Exhibit 2

References Cited

Minnesota Pollution Control Agency Environmental Data Access, Station ID MN0067687

Discharge Station Information

Station Name:	AREA 1 PIT TO SECOND CREEK
Waterbody Name:	
Data Steward Org:	NPDES PERMITTEE
Station ID:	MN0067687-SD-1
Hydrologic Unit Code (HUC):	04010201
Assessment Unit:	
Period of Record:	2005 through 2012
Lat/Lon	47.57603606,-92.15530629

Year 2005 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal												
Bicarbonates (HCO3)	396 mg/L	CalMoAvg									330.25	341	345	362
Bicarbonates (HCO3)	445 mg/L	CalMoMax									337	351	356	367
Cadmium, Total (as Cd)	ug/L	SingleVal												
Chloride, Total	mg/L	SingleVal									10.5	10.1	10.8	10.2
Chromium, Total (as Cr)	ug/L	SingleVal												
Cobalt, Total (as Co)	ug/L	SingleVal												
Copper, Total (as Cu)	ug/L	SingleVal												
Flow	MG	CalMoTot									52.9	66.5	54.6	77.5
Flow	mgd	DailyAve									1.76	2.15	1.82	2.5
Flow	mgd	DailyMax									2.96	2.85	1.94	2.56
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	740 mg/L	CalMoAvg									706.25	710	692	714
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	831 mg/L	CalMoMax									718	718	700	735
Lead, Total (as Pb)	ug/L	SingleVal												
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax									0.000009	0.0000076	0.0000077	0.0000087
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg									<0.725	<0.575	0.95	0.65
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax									1.0	0.7	1.2	0.9
Molybdenum, Total (as Mo)	ug/L	SingleVal									<5	<5	<5	<5
Nickel, Total (as Ni)	ug/L	SingleVal												
Selenium, Total (as Se)	ug/L	SingleVal												
Sodium, Total (as Na)	mg/L	SingleVal									15.1	16	13.3	16
Solids, Total Dissolved (TDS)	1619 mg/L	CalMoAvg									825	913.5	830	879.5
Solids, Total Dissolved (TDS)	1818 mg/L	CalMoMax									887	954	830	881
Solids, Total Suspended (TSS)	mg/L	CalMoAvg									2.75	2.5	<1	<2
Solids, Total														

Suspended (TSS)	mg/L	CalMoMax	4	3	<1	3
Specific Conductance	2159 umh/cm	CalMoAvg	1206.33	1244.5	1221.5	1296.5
Specific Conductance	2425 umh/cm	CalMoMax	1263	1249	1276	1308
Sulfate, Total (as SO4)	mg/L	SingleVal	382	398	491	364
Thallium, Total (as Tl)	ug/L	SingleVal				
Zinc, Total (as Zn)	ug/L	SingleVal				
pH	6.5 SU	CalMoMin	8.03	8.24	8.06	8.6
pH	8.5 SU	CalMoMax	8.19	8.27	8.11	8.6

Year 2006 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal								0.9				
Bicarbonates (HCO3)	396 mg/L	CalMoAvg	361	359	356.5	331.5	355.5	339.5	327.5	158.5	328.5	172	343.5	358
Bicarbonates (HCO3)	445 mg/L	CalMoMax	363	364	364	338	357	345	333	317	330	334	353	359
Cadmium, Total (as Cd)	ug/L	SingleVal								<0.1				
Chloride, Total	mg/L	SingleVal	10.2	11.3	6.7	10.3	10.1	10.2	10.3	10.6	9.9	10.1	10.9	10.6
Chromium, Total (as Cr)	ug/L	SingleVal								11.6				
Cobalt, Total (as Co)	ug/L	SingleVal								<0.1				
Copper, Total (as Cu)	ug/L	SingleVal								1.0				
Flow	MG	CalMoTot	91.14	80.9	86.2	3.16	101.4	118.84	65.88	105.9	60.7	71.4	50.26	42.07
Flow	mgd	DailyAve	2.94	2.89	2.78	94.9	3.27	3.96	2.125	3.42	2.02	2.303	1.68	1.36
Flow	mgd	DailyMax	3.04	3.09	2.82	95.8	4.18	4.18	2.56	3.67	2.51	2.579	1.72	1.38
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	740 mg/L	CalMoAvg	763	717	738	727	750	729.5	736.5	739.5	726.5	747.5	766.5	774
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	831 mg/L	CalMoMax	766	721	752	730	751	748	741	744	729	749	798	790
Lead, Total (as Pb)	ug/L	SingleVal								0.1				
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax	0.0000081	0.000025	0.0000083	0.0000145	0.0000095	0.0000206	0.0000097	0.0000236	0.0000124	0.0000069	0.0000043	0.0000040
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg	<0.6	1.15	0.625	0.925	0.65	0.925	1.025	1.05	1.025	0.775	0.325	0.35
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax	0.7	2.1	0.8	1.2	0.8	1.3	1.3	1.7	1.3	0.9	0.7	0.8
Molybdenum, Total (as Mo)	ug/L	SingleVal	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Nickel, Total (as Ni)	ug/L	SingleVal								0.7				
Selenium, Total (as Se)	ug/L	SingleVal								<0.5				
Sodium, Total (as Na)	mg/L	SingleVal	16.7	15.7	15.2	14.4	15	15.3	14.6	14.3	14.6	15	16.5	14.8
Solids, Total Dissolved (TDS)	1619 mg/L	CalMoAvg	812	889.5	872	1111	853	868	843	841	848	864.5	886.5	871.5
Solids, Total Dissolved (TDS)	1818 mg/L	CalMoMax	841	926	877	1560	859	872	847	873	861	884	932	890

Solids, Total Suspended (TSS)	mg/L	CalMoAvg	<1.1	1.8	1.4	<1	<1	2	<1	2	2	1.6	1	1
Solids, Total Suspended (TSS)	mg/L	CalMoMax	1.2	2.4	1.6	<1	<1	4	2	3	3	2	2	2
Specific Conductance	2159 umh/cm	CalMoAvg	1315	1296.5	1314.5	1090	1310	1295.5	1272	1225.5	1208.5	1247	1283.5	1238
Specific Conductance	2425 umh/cm	CalMoMax	1320	1340	1330	1107	1314	1324	1274	1228	1223	1276	1289	1240
Sulfate, Total (as SO4)	mg/L	SingleVal	411	426	379	346	376	380	377	400	462	371	387	356
Thallium, Total (as Tl)	ug/L	SingleVal								<0.1				
Zinc, Total (as Zn)	ug/L	SingleVal								<5				
pH	6.5 SU	CalMoMin	8.6	8.4	8.5	8.12	8.0	8.1	8.09	8.2	8.08	8.15	8.2	8.3
pH	8.5 SU	CalMoMax	8.7	8.6	8.5	8.3	8.3	8.4	8.14	8.2	8.3	8.15	8.3	8.5

Year 2007 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal								1.2				
Bicarbonates (HCO3)	396 mg/L	CalMoAvg	358	368	378	326	343.5	326	327.5	316.5	326.5	328	336	346.5
Bicarbonates (HCO3)	445 mg/L	CalMoMax	364	369	382	331	351	333	331	321	328	329	344	350
Cadmium, Total (as Cd)	ug/L	SingleVal								<0.1				
Chloride, Total	mg/L	SingleVal	9.06	10.9	10.8	8.67	9.37	9.6	9.63	10.2	10.2	9.99	10.4	10.2
Chromium, Total (as Cr)	ug/L	SingleVal								4.1				
Cobalt, Total (as Co)	ug/L	SingleVal								<0.1				
Copper, Total (as Cu)	ug/L	SingleVal								1.6				
Flow	MG	CalMoTot	36.27	23.62	41.04	67.5	83.7	159.9	97.03	81.2	75	117.18	117.15	98.9
Flow	mgd	DailyAve	1.17	0.84	1.324	2.25	2.7	5.33	3.13	2.62	2.5	3.78	3.905	3.19
Flow	mgd	DailyMax	1.21	0.88	1.706	2.64	3.26	5.57	3.44	3.00	2.85	4.06	3.96	3.21
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	740 mg/L	CalMoAvg	775.5	863	814.5	668.5	727	725	706.5	697.5	711.5	705	729	758.5
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	831 mg/L	CalMoMax	776	865	855	691	738	732	729	715	736	728	729	791
Lead, Total (as Pb)	ug/L	SingleVal								<0.1				
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax	0.0000027	0.0000023	0.0000045	0.000012	0.0000074	0.000042	0.0000091	0.0000068	0.000011	0.0000077	0.0000225	0.0000061
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg	0.15	0.425	0.45	1.275	0.65	0.45	0.7	0.678	0.475	0.25	0.525	<0.5
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax	0.6	0.7	0.7	1.7	0.7	1.0	0.8	0.8	1.0	0.5	1.5	<0.5
Molybdenum, Total (as Mo)	ug/L	SingleVal	<5	<5	<5	<5	<10	<10	<10	<10	<5	<5	<5	<5
Nickel, Total (as Ni)	ug/L	SingleVal								0.59				
Selenium, Total (as Se)	ug/L	SingleVal								<0.5				
Sodium,	mg/L	SingleVal	14.9	16.6	16.4	13.4	14.2	14.2	14.7	14.6	14.9	13.6	14.5	15.5

Total (as Na)														
Solids, Total Dissolved (TDS)	1619 mg/L	CalMoAvg	953.5	950	878	737	827	719	834	778.5	756	787	791.5	837.5
Solids, Total Dissolved (TDS)	1818 mg/L	CalMoMax	985	980	883	757	843	719	876	784	758	808	814	857
Solids, Total Suspended (TSS)	mg/L	CalMoAvg	1.2	1	0.6	2	<1	1	2.65	1.6	<1	0.6	1	0.6
Solids, Total Suspended (TSS)	mg/L	CalMoMax	1.2	2	1.2	3	<1	2	3.3	2	<1	1.2	2	1.2
Specific Conductance	2159 umh/cm	CalMoAvg	1259	1209.5	1221	1184.5	1207	1163	1172.5	1254.5	1195	1212	1162.5	1242
Specific Conductance	2425 umh/cm	CalMoMax	1262	1211	1222	1189	1233	1170	1205	1285	1216	1233	1207	1318
Sulfate, Total (as SO4)	mg/L	SingleVal	332	403	411	307	316	340	346	365	375	366	362	372
Thallium, Total (as Tl)	ug/L	SingleVal								<0.1				
Zinc, Total (as Zn)	ug/L	SingleVal								<5				
pH	6.5 SU	CalMoMin	8.3	8.2	8.2	7.8	8.2	8.0	7.8	8.2	8.2	8.2	8.4	8.4
pH	8.5 SU	CalMoMax	8.4	8.3	8.3	8.1	8.4	8.1	8.0	8.3	8.4	8.3	8.4	8.5

Year 2008 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal								1.2				
Bicarbonates (HCO3)	396 mg/L	CalMoAvg	359.5	368	372.5	329	322.5	373	317.5	319	320.5	334.5	342	352.5
Bicarbonates (HCO3)	445 mg/L	CalMoMax	361	374	379	361	339	421	324	323	325	340	345	356
Cadmium, Total (as Cd)	ug/L	SingleVal								0.026				
Chloride, Total	mg/L	SingleVal	10.1	10.4	10.5	10.6	9.69	10	4.83	9.98	10	10.4	10.1	10.1
Chromium, Total (as Cr)	ug/L	SingleVal								0.88				
Cobalt, Total (as Co)	ug/L	SingleVal								0.25				
Copper, Total (as Cu)	ug/L	SingleVal								0.37				
Flow	MG	CalMoTot	96.1	99.76	111.0	117.3	119.51	98.9	186	58.1	15.9	0.002	149.4	163.1
Flow	mgd	DailyAve	3.1	3.44	3.58	3.91	3.855	3.30	3.00	1.88	0.53	0.032	4.981	5.262
Flow	mgd	DailyMax	3.5	3.54	3.65	4.28	5.53	3.41	3.22	2.16	0.81	0.0465	5.312	5.269
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	740 mg/L	CalMoAvg	724.5	754	746.5	716.5	693	689	752	690	678.5	729	720.5	746
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	831 mg/L	CalMoMax	729	769	839	811	761	702	767	694	696	732	736	755
Lead, Total (as Pb)	ug/L	SingleVal								0.64				
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax	0.0000066	0.000052	0.0000097	0.0000113	0.0000167	0.0000109	0.0000116	0.0000065	0.0000021	0.0000001	0.000023	0.000014
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg	0.25	1.3	0.625	0.475	0.625	0.775	0.775	0.8	0.95	0.525	1.15	0.65
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax	0.5	3.9	0.7	0.7	0.8	0.9	0.9	0.9	1.5	0.7	1.3	0.7

Molybdenum, Total (as Mo)	ug/L	SingleVal	<5	<5	<5	<5	<5	<5	<5	1.7	<5	<5	<5	5.46
Nickel, Total (as Ni)	ug/L	SingleVal								1.1				
Selenium, Total (as Se)	ug/L	SingleVal								0.52				
Sodium, Total (as Na)	mg/L	SingleVal	15.3	15.6	14.3	16.4	15.2	13.4	14.1	13.6	13.5	14	14.6	14.6
Solids, Total Dissolved (TDS)	1619 mg/L	CalMoAvg	858.5	810	872.5	601	827.5	743.5	751.5	762	758	758	841.5	824.5
Solids, Total Dissolved (TDS)	1818 mg/L	CalMoMax	871	852	934	822	879	751	755	768	766	766	911	891
Solids, Total Suspended (TSS)	mg/L	CalMoAvg	0.5	1	<1	0.6	1	<1	<1	0.6	1	<1	0.8	<1
Solids, Total Suspended (TSS)	mg/L	CalMoMax	1	2	<1	1.2	2	<1	<1	1.2	2	<1	1.6	<1
Specific Conductance	2159 umh/cm	CalMoAvg	1376.5	1429	1449.5	1199	1211.5	1210	1201.5	1224	1190.5	1189.5	1186.5	1216
Specific Conductance	2425 umh/cm	CalMoMax	1425	1439	1462	1280	1230	1210	1205	1231	1206	1195	1201	1228
Sulfate, Total (as SO4)	mg/L	SingleVal	374	384	370	378	350	351	178	346	358	348	352	352
Thallium, Total (as Tl)	ug/L	SingleVal								<0.4				
Zinc, Total (as Zn)	ug/L	SingleVal								2.0				
pH	6.5 SU	CalMoMin	8.4	8.4	8.3	8.3	8.2	8.2	8.2	8.11	8.04	8.13	8.00	8.4
pH	8.5 SU	CalMoMax	8.5	8.4	8.4	8.5	8.3	8.3	8.3	8.23	8.06	8.24	8.55	8.5

Year 2009 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal								<2				
Bicarbonates (HCO3)	396 mg/L	CalMoAvg	271	358	355.5	347.5	333.5	332	323.5	313.5	307	318	333	335.5
Bicarbonates (HCO3)	445 mg/L	CalMoMax	358	359	362	354	335	332	334	316	310	325	334	340
Cadmium, Total (as Cd)	ug/L	SingleVal								<0.2				
Chloride, Total	mg/L	SingleVal	10.2	10.5	10.6	10.4	9.9	9.93	9.73	9.8	10.1	10.5	10.6	10.2
Chromium, Total (as Cr)	ug/L	SingleVal								<1				
Cobalt, Total (as Co)	ug/L	SingleVal								<0.2				
Copper, Total (as Cu)	ug/L	SingleVal								<0.7				
Flow	MG	CalMoTot	165.1	150.8	162.4	153.9	173.6	166	1.66	160	135	141	115.18	142.59
Flow	mgd	DailyAve	5.324	5.386	5.239	5.129	5.599	5.5	5.3	5.2	4.5	4.6	3.84	4.6
Flow	mgd	DailyMax	5.368	5.484	5.252	5.234	5.600	5.8	6.7	6.3	6.0	5.8	7.25	5.8
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	740 mg/L	CalMoAvg	749	749	773	754.5	736	721.5	731	716.5	724	722	724.5	725
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	831 mg/L	CalMoMax	751	765	806	761	742	729	732	727	733	726	728	730

Lead, Total (as Pb)	ug/L	SingleVal								<0.5				
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax	0.000014	0.000015	0.000020	0.000016	0.000030	0.000023	0.000040	0.000016	0.000016	0.000010	0.000011	0.000013
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg	0.65	0.6	1.0	0.75	1.2	0.85	0.8	0.75	0.8	0.3	0.65	0.65
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax	0.7	0.7	1.0	0.8	1.4	1.1	1.9	0.8	0.9	0.6	1.3	0.8
Molybdenum, Total (as Mo)	ug/L	SingleVal	1.7	6.91	2.1	<5	5.48	1.63	1.86	1.53	5.1	<5	<5	5.53
Nickel, Total (as Ni)	ug/L	SingleVal								<0.6				
Selenium, Total (as Se)	ug/L	SingleVal								<0.3				
Sodium, Total (as Na)	mg/L	SingleVal	14.6	14.9	14.4	15.6	14.4	14.9	14.2	14.5	14.1	14.1	14.4	14.5
Solids, Total Dissolved (TDS)	1619 mg/L	CalMoAvg	871	877.5	855	794.5	767.5	815	789	730	804	792	881.5	834.5
Solids, Total Dissolved (TDS)	1818 mg/L	CalMoMax	913	883	880	798	787	868	841	735	828	804	932	835
Solids, Total Suspended (TSS)	mg/L	CalMoAvg	1	1	<1	<1	0.6	0.6	2.4	2.85	0.80	1.6	1.2	2
Solids, Total Suspended (TSS)	mg/L	CalMoMax	2	2	<1	<1	1.2	1.2	3.2	3.3	1.6	1.6	2.4	3
Specific Conductance	2159 umh/cm	CalMoAvg	1241	1221	1246.5	1210.5	1184	1180.5	1170.5	1152	1156	1165	1174.5	1214
Specific Conductance	2425 umh/cm	CalMoMax	1244	1245	1256	1218	1193	1187	1177	1155	1160	1174	1177	1216
Sulfate, Total (as SO4)	mg/L	SingleVal	364	374	382	364	351	349	365	349	365	373	393	396
Thallium, Total (as Tl)	ug/L	SingleVal								<0.4				
Zinc, Total (as Zn)	ug/L	SingleVal								<6				
pH	6.5 SU	CalMoMin	8.46	8.37	8.35	8.29	8.33	8.4	8.3	8.3	8.3	8.3	8.3	8.2
pH	8.5 SU	CalMoMax	8.50	8.48	8.42	8.35	8.35	8.4	8.4	8.3	8.3	8.5	8.3	8.2

Year 2010 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal												
Bicarbonates (HCO3)	396 mg/L	CalMoAvg	346	347	346	330	336	322						
Bicarbonates (HCO3)	445 mg/L	CalMoMax	347	348	347	333	338	334						
Cadmium, Total (as Cd)	ug/L	SingleVal												
Chloride, Total	mg/L	SingleVal	10	9.87	10.1	9.67	10.3	9.89						
Chromium, Total (as Cr)	ug/L	SingleVal												
Cobalt, Total (as Co)	ug/L	SingleVal												
Copper, Total (as Cu)	ug/L	SingleVal												
Flow	MG	CalMoTot	110.67	79.6	88.4	83.7	88.7	83.2						
Flow	mgd	DailyAve	3.57	2.8	2.9	2.79	2.86	2.77						
Flow	mgd	DailyMax	8.34	3.5	4.3	3.72	3.56	3.49						
Hardness, Calcium & Magnesium,	740 mg/L	CalMoAvg	762	779	785	740	726	742						

Calculated (as CaCO3)								
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	831 mg/L	CalMoMax	769	800	800	753	735	754
Lead, Total (as Pb)	ug/L	SingleVal						
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax	0.000014	0.000015	0.000012	0.000005	0.000006	0.000005
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg	0.8	0.8	0.6	<0.5	<0.5	0.25
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax	1.0	1.1	1.1	<0.5	<0.5	0.5
Molybdenum, Total (as Mo)	ug/L	SingleVal	6.9	6.8	<5	<5	5.36	1.98
Nickel, Total (as Ni)	ug/L	SingleVal						
Selenium, Total (as Se)	ug/L	SingleVal						
Sodium, Total (as Na)	mg/L	SingleVal	15	15.6	15.4	15.3	17.6	18.7
Solids, Total Dissolved (TDS)	1619 mg/L	CalMoAvg	843.5	835	830	880	793	868
Solids, Total Dissolved (TDS)	1818 mg/L	CalMoMax	857	838	833	888	825	889
Solids, Total Suspended (TSS)	mg/L	CalMoAvg	2.15	<1	1.6	1.9	2.3	1.2
Solids, Total Suspended (TSS)	mg/L	CalMoMax	3	<1	2	2.7	3.6	2.4
Specific Conductance	2159 umh/cm	CalMoAvg	1240	1258	1169	1160	1226	1233
Specific Conductance	2425 umh/cm	CalMoMax	1243	1258	1232	1231	1230	1250
Sulfate, Total (as SO4)	mg/L	SingleVal	400	381	398	371	403	374
Thallium, Total (as Tl)	ug/L	SingleVal						
Zinc, Total (as Zn)	ug/L	SingleVal						
pH	6.5 SU	CalMoMin	8.2	8.3	8.1	8.1	8.4	8.1
pH	8.5 SU	CalMoMax	8.4	8.4	8.3	8.3	8.4	8.4

Year 2011 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal												
Bicarbonates (HCO3)	268 mg/L	CalMoAvg												
Bicarbonates (HCO3)	301 mg/L	CalMoMax												
Cadmium, Total (as Cd)	ug/L	SingleVal												
Chloride, Total	mg/L	SingleVal												
Chromium, Total (as Cr)	ug/L	SingleVal												
Cobalt, Total (as Co)	ug/L	SingleVal												
Copper, Total (as Cu)	ug/L	SingleVal												
Flow	MG	CalMoTot												
Flow	mgd	DailyAve												
Flow	mgd	DailyMax												
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	268 mg/L	CalMoAvg												
Hardness, Calcium & Magnesium, Calculated	301 mg/L	CalMoMax												

(as CaCO3)		
Lead, Total (as Pb)	ug/L	SingleVal
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax
Molybdenum, Total (as Mo)	ug/L	SingleVal
Nickel, Total (as Ni)	ug/L	SingleVal
Selenium, Total (as Se)	ug/L	SingleVal
Sodium, Total (as Na)	mg/L	SingleVal
Solids, Total Dissolved (TDS)	752 mg/L	CalMoAvg
Solids, Total Dissolved (TDS)	842 mg/L	CalMoMax
Solids, Total Suspended (TSS)	mg/L	CalMoAvg
Solids, Total Suspended (TSS)	mg/L	CalMoMax
Specific Conductance	1074 umh/cm	CalMoAvg
Specific Conductance	1203 umh/cm	CalMoMax
Sulfate, Total (as SO4)	mg/L	SingleVal
Thallium, Total (as Tl)	ug/L	SingleVal
Zinc, Total (as Zn)	ug/L	SingleVal
pH	6.5 SU	CalMoMin
pH	8.5 SU	CalMoMax

Year 2012 Data

Pollutant	Limit	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsenic, Total (as As)	ug/L	SingleVal												
Bicarbonates (HCO3)	268 mg/L	CalMoAvg										323		
Bicarbonates (HCO3)	301 mg/L	CalMoMax										323		
Cadmium, Total (as Cd)	ug/L	SingleVal												
Chloride, Total	mg/L	SingleVal										15.6		
Chromium, Total (as Cr)	ug/L	SingleVal												
Cobalt, Total (as Co)	ug/L	SingleVal												
Copper, Total (as Cu)	ug/L	SingleVal												
Flow	MG	CalMoTot										111		
Flow	mgd	DailyAve										3.57		
Flow	mgd	DailyMax										3.74		
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	268 mg/L	CalMoAvg										771		
Hardness, Calcium & Magnesium, Calculated (as CaCO3)	301 mg/L	CalMoMax										786		
Lead, Total (as Pb)	ug/L	SingleVal												
Mercury, Total (as Hg)	0.000070 kg/day	CalMoMax										0.00000073		
Mercury, Total (as Hg)	1.8 ng/L	CalMoAvg										0.54		
Mercury, Total (as Hg)	3.2 ng/L	CalMoMax										0.56		
Molybdenum, Total (as Mo)	ug/L	SingleVal										<10		
Nickel, Total (as Ni)	ug/L	SingleVal												
Selenium, Total (as Se)	ug/L	SingleVal												
Sodium, Total (as Na)	mg/L	SingleVal										36.4		
Solids, Total Dissolved (TDS)	752 mg/L	CalMoAvg										928		
Solids, Total Dissolved (TDS)	842 mg/L	CalMoMax										963		
Solids, Total Suspended (TSS)	mg/L	CalMoAvg										<1.0		
Solids, Total Suspended (TSS)	mg/L	CalMoMax										2.0		
Specific Conductance	1074 umh/cm	CalMoAvg										1340		
Specific Conductance	1203 umh/cm	CalMoMax										1362		
Sulfate, Total (as SO4)	mg/L	SingleVal										462		
Thallium, Total (as Tl)	ug/L	SingleVal												
Zinc, Total (as Zn)	ug/L	SingleVal												
pH	6.5 SU	CalMoMin										8.15		
pH	8.5 SU	CalMoMax										8.4		

Data Download Options

Minnesota Rule 7050.0224(2)

7050.0224 SPECIFIC WATER QUALITY STANDARDS FOR CLASS 4 WATERS OF THE STATE; AGRICULTURE AND WILDLIFE.

Subpart 1. **General.** The numeric and narrative water quality standards in this part prescribe the qualities or properties of the waters of the state that are necessary for the agriculture and wildlife designated public uses and benefits. Wild rice is an aquatic plant resource found in certain waters within the state. The harvest and use of grains from this plant serve as a food source for wildlife and humans. In recognition of the ecological importance of this resource, and in conjunction with Minnesota Indian tribes, selected wild rice waters have been specifically identified [WR] and listed in part 7050.0470, subpart 1. The quality of these waters and the aquatic habitat necessary to support the propagation and maintenance of wild rice plant species must not be materially impaired or degraded. If the standards in this part are exceeded in waters of the state that have the Class 4 designation, it is considered indicative of a polluted condition which is actually or potentially deleterious, harmful, detrimental, or injurious with respect to the designated uses.

Subp. 2. **Class 4A waters.** The quality of Class 4A waters of the state shall be such as to permit their use for irrigation without significant damage or adverse effects upon any crops or vegetation usually grown in the waters or area, including truck garden crops. The following standards shall be used as a guide in determining the suitability of the waters for such uses, together with the recommendations contained in Handbook 60 published by the Salinity Laboratory of the United States Department of Agriculture, and any revisions, amendments, or supplements to it:

Substance, Characteristic, or Pollutant	Class 4A Standard
Bicarbonates (HCO_3)	5 milliequivalents per liter
Boron (B)	0.5 mg/L
pH, minimum value	6.0
pH, maximum value	8.5
Specific conductance	1,000 micromhos per centimeter at 25°C
Total dissolved salts	700 mg/L
Sodium (Na)	60% of total cations as milliequivalents per liter

Sulfates (SO_4)	10 mg/L, applicable to water used for production of wild rice during periods when the rice may be susceptible to damage by high sulfate levels.
Radioactive materials	Not to exceed the lowest concentrations permitted to be discharged to an uncontrolled environment as prescribed by the appropriate authority having control over their use.

Subp. 3. **Class 4B waters.** The quality of Class 4B waters of the state shall be such as to permit their use by livestock and wildlife without inhibition or injurious effects. The standards for substances, characteristics, or pollutants given below shall not be exceeded in the waters of the state:

Substance, Characteristic, or Pollutant	Class 4B Standard
pH, minimum value	6.0
pH, maximum value	9.0
Total salinity	1,000 mg/L
Radioactive materials	Not to exceed the lowest concentrations permitted to be discharged to an uncontrolled environment as prescribed by the appropriate authority having control over their use.
Toxic substances	None at levels harmful either directly or indirectly

Additional selective limits may be imposed for any specific waters of the state as needed.

Subp. 4. **Class 4C waters; wetlands.** The quality of Class 4C wetlands shall be such as to permit their use for irrigation and by wildlife and livestock without inhibition or injurious effects and be suitable for erosion control, groundwater recharge, low flow augmentation, stormwater retention, and stream sedimentation. The standards for Classes 4A and 4B waters shall apply to these waters except as listed below:

Substance, Characteristic, or Pollutant	Class 4C Standard

pH	Maintain background
Settleable solids	Shall not be allowed in concentrations sufficient to create the potential for significant adverse impacts on one or more designated uses.

For the purposes of this subpart, "maintain background" means the concentration of the water quality substance, characteristic, or pollutant shall not deviate from the range of natural background concentrations or conditions such that there is a potential significant adverse impact to the designated uses.

Statutory Authority: *MS s 115.03; 115.44*

History: *18 SR 2195; 22 SR 1466; 24 SR 1105; 32 SR 1699*

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A Review of Wastewater Treatment by Reverse Osmosis

A Review of Wastewater Treatment by Reverse Osmosis

Michael E. Williams, Ph.D., P.E,

Since the development of the first practical cellulose acetate membranes in the early 1960's and the subsequent development of thin-film, composite membranes, the uses of reverse osmosis have expanded to include not only the traditional desalination process but also a wide variety of wastewater treatment applications. Several advantages of the RO process that make it particularly attractive for dilute aqueous wastewater treatment include: (1) RO systems are simple to design and operate, have low maintenance requirements, and are modular in nature, making expansion of the systems easy; (2) both inorganic and organic pollutants can be removed simultaneously by RO membrane processes; (3) RO systems allow recovery/recycle of waste process streams with no effect on the material being recovered; (4) RO membrane systems often require less energy and offer lower capital and operating costs than many conventional treatment systems; and (5) RO processes can considerably reduce the volume of waste streams so that these can be treated more efficiently and cost effectively by other processes such as incineration (Cartwright, 1985; Sinisgalli and McNutt, 1986; Cartwright, 1990; McCray et al., 1990; Cartwright, 1991; Williams et al., 1992). In addition, RO systems can replace or be used in conjunction with others treatment processes such as oxidation, adsorption, stripping, or biological treatment (as well as many others) to produce a high quality product water that can be reused or discharged.

Applications that have been reported for RO processes include the treatment of organic containing wastewater, wastewater from electroplating and metal finishing, pulp and paper, mining and petrochemical, textile, and food processing industries, radioactive wastewater, municipal wastewater, and contaminated groundwater (Slater et al., 1983a; Cartwright, 1985; Ghabris et al, 1989; Williams et al., 1992). Table 1 lists RO and nanofiltration applications along with selected references. A review of RO and nanofiltration wastewater treatment follows; a thorough discussion of the application of RO membranes to seawater and brackish water desalination can be found in Williams et al. (1992).

RO Separation of Organic Pollutants from Wastewater

Many studies have been performed on the separation of organics and organic pollutants by RO membranes, and these studies have identified some of the unique aspects associated with organic separation. Sourirajan (1970) and Sourirajan and Matsuura (1985) have compiled separation and flux data of cellulose acetate membranes for a large number of organic compounds, including many organic pollutants. They found that organic separation can vary widely (from <0% to 100%) depending on the characteristics of the organic (polarity, size, charge, etc.) and operating conditions (such as feed pH, operating pressure, etc.). In an early study, Anderson et al. (1972) reported some of the factors influencing separation of several different organics (including acetone, urea, phenol, 2,4-dichlorophenol, nitrobenzene) by cellulose acetate membranes. Rejections varied considerably for the different solutes, and rejections of ionizable organics were greatly dependent on degree of dissociation; nonionized and hydrophobic solutes were found to be strongly sorbed by the membranes and exhibited poor rejection. Duvel and Helfgott (1975) also found organic separations varied with molecular size and branching; they postulated organic separation was also a function of the solute's potential to form hydrogen bonds with the membrane.

Table 1. Selected Wastewater Applications of Reverse Osmosis.

Application	Species Removed	Reference
Reverse Osmosis		
Seawater, Brackish Water Desalination	Various Salt Species	Williams et al. (1992)
Organic Pollutants Removal	Various organics	Sourirajan (1970); Anderson et al. (1972); Shuckrow et al. (1981); Kurihara et al. (1981); Lynch et al. (1984); Sourirajan and Matsuura (1985); Pusch et al. (1989)
	Herbicides, pesticides	Edwards and Schubert (1974); Chian et al. (1975)
	Polar organics	Fang and Chian (1976); Koyama et al. (1982)
	Phenolic	Koyama et al. (1984); compounds Bhattacharyya et al. (1987); Bhattacharyya Madadi
and (1988); Williams et al. (1990); Bhattacharyya and Williams (1992a)		
	PAH compounds	Light (1981); Bhattacharyya et al. (1987)
	Amines, chlorinated hydrocarbons	Light (1981) Rickabaugh et al. (1986); Cheng et al. (1991); Bhattacharyya and
	Williams (1992a)	
Electroplating and Metal-finishing Rinse Water Treatment	Nickel	McNulty et al. (1977); Spatz (1979); Robison (1983)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Electroplating and Metal-finishing Rinse Water Treatment	Nickel, chromium, gold	Imasu (1985)
	Aluminum, phosphoric acid	Thorsen (1985)
	Various metals	Davis et al. (1987)
	Cadmium	Slater et al. (1987a)
Pulp and Paper Processing Effluent Treatment	Spent sulphite liquor components	Glimenius (1980); Olsen (1980); Paulson and Spatz (1983); Jönsson and Wimmerstedt (1985)
	Wash water components	Hart and Squires (1985)
	Bleach plant effluent compounds	Dorica et al. (1986); Simpson and Groves (1983); Jönsson and Wimmerstedt (1985); Ekengren et al. (1991)
Food Processing Effluent Treatment	Meat processing COD	Hart and Squires (1985); Gekas et al. (1985)
	Olive mills COD, TDS	Canepa et al. (1988); Anonymous (1988a)
	Various contaminants	Mohr et al. (1989)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Radioactive Processing	Radionuclides	Ebra et al. (1987)
Effluent Treatment	Uranium conversion process effluent	Hsiue et al. (1989)
	Various uranium species	Chu et al. (1990); Garret (1990)
	Uranium nitrate	Prabhakar et al. (1992)
Other Wastewater Treatment		
Blast-Furnace Scrubber Water	TDS	Terril and Neufeld (1983)
Coal Mining Drainage	TDS	Hart and Squires (1985)
Cooling Tower Blowdown	TDS	Schutte et al. (1987); Bryant et al. (1987)
Fuel Processing Wastewaters	TDS, COD, organics	Bhattacharyya et al. (1984); Siler and Bhattacharyya (1985); McCray and Ray (1987); Krug and Attard (1990)
Evaporator Condensates	TOC	Lyandres et al. (1989)
Ammonium Nitrate/ Explosive Manufacturing Wastewater	Ammonium nitrate	Hays et al. (1988); Davis et al. (1990)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Textile Dyehouse Effluents	Color, organics, TDS	Treffry-Goatly et al. (1983); Slater et al. (1987b); Calabro et al. (1990); Gaeta and Fedele (1991)
Contaminated Water Supply Treatment		
Leachates	TOC (1977)	Chian and De Walle
	TDS, COD	Slater et al. (1983b)
	Alkalinity, COD, TDS, NH_3	Kinman and Nutini (1990)
	Heavy metals, organics, TOC	Bhattacharyya and Kothari (1991)
	TOC, nitrate, metals	Stürken et al. (1991)
Drinking Water	Agricultural chemicals	Chian et al. (1975); Johnston and Lim (1978); Regunathan et al. (1983); Baier et al. (1987); Fronk (1987)
	Humic, fulvic materials	Nusbaum and Riedinger (1980); Odegaard and Koottatep (1982); Bhattacharyya and Williams (1992a)
	Radium, various contaminants, color	Sorg et al. (1980) Sorg and Love (1984); Taylor et al. (1987) Tan and Sudak (1992)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Municipal	TDS, organics Wastewater	Cruver (1976); Fang and Chian (1976); Lim and Johnston (1976); Tsuge and Mori (1977)
	TDS, TOC	Stenstrom et al. (1982)
	TDS, organics (at Water Factory 21)	Richardson and Argo (1977); Allen and Elser (1979); Argo and Montes (1979); Nusbaum and Argo (1984); Reinhard et al. (1986)
	TDS, TOC, fecal coliform	Suzuki and Minami (1991)
Nanofiltration		
Contaminated Drinking Water Treatment	Color, TOC, hardness, TDS, THMFP	Conlon (1985); Eriksson (1988); Cadotte et al. (1988); Dykes and Conlon (1989); Conlon and McClellan (1989); Watson and Hornburg (1989); Lange et al. (1989); Amy et al. (1990); Conlon et al. (1990); Tan and Amy (1991)
	Agricultural chemicals	Taylor et al. (1989b); Duranceau et al. (1992)
Wastewater Treatment		
Wood Pulping Process Wastewater	Color, organics	Bindoff et al. (1987); Ikeda et al. (1988)

Table 1. Selected Wastewater Applications of Reverse Osmosis (continued).

Application	Species Removed	Reference
Wastewater Treatment		
Textile Mill Effluents	Hardness, color, organics	Simpson et al. (1987); Perry and Linder (1989); Gaeta and Fedele (1991)
Food Processing Effluents	COD	Ikeda et al. (1988); Cadotte et al. (1988); Anonymous (1988b)
Other Wastewaters	Cadmium, nickel	Bhattacharyya et al. (1989)
	Various organic pollutants	Williams et al. (1990); Rautenbach and Gröschl (1990b); Dyke and Bartels (1990); Bhattacharyya and Williams (1992a)
	Uranium species	Chu et al. (1990)

COD:	Chemical Oxygen Demand
TDS:	Total Dissolved Solids
THMFP:	Trihalomethane Formation Potential
TOC:	Total Organic Carbon

membranes, significant decreases in water flux could occur even when only traces of organics were present. They indicated these flux declines could be caused by organic sorption on the membranes.

Saavedra et al. (1991) considered the use of polyamide membranes for the treatment of a phenol production waste stream; the stream contained organic acid salts and organic peroxides. While the organic salts were highly removed (>94%), the peroxides were poorly rejected. Studies with the peroxides indicated that some of these could cause significant water flux drop.

Bhattacharyya et al. (1991) reported separation results for a wastewater containing tributyl phosphate, metal salts (Na^+, NO_3^{2-}, Fe^{3+}, Al^{3+}, etc.), and metal hydroxide precipitates. Tributyl phosphate and metals rejections were high (91% to 99%). Declines in water flux were caused by osmotic pressure of the metal salts, tributyl phosphate adsorption, and enhancement of precipitate fouling of the membrane caused by tributyl phosphate adsorption on the precipitate. Cheng et al. (1991) reported the effects of dilute solutions of the halocarbons $CHCl_3$, $CHBr_3$, and CCl_4 on the performance of DuPont cellulose acetate, polyamide, and thin-film composite membranes. The halocarbons were mostly poorly rejected (5% to 83%) by the three membranes; however, these caused water flux drops of up to 31%. The results indicated that water flux drop was caused by halocarbon adsorption.

RO Treatment of Industrial Wastewater

Electroplating and Metal-Finishing Process Wastewaters

In most cases, process wastewaters from the electroplating and metal-finishing industries must be treated to remove heavy metals before being discharged. Reverse osmosis is ideal for this wastewater treatment for many of these operations since it allows both recovery of the heavy metals and reuse of the product water in the process. The RO process has been used in the treatment and recovery of wastewater containing nickel, acid copper, zinc, copper cyanide, chromium, aluminum, and gold (Schrantz, 1975; Sato et al., 1977; Kamizawa et al., 1978; Cartwright, 1985).

McNulty et al. (1977) reported high rejections of nickel and total solids from electroplating bath rinse water. Spatz (1979) discussed the use of RO in the nickel plating industry to recover nickel from nickel plating bath rinse water. In this process the permeate was recycled as rinse water, and the concentrate was recycled back to the plating bath. This allowed 97% recovery of the rinse water, and nickel consumption was significantly reduced. Robison (1983) also discussed the use of a RO process to recover nickel from plating rinse water; recycle of the permeate and nickel concentrate resulted in substantial savings for the plating operation.

Imasu (1985) reported on the use of cellulose acetate and polyamide (FT30) membranes at three Japanese plating shops with nickel, chromium, and gold plating lines. Up to 80% water recoveries with high metal and TDS (>95%) rejections were possible, and the product water was recycled. The RO processes were found to be cost-effective in treating the wastewaters, and the compact nature of the RO system made it highly desirable to the customers because of space limitations.

Thorsen (1985) discussed the RO treatment of effluent from an electrolytic polishing process for aluminum products. The streams contained phosphoric acid and aluminum from rinse water. DDS HR-98 membranes allowed 96% to 98% acid recovery (up to an acid concentration of 20%) and produced permeate water suitable for reuse. The membranes appeared to be stable to the feed even at the low pH values (0.9 to 1.0) found at high recoveries.

Davis et al. (1987) discussed two case histories of heavy metal wastewater treatment using RO membranes. In the first case, spiral-wound polyamide membranes allowed 75% water recovery with TDS rejections of >99% for a heavy metal-containing wastewater. Scaling and fouling were reduced by pretreatment and periodic cleaning. In the second case, rinse water effluents from a metal forming facility were treated. Polyamide membranes gave rejections over 99% for calcium, cadmium, chromium, copper, iron, magnesium, manganese, molybdenum, nickel, and tungsten and up to 90% recovery of the effluent as purified water suitable for reuse in the plant was found to be possible. It was noted subsequent treatment to recover molybdenum for reuse in the facility was also possible. The RO system was determined to be a cost-effective alternative to evaporation.

Slater et al. (1987a) reported on the use of RO membranes to remove cadmium from metal processing wastewaters. The FT30 membranes used had cadmium rejections of >99.5% in most cases and produced a high quality product water suitable for reuse. Rejections of other metals (zinc, silver, copper, nickel, and tin) and overall conductivity were >97% even at water recoveries up to 75%, and water fluxes remained at reasonably high levels. It was concluded that the RO could be an efficient and cost-effective process for treatment of the wastewater.

Pulp and Paper Processing Wastewaters

The use of RO membranes in combination with other processes to treat wastewaters in the pulp and paper industry has also been investigated. Morris et al. (1972) and Wiley et al. (1978) conducted early studies with pulp and paper wastewaters. Glimenius (1980) and Olsen (1980) outlined the use of RO to concentrate spent sulphite liquor (SLL, which consists of lignosulfates and other organics as well as various inorganics) containing wastewater before it was sent to an evaporator, resulting in lower energy costs for the evaporator. Paulson and Spatz (1983) also detailed the use of RO and ultrafiltration/RO processes to concentrate SLL wastes before further treatment by evaporation. In the process RO membranes concentrated solids from less than 2% to 10%; it was noted that this preconcentration would greatly reduce evaporator costs because of reduced volume to be treated. High rejections of solids (>95%), BOD (88%), and COD (>96%) were reported for short-term tests. Ultrafiltration treatment prior to a high pressure RO membrane was reported to allow even further preconcentration prior to evaporation. It was pointed out that RO processes would also produce an excellent quality water for reuse in the pulping process. Chakravorty and Srivastava (1987) and Chakravorty (1989) also reported good separation results for an ultrafiltration/reverse osmosis process for pulp and paper mill effluents.

Jönsson and Wimmerstedt (1985) discussed the use of RO concentration prior to SLL evaporation, concentration of weak black liquor by RO, and the use of RO to treat bleach effluent; rejections of both organics and inorganics in these effluents were >90%. They also reported the use of PCI ZF99 tubular membranes to treat waste paper white water. For these membranes rejections of TDS (99.4%) and COD (>99.8%) were found to be good even at high water recoveries (up to 95%). Hart and Squires (1985) indicated ZF99 membranes gave high rejections of lignin, TOC, sugars, and color in wash waters, making the permeate suitable for reuse; however, periodic membrane cleanings were required to restore water flux of the membranes. Simpson and Groves (1983) and Ekengren et al. (1991) have reported some success in the use of membranes to treat bleach plant effluent. The ultrafiltration and RO processes used gave high removals of inorganics, COD, and chloroorganic compounds. Dorica et al. (1986) also studied the use of ultrafiltration and RO processes to minimize discharges of chlorinated organics and other pollutants in bleach plant effluents. Reverse osmosis membranes completely removed color and 95% to 99.8% of organics, chloride, and organic chlorine for water recoveries of 75% to 85%; feeds consisted of ultrafiltration filtrate of caustic extraction effluent and effluent from a chlorination stage.

Food Processing Wastewaters

Reverse osmosis also has been used to treat food processing wastewaters so that these could be discharged or recycled; in many cases it was indicated a concentrate stream rich in nutrients was produced. Hart and Squires (1985) discussed the use of ZF99 tubular membranes to concentrate slaughter house effluent rich in COD, and Gekas et al. (1985) also reported on the use of a RO system to treat meat processing wastewaters. Canepa et al. (1988) studied treatment of olive mills wastewater containing high total solids and COD with a combination ultrafiltration/RO process. For the RO membranes rejections of TDS were >99% and COD were 93% for water recoveries of 70%. The permeate was suitable for recycle. The use of an ultrafiltration/RO process to reduce effluents from olive canning operations and allow recycling of processing water has also been reported (Anonymous, 1988a). Mohr et al. (1989) discuss several uses of RO in wastewater treatment in the food industry, including for concentration of whey, fruit processing waters, and stillage waters.

Radioactive Processing Wastewaters

Because of high rejection of inorganic compounds, RO membranes have been studied for treatment of radioactive effluents. Ebra et al. (1987) described a treatment facility that included RO processes to remove low levels of radionuclides and hazardous chemicals prior to discharge. Hsiue et al. (1989) reported on the use of RO membranes to treat uranium conversion process effluent containing toxic, corrosive, and radioactive compounds. The FT30 membranes studied had rejections of uranium ≥99.5% for water recoveries up to 70%, and the results indicated that the treated effluent would meet regulatory discharge standards. Chu et al. (1990) used a three stage process consisting of nanofiltration, reverse osmosis, and precipitation to treat uranium effluents. The process removed both soluble and suspended uranium species; it was found that 95% uranium recovery was possible, and the treated effluent met environmental standards. The RO membranes (FT30) gave uranium rejections of >99%. Prabhakar et al. (1992) indicated cellulose acetate membranes could effectively remove 99% of uranium from effluents containing uranium nitrate when the uranium was complexed with EDTA. Garret (1990) also studied removal of uranium and other radioactive elements by RO membranes.

RO Treatment of Other Wastewaters

Reverse osmosis has also been applied to a variety of other wastewaters. Terril and Neufeld (1983) used RO membranes to remove contaminants (calcium, magnesium, zinc, sulfate, chloride, ammonia and others) in blast-furnace scrubber water, allowing recycle of the product water. Hart and Squires (1985) discussed the use of RO to treat coal mining drainage (containing mostly sodium salts); TDS removals from the permeate were high. Sinisgalli and McNutt (1986) described a process in which RO was integrated with other treatment systems to remove contaminants from a complex industrial wastewater; this wastewater contained contaminants from semiconductor manufacturing lines and plating baths as well as cooling tower blowdown and other facility wastewaters. The treatment process allowed recycle of the product water, reduced operating costs, and compliance with environmental regulations. Reverse osmosis has also been used to demineralize cooling tower blowdown in the power generation industry (Schutte et al., 1987; Bryant et al., 1987).

Bhattacharyya et al. (1984) used FT30 and DuPont B9 (polyamide) membranes to remove contaminants from biotreated coal-liquefaction wastewater. TDS rejections were >77%, and the membranes removed 94% to 98% of the organics and 100% of the color present. Siler and Bhattacharyya (1985) reported on the use of RO membranes to treat oil shale retorting wastewaters containing organics (aliphatic acids and phenolics), inorganics (NH_3, S^{2-}, Cl^-, alkalinity), color, odor, oils, and suspended solids. Rejections with and without various pretreatment by activated carbon, filtration, etc. (which greatly affected flux) ranged from 60% to 94% for conductivity and 75% to 88% for TOC. McCray and Ray (1987) used a RO system to treat process condensate wastewater from a synfuel process which contained high concentrations of organics (phenols, oils and greases, carboxylic acids, cyclic hydrocarbons, etc.) and inorganics such as ammonia, sulfides, carbonates, cyanides, and heavy metals. Studies at high pH indicated contaminants were rejected >95% and fluxes could be maintained at acceptable levels even for water recoveries up to 80%. Krug and Attard (1990) conducted studies using ultrafiltration followed by RO for the treatment of oily wastewater; oil removals greater than 96% were found.

Lyandres et al. (1989) used RO membranes (FT30 and PEC-1000) to treat evaporator condensates from a hazardous waste treatment facility; the condensate contained light organic compounds (mostly carboxylic acids and amines) and small amounts of inorganics. Both membranes removed more than 98% of TOC. Hays et al. (1988) and Davis et al. (1990) have discussed the use of RO membranes to remove and recover ammonium nitrate from manufacturing and explosive manufacturing effluents; ammonium nitrate removals of >87% were found. Reverse osmosis membranes have also been used with some success in the treatment of textile dyehouse effluents (Treffry-Goatly et al., 1983; Slater et al., 1987b; Calabro et al., 1990; Gaeta and Fedele, 1991). Reverse osmosis allows recovery of dyes and auxiliary chemicals and recycle of the product water as rinse water, minimizing discharge of pollutants.

RO Treatment of Contaminated Water Supplies

Leachates

Several studies have been conducted on the treatment of landfill leachates with RO processes. Chian and De Walle (1977) found RO membranes could be used to remove >91% of TOC from sanitary landfill leachate. Slater et al. (1983b) discussed the use of tubular cellulose acetate membranes to treat industrial landfill leachates and found TDS removals of 98% and COD removals of 68%. Water recoveries of up to 75% were possible without significant fouling. McArdle et al. (1987) indicated that RO membranes could be used as a treatment technology for leachate from hazardous waste land disposal facilities. Rautenbach and Ingo (1988) discussed treatment problems of landfill drainage at high water recovery rates. Kinman and Nutini (1990) also described RO treatment of landfill leachate; removals of 94.5% alkalinity, 97% COD, 97% total solids, 92.1% volatile solids, and 96.6% ammonia were reported. Stürken et al. (1991) and Peters (1991) also indicated RO membranes could remove 98% of COD, TOC, and ammonium ions, 96% of nitrate, and heavy metals. Bhattacharyya and Kothari (1991) used FT30 membranes to treat soil-wash leachates so that the treated water could be recycled back to the soil-washing step. The leachate contained heavy metals and organic contaminants. TOC rejections as high as 80-85% and heavy metal (Pb, Zn, Ni, Cu) rejections of 94% to 98% were found. However, water flux decreases of up to 33% were noted. The effects of addition of EDTA or surfactant and feed preozonation were also investigated; feed preozonation substantially improved membrane water flux. Specific organic rejections included >98% for pentachlorophenol and 2,4-dinitrophenol, >97% for ethylbenzene, >81% for xylene, and >90% for chloroaniline. Lepore and Ahlert (1991) reported the treatment of landfill leachates containing organic acids; they found good separations of volatile fatty acids, and TDS was removed sufficiently to allow discharge of the product water.

Application of Membrane Separation Technology to Mitigation of Mine Effluent and Acidic Drainage

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Application of Membrane Separation Technology to Mitigation of Mine Effluent and Acidic Drainage

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1. INTRODUCTION

The objective of this report is to provide a general overview of membrane separation technology and its application to the treatment and management of mining effluents, including acidic drainage (AD). In 2006, CANMET-MMSL conducted a review of available technologies for the treatment and management of mine water and mining effluents for Cameco Corporation, which was partially funded by CANMET-MMSL (Mortazavi *et al.*, 2005). The review covered a wide range of treatment technologies ranging from chemical treatment methods to membrane separation processes. The current report is an expanded version of the membrane separation technology section of the previous study.

Mitigation and management of saline water and wastewater as well as the management of acidic and neutral drainage are among the most important challenges faced by the mining industry. The challenge is meeting economic objectives of the mining operations while maintaining environmental performance and long-term sustainability. In recent years, increased regulatory pressures and increased emphasis on water conservation combined with other drivers such as risk and cost reduction has resulted in substantial changes in operations. As a result, the industry has become more open to adopting more innovative technologies such as membrane separation.

One of the major issues that the mining industry is facing is increased salt loading and salinity. Water, in mining and mineral processing operations, dissolves sodium, potassium, magnesium, chloride and other readily soluble salts. This results in increasingly large volumes of saline and brackish water, especially in dry and arid areas due to solution recycling at zero discharge facilities. Direct impacts of increased salt loading and salinity are increased operational costs and problems in meeting environmental discharge requirements.

Processing of industrial wastewater is a growing niche for membrane separation and therefore a continuously expanding market which is supported by the increasing pressure for water use minimization, recovery and recycle. Increased public awareness of environmental issues, more stringent environmental regulations and improved process economics, have resulted in an