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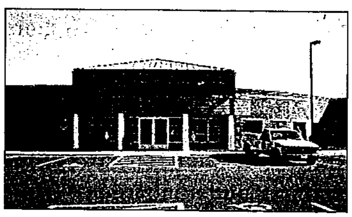
In December 2000, the US Environmental Protection Agency published the final radionuclides rule. The standard of 5 pCi/L for combined radium (Ra) 226 and 228 will affect more than 500 US systems and 1.4 million people in 177 cities in the Midwest. The best available technology for Ra removal includes ion exchange, lime softening, and reverse osmosis. However, hydrous manganese oxide and manganese greensand filtration is capable of removing up to 80% of Ra. For plants designed to remove iron and manganese by a manganese greensand filtration system, the cost of removing Ra is minimal. Results of pilot- and full-scale studies are reported from Bellevue Sanitary District 1 in Brown County, Wis.; Knoxville, Iowa; Garretson and Elk Point, S.D.; Marcus, Iowa; and Savage, Lakeville, and Hinckley, Minn. Also discussed are the relationship between total dissolved solids and Ra removal and the disposal of water containing Ra, which is a major concern.

Radium removal by HMO and manganese greensand



The plant in Lakeville, Minn., came online in March 1998.

In 1976, the US Environmental Protection Agency (USEPA) established a standard of 5 pCi/L for combined levels of radium (Ra) 226 and Ra 228 in drinking water. A maximum contaminant level (MCL) of 15 pCi/L for gross alpha including Ra 226 but excluding radon and total uranium was also established. More than 500 municipal water supplies (Singh, 1990) may exceed the 5 pCi/L standard in the United States, most notably in Florida, Vermont, the uranium mining areas of the Mountain states, the Piedmont Coastal Plains area of the East Coast, and the midwestern states of Iowa, Illinois, Wisconsin, Missouri, and Minnesota. It is estimated that 1.4 million people in 177 cities in the Midwest area receive water that exceeds the 5 pCi/L standard. In the early 1980s, considerable research was under way to find a cost-effective removal technology for Ra.

Ra 226 and 228 are daughter products of uranium and thorium decay. Radiation is released in the form of alpha, beta, and gamma rays during this decay. Ra 226 is a decay product of uranium 236 and is primarily an alpha emitter. Ra 228 and 224 are decay products of thorium 232 and are primarily beta emitters. The health effects of ingestion or contact with Ra 226 and 228 may involve ionization of body cells, which in turn may result in developmental abnormalities, cancer, or death. Epidemiological studies have established a strong connection between certain occupational and therapeutic exposure to the isotopes of Ra and bone cancer (Bennet, 1978).

TABLE 1 Raw water quality—Knoxville, Iowa

	Well Number 1	Well Number 2	Well Number 3	Average
Capacity—*gpm (L/s)*	1,000 (63)	1,000 (63)	1,000 (63)	1,000 (63)
Total hardness—*mg/L*	248	257	273	259.33
Alkalinity—*mg/L*	258	257	268	261
Calcium—*mg/L*	58	60	63	60.33
Magnesium—*mg/L*	25	26	28	26.33
Iron—*mg/L*	0.14	0.10	0.21	0.15
Manganese—*mg/L*	<0.02	<0.02	<0.02	<0.02
Chloride—*mg/L*	50	54	56	53.33
Sulfate—*mg/L*	210	240	240	230
Potassium—*mg/L*	17	18	19	18
Total solids—*mg/L*	666	720	736	707.33
TDS—*mg/L*	666	720	736	707.33
Specific conductivity	1,100	1,200	1,200	1,166.67
pH	7.5	7.6	7.7	7.6
Arsenic—*µg/L*	NA*	NA	NA	NA
Barium—*mg/L*	NA	NA	NA	NA
Cadmium—*µg/L*	NA	NA	NA	NA
Chromium—*µg/L*	NA	NA	NA	NA
Copper	NA	NA	NA	NA
Fluoride—*mg/L*	1.6	1.5	1.4	1.5
Lead—*µg/L*	NA	NA	NA	NA
Mercury—*µg/L*	NA	NA	NA	NA
Nitrate nitrogen—*mg/L*	<0.1	0.4	<0.1	0.2
Selenium—*µg/L*	NA	NA	NA	NA
Silver—*µg/L*	NA	NA	NA	NA
Sodium—*mg/L*	140	160	160	153.33
Zinc	NA	NA	NA	NA
pH of stability	7.5	7.5	7.6	7.5
Radium 226 + radium 228—*pCi/L*	8.2	5.5	7.5	7.1
Gross alpha—*pCi/L*	3.7	9.0	16.0	9.6

*NA—not available

TABLE 2 Radium removal—Knoxville, Iowa

	Raw	Finished	Removal—%
Radium 226—*pCi/L*	6.2	2.2	65
Radium 228—*pCi/L*	1.4	0.6	57
Total	7.8	2.8	64

TABLE 3 Water quality data—South Dakota

	Elk Point	Garretson
Calcium—*mg/L*	26	82.2
Magnesium—*mg/L*	49.5	31
Iron—*mg/L*	8.65	0.1
Manganese—*mg/L*	0.52	0.04
Total dissolved solids	1,222	405
Hardness—*mg/L as calcium carbonate*	768	332.5

In 1991, on the basis of new data, USEPA proposed a relaxation of the standards to 20 pCi/L each for Ra 226 and 228 isotopes. Total gross alpha of 15 pCi/L without Ra 226 remained the same as that prescribed in the 1976 rule. Several of the utilities that had researched Ra removal techniques and had completed pilot studies for compliance with the 1976 rule ceased all efforts because most of them were in compliance with the proposed rule.

In early 1998, USEPA informed the water community of its intent to keep the combined MCL for Ra 226 and 228 at 5 pCi/L. This caught several utilities in the Midwest by surprise because most of them were waiting for the relaxation of the standard proposed in 1991 of 20 pCi/L each for Ra 226 and 228 isotopes. In December 2000, USEPA published the final rule. The final radionuclides rule retains the current standards for combined Ra 226 and 228 (5 pCi/L), gross alpha (15 pCi/L), and beta particle and photon radioactivity (4 mrems/L) and regulates uranium for the first time at 30 µg/L.

Ra is a member of the alkaline earth metal family. Members of this chemical family include magnesium (Mg^{+2}), calcium (Ca^{+2}), strontium (Sr^{+2}), barium (Ba^{+2}), and radium (Ra^{+2}). Two of these elements, calcium (Ca) and magnesium (Mg), are the primary constituents of water hardness and commonly are removed using softening processes. Because of the similarities between hardness (Mg^{+2}, Ca^{+2}) and nonhardness (Ra^{+2} and so forth) members of the alkaline earth metal family, softening processes intended to remove Ca and Mg also remove Ra as a secondary benefit. Most currently available Ra removal treatment processes (lime–soda softening, reverse osmosis [RO], and ion exchange) were designed for hardness (Mg^{+2}, Ca^{+2}) removal and not radium (Ra^{+2}) removal. This shows the importance of understanding the similarities in characteristics between members of the alkaline earth metal family. In this family, adsorptive preference increases as the atomic weight increases; thus, relative adsorptive preference in the family is as follows: $Mg^{+2} < Ca^{+2} < Sr^{+2} < Ba^{+2} < Ra^{+2}$.

The best available technology (BAT) identified by USEPA for Ra reduction includes ion exchange, lime softening, and RO. All of these processes have been shown to remove 70–97% of Ra (Groth, 1999). Lime softening has resulted in >90% removal of Ra during coprecipitation of Ra with Ca and Mg[3]. Ion exchange and RO have been shown to remove up to 97% of Ra (Sorg & Logsdon, 1980). However, each of these technologies may be expensive to implement and operate, especially for small utilities. It was reported (Kondpally, 1991) that the cost of Ra removal for three Illinois communities with populations ranging from 1,077 to 1,982 people was generally around \$4/1,000 gal (\$1.06/1,000 L) after RO was installed. McKelvey and colleagues (1993) reported that the cost of Ra removal for a system serving 50 people was \$4.18/1,000 gal (\$1.10/1,000 L).

Batch and pilot-scale filter studies showed up to 80% removal of Ra by the addition of preformed hydrous manganese oxides (HMOs) (May & Spiess, 1979). Valentine et al (1990) advocated the use of preformed MnO_2 for Ra removal from water with subsequent separation of the solid phase by sand filtration. Teams of researchers have completed pilot-plant studies to determine the possibility of removing Ra by manganese greensand filtration systems. Manganese greensand filtration is typically used for the removal of iron (Fe) and manganese (Mn) in well water and could offer the added advantage of removing Ra. Manganese greensand is a naturally occurring gluconite material that has the ability of catalytically oxidizing Mn and Fe normally using potassium permanganate ($KMnO_4$). This article reviews the pilot- and full-scale results of Ra removal by "nonstandard" systems.

FIGURE 1 Knoxville, Iowa, plant process train schematic

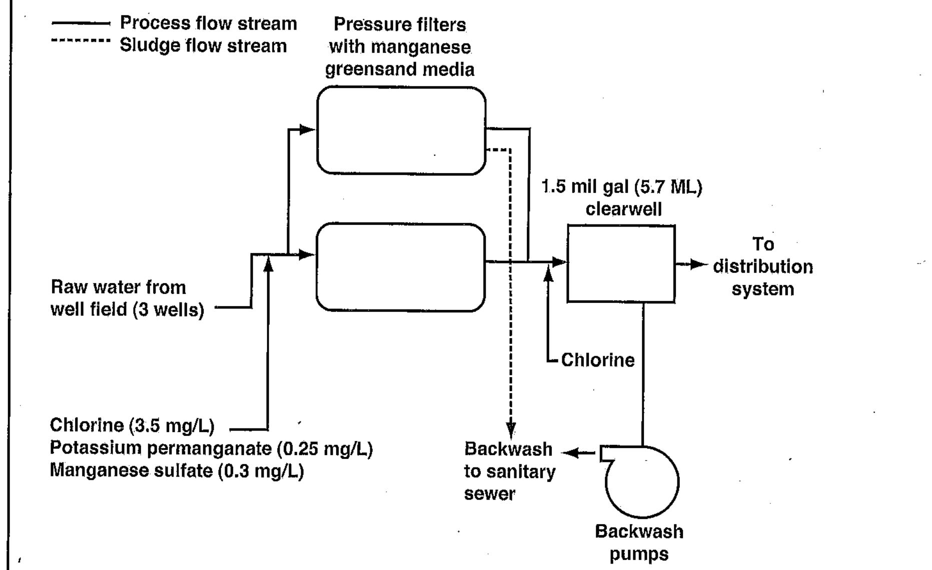
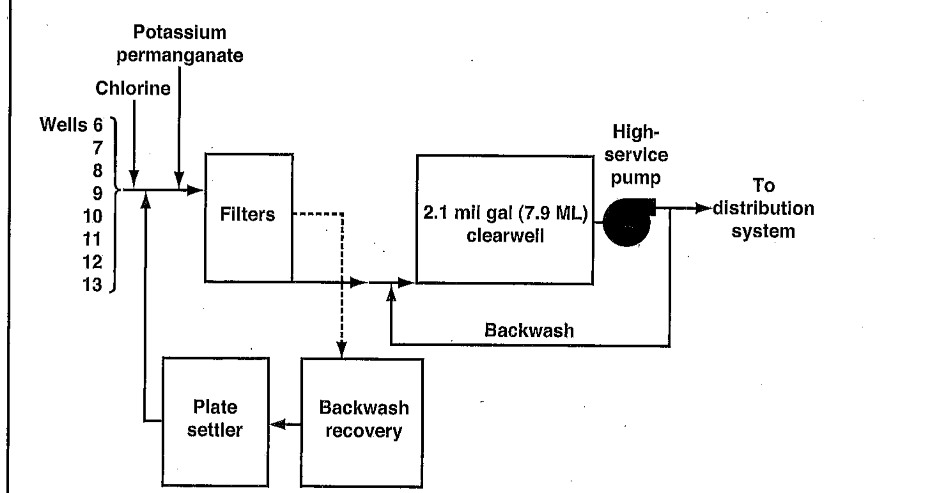


FIGURE 2 Lakeville, Minn., water treatment plant schematic



HMO STUDIES

In 1990, Bellevue Sanitary District Number 1 in Brown County, Wis., conducted a pilot-plant study for removal of Ra in three city wells. Well number 1 contained 9.4 pCi/L of Ra 226 and 5.2 pCi/L of Ra 228, for a total of 14.6 pCi/L. Well number 2 contained 11 pCi/L of Ra 226 and 4.4 pCi/L of Ra 228 for a total of 15.4 pCi/L. Well number 3 had 16.9 pCi/L of Ra 226 and 4.4 pCi/L of Ra 228 for the highest total Ra at 21.3 pCi/L. At a dosage of 0.5 mg/L of HMO followed by manganese greensand filtration, the Ra level in all three wells was reduced to below 5 pCi/L. The HMO was produced by manganese sulfate and $KMnO_4$.

The City of Knoxville, Iowa, designed and installed a plant for removal of Ra, Fe, and Mn. The pressure plant is served by three Jordan aquifer wells with a combined capacity of 3,000 gpm (189 L/s). The Jordan aquifer wells are deep rock wells drilled down to the water-bearing Jordan sandstone. The raw water quality data are shown in Table 1. The treatment process train and dosages of various chemicals are shown in Figure 1. The filters contain 12 in. (300 mm) of anthracite and 24 in. (610 mm) of manganese greensand supported by 16 in.

TABLE 4 Raw water quality—Lakeville, Minn.

	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Average
Capacity—*gpm (L/s)*	1,400 (88)	1,200 (76)	1,500 (95)	1,200 (76)	1,500 (95)	1,200 (76)	1,200 (76)	1,200 (76)	
Total hardness—*mg/L*	300	331	265	310	250	300	197	320	284.13
Alkalinity—*mg/L*	300	350	237						295.67
Calcium—*mg/L*	190		67						128.50
Magnesium—*mg/L*	110		23						66.50
Iron—*mg/L*	0.3	0.64	0.24	0.37	0.4	0.4	0.211	0.4	0.37
Manganese—*mg/L*	0.04	0.04	0.09	0.07	0.07	0.09	0.124	0.09	0.08
Chloride—*mg/L*	.62	2	1.6	ND*	1	ND	0.8	ND	1.20
Sulfate—*mg/L*	<5	14		7	10	17	4.0	21	12.17
Potassium—*mg/L*	1,991								1991.00
Total solids—*mg/L*	320			340	290	300	202	330	297.00
Total dissolved solids—*mg/L*		336	280	310	270	270	215	340	288.71
Specific conductivity	520								520.00
pH	7.7	8.0	7.6	7.5	7.4	7.3	7.74	7.6	7.61
Arsenic—*µg/L*	<5	<1							<3
Barium—*mg/L*	210								210
Cadmium—*µg/L*	<1								
Chromium—*µg/L*	<5								
Fluoride—*mg/L*	0.18	0.20							0.19
Lead—*µg/L*	<10								
Mercury—*µg/L*	<0.1								
Nitrate nitrogen—*mg/L*	<.4	<0.01	<0.1	1.6	ND	ND	<0.5	ND	1.60
Selenium—*µg/L*	<5								
Silver—*µg/L*	<5								
Sodium—*mg/L*	5.13								
Radium 226—*pCi/L*		3.4		4.3±0.3	2.9±0.2	4.5±0.3	4.4±0.4	4.2±0.3	
Radium 228—*pCi/L*		ND		2.0±0.6	1.2±0.7	1.8±0.7	<1.0	1.9±1.4	
Gross alpha—*pCi/L*		16.4		28±3	19±3	21±2	3.6±0.4	6.7±4.0	
Gross beta—*pCi/L*								6.6±2.7	
Radium 222—*pCi/L*				120±30	270±20	260±20			

*ND—not detected

FIGURE 3 Lakeville, Minn., filter detail diagram

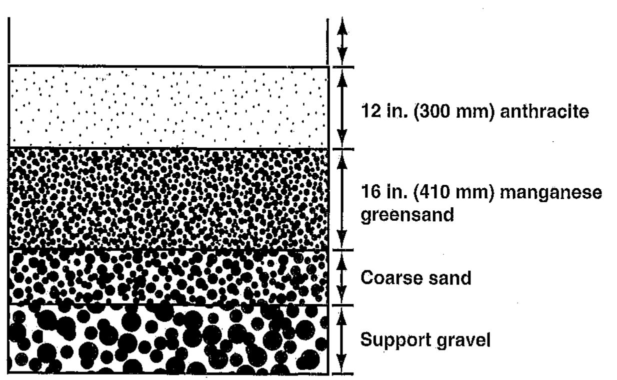


TABLE 5 Radium removal—Lakeville, Minn.

	Raw	Finished	Removal—%
Radium 226—*pCi/L*	4.4	2.7	39
Radium 228—*pCi/L*	ND*	ND	ND
Total	4.4	2.7	39

*ND—not detected

(410 mm) of coarse sand and gravel. Filter runs are about two weeks in duration. The filters are backwashed by air-scour at 2 cfm/sq ft (0.6 $m^3/min/m^2$) followed by water backwash at a rate of 12 gpm/sq ft (8.1 $L/s/m^2$). The disposal of the backwash water is to the sanitary sewer. Currently, there are no known regulatory monitoring requirements for the disposal of the backwash water into the sanitary sewer.

The Ra removals for the Knoxville, Iowa, plant are shown in Table 2. The 65% removal rate of Ra 226 is somewhat higher than the 57% removal rate of Ra 228. The overall Ra removal rate is 64%. This process is well-suited for communities that have total Ra 226 and 228 content of up to 10 pCi/L.

MANGANESE GREENSAND

Manganese greensand filtration currently used for removing nuisance contaminants of Fe and Mn has been suggested as a promising, low-cost means of removing Ra. In the Midwest, several communities completed pilot-plant studies for Ra removal using manganese greensand filtration.

A pilot study was conducted in Garretson, S.D., in January 1990 by South Dakota State University in cooperation with the South Dakota Department of Water and Natural Resources to determine the efficiency of Ra removal by $KMnO_4$ oxidation followed by filtration through a manganese greensand filter. Raw water quality data are shown in Table 3. The study results showed that Ra 226 was reduced from 3.2 to 0.63 pCi/L, a reduction of 80%. Ra 228 was reduced from 5.47 to 1.52 pCi/L, a reduction of 72%. Raw water Ra content (Ra 226 and 228) of 8.67 pCi/L was reduced to 2.15 pCi/L in the treated water, a reduction of more than 75%. After 55 h of operation, the Ra content of the effluent water exceeded 5 pCi/L. The results of the study indicated that the efficiency of the process decreased with a lower Mn-to-Fe ratio, higher filter loading rates, and lower media bed volume. It was also observed that the efficiency of the process reduced with time.

The city of Marcus, Iowa, has two wells that serve the water treatment plant. In 1990, the city replaced the existing media with manganese greensand in three pressure filters. The well water has a hardness of more than 958 mg/L. Test results showed that raw water Ra levels of 9.9 pCi/L were reduced to 1.2 pCi/L, an 88% removal of Ra. The city was removed from the three-month sampling and reporting list because it no longer exceeded the Ra standard.

TABLE 6 Raw water quality—Hinckley, Minn.

	Well Number 4
Capacity—*gpm (L/s)*	400 (25)
Total hardness—*mg/L*	137
Alkalinity—*mg/L*	160
Calcium hardness (as calcium carbonate)—*mg/L*	83.5
Magnesium—*mg/L*	53.9
Iron—*mg/L*	1.88
Manganese—*mg/L*	0.160
Total organic carbon—*mg/L*	NA*
Chloride—*mg/L*	7.2
Sulfate—*mg/L*	5.3
Potassium—*mg/L*	NA
Total suspended solids—*mg/L*	301
Total dissolved solids—*mg/L*	189
Specific conductivity	NA
pH	6.94
Arsenic—*µg/L*	NA
Barium—*mg/L*	NA
Cadmium—*µg/L*	NA
Chromium—*µg/L*	NA
Fluoride—*mg/L*	NA
Lead—*µg/L*	NA
Mercury—*µg/L*	NA
Nitrate nitrogen—*mg/L*	<0.5
Selenium—*µg/L*	NA
Silver—*µg/L*	NA
Sodium—*mg/L*	NA
pH of stability	NA
Radium 226—*pCi/L*	6.8±0.4
Radium 228—*pCi/L*	<1
Gross alpha—*pCi/L*	NA
Gross beta—*pCi/L*	NA
Radium 222—*pCi/L*	NA

*NA—not available

TABLE 7 Radium removal—Hinckley, Minn.*

	Raw	Finished	Removal—%
Radium 226—*pCi/L*	5.6	4.3	23
Radium 228—*pCi/L*	6.5	5.3	18
Total	12.1	9.6	21

*The plant has a capacity of 400 gpm (25 L/s) and began operation in 1998. Raw water quality is iron—1.88 mg/L, manganese—0.16 mg/L.

The city of Elk Point, S.D., has three wells and six filters serving a population of 1,656 people. Raw water quality data are shown in Table 3. The process involves forced air aeration followed by addition of $KMnO_4$ and filtration by manganese greensand filters. Filtration rates are 3.1 gpm/sq ft (2.1 mm/s). The level of Ra 226 and 228 in the raw water was 11 pCi/L. This was reduced to 2 pCi/L, a reduction of 82%.

A study of three plants was conducted in Minnesota in 1998 to determine the efficiency of Ra removal by manganese greensand filtration. The Lakeville, Hinckley, and Savage, Minn., plants use the manganese greensand filtration system to remove Fe and Mn and to help contain higher levels of Ra 226 and 228. However, these three plants were not specifically designed to remove Ra. The Minnesota Department of Health staff agreed to draw samples of raw and treated water, and the department laboratory analyzed the samples for both Ra 226 and 228. Ra removal for these three plants ranged from 21 to 73%.

The city of Lakeville, Minn. constructed a 10 mgd (37 ML/d) gravity Fe and Mn removal plant that came online in March 1998. This plant was selected for the study because raw water data showed that in one of its wells the levels of Ra 226 and 228 were higher than the MCL. The plant schematic is shown in Figure 2, and the filter cross-section is shown in Figure 3. Raw water quality data for wells 6–13 is shown in Table 4. The water from wells 6–13 is oxidized by the addition of chlorine and then is filtered. The filtered water is stored in a 2.1 mil gal (7.9 ML) clearwell to be pumped into the distribution system. Table 5 shows the results of Ra removal by the manganese greensand filtration process. The removal of Ra 226 is 39%. Ra 228 was not detected in either the raw water or the plant effluent.

In Hinckley, Minn., in 1998 a 400 gpm (25 L/s) Fe and Mn removal plant was constructed on well number 4. The raw water quality data are shown in Table 6. The process involves oxidation by $KMnO_4$ and filtration. The filter contains 12 in. (300 mm) of anthracite and 18 in. (460 mm) of manganese greensand and is supported by 12 in. (300 mm) of gravel. A filter cross-section is shown in Figure 4. The raw and finished water Ra levels are shown in Table 7. Results show that the total Ra removal rate is only 21%, not enough to meet the MCL of 5 pCi/L. The city is currently required to publish a quarterly notification of violation.

In Savage, Minn., an Fe and Mn removal plant was constructed in the late 1980s. Raw water quality data are shown in Table 8, and the plant schematic is shown in Figure 5. Raw water from wells 3, 5, 6, and 7 is aerated to oxidize the Fe. This is followed by chlorine and $KMnO_4$. The water is then filtered and stored in a 1.5 mil gal (5.7 ML) ground storage reservoir to be pumped into the system. In 1996, the city decided to convert the filter to a manganese greensand filter containing manganese greensand and anthracite.

Table 9 shows the raw and treated water Ra levels in Savage. The results indicate a 63% removal of Ra 226 and an 83% removal of Ra 228. The raw water Ra levels of 15.6 pCi/L are reduced to 4.2 pCi/L so the plant effluent is below the MCL of 5 pCi/L for Ra 226 and 228. This was after the plant had been in operation with a manganese greensand filtration system for about three years.

FIGURE 4 Hinckley, Minn., water treatment plant schematic

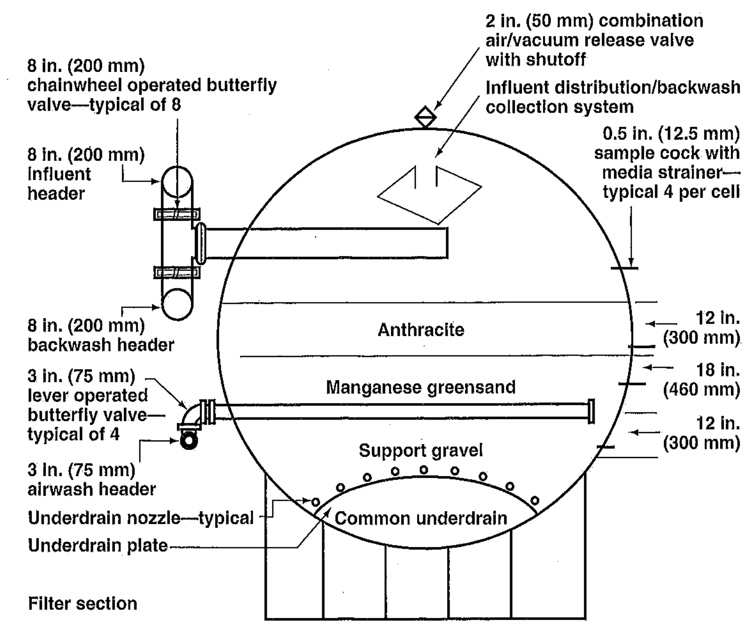
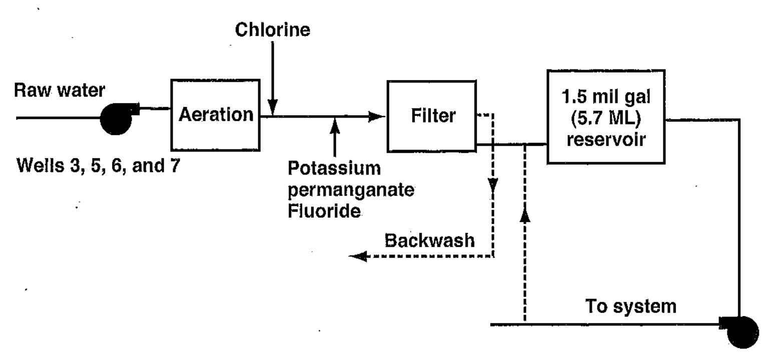


FIGURE 5 Savage, Minn., water treatment plant schematic



DISCUSSION

The decision by USEPA to maintain a 5-pCi/L standard for Ra 226 and 228 will present a challenge to numerous utilities, especially the smaller ones because they lack the resources and technical know-how to implement the BAT for Ra removal. The cost for RO is generally around $4/1,000 gal ($1.06/ 1,000 L) versus <$2/1,000 gal ($0.53/1,000 L) for a manganese greensand filtration system. The use of the HMO and manganese greensand filtration processes provides a low-cost option for meeting the standard. The costs are less than half of the cost of BAT for Ra removal. Some researchers (McKelvey et al, 1993) have indicated that the Ra removal efficiencies decrease over time. Also, the removal efficiencies increase with an increase in levels of Fe and Mn in the raw water, particularly Mn. Mott et al (1993) showed that influent Ra concentration of 100 pCi/L was reduced to 2–9 pCi/L in column-type filtration experiments that used manganese greensand as a catalytic filter for removing Fe and Mn from aqueous suspension.

The Savage Water Treatment Plant was converted to a manganese greensand filter in February 1996. The Ra removal efficiencies have not decreased after four years of operation. The removal of Ra in the Hinckley plant is only 21%, significantly less than at the Lakeville and Savage plants. The raw water at Hinckley has an Fe content of 1.88 mg/L. Researchers have shown that Fe oxides interfere with Mn oxide in mixed Fe–Mn oxides. It is likely that high levels of Fe in the Hinckley water reduce the adsorption of Ra because of competing ions. These results seem to concur with those obtained at the University of Iowa, where Ra removal was reduced from 90% when no Fe was present to 20–30% when Fe was present. It was not clear whether the iron oxide simply blocked access to the sorptive sites or if it actually adsorbed onto the manganese oxide. It has been shown that Ra adsorption increases with pH. The pH of the raw water is 6.96 compared with about 7.6 for both Lakeville and Savage. The lower pH may have contributed to lower Ra removal at Hinckley.

Review of water quality data shows that the Ra removal efficiency seems to be somewhat related to the total dissolved solids (TDS) in the raw water (Figure 6). Ra removal increases with the increase in TDS. Hinckley, Lakeville, and Savage waters have an average TDS of 189, 289, and 380 mg/L, respectively, and a Ra removal efficiency of 21, 39, and 72%, respectively.

TABLE 8 Raw water quality—Savage, Minn.

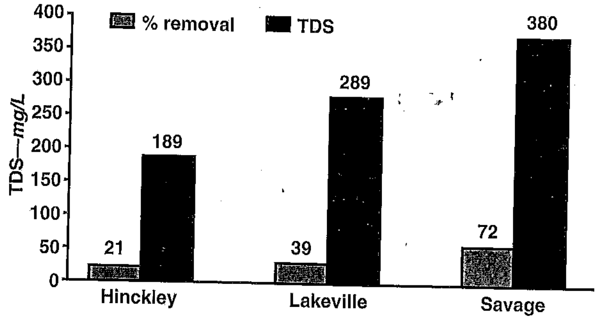
	Well 3	Well 5	Well 6	Well 7	Average
Capacity—*gpm (L/s)*	1,250 (78.8)	480 (30)	1,300 (82)	1,400 (88)	1,107.50 (70)
Total hardness—*mg/L*	331		350	200	293.67
Alkalinity—*mg/L*	340		350	210	300
Calcium—*mg/L*	116		87	82	95
Magnesium—*mg/L*	0.09		0.48	82	27.52
Iron—*mg/L*	0.544	0.013	1.4	0.37	0.58
Manganese—*mg/L*	0.076	0.084	0.48	ND*	0.21
Total organic carbon—*mg/L*	2.0	1.4	1.4	1.2	1.50
Chloride—*mg/L*	1		6.9	32	13.30
Sulfate—*mg/L*	6.5		22		14.25
Potassium—*mg/L*	2.4			70	36.20
Total solids—*mg/L*	340			420	380
Total dissolved solids—*mg/L*			370	390	380
Specific conductivity	610				610
pH	7.7		7.5	7.5	7.57
Arsenic—*μg/L*	<5				
Barium—*mg/L*	<200				
Cadmium—*μg/L*	<1				
Chromium—*μg/L*	<5				
Fluoride—*mg/L*	0.27		ND	0.4	
Lead—*μg/L*	<10		0.002		
Mercury—*μg/L*	0.23				0.23
Nitrate nitrogen—*mg/L*	0.05		ND	ND	
Selenium—*μg/L*	<5				
Silver—*μg/L*	<5				
Sodium—*mg/L*	6.5		3	52	20.50
pH of stability					
Radium 226—*pCi/L*			0.29±0.08	6.5±0.3	
Radium 228—*pCi/L*			0.5±0.6	8.3±1.1	
Gross alpha—*pCi/L*				27±3	
Gross beta—*pCi/L*				30±2	
Radium 222—*pCi/L*				180±20	

*ND—not detected

TABLE 9 Radium removal—Savage, Minn.

	Raw	Finished	Removal—%
Radium 226—*pCi/L*	7.5	2.8	63
Radium 228—*pCi/L*	8.1	1.4	83
Total	15.6	4.2	73

FIGURE 6 Correlation between TDS and radium removal efficiency



% removal ≈ (0.2656)(TDS) − 31.9575; correlation coefficient = 0.981; TDS—total dissolved solids

It appears that there is some relationship between Ra removal and total hardness. However, the relationship is nonlinear. For example, average hardness for Hinckley, Lakeville, and Savage is 137, 285, and 293 mg/L, respectively. However, the Ra removal efficiency only increases from 21% for Hinckley to 39% for Lakeville and 73% for Savage.

Disposal of water containing Ra is a major concern to utilities that are evaluating different options for Ra removal. Most of the manganese greensand filter plants dispose of the Fe and Mn sludge to sanitary sewers. The Minnesota Department of Health issued guidelines for the disposal of Ra generated from removal in drinking water in January 1992. It stated: "Radium discharged must be readily soluble or dispersible in water. Radium may be released into a sanitary sewer provided that is does not exceed a level determined below when diluted with the average daily volume of waste water discharged to the sanitary sewer by the releasing facility.

$$\frac{\text{Concentration Ra 226}}{\text{400 pCi/L}} + \frac{\text{Concentration Ra 228}}{\text{800 pCi/L}} < 1\text{"} \quad (1)$$

Although both HMO and manganese greensand filtration hold some promise for Ra removal, it is recommended that a pilot-plant study be completed before these lower-cost options for Ra removal are implemented. Utilities that have Ra levels up to 20% above the 5 pCi/L standard are the most likely to benefit by using either HMO or manganese greensand filtration processes.

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