	Radionuclides Reduced	Additional Water Quality Parameters of Interest	Potential Water Quality Issues to Consider	Waste Disposal	Environmental Impacts	Other Considerations
Bottled Water (Delivered or Purchased)	Medium	None	None	Some bottled waters are NSF/ANSI certified	No	Bottled water should have very low concentrations or no radionuclides	Lack of fluoride in most bottled waters; bottled water regulated by FDA, not EPA	Lack of disinfectant residual may cause concern regarding microbial contamination	Waste from bottles may burden landfills (under purchased water scenario)	Waste from bottles may burden landfills (under purchased water scenario)	
POU RO	Medium	- Need long-term O&M and monitoring plans to ensure proper performance - Replacement of exhausted membranes, particulate pre-filters, and pre- and post-treatment GAC filters (if necessary) - Maintenance and cleaning of storage tank - Maintenance of (re) pressurization pumps (if used)	Basic	Yes - Standard 58 for reverse osmosis - Reduction claim for radium	Yes	Combined radium, beta and photon activity, gross alpha, and uranium	Hardness, iron, manganese, chlorine	Fouling; chlorine can harm membranes in some RO units; typically add calcite or soda ash to effluent to raise pH and prevent corrosion in pipes; RO treated water is low in sodium and other essential nutrients	Reject stream (must have a drain or tank to discharge to) and spent membranes	Low production rate (around 20-30%), storage is typically needed, may not be the optimal treatment technology in arid or water-limited regions due to low recovery rate	- Membranes and GAC media (if used) may be susceptible to microbial colonization - Entry into customers' homes is required for installation, operation, and maintenance; may complicate insurance agreements - Plumbing and/or electrical supply in the homes may need to be updated before installation - Some homes may require extra construction if the treatment unit does not fit in the existing space - State will need to determine level of operator certification required

	Potential Public Health Protection	O&M Requirements for Water System	Operator Skill Level Required	NSF/ANSI Certified Units?	Small Systems Compliance Technology (SSCT)?	Radionuclides Reduced	Additional Water Quality Parameters of Interest	Potential Water Quality Issues to Consider	Waste Disposal	Environmental Impacts	Other Considerations
POU IX	Medium	- Need long-term O&M and monitoring plans to ensure proper performance - Replacement of spent resin cartridges and particulate pre-filters (if used)	Basic	No	Yes	Combined radium (cation IX), beta and photon activity, and uranium (anion IX) (not a compliance technology for gross alpha)	Iron, manganese, copper, TSS	Fouling, competing ions: may shorten media life since POU IX cannot be backwashed	Regenerant brine, backwash water, and rinse water , resin		- Media may be susceptible to microbial colonization - Plumbing and/or electrical supply in the homes may need to be updated before installation - Some homes may require extra construction if the treatment unit does not fit in the existing space - Potential exposure to radionuclides in the treatment device may be an issue - Entry into customers' homes is required for installation, operation, and maintenance; may complicate insurance agreements - State will need to determine level of operator certification required
Public Awareness and Education	Low	Educational flyers and regulatory updates	None	Not Applicable	No	None – no control over how consumer chooses to address the issue	Not applicable		None		Not an approved EPA compliance alternative; will be an important component of any interim measure
POE RO	High	- Need long-term O&M and monitoring plans to ensure proper performance - Replacement of exhausted membranes, particulate pre-filters, and pre- and post-treatment GAC filters (if necessary) - Maintenance and cleaning of storage tank - Maintenance of (re) pressurization pumps (if used)	Intermediate	No	No, due to concerns about cost and waste disposal	All (combined radium, beta and photon activity, gross alpha, and uranium)	Hardness, iron, manganese, chlorine	Fouling; chlorine can harm membranes in some RO units; typically add calcite or soda ash to effluent to raise pH and prevent corrosion in pipes; RO treated water is low in sodium and other essential nutrients	Reject stream and used membranes	Low production rate (around 20-30%), storage is typically needed, may not be the optimal treatment technology in arid or water-limited regions due to low recovery rate	- Membranes and GAC media (if used) may be susceptible to microbial colonization - Plumbing and/or electrical supply in the homes may need to be updated before installation of system - Some homes may require extra construction if the treatment unit does not fit in the existing space - State will need to determine level of operator certification required

	Potential Public Health Protection	O&M Requirements for Water System	Operator Skill Level Required	NSF/ANSI Certified Units?	Small Systems Compliance Technology (SSCT)?	Radionuclides Reduced	Additional Water Quality Parameters of Interest	Potential Water Quality Issues to Consider	Waste Disposal	Environmental Impacts	Other Considerations
POE IX	High	- Need long-term O&M and monitoring plans to ensure proper performance - Regular regeneration and periodic backwashing - Replacement of salt used for resin regeneration - Replacement of lost or spent resin and replacement of particulate pre-filters - Maintenance and cleaning of storage tank; if used.	Intermediate	Yes - Standard 44 for cation exchange	No, due to concerns about cost and waste disposal	Combined radium (cation IX), beta and photon activity, and uranium (anion IX) (not a compliance technology for gross alpha)	Iron, manganese, copper	Fouling, competing ions	Regenerant brine, backwash water, and rinse water		- Media may be susceptible to microbial colonization - Plumbing and/or electrical supply in the homes may need to be updated before installation - Some homes may require extra construction if the treatment unit does not fit in the existing space - Potential exposure to radionuclides in the treatment device may be an issue - State will need to determine level of operator certification required

The results summarized in Table 4-1 were presented to CDPHE at the Interim Protection Measures and POU/POE Treatment for Compliance Workshop on November 28, 2007. The set of slides presented at that workshop are included in Appendix H. Cost estimates for POU/POE treatment options compiled as part of this task are summarized in Appendix C. These feasibility level estimated costs were provided for comparative purposes only and are not specific to water systems in Colorado. Cost estimates do not include residuals disposal or insurance coverage.

The specific results of the risk assessment can be found in Appendix B. The observations made from the risk assessment are as follows:

- 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, two 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.

Pirnie also researched and conducted interviews with other States to determine their POU/POE treatment policies. Pirnie identified several States that have POU and/or POE requirements and/or guidance in place including Arizona, California, Delaware, Florida, Idaho, Illinois, Massachusetts, New York, Pennsylvania, South Carolina, Utah, Vermont, Virginia, Washington, and Wisconsin. Several of those States allow POU and/or POE treatment for compliance with the Radionuclides Rule (Narasimhan et al, 2005). Results of the "state of the industry" interviews to assess other States' policies for long-term use of POU/POE treatment for compliance are summarized in Table 4-2.

As shown in Table 4-2, of the States interviewed, only Illinois had water systems (two home owners' associations (HOAs)) using POE for compliance with the Radionuclides Rule as of October 2007. Arizona has almost 20 systems using POU and/or POE for arsenic and fluoride compliance. Arizona expected to have more water systems with POU/POE installed than are currently in place; however, water systems have experienced insurance issues with having treatment devices installed in private homes, but owned and operated by the water system.

Table 4-2.
Selected Summary of States' POU/POE Policies as of October 2007

States that allow POU/POE for Radionuclides Treatment	Additional State Requirements over Code of Federal Regulations (CFR)	Contaminants	Size of systems allowed to use POUs	Size of Systems using POUs	Info on Systems currently using POEs for compliance
Arizona	Arizona regulations require the water system to develop and have approved a written monitoring plan, obtain Arizona Department of Environmental Quality approval of design of the POU device, install a sufficient number of devices to ensure every person served by the system is protected, and that the rights and responsibilities of persons served by the water system convey with title upon sale of property.	Radionuclides, arsenic, chromium, volatile organic compounds	All	Approximately 18 systems (<50 connections) have POU and/or POE in place for arsenic or fluoride for long-term treatment	~3 systems have POE or POU and POE in place for arsenic and/or fluoride
Illinois	POU and POE are not allowed for municipalities, only private systems such as home owners associations (HOAs); must have 100% participation	Only radium	None	None	Two small HOAs with less than 60 homes currently have POE cation exchange (water softeners) installed for removal of radium

States that allow POU/POE for Radionuclides Treatment	Additional State Requirements over Code of Federal Regulations (CFR)	Contaminants	Size of systems allowed to use POUs	Size of Systems using POUs	Info on Systems currently using POEs for compliance
Texas	When POU/POE devices are used for compliance, the water system must develop a program for the long-term operation, maintenance, and monitoring of the devices to ensure adequate performance.	Any non-microbial contaminant violating the MCL	<10,000	None, though an application from a public school is under review (Source: conversation with Mike Howell, Texas Commission of Environmental Quality)	None used
Wisconsin	The Wisconsin Department of Commerce requires installation of POU on all faucets in a home; cannot install POU on only one faucet (Source: phone conversation with Wisconsin Department of Natural Resources)	Radionuclides, Total Coliform Rule, and nitrate	All	None	Small non-community GW systems for TCR compliance

As of March 2009, CDPHE was still in the process of developing policy for systems regarding interim compliance measures and use of POU/POE treatment for long-term compliance with USEPA primary drinking water regulations, including the Radionuclides Rule.

4.2. Task 2: Water Quality Sampling

As discussed in Section 3.3, water quality samples were collected at all of the systems at least once, and from a subset of the systems a second time. Results of the first round of sampling are provided in this Report. The number of systems with source waters exceeding Radionuclides Rule MCLs, based on the first set of samples collected through CO-RADS, are summarized in Figure 4-1.

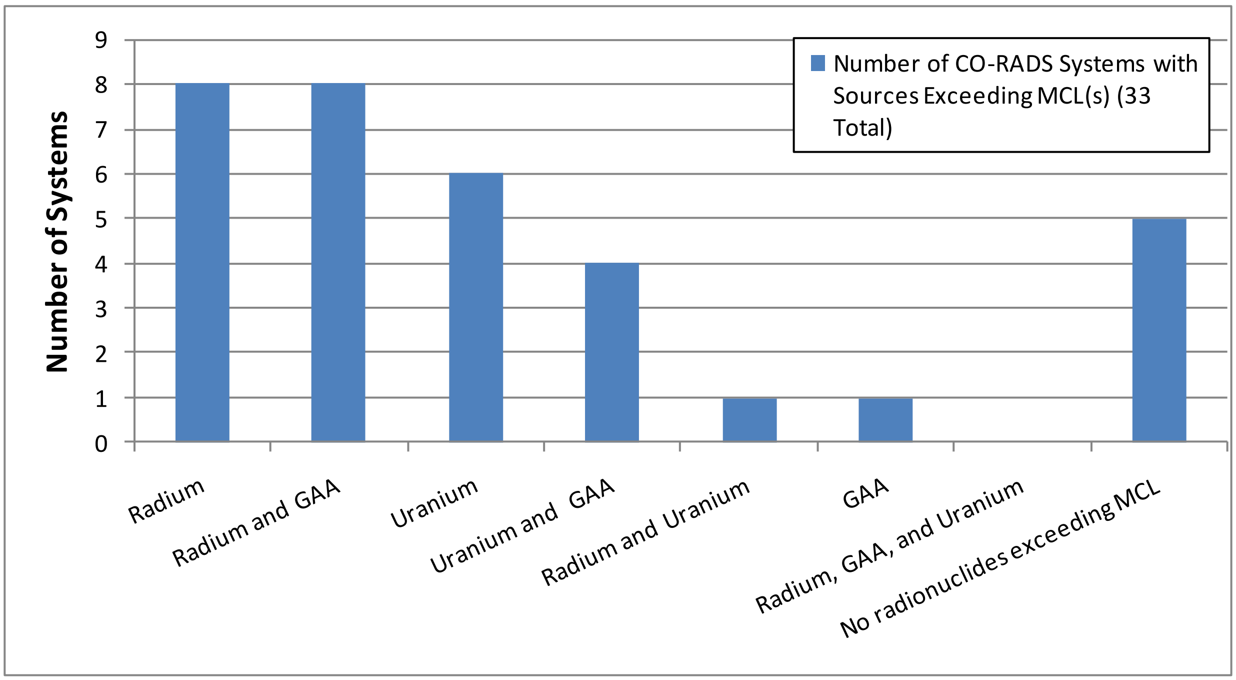


Figure 4-1.
Number of CO-RADS Systems with One or More Sources Exceeding the Radionuclides Rule MCLs Based on One CO-RADS Water Quality Sampling Event at Each System

Most of the systems (16) had radium or radium and GAA exceeding the MCL. Ten systems had uranium or uranium and GAA exceeding the MCL and radionuclide concentrations measured in source water samples collected from five of the systems did not exceed any of the MCLs.

In addition, radon concentrations measured in 15 of the systems' source waters exceeded the proposed MCL of 300 pCi/L. The proposed Radon Rule has not been finalized and depending on how Colorado chooses to implement the Radon Rule, an alternate MCL of 4,000 pCi/L could be established for systems that develop a multi-media mitigation plan.

Radon is a gas that is present in water because of the natural radioactive breakdown of uranium and has been shown to cause lung cancer.

The combined radium, uranium, adjusted GAA, and radon concentrations measured in the sources at the CO-RADS systems are illustrated in Figures 4-2 through 4-5, respectively. Note multiple sources were sampled at several of the systems.

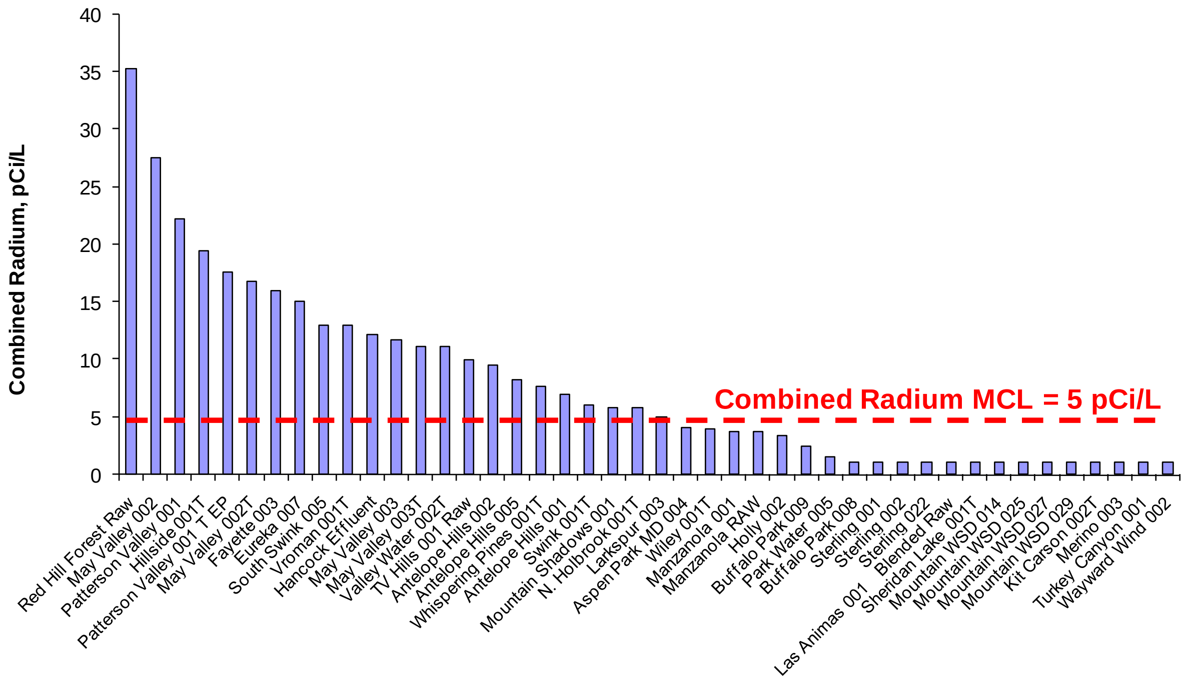


Figure 4-2.
Combined Radium Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples

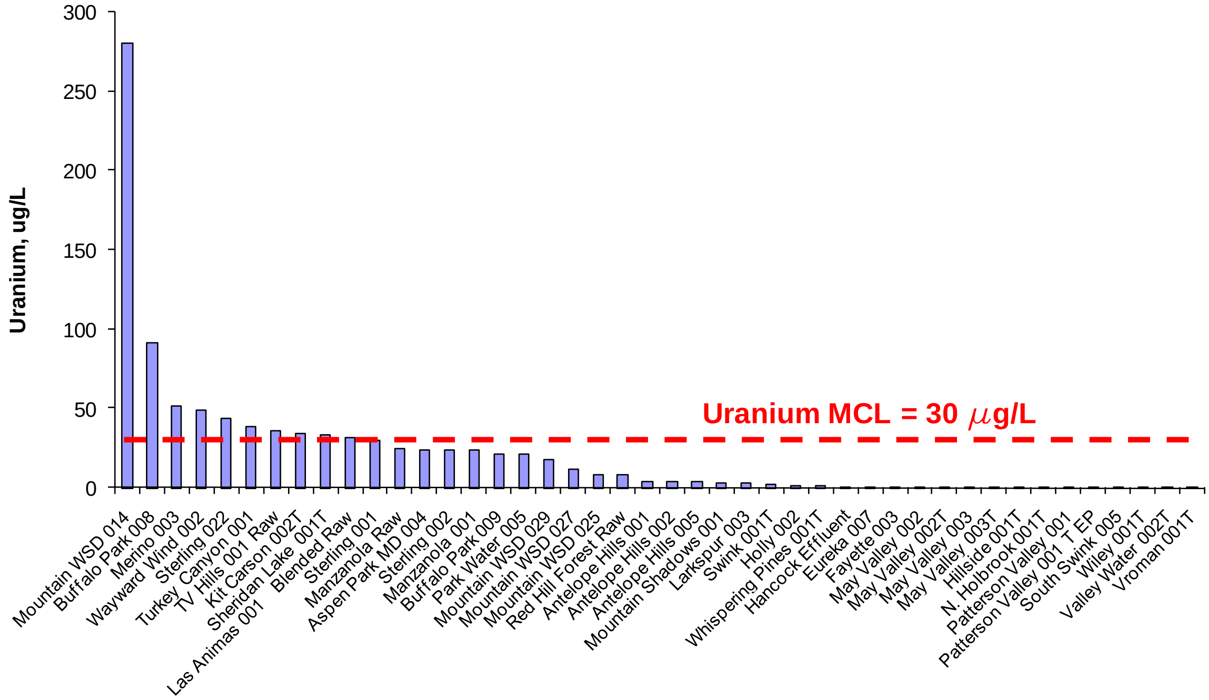


Figure 4-3.
Uranium Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples

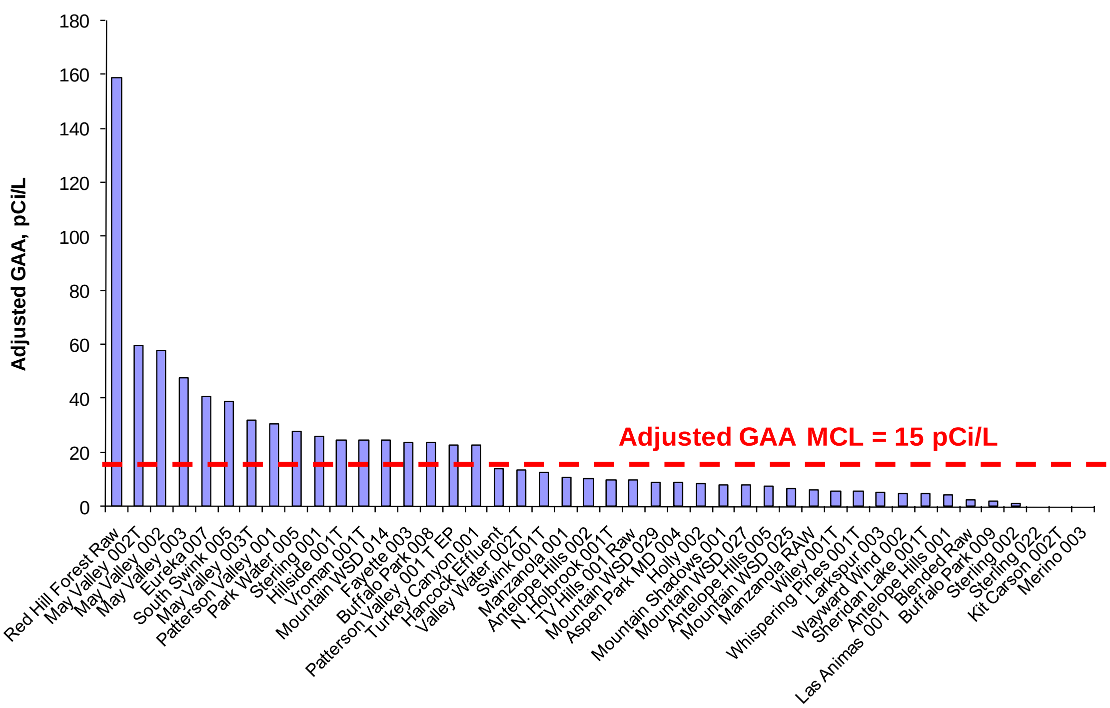


Figure 4-4.
Adjusted GAA Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples

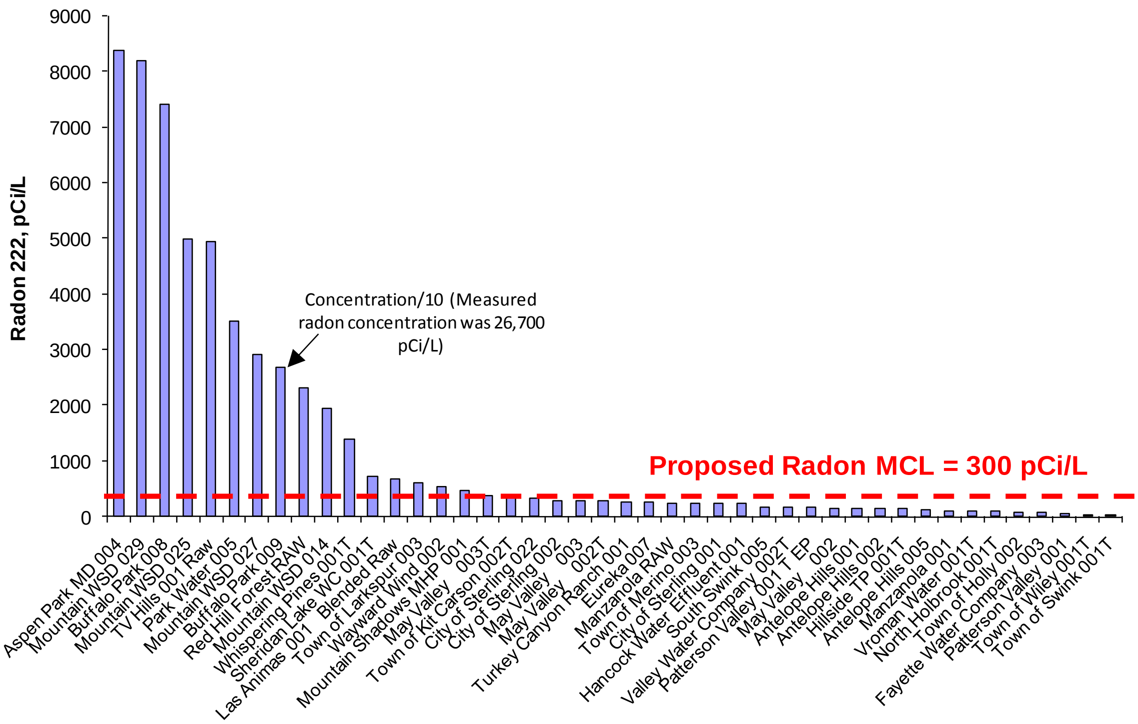


Figure 4-5.
Radon-222 Concentrations Measured in CO-RADS Systems' Source Waters in the First Round of Samples

Several water quality parameters were of concern due to their impact on pretreatment requirements for certain treatment processes. These parameters include TDS, hardness, sulfate, iron, manganese, and TOC. The average, minimum, and maximum concentrations of these parameters measured in CO-RADS systems' source waters are summarized in Table 4-3. Table 4-3 also provides the applicable SMCL for comparison.

Table 4-3.
Concentrations of Water Quality Parameters that Can Impact Water Treatment Determinations: Average, Minimum and Maximum Concentrations Measured in All CO-RADS Systems' Source Waters

Water Quality Parameter	SMCL	Average Concentration	Minimum Concentration	Maximum Concentration	Count
Hardness (mg/L as $CaCO_3$)	N/A[1]	308[2]	7	1,203	45
Iron, Total (mg/L as Fe)	0.3	0.4	0.01	3.2	45
Manganese, mg/L	0.05	0.03	BDL[3]	0.32	45
Sulfate, mg/L	250	529	5	1,700	44
TDS, mg/L	500	946	140	2,800	45
TOC, mg/L	N/A	2	0	14	44

[1]N/A = not applicable
[2]Hardness concentrations above 300 mg/L as $CaCO_3$ are considered to be very hard (AWWA, 2004)
[3]Below Detection Limit

In general, most of the CO-RADS systems have very challenging water qualities to treat. Aesthetic quality of these water is also impacted by these water quality parameters (e.g., hardness, TDS, iron)

4.3. Task 3: Radionuclides Rule Compliance Alternatives

The following sub-sections describe the treatment and non-treatment solutions that were identified and evaluated as part of CO-RADS and the compliance alternatives considered for the CO-RADS systems.

4.3.1. Treatment Alternatives

Table 4-4 provides a comprehensive list of treatment technologies identified for radionuclides removal, indicates the specific contaminant(s) that are removed, and if they are a BAT or SSCT for radionuclides.

**Table 4-4.
Radionuclides Treatment Alternatives**

Technology	Contaminant Removed	Brief Description	BAT/SSCT?
Ion Exchange			
Cation Exchange	Ra	Positively charged ions (cations) are exchanged with sodium using a fixed bed of resin in a flow through vessel that is regenerated with sodium chloride brine solution.	BAT/SSCT
Anion Exchange	U	Negatively charged ions (anions, such as uranium) in water are exchanged with negatively charged ions (chloride) in a fixed bed of resin in a flow through vessel that is regenerated with a sodium chloride brine solution.	BAT/SSCT
Adsorption			
Activated Alumina	U	Uranium is removed by adsorption to media in a flow through vessel. Depending on system design, periodic regeneration may be required.	SSCT*
Greensand Filtration	Ra	Activated media (e.g. media coated with hydrous manganese oxide (HMO)) pressure filters remove divalent cations by adsorption.	SSCT
Membranes			
High Pressure Membranes - Reverse Osmosis (RO) or Nanofiltration (NF)	Ra, U, alpha emitters	Contaminants are removed by pressure driven membrane processes.	BAT/SSCT
Electrodialysis-electrodialysis reversal (ED/EDR)	Ra, U	Contaminants are removed by a voltage driven membrane process.	SSCT
Physical/chemical Removal			
Lime Softening – filtration	Ra, U	Lime or soda ash is added to precipitate ions, followed by sedimentation and filtration. (Large system application)	BAT/SSCT**

Technology	Contaminant Removed	Brief Description	BAT/SSCT?
Enhanced coagulation – filtration	U	Addition of alum or ferric for uranium removal, followed by sedimentation and filtration (Large system application)	BAT/SSCT**
Preformed Hydrous Manganese Oxide Filtration (HMO)	Ra	Radium adsorbs to preformed HMO added to water post oxidation. The HMO is then removed by filtration.	SSCT
Co-precipitation with barium sulfate	Ra	Barium chloride is added to precipitate radium sulfate, followed by filtration.	SSCT

* While activated alumina is an SSCT for radionuclides, the Radionuclides Rule does not recommend it as a compliance technology for systems serving less than 10,000 customers.
** According to the Radionuclides Rule published in the federal register, enhanced coagulation/filtration is an SSCT for small systems that can modify an existing coagulation/filtration process and lime softening is considered too complex for small systems due to the complex water chemistry involved.

Sources: National Drinking Water Clearing House. 2000; USEPA, 2000; USEPA, 2002; USEPA 2006

While ion exchange and HMO are not formally denoted as BATs or SSCTs for alpha emitters (Table 4-4), research indicates that ion exchange treatment will remove GAA associated with uranium and radium and HMO will remove GAA associated with radium; therefore, these technologies were further evaluated.

Bench-scale tests conducted on water from three communities participating in CO-RADS indicated GAA associated with radium is removed by cation exchange. For example, over 93% of GAA at approximately 62 pCi/L was removed by cation exchange from one system's source water. Similarly, over 95% of the GAA (approximately 97 pCi/L in the source water) was removed through cation exchange in a second source water.

Pilot studies (not associated with CO-RADS) conducted on uranium-contaminated groundwater wells in West Jefferson County, CO showed GAA removal of 90-99% by anion exchange. The raw water contained 16-50 pCi/L of uranium and 50-170 pCi/L of gross alpha activity. Anion exchange column influent gross alpha concentrations as high as 120 pCi/L were reduced to less than 2 pCi/L. Subsequent monitoring of a full-scale anion exchange system at the site for uranium removal showed 89-99% removal of gross alpha over an 8-month monitoring period (Varani, F.T. et. al, 1987).

Bench-tests conducted on HMO at a dose of 1.0 mg/L as part of CO-RADS indicate 80-90% of GAA is removed from water contaminated with radium above the MCL. For example, a GAA of 55 pCi/L was reduced to 5 pCi/L (91% removal) in water containing 11.4 pCi/L of radium-226. The radium-226 was reduced to 0.4 pCi/L in this study.

Ion exchange and HMO removed GAA in the cases described above because it was associated with either the radium or uranium in the source water. Since ion exchange and HMO are not BATs or SSCTs for adjusted GAA, additional research is required to support these technologies as compliance alternatives. Specifically, it was recommended to CO-RADS systems that removal of GAA by ion exchange and HMO be tested on a system-specific basis (e.g., every system participating in CO-RADS that is out of compliance with adjusted GAA and is considering ion exchange or HMO as a compliance solution should conduct some bench/pilot testing) before an ion exchange or HMO treatment system is designed for compliance with the adjusted GAA MCL.

The list of treatment technologies were evaluated for their feasibility for application at CO-RADS systems. The results of this evaluation are summarized in Table 4-5.

Table 4-5.
Potential CO-RADS Treatment Technologies

Treatment Technology	Contaminant Removed	Consistently Achieves ~0.5x MCL	Operational Complexity and Certification	Worker Exposure to Radiation	Industry Experience with Technology	Primary Reasons Technology was not Further Evaluated
Ion Exchange						
Anion exchange	Uranium and adjusted GAA[1]	Yes	Intermediate	Low – if proper operational and safety procedures are in place	Widely used	Technology was further evaluated
Cation exchange	Radium and adjusted GAA[1]	Yes	Intermediate	Low – if proper operational and safety procedures are in place	Widely used	Technology was further evaluated
Adsorption						
Activated alumina (regenerated)	Uranium	Yes	Advanced – handling of chemicals during regeneration and pH adjustment	Low – if proper operational and safety procedures are in place	Very limited	• Treats 1,000's of bed volumes compared to 10,000-300,000 for anion exchange • System operation is complex • Very limited use in industry • Input from industry expert
Activated alumina (disposable)	Uranium	Yes	Advanced – chemicals handling of chemicals for pH adjustment	Low – if proper operational and safety procedures are in place	Very limited	
Greensand filtration	Radium	No – percentage removal typically ranges from 50 to 60%	Basic	Potentially high – radium accumulates on media	Wide	• Not confident it will achieve compliance • Worker exposure considerations and residuals management
Membranes						
High pressure membranes (RO/NF)	Uranium, radium, and adjusted GAA	Yes	Advanced	Low	Widely used	Technology was further evaluated
Electrodialysis-electrodialysis reversal (ED/EDR)	Uranium and Radium	Yes	Basic to intermediate	Low	Extremely limited use	• Extremely limited use • No identified benefit over RO/NF

Treatment Technology	Contaminant Removed	Consistently Achieves ~0.5x MCL	Operational Complexity and Certification	Worker Exposure to Radiation	Industry Experience with Technology	Primary Reasons Technology was not Further Evaluated
Physical/chemical Removal						
Lime softening	Uranium and Radium	Yes	Advanced	Low	Widely used	Technology was further evaluated for systems serving >10,000 customers
Enhanced coagulation	Uranium	Yes	Advanced	Low	Widely used	Technology was further evaluated for systems serving >10,000 customers
Hydrous manganese oxide (HMO)	Radium and GAA[2]	Under certain conditions[3]	Intermediate	Potentially high – requires thorough filter backwashing process to mitigate	Limited	Technology was further evaluated
Co-precipitation with barium sulfate	Radium	? – requires high sulfate in raw water or addition of sulfate	Intermediate to advanced	Low	Very limited	• Not confident it will achieve compliance • Requires static mixing, detention basin, and filtration

[1]Research indicates that adjusted GAA association with uranium can be removed from water using anion exchange (CO-RADS bench scale testing results and Varani, F.T. et al 1987) and GAA associated with radium can be removed by cation exchange (CO-RADS bench testing results).
[2]Bench-scale tests conducted as part of CO-RADS indicate 1.0 mg/L of HMO can remove GAA associated with the radium removed through the process.
[3] There is limited use of HMO in the water treatment industry for radium removal. As such, there is minimal published data that demonstrate radium removal by HMO under varying source water quality conditions. Limited bench-test results conducted as part of CO-RADS indicate that HMO may be a feasible technology for radium removal, though more testing is needed to confirm consistent removal below the MCL for different source waters and in full-scale applications.

Table 4-6 summarizes the treatment technologies that were and were not further evaluated for CO-RADS systems based on the information provided in Table 4-5.

Table 4-6.
Summary of Treatment Technologies Evaluated for CO-RADS

Further Evaluated	• Anion Exchange • Cation Exchange • High Pressure Membranes
Further Evaluated for Select Systems	• Lime Softening – system with more than 10,000 customers • Enhanced Coagulation – systems with more than 10,000 customers • Hydrous Manganese Oxide (HMO)
Not Further Evaluated	• Activated Alumina • Greensand Filtration • Electrodialysis / Electrodialysis Reversal • Co-precipitation with Barium Sulfate

CDPHE decided to focus resources on proven treatment technologies that would confidently provide CO-RADS systems with compliance. As shown in Table 4-6, ion exchange and RO/NF were the only treatment alternatives that were further evaluated for all CO-RADS systems. Ion exchange typically included cation exchange and anion exchange, though radium selective complexer (RSC) (a form of cation exchange) was defined for one system. In general, RSC was avoided due to accumulation of high levels of radium on the resin that could lead to worker exposure issues and the need for a Radioactive Materials License.

Lime softening and enhanced coagulation were selected to be further evaluated for systems serving more than 10,000 customers. HMO was further evaluated for two types of systems:

1. Systems that had existing sand filtration and
2. Systems that would need to install sand filtration as pretreatment for other treatment alternatives

In the case of systems that already had sand filtration, Pirnie was not able to fully evaluate filtration and backwash capabilities of the systems for radium removal; therefore, cost estimates for HMO conservatively assume full replacement of the filters in the applicable CO-RADS Reports. HMO cost estimates can be further evaluated, and potentially reduced, by the system if existing filtration is in place. Both HMO options (with existing or new pressure filters) assume the system would be willing to implement demonstration testing and work closely with CDPHE to approve this treatment technology.

The remaining technologies listed in Table 4-6 were not further evaluated for CO-RADS systems. These technologies may be found to be preferred for certain systems upon further research, testing, and investigation.

4.3.2. Liquid Residuals Disposal Options

Disposal of liquid residuals produced by technologies used to treat radionuclide-contaminated water is one of the primary challenges with treatment for radionuclides. Alternatives for treating and disposing liquid residuals from these treatment processes were evaluated. The liquid residuals disposal options for CO-RADS and their relative costs are illustrated in Figure 4-6.

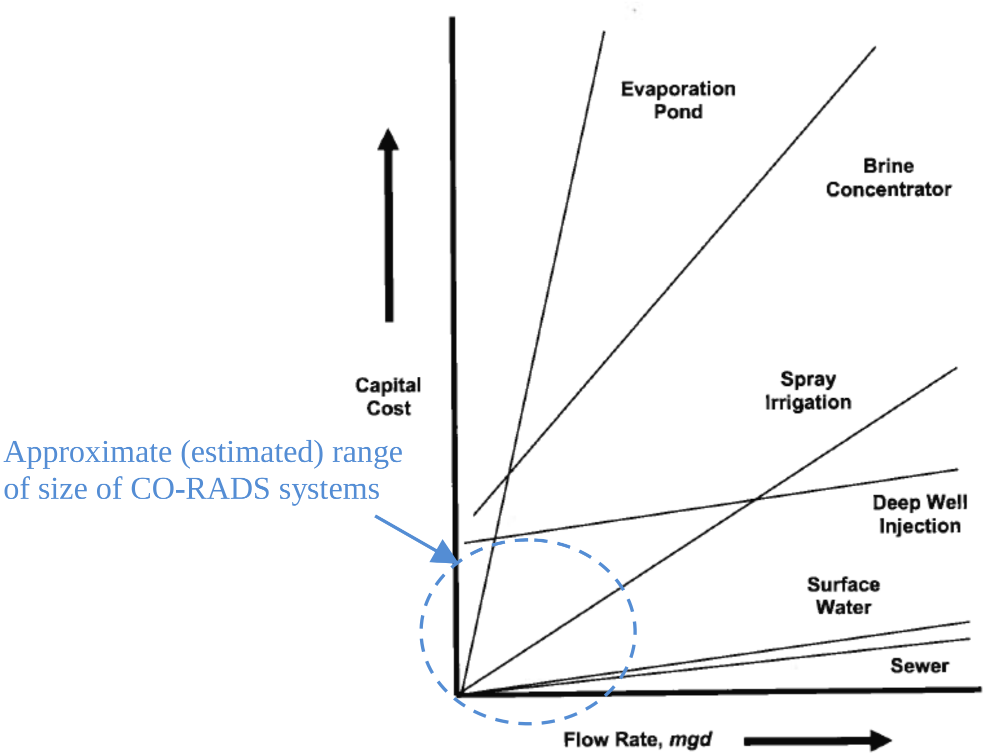


Figure 4-6.
Relative capital cost of concentrate management options (AWWA, 2007)

If treatment of liquid residuals on-site is not feasible (e.g., evaporation pond), the system will be faced with significant challenges regarding the handling and disposal of the waste streams by other methods. A summary of the obstacles faced by CO-RADS systems for implementing these various liquid residuals disposal options is provided in Table 4-7.

Table 4-7.
Summary of Feasibility of Liquid Residuals Disposal Options

Disposal Options	Obstacles for CO-RADS Systems	Further Evaluated for CO-RADS?
Evaporation pond	• Very large and expensive for RO/NF liquid residuals	Yes
Surface water	• Significant permitting challenges • Liquid would likely require treatment prior to discharge • This may be a feasible option for some CO-RADS systems pending further evaluation	No
Sewer/POTW	• Few systems have POTWs • Capacity, treatment technology, and discharge requirements • Potential impact to POTW treatment process • This may be a feasible option for some CO-RADS systems pending further evaluation	No
Spray irrigation	• Only if discharge provides a benefit to the land other than water; RO/NF and ion exchange brines and HMO backwash do not provide a benefit.	No
Deep well injection	• Impractical for various permitting and financial reasons	
Brine concentrator (ZLD)	• Cost prohibitive	

The analyses conducted as part of CO-RADS assumed RO/NF, ion exchange, and HMO liquid residuals were treated in a lined evaporation basin built on-site (as discussed later in Section 4.4). This assumption has a significant impact on costs for RO/NF treatment systems. RO/NF treatment technologies produce a large volume of liquid residuals. Specifically, significant volumes of water are rejected by the membranes (as a percentage of raw water flow there will be approximately 15 to 40% wasted, depending on the type of membranes and other water quality parameters) that must subsequently be handled and disposed of. CDPHE indicated from recent permitting and approval efforts that RO/NF would be a challenging technology solution for small communities to implement because of the following:

- ***Significant challenges permitting discharges of wastes directly to surface waters in Colorado*** **–** while this may be a feasible solution for some communities participating in CO-RADS, the permitting will be very challenging. In order to meet radionuclide stream standards for the specific segment where the discharge would occur, there would need to be significant dilution in that segment. Additionally, CDPHE indicated that water quality parameters other than radionuclides (such as total dissolved solids, nitrate, or selenium) may limit the ability of CO-RADS systems to comply with permit requirements, depending on the water body and the contaminants in the waste stream. Pirnie suggested that systems wishing to evaluate this alternative contact the WQCD Permits Unit to discuss feasibility.

- ***Waste discharge to publicly owned treatment works (POTWs) will only be allowed at the influent to the facility*** **–** in cases where CO-RADS systems have POTWs, CDPHE's current position is that an RO/NF concentrate waste stream would need to be treated through the POTW (not just blended with the effluent). Depending on the type of treatment at the POTW, this can pose a significant issue to maintaining biological treatment integrity (the POTWs can be disturbed when significant volumes of water with high concentrations of total dissolved solids start passing through the facility) and can also impact the ability of the POTW to meet all discharge permit requirements. CO-RADS systems' POTWs were not evaluated as part of this project; therefore, RO/NF with disposal to POTW could not be fully evaluated or recommended as part of this project. However, this could be an option for systems that further evaluate the capacity of their POTWs to receive and treat RO/NF waste and work with CDPHE to permit this disposal alternative.
- ***Other waste handling and disposal options for small communities participating in CO-RADS*** – CDPHE is currently participating in the Membrane Treatment Workgroup to evaluate other potential handling and disposal options for high pressure membrane waste. These include evaporation basins and techniques referred to as zero liquid discharge. These techniques can be land intensive and costly and technologies other than evaporation basins have not been widely tested or proven.

For the relatively low flow rates that would be treated by CO-RADS systems, discharge to sewer, discharge to surface water, and spray irrigation may have been less expensive; however site specific evaluations of discharge to sewer and surface water could not be evaluated in sufficient detail in this project and spray irrigation is only viable if the waste stream provides beneficial land use.

4.3.3. Proprietary Solutions

Proprietary solutions were also considered as a treatment alternative for CO-RADS systems. Several companies provide packaged treatment equipment, system operations, and residuals disposal into one contractual agreement that allows the system to comply with the Radionuclides Rule. Treatment technologies employed under these packages are covered in Table 4-4, but are frequently operated differently, requiring specific approval by CDPHE. Currently, none of these solutions have been approved by CDPHE in the State of Colorado, but they have been employed successfully elsewhere in the United States. CDPHE is open to systems using this as a compliance alternative. Unfortunately, Pirnie and WQCD were unable to evaluate proprietary solutions separately for each CO-RADS system because of the need for site-specific vendor quotes. Systems were encouraged to evaluate this option further, and information provided in the CO-RADS Reports should be useful for cost comparisons.

4.3.4. Non-Treatment Alternatives

Treatment of existing water sources is not the only compliance option for CO-RADS systems. However, these options were difficult for Pirnie and WQCD to evaluate in detail due to significant non-regulatory and non-cost factors. Therefore, systems were given information to perform an evaluation of non-treatment alternatives in the CO-RADS Reports. Non-treatment alternatives could include the following:

- ***Regional entity responsible for water supply*** – Connect to a neighboring system that is supplying water in compliance with the Radionuclides Rule or connect to a system that is planning a new treatment facility for radionuclides removal. Due to the numerous possibilities associated with this option such as, the need for agreements between entities to be established, impact to water rights, and other considerations, Pirnie and WQCD were unable to thoroughly evaluate each possibility and whether systems had the desire and capability to regionalize and address associated issues. A matrix summarizing preliminary regionalization information collected through CO-RADS is included in Appendix I.
- ***Supplement existing source with another source*** - Obtain another source of water, either groundwater or surface water, that is not contaminated by radionuclides to supplement or replace a contaminated source. There is a risk associated with pursuing new sources, particularly when drilling new wells that the new source may not be of sufficient water quality; therefore, in general, Pirnie and WQCD could not make recommendations regarding this option with confidence.
- ***POU and POE treatment devices*** – Treatment devices located at the customers ‘connection points’ may be a feasible alternative for smaller systems. The Interim Measures and Point-of-Use and Point-of-Entry Treatment Evaluation Report (Malcolm Pirnie, 2008b) outlines the potential requirements for using these types of devices as a compliance option. Currently, CDPHE has not approved these devices for use in Colorado. A recent study on POU for arsenic removal (Narasimhan et al, 2005) found that the annualized cost breakpoint for POU reverse osmosis and POU adsorption (using throw away media) compared to centralized treatment was 120 and 200 connections, respectively. In general, POU will only be considered for systems serving less than approximately 120 to 200 connections. In order for a system to implement POU or POE, there are a number of liabilities and responsibilities that a system must take on. In general, Pirnie and WQCD were unable to evaluate whether systems had the desire to take on such liabilities and responsibilities. CDPHE is currently working on its POU/POE policy and plans to have it completed Spring 2009.

It is important for systems to consider regionalization opportunities other than those described in the first bullet above that could result in cost savings for systems, including the following:

- Coordination of chemical orders and deliveries to receive a lower bulk rate
- Regionalization residuals handling, shipping, or disposal options

- Coordinated public outreach and education efforts

For most CO-RADS systems, cation exchange or anion exchange were defined in more detail as compliance options. However, based on water quality and site-specific issues, other treatment technologies were also defined, including HMO, radium selective ion exchange, RO, and conventional treatment.

4.4. Task 4: Residuals Handling and Disposal and Worker Exposure

Decisions made through the RMW had the following impact on CO-RADS systems:

- Direction received from the RMW was that direct surface water discharge, groundwater discharge, spray irrigation, and deep well injection would face significant permitting challenges and may not be feasible options, and therefore, CDPHE determined that significant attention and resources should not be focused on evaluating these options.
- Pirnie should assume that blending of liquid residuals and POTW effluent would not be permitted. The discharge of liquid residuals to the influent of the POTW, so that the residuals would be treated by the process, would be permitted, however, the POTW may be subject to permit modifications. Furthermore, evaluation of the capacity of the POTW to handle such waste or evaluating potential permit modifications was beyond the scope of this project.
- After other options were ruled out through the work with the RMW, the RMW provided direction to Pirnie to assume that, in general, liquid residuals produced by treatment systems at CO-RADS systems would be treated in a concrete-lined evaporation basin. This basin would be supplemented with one foot of soil that would periodically be removed and disposed of at an acceptable facility. CO-RADS Reports assumed the soil would be disposed of at a Resource Conservation and Recovery Act Level C (RCRA C) landfill. Information on alternative disposal strategies was provided to each CO-RADS system; however, the systems must work with CDPHE to evaluate these alternatives.
- A template for a residuals management plan (RMP) was provided to each CO-RADS system. An RMP must be completed by each system in the design phase of the project before it can be approved by CDPHE. Pirnie developed a significant amount of information for each CO-RADS system that could be used to complete a RMP.
- Results of the worker exposure modeling (described in Section 3.4) were reviewed by CDPHE. CDPHE determined the estimated levels of radiation around ion exchange treatment equipment could be mitigated and would not likely require a Radioactive Materials License. As a result, cation exchange and anion exchange were the selected defined compliance alternatives for many of the CO-RADS systems.

4.4.1. Monitoring and Mitigating Worker Exposure

Based on the findings of the CO-RADS worker exposure evaluation, it appears that radiation exposure issues can be mitigated by limiting the time that operators are in close proximity to treatment vessels (particularly ion exchange). Additional site-specific modeling and confirmation of this analysis should be performed by CO-RADS systems to confirm modeling assumptions and findings if a compliance alternative involves treatment.

The magnitude of radiation exposure can vary and is primarily based on time of exposure, distance from the source, and shielding between the source and the dose. Options for reducing gamma exposure based on these factors are described below:

- *Time* - amount of time that the person is exposed to the radiation. The practice of measuring the hourly exposure at different areas in the vicinity of the vessels when they are close to being removed would provide information on worker exposure. The room could be gridded and exposures at each grid point known prior to any work in the area. A work order that limits the exposure could be created before any work in the area. The work order limits would need to be strictly followed.
- *Distance* - amount of space between the worker and the source of radiation. Radiation dose is a function of the distance from the vessels. Radiation doses decrease quickly the further away a person is from the vessels. The grid approach described above would provide a way to determine the radiation dose at varying distances from the vessels.
- *Shielding* - different materials that separate the worker from the source of radiation can reduce the amount of exposure. For example, 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. The shield would have to be wide enough to shield gamma rays from all of the vessels. An alternative would be to 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, which is an unlikely event.

In general, shielding will likely not be required for CO-RADS systems to implement the defined alternative in the CO-RADS Reports. However, exposure monitoring should be conducted to verify this assumption after treatment has been installed and operation. Additionally, 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 owner/manager 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 (i.e., per worker).

Exposures outside the water treatment 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. It would be prudent to fence in the facility to keep the public away and minimize any public exposure. Instead of a fence, landscaping could be strategically constructed around the area to increase the distance from the building by a few feet, which would eliminate the dose from the vessels for all practical purposes.

4.5. Task 5: Bench and Pilot Testing

A summary of the results of the CO-RADS bench and pilot testing efforts and of the advantages and disadvantages of each technology tested is provided in Table 4-8. Removal of radionuclides by each treatment technology varied in the testing. These results are for specific water qualities; therefore, additional testing should be considered by systems for a specific treatment technology to confirm removal and system-specific design criteria. The Bench and Pilot Testing Report is included in Appendix J.

Table 4-8.
Summary of CO-RADS Bench- and Pilot-Scale Testing Results

Treatment Technology	Conditions Tested	Radionuclide Removal Observed in Testing (%)	Advantages	Disadvantages	Additional Considerations for CO-RADS Systems
Nanofiltration	Flat sheet membrane and pilot tests	• Radium-226: 98-99% • Uranium: 95-98% • GAA: 71-96% • Gross Beta:92-93%	• Can address other water quality (and potentially compliance) issues (e.g., TDS, hardness, sulfate) • Operates at higher recovery than RO • Operates at lower pressure than RO (relatively lower energy costs) • Is a physical barrier to radionuclides – treatment disruptions will not impact radionuclide removal	• Large volume of liquid residuals to manage • Low water recovery • May require pre- and post-treatment • Energy intensive	• Significant volume of liquid residuals produced • Requires a Class C operator certification to operate • Site-specific testing is recommended to determine design criteria, potential fouling, and pre- and post-treatment needs.
Reverse Osmosis	Flat sheet membrane tests	• Radium-226: 98% • Uranium: not tested • GAA: 92% • Gross Beta: 93%	• Can address other water quality (and potentially compliance) issues (e.g., TDS, hardness, sulfate) • Is a physical barrier to radionuclides – treatment disruptions will not impact radionuclide removal	• Very large volume of liquid residuals to manage • Low water recovery • Will likely require pre- and post-treatment • Very energy intensive	• Significant volume of liquid residuals produced • Requires a Class C operator certification to operate • Site-specific testing is recommended to determine design criteria, potential fouling, and pre- and post-treatment needs.

Treatment Technology	Conditions Tested	Radionuclide Removal Observed in Testing (%)	Advantages	Disadvantages	Additional Considerations for CO-RADS Systems
Enhanced Coagulation	Alum doses of 5, 10, and 20 mg/L at pH 6.2 and 7.5; Raw uranium concentration = 47 μg/L	• Radium-226: not tested • Uranium: 19-87% • GAA: 0-82% • Gross Beta: not tested	• TOC and particles also removed	• Results in radionuclide accumulation in treatment plant sludge • Requires significant infrastructure if conventional treatment is not already in place • Is not a physical barrier to radionuclides; treatment must be carefully controlled to achieve targeted removal	• Not recommended for systems serving less than 10,000 customers • Site-specific bench-scale tests recommended • Continuous optimization may be required • Requires a Class B operator certification to operate
	Ferric doses of 5, 10, and 20 mg/L at pH 6.2 and 7.5 (20 mg/L dose not tested at pH 6.2) ; Raw uranium concentration = 47 μg/L	• Radium-226: not tested • Uranium: 0-36% • GAA: 0-15% • Gross Beta: not tested	• TOC and particles also removed	• Tests did not show significant removal of uranium for any of the scenarios tested • Results in radionuclide accumulation in treatment plant sludge • Requires significant infrastructure if conventional treatment is not already in place	• Not recommended for systems serving less than 10,000 customers • Site-specific bench-scale tests recommended • Continuous optimization may be required • Requires a Class B operator certification to operate
Cation Exchange	Purolite C-100E resin; Regenerated after hardness breakthrough	• Radium-226: effluent concentration ≤ 0.5 pCi/L in all samples • Uranium: not tested • GAA: ≤ 4 pCi/L in waters with no uranium; little removal in waters	• Hardness also removed	• Not a physical barrier to radionuclides; system can produce water with radionuclides exceeding the MCL if not operated correctly	• Site-specific bench-scale tests are recommended to confirm design parameters • Requires a Class C operator certification to

Treatment Technology	Conditions Tested	Radionuclide Removal Observed in Testing (%)	Advantages	Disadvantages	Additional Considerations for CO-RADS Systems
		with uranium • Gross Beta: not tested		• Pre- and post-treatment may be required • Radium will accumulate in the resin	operate
HMO	Doses of 0.5 and 1.0 mg/L	• Radium-226: 52-96% • Uranium: not tested • GAA: 37-92% (GAA associated with uranium not removed in one water) • Gross Beta: not tested	• Can be added as a retrofit to an existing filtration system	• May not reduce combined radium and gross alpha to levels below the MCLs in waters with elevated levels of radium • No installations in CO and few in the US • Sludge produced contains high levels of radium • Removal of radium varies • HMO dose limited at ~1.0 mg/L due to discoloration of water above that dose	• Demonstrating testing likely required • Existing filters may need upgrade to backwash system • Requires a Class B operator certification to operate

4.6. Task 6: CO-RADS Reports

There are some distinct differences between the CO-RADS Reports and a typical PER. A typical PER is developed for a water system by an engineering firm that the system has hired. Throughout the development of the PER, the engineering firm has ongoing contact with the system and the system selects the recommended compliance option that is presented in the PER. The CO-RADS Reports were developed by an engineering firm hired by WQCD, Malcolm Pirnie, Inc. The scope of this project did not allow for Pirnie to have extensive contact with the systems, and therefore, the system has not necessarily selected the compliance option defined in the CO-RADS Report. As such, the system may elect to pursue an alternate option.

A comparison of a PER and a CO-RADS report is provided in Table 4-9.

Table 4-9.
Comparison of a PER and the CO-RADS Reports

PER	CO-RADS Reports
• Planning: used for budgeting and scheduling • Variable level of detail and associated cost accuracy • Subsequent design stages and associated cost accuracy provide more project definition • Definitive selection of alternative with which to proceed	• CO-RADS Report will provide groundwork for PER development • Defined alternative is the best option within the constraints of the CO-RADS project - system ultimately decides which option to move forward with • Defined alternative can serve as a comparison to other options • Definitive level of design detail (15%) for defined alternative • Level 4 cost estimates with accuracy of -20% to +30%

The CO-RADS Reports contained the following recommendations to systems for steps to take after receiving their CO-RADS Reports to begin moving forward with compliance with the Radionuclides Rule:

- Review CO-RADS Report
- If desired, evaluate alternate compliance alternatives to compare to the “Defined Alternative” selected in Section 7
- Select preferred compliance option
- Finalize PER
  - Can be done as an addendum to the CO-RADS Report

- Verify/supplement sections 3-5 (which pertains to the system's background information)
- If defined option in CO-RADS Report is selected, no further modification is needed, unless to supplement sections 3-5.
- If an alternate option is selected (other than the "Defined Alternative" described in Section 7), recreate Section 7 of this Report for the new alternative

- Submit to WQCD for review

4.6.1. Fundamental Assumptions and Summary of Defined Alternatives

Several important assumptions were made through the CO-RADS Report development process that impacted the defined alternatives and associated cost estimates:

- All liquid residuals from radionuclide treatment processes would be treated in concrete-lined evaporation basins constructed on the site. These basins would be supplemented with one-foot of soil and radionuclides would accumulate in the soil as water evaporates. It was assumed the basin(s) would be cleaned at least every 20 years or more frequently, depending on the treatment system and basin design for the specific system.
- Design of radionuclide treatment processes that would potentially result in the system needing a Radioactive Materials License were avoided to the extent possible. Only in cases where systems with radium contaminated source waters also had very high hardness was radium selective ion exchange considered.
- Systems were designed redundancy per CDPHE's Design Criteria for Potable Water Systems. For example, ion exchange treatment systems were typically designed to always have one vessel in service and one in standby. While redundancy may result in increased capital cost, lack of redundancy could result in increased risk of water system down time and increased O&M costs.
- For the most part, 100% of the flow was assumed treated by the proposed treatment alternative. This assumption is based on the highly variable nature of radionuclide analysis in the laboratory making it difficult to determine blending ratios and the required safety factor of treating to 50% of the MCL, which in most cases didn't allow for much raw water blending.
- Discharges to POTW, where available, were not evaluated. This would have required highly detailed information on treatment system design and operation that was not part of the project scope. It would have also required several substantial assumptions by the project team and CDPHE about effluent limits and the build up of radioactive material in the plant biomass. In the case of RO permeate, the tolerability of the biological process to very high salinity would have to be investigated and verified.
- Blending liquid residual streams with wastewater effluent was not evaluated based on a recommendation from the RMW.

- Operator time requirements were assumed to be 20 hours a week, on an annual basis, to perform additional operation and maintenance duties associated with the additional treatment processes in the defined alternative.

Several potential compliance alternatives could not be evaluated through CO-RADS. Therefore, an “Additional Information” section was included in each Report to provide systems with information to assist evaluation of these alternatives, including POU/POE treatment, proprietary solutions, regionalization, and high pressure membranes. The information provided in each of the CO-RADS Reports is included in Appendix K.

A summary of the defined compliance alternatives for the CO-RADS systems is provided in Table 4-10. Defined compliance alternatives were not provided for the following systems:

- Las Animas already has treatment in place; therefore, its Report contained information on residuals handling options.
- Red Hill Forest and Blue Mountain Water District both have treatment in place (ion exchange); therefore, opinions of probable cost were provided for installation of a lined evaporation basin to treat liquid residuals.
- Sterling is the largest CO-RADS system and has a challenging situation regarding compliance with the Radionuclides Rule. Per CDPHE’s recommendation, Pirnie provided opinions of probable cost for three treatment alternatives, but did not select a defined alternative for the City.

Table 4-10.
Summary of Defined Alternatives for CO-RADS Systems

System Name	Compliance Alternatives Considered	Defined Compliance Alternative
Antelope Hills HOA	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Aspen Park MD	*RO/NF *Cation exchange	Cation Exchange
Blue Mountain Water District	District already has treatment in place – opinions of probable cost were provided for a lined evaporation basin	
Buffalo Park Development (aka Homestead Water)	*RO/NF *Anion exchange	Anion Exchange
Camelot Subdivision	*RO/NF *Cation exchange *HMO	Cation Exchange
Eureka Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Fayette Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange

System Name	Compliance Alternatives Considered	Defined Compliance Alternative
Hancock Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Hillside Trailer Park	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Holly, Town of	*RO/NF *Cation exchange *HMO	Cation Exchange
Kit Carson, Town of	*RO/NF *Anion exchange	Oxidation/Filtration + Anion Exchange
Larkspur, Town of	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Las Animas, City of	City already has treatment – information on residuals handling was provided	
Manzanola, Town of	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
May Valley Water Association	*RO/NF *Cation exchange *RSC *HMO	Radium Selective Complexer
Merino, Town of	*RO/NF *Anion exchange	Anion Exchange
Mountain Shadows	*RO/NF *Cation exchange *HMO	Cation Exchange
Mountain Water and Sanitation District	*RO/NF *Anion exchange + Cation exchange *Anion exchange + HMO	Anion Exchange + Hydrous Manganese Oxide
North Holbrook Water Company	*RO/NF *Cation exchange *HMO	Cation Exchange
Park Water Company Wonderview	*RO/NF *Anion exchange	Anion Exchange
Patterson Valley Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Redhill Forest	District already has treatment in place – opinions of probable cost were provided for a lined evaporation basin	
Sheridan Lake Water Company	*RO/NF *Anion exchange	Anion Exchange
South Swink Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange

System Name	Compliance Alternatives Considered	Defined Compliance Alternative
Sterling, City of	*RO/NF *Conventional Treatment (enhanced coagulation)	Cost estimates were provided for both treatment technologies
Swink, Town of	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Turkey Canon Ranch Water District	*RO/NF *Anion exchange	Anion Exchange
TV Hills Water	*RO/NF *Anion exchange (system already has cation exchange)	Oxidation/Filtration + Cation Exchange + Anion Exchange (replacement of existing cation exchange)
Valley Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Vroman Water Company	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange
Wayward Wind Mobile Home Park	*RO/NF *Anion exchange	Anion Exchange
Whispering Pines Mobile Home Park	*RO/NF *Cation exchange	Cation exchange
Wiley, Town of	*RO/NF *Cation exchange *HMO	Oxidation/Filtration + Cation Exchange

A summary of the treatment processes defined for each CO-RADS system is provided in Figure 4-7. Cation and anion exchange systems (with and without oxidation/filtration pretreatment for iron and manganese) were the defined alternatives for most of the systems.

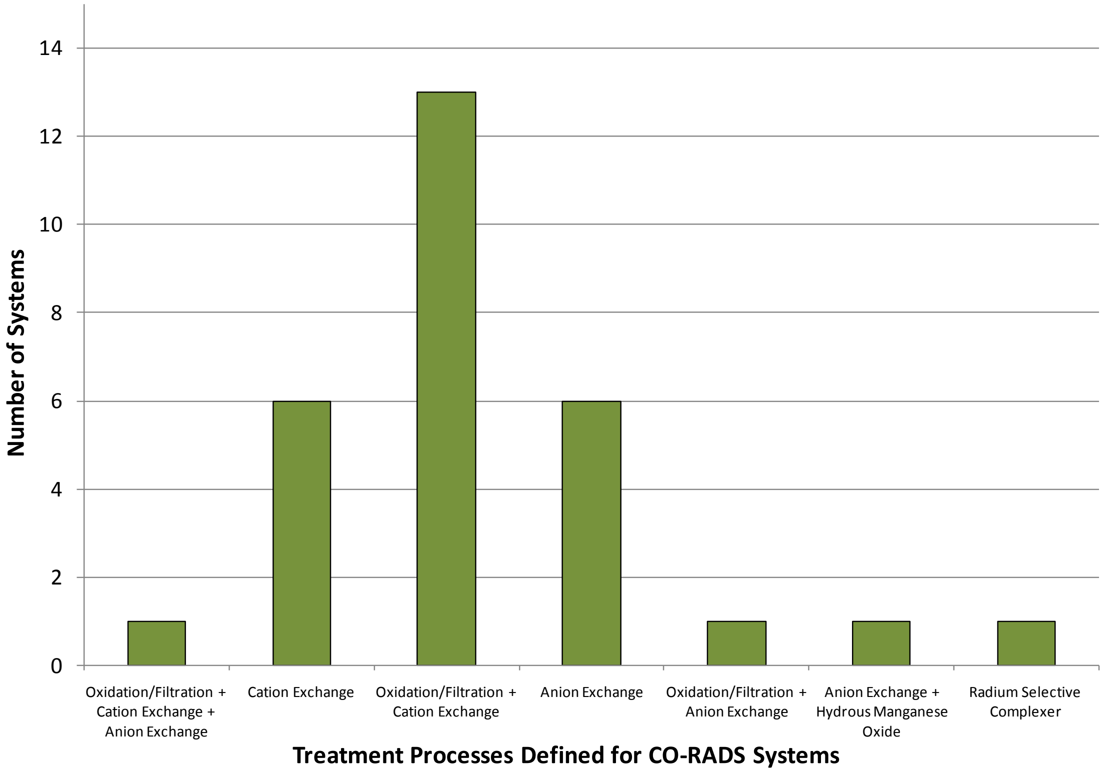


Figure 4-7.
Summary of Treatment Processes Defined for CO-RADS Systems

4.6.2. CO-RADS Costs Compared to EPA Costs

Opinions of probable cost for the compliance alternatives defined for CO-RADS systems varied depending treated flow rates, water quality, pretreatment requirements, and site-specific constraints and conditions. Opinions of probable costs developed for CO-RADS systems were compared to costs estimated using the method used by EPA for the Radionuclides Rule (USEPA, 2000a). EPA costs estimates were developed as described in the referenced document based on models and surveys and applied to CO-RADS systems based on design and average flows and cost curves. A summary of the major differences in assumptions for the EPA and CO-RADS cost estimates is provided in Table 4-11. This list is not complete, but captures some of the major differences between the two cost estimates.

Table 4-11.
Primary Differences in EPA and CO-RADS Cost Development Assumptions

Design/cost Element	CO-RADS Assumption	EPA Assumption	Impact on CO-RADS Costs
Additional capital costs	Site work: 15% of capital Yard piping: 10% of capital Interior piping: 15% of capital Electrical, instrumentation and control: 20% of capital General conditions: 15% of capital, including above fees Engineering, legal, and administrative: 25% of capital, including above fees	Cost indices from Bureau of Labor and Statistics applied	Could not be determined from existing EPA data
Volume of water treated by ion exchange	Cation exchange - varied per based on water quality (hardness) between ~130 and 1,300 bed volumes Anion exchange – volume treated ranged from 10,000 to 50,000 bed depending on water quality	Fixed volume treated (150 bed volumes for cation exchange and approximately 300 bed volumes for anion exchange)	Bed volumes to breakthrough has a significant impact on capital and O&M cost estimates for cation exchange systems. In general the assumptions for anion exchange should results in lower CO-RADS capital cost estimates compared to EPA cost estimates, but this depends on pretreatment and other design considerations.
Evaporation basin	Sized based on daily average flow rate Concrete-lined basin (1-foot thick) supplemented with one foot of soil Solids disposed of at a RCRA C landfill	Sized based on daily average flow rate Synthetic membrane liner with geotextile support fabric supplemented with one foot of sand Solids disposed of at a non-hazardous landfill	Due to these differences, capital costs estimated for CO-RADS were much higher than those for EPA. For example, CO-RADS capital costs were an order of magnitude higher than EPA costs for the two systems that only received costs for evaporation basins.
Pretreatment	Pretreatment included in some cases to remove iron, manganese, and/or particles Costs for pretreatment included in capital and/or O&M costs depending on the site-specific situation	Do not include pretreatment	Significantly increases capital and O&M costs for applicable systems.

Design/cost Element	CO-RADS Assumption	EPA Assumption	Impact on CO-RADS Costs
Labor	One half-time employee assumed for all systems ($20,000 per year)	Hourly labor estimated as $28-$40/hour depending on system size (the number of hours per system was not provided in the EPA cost document)	Significantly increases O&M cost estimates.
Electricity	$0.10/kWh	$0.08/kWh	

The EPA and CO-RADS costs developed for compliance alternatives for each system are compared in Table 4-12. NPV costs are shown for both CO-RADS and EPA estimates. Capital and 20-year O&M NPV CO-RADS costs are also shown in Table 4-12, while capital and 20-year O&M NPV EPA costs are included in Appendix L. The accuracy ranges of EPA and CO-RADS cost estimates were -20% to +30% for CO-RADS and -30% to +50% for EPA. A wider range of accuracy was applied to the EPA costs because these values are based on cost curves and general treatment assumptions, whereas CO-RADS costs are based on site-specific information and vendor quotes.

Blue Mountain, Las Animas, and Red Hill Forest are not included in the table because compliance alternatives were not defined for these systems. Mountain WSD is not included because EPA did not develop costs for hydrous manganese oxide treatment.

Table 4-12.
Comparison of EPA and CO-RADS Cost Estimates for Complying with the Radionuclides Rule

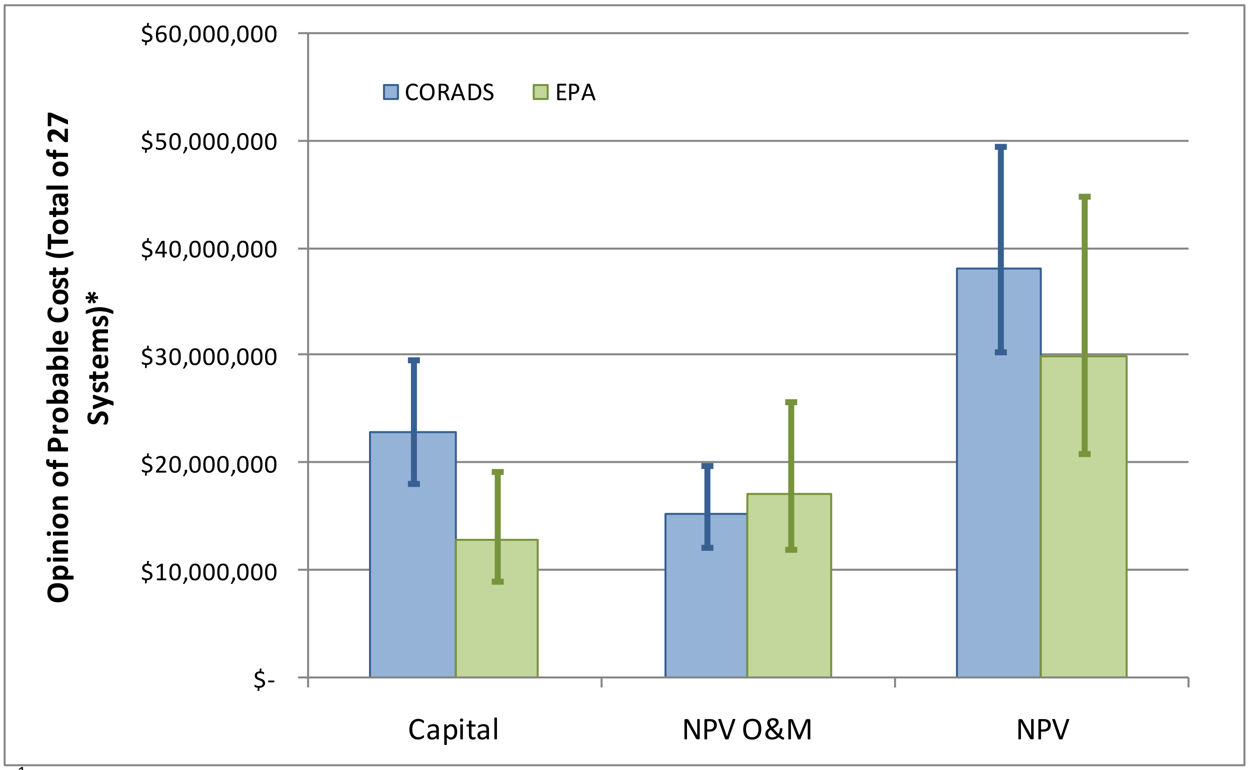
System Name[1]	CO-RADS Methodology: CO-RADS Total Project Cost	CO-RADS Methodology: NPV -20%	CO-RADS Methodology: NPV +30%	EPA Methodology: EPA Total Project Cost	EPA Methodology: NPV -30%	EPA Methodology: NPV +50%
Antelope Hills HOA	$ 1,590,000	$ 1,272,000	$ 2,067,000	$ 810,000	$ 567,000	$ 1,215,000
Aspen Park MD	$ 880,000	$ 704,000	$ 1,144,000	$ 790,000	$ 553,000	$ 1,185,000
Buffalo Park/ Homestead Water	$ 1,310,000	$ 1,048,000	$ 1,703,000	$ 1,540,000	$ 1,078,000	$ 2,310,000
Camelot	$ 560,000	$ 448,000	$ 728,000	$ 560,000	$ 392,000	$ 840,000
Eureka WC	$ 1,340,000	$ 1,072,000	$ 1,742,000	$ 1,230,000	$ 861,000	$ 1,845,000
Fayette WC	$ 1,240,000	$ 992,000	$ 1,612,000	$ 690,000	$ 483,000	$ 1,035,000
Hancock WC	$ 1,030,000	$ 824,000	$ 1,339,000	$ 1,790,000	$ 1,253,000	$ 2,685,000
Hillside TP	$ 1,100,000	$ 880,000	$ 1,430,000	$ 780,000	$ 546,000	$ 1,170,000
Holly, Town of	$ 3,500,000	$ 2,800,000	$ 4,550,000	$ 1,860,000	$ 1,302,000	$ 2,790,000
Kit Carson, Town of	$ 1,760,000	$ 1,408,000	$ 2,288,000	$ 1,640,000	$ 1,148,000	$ 2,460,000
Larkspur	$ 1,310,000	$ 1,048,000	$ 1,703,000	$ 1,060,000	$ 742,000	$ 1,590,000
Manzanola, Town of	$ 2,160,000	$ 1,728,000	$ 2,808,000	$ 1,310,000	$ 917,000	$ 1,965,000
May Valley WTP#1 ($*10)[2]	$ 1,060,000	$ 848,000	$ 1,378,000	Costs were not developed by EPA for treatment of radium by a radium selective complexer.		
May Valley WTP #2 ($*10)[2]	$ 1,540,000	$ 1,232,000	$ 2,002,000			
Merino, Town of	$ 1,040,000	$ 832,000	$ 1,352,000	$ 3,210,000	$ 2,247,000	$ 4,815,000
Mountain Shadows	$ 860,000	$ 688,000	$ 1,118,000	$ 780,000	$ 546,000	$ 1,170,000
North Holbrook	$ 400,000	$ 320,000	$ 520,000	$ 540,000	$ 378,000	$ 810,000
Park WC Wonderview	$ 560,000	$ 448,000	$ 728,000	$ 490,000	$ 343,000	$ 735,000
Patterson Valley WC	$ 1,160,000	$ 928,000	$ 1,508,000	$ 730,000	$ 511,000	$ 1,095,000
Sheridan Lake WC	$ 550,000	$ 440,000	$ 715,000	$ 730,000	$ 511,000	$ 1,095,000
South Swink	$ 3,300,000	$ 2,640,000	$ 4,290,000	$ 1,730,000	$ 1,211,000	$ 2,595,000
Sterling, City of ($*100)[3]	$ 900,000	$ 720,000	$ 1,170,000	Cost estimates were not developed by EPA for RO/NF and Z		
Sterling, City of ($*100)[3]	$ 240,000	$ 192,000	$ 312,000	Cost estimates were not developed by EPA for enhanced coagulation and sludge lagoons.		
Swink, Town of	$ 1,100,000	$ 880,000	$ 1,430,000	$ 490,000	$ 343,000	$ 735,000
Turkey Canon Ranch WD	$ 600,000	$ 480,000	$ 780,000	$ 570,000	$ 399,000	$ 855,000
TV Hills Water LLC	$ 1,600,000	$ 1,280,000	$ 2,080,000	$ 1,090,000	$ 763,000	$ 1,635,000
Valley WC	$ 1,670,000	$ 1,336,000	$ 2,171,000	$ 1,160,000	$ 812,000	$ 1,740,000
Vroman WC	$ 1,400,000	$ 1,120,000	$ 1,820,000	$ 890,000	$ 623,000	$ 1,335,000
Wayward Wind MHP & CG	$ 1,110,000	$ 888,000	$ 1,443,000	$ 2,050,000	$ 1,435,000	$ 3,075,000
Whispering Pines MHP	$ 740,000	$ 592,000	$ 962,000	$ 570,000	$ 399,000	$ 855,000
Wiley, Town of	$ 4,200,000	$ 3,360,000	$ 5,460,000	$ 1,190,000	$ 833,000	$ 1,785,000
Total	**$ 72,670,000**	**$ 58,136,000**	**$ 94,471,000**	**$ 30,280,000**	**$ 21,196,000**	**$ 45,420,000**

[1]Blue Mountain, Red Hill Forest, and Las Animas are not included because compliance alternatives were not defined for these systems. Mountain WSD is not included because EPA did not develop cost estimates for HMO.

[2]May ValleyCO-RADS cost estimate is for RSC treatment. EPA cost estimate is for cation exchange (operated in regeneration mode).

[3]A defined alternative was not selected for Sterling. Cost estimates were provided for two treatment options RO/NF with liquid resiuals treated by zero liquid discharge and enhanced coagulation. Costs are listed in the table for the respective treatment options.

The sum of capital costs, 20-year NPV O&M costs, and total project NPV costs estimated by CO-RADS and by EPA for 27systems are illustrated in Figure 4-8. This figure illustrates the sum of the opinion of probable costs developed for the CO-RADS systems compared to opinions of probable cost developed by EPA for treatment for compliance with the Radionuclides Rule. EPA opinions of probable cost were developed based on design and average flow rates.



* [1]Blue Mountain, Red Hill Forest, and Las Animas are not included because compliance alternatives were not defined for these systems. Mountain WSD is not included because EPA did not develop cost estimates for HMO. Sterling and May Valley are not included because comparable costs for the defined alternatives were not developed by EPA.

Figure 4-8.
Comparison of Opinions of Probable Cost for Radionuclides Rule Compliance Developed through CO-RADS and by EPA (N=27)

In general, the CO-RADS and EPA cost estimates were similar with a 25% difference in the total NPV of the compliance alternatives estimated through CO-RADS and using EPA cost curves.

An estimate of how much water rates will increase due to the CO-RADS costs is included in Appendix M. Appendix M also includes an analysis of the rates compared to median household incomes for the County the CO-RADS system resides. Results showed the cost of the CO-RADS defined alternatives will represent 0.4%-23.3% of median household incomes, with an average of 4.7%. These estimates include gross assumptions regarding number of taps and payment structure for the project cost. In addition, this analysis does not include existing rates or evaluate the sufficiency of existing rates to support the water system.

5. CO-RADS Observations

There were multiple important observations made through CO-RADS, both in the field and through the evaluations of the systems and compliance alternatives that impact costs for compliance alternatives and/or should be considered by CDPHE as it proceeds with the process of helping these systems achieve compliance.

5.1. Field Observations

Observations made through site visits conducted as part of CO-RADS are summarized below:

- Pirnie and CDPHE found that media in both sand filters and greensand filters currently employed by CO-RADS systems to remove iron and/or manganese are removing a significant fraction of radionuclides from the treated source water. For example, one sampling event showed 90% of source water radium was removed by greensand filtration at Blue Mountain and approximately 20% was removed by oxidation and sand filtration at May Valley. Results of the sampling event are summarized in a memo in Appendix P. This is important because most of the systems and many CDPHE representatives were not aware that many small water systems across Colorado are removing radionuclides. As such, there are likely many systems across Colorado that have radionuclides in their source water that are generating radioactive materials in their existing treatment facilities and are not disposing of radioactive residuals properly. Specifically, filter media (sand, anthracite, and greensand) and spent filter backwash samples collected through CO-RADS indicate residual waste streams need to be carefully monitored, handled, and disposed of. This applies for systems that participated in CO-RADS as well as any water system that has the potential to remove radionuclides from their source water. Many of the systems that were visited have unpermitted discharges of filter backwash water to nearby drainage ways or simply to a field. This may require permitting from wastewater, solid waste, and/or radiation management entities for current practices, which could result in significant costs.

  In addition to disposal concerns for the radioactive residuals, accumulation of radionuclides on filter media can result in unanticipated exposure of workers to radiation. A radiation survey conducted at one CO-RADS system by CDPHE demonstrated radiation doses ranging from 40-450 μrem/hour around the system's pressure sand filters. The full results of this survey can be obtained from CDPHE.

- Several CO-RADS systems currently handle liquid residuals from radionuclide treatment process. Two systems discharge liquid residuals to the ground and one to an evaporation basin (Figure 5-1) that may not comply with CDPHE's criteria for a lined evaporation basin. A fourth system discharges the liquid residuals to a POTW effluent.

Figure 5-1.
Evaporation Basin where Liquid Residuals from Radionuclide Treatment are Discharged at one of the CO-RADS Systems

In addition, as discussed further below, some systems are inadvertently removing radionuclides from water through other treatment processes, like iron filtration. In some cases, liquid residuals from these processes, that likely contain elevated levels of radionuclides, are discharged to the ground (an example of a CO-RADS' system's discharge to the ground is shown in Figure 5-2).

Figure 5-2.
Picture of a CO-RADS System's Discharge of Spent Filter Backwash to the Ground

- Some CO-RADS systems do not have the proper disinfectant residual contact time to achieve CT. CDPHE has changed its method for calculating CT and all systems should verify they achieve 4-Log viral inactivation before water is delivered to the first customer.
- Based on Pirnie's high-level TMF evaluation conducted as part of CO-RADS, it appears many CO-RADS systems have significant TMF capacity deficiencies. Specifically, a majority of the systems lack the appropriate level of staffing, funding, and businesses processes to operate and manage their water systems. This will be even more challenging for the water systems as they implement compliance alternatives for the Radionuclides Rule.
- Several CO-RADS systems indicated various challenges with regional solutions to the Radionuclides Rule, including costs and concerns regarding water rights. However, most of the CO-RADS systems had not fully identified or evaluated potential regional solutions. Based on information collected and reviewed through CO-RADS, regionalization could result in significant benefits, particularly cost savings, for many of the participating systems.
- CO-RADS systems expressed an interest in POU/POE treatment systems for compliance with the Radionuclides Rule and wanted to know more about CDPHE's compliance requirements.
- Many CO-RADS system representatives did not understand why they were required to comply with the Radionuclides Rule and felt the process to compliance was going

to be very challenging, if not impossible. Many representatives also did not understand the potential health effects of ingesting water contaminated with radionuclides.

5.2. Impact of CO-RADS Assumptions on Costs

Several CO-RADS assumptions affected the opinions of probable cost developed for the defined alternative as follows:

- Concrete-lined evaporation basins for treating liquid residuals constituted a significant portion of the estimated capital project cost for many of the systems. On average, 59% of the estimated capital project cost for the systems was for construction of a lined evaporation basin. In addition, the estimated cost for concrete-lined basins determined through CO-RADS is approximately an order of magnitude higher than capital costs estimated by EPA for membrane-lined basins.
- The portion of estimated capital cost for construction of the evaporation basin for each applicable system is included in Appendix N. Appendix N also includes the portion of 20-year O&M NPV costs associated with cleaning the evaporations basins at each applicable system. Inclusion of a part-time employee at a cost of $20,000/year to the systems significantly increased the O&M costs over a 20-year project period. On average, 59% of the NPV O&M cost was due to labor for this additional part-time employee. The portion of the estimated 20-year NPV O&M cost for additional labor to operate and maintain the systems is included in Appendix N for each system.
- As required by CDPHE design guidelines, redundant treatment infrastructure increases capital cost estimates; however, a treatment system without redundant infrastructure may lead to increased O&M costs and increase the risk of the treatment system being off-line for extended periods.
- By removing discharge options from the evaluation, including discharges to surface water, discharges to POTW, and blending with POTW effluent, as directed by the RMW, higher cost options were included in the defined alternatives. All three of the options listed above would likely be more cost effective than constructing lined evaporation ponds.

5.3. Water Quality Challenges

In addition to radionuclide contamination, many systems have very challenging water qualities that impact treatability and treatment costs. Of particular importance to most CO-RADS systems, hardness, TDS, iron, TOC, and sulfate concentrations all impact systems' abilities to treat water and can result in aesthetic issues. As indicated in Section 4.2, the water systems participating in CO-RADS had challenging source waters to treat. As a result, pretreatment was required for many of the systems before the radionuclide treatment technology which resulted in increased treatment and residuals costs.

To illustrate this, an example system has radium-contaminated source water and needs a 100 gpm cation exchange system to treat the water. The estimated costs for a treatment system to treat a water hardness of 450 mg/L as $CaCO_3$ versus a water hardness of 150 mg/L as $CaCO_3$ (all other water quality parameters are exactly the same), are illustrated in Figure 5-2. The treatment system includes cation exchange treatment, a concrete-lined evaporation basin, and a treatment building. The O&M costs include all estimated O&M activities over a 20-year period. Costs were developed as described in Section 3.6.3.

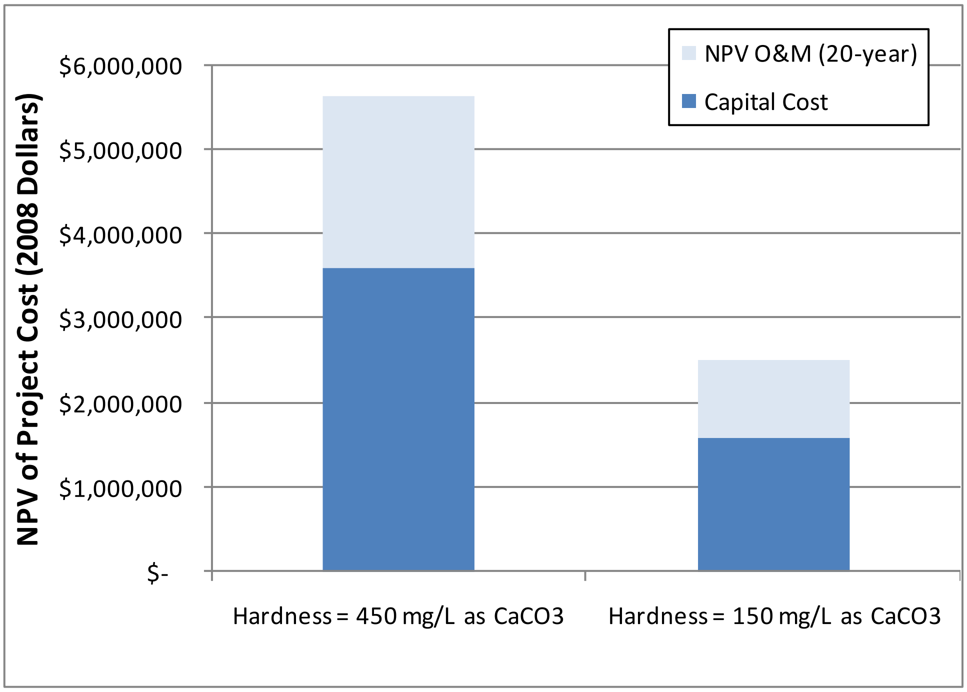


Figure 5-3.
Comparison of Estimated Costs for a Generic 100 gpm Cation Exchange Treatment System to Treat Water with Two Different Hardness Concentrations

As shown in the figure, the NPV project cost for a system treating water with a hardness of 450 mg/L as $CaCO_3$ is more than twice the cost to treat water with a hardness of 150 mg/L as $CaCO_3$ due the larger volume of liquid residuals produced by the treatment system.

6. Recommendations

Pirnie submits the recommendations summarized in Table 6-1 to CDPHE based on the CO-RADS work, including interaction with the participating systems, research on compliance alternatives, and the ultimate results of the CO-RADS Reports.

Table 6-1.
Recommendations Based on CO-RADS Work

Topic	Finding/Observation	Recommendation
Community/Public Outreach and Education	Communities would benefit from education and outreach from CDPHE. Communities need to educate and reach out to customers.	Implement a public outreach and education campaign to help water systems and their customers better understand the radionuclides health effects, the Radionuclides Rule requirements, and CO-RADS implications. Technical, managerial, and financial planning should be an essential element of this effort.
Residuals Management	Several residuals management decisions were made through CO-RADS that require further action.	CDPHE should evaluate the implications of lined evaporation basins for treating liquid residuals from centralized radionuclide treatment systems to confirm it is the best solution for systems. This should include an evaluation of other allowable strategies for the basins and alternative ZLD options. CDPHE should review the residuals handling practices at water systems that have existing treatment for radionuclides or that have filters that are also likely removing radionuclides. This should include both solid and liquid waste streams. Alternate evaporation pond designs could be considered. Liner materials like HDPE and clay should be considered. Access to the ponds for removal of residuals with some frequency and without damaging the lining material should be considered with these materials. Additional controls and monitoring may be required for these materials as well. This may not reduce the cost of the ponds.

Topic	Finding/Observation	Recommendation
TENORM Manual	TENORM Manual is difficult to read and use for systems	Update the TENORM manual based on decisions made through CO-RADS, including the updated flow chart for determining how to dispose of liquid residuals from radionuclide treatment processes. Pirnie drafted a new liquid residuals flow chart that was used for CO-RADS and is included in Appendix O. To assist systems in complying with all of the radionuclides rule requirements, especially residuals handling, CDPHE should assign a point person, most likely from the Water Quality Control Division, responsible for making sure that systems comply with all permitting requirements. The point person would assist the system in contacting relevant staff in other CDPHE departments, and would review all of the engineering work, permit applications, and construction approvals for the system. CDPHE should consider placing jurisdiction of residuals produced in drinking water treatment to WQCD to ensure that residuals issues are addressed during the design of water treatment improvements. The TENORM manual should be streamlined by reducing background information. The document should be updated for readability and flow
TMF Capacity	Many CO-RADS systems lack TMF capacity.	CDPHE should consider including CO-RADS systems in the TMF capacity training program, either in one-on-one capacity development training or in group workshops.
Regionalization	Many CO-RADS systems should evaluate potential regionalization opportunities.	CO-RADS systems could benefit from education about potential regionalization opportunities, including regionalized water supply and treatment, chemical deliveries, residuals handling and disposal services, and using other district, city, county and other organizational resources. Many of these activities would take a significant amount of time to plan, organize, and execute; therefore, systems should start working on these opportunities as soon as possible. CDPHE (or another governmental entity) may consider organizing community round table discussions to discuss potential opportunities and to help systems start communicating with each other. Facilitation of these meetings can help system representatives overcome personal barriers and aversions to considering regionalization that they may not be able to surmount on their own.
POU/POE Policy	An established CDPHE policy will help CO-RADS systems evaluate this alternative.	POU/POE treatment could be the most economic compliance solution for some of the small systems participating in CO-RADS. CDPHE should finalize its policy for POU/POE treatment as soon as possible so systems can fully evaluate the costs and O&M requirements for implementing a POU/POE treatment program.

Topic	Finding/Observation	Recommendation
Radionuclides Rule Compliance and Approval Process	Systems will need to work with several departments within CDPHE to complete the Radionuclides Rule compliance process.	CDPHE should work across internal departments to develop a simple process for systems to follow as it progresses through the compliance selection and implementation process. This should include helping systems understand which departments to contact for different types of information and approvals. It needs to be very clear to the systems how to contact each department and when. One primary point of contact at CDPHE would be ideal.
Bench- and Pilot-Scale Testing of Treatment Technologies	Testing conducted through CO-RADS did not evaluate every water quality scenario for every treatment technology.	Systems will need to work closely with CDPHE as they move forward with the evaluation and design of treatment technologies for compliance with the Radionuclides Rule. The efficiency and cost of the technologies are highly dependent on site-specific water quality. Bench/pilot testing of selected technologies using the systems' source water is recommended to confirm design criteria and associated costs.
CO-RADS Assumptions	Several assumptions made through CO-RADS impact costs.	CDPHE should evaluate the assumptions made through CO-RADS that could save systems money, including treatment redundancy, labor requirements, and evaporation basin cleaning frequency.

7. References

AWWA. AWWA Field Operator Field Guide. Denver, CO. 2004.

National Drinking Water Clearing House. March 2000. “Radionuclides Tech Brief: A National Drinking Water Clearing House Fact Sheet. Tech Brief 13

USEPA. “Uranium in US Surface Water, Ground, and Domestic Water, Volume 1”. Prepared by Oak Ridge National Laboratory. EPA570/9-81-001. Pp. 217-222. April 1981

USEPA, 2000. National Primary Drinking Water Regulations; Radionuclides; Final Rule. 40 CFR Parts 9, 141, and 142. Federal Register Vol. 65, No 236.

USEPA, 2000a. Technologies and Costs for the Removal of Radionuclides from Potable Water Supplies. Targeting and Analysis Branch Standards and Risk Management Division, Office of Ground Water and Drinking Water. Washington, DC. June 2000.

USEPA, 2002. Implementation Guidance for Radionuclides. EPA 816-F-00-002. March 2002.

USEPA. “Radionuclides in Drinking Water: A Small Entity Compliance Guide”. Office of Ground Water and Drinking Water. EPA 815-R-02-001. February 2005.

USEPA, 2006. A System’s Guide to the Management of Radioactive Residuals from Drinking Water Treatment Technologies. EPA 816-F-06-012. August 2006.

Varani F.T., Jelinek, R.T., Correll, R.J. *Occurrence and Treatment of Uranium in Point of Use System in Colorado.* Radon, Radium and Other Radioactivity in Ground Water: Hydrogeologic Impact and Application to Indoor Airborne Contamination. Proceedings of the NWWA Conference April 7-9, 1987, Somerset, New Jersey. 1987. p 535-546.