Appendix E - Treatment Technology Feasibility Evaluation

MALCOLM PIRNIE

Technical Memorandum

Date:	February 20, 2008
To:	Jon Erickson - CDPHE
From:	Jason Kerstiens, Ben Johnson, Zaid Chowdhury - Malcolm Pirnie, Inc.
Re:	Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) Feasible Technology Evaluation
Project No.:	5322-009

1.0 Introduction

The Colorado Department of Public Health and Environment (CDPHE) and Malcolm Pirnie recognize that some of the technologies available for radionuclide treatment will not be feasible for the communities participating in the Colorado Radionuclide Abatement and Disposal Strategy (CO-RADS) project. Therefore, focusing the efforts of this project on those technologies that are the most promising is the best use of CDPHE's resources. As a result, Malcolm Pirnie conducted an evaluation to determine feasible technologies for radionuclide removal that will be further evaluated as compliance options for CO-RADS systems. This technical memorandum summarizes the methodology used for this evaluation, the results, and recommendations to CDPHE.

2.0 Feasible Technology Evaluation Methodology

Malcolm Pirnie identified radionuclide treatment technologies that the United States Environmental Protection Agency (USEPA) considers small system compliance technologies (SSCTs) for the Radionuclides Rule. Table 1 summarizes the technologies that were evaluated for various radionuclide(s) removal (specifically, radium, uranium, and gross alpha emitters), and includes a brief description of each technology.

Table 1. Radionuclide treatment technologies

Technology	Radionuclide(s) Treated (from Radionuclides in Drinking Water: A Small Entity Compliance Guide, EPA, February 2002)	Technology Description
Cation Exchange (CIX)	Radium	Divalent cations (e.g. hardness) are exchanged with sodium using a fixed bed of resin in a flow through vessel that is regenerated with sodium chloride brine solution.
Anion Exchange (AIX)	Uranium	Anions (uranium IV complex anions) are exchanged with chloride using a fixed bed of resin in a flow through vessel, that is regenerated with a sodium chloride brine .

Technology	Radionuclide(s) Treated (from Radionuclides in Drinking Water: A Small Entity Compliance Guide, EPA, February 2002)	Technology Description
High Pressure Membranes - Reverse Osmosis (RO) or Nanofiltration (NF)	Radium, uranium, alpha emitters	Contaminants are removed by pressure driven membrane processes. RO membranes reject most organic and inorganic ions, while NF is more selective towards the removal of divalent larger ions.
Greensand Filtration	Radium	Activated media (e.g. media coated with manganese oxide) pressure filters remove divalent cations by adsorption.
Preformed Hydrous Manganese Oxide Filtration (HMO)	Radium	Radium adsorbs to preformed hydrous manganese oxide (HMO), which is added to water post oxidation. The HMO particles are then removed by filtration.
Activated Alumina	Uranium	Uranium is removed by adsorption to media in a flow through vessel. The media is used until it reaches capacity and then it must be either replaced or regenerated.
Co-precipitation with Barium Sulfate	Radium	Barium Chloride is added to coprecipitate a radium-containing highly insoluble barium sulfate sludge, followed by sedimentation and filtration and is primarily used in wastewater applications.
Lime Softening - Filtration	Radium, uranium	Lime or soda ash is added to precipitate ions, which is followed by sedimentation and filtration. (Large system application)
Enhanced Coagulation – Filtration	Uranium	Alum or ferric is added to facilitate removal of uranium by sedimentation and filtration. (Large system application)
Electrodialysis - Electrodialysis Reversal (ED/EDR)	Radium, uranium	Contaminants are removed by a electrical potential driven membrane process (electromembrane process).

Malcolm Pirnie used the following categories of information to summarize background information on each technology that has been identified above in Table 1:

- Radionuclide(s) removed: radium (Ra), uranium (U), alpha emitters
- Description of technology
- Best available technology delineation (BAT)
- Typical % removal achieved – this summarizes the typical ranges of removal achieved by each technology

- Additional constituents removed – many of the technologies remove other contaminants that impact water quality
- Residuals produced by each technology
- Water quality parameters that could foul a treatment system or interfere with treatment performance
- Pre- and post-ancillary treatment that may be required
- Qualitative estimates of capital and O&M costs
- Footprint of technologies (qualitative comparison)
- Operational complexity
- Required level of operator certification
- History of use (industry wide and installations for treatment of radionuclides).

For this analysis, the costs, footprint, and operational complexity are considered only at a qualitative level. This analysis also assumed that the system has no existing infrastructure that can be used for addition of a treatment technology. Malcolm Pirnie collected and reviewed information from the following sources:

- USEPA Radionuclides Rule guidance documents
- American Water Works Association (AWWA) water treatment resources
- Industry research on radionuclide treatment technologies from various sources
- In-house technical information, including Malcolm Pirnie and CSM resources
- Vendor-supplied information (see below for more details)
- CDPHE operator certification requirements

Malcolm Pirnie contacted six vendors/manufacturers of water treatment processes to gather information on technologies. In general, the vendors are very interested in CO-RADS, but some were hesitant to provide too much information at this point in the project. Information requests were submitted to individual technology vendors requesting the following:

- Product cut-sheets
- Installation lists
- Equipment footprints
- Process schematics
- Water quality parameters of concern
- Resulting residuals streams
- Removal efficiencies

- Cost estimates

Using the background information described above, Malcolm Pirnie evaluated the feasibility of each technology by comparing them using the following six criteria:

- Typical percentage of radionuclide removed
- Additional constituents removed (to further improve treated water quality)
- Residuals handling and disposal
- Qualitative cost estimates
- Operational complexity
- History of use in the water treatment industry

Each technology was given a score of 1 to 5 (5 being the most beneficial for water systems) for each criterion and the sum of the scores was used to rank the relative feasibility of the technologies. The feasible technology evaluation only included the technologies that are appropriate for smaller water systems that serve less than 10,000 customers based on the EPA SDWA definition of small systems. This delineation is made based upon operations, affordability and ease of implementation. Only one water system participating in CO-RADS, the City of Sterling, serves greater than 10,000 customers and appropriate technology solutions will be evaluated separately from the smaller water systems in CO-RADS.

3.0 Feasible Technology Evaluation Results and Recommendations

Malcolm Pirnie summarized the results of the background information in Attachment A and provided the results of the feasible technology evaluation in Attachment B. The feasible technology evaluation (focused on water systems serving less than 10,000 customers) resulted in three groups of technologies in decreasing order of feasibility:

1. Feasible technologies: cation exchange, anion exchange, and high pressure membranes (RO/NF)
2. Potentially feasible technologies (further analysis required): greensand filtration, activated alumina and preformed HMO
3. Not feasible technology: ED/EDR

The analysis indicates that the majority of CO-RADS efforts should be focused on the feasible treatment technologies and more limited efforts on potentially feasible technologies. Justification for further evaluation as part of the CO-RADS project are provided in Table 2. One important item that needs additional consideration is the

residuals handling requirements that have not been fully delineated at this point in the CO-RADS project (these will be further evaluated as part of CO-RADs Task 4).

Table 2. Recommended feasible technologies for further evaluation

Treatment Technology	Feasible Technology for CO-RADS?	Justification
Ion Exchange (cation and anion)	Yes	IX options remove at least 95% of the radionuclide of concern are relatively inexpensive, require a small footprint, and may be retrofitted into existing pressure vessel infrastructure at some of the CO-RADS systems. IX is also currently used by multiple systems for removal of radium and uranium from drinking water.
High Pressure Membranes RO/NF	Yes	RO/NF remove at least 95% of radionuclides, in addition to other water quality parameters that may be a concern. RO/NF can be expensive, but it is used by several utilities for treating water contaminated with radionuclides. The additional aesthetic benefits of RO may make this a favorable option for water systems that need to satisfy customers and board members.
Activated Alumina	Possibly, but additional information is required	Activated alumina has been employed to remove fluoride and arsenic in the full-scale treatment applications, but Malcolm Pirnie has not identified any systems using the technology for full-scale uranium removal. Uranium-specific treatment information will be required to make a definitive decision on the viability of activated alumina.
Greensand Filtration	Possibly, but only in limited applications	Greensand filtration only removes up to ~50% of radium. As a result, source waters cannot have very high levels of radium, or else this technology will not be able to help the water system comply with the MCL (5 pCi/L).
HMO	Possibly, but additional information is required	It has been reported that HMO can remove up to 95% of radium (after iron and manganese are oxidized) and may be easily retrofitted into plants that already have filtration. However, Malcolm Pirnie has identified a very limited number of installations at water treatment plants and has not seen adequate information to support this as a feasible technology for CO-RADS.
ED/EDR	No	High capital and operation and maintenance costs and extensive pre-treatment requirements and post-treatment chemical conditioning. In addition, ED/EDR history of use is limited with no known installations specifically for the removal of

		radionuclides from drinking water.

No additional analysis was performed on the technology solutions that are most applicable to larger water systems that serve greater than 10,000 customers. It is assumed that those technologies will be further evaluated for the City of Sterling, as appropriate. Those technologies include:

- Co-precipitation with barium sulfate
- Lime softening
- Enhanced coagulation

These technologies require a relatively large footprint, have high capital and operation and maintenance costs, and can be more complicated to operate that the other technologies. However, they may provide a benefit to the City of Sterling by achieving other water treatment goals, in addition to removal of radionuclides.

References

(1) National Drinking Water Clearing House. March 2000. "Radionuclides Tech Brief: A National Drinking Water Clearing House Fact Sheet. Tech Brief 13.

(2) American Water Works Association & American Society of Civil Engineers. 1990. *Water Treatment Plant Design; 3rd ed.* The McGraw-Hill Companies, Inc.

(3) U. S. Environmental Protection Agency. September 1998. *Small System Compliance Technology List for the Non-Microbial Contaminants Regulated Before 1996.* EPA 815-R-98-002.

(4) U. S. Environmental Protection Agency. March 2000. *Radionuclides Notice of Data Availability Technical Support Document*. Office of Ground Water and Drinking Water.

(5) Colorado Department of Public Health and Environment. Water and Wastewater Facility Operators Certification Requirements. Regulation No. 100. 5 CCR 1003-2. Effective Date: September 30, 2007.

(6) Tonka Equipment Company. P.O. Box 41126, Plymouth, MN 55441. (763) 559-2837. Sherri Westphal

(7) Basin Water, Inc. 8731 Prestige Ct., Rancho Cucamonga, CA 91730. (713) 828-3460. Bob Black.

(8) Infilco Degrement, Inc. 8007 Discover Dr., Richmond, VA 23229. (804) 756-7691. John Dyson.

(9) Water Remediation Technology, LLC. 700 Terra View Circle, Fort Collins, CO 80525. (970) 226-0644. Ryan Peterson.

(10) Roberts Water Technologies, Inc. P.O. Box 167, Darby, PA 19023. (610) 583-3131. Michael Gregg.

(11) American Water Works Association. 1999. *Water Quality & Treatment 5th Edition.* The McGraw-Hill Companies, Inc.

(12) Clifford, Dennis. "Fundamentals of Radium and Uranium Removal from Drinking Water Supplies" EPA Webcast: http://www.epa.gov/safewater/dwa/pdfs/webcast/presentations/rads_treatment_dennis_clifford.pdf

(13) Lowry, JD., Lowry, SB. "Radionuclides in Drinking Water". Journal AWWA. 80(7):51–64

(14) Wang, L., Chen, A., Fields, K. (October 2000) "Arsenic Removal from Drinking Water by Ion Exchange and Activated Alumina Plants" EPA/600/R-00/088

(15) Matzke, A. "The Radionuclides Rule: Overview, Disposal Options, EPA Products" CRCPD's 38th National Conference on Radiation Control, Detroit, MI, May,10 2006.

(16) USEPA, "Removing Multiple Contaminates from Drinking Water: Issues to Consider" Poster presentation: EPA 816-H-07-004. December 2007

(17) Wang, L., Chen, A., Tong, N., Coonfare, C. April, 2007. "Arsenic Removal from Drinking Water by Ion Exchange U.S. EPA Demonstration Project at Fruitland, ID Six-Month Evaluation Report" EPA/600/R-07/017

(18) WHO. June, 2005. "Uranium in Drinking Water". http://www.who.int/water_sanitation_health/

(19) U. S. Environmental Protection Agency Office of Ground Water and Drinking Water. March 2000. *Radionuclides Notice of Data Availability Technical Support Document.*

(20) U. S. Environmental Protection Agency. *Disposal of Water Treatment Plant Waste Containing Radionuclides.* EPA Webcast: http://epa.gov/safe**water**/dwa/pdfs/webcast/presentations/**disposal**_issues.ppt.

(21) State of Wisconsin. "DNR Application of DHFS Radionuclide Wastewater Disposal Criteria for Cation and Anion Exchange Unit and Other Water Treatment Plant Wastewater Discharge Containing Naturally Occurring Radionuclides".

Attachments:

- Attachment A: Background Information on Small System Compliance Technologies for Radionuclide(s) Removal

- Attachment B: Feasible Technology Evaluation Results

Appendix E - Attachment A: Background Information on Small System Compliance Technologies for Radionuclide(s) Removal

Technology	Radionuclide(s) Treated	Brief Description	BAT?	Typical % Removal Achieved[5]	Additional Constituents Removed	Residual Streams (Liquid and Solid)	Water Quality Parameters that can Impact Treatment Efficacy	Potential Ancillary Treatment		Capital Cost[2] (Low, Medium or High)	O & M Costs[2] (Low, Medium or High)	Footprint[2] (Small, Medium or Large)	Operation Complexity[2] (Basic, Intermediate or Advanced)	Level of Required Operator Certification[3] (Class)	Technology's Use in Water Treatmnet Industry	Example Radionuclide Treatment Installations[4]
								Pre	Post							
Cation Exchange (IE)	Ra	Divalent cations (e.g. hardness) are exchanged with sodium using a fixed bed of resin in a flow through vessel that is regenerated with sodium chloride brine solution.	Yes	>95%	Calcium, magnesium, copper, iron, lead, zinc, ammonia, barium	▪Pre-treatment residual stream (if necessary) ▪Backwash ▪Regeneration brine stream ▪Resin ▪Rinse water	Particulates, organic matter, oils, oxidants, competing ions (namely manganese, copper, iron, calcium, magnesium, lead and zinc)	▪Air Stripping[1] ▪Filtration (If necessary) ▪Oxidation of iron and manganese	▪Potential need for corrosion control	Low	Medium	Small	Intermediate	C (B if > 2 MGD)	Wide use in the industry	▪Blue Mountain, CO (Culligan) ▪TV Hills, CO (Unidentified Vendor) ▪NJ (Basin Water) ▪Unidentified Location (Roberts Filter)
Anion Exchange (IE)	U	Monovalent anions (uranium IV complex anions) are exchanged with divalent anions using a fixed bed of resin in a flow through vessel and is regenerated with a sodium chloride brine solution.	Yes	>95%	Additional anions, alkalinity, arsenic, sulfate, nitrate, flouride, selenium	▪Pre-treatment residual stream (if necessary) ▪Backwash stream ▪Regeneration brine stream ▪Resin ▪Rinse water	Particulates, organic matter, oils, oxidants, nitrate, sulfate, competing ions (namely fluroide, arsenic and selenium)	▪Air stripping[1] ▪Particulate filtration ▪Oxidation (e.g. iron and manganese)	▪Corrosion control	Low	Medium	Small	Intermediate	C (B if > 2 MGD)	Wide use in the industry	▪Blue Mountain, CO (Sybron A-641) ▪McCook, NE (Tonka Equipment Company) ▪CA (Basin Water) ▪CO (POU/POE Culligan)
High Pressure Membranes - Reverse Osmosis (RO) or Nanofiltration (NF)	Ra, U Alpha emitters	Contaminants are removed by pressure driven membrane processes.	Yes	>99%	Removes monovalent (reverse osmosis only), divalent and trivalent ions as well as nearly all other contaminants of concern.	▪Pretreatment residual stream(s) - if appicable ▪Liquid concentrate reject stream ▪Membranes	Silica, TDS (total dissolved solids), Hardness, TOC, (total organic carbon), Particulates, Turbidity	▪Air stripping[1] ▪Particulate filtration ▪Fltration ▪Scale inhibitor ▪Acid addition §Oxidation (e.g. iron and manganese)	▪Chemical Conditioning ▪Air stripping	High	High	Large	Intermediate	C (B if > 2 MGD)	Wide use in the industry	▪Las Animas, CO (Hydranautics Membranes) ▪Unidentified Location (Osmonics) ▪Colorado (POU/POE Culligan)
Preformed Hydrous Manganese Oxide Filtration (HMO)	Ra	Radium adsorbs to preformed hydrous manganese oxide (HMO) added to water post oxidation. The HMO is then removed by filtration.	No	50-95%	Iron, manganese, however, it is recommended that these be oxidzed with a cheaper oxidant prior to application of HMO	▪Backwash HMO Stream	Iron, manganese, radium levels.	▪Air stripping[1] ▪Oxidation (e.g. iron and manganese)	▪Fltration	Low to Medium	Low to Medium	Medium	Intermediate	B	Limited installations identified	▪Twelve systems in WI, IL, MN, (Tonka Equipment Company)
Activated Alumina	U	Uranium is removed by adsorption to media in a flow through vessel. Depending on system design, periodic regeneration may be required.	No	90%[7]	Additional ions	▪Pre-treatment residual stream (if necessary) ▪Backwash stream ▪Regeneration brine stream and acid neutralizer solution ▪Resin ▪Rinse water	Sulfate, competing ions (namely copper, lead, zinc, fluoride, arsenic and selenium)	▪Acid pre-treatment (pH control)[6] ▪Air stripping[1]	▪pH adjustment	Medium	Medium to High	Small	Basic	C (B if > 2 MGD)	Some use in the water industry for specific applications, often for arsenic or fluoride treatment	No installations identified to date
Greensand Filtration	Ra	Activated media (e.g. media coated with HMO) pressure filters remove divalent cations by adsorption.	No	Up to ~50%	Iron, manganese	▪Backwash stream ▪Media (on replacement)	Iron, manganese, radium levels.	▪Air stripping[1] ▪KMnO4 addition may be required to maintain adsorptive property of media	NA	Medium	Low	Medium	Basic	C (B if > 2 MGD)	Wide use throughout industry for manganese and iron control	▪Unidentified Location (Roberts Filter)
Electrodialysis-electrodialysis reversal (ED/EDR)	Ra, U	Contaminants are removed by a voltage driven membrane process (electromembrane process).	No	>90% - dependent on membrane selection (RO, NF, UF, MF)	Membrane selection dependent - (RO, NF, UF, MF) - Removes monovalent, divalent and trivalent ions as well as nearly all other contaminants of concern.	▪Membrane ▪Liquid concentrate reject stream	Competing ions, pH, hydrogen sulfide, iron and manganese, dissolved organics	▪Air stripping[1] ▪Particulate filtration ▪Filtration ▪Scale inhibitor ▪Acid addition ▪Temperature control <40°c	▪Chemical Conditioning	High	High	Large	Advanced	C	Not widespread	No installations identified to date
Co-precipitation with barium sulfate	Ra	Barium chloride is added to precipitate radium sulfate, followed by filtration and is primarily used in wastewater applications.	No	50-95%	Additional cations	▪Barium sludge ▪Backwash water ▪Spent fiter media	Sulfate	▪Air stripping[1] ▪Rapid mix ▪Flocculation ▪Sedimentation	▪Filtration	High	Medium	Large	Intermediate to Advanced	B	Limited installations identified (often used in wastewater treatment)	No installations identified to date
Lime Softening - filtration	Ra, U	Lime or soda ash is added to precipitate ions, which is followed by sedimentation and filtration. (Large system application)	Yes	80-99%	Dissolved minerals, surfactants, heavy metals, algal growth, silica, fluoride, Fe, Mn, turbidity	▪Lime sludge ▪Filter backwash ▪Spent media	Calcium and magnesium (levels determine lime dose), alkalinity, water stability	▪Air stripping[1] ▪Rapid mix ▪Flocculation ▪Sedimentation	▪Recarbonation ▪pH adjustment ▪Filtration	High	High	Large	Advanced	B	Wide use in the industry	▪Unidentified Location (Infilco Degrement, Inc.)
Enhanced coagulation - filtration	U	Addition of ALUM or ferric for uranium removal, followed by sedimentation and filtration (Large system application)	Yes	50-90%	Conventional treatment contaminant removal	▪Sludge from sedimentation ▪Backwash from filtration ▪Media (on replacement)	TOC, iron, aluminum, water stability	▪Air stripping[1] ▪Rapid mix ▪Flocculation ▪Sedimentation	▪pH adjustment ▪Filtration	High	Medium	Large	Advanced	B	Wide use in the industry	No installations identified to date

1. Air stripping will be recommended as a pre/post-treatment option for systems with Radon issues.
2. Assumes system has no existing infrastructure that can be used for addition of the treatment technology. System specific evaluation will be required for quantitative estimates.
3. Based on Regulation No. 100 *Water and Wastewater Facility Operators Certification Requirements* for the specific purpose of complying with primary drinking water standards.
4. Information gathered through CO-RADS and provided by vendors and manufacturers (6 out of 17 vendors provided installation information).
5. Approximations assume well operated systems
6. http://www.drinking-water.org/html/en/Treatment/Adsorption-and-Ion-Exchange-Systems-technologies.html
7.Lowry JD, Lowry SB (1988) Radionuclides in drinking water. Journal of the American Water Works
NA - Not Applicable

Appendix E - Attachment B - Comparison of Potential CO-RADS Treatment Technologies

Technology	Radionuclide(s) Treated	Brief Description	BAT?	Typical % Removal Achieved	Additional Constituents Removed	Residual Streams (Liquid and Solid)	Water Quality Parameters that can Impact Treatment Efficacy	Potential Ancillary Treatment		Capital Cost[2] (Low, Medium or High)	O & M Costs[2] (Low, Medium or High)	Footprint[2] (Small, Medium or Large)	Operation Complexity[2] (Basic, Intermediate or Advanced)	Level of Required Operator Certification[3] (Class)	Technology's Use in Water Treatmnet Industry	Example Radionuclide Treatment Installations[4]
								Pre	Post							
Recommended Feasible Technologies																
Cation Exchange (IE)	Ra	Divalent cations (e.g. hardness) are exchanged with sodium using a fixed bed of resin in a flow through vessel that is regenerated with sodium chloride brine solution.	Yes	>95%[5,8]	Calcium, magnesium, copper, iron, lead, zinc, ammonia, barium	▪Pre-treatment residual stream (if necessary) ▪Backwash ▪Regeneration brine stream ▪Resin ▪Rinse water	Particulates, organic matter, oils, oxidants, competing ions (namely manganese, copper, iron, lead and zinc)	▪Air Stripping[1] ▪Filtration (If necessary) ▪Oxidation of iron and manganese	▪Potential need for corrosion control	Low	Medium	Small	Intermediate	C (B if > 2 MGD)	Wide use throughout industry	▪Blue Mountain, CO (Culligan) ▪TV Hills, CO (Unidentified Vendor) ▪NJ (Basin Water) ▪Unidentified Location (Roberts Filter)
Anion Exchange (IE)	U	Monovalent anions (uranium IV complex anions) are exchanged with divalent anions using a fixed bed of resin in a flow through vessel and is regenerated with a sodium chloride brine solution.	Yes	>95%[5,8]	Additional anions, alkalinity, arsenic, sulfate, nitrate, flouride, selenium	▪Pre-treatment residual stream (if necessary) ▪Backwash stream ▪Regeneration brine stream ▪Resin ▪Rinse water	Particulates, organic matter, oils, oxidants, nitrate, sulfate, competing ions (namely fluroide, arsenic and selenium)	▪Air stripping[1] ▪Particulate filtration ▪Oxidation (e.g. iron and manganese)	▪Corrosion control	Low	Medium	Small	Intermediate	C (B if > 2 MGD)	Wide use throughout industry	▪Blue Mountain, CO (Sybron A-641) ▪McCook, NE (Tonka Equipment Company) ▪CA (Basin Water) ▪CO (POU/POE Culligan)
High Pressure Membranes - Reverse Osmosis (RO) or Nanofiltration (NF)	Ra, U Alpha emitters	Contaminants are removed by pressure driven membrane processes.	Yes	>99%[8]	Removes monovalent, divalent and trivalent ions as well as nearly all other contaminants of concern.	▪Pretreatment residual stream(s) - if appicable ▪Liquid concentrate reject stream ▪Membranes	Silica, TDS (total dissolved solids), Hardness, TOC, (total organic carbon), Particulates, Turbidity	▪Air stripping[1] ▪Particulate filtration ▪Fltration ▪Scale inhibitor ▪Acid addition §Oxidation (e.g. iron and manganese)	▪Chemical Conditioning ▪Air stripping	High	High	Large	Intermediate	C (B if > 2 MGD)	Wide use throughout industry	▪Las Animas, CO (Hydranautics Membranes) ▪Unidentified Location (Osmonics) ▪Colorado (POU/POE Culligan)
Preformed Hydrous Manganese Oxide Filtration (HMO)	Ra	Radium adsorbs to preformed hydrous manganese oxide (HMO) added to water post oxidation. The HMO is then removed by filtration.	No	50-95%[8]	Iron, manganese, however, it is recommended that these be oxidzed with a cheaper oxidant prior to application of HMO	▪Backwash HMO Stream	Iron, manganese, radium levels.	▪Air stripping[1] ▪Oxidation (e.g. iron and manganese)	▪Fltration	Low to Medium	Low to Medium	Medium	Intermediate	B	Limited installations found.	▪Twelve systems in WI, IL, MN, (Tonka Equipment Company)
Recommended Feasible Technologies for Systems Serving>10,000																
Co-precipitation with barium sulfate	Ra	Barium chloride is added to precipitate radium sulfate, followed by filtration and is primarily used in wastewater applications.	No	50-95%[8]	Additional cations	▪Barium sludge ▪Backwash water ▪Spent media	Sulfate	▪Air stripping[1] ▪Rapid mix ▪Slow mix ▪Sedimentation	▪Filtration	High	Medium	Large	Intermediate to Advanced	B	Limited installations found - use in Wastewater.	No installations identified to date
Lime Softening - filtration	Ra, U	Lime or soda ash is added to precipitate ions, which is followed by sedimentation and filtration. (Large system application)	Yes	80-99%[8]	Dissolved minerals, surfactants, heavy metals, algal growth, silica, fluoride, Fe, Mn, turbidity	▪Lime sludge ▪Filter backwash ▪Spent media	Calcium and magnesium (levels determine lime dose), alkalinity, water stability	▪Air stripping[1] ▪Rapid mix ▪Slow mix ▪Sedimentation	▪Recarbonation ▪pH adjustment ▪Filtration	High	High	Large	Advanced	B	Wide use throughout industry	▪Unidentified Location (Infilco Degrement, Inc.)
Enhanced coagulation - filtration	U	Addition of ALUM or ferric for uranium removal, followed by sedimentation and filtration (Large system application)	Yes	50-90%[8]	Conventional treatment contaminant removal	▪Sludge from sedimentation ▪Backwash from filtration ▪Media (on replacement)	TOC, iron, aluminum, water stability	▪Air stripping[1] ▪Rapid mix ▪Slow mix ▪Sedimentation	▪pH adjustment ▪Filtration	High	Medium	Large	Advanced	B	Wide use throughout industry	No installations identified to date
Technologies Considered Infeasible for CO-RADS Systems																
Activated Alumina	U	Uranium is removed by adsorption to media in a flow through vessel. The media is used until it reaches capacity and then it must be replaced.	No	90%[7]	Additional ions - Chlorides Fluoride, Arsenic, Sulfate, Ammonia	▪Media (on replacement)	Sulfate, competing ions (namely copper, lead, zinc, fluoride, arsenic and selenium)	▪Acid pre-treatment (pH control)[6] ▪Air stripping[1]	NA	Medium	Medium to High	Small	Basic to Intermediate	C (B if > 2 MGD)	Limited installations found for arsenic treatment.	No installations identified to date
Greensand Filtration	Ra	Activated media (e.g. media coated with HMO) pressure filters remove divalent cations by adsorption.	No	Up to 60%[9]	Iron, manganese	▪Backwash stream ▪Media (on replacement) ▪Sludge	Iron, manganese, radium levels.	▪Air stripping[1]	NA	Medium	Low	Medium	Basic	C (B if > 2 MGD)	Wide use throughout industry	▪Unidentified Location (Roberts Filter)
Electrodialysis-electrodialysis reversal (ED/EDR)	Ra, U	Contaminants are removed by a voltage driven membrane process (electromembrane process).	No	>90% - dependent on membrane selection (RO, NF, UF, MF)	Membrane selection dependent - (RO, NF, UF, MF) - Removes monovalent, divalent and trivalent ions as well as nearly all other contaminants of concern.	▪Membrane ▪Liquid concentrate reject stream	Competing ions, pH, hydrogen sulfide, iron and manganese, dissolved organics	▪Air stripping[1] ▪Particulate filtration ▪Filtration ▪Scale inhibitor ▪Acid addition ▪Temperature control <40°c	▪Chemical Conditioning	High	High	Large	Advanced	C	None found	No installations identified to date

1. Air stripping will be recommended as a pre/post-treatment option for systems with Radon issues.
2. Assumes system has no existing infrastructure that can be used for addition of the treatment technology. System specific evaluation will be required for quantitative estimates.
3. Based on Regulation No. 100 *Water and Wastewater Facility Operators Certification Requirements* for the specific purpose of complying with primary drinking water standards.
4. Information gathered through CO-RADS and provided by vendors and manufacturers (6 out of 17 vendors provided installation information).
5. For a well operated system
6. http://www.drinking-water.org/html/en/Treatment/Adsorption-and-Ion-Exchange-Systems-technologies.html
7. Lowry JD, Lowry SB (1988) Radionuclides in drinking water. Journal of the American Water Works
8. Fundamentals of Radium and Uranium Removal from Drinking water Supplies (presentation from Dennis Clifford)
9. Small systems compliance tehcnology lsit for non-microbial contaminates regulated before 1996, USEPA Sep. 1998

NA - Not Applicable