

Validation of an Arsenic Rejection Computer Model for RO/NF membranes

Mohannad Malki, Technical Director, American Water Chemicals, 1802 Corporate Center Lane,
Plant City, FL 33563, USA
momalki@membranechemicals.com, Ph: 813-246-5448

Abstract

Arsenic contamination in groundwater supplies has long been a problem, and membrane technology is among the efficient methods for its removal for providing safe drinking water.

In 2004, the EPA decreased the maximum contaminant level (MCL) for Arsenic from 50 ppb to only 10 ppb. This made compliance more challenging for many existing facilities, while also creating additional design considerations for future membrane plants.

Currently, no membrane projection software predicts arsenic rejection, and no membrane manufacturers guarantee arsenic concentrations in the finished water quality. The only way to predict arsenic rejection through membrane systems is therefore to perform piloting at the location, which can be both costly and time consuming. Some systems have been “over-engineered” using ferric coagulation with filtration as pretreatment for reverse osmosis.

It is known that As(V) is better rejected by membranes than As(III), and that conversion of the latter to the higher oxidation state can be achieved by chlorination. It is therefore important to have the ability to predict membrane rejection of both oxidation states to determine whether chlorination is necessary.

Using the weak acid properties of Arsenous and Arsenic acid, AKA As(III) and As(V), a computer model for rejection by RO membranes was developed based on the pH dependent valences of the various weak acid species. The weak acid constants (pKa) were corrected for temperature and ionic strength using the Van't Hoff equation, and a modified Debye-Huckel equation respectively.

Membranes from various manufacturers were tested to validate the models. These included high rejection membranes, low energy membranes, and Nanofiltration membranes. Standard manufacturer test solutions contaminated with known levels of As(III) or As(V) were applied at standard test temperature and pressure conditions in a cell test apparatus.

The testing at the membrane manufacturer QC test conditions allowed for easy normalization of the data to full scale systems for the referenced membrane models. A good correlation was found between the predicted rejection values for As(III) and As(V) as compared to the computer model.

Introduction

The purpose of this study was to develop a model to predict rejection of both arsenous and arsenic acid. This was accomplished by first making some assumptions, and then validating the model through cell testing of high rejection nanofiltration (NF), ultra-low energy reverse osmosis (ULE-RO), low energy high rejection RO (LE-RO) and high rejection RO (HR-RO) membranes from Filmtec, Hydranautics, and Toray.

Inorganic arsenic in natural waters exists primarily in two forms, arsenous acid – As (III) and arsenic acid – As (V), both of which are polyprotic weak acids [1]. All weak acids share a common property in that they deprotonate with increasing pH, and thereby become more negatively charged.

It has been established that oxidizing As (III) to As (V) results in significantly improved rejection by RO membranes [2]. This is likely because arsenous acid carries a neutral charge at neutral pH, whereas arsenic acid exists as a combination of monovalent and divalent anions at the same pH range.

In order to predict membrane rejection of arsenic, it was essential to first establish the charge carried by each form of arsenic at various conditions. This was calculated using available dissociation constants and some basic mathematical derivations described in the next section.

Some assumptions were then made about arsenic rejection as follows:

1. Protonated (uncharged) arsenous and arsenic acids would be rejected better than boron (due to the greater molecular weight of the arsenic species)
2. Monovalent arsenous and arsenic acids would be rejected similarly to chloride
3. Divalent arsenous and arsenic acids would be rejected similarly to sulfate
4. Trivalent arsenous and arsenic acids would be rejected better than sulfate (we did not find any data on phosphoric acid in the trivalent state, which has an almost identical structure to that of arsenic acid)

These assumptions were initially incorporated into the membrane projection software to predict arsenic rejection. At the same time, cell testing was commenced to validate these assumptions, and correct the rejections for the different valence states based on experimental results.

Considerations in Calculating Deprotonation States of Arsenous and Arsenic Acids

By summing the different forms of arsenic to unity, and substituting equivalents from tables 1 and 2, one can solve for each of the deprotonation states of arsenous acid or arsenic acid as a function of pH:

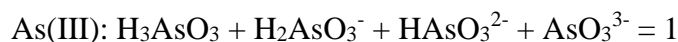


Table 1: Arsenous acid – As(III) Dissociation Constants [1]

$\text{H}_3\text{AsO}_3 = \text{H}_2\text{AsO}_3^- + \text{H}^+$	$\text{pKa}_1 = 9.20$
$\text{H}_2\text{AsO}_3^- = \text{HAsO}_3^{2-} + \text{H}^+$	$\text{pKa}_2 = 12.10$
$\text{HAsO}_3^{2-} = \text{AsO}_3^{3-} + \text{H}^+$	$\text{pKa}_3 = 19.22$

Table 2: Arsenic acid – As(V) Dissociation Constants [1]

$\text{H}_3\text{AsO}_4 = \text{H}_2\text{AsO}_4^- + \text{H}^+$	$\text{pKa}_1 = 2.19$
$\text{H}_2\text{AsO}_4^- = \text{HAsO}_4^{2-} + \text{H}^+$	$\text{pKa}_2 = 6.94$
$\text{HAsO}_4^{2-} = \text{AsO}_4^{3-} + \text{H}^+$	$\text{pKa}_3 = 11.50$

The acid dissociation constants can then be corrected for temperature by utilizing the Van't Hoff equation and the enthalpy of reaction for each deprotonation reaction, where:

$$\Delta_r G^\circ = -RT \ln K$$

And

$$\Delta_r G^T = (T/298.15) \Delta_r G^\circ + \Delta_r H^\circ (1 - (T/298.15))$$

Where;

$\Delta_r G^\circ$ = Gibbs Free Energy of Reaction

$\Delta_r H^\circ$ = Enthalpy of Reaction

R = Universal Gas Constant

T = Temperature (°K)

Ka = Acid Dissociation Constant

And finally, the acid dissociation constants can be corrected for ionic strength by estimating the activity of the ions. The activity coefficients can be estimated using a modified Debye-Huckel equation, or a more accurate estimation using either the SIT (Specific Ion Interaction Theory) or Pitzer models.

The use of activity coefficients to correct for the dissociation constants is described in the following equation for the first dissociation of arsenous acid:



Which can otherwise be expressed as:

$$[\text{H}_2\text{AsO}_3^-][\text{H}^+] / [\text{H}_3\text{AsO}_3] = K_{a1} \gamma_{\text{H}_3\text{AsO}_3} / (\gamma_{\text{H}_2\text{AsO}_3^-} \gamma_{\text{H}^+}) = K_{a'1}$$

Where;

$\gamma_{\text{H}_3\text{AsO}_3}$ is the activity coefficient of fully protonated arsenous acid as a function of ionic strength

$\gamma_{\text{H}_2\text{AsO}_3^-}$ is the activity coefficient of monovalent arsenous acid as a function of ionic strength

γ_{H^+} is the activity coefficient of hydronium ions as a function of ionic strength

The pH dependence of arsenous and arsenic acids in a pure solution at 25°C is well portrayed by the graphs in Figures 1 and 2 [1].

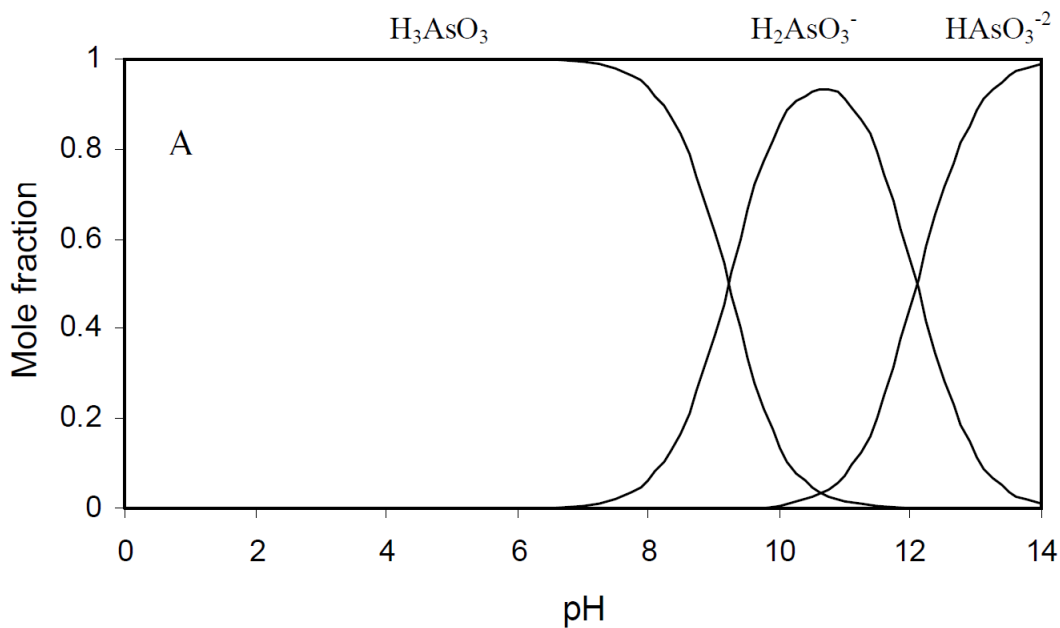


Figure 1: Speciation of arsenous acid in a solution with zero ionic strength and 25°C [1]

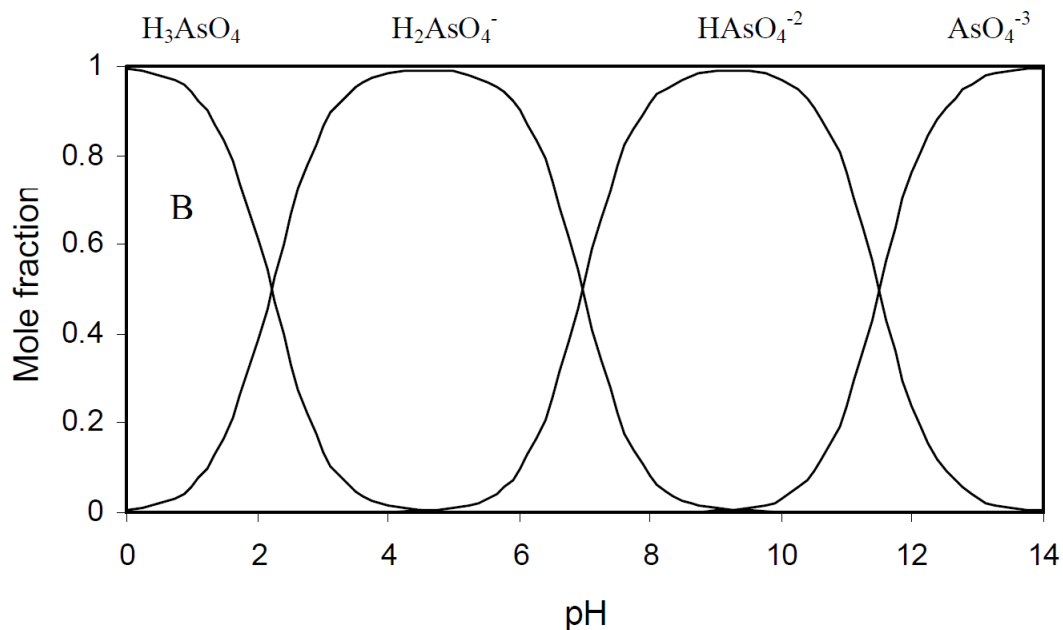


Figure 2: Speciation of arsenic acid in a solution with zero ionic strength and 25°C [1]

Experimental Protocol

All membranes samples were soaked in deionized water for 24 hours prior to testing.

Each membrane was first tested using the manufacturer's standard wet test conditions, to ensure that flux and salt rejection were consistent with those specified by the manufacturer. This allowed for the elimination of membrane coupons with localized manufacturing imperfections such as pinholes, or mishandling errors such as surface scratches. This also helped to identify any O-ring leaks in the membrane cells prior to commencement of testing. The tests were performed using conductivity, with calibration curves developed for various sodium chloride concentration ranges. In the case of the ESNA1-LF, conductivity calibrations were performed for various concentration ranges of $CaCl_2$ solution in order to use the test solution specified by the manufacturer.

If the membrane met the manufacturer's specifications, the testing was commenced. A new solution was made, but the same membrane coupons that had passed the initial performance test were used without removal from their cells. In each case, the system was flushed thoroughly with deionized water until conductivity of the rinse solution was below detection.

In preparing the new test solutions, high purity arsenous and arsenic acid reagents were used. Two issues were given consideration:

1. Few labs could speciate between As(III) and As(V) and those that could, often gave inaccurate results (based on our experience).
2. Part per billion concentrations of arsenic in 1500 ppm or 2000 ppm NaCl solutions would likely not be measured accurately using ICP-OES, or even ICP-MS, if they were within range of the detection limit.

Tests were therefore performed separately for As (III) and As (V) so that passage could be determined by measuring for total arsenic. Furthermore, a high concentration of 50 ppm arsenic was used for all tests to ensure that values in the permeate would be well above the detection limit, and to minimize the margin of error caused by the significant Na⁺ concentrations when using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES).

Testing for As(III) was performed at pH 6 where arsenous acid was fully protonated and pH 11 where arsenous acid was mostly monovalent. Monovalent arsenous acid could not be fully isolated at any pH range due to the coexistence of protonated and divalent species.

Testing for As (V) was performed at pH 4 where arsenic acid was entirely monovalent, and pH 9 where arsenic acid was entirely divalent.

Although test solutions strengths varied depending on membrane type (NF vs RO) and manufacturer (Hydranautics vs Filmtec and Toray), the effect of ionic strength was determined to be minimal at the concentrations of 1500 ppm and 2000 ppm. Furthermore, the complexity of adjusting each experiment to a slightly different pH would have increased the possibility of human error.

Upon completion of each set of experiments, the initial feed, final feed, and permeate solutions were analyzed. The final feed solution was important to incorporate into the calculation to ensure an accurate arsenic rejection value.

In each case, analysis was performed by ICP-OES for sodium, calcium (where applicable) and total arsenic. Analysis for chloride was also performed using Ion Chromatography (IC).

In each case, the monovalent arsenic rejection was compared to the measured chloride rejection, considering that chloride rejection could vary slightly with pH. In cases where the manufacturer also specified a rejection value for boron at neutral pH, a comparison was made to the rejection of the fully protonated arsenous acid. Where no established arsenic data was available from the manufacture, a literature search obtained data in a few cases.

Results

Nanofiltration (NF)

Table 3: Analytical Results – ESNA1

Hydranautics ESNA1								
As Species	pH	Source	Cl	Ca	As	Cl %Rej	Ca %Rej	As %Rej
As +3	6	Feed Start	400	210	47	88.6%	87.0%	23.9%
		Feed End	399	210	45			
		Permeate	52	24	35			
As +3	11	Feed Start	351	190	47	79.5%	86.3%	74.7%
		Feed End	348	200	48			
		Permeate	48	40	12			
As +5	4	Feed Start	373	210	52	83.8%	79.9%	96.9%
		Feed End	376	210	51			
		Permeate	75	34	1.6			
As +5	9	Feed Start	355	200	49	89.5%	85.1%	99.0%
		Feed End	355	200	51			
		Permeate	53	21	0.51			

Table 4: Analytical Results – NF90

Filmtec NF90								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	1300	800	50	93.6%	93.2%	62.4%
		Feed End	1400	840	51			
		Permeate	86	56	19			
As +3	11	Feed Start	1300	820	52	97.2%	94.7%	97.9%
		Feed End	1300	850	53			
		Permeate	37	44	1.1			
As +5	4	Feed Start	1200	740	48	94.6%	95.9%	99.1%
		Feed End	1300	840	54			
		Permeate	67	32	0.47			
As +5	9	Feed Start	1300	770	49	96.9%	96.6%	99.7%
		Feed End	1400	840	53			
		Permeate	42	27	0.17			

Low Energy Reverse Osmosis (ULE-RO)

Table 5: Analytical Results – ESPA4

Hydranautics ESPA4								
As Species	pH	Source	TestAmerica Results					
			Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	330	210	53	99.3%	99.2%	61.1%
		Feed End	360	220	55			
		Permeate	2.4	1.8	21			
As +3	11	Feed Start	300	250	58	99.4%	97.6%	94.8%
		Feed End	320	250	58			
		Permeate	2	6.1	3			
As +5	4	Feed Start	350	220	50	96.4%	97.5%	99.5%
		Feed End	370	230	52			
		Permeate	13	5.7	0.28			
As +5	9	Feed Start	330	220	50	99.3%	94.5%	99.8%
		Feed End	350	220	51			
		Permeate	2.5	12	0.096			

Table 6: Analytical Results – TMH

Toray TMH								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	330	220	53	98.4%	98.6%	77.6%
		Feed End	350	230	54			
		Permeate	5.5	3.2	12			
As +3	11	Feed Start	300	240	70	99.3%	97.7%	98.4%
		Feed End	310	260	76			
		Permeate	2.2	5.7	1.2			
As +5	4	Feed Start	320	230	54	97.2%	97.3%	98.2%
		Feed End	320	230	55			
		Permeate	8.9	6.2	0.96			
As +5	9	Feed Start	290	230	55	99.3%	99.1%	99.3%
		Feed End	310	240	55			
		Permeate	2	2.1	0.4			

Table 7: Analytical Results – XLE

Filmtec XLE								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	1184	690	48	95.1%	94.9%	81.2%
		Feed End	1190	730	50			
		Permeate	58	36	9.2			
As +3	11	Feed Start	1431	750	48	97.1%	95.6%	97.6%
		Feed End	1463	780	51			
		Permeate	42	34	1.2			
As +5	4	Feed Start	1277	770	52	92.9%	93.2%	97.5%
		Feed End	1282	770	52			
		Permeate	91	52	1.3			
As +5	9	Feed Start	1228	780	51	96.8%	96.6%	98.9%
		Feed End	1239	790	53			
		Permeate	39	27	0.57			

Low Energy High Rejection (LE-RO)

Table 8: Analytical Results – ESPA2-LD

Hydranautics ESPA2-LD								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	930	610	47	99.6%	99.5%	81.3%
		Feed End	1000	640	48			
		Permeate	3.9	3.2	8.9			
As +3	11	Feed Start	910	630	51	99.6%	99.0%	98.2%
		Feed End	960	640	52			
		Permeate	3.8	6.2	0.95			
As +5	4	Feed Start	960	600	47	99.0%	98.9%	99.6%
		Feed End	970	620	52			
		Permeate	10	6.9	0.2			
As +5	9	Feed Start	930	620	51	99.6%	99.7%	99.9%
		Feed End	930	620	51			
		Permeate	3.5	2	0.041			

Table 9: Analytical Results – TMG(D)

Toray TMG(D)								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	340	250	59	99.1%	98.9%	83.8%
		Feed End	370	250	61			
		Permeate	3.3	2.7	9.7			
As +3	11	Feed Start	310	250	58	99.2%	98.2%	98.9%
		Feed End	320	260	60			
		Permeate	2.4	4.7	0.64			
As +5	4	Feed Start	340	240	55	98.3%	98.2%	99.3%
		Feed End	340	230	53			
		Permeate	5.8	4.2	0.4			
As +5	9	Feed Start	300	220	51	99.2%	98.9%	99.8%
		Feed End	310	230	53			
		Permeate	2.4	2.4	0.1			

Table 10: Analytical Results – ECO

Filmtec ECO								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	1251	780	48	99.1%	99.1%	83.7%
		Feed End	1248	730	44			
		Permeate	11	7	7.5			
As +3	11	Feed Start	1225	710	46	99.4%	99.0%	98.5%
		Feed End	1221	810	53			
		Permeate	7	7.6	0.75			
As +5	4	Feed Start	1269	780	51	96.9%	97.3%	99.1%
		Feed End	1248	830	55			
		Permeate	39	22	0.5			
As +5	9	Feed Start	1256	770	50	99.5%	99.3%	99.7%
		Feed End	1376	800	53			
		Permeate	7	5.4	0.15			

High Rejection Reverse Osmosis (HR-RO)

Table 11: Analytical Results – CPA5

Hydranautics CPA5								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	935	530	44	99.3%	99.1%	86.8%
		Feed End	955	630	53			
		Permeate	7	5.4	6.4			
As +3	11	Feed Start	812	590	51	99.6%	99.2%	99.1%
		Feed End	1001	620	53			
		Permeate	4	5.1	0.47			
As +5	4	Feed Start	941	590	51	97.3%	97.8%	99.2%
		Feed End	947	590	51			
		Permeate	26	13	0.43			
As +5	9	Feed Start	895	590	51	99.5%	99.4%	99.9%
		Feed End	901	620	54			
		Permeate	4	3.7	0.07			

Table 12: Analytical Results – TM700D

Toray TM700D								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	1300	780	49	99.6%	99.5%	87.7%
		Feed End	1300	800	50			
		Permeate	5	3.9	6.1			
As +3	11	Feed Start	1200	810	50	99.7%	99.3%	99.3%
		Feed End	1300	830	50			
		Permeate	3.3	5.4	0.33			
As +5	4	Feed Start	1300	770	51	99.3%	99.3%	99.9%
		Feed End	1300	820	55			
		Permeate	9.2	5.9	0.078			
As +5	9	Feed Start	1300	810	53	99.7%	99.6%	99.9%
		Feed End	1300	830	54			
		Permeate	3.4	3.1	0.029			

Table 13: Analytical Results – BW30XFR

Filmtec BW30XFR								
As Species	pH	Source	Cl	Na	As	Cl %Rej	Na %Rej	As %Rej
As +3	6	Feed Start	1117	680	44	99.3%	98.9%	91.8%
		Feed End	1240	760	49			
		Permeate	8.3	8	3.8			
As +3	11	Feed Start	1300	830	51	99.7%	99.4%	99.7%
		Feed End	1300	870	54			
		Permeate	4.2	4.7	0.16			
As +5	4	Feed Start	1300	850	54	98.4%	99.5%	99.9%
		Feed End	1300	860	55			
		Permeate	21	4.2	0.059			
As +5	9	Feed Start	1300	840	53	99.6%	99.5%	99.9%
		Feed End	1300	840	53			
		Permeate	5.1	3.9	0.062			

Table 15: Summary of Results

Membrane Type	Membrane Model	QC Test %Rejection by Conductivity		Boron %Rejection (@pH 7-8)	Protonated As(III) % Rejection pH 6		Monovalent As(III) % Rejection pH 11		Monovalent As(V) % Rejection pH 4		Divalent As(V) % Rejection pH 9	
		Spec	QC		Cl ⁻	As ³⁺	Cl ⁻	As ³⁺	Cl ⁻	As ⁵⁺	Cl ⁻	As ⁵⁺
NF	ESNA1	87-96%	87.1%	NE	86.9%	23.9%	86.3%	74.7%	79.9%	96.9%	85.1%	99.0%
	NF90	85-95%	91.9%	20% [3]	93.6%	62.4%	97.2%	97.9%	94.6%	99.1%	96.9%	99.7%
ULE-RO	ESPA4	99.2%	99.3%	25% [3]	99.3%	61.1%	99.4%	94.8%	96.4%	99.5%	99.3%	99.8%
	TMH	99.3%	99.2%	NE	98.4%	77.6%	99.3%	98.4%	97.2%	98.2%	99.3%	99.3%
	XLE*	99.0%	95.3%	18%	95.1%	81.2%	97.1%	97.6%	92.9%	97.5%	96.8%	98.9%
LE-RO	ESPA2-LD*	99.6%	99.6%	58%	99.6%	81.3%	99.6%	98.2%	99.0%	99.6%	99.6%	99.9%
	TMG(D)	99.7%	99.1%	NE	99.1%	83.8%	99.2%	98.9%	98.3%	99.3%	99.2%	99.8%
	ECO*	99.7%	99.4%	73%	99.1%	83.7%	99.4%	98.5%	96.9%	99.1%	99.5%	99.7%
HR-RO	CPA5*	99.7%	99.4%	78%	99.3%	86.8%	99.6%	99.1%	97.3%	99.2%	99.5%	99.9%
	TM700D	99.8%	99.6%	NE	99.6%	87.7%	99.7%	99.3%	99.3%	99.9%	99.7%	99.9%
	BW30XFR	99.65%	99.6%	80%	99.3%	91.8%	99.7%	99.7%	98.4%	99.9%	99.6%	99.9%

NE: Not Established

*Provided verbally or via e-mail by membrane manufacturer's technical representative. No published data available to reference.

Discussion and Conclusion

Chloride rejection was consistently found to be variable with pH. Lower pH levels corresponded to lower chloride rejection values, and higher pH corresponded to greater chloride rejection values. This was not unexpected considering that the anionic charge on the membrane is due to weak acid groups. Comparison of arsenic rejection to that of chloride at the various pH points therefore allowed for a direct correlation, eliminating the need to correct for membrane performance variability as a function of pH.

In reviewing the results, it was evident that in all cases, monovalent As(V) was rejected better than chloride. This higher rate of rejection was most pronounced in the nanofiltration (NF) membranes. One possible explanation for this behavior may be that the pKa values used were slightly inaccurate; some divalent arsenic acid species may have existed at the pH where only monovalent species were thought to exist. However, other factors may also come into play such as molecular weight, hydration radius, etc...

Divalent As(V) was rejected even more effectively. The data from the NF membranes suggested that divalent arsenic acid rejection was better than that of sulfate. Overall, the results clearly showed that when As(III) was oxidized to As(V), all membranes tested were very effective at arsenic removal. The NF membranes both exhibited rejections well above expectations; it is worthwhile noting that the NF-90 rejected As(V) comparably to RO membranes.

Monovalent As(III), which could not be isolated entirely, had a slightly lower rejection than that of chloride in most cases. The exceptions were three Filmtec membranes (NF90, XLE, XFR) which exhibited a rejection slightly higher than or equal to that of chloride. The As(III) rejection trend was expected, since a small fraction of the arsenous acid was protonated at the pH at which the test was performed.

The trend for rejection of protonated As(III) rejection – the uncharged arsenous acid – was very close to expectation. The NF membranes exhibited the lowest rejection, ULE-RO membranes performed better, LE-RO membranes performed even better, and the high rejection RO (HR-RO) membranes exhibited the best rejection.

However, rejection values of the latter were the most intriguing results obtained from this study. The high rejection membranes all performed beyond expectation. The best measured results were those of the BW30XFR which exhibited a 92% rejection of the uncharged arsenous acid. Repetition of this test using a different set of membrane coupons yielded an even higher rejection of 94%.

The BW30XFR in particular had been selected in this study because of the boron rejection value provided in its marketing literature. The boron rejection of 80% at neutral pH was exceptionally high for a brackish water RO membrane. No other literature for brackish water membranes

claimed such a high boron rejection value in that pH range (Toray only listed boron rejection at elevated pH values where boron would be deprotonated). Boron exists in nature as boric acid, and also exhibits weak acid properties. At neutral pH, boric acid has a neutral charge and rejection would therefore be primarily a function of molecular weight. Arsenous acid which has a much higher molecular weight, was therefore expected to be rejected more efficiently; however, a 92% - 94% rejection was much higher than anticipated. It was observed that except for the XLE, all membranes exhibited an uncharged As(III) passage that was approximately half that of their uncharged boron passage.

While the other high rejection membranes tested had slightly lower rejections for fully protonated arsenous acid, these results suggested that in a large majority of plants, the use of HR-RO membranes would obviate the need for oxidation in the pretreatment; elimination of chlorination would resolve many issues such as iron oxidation and biological fouling at many of these RO plants, not to mention the risks of membrane halogenation. Bisulfite, thiosulfate and other reducing agents would reduce As(V) to As(III) [4] thereby negating the benefits chlorinating for enhanced arsenic rejection. Pilot data at one plant in South Texas found that dechlorination with bisulfite did indeed lower arsenic rejection compared to when no bisulfite was applied; in that case, a minimal chlorine dosage had been applied at the wells so that there was no detectable residual when sampled at the RO.

The experimental results showed relatively good correlation to the software projection models for arsenic and arsenous acids. The monovalent arsenous acid rejection was found to be slightly lower than that of chloride with most membranes that were tested; however, this was most likely because of the coexistence of protonated arsenous acid species. For the purpose of the model, the assumption was maintained that monovalent arsenous acid rejection was equal to that of chloride. On the other hand, the monovalent arsenic acid was found to have slightly higher rejection than that of chloride, and this was consistent for all membranes. It was possible that other variables such as molecular structure, molecular weight or hydration radius may have been responsible for this behavior.

The divalent arsenic acid was found to have the highest rejection. No sulfates were present in any of the test solutions used in this study, and thus no comparison to sulfates could be made directly; however, the data gathered from the NF90 tests found that divalent arsenic acid exhibited very similar rejection to the specified $MgSO_4$ rejection in Filmtec's literature. This study also found that nanofiltration membranes rejected monovalent and divalent arsenic acid – As(V) - almost as well as RO membranes. It was also determined that high rejection RO membranes could reject protonated arsenous acid, As(III), very efficiently.

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