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The separation of lead on reverse osmosis and nano filtration membranes

Research conducted by CRPP and NRC

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The monitoring of lead 212 in the 1000 tonne D_2O detector of the Sudbury Neutrino Observatory (SNO) is to serve a dual purpose: doublechecking the main method for assessing the thorium 232 levels in the water (i.e. trapping of radium 224 and subsequent measurement of the radon 220 daughter); and providing an estimate of the unsupported radon in the system, such as radon emanating from immobilized contamination on the walls of the acrylic vessel.

The levels one hopes to achieve in the 1000 tonne detector are in the order of 1 lead atom/tonne. Such extremely low levels have not been measured in the past. An essential requirement for the measurement of such low lead concentrations is the ability to concentrate a large volume of water (approximately 30 tonne corresponding to 10-30 lead atoms) in a period of time which is short compared with the half life of lead 212 (i.e. 11 hours). During this concentration stage one has to insure the highest possible recovery of lead from the aqueous phase. The immediate problem is that of the instability of lead in solutions at neutral pH, which is the pH at which the detector is to be maintained. At such pH lead is known to form hydroxide complexes and to attach to surfaces (Gibson 1961; Mitzuike 1987). The common practice for circumventing this problem is by acidifying the studied aqueous phase, but this is not a desirable option in the SNO detector, mainly due to possible corrosion/ aging effects on the stainless steel (SS) and plastic components.

The following is a report on two preliminary steps suggested for the concentration of lead 212 out of 30 tonnes of D_2O. The first is the complexation of lead in the 1000 tonne detector (within the acrylic vessel) by the addition of a known spike of tetra sodium EDTA. The other is to use reverse osmosis (RO) filtration in order to achieve a 1000-10000 fold concentration of the lead solution, down to a volume of 1-30 litres. Further steps in the lead monitoring scheme will be the subject of subsequent reports and are outlined in a report entitled 'General concepts for monitoring of lead 212 in the SNO experiment', available at the Kingston water meeting, Sept. 3, 1992.

§1 EDTA as a lead stabilizing agent

Lead solutions of 2-8 ppm lead as lead nitrate were prepared. Several liquid media were tested: ultra pure water (designated as H_2O); 0.002% and 0.1% Chloral Hydrate (C.H.); 0.002% and 0.1% NaCl; 0.8%, 8 ppm and 8 ppb EDTA in the ammonium form. In the case of EDTA solutions lead concentrations ranged between 2 to 16 ppm. Standard lead solutions in the same concentration range were prepared using 1% HNO_3 as the solvent media. The solutions were all prepared in polypropylene (PP) or high density polyethylene (HDPE) vials which were thoroughly prewashed with 10% HNO_3 and rinsed in tapwater, distilled water and ultrapure water. Prior to analysis by FAA samples were transferred to a new set of PP/HDPE vials and acidified to 1% HNO_3 (prepared from a concentrated 70% Anachemia acid). The FAA analysis was conducted on a Varian 1475 instrument

with deuterium arc correction, and an automatic sampler. Results are in tables 1 and 2.

It is apparent that spike recovery for all samples except those containing EDTA is rather poor. Furthermore, the results for H_2O, 0.002% NaCl and C.H. and 0.1% C.H. indicate that with increasing concentrations the missing lead fraction decreases, approaching a constant value, which is suggestive of an adsorption mechanism being responsible for the missing lead. In contrast, the recovery of lead from the EDTA solutions is much higher, at about 100%, taking into account the experimental error on the lead measurement. No clear dependence of the recovery on the EDTA concentration is apparent.

It was demonstrated that, on a small scale, addition of low levels of EDTA (ammonium salt at $\leq$0.8%) to lead solutions of several ppm of lead, prevents loss of lead from the solution. Since one would wish to minimize the number of foreign ions introduced into the SNO detector, it was suggested to use tetrasodium EDTA (sodium edetate) rather than the ammonium salt, and this is the compound used in the RO experiments described ahead.

§2 RO separation of lead and lead-EDTA complexes

In RO separation processes, membranes which are microporous barriers of (in the present study) polymeric material, induce a pressure driven separation where a feed solution is split into two streams. The portion passing through the membrane is referred to as permeate or filtrate, while the portion remaining on the feed side of the membrane is called the retentate or the concentrate. In the case of RO, the membrane pore size is small enough to allow retention of ions in solution and only water passes through the membrane. The trans-membrane pressure must exceed the osmotic pressure of the feed solution in order to reverse the normal osmotic flow and allow permeation to occur.

In the membrane testing process one is dealing with a known, fixed membrane area. For a specific system, changes in performance can be tracked by measuring the permeate rate, the volume of permeate collected over a period of time. In order to compare the performance of different systems or scale up from laboratory results, the membrane area must be considered and a more useful measure of membrane performance is the permeate flux: the volume of permeate produced by the membrane per unit time per unit membrane area.

In the present study lead separation by RO membranes was tested on various lead solutions: $\approx$300 and $\approx$750 ppm of lead both as lead chloride and as lead nitrate (aiming to check concentration effect as well as the anion effect on the separation).
Lead+EDTA separations were studied on solutions of $\approx$300 ppm lead chloride in a 400 ppm and 3500 ppm EDTA (sodium form).
The effect of additional NaCl on the separation was checked by studying solutions

of ≈300 ppm lead chloride in a 3500 ppm EDTA (sodium form) solution with 3% and 0.3% NaCl. All solutions were prepared in a polypropylene tank, using ultra pure water of pH value of 7.0±0.5, and mixed thoroughly overnight by use of a magnetic stirrer. The volume of solution used typically was 3-4 litres. Most solutions were prepared at CRPP.

The RO system was operated at 250 psi and the concentrate stream as well as the permeate stream were continuously cycled back to the main feed. All metal parts of the system were of acid resistant stainless steel (SS). Most membranes tested were RO membrane except for the DS5 and the R82 membranes which are of the nanofiltration and tight ultrafiltration types respectively. The FT (Filmtec) membranes used were of sea water type while the DU (DuPont) membranes used were designed for brackish water. The last two numbers on each of the membranes designated in the tables are the coupon serial numbers. About 30 cc of feed and permeate samples were collected at the beginning and at the end of each run (usually after 1 and 4-5 hours respectively). After collection, samples were acidified to 1% HNO_3 using Anachemia 70% HNO_3. All runs except those with NaCl were performed in duplicate. The pH of the solutions was measured prior to the RO procedure as were the pH of the feed solutions and the combined permeates. Tables 3-9 include the pH data as well as the lead content in the permeate, the permeate flux and the fraction of lead from the initial feed found in the concentrate, for the runs involving lead chloride (tables 3,4), lead nitrate (tables 5,6), lead chloride+low EDTA concentration, lead chloride+high EDTA concentration (tables 7 and 8 respectively) and lead chloride+EDTA+NaCl solutions (table 9). Duplicate runs are denoted as 'run # 2'. In some runs the membranes were also collected and some of them were analysed for adsorbed lead by means of ESCA. The effect of NaCl salt on the analysis of lead by FAA was studied: it was found that at a concentration of 0.01% NaCl in the analysed sample there was no difference between the NaCl containing samples and ones with no NaCl. At a concentration of 0.1% NaCl the results were somewhat higher than for 'no salt samples', the difference being smaller than 10%. Since all samples analysed were diluted to levels of 0.1% NaCl and less, no correction for this effect was deemed necessary. Prior to the beginning of the experiments the RO system was washed with 15% nitric acid and the wash was analysed for lead. Both the permeates and the feed showed insignificant levels of lead (i.e. less than 20 ppb lead). Another wash, performed between the lead chloride and the lead nitrate runs (not including the membranes), showed only 10-20 mg lead in the acid after 2 hours wash, suggesting low ($\leq$ 1%) lead losses on the surfaces of the feed tank and the piping system. In the case of solutions including NaCl, sodium analysis (as well as lead analysis) was carried out for the feed and the permeates, using the Varian 1475 FAA at a wave length of 589 nm (no D_2 correction).

pH measurements for the lead salt runs (tables 3-7) show a lower pH values in the solutions as compared with the original water. Such a lowering of pH reflects hydrolysis by the lead ions. When adding EDTA at low levels (table 7) the pH of the EDTA-lead solutions is still lower than that for the original water used

to prepare the lead-EDTA solution. The extremely low pH values observed for the 1st run are hard to account. Accordingly, we will only assess the results for the second run where the lower pH in the EDTA-lead solution is probably due to the low ratio of EDTA/lead, so that some of the lead is still free to hydrolyze. Furthermore, other metal ions, such as those leached from the SS components in the system, might hydrolyze and lower the pH. When adding EDTA at 3500 ppm (table 8) the pH was significantly alkaline, reflecting the excess EDTA which is present in the solution. The same is suggested by the pH values measured for the runs where NaCl is present (table 9).

Tables 3 and 4 include the separation data for lead chloride salt at 300 and 750 ppm respectively. The increase in the concentration of lead in the feed as a function of time reflects the fact that some of the permeate stream is removed from the system while the concentrate is being recycled into the feed. No significant additional dependence of the separation performance on time is apparent. Similarly the lead salt concentration does not seem to affect the separation. While the RO membranes exhibit a separation of 92-96% (lower than the typical 99% separation achieved for NaCl at 3500 ppm under the same pressure), the nanofiltration membrane allows more than 30% of the lead into the permeate. ESCA analysis revealed the presence of small amounts of lead on the membranes analysed.

The separation results for lead nitrate are reported in tables 5 and 6. The data are generally similar to those for lead chloride, but the performance of the DS5 membranes is three folds better while that for the DU RO membranes is worse (by about a factor of two). However, since the lead chloride and lead nitrate tests were performed on two different sets of coupons these differences in separation performance should be considered with caution.

Addition of EDTA (sodium form) at 400 ppm (table 7, second run) improved the lead separation for four of the six membranes studied (i.e. DS5, DU and FT and one of the DS3B membranes). With the addition of 3500 ppm EDTA (sodium form, table 8) and using the same set of coupons, all membranes show a significant improvement in lead separation, where the fraction of lead in the permeate for all RO membranes is smaller than 1% and for the DS5 nanofiltration membrane is in the order of 1%. Such separation by the nanofiltration membrane is significantly better than that achieved for NaCl at 3500 ppm, not in the presence of lead (J. Hazlett, unpublished data) as well as for NaCl in the presence of lead (table 9).

It is clear that addition of excess amount of EDTA (in this case a 1:10 weight ratio of lead to EDTA (sodium form)) greatly improves the separation of lead across RO membranes as well as across a DS5 nanofiltration membrane. This improvement is attributed to the relatively large size of the lead-EDTA complex (at least five times larger than the lead ion). RO separation is thus proven to be an effective way of concentrating lead from pure water in the presence of EDTA, at a pH determined by the EDTA levels necessary to complex all of the lead.

The effect of a high concentration (3%) of NaCl on the lead-EDTA separation system is demonstrated in table 9. The osmotic pressures generated by such a large

amount of salt are similar to the pressures under which the RO system is run (250 psi) and as a result both the lead separation and the sodium separation are poor. It is interesting to note though, that even under these unfavorable operating conditions, lead separation is significantly better than sodium separation for all membranes tested, and in particular for the nanofiltration DS5 (by a factor of 8). When the NaCl salt concentration was lowered to 0.3% (table 9) both the lead and the sodium separation improved, that for lead reaching levels identical to those achieved with no salt present. The superior lead separation as compared with that for sodium is probably due to the formation of a large size lead-EDTA complex (in the order of 10 angstrom) as compared with the smaller size sodium ion, where the lead-EDTA complex is much more stable than the sodium one and where the molar concentration of EDTA is too low to efficiently complex the sodium but is sufficient to efficiently complex the lead. Thus the use of a DS5 type membrane may allow a fair separation between the two ions, if necessary.

§3 References

1. Gibson W. M., 1961. The Radiochemistry of Lead. Nuclear Science Series, NAS-NS-3040.

2. Mizuike A., 1987. Recent developments in trace metal speciation in fresh water. Pure and Applied Chem., 59, 555-564.

date	solution	A-Pb spike, ppm	B-measured Pb, ppm	A-B, % of spike
5.12.91	H_2O	2.2	1.6 ± 0.2	27
		4.4	3.3 ± 0.2	23
		8.6	7.1 ± 0.2	17
	0.002 % C.H.	2.1	1.3 ± 0.3	38
		4.3	3.4 ± 0.3	21
		8.5	7.2 ± 0.2	15
	0.002 % NaCl	2.1	1.7 ± 0.2	24
		4.3	3.4 ± 0.3	21
		8.5	7.2 ± 0.2	15
	0.1 % C. H.	2.2	1.4 ± 0.2	36
		4.4	3.2 ± 0.2	27
		8.6	7.1 ± 0.3	17
	0.1 % NaCl	2.2	1.8 ± 0.2	18
		4.4	3.4 ± 0.2	23
		8.6	7.2 ± 0.2	16

Lead concentrations as measured by flame Atomic Adsorption ('AA'), in Chloral Hydrate ('C.H.') and NaCl solutions.

Table 1

date	solution	A-Pb spike ppm	B-measured Pb ppm	A-B, % of spike
12.3.92	8 ppb EDTA	2.0	2.2 ± 0.2	-10
		4.1	4.2 ± 0.2	-2
		6.1	5.7 ± 0.2	7
		11.1	11.9 ± 0.2	-7
		16.2	16.0 ± 0.2	1
	8 ppm EDTA	2.0	2.2 ± 0.2	-10
		3.9	3.8 ± 0.2	3
		5.9	5.7 ± 0.2	3
		10.3	11.3 ± 0.2	-10
		15.7	16.0 ± 0.2	-2
	8 ppT EDTA	2.0	2.2 ± 0.2	-10
		4.0	4.1 ± 0.2	-2.5
		6.1	5.6 ± 0.2	8
		11.1	11.7 ± 0.2	-5
		16.1	16.0 ± 0.2	1

Lead concentrations as measured by flame Atomic Adsorption ('AA'), in EDTA solutions. EDTA is in the NH_4^+ form.

Table 2

400 ppm PbCl2

Run #1

pH of feed 5.3 to 5.2
pH of permeate 5.2

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		257.5			287.5	
DS5-19	3.67	84.0	67.4	3.86	92.0	68.0
DS3B-4	0.66	11.1	95.7	0.71	11.6	96.0
DS3B-13	0.47	13.6	94.7	0.52	14.9	94.8
FT-45	0.64	16.5	93.6	0.64	16.5	94.3
FT-39	0.75	13.7	94.7	0.78	13.6	95.3
DU-30	0.59	2.2	99.1	0.68	7.4	97.4

Run #2

pH of feed 5.3 to 5.0
pH of permeate 5.3 to 5.2

	1 hour			4 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		247.5			250.0	
DS5-19	3.29	82.0	66.9	3.60	85.0	66.0
DS3B-4	0.61	14.8	94.0	0.66	15.8	93.7
DS3B-13	0.45	17.2	93.1	0 49	18.0	92.8
FT-45	0.54	15.2	93.9	0.59	15.5	93.8
FT-39	0.66	12.6	94.9	0.73	13.4	94.6
DU-30	0.61	14.0	94.3	0.66	18.2	92.7

Pressure: 250-240 psig
Flow: 0.43 L/min
Temperature: 24.5-27.6, 22-26.5 °C

Table 3

1000 ppm PbCl2

Run #1

pH of feed 5.9 to 5.8
pH of permeate 5.9 to 5.7

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		655.0			710.0	
DS5-19	3.53	300.0	54.2	3.65	290.0	59.2
DS3B-4	0.64	26.7	95.9	0.66	25.5	96.4
DS3B-13	0.45	32.7	95.0	0.47	32.0	95.5
FT-45	0.56	35.0	94.7	0.59	33.5	95.3
FT-39	0.68	28.3	95.7	0.73	27.5	96.1
DU-30	0.59	34.0	94.8	0.68	45.2	93.6

Table 4

Run #2

pH of feed 6.0 to 5.8
pH of permeate 6.1 to 5.9

	1 hour			4 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		670.0			700.0	
DS5-19	3.48	255.0	61.9	3.53	257.5	63.2
DS3B-4	0.66	31.2	95.3	0.68	29.0	95.9
DS3B-13	0.47	38.0	94.3	0.49	36.5	94.8
FT-45	0.56	33.7	95.0	0.59	37.5	94.6
FT-39	0.68	29.2	95.6	0.73	27.3	96.1
DU-30	0.64	44.2	93.4	0.68	47.5	93.2

Pressure: 250-240 psig
Flow: 0.43 L/min
Temperature: 24.5-27.6, 22-26.5 °C

478 ppm Pb(NO3)2

Run #1

pH of feed 4.72 to 4.65
pH of permeate 4.42 to 4.45

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		255.0			272.5	
DS5-28	3.46	29.5	88.4	3.62	26.0	90.5
DS3B-14	1.22	16.3	93.6	1.27	13.2	95.2
DS3B-15	1.25	13.6	94.7	1.29	11.1	95.9
FT-40	0.75	16.8	93.4	0.94	14.8	94.6
FT-41	0.80	22.0	91.4	0.85	18.8	93.1
DU-27	0.94	8.0	96.9	1.01	29.2	89.3

Run #2

pH of feed 4.57 to 4.55
pH of permeate 4.07

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		262.5			266.2	
DS5-28	3.53	32.0	87.8	3.55	30.0	88.7
DS3B-14	1.18	16.5	93.7	1.20	15.0	94.4
DS3B-15	1.20	14.6	94.5	1.22	12.4	95.4
FT-40	0.73	16.9	93.6	0.78	13.8	94.8
FT-41	0.78	21.8	91.7	0.82	17.8	93.3
DU-27	0.96	24.2	90.8	0.99	32.2	87.9

Pressure: 250-240 psig
Flow: 0.43 L/min
Temperature: 24.5-27.6, 22-26.5 °C

Table 5

1193 ppm Pb(NO3)2

Run #1

pH of feed 5.45
pH of permeate 5.27 to 5.17

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		600.0			625.0	
DS5-28	3.53	85.0	85.8	3.55	75.0	88.0
DS3B-14	1.18	37.0	93.8	1.20	35.3	94.4
DS3B-15	1.20	29.3	95.1	1.22	25.8	95.9
FT-40	0.73	33.5	94.4	0.78	29.3	95.3
FT-41	0.78	52.3	91.3	0.82	42.8	93.2
DU-27	0.96	75.0	87.5	0.99	84.0	86.6

Run #2

pH of feed 5.28 to 5.22
pH of permeate 4.75 to 4.77

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		657.5			672.5	
DS5-28	3.72	91.3	86.1	3.86	82.5	87.7
DS3B-14	1.22	34.5	94.8	1.27	31.3	95.3
DS3B-15	1.20	30.5	95.4	1.25	25.3	96.2
FT-40	0.78	32.1	95.1	0.82	26.4	96.1
FT-41	0.82	43.5	93.4	0.85	34.4	94.9
DU-27	0.94	70.5	89.3	0.99	75.3	88.8

Pressure: 250-240 psig
Flow: 0.43 L/min
Temperature: 24-26.5, 24.5-27 °C

Table 6

400 ppm EDTA + 400 ppm PbCl2

Run #1

pH of feed 3.36 to 3.22
pH of permeate 3.56 to 3.51

	1 hour			5 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		222.5			245.0	
DS5-33	3.51	34.0	84.7	3.51	34.0	86.1
DS3B-6	1.29	45.6	79.5	1.22	39.4	83.9
DS3B-7	0.92	10.0	95.5	0.94	7.2	97.1
FT-43	0.73	8.3	96.3	0.73	5.2	97.9
FT-44	0.89	17.1	92.3	0.87	12.0	95.1
DU-31	0.73	2.0	99.1	0.78	0.8	99.7

Run #2

pH of feed 5.57 to 5.48
pH of permeate 5.63 to 5.54

	1 hour			4 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		275.0			277.0	
DS5-33	3.13	24.5	91.1	2.92	24.5	91.2
DS3B-6	1.20	40.0	85.5	1.08	29.0	89.5
DS3B-7	0.92	4.7	98.3	0.85	4.1	98.5
FT-43	0.75	4.3	98.4	0.71	3.3	98.8
FT-44	0.87	10.7	96.1	0.80	8.5	96.9
DU-31	0.73	0.6	99.8	0.68	0.3	99.9

Pressure: 250-240 psig, 220-210 psig
Flow: 0.43 L/min
Temperature: 24.5-27 °C

Table 4

3500 ppm EDTA + 400 ppm PbCl2

Run #1

pH of feed 10.31 to 10.28
pH of permeate 9.85 to 9.94

	1 hour			4 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		245.0			257.0	
DS5-33	3.53	2.0	99.2	3.76	2.0	99.2
DS3B-6	1.48	2.0	99.2	1.67	0.8	99.7
DS3B-7	1.34	0.5	99.8	1.53	0.2	99.9
FT-43	0.75	1.9	99.2	0.80	0.6	99.8
FT-44	0.82	2.6	98.9	0.87	0.9	99.7
DU-31	0.82	4.6	98.1	1.11	1.6	99.4

Run #2

pH of feed 10.08 to 10.05
pH of permeate 9.67 to 9.82

	1 hour			4 hours		
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)
Feed		280.0			277.5	
DS5-33	3.86	3.8	98.6	4.05	3.4	98.8
DS3B-6	1.60	2.5	99.1	1.72	1.7	99.4
DS3B-7	1.44	0.5	99.8	1.55	0.3	99.9
FT-43	0.78	1.1	99.6	0.82	0.9	99.7
FT-44	0.85	1.9	99.3	0.89	1.8	99.4
DU-31	1.15	1.4	99.5	1.27	0.9	99.7

Pressure: 255-245 psig
Flow: 0.43 L/min
Temperature: 24-27 °C

Table 8

3500 ppm EDTA + 385 ppm PbCl2 + 30000 ppm NaCl

pH of feed 9.18 to 9.17
pH of permeate 9.22 to 9.09

	1 hour					4 hours				
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Na Content (ppm)	Na Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Na Content (ppm)	Na Separation (%)
Feed		260.0		12,000.0			265.0		12,000.0	
DS5-33	2.54	21.7	91.7	7,500.0	37.5	2.64	21.5	91.9	8,680.0	27.7
DS3B-6	0.21	20.5	92.1	4,100.0	65.8	0.21	17.5	93.4	4,180.0	65.2
DS3B-7	0.12	5.7	97.8	3,340.0	72.2	0.12	4.9	98.2	3,600.0	70.0
FT-43	0.05	21.5	91.7	3,340.0	72.2	0.05	17.7	93.3	3,360.0	72.0
FT-44	0.09	25.8	90.1	3,800.0	68.3	0.09	23.5	91.1	4,000.0	66.7
R82-43	2.35	109.0	58.1	10,180.0	15.2	2.42	103.0	61.1	10,440.0	13.0

Pressure: 260-250 psig
Flow: 0.43 L/min
Temperature: 24-26 °C

3500 ppm EDTA + 397 ppm PbCl2 + 3000 ppm NaCl

pH of feed 9.64 to 9.53
pH of permeate 9.53 to 9.23

	1 hour					4 hours				
Membrane Coupon	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Na Content (ppm)	Na Separation (%)	Permeate Flux (m3/m2/day)	Pb Content (ppm)	Pb Separation (%)	Na Content (ppm)	Na Separation (%)
Feed		232.5		1,850.0			260.0		1,980.0	
DS5-52	2.96	0.9	99.6	480.0	74.1	3.15	1.0	99.6	494.0	75.1
DS3B-14	1.53	1.0	99.6	61.5	96.7	1.60	1.0	99.6	71.0	96.4
DS3B-15	1.22	1.1	99.5	41.7	97.7	1.39	0.9	99.7	51.0	97.4
FT-52	0.64	1.9	99.2	48.2	97.4	0.66	0.9	99.7	37.7	98.1
FT-53	1.20	9.5	95.9	92.0	95.0	1.27	6.1	97.7	77.0	96.1
R82-44	3.15	67.5	71.0	1,250.0	32.4	3.13	55.2	78.8	1,320.0	33.3

Pressure: 260-250 psig
Flow: 0.43 L/min
Temperature: 24-26 °C

Table 9