Reverse Osmosis: On-Site Treatability Study

Of

Landfill Leachate At The PAS Site In Oswego, NY

by

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In the recent years, the development of new Reverse Osmosis (RO) membranes has opened broader horizons to this technology. Better resistance over a wider pH range, higher treatment fluxes, greater stability and tolerance in the presence of organic solvents and oxidizing agents allow for the use of RO at hazardous waste disposal sites. In a series of demonstrations, RO was tested at Canadian landfills and proved effective in concentrating not only inorganic species but volatile and semi-volatile organic compounds. At the end of the summer of 1988, a study was undertaken to evaluate the capability of this process technology at the Pollution Abatement Services site in Oswego, N.Y. The encapsulated site generates roughly 750,000 U.S. gallons of leachate annually. This aqueous solution contaminated with metals and solvents at the parts per million level, is collected and transported to a treatment/disposal facility periodically. RO is envisaged to be a means to reduce the amount of hazardous wastes to be treated either on-site or at an off-site stationary treatment/disposal facility. The study involved testing four different brands of 4-inch diameter spiral-wound membranes, under varying pretreatment schemes. In general, rejection of Sb, Ni, and As was good, however Zn was poorly removed whereas Pb permeated through some membranes. For semi-volatile organic compounds, one membrane, the Filmtec SW30HR-4040 exhibited a constantly excellent level of rejection ranging from an average 93.6% for phenols to as high as 99.6% for benzoic acid. The difference in membrane performance is most striking when volatile organic compounds are considered: the family of organic compounds, the boiling point, and the molecular weight of an organic compound are but some of the factors that are linked to each membrane behaviour. Overall, the Filmtec SW30HR-4040 outperformed all other membranes for the removal of volatile organic compounds. The results indicate that RO is a promising technology for in-situ treatment of hazardous waste disposal site leachate.

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1.0 Introduction

The Pollution Abatement Services (PAS) site in Oswego, New York, was remediated in the mid-1980's when drums of toxic wastes were removed from the site, and the contaminated soil was contained by means of traditional methods: a slurry wall along its perimeter, a leachate collection system, and a clay and high density polyethylene cap. The continuous monitoring and maintenance of this Superfund site has consisted of the collection and off-site treatment of approximately 65,000 gallons of leachate monthly. The leachate management methods has cost government agencies money, manpower and time. To reduce these expenditures, Region II of the United States Environmental Protection Agency (US EPA) requested the engineering assistance of the US EPA Environmental Response Team (ERT) to explore the feasibility of on-site treatment technologies.

In agreement with the 1986 Superfund Amendments Reauthorization Act (SARA), alternative and innovative technologies were preferentially addressed. Environmental engineers from the US EPA, Environment Canada, and the Response Engineering and Analytical Contractor (REAC) analyzed previous successful bench-scale work and selected reverse osmosis (RO) and enhanced ultraviolet oxidation, also called UV photolysis/ozonation/hydrogen peroxide, for a field pilot-scale study.

This paper concerns the application of reverse osmosis for on-site treatment of hazardous wastes. It reviews the basic principles that govern the process and reports on the treatability study that was conducted at the PAS site in the summer of 1988. Since four different brands of RO membranes were investigated, the evaluation of their performance focuses on the quality of their respective permeate. The purpose of this paper is to provide the preliminary results of this study.

2.0 Reverse Osmosis: The Treatment Technology

2.1 Process Description

Reverse osmosis (RO) is a membrane technology which can serve a dual-purpose in hazardous waste treatment. It is a means to reduce wastewater volumes, and in the process, the membrane generally retains most of the contamination within one of the two effluents, namely the concentrate. The permeate stream is aimed to be discharged in the environment, whereas the concentrate requires further treatment.

RO is accomplished by pumping an aqueous dilute solution at a high pressure over a semi-permeable membrane. As the solution sweeps the surface of the membrane, the solvent, water, is preferentially attracted. Its transport across the polymeric layer is driven by the difference between the osmotic pressure of the solution at that location on the membrane and the hydrostatic pressure of the solution.

The chemical substances present in a given feed solution differ in their affinity for the membrane material. The interaction between the membrane, the solute components, and the solvent governs the performance of any such system. Different schools of thought have explained the mechanism by which solutes are transported across the membrane. The most prevalent theories are : the preferential sorption-capillary flow mechanism (Sourirajan and Matsuura, 1985) and the solution-diffusion transport mechanism (Lonsdale et al. 1965).

Once the initial separation has been performed, the solution retained at the membrane surface is subjected to further separation as it flows along the polymeric surface. Thus, there is not only a step-wise change in solute concentration between the two sides of the membrane but also a gradual increase from the feed influent end to the concentrate effluent end on the same side of the membrane.

2.2 Applications

Reverse osmosis has been used extensively for the past twenty-five years to remove inorganic compounds for the production of potable water from brackish water and seawater. Economic and environmental considerations have promoted its use for concentrating electroplating rinse waters since the '70s, and its use has been explored for other hazardous waste treatment since then. Beginning in 1984, Environment Canada has been demonstrating reverse osmosis in the field for treating dilute organic solutions such as landfill leachate, industrial wastewater, and contaminated aqueous solutions generated by chemical spills. Some of the solutions successfully investigated in Canada include:

◊ spilled wood protection solutions containing tetra and pentachlorophenols (PCPs);

◊ leachate contaminated by volatile organic compounds;

◊ leachate contaminated by polychlorinated biphenyls (PCBs);

◊ potato wash water;

◊ fish blood water;

◊ pesticide container wash water;

◊ industrial wastewaters containing monoethylene glycol;

◊ surface runoff contaminated by benzene, toluene, and xylenes (BTX);

◊ solvent contaminated wastewater from an aircraft maintenance facility.

2.3 Pollutant Concentration Considerations

The influent pollutant concentration for which a reverse osmosis system will economically produce a permeate of sufficient quality for discharge in a sewer system or into surface waters varies from one chemical compound to another, and from one application to another. For example, a treatability study of an industrial waste effluent revealed that a reverse osmosis membrane would not withstand long-term exposure to a 1% phenol solution. However, selection of another membrane and a change in the chemical nature of the phenol allows the RO system to increase the phenol concentration up to 8% without either affecting the physico-chemical or the structural integrity of the RO membrane. As the permeate from the first stage is, at 1500 ppm phenol concentration, still too highly contaminated, a second stage has been added and the permeate meets the effluent discharge criteria set by the concerned jurisdiction. The phenol recovered by the two-stage RO system is expected to pay for the pollution control system within twelve months.

In this section, a review will be made of the two characteristics that play the most significant roles in defining the ranges of pollutant concentrations in which RO will be effective. These are the osmostic pressure and the chemical compatibility between the pollutants and the membrane materials.

2.3.1 Osmotic Pressure

Osmosis is a natural phenomenon. The term defines the diffusion of a solvent through a semi-permeable membrane which separates two solutions having different molar concentrations of solute. The semi-permeability of the membrane refers to this property to allow the solvent through but not the solute. An equilibrium is reached when the solvent flow stops. At this point, the hydrostatic pressure difference between the two liquid columns represents the osmotic pressure difference between the two solutions. To generate a net water transport through the membrane, the osmotic pressure difference must be overcome (Figure 1).

The osmotic pressure of an aqueous solution is caused by the presence of chemical species other than water. The type of compound and its concentration, the pH, and the temperature of the solution have an influence on the osmotic pressure, and thus, on the driving pressure necessary to induce reverse osmosis. The wastewater should exert an osmotic pressure no greater than the membrane's operating pressure limit to allow for water permeation.

2.3.2 Compatibility With Membrane Materials

The choice of a membrane is governed to a great extent by its chemical resistance. The membrane surface material, the backing polymer, the adhesive agents, the seals, and all related hardware must sustain the chemical abuse to which the pollutants might subject them. Reverse osmosis systems are mostly sensitive to long-term exposure to oxidants, and to low molecular weight halogenated organic solvents. Also, field experience reveals that some RO membranes tend to swell from long-term contact with BTX.

Membrane research and development continuously evolves as a result of customer demands, the introduction of new synthetic materials, and the quest for better performing membranes. Chemical resistance is constantly increased, in particular that to free chlorine, and the allowable feed pH range has been widened.

Finally, compatibility includes the notion that any pollutant will be rejected. It is undesirable that a membrane preferentially allows the permeation of contaminants.

2.4 Performance

In hazardous waste treatment, the ideal reverse osmosis membrane is one which: retains all pollutants; possesses a very high water permeation rate; chemically resists virtually all compounds; and needs very little maintenance (washing or replacement). However, RO membranes do not separate 100% of the contaminants and cannot recover 100% of the water from the contaminated solution. Thus, performance assessment of RO membranes is primarily based on the qualitative (percent rejection) and quantitative (water permeation) aspects of the separation.

2.4.1 Qualitative Aspects

Qualitative membrane performance is assessed by measuring the concentration of given solutes in the feed solution and in the permeate stream. From this data, the percent rejection is calculated by means of the following formula:

$$R_i = \left(1 - C_{ip} / C_{if} \right) \times 100\%$$

where: R_i is the rejection of solute "i" expressed as a percentage;

C_{ip} represents the concentration of solute "i" in the permeate;

C_{if} represents the concentration of solute "i" in the feed solution.

Rejection is considered from the perspective that a given solute is prevented from entering the permeate stream by the semipermeable membrane. In this sense, one should not confuse it with the removal of a given solute from the permeate.

Typically, a membrane retained for its rejection capability will cause a change in the pollutant concentration by one order of magnitude or more (in other words, a 90% rejection or more). As a result, the concentration of each pollutant in the feed greatly affects the number of stages needed to meet the effluent discharge criteria for the permeate.

2.4.2 Quantitative Aspects

RO systems are amenable to modular design. This characteristic allows for the manufacturing of systems to serve specific purposes, and yet, the productivity of each system can be increased by adding membrane modules, or replacing membranes within each module by better, and newly developed membranes, or by plumbing a second system to the first one.

All designs are based on the permeation rate of membranes. As each aqueous solution interacts differently with a given membrane, a systematic approach to determine the best membrane for each application must address the following aspects: the osmotic pressure expected and the necessity of special cleaning methods. In addition, the chemical compatibility of all materials should be examined.

Water recovery ratio is another quantitative criterion which is particularly important for wastewater volume reduction applications. It is defined as the portion of the feed solution which is recovered as permeate, and it conveniently corresponds to the volume reduction achieved. The ratio of the permeate flowrate to the sum of the concentrate and the permeate flowrates represents this quantity:

$$\Delta \quad = \quad Q_p \ / \ (Q_p + Q_c)$$

where: Δ is the water recovery ratio (expressed in percent or as a fraction);

Q_p is the permeate flowrate;

Q_c is the concentrate flowrate (units consistent to those used for Q_p).

Water recovery is limited by the rise in osmotic pressure that accompanies a volume reduction, and the precipitation of salts at the surface of the membrane. Therefore, a compromise must be reached between how much permeate should be recovered and the membrane maintenance needed to keep the membrane permeating.

2.4.3 Mass Rejection Rate

The mass rejection rate is a practical means to compare membranes. Its concept embraces the needs for high permeation rates, and for high contaminant rejections. Its calculation is performed by multiplying the permeate flowrate by the concentration difference existing between the feedwater and the permeate for a given contaminant. It represents the mass of a given contaminant which is prevented from entering the permeate or reciprocally that which is retained within the concentrate. A mass balance performed around a membrane system yields:

$$m_i = \left(C_{if} - C_{ip}\right) \cdot Q_p = \left(C_{ic} - C_{if}\right) \cdot Q_c$$

where: m_i is the mass rejection rate of solute "i";

C_{ic} is the concentration of solute "i" in the concentrate;

all other quantities, C_{if}, C_{ip}, Q_p, and Q_c were defined above.

2.5 Limitations To Reverse Osmosis

The following aspects may cause interferences to the RO membrane's performance: the feedwater source, the chemical compatibility of the membrane with respect to the feedwater composition, the solution osmotic pressure, fouling factors and scaling agents. Silt or colloids can become entrapped and significantly reduce productivity and rejection. The fouling potential is especially high for levels of iron higher than 0.1 ppm as the divalent form (Fe^{++}) will likely form colloidal iron (Fe^{+++}) in the presence of oxygen. Those salts which are most susceptible to precipitate as a scale on the membrane surface are calcium carbonate (limestone), calcium sulfate (gypsum), and silica. Hence, pretreatment should be addressed carefully as it will impact on the longevity of the RO membranes.

Various protective, monitoring and control components must be integrated to allow for the safe and reliable field operation of any reverse osmosis system. On the upstream end of the membranes, also called the feed end, filters act as a preventive measure by removing suspended solids down to the micronic size range. Generally it is recommended that particles having a size greater than one fifth of the smallest dimension of the feed conveying channel be removed. As a rule of thumb, 5 µm filters represents a suitable size for reverse osmosis (Lombard, 1986). In addition, pressure and temperature gauges and switches are normally incorporated. These ensure that the membranes will be used under normal operating conditions.

Currently, automation has yet to be developed to allow for feedback regulation of key operation parameters such as pressure, temperature, recirculation rate, and conductivity in the permeate.

3.0 Methodology

3.1 Leachate Characterization

Leachate characterization was carried out in December 1987. Samples collected at the PAS site in Oswego, NY , were analyzed by REAC. The analyses focused on: the total priority pollutants; total and suspended solids; titration curves; pH; TOC; BOD; COD; and flashpoint. The TOC level was 870 mg/l. Furthermore, the volatile organic compounds with the highest concentrations were: methylene chloride (25900 μg/l); trans-1,2-dichloroethene (13300 μg/l); xylenes (10000 μg/l total); toluene (6300 μg/l); and ethylbenzene (4100 μg/l). Also, analyses showed phenol (935 μg/l) and 2,4-dimethylphenol (435 μg/l) as the primary base/neutral/acid extractable compounds. No organochlorinated pesticide, nor polychlorinated biphenyl (PCB) was detected. Among all investigated metals, nickel (2150 μg/l), arsenic (35.3 μg/l), chromium (22.8 μg/l), and cadmium (16.0 μg/l) displayed the highest concentrations.

3.2 Bench Scale Treatability Study

As a result of the leachate characterization, phase I engineering studies were undertaken. Another sampling effort was performed at the PAS site on 23 February, 1988. It involved the complete filling of two 55-gallon lined drums (to eliminate headspace) and overpacking in 85-gallon drums. Subsequently, bench-scale testing was conducted at the River Road Environmental Technology Centre in Ottawa, Ontario, CANADA. Two leachate treatment schemes were investigated from 24 to 27 February, 1988. They were: powdered activated carbon adsorption followed by microfiltration (PAC-MF) and reverse osmosis; and two-pass reverse osmosis.

In both treatment tests, the landfill leachate was mildly acidified by hydrochloric acid addition to pH 6. As the rate of oxidation by oxygen is inversely proportional to the hydronium ion concentration, lowering the pH is meant to preserve iron as a ferrous salt solution, thereby preventing colloidal fouling of the membrane. The use of 5 μm filters provided additional protection against debris and particulate clogging. Analyses for the bench-scale studies covered: total priority pollutants plus 40 other pollutants except PCBs and pesticides; iron, calcium, and priority pollutant metals, sulfate; cyanide; total suspended and dissolved solids; TOC; and COD.

The rejection percentages of first pass RO alone, without PAC-MF, were respectively: 60.0% for methylene chloride; 78.4% for trans-1,2-dichloroethene; above 99.9% for xylenes (total); 98.9% for toluene; above 99.9% for ethyl benzene; and above 99.9% for benzene. For the semi-volatile organics phenol was rejected at 79.8% whereas higher results were exhibited for 2,4-dimethylphenol at 96.8%. In the case of inorganics, nickel (98.1%), arsenic (above 99.9%), lead (above 99.9%), and chromium (above 99.9%) were easily removed by reverse osmosis. TOC level was reduced by 88.8%. Second pass permeate did not significantly increase rejections over the first pass permeate levels.

The success achieved in this evaluation demonstrated reverse osmosis to be a technically feasible treatment for the PAS site. Also, potential savings identified in a subsequent economic analysis substantiated the need to proceed with the phase II engineering studies (Evangelista, 1988). On the other hand, powdered activated carbon adsorption followed by microfiltration separation appeared to be an unnecessary treatment step because of the economics and the generation of additional solid wastes.

3.3 Reverse Osmosis System Configuration For The On-Site Tests

The raw leachate was pretreated to lower the concentrations of the ferrous ion, and calcium carbonate, and solubilize residual metallic species. The following describes the pretreatment system. Batches of raw leachate were pumped from the recovery wells and piped to a concrete in-ground storage tank with a capacity of 200,000 litres. A stainless steel submersible pump fed raw leachate to the pretreatment system. The RO pretreatment steps included: basification; clarification; dead-end filtration; acidification and dead-end filtration. Basification included the injection of a 25% sodium hydroxide aqueous solution into the raw leachate stream within an on-line static mixer. Then, the basified leachate discharged into an 800-litre reaction tank. The flocculating solution was transferred to a Lamella® clarifier. The clarified effluent was then pumped through 5-micron and 0.2-micron cartridge filters in series, acidified by means of a 50% hydrochloric acid on-line injection, statically mixed, and finally discharged into a 2000-litre feed tank (Figure 2). Flows and pH were monitored and adjusted as to maintain a pH of 10 in the reaction tank, and a pH of 5 in the RO feed tank. The acidified leachate was then filtered through a 0.2-micron cartridge filter and introduced to two high pressure pumps before contacting the RO membranes for separation.

Environment Canada's mobile RO system was used for the phase II engineering studies. Its configuration was arranged to two pairs of 4"x40" spiral-wound membranes in series in each bank. Four different manufacturers' membranes were utilized in the course of this evaluation; therefore, each pair of RO membranes was representative of one brand.

Lamella® is a registered trademark of Axel Johnson Engineering AB, SWEDEN

Tests were carried out over a period of 10 days in August, and September 1988. The distinction between each trial was established by a variation in the water recovery ratio, and in the operating pressure. Sufficient time was allowed between each sampling effort for the membranes' acclimatization.

Membrane separation generated concentrate and permeate effluents. The permeate could, at any point in time, be discretized into four separate streams for sampling purposes, each one being the product of one membrane type. The effluents were either directed to the enhanced ultraviolet oxidation system for further treatment or returned to an injection well in the landfill.

3.4 Sampling And Analysis Of Samples

Samples were taken at appropriate times during the trials from the RO feed solution, also called basified/acidified leachate, from each of the four permeate ports, and from the concentrate. The Lamella® clarifier sludge, and the raw leachate were each sampled on one occasion. REAC Standard Operating Procedures (SOPs) #2001 to 2005 were observed for sampling, sample storage, and sample shipment. All abovementioned SOPs are approved by the ERT (Evangelista, 1989). On-site analyses were performed for volatile organic compounds (VOCs) as per US EPA methods 601 and 602 using a Hewlett Packard (HP) 7675A purge and trap unit followed by a HP 5830 gas chromatograph (GC) with a flame ionization detector.

VOC analyses were verified off-site for some samples by a modified version of US EPA method 524.2 using a HP 5995C gas chromatograph/mass spectrophotometer (GC/MS) equipped with a Tekmar LSC 2000 purge and trap concentrator. The use of a reduced sample size, that is 5 ml, corresponded to the only adaptation to the analytical method of US EPA method 524.2 (Evangelista, 1989).

Off-site analyses were performed for the semi-volatile organics, also known as base neutral/acid extractables (BNAs), and priority pollutant metals. BNA analyses were done in conformity with the separator extraction technique of US EPA method 625 by means of a HP 5995C GC/MS. Finally, priority pollutant metals were analyzed according to the US EPA method 7000 series. Zinc and nickel were quantified by flame atomic absorption spectrophotometry using a Varian SpectrAA-300. In the case of arsenic and lead, graphite furnace atomic absorption spectrophotometry was performed using either a Varian 400-Z or a Varian SpectrAA-20 both set up with a GTA-95 graphite furnace unit (Evangelista, 1989).

4.0 Results and Discussion

For each test, the percent rejection of each membrane was computed for each pollutant. Then, the mean rejection was computed from the results of all tests. Table 1 lists those latter values for each of the four membranes labelled A to D. The selected pollutants were chosen because they represent various families of contaminants and because of their relative occurrence in the PAS site leachate. Therefore, the results tabled herein represent only a portion of those generated during the phase II engineering studies at the PAS site. However, the selection of representative pollutants is meant to provide a broad coverage of the quantification process. All the data can be found elsewhere (Evangelista, 1989).

In general, the RO membranes tested in this study rejected the heavy metals with the highest success. Among the organic compounds, the base/neutral/acid extractable compounds were more easily rejected than the VOCs. Membrane A rejected volatile organic compounds and semi-volatile organics at levels that did not reach 85% in most cases. The only exception was 2-methylnaphtalene (85.0%). A contaminant reduction of that order of magnitude was accomplished for all metals except for lead (10.3%) and zinc (45.4%). Membrane B tended to retain organic compounds at a higher percentage than membrane A. Among the VOCs, bromoform (91.5%), 1,1,1-trichloroethane (85.2%), and methyl isobutyl ketone (85.4%) were retained in the concentrate with the greatest rejection efficiency. The results for membrane B also revealed with more clarity than those for membrane A a trend of higher rejection levels with higher molecular weight. Benzoic acid (85.5%) and 1,2-dichlorobenzene (91.7%) were the BNAs which were separated with the greatest ease by membrane B. Rejections for metals exceeded the 85% level except for lead (16.9%) and zinc (33.6%). For membrane C, separation levels rarely exceeded 80%. The compounds that were separated above that percentage were: meta- and para-xylene (coeluted 84.6%); ortho-xylene (83.4%); 1,1,1-trichloroethane (85.7%); and copper (84.4%). Membrane D demonstrated its capacity to remove in excess of 90% of the contamination associated to six VOCs. These were: 1,1,1-trichloroethane (93.3%); bromodichloromethane (91.6%); bromoform (99.5%); ethylbenzene (94.9%); meta- and para-xylene (co-eluted 96.3%); and ortho-xylene (96.7%). Five compounds among the BNAs were separated at levels above 85%: 1,2 dichlorobenzene (87.9%); 4-methylphenol (89.8%); 2,4-dimethylphenol (88.5%); naphtalene (88.9%); 2-methylnaphtalene (92.6%). As for all membranes, removal of metals reached one order of magnitude except for lead (29.1%), and zinc (53.3%).

Overall, membrane D exhibited the best performance with the highest rejection levels for the majority of the contaminants. Of all membranes, membrane D achieved an order of magnitude change in the greatest number of pollutant concentrations.

The results indicate that the molecular size and polarity have an impact on the performance of RO membranes. The RO membrane rejects the larger molecules because the membrane acts as a molecular sieve. On the other hand, polar molecules are less amenable to separation than non-polar molecules. For example, benzene and toluene showed higher levels of rejection than the polar compounds phenol and 4-methylphenol. It is believed that the phenolics, when dissociated, can form a hydrogen bond with the membrane and diffuse through it more readily than a non-dissociated molecule.

To complete our analysis of the performance from a quantitative standpoint, the permeation rate of the single-stage RO system was examined for all twelve tests. Between 0 and 21.3 hours, six different tests were performed on separate days of operation where most of the fluctuations in the permeate flowrates are related to the start-up conditions, and the adjustment of the operating pressure (Figure 3). At 10.3 hours, the "spike" illustrates the effect of pressurizing the system from 600 psi to 800 psi. On the other hand, the increase in the combined permeate flowrate (12.5 to 27.0 litres per minute) that appears at 12.5 hours results from the use of a more dilute solution, namely the enhanced ultraviolet oxidation effluent. In the following tests, normal pretreatment of the leachate was resumed. The increase in the osmotic pressure that accompanied the change in the feed solution at 15.2 hours and a reduction of the operating pressure to 600 psi caused a decrease in the permeation rate from 28 to 22 lpm. This test ended at 19.5 hours. As the solutions left in the tanks lost during the following 20 hours of downtime part of their organic contamination through volatilization, the permeate rates reflected these losses at start-up. A pressure of 600 psi was maintained and flows gradually decreased to 10 litres per minute. This trial ended at 21.3 hours.

In the next sequence of tests, the variation in the permeate fluxes was mostly accounted by the adjustment of the water recovery ratio and the fluctuation in the chemical composition of the PAS site leachate. After 21.3 accumulated hours of operating time, tests were initiated at 800 psi, and the system was not shutdown until 63.8 hours. Varying the recovery ratio at a given pressure affected the permeation rate. When more water was recovered, the osmotic pressure increased at the membrane surface, therefore decreasing the permeation flux. On the other hand, different osmotic pressures of the feed were associated to different chemical compositions of the landfill leachate. At a fixed operating pressure and water recovery ratio, the changes in the osmotic pressure translated into a variable net driving pressure, and caused the instability in the permeate flowrates. The concentration ranges listed in Table 1 illustrate that for some chemical species, the concentration varied by as much as three orders of magnitude.

5.0 Conclusion

Rejection of metals is generally easily accomplished. Caution should be exercized when semi-volatile and volatile organic compounds are involved since the rejection efficiency is somewhat lower than for inorganic species. Still, acceptable levels of rejection can be achieved on some volatile organic compounds. For instance, membrane D rejected several volatile compounds at levels exceeding 90%. Therefore, membrane selection is an important step of any treatability study which is to involve reverse osmosis as a hazardous treatment process.

The preliminary results of the phase II engineering studies at the PAS site in Oswego, NY, demonstrated that reverse osmosis can be used as an effective part in a treatment process for landfill leachate. The economics of this separation process depends to a great extent on the liquid wastes themselves. The pretreatment of the feed water, the treatment/disposal of both the RO concentrate and the clarifier sludge bear heavily on the economics of the process. Discharge limits ultimately govern the costs and the benefits associated with this technology. The low rejections of volatile organics suggest that other treatment methods be coupled to a reverse osmosis system. Thus, RO should not be regarded as a panacea but as means to resolve specific contamination problems within the context of a treatment train where it can conveniently complement additional treatment processes.

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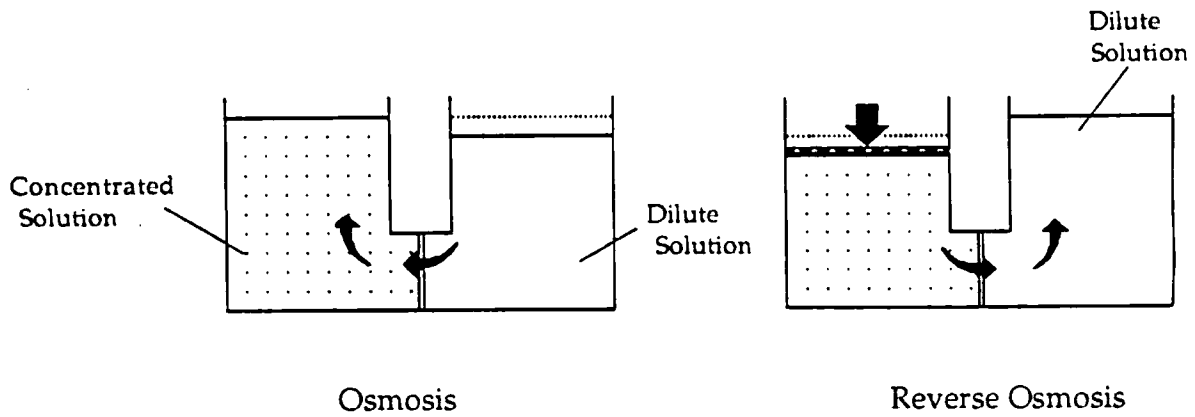
Figure 1 - Osmosis: water transport through the semi-permeable membrane is from the dilute solution to the concentrated solution. At equilibrium, water flow stops, and the chemical potential is equal on both sides. The head difference is the osmotic pressure.
Reverse osmosis: a pressure exceeding the osmotic pressure forces the water transport across the semi-permeable membrane. Solutes are for the most part retained on the side of the membrane where the pressure is applied.
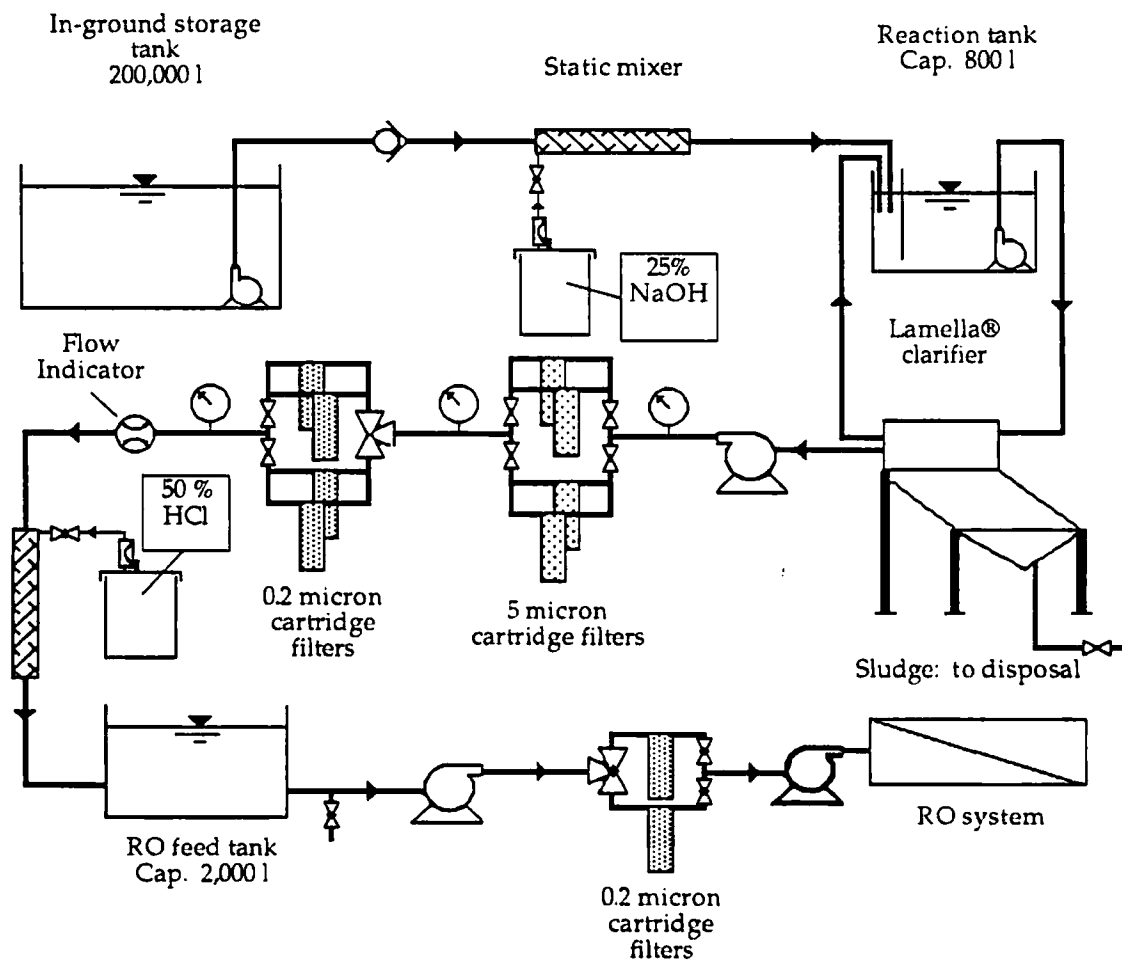

Figure 2 - Pretreatment System Utilized for the Phase II Engineering Studies at the PAS Site in Oswego, NY.
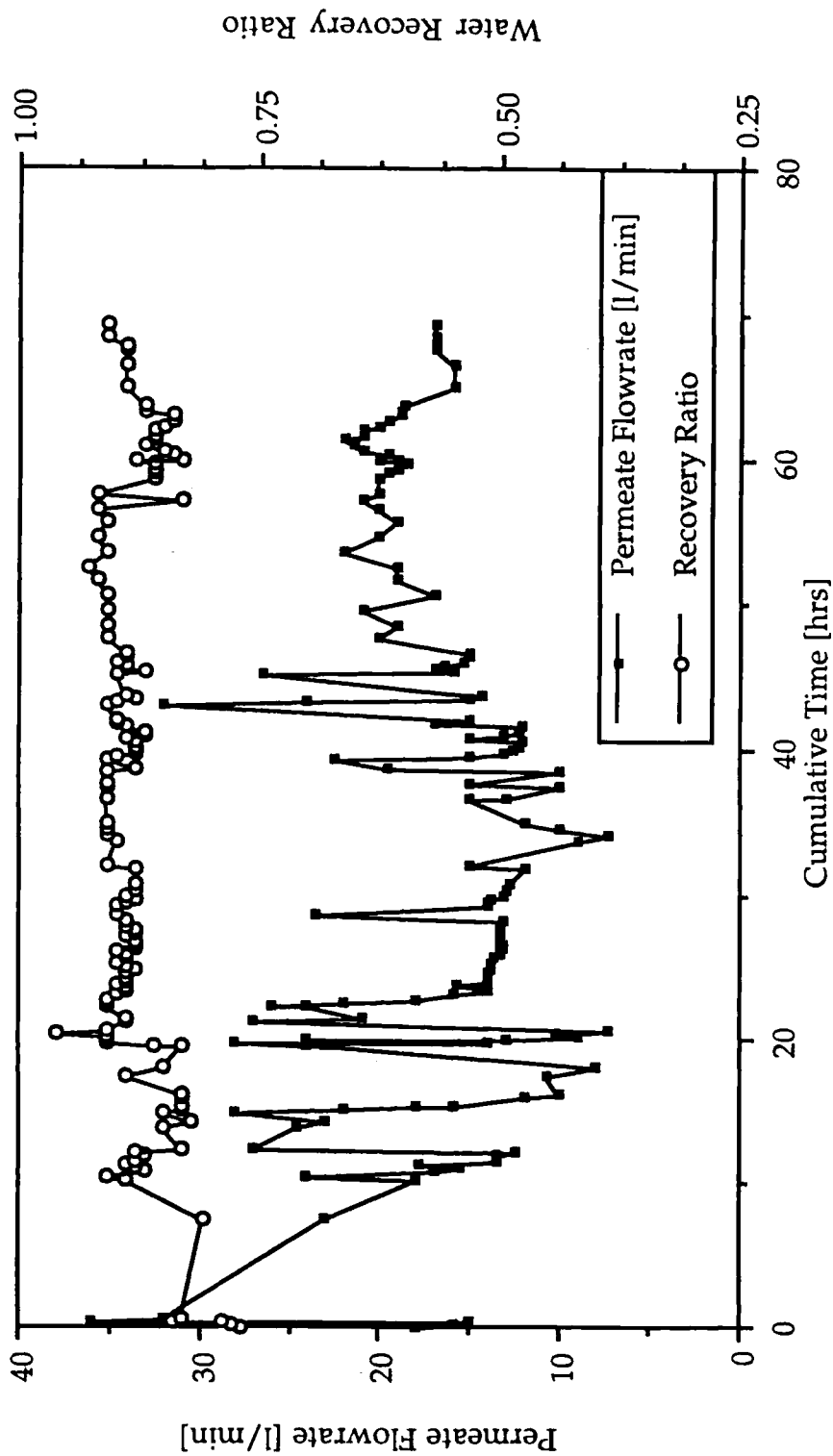
Figure 3 - Permeate Flowrate and Water Recovery During Phase II Engineering Studies at The PAS Site, Oswego, NY.

Table 1 - Summary of the Results
for the Phase II Engineering Studies at the PAS Site, Oswego, NY.

Compound/Metal	Concentration Range (in the feed) [µg/l]	Average Percent Rejection For All Tests				
		Membrane A [%]	Membrane B [%]	Membrane C [%]	Membrane D [%]
Dichloromethane	129 - 99642	34.3	51.5	42.5	50.5
Acetone	4912 - 68768	46.0	49.5	31.6	73.8
1,1-Dichloroethane	178 - 3612	57.2	64.7	64.3	88.2
1,2-Dichloroethane	635 - 6931	41.0	52.3	53.7	75.3
trans-1,2- Dichloroethene	319 - 62577	11.7	37.3	37.0	47.4
Benzene	60 - 2561	56.7	58.0	55.8	83.9
Bromoform	226 - 198966	74.9	91.5	69.1	99.5
Toluene	75 - 26145	57.7	68.4	53.3	83.7
Ethylbenzene	1266 - 19211	66.1	74.3	74.6	94.9
o-Xylene	3339 - 52033	71.9	83.2	83.4	96.6
Phenol	121 - 7155	54.5	55.7	37.8	72.2
4-Methylphenol	67 - 4811	78.6	57.4	59.8	89.8
Benzoic Acid	46 - 42331	67.9	85.5	51.7	83.3
Arsenic	23 - 67	96.1	85.5	46.1	98.6
Lead	4 - 59	10.3	16.9	20.0	29.1
Nickel	1070 - 2630	>99.9	93.8	53.6	88.2