Appendix G – Bench and Pilot Testing Plan

Colorado Department of Public Health and Environment

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Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS)

DRAFT
Task 5 Bench- and Pilot-scale Testing Plan

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1. Introduction

1.1. CO-RADS Background

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

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

The maximum contaminant level goal (MCLG) established for radionuclides by the EPA is zero.

Radionuclides are naturally present in the environment, including groundwater sources. Typically, the levels of naturally occurring radioactive material (NORM) are not a significant health concern in drinking water; however, Colorado has over 40 water systems that are currently or expected to be in violation of one or more of the radionuclide MCLs (33 systems are participating in this study). This presents a health concern for nearly 40,000 consumers.

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

The systems affected by radionuclides in Colorado are small groundwater systems with limited resources that may struggle to find feasible compliance options. WQCD has initiated the Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) to address the issues associated with removal of radionuclides from drinking water and offer compliance and technical assistance to the communities affected by these contaminants.

The ultimate goal of this project is to resolve drinking water radionuclide violations. The project has been structured to include 5 distinct phases, as outlined below:

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

Malcolm Pirnie, Inc. (MPI) in conjunction with the Colorado School of Mines (CSM) has been contracted by WQCD to perform Phases 2 and 3. This testing plan describes the bench- and pilot-scale testing that will be conducted for Task 5 of this project.

1.2. CO-RADS Task 5 Objectives

The objectives of the bench- and pilot-scale testing are to evaluate potential treatment technologies for specific CO-RADS systems based on the following criteria:

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

2. Testing Approach

Source waters for the 33 systems participating in this study were divided into seven categories based on the radionuclide concentrations in the sources above the MCL:

1. Radium (Ra) only
2. Uranium (U) only
3. Gross Alpha Activity (GAA) only
4. Ra and U
5. Ra and GAA
6. Ra, GAA, and U
7. U and GAA

Three source waters were selected for bench- and pilot-scale testing based on radionuclide contamination (categories defined above), water quality and representation of the other 28 systems. The source waters include:

- Blue Mountain
- May Valley
- Sterling

Several technologies will be tested at the bench- and/or pilot-scale:

- Ion exchange (IX) – cationic
- High pressure membranes (nanofiltration (NF) and reverse osmosis (RO))
- Enhanced coagulation
- Pre-Formed HMO Filtration

The assessment of each technology will focus on design criteria required to remove regulated contaminants, possible interference from other constituents present in the source water, quantity and quality of waste streams generated (residual characterization and management), and required process controls. Bench and pilot testing data will be supplemented by vendor information, existing system operational data and published literature.

2.1. Cation Exchange

IX processes are considered effective in removal of radionuclides from water but the evaluation of their specific capabilities is complex. In order to assess the relative removal efficiency, competitiveness of co-ions, and economic viability, different bench-scale tests will be performed. These include continuous rapid small-scale column tests (RSCCTs)

that aim at evaluating adsorption capacity, competitive exchange, fouling by iron and manganese, and breakthrough profiles of radionuclides in the presence of co-ions.

A set of RSCCTs will be conducted on two source waters, one containing radium and high hardness and one containing radium and low hardness (May Valley and Blue Mountain, respectively). These experiments will confirm key design parameters (radium removal and number of bed volumes) and provide additional information on co-ion competitiveness, breakthrough, fouling rates, and required pretreatment. Testing will be conducted before and after the filter at May Valley to investigate the impact of iron fouling on the resin.

In this set of experiments, source water contact time will be set to the manufacturer-recommended time and the columns will be operated until hardness breakthrough and then be regenerated with sodium chloride (NaCl) or potassium chloride (KCl). Five exhaustion-regeneration cycles will be run on each water source. Samples for IC, ICP, TOC and radionuclides will be taken periodically (more frequently in the early stage of operation), as summarized in Table 1.

Table 1. Number of samples or continuous cation exchange mini-columns

Source water	# of samples				Test Conditions
	Feed	Product	Brine	Total	
Source water #1 Ra w/high hardness (May Valley)	1	10	1	12	**Water flowrate**: ~6 mL/min **Column size:** ½" ID, 12" height **Resin weight:** TBD **Run time:** 5 Regeneration cycles **Pretreatment:** not necessary, prevent source water oxidation
Source water #2 Ra w/low hardness (Blue Mountain)	1	10	1	12	
Total radionuclide samples per water source: ***Ra-226 = 24*** ***Ra-228 = 2 (one for each source water feed)*** ***Uranium = 0*** ***GAA = 14 (One feed, five product, and one brine sample will be analyzed for each source water)***					–4 sampling events: IC, ICP, TOC 4 sampling events: RAD

Iron and manganese fouling of the resin will be tested. Columns will be operated at the above operating conditions in the presence of high concentration iron and manganese in the feed water. Headloss, hardness, iron, and manganese will be monitored. Radium CSM will also characterize residuals, including brine stream(s) and spent resins.

2.2 High Pressure Membranes

Two NF membranes and one RO membrane will be tested at the bench-scale for removal of radionuclides by flat-sheet membrane tests. Two flat-sheet membrane test cells will be operated in parallel at a constant permeate flux of 15 $L/m^2 \cdot hr$ (LMH) and constant temperature of 10°C. Each membrane (NF and RO) will be tested for one hour. Water samples to determine rejection of contaminants will be taken from the permeate at the

end of each experiment. This will allow CSM to compare the rejection for each membrane under the same operating conditions. Testing will be conducted with one water source (May Valley) contaminated with both Ra and U. A schematic of the flat-sheet membrane testing unit is given in Figure 1. Operating conditions for the flat-sheet membrane tests are provided in Table 2.

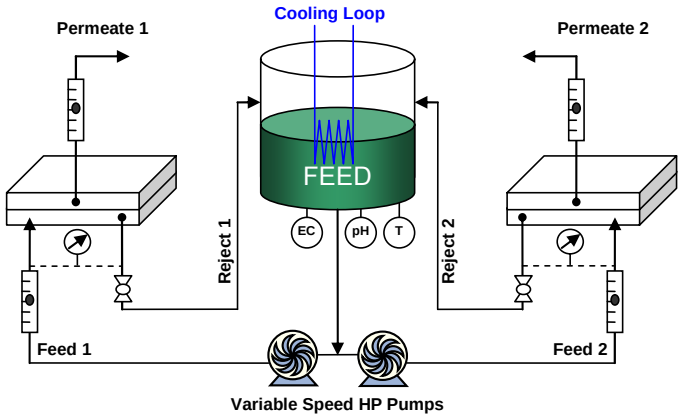

Figure 1. Schematic of the flat-sheet membrane testing unit (CSM)

Table 2. Operational parameters for flat-sheet membrane tests

Parameter	Value	Unit
Feed flow rate	1,400 (22)	mL/min (GPH)
Cross-sectional flow area	0.82	cm²
Cross-flow velocity	0.28	m/s
Membrane surface area	139	cm²
Permeate flow during experiments	7.0	mL/min per cell
Permeate flux during experiments	30	L/(m²·h)
Temperature	10±1	°C
Feed pH	7.0	
Applied feed pressure for membrane compaction	200	psi

Pilot-scale testing will be performed with a dual-stage membrane system (one 4040 spiral-wound element in each stage) using one type of membrane only. Membrane performance will be tested at two recoveries, 30 percent during single pass and 80 percent during circulation. Two sources, May Valley and Sterling, will be tested.

A combination of flat-sheet testing and dual-stage element testing will provide sufficient information for developing preliminary designs for the participating utilities. The results of bench testing will be combined with computer models from various membrane suppliers to estimate design parameters and costs for full-scale treatment processes. The results will be used to confirm/calibrate EPA's residual (SPARRC) model. Bench- and pilot-scale testing scenarios for high pressure membranes are summarized in Table 3.

Table 3. Bench-scale and pilot-scale testing of NF and RO: 1 source of water								
Source Water	**RO1 Bench**	**NF1 Bench**	**NF2 Bench**	**NF Pilot**	**Number of Samples**			**Test Conditions**
					Feed	**Product**	**Total**	
Source water #1	√	√	√		3	6	9	See Table 2
Source water #1 Radium (2 recoveries)				√	1	5	6	
Source water #2 Uranium (2 recoveries)				√	1	5	6	
Total radionuclide samples: ***Ra-226 = 15*** ***Ra-228 = 4 (feed samples for Source #1)*** ***Uranium = 6*** ***GAA = 21 (one feed and two product for each of the three flat-sheet tests and each water quality sample collected in the pilot will be analyzed)***					– 4 sampling events: IC, ICP, TOC 4 sampling events: RAD			

2.2. Coagulation

Coagulation followed by sedimentation and filtration will be tested on Sterling water only because Sterling is the only CO-RADS system that is large enough to potentially implement coagulation as a compliance option. The coagulation-testing matrix includes:

- Two coagulants
- Three doses
- Two pH conditions

Coagulant will be added to six 2L jars that will be operated under standard jar testing conditions for each test. Water temperature will be adjusted to 10°C. Water samples for analysis will be taken from the source and from each jar (+ 1 blank).

Table 4. Bench-scale coagulation jar testing				
	# of U samples			Test Conditions
Source water	Feed	Product	Total	
Source water #1 Sterling	1	12	13	**Coagulant:** Ferric Sulfate and Aluminum Sulfate **Testing Matrix:** 2 coagulants x 3 doses x 2 pH **Rapid Mix:** 1 min **Slow Mix:** 30 min **Surface Overflow Rate:** 0.5 gpm/sf **Filtration:** 45 µm membrane filter
Total radionuclide samples: ***Ra-226 = 0*** ***Ra-228 = 0*** ***Uranium = 13*** ***GAA = 13***				IC, ICP, TOC, Turbidity

2.3. Pre-formed Hydrous Manganese Oxide (HMO)

Pre-formed hydrous manganese oxide followed by filtration will be tested on two different source waters (Blue Mountain and May Valley). One dose of HMO will be added to the water and allowed adequate contact time and then filtered. Water temperature will be adjusted to 10°C. No pH optimization will be performed. Water samples for analysis will be taken from the feed and from each dose (+ 1 blank) for each source.

Table 5. Bench-scale pre-formed hydrous manganese oxide testing				
	# of U samples			Test Conditions
Source water	Feed	Product	Total	
Source water #1 high hardness	1	4	5	**Contact Time:** 25 min **Doses:** 2 different doses **Filtration:** 45 µm membrane filter
Source water #2 low hardness	1	4	5	
Total radionuclide samples: ***Ra-226 = 10*** ***Ra-228 = 2 (one for each feed)*** ***Uranium = 0*** ***GAA = 10***				IC, ICP, TOC, Turbidity