An Evaluation of Low Vapor Pressure Liquids for Membrane Introduction Mass Spectrometry

R. C. Johnson, K. Koch, N. Kasthurikrishnan, W. Plass, J. S. Patrick and R. G. Cooks* Department of Chemistry, Purdue University, West Lafayette, IN 47907-1393, USA

Four liquids of low vapour pressure have been examined for use as semi-permeable membranes in the sampling and analysis of volatile organic compounds by the technique of membrane introduction mass spectrometry (MIMS). The chosen liquids are inert and hydrophobic and can be formed to any desired thickness or shape. The selected polymers—polyphenyl ether, alkylated cyclopentane, perfluorinated ether and silicone oil—were supported on a microporous substrate and mounted in a direct insertion membrane probe. Polyphenyl ether, alkylated cyclopentane and silicone oil each formed stable semi-permeable barriers which passed the analytes of interest while discriminating strongly against the water solvent. These highly stable liquids also showed no significant loss of mass or contribution to the background of the mass spectrometer. Optimal injection volumes (2.25 ml) and membrane temperatures (90 °C) gave 10%-90% rise times of 44-55 s for the three liquids compared with 35 s for a reference silicone membrane. Comparable detection limits at the low-ppb level were observed for benzene, toluene, *trans*-1,2-dichloroethylene, chlorobenzene, carbon tetrachloride and nitrobenzene using the silicone reference and alkylated cyclopentane membranes. \bigcirc 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

The objective of this work was to evaluate alternatives to traditional solid polymers as membranes for membrane introduction mass spectrometry (MIMS).¹⁻⁵ Liquid membranes offer advantages with respect to their ease of manipulation: specifically their thickness is continuously adjustable and they can take any desired shape. In addition, the chemical nature of liquids may be varied by mixing them with appropriate additives. Four liquids of varying chemical structure were evaluated, including two slightly polar ethers, a silicone oil and a non-polar hydrocarbon. The experiments described here focus on the evaluation of the liquids in MIMS in comparison with traditional silicone polymer films.

The simple, rugged technique of membrane introduction mass spectrometry allows on-line monitoring of volatile compounds in solution (typically water)^{6,7} or gases (often air)⁸⁻¹⁰ using a semi-permeable membrane barrier as the sample inlet. The membrane separation process is usually based on pervaporation, the passage of solute from solution into the vapor phase. It involves three steps: (i) partitioning of the analyte onto the highpressure side of the membrane, (ii) its diffusion through the membrane and (iii) subsequent desorption into the

* Correspondence to: R. G. Cooks, Department of Chemistry, Purdue University, West Lafayette, IN 47907-1393, USA.

Email: cooks@purdue.edu.

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CCC 1076-5174/97/121299-05 \$17.50 © 1997 John Wiley & Sons, Ltd. gas phase or vacuum on the low-pressure side. Enrichment occurs when the rate of solute transfer exceeds that of the solvent^{11,12} and this typically limits analytes of interest to volatile organic compounds (VOCs) with boiling points below 200 °C, though recent work with semi-volatile compounds has been successful.^{13,14}

Typically an ion trap or quadrupole mass filter is used in MIMS experiments. Analytes are ionized by electron impact and chemical ionization, separated by mass-to-charge ratio (m/z) and detected using an electron multiplier. Selected ion monitoring (SIM) is often employed to increase the sensitivity for particular analytes by recording only the ion chromatograms (time-dependent responses) for specific ions. When triple quadrupoles or more recent models of ion traps are used in conjunction with MIMS, tandem mass spectrometry (MS/MS) can be used to further identify and quantify coeluting analytes.

MIMS is appropriately applied in circumstances where the reacting system is well characterized but needs to be continuously monitored for a few key analytes which are indicators of reaction status.^{15–17} For example, fermentations have been monitored using MIMS by following the production of ethanol and acetaldehyde.^{18–20} The advantage of MIMS for these experiments is the rapid analysis time (5 min or less), its suitability for long-term continuous monitoring and the fact that the system requires little sample pretreatment beyond filtering. Feedback control has been combined with MIMS and is triggered using the chemical information from MIMS to make system adjustments such as the addition of glucose to optimize ethanol production.²¹

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A common MIMS configuration involves the use of a flow injection analysis (FIA) procedure^{22–24} in which the solution flows through or over a capillary or sheet membrane mounted in a direct insertion probe.²⁵ This direct insertion probe places the membrane directly in the source of the mass spectrometer, minimizing contamination of connecting vacuum lines, producing shorter response times and allowing ppt limits of detection in favorable cases.^{26,27} The most commonly used sheet membrane are the silicones, typically 0.0127 cm thick, although several other types of polymers in various thicknesses have been utilized.^{28–31}

Low-vapor-pressure liquids also potentially serve as semi-permeable membranes owing to their high chemical, physical and thermal stabilities, properties which have been developed for high-performance lubrication and vacuum system applications. Polyphenyl ethers and silicone oils are commonly used as diffusion pump fluids, perfluorinated polyethers have seen applications from aerospace lubrication to pump oils, while alkylated cyclopentane has been developed primarily as an aerospace lubricant. As a result of these technological imperatives, each of these classes of liquids has been extensively studied and characterized for attributes such as vapor pressure, viscosity and density. The characteristics of these liquids of particular interest here include (i) hydrophobicity, (ii) low vapor pressure, (iii) capability of sustained operation without contributing to the instrument background and (iv) permeability to the organic compounds of interest. In addition, the possibility exists that these liquids could be mixed with additives to form homogeneous liquid solutions which can be used to selectively bind particular analytes and so decrease detection limits for specific chosen compounds.

The work described here builds on earlier studies using polymer membranes as well as the work of Baumgardner *et al.* who used Krytox (a perfluorinated ether) within a single micropore to create a gas monitor with high spatial resolution.³² In other related work, lowvapor-pressure liquids have been used with hollow fiber capillaries for gas separation of CO₂ and N₂.³³

EXPERIMENTAL

Experiments were performed using a Finnigan MAT (San Jose, CA) ITS-40 ion trap mass spectrometer equipped with a solids inlet port. The evaluation of the liquids was performed using a direct insertion probe (DIP) which was created by modifying a Finnigan solids probe to accept a sheet membrane.²² The DIP was maintained at 90 °C and operated with a solution flow rate of 1.5 ml min⁻¹. Flow injection was performed manually to pass aliquots of sample across the membrane in a continuous water stream. Sample transfer lines consisted of PTFE tubing (1.59 mm o.d. and 0.76 mm i.d.) connected to the DIP with short segments of Tygon tubing (PN#95601-28, Cole-Palmer, Vernon Hills, IL). A peristaltic pump (Gilson, Model M312) was used for flow control. Solutions were created by serial dilution of 100 ppm stock solutions of benzene, toluene, trans-1,2-dichloroethylene, carbon tetrachloride and nitrobenzene in deionized water.

Electron impact (EI) was the ionization method used for comparison of the membranes. Chemical ionization (CI), with water as the reagent gas,³⁴ was also investigated but yielded no significant improvement in sensitivity for these compounds. Ionization times were individually optimized for the membranes and were between 10 and 14 ms for each membrane. The electron multiplier was operated at a fixed potential of 1950 V. The pressure in the ion trap was maintained at nominal 4 mTorr (0.5 Pa) at ambient temperature. The mass range scanned was m/z 30–200. Ions of interest were m/z78 (benzene), m/z 91 and 92 (toluene), m/z 96 and 98 (trans-1,2-dichloroethylene), m/z112 and 114 (chlorobenzene), m/z 117, 119 and 121 (carbon tetrachloride) and m/z 123 (nitrobenzene).

Lower limits of detection for each membrane liquid were determined for each analyte of interest at a minimum signal-to-noise ratio (S/N) of three. The S/N was determined from single-ion chromatograms of each analyte, measuring the analyte response relative to the baseline signal recorded before the peak in the FIA response. The 10%-90% rise time of each pervaporation peak was measured over all concentrations within the linear dynamic range of each membrane. Optimum sampling periods were found to be about 1.5 min with consumption of a total sample volume of 2.25 ml. The lower limits of detection and 10%-90% rise times were directly compared with data for a reference silicone membrane (non-reinforced, 0.0127 cm thick; Technical Products Inc., Decatur, GA). The silicone membrane used here has been previously characterized for optimum temperature and shows no significant change in signal in the range 85-90 °C.¹⁸ The supporting materials (polypropylene membrane and stainless steel supports) and the silicone reference membrane were cut to size using a membrane template which was designed to allow convenient membrane preparation.

Liquid membranes

Polyphenyl ether (Santovac 5, Monsanto Corporation, St Louis, MO), alkylated cyclopentane (Penzane 2001, Nye Lubricants, New Bedford, MA), perfluorinated ether (Krytox 16350, Dupont, Wilmington, DE) and silicone oil (705 diffusion pump oil, Dow Corning, Midland, MI) were chosen as liquid membranes. Table 1 gives some characteristics of each of the liquids, including molecular weight, vapor pressure and density.

Two layers of microporous polypropylene with 10 μ l of the selected liquid sandwiched between them formed the liquid membrane assembly. This configuration was externally supported by a 50 μ m thick stainless steel mesh with a 30 μ m pore size (30% open area; Spectra/Mesh, Spectrum, Houston, TX). The microporous polypropylene support (Celgard 2502, Hoechst Celanese, Charlotte, NC) was 0.00508 cm thick (\pm 10%) with a pore size of 0.05 μ m and 37%–48% porosity. The microporous membrane could not be used in the absence of a low-vapor-pressure liquid owing to the large quantity of water which passed through it.

The liquid membranes were evaluated 2 days after being introduced into the ion trap mass spectrometer and were found to contribute relatively little to the

Name	MW (g mol ⁻¹)	Vapor pressure at 25 °C (Torr)	Vapor pressure at 100 °C (Torr)	Density at 25 °C (g ml ⁻¹)
Alkylated cyclopentane Polyphenyl ether Perfluorinated ether Silicone oil	950 454 11 000 546	$8.5 \times 10^{-13} 4 \times 10^{-10} 3 \times 10^{-14} 3 \times 10^{-10}$	5 × 10 ^{−5} 1 × 10 ^{−9} 8.14 × 10 ^{−6}	0.841 1.204 1.92 (at 20° C) 1.09
^a Data from manufacturers	'literature			

Table 1. Characteristics of liquids used as semi-permeable membranes^a



Figure 1. Temperature dependence of mass spectrometer response to a 250 ppb toluene solution introduced using a polyphenyl ether membrane.



injection time for a 250 ppb toluene solution introduced using a polyphenyl ether membrane.

background over the entire period (4 days) of continuous use. Thickness measurements of the liquid membranes, made using a micrometer, showed that the liquid membrane has the same thickness as the support (polypropylene), indicating that the liquid lies within the pores of the support.

RESULTS AND DISCUSSION

In order to increase enrichment across a semipermeable membrane interfaced to a mass spectrometer. the system must be optimized so as to allow the maximum flux of analyte to cross the membrane while passing a minimum quantity of solvent. Initial experiments focused on optimizing the variables which affect analyte response, including the temperature of operation and the volume of sample injected. A flow rate of 1.5 ml min⁻¹ of an aqueous solution of 250 ppb toluene was chosen initially. The temperature selected for membrane operation was typically between 60 and 90 °C and was limited at low temperatures by the decreased vapor pressure of the analyte and at high temperatures by increased water permeation. Typical temperaturedependent data are shown in Fig. 1 and these results led to the choice of 90 °C as the optimal temperature for these liquid membranes. Operation at higher temperature (i.e. 94-95 °C) caused minor membrane degradation over extended operating periods (more than 2 days), so increasing the instrumental background. The injection volume strongly influences the response of the analyte, the analyte signal increasing in height and area with analyte volume until steady state values are reached. Typical volume-dependent data are shown in Fig. 2. Based on these results, an optimal injection time

Silicone (reference)	Alkylated cyclopentane	Polyphenyl ether	Silicone oil	Perfluorinated ether
1.00	5.0	13	25	130
1.00	1.7	8.3	8.3	83
1.00	8.3	8.3	8.3	83
1.00	1.7	17	8.3	83
1.00	5.0	50	130	250
1.00	c	4.2	8.3	42
	Silicone (reference) 1.00 1.00 1.00 1.00 1.00 1.00	Silicone (reference) Alkylated cyclopentane 1.00 5.0 1.00 1.7 1.00 8.3 1.00 1.7 1.00 5.0 1.00 5.0 1.00 5.0 1.00 5.0 1.00 5.0 1.00 5.0 1.00 °	Silicone (reference) Alkylated cyclopentane Polyphenyl ether 1.00 5.0 13 1.00 1.7 8.3 1.00 8.3 8.3 1.00 1.7 17 1.00 5.0 50 1.00 5.0 50 1.00 5.0 50 1.00 ° 4.2	Silicone (reference) Alkylated cyclopentane Polyphenyl ether Silicone oil 1.00 5.0 13 25 1.00 1.7 8.3 8.3 1.00 8.3 8.3 8.3 1.00 1.7 17 8.3 1.00 5.0 50 130 1.00 5.0 50 130 1.00 ° 4.2 8.3

Table 2. Ratio of detection limits^a for each membrane compared with reference silicone membrane

^a Ratio = detection limit for each membrane/detection limit for reference membrane.
^b Absolute lower limit of detection (ppb) used as reference value for the liquid membranes.

° Chlorobenzene data not taken.

of 90 s was chosen for toluene and this corresponds to a total injection volume of 2.25 ml at a flow rate of 1.5 ml min⁻¹. Each membrane was individually optimized and each gave similar results: the optimum temperature of operation for all the membranes was 90 °C and the optimum sample volume was about 2.25 ml.

Multicomponent solutions are often used for the efficient evaluation of new membrane configurations for MIMS.³⁰ Various solutions containing mixtures of benzene, toluene, nitrobenzene, trans-1,2-dichloroethylene, chlorobenzene and carbon tetrachloride were therefore monitored to evaluate the analyte detection limits for each membrane (Table 2). Lower limits of detection are influenced by the total amounts of analyte monitored: an instrument which is used to monitor highly concentrated solutions loses sensitivity for solutions containing trace components because of contamination and carry-over effects. Accordingly, the relatively rapid changing of membrane interfaces needed to evaluate different membranes expeditiously causes fluctuations in the vacuum environment of the mass spectrometer and decreases the sensitivity of the instrument for trace analysis. Accordingly, the focus of this study was on limits of detection relative to those for a silicone reference membrane, not on the absolute values. Table 2 shows the absolute detection limits for the silicone reference membrane and the ratio of the detection limits of the various liquid membranes to the values for this reference system.

The diffusion coefficient of a specific compound within a membrane is well established as an influential parameter on the detection limit and sensitivity for that compound.^{11,12,35} Using toluene as a reference compound, the 10%–90% rise time for each membrane was measured and the diffusivity quantified (Table 3) using the previously developed relationships¹¹

$$t_{10\%-90\%} = 0.237(L^2/D) \tag{1}$$

$$I_{\rm ss} = ADS(P_{\rm s}/L) \tag{2}$$

where $t_{10\%-90\%}$ is the 10%–90% rise time (s), L is the membrane thickness (cm), D is the diffusion coefficient (cm² s⁻¹), I_{ss} is the steady state flow (mol s⁻¹), A is the membrane area (cm²), S is the solubility constant of analyte in the membrane (mol Torr⁻¹ cm⁻³) and P_s is the vapor pressure of analyte in the sample (Torr).

Equation (2) illustrates the fact that the quantity of analyte which permeates a membrane is proportional to the diffusion coefficient. As expected, the trends in detection limits noted in Table 2 correlate in a roughly inverse fashion with the measured diffusion coefficients (Table 3). Note that the diffusivity for the silicone oil was calculated to be equal to that for the alkylated cyclopentane but it gave much higher detection limits. This inconsistency suggests that the silicone oil experiment requires further optimization, although the relatively high noise levels observed with this liquid might also be responsible.

Each of the liquid membranes displayed a linear response with amount of analyte for toluene, benzene, *trans*-1,2-dichloroethylene, chlorobenzene, carbon tetrachloride and nitrobenzene (see r^2 values, Table 3). Figure 3 depicts the toluene response using the polyphenyl ether (similar data were recorded for silicone oil), alkylated cyclopentane and perfluorinated ether membranes. Small memory effects were noted in the per-



Figure 3. Comparison of toluene responses using (A) polyphenyl ether, (B) alkylated cyclopentane and (C) perfluorinated ether membranes. Note rise in baseline for polyphenyl ether and perfluorinated ether but not for alkylated cyclopentane. Perfluorinated ether suffered from memory effects as well as long elution periods. Silicone oil membrane (not shown) gives similar responses to those for polyphenyl ether.

Table 3. 10%-90% rise times and linear dynamic range for toluene

Membrane	10%–90% rise (s)° (±1 std. dev.)	Linear dynamic range (ppb)ª	r ^{2 ь}	Diffusion coefficien (10 ⁻⁷ cm ² s ⁻¹)°
Polyphenyl ether	54 ± 2.0	25-10000	0.99	4.8 ± 0.17
Alkylated cyclopentane	46 ± 1.6	20-1000	0.99	5.3 ± 0.18
Perfluorinated ether	53 ± 6.2	250-10000	0.99	4.6 ± 0.49
Silicone oil	51 ± 0.94	50-10000	0.99	5.3 ± 0.10
Silicone (reference)	35 ± 5.0	6–10000	0.97	15 ± 1.8

^a Linear dynamic range limited by space charging within the ion trap.

 ${}^{b}r^{2}$ calculated from linear regression of calibration.

^e Diffusivity calculated from Eqn (1) using experimental thickness of each membrane.

fluorinated ether and polyphenyl ether at the higher concentrations [see Figs 3(A) and 3(C)], but not with the use of the alkylated cyclopentane, even at ppm concentrations [see Fig. 3(B)]. The toluene response using the polyphenyl ether membrane is shown on an expanded scale in Fig. 4. Quantitation with MIMS was performed through measurement of peak height relative to the baseline preceding the peak in the ion chromatogram. The rise in baseline observed in Figs 3(A) and 3(C) therefore interferes with analyte quantitation and is most prominent when making measurements on solutions of decreasing concentration. The solution to this problem is to incorporate longer periods of time between injections when solutions of widely varying concentrations must be studied. Typically, however, MIMS is used for the quantitation of analytes at the low-ppb and high-ppt level, where such memory effects are negligible. The use of external standards, injected alternatively to the sample, should further improve precision.18

There were no noticeable differences in the mass spectra recorded using different liquid membranes, as may be seen in Fig. 5 which compares toluene mass spectra recorded using polyphenyl ether and alkyated cyclopentane membranes respectively. The mass spectrum of a complex mixture containing toluene, benzene, *trans*-1,2-dichloroethylene, carbon tetrachloride and



Figure 4. Expanded display of toluene response using polyphenyl ether liquid membrane.



Figure 5. Comparison of toluene mass spectra recorded using (A) polyphenyl ether and (B) alkylated cyclopentane membranes inlets. Background subtraction was performed using measurements made immediately prior to the analyte FIA peak.





Figure 6. Mass spectrum of a mixture of 500 ppb benzene (m/z 78), toluene (m/z 91 and 92), *trans*-1,2-dichloroethylene (m/z 96 and 98), carbon tetrachloride (m/z 117, 119 and 121) and nitrobenzene (m/z 123) using a polyphenyl ether membrane.

nitrobenzene is given in Fig. 6, and reproducible spectra were recorded for all four liquid membranes. The corresponding single-ion-monitoring data are displayed in Fig. 7 (polyphenyl ether membrane). Ions of interest in this mass spectrum are benzene (m/z 78), toluene (m/z 91 and 92), trans-1,2-dichloroethylene (m/z 96 and 98), carbon tetrachloride (m/z 117, 119 and 121) and nitrobenzene (m/z 123).

The only liquid membrane tested which gave poor performance was the perfluorinated ether, whose degradation products, contributed significantly to the instrument background (e.g. CF_3^+ at m/z 69). This degradation may be induced by electron beam heating. While not quite suitable for these experiments, perfluorinated ether has been used in air-monitoring experiments³² and alternative versions of this polymer will continue to be of interest.

CONCLUSION

These experiments demonstrate that the liquid membranes chosen have properties which make them competitive with the solid silicone membranes to which they are viable alternatives in MIMS. Further research will



Figure 7. Single-ion monitoring of toluene $(m/z \ 91 \ and \ 92)$, benzene $(m/z \ 78)$, nitrobenzene $(m/z \ 123)$, carbon tetrachloride $(m/z \ 117, \ 119 \ and \ 121)$ and *trans*-1,2-dichloroethylene $(m/z \ 96 \ and \ 98)$ in a mixed sampled using a polyphenyl ether membrane.

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focus on exploiting the ease with which liquids can be spread to provide semi-permeable materials of varying thickness and increased surface area.³⁰

Membrane selectivity is a high priority in the further development of these membranes and will be examined through the addition of high-molecular-weight, nonvolatile compounds to the liquids so as to selectively bind particular organic compounds.²⁹ This might allow one to monitor the products of particular reactions with increased selectivity. This objective serves to highlight the potentially unique properties of liquid membranes, which are not simply substitutes for conventional solid pre-cast membranes.

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