

Perfluorosulfonic Acid Membrane Catalysts for Optical Sensing of Anhydrides in the Gas Phase

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Continuous, on-site monitoring of personal exposure levels to occupational chemical hazards in ambient air is a long-standing analytical challenge. Such monitoring is required to institute appropriate health measures but is often limited by the time delays associated with batch air sampling and the need for off-site instrumental analyses. In this work, we report on the first attempt to use the catalytic properties of perfluorosulfonic acid (PSA) membranes to obtain a rapid, selective, and highly sensitive optical response to trimellitic anhydride (TMA) in the gas phase for portable sensor device application. TMA is used as starting material for various organic products and is recognized to be an extremely toxic agent by the National Institute for Occupational Safety and Health (NIOSH). Resorcinol dye is shown to become immobilized in PSA membranes and diffusionally constrain an orange brown product that results from acid-catalyzed reaction with more rapidly diffusing TMA molecules. FTIR, UV/vis, reaction selectivity to TMA versus trimellitic acid (TMLA), and homogeneous synthesis are used to infer 5,7-dihydroxyanthraquinone-2-carboxylic acid as the acylation product of the reaction. The color response has a sensitivity to at least 3 parts per billion (ppb) TMA exposure and, in addition to TMLA, excludes maleic anhydride (MA) and phthalic anhydride (PA). Solvent extraction at long times is used to determine that the resorcinol extinction coefficient in 1100 EW PSA membrane has a value of 1210 m²/g at 271.01 nm versus a value of 2010 m²/g at 275.22 nm in 50 vol% ethanol/water solution. The hypsochromic wavelength shift and reduced extinction coefficient suggest that the polar perfluorosulfonic acid groups in the membrane provide the thermodynamic driving force for diffusion and immobilization. At a resorcinol concentration of 0.376 g/L in the membrane, a partition coefficient of nearly unity is obtained between the membrane and solution concentrations and a maximum conversion rate of one ambient TMA molecule for every two membrane-immobilized resorcinol molecules is observed in 15 min.

Trimellitic anhydride (TMA) is used as starting material for various organic products.¹ Worldwide, approximately 100 000 t/year of TMA is produced out of which 65 000 t are produced in the U.S. In the U.S., 65% of TMA produced is used in the polymer industry as a synthesis plasticizer for polyvinyl chloride (PVC)

resins. These plasticizers have various applications including automotive parts, wire/cable insulations, and medical equipment.²

The National Institute for Occupational Safety and Health (NIOSH) recognizes TMA to be an extremely toxic agent, as exposure may result in noncardiac pulmonary edema without warning. NIOSH estimates about 20,000 workers in the U.S. have developed occupational illnesses due to TMA exposure in various applications and processes.^{2,3}

Occupational exposures to TMA or its hydrolysis product, trimellitic acid (TMLA), mainly occur through inhalation and dermal routes. TMA is readily converted into TMLA in the body. The toxicity of TMLA is most likely to have the same health effects as that of TMA, as both have similar chemical properties and are known to cause mild skin and severe eye irritation.² However, clinical studies investigating TMA exposure in workers have found that this chemical may also act as a hapten, which can bind to endogenous proteins causing respiratory sensitization that can lead to asthma and other immunologic respiratory disorders.² TMA's principal immunologic effect on the lungs and skin has been confirmed in animal inhalation studies. Workers exposed to TMA commonly develop elevated TMA-specific IgG and IgE antibody responses, which appear to be exposure related and are believed to be a precursor to clinical illness.² NIOSH has established a recommended exposure limit (REL) for TMA of 0.005 ppm in air (40 µg/m³) as a time-weighted average for up to a 10-h workday and a 40-h workweek.⁴ The American Conference of Governmental Industrial Hygienists (ACGIH) has assigned TMA a ceiling limit value of 40 µg/m³, which should not be exceeded during any part of the working exposure.⁵ Immunosurveillance programs designed to identify TMA-exposed workers with early signs of TMA induced-illness are ongoing in order to allow for quick removal of these individuals from further exposure. This approach, which depends on routine TMA air monitoring of workers, has resulted in a significant reduction in TMA-induced occupational illness.²

The most accurate methods for TMA detection presently involve batch air sampling followed by gas chromatography (GC)

(2) www.inchem.org/documents/sids/sids/TLANA.pdf (2002).

(3) http://www.cdc.gov/NIOSH/78121_21.html (1997).

(4) Recommendations for occupational safety and health: Compendium of policy documents and statements. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Cincinnati, OH, DHHS (NIOSH) Publication No. 92–100, 1992.

(5) *Threshold limit values for chemical substances and physical agents and biological exposure indices*; American Conference of Governmental Industrial Hygienists: Cincinnati, OH, 1994–1995; p 35.

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(1) <http://www.osha.gov/SLTC/healthguidelines/trimelliticacidanhydride/recognition.html> (1996).

with flame ionization detection,^{6,7} high performance liquid chromatography (HPLC),^{8,9} or complex chemical derivatization schemes.^{6,10} Unfortunately, such instrumentation and capability is rarely available on worksites and substantial time typically elapses from the time a sample is collected to the time when the results are reported back so that appropriate interventions could be implemented. Furthermore, ambient air analysis is often found to poorly correlate with the actual personal exposure levels of highly exposed workers. Consequently, because it is presently not possible to continuously monitor personal exposure levels, it is difficult to institute appropriate exposure health standards or assess the effectiveness of remediation measures on an ongoing basis.

The incorporation of optically responsive dyes into polymeric membranes has been extensively investigated for various sensing applications requiring rapid response times.^{11–19} The use of lipophilic dye analogues^{11,12} as well as high molecular weight dyes¹³ can make these membrane–dye systems particularly durable. However, only ion exchange sensing mechanisms have been explored that have limited application to vapor-phase detection. For example, protonation and deprotonation of dyes incorporated into perfluorosulfonate ionomer (PFSI) membranes has been used both for the measurement of water content in alcohols¹⁴ and ionic liquids¹⁵ and for the quantification of ammonia vapor and/or humidity in air.^{16–19}

Protonated PFSIs (or perfluorosulfonic acids, PSAs) are superacids which can replace solid acid catalysts in heterogeneous organic synthesis.^{20,21} Reactions to which PSAs have been applied include esterification,²² dehydration,^{23,24} Friedel–Crafts aromatic alkylation and acylation,^{25–28} hydrocarboxylation,²⁹ and dimer-

ization.³⁰ In these applications, PSAs are typically dispersed over porous silica and zeolite supports. The use of PSAs as a solid catalyst between dye molecules and organic vapor to yield a color response has never been previously explored.

In this work, we demonstrate that it is possible to react TMA from the gas phase with the resorcinol dye in the presence of PSA as a solid acid catalyst to yield a highly sensitive and selective response in the visible region of the electromagnetic spectrum. We describe the characteristics of this response as well as the identification of the responsible product molecule.

EXPERIMENTAL SECTION

Resorcinol dye was imbibed into PSA membrane by immersing Nafion membrane (Aldrich, Nafion 117, protonated perfluorinated membrane, 0.007 in. thick) into a 50 vol% solution of ethanol (Acros Organics, ≥95% purity, ACS spectrophotometric grade) in deionized (DI) water containing 0.400 g/L resorcinol (Acros Organics, 98%). This solution concentration is well below the solubility limit for resorcinol (58.4 wt % to 61 wt % at 20 °C).³¹ DI water was obtained by passing the house water supply through a Millipore Synthesis unit until 18.2 MΩ cm resistivity was achieved. UV/vis (Ocean Optics HR 2000+ CG-UV-NIR High-Resolution Spectrometer, 1 cm path length through a quartz cuvette) was employed to monitor resorcinol solution spectra before and after dye incorporation into the membrane to both confirm negligible depletion of solution concentration and to determine the Beer–Lambert Law extinction coefficient of the dye.

PSA membranes were immersed in dye solution for 31 min and then rinsed with DI water followed by air drying at room temperature. UV/vis was employed for ex situ monitoring of dye uptake into membrane. Resorcinol incorporation was found to be very stable, with extraction of the imbibed dye requiring long immersion times (24–48 h) in ethanol–water solution. Such extraction was used to independently determine the dye concentration in the membrane and also assess changes to the resorcinol Beer–Lambert Law extinction coefficient relative to the solution. Removal of dye from the membrane was confirmed using UV/vis. The dimensions of the dried membrane samples were maintained constant for all measurements (0.6 cm length, 2 cm width, and 0.0178 cm thickness). For all UV/vis measurements in this study, a minimum of two replicates was used to obtain an average at each concentration. The associated standard deviation is indicated by the error bars in the figures.

The three anhydrides used in this study were TMA (Acros organics, 1,2,4- benzenetricarboxylic anhydride, 97%), PA (Acros organics, phthalic anhydride, 99%), and MA (Acros organics, maleic anhydride, 99%). The maximum anhydride vapor pressures investigated were 0.0013 kPa for TMA (100 ppm exposure at 170 °C in air), 0.0038 kPa for PA (230 ppm exposure at 170 °C in air), and 0.75 kPa for MA (30000 ppm exposure at 170 °C in air). Since these maxima were well below the saturation vapor pressures^{32–34}

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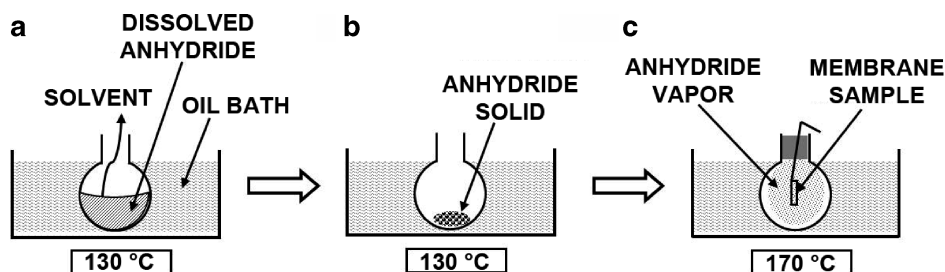


Figure 1. Schematic of the experimental procedure. Flask containing analyte dissolved in solvent is immersed in oil bath as shown in part a at a temperature (130 °C) sufficient to evaporate the solvent but leave behind the solid anhydride as shown in part b. After 30 min, a dyed membrane is suspended into the flask on a freshly gold-coated metal strip. The flask is then tightly closed with a Teflon stopper and immersed into a second oil bath at the temperature required to melt and volatize the solid (170 °C) as shown in part c. The membrane removed after 15 min exposure in this second bath.

at 170 °C (0.085 kPa for TMA, 42.7 kPa for MA, and 34.3 kPa for PA), complete evaporation of each anhydride was assumed at this temperature. Control data were obtained by exposing the resorcinol-imbibed membranes to precisely the same conditions but in the absence of anhydride in the surrounding environment. Each membrane was exposed to the desired environmental conditions using the procedure diagrammed in Figure 1.

Exposure of the membranes to ppb levels of TMA and PA anhydride vapor was achieved by successive dilution of the anhydride solid in acetone (Sigma-Aldrich, ACS spectrophotometric grade, $\geq 99.5\%$ purity). FTIR (DIGILAB, FTIR Excalibur series) was employed to confirm the absence of hydrolysis to the acid anhydride during this process. At the end of the series dilution, a volume of 100 μL of anhydride solution at the desired concentration was pipetted into a 500 mL flask. The flask was immersed into an oil bath (Fisher Scientific, Model 9501), and the solvent evaporated at a temperature of 130 °C (below the melting point of the TMA and PA). A membrane of consistent dimensions (0.6 cm \times 2 cm) was attached using Teflon tape (FLUOKEM Teflon Resin Lab-Thread Tape SCIENCEWARE) to the end of a thin sliver of stainless steel freshly coated with electroplated gold and suspended from a Teflon stopper which was used to seal the end of the flask. The sealed flask was then immersed at an equilibrated oil bath temperature of 170 °C (above the melting point of each solid), and the anhydride allowed to volatize. For the MA exposures, a sample of the solid anhydride was weighed and placed directly into the flask, eliminating the solvent evaporation step. The membrane was suspended and sealed in the flask and immersed into an oil bath at 170 °C for 15 min. A visible membrane color change was observed in the presence of *both* immobilized resorcinol and anhydride in the flask that persisted upon removal to ambient laboratory conditions. UV/vis and FTIR spectra of the samples were obtained *ex situ* and were found to be invariant with time for at least one week in ambient.

RESULTS AND DISCUSSION

Optical Sensitivity to TMA Exposure. UV/vis spectra of 0.0266 g/L resorcinol dye in ethanol/water solution (after subtraction of the pure ethanol/water background, 1 cm path length) and that of PFSI membrane after 31 min uptake from 0.400 g/L resorcinol in ethanol/water solution (with membrane background

subtracted, 0.0178 cm path length) are shown in Figure 2. We note that the peak wavelengths positions in the solution spectra are similar to existing literature data for resorcinol.³⁵

There are two characteristic peaks associated with the presence of resorcinol in the solution spectra at 219.38 and 275.22 nm as shown in Figure 2. Calibration of the lower intensity peak at 275.22 nm was used to quantify the solution concentrations in subsequent extraction studies to permit application to a broader range of concentrations without signal saturation. The inset in Figure 2 depicts absorption at a wavelength of 275.22 nm versus concentration for resorcinol in 50% aqueous ethanol solution from which a Beer–Lambert Law extinction coefficient of 2010 m^2/g is obtained using linear regression (correlation coefficient is 0.997).

To calculate the resorcinol extinction coefficient and concentration in the membrane, extraction studies were performed as described in the Experimental Section. Figure 3 shows the UV/vis spectra of a membrane originally exposed to 3 g/L resorcinol solution before and after extraction as well as the spectrum of the solution into which the dye was extracted (PSA background is subtracted). In both Figure 2 and Figure 3, we note that the wavelength of the lower intensity resorcinol peak shifts from 275.22 nm in solution to 271.01 nm in the membrane. This hypsochromic shift is associated with an increase in the polarity of the environment of the dye molecule.^{36,37}

The inset of Figure 3 is the Beer–Lambert plot of the absorbance of the membrane at 271.01 nm versus the resorcinol concentration. A membrane-immobilized resorcinol extinction coefficient of 1210 m^2/g is computed using linear regression (correlation coefficient is 0.981) as compared to the solution value of 2010 m^2/g . The extinction coefficient is governed by the size of the absorbing system and the probability of the associated electronic transition.³⁷ Here, the smaller membrane-phase extinction coefficient reflects reduced probability of light absorption by immobilized resorcinol and suggests a high degree of intermolecular interaction with the membrane. Such behavior, coupled with the hypsochromic shift previously noted, indicates that the polar environment associated with the perfluorosulfonic acid groups in the membrane provides the

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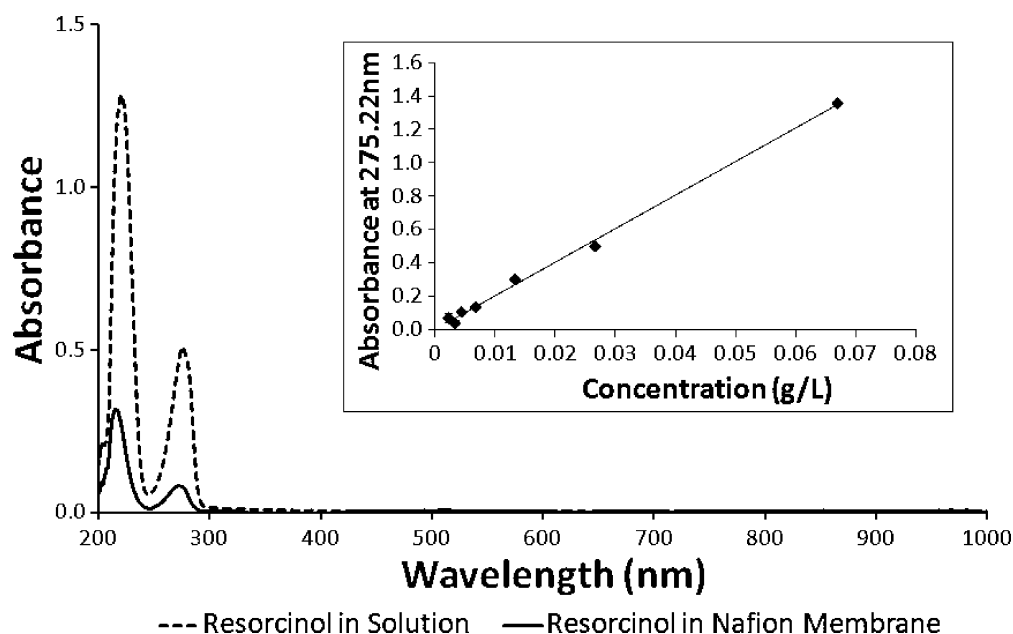


Figure 2. UV/vis spectra of resorcinol in solution with ethanol (0.0266 g/L, dashed line) and in PSA membrane (0.376 g/L, solid line) after equilibration of uptake (PSA background is subtracted). The inset shows light absorption at 275.22 nm versus solution concentration of resorcinol.

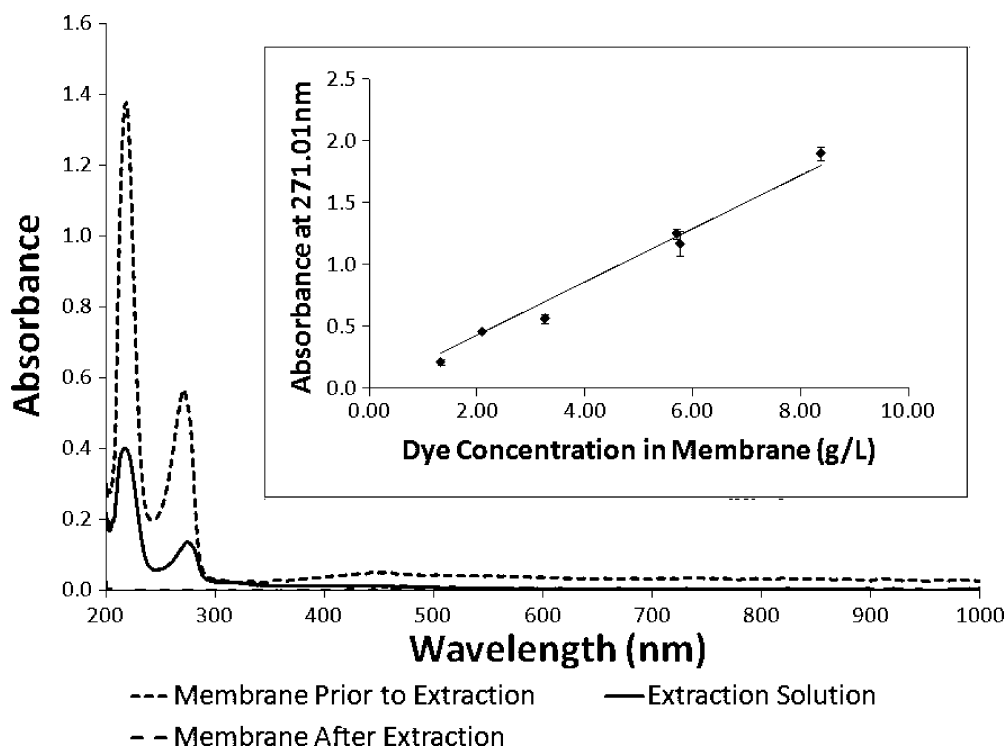


Figure 3. UV/vis spectra of resorcinol in extracted solution (dashed line) and in PSA membrane before (solid line) and after extraction (dashed line) (PSA background is subtracted). The membrane is prepared from 3 g/L dye solution. The inset shows light absorption versus resorcinol membrane concentration.

thermodynamic driving force for resorcinol diffusion and immobilization.

Figure 4 shows the time-invariant UV/vis spectra of a PSA membrane containing 0.376 g/L (about 188 ppm) resorcinol after exposure to various levels of TMA as described in the Experimental Section (where the PSA background has been subtracted).

The partition coefficient between the resorcinol membrane and solution concentrations for this membrane was found to be nearly unity. The inset in Figure 4 shows the change in light absorbance with exposure level at 375.28 nm (UV) and 443.05 nm (VIS), where the average and standard deviation for a minimum of two samples is provided at each concentration.

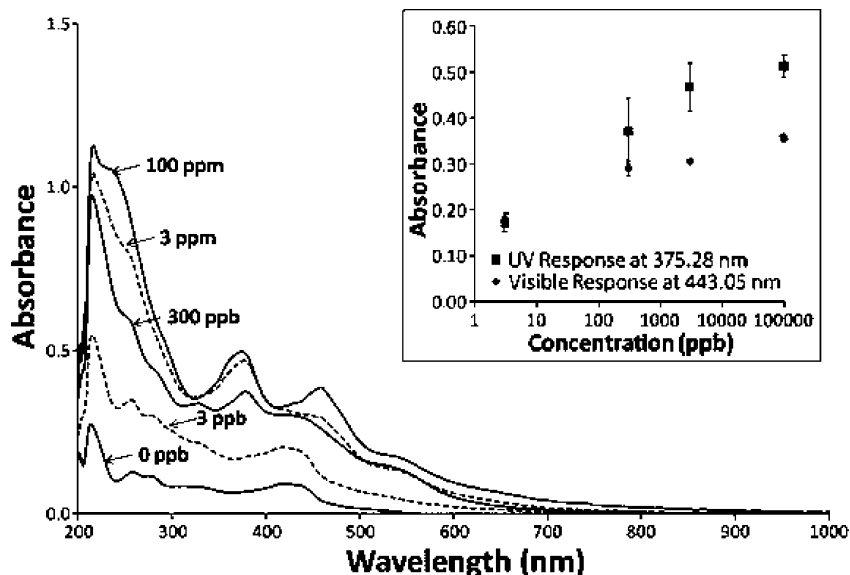


Figure 4. UV–vis spectra of resorcinol-dyed PSA membranes after exposure to various concentrations of TMA (PSA background subtracted). The inset shows variation of light absorption versus concentration at two wavelengths.



Figure 5. Appearance of the resorcinol-dyed PSA membranes exposed to various concentrations of TMA. Left to right: 0 ppm, 3 ppb, 3 ppm, 100 ppm.

A distinct red color shift is observed in the spectra, as shown in Figure 4, and is reflected in the visible appearance of the dyed membranes after exposure, as shown in Figure 5, versus a control sample (no anhydride exposure but otherwise subjected to same procedure). An increase in light absorption at 443.05 nm with increasing TMA exposure is observed in the inset of Figure 4 that is consistent with the increase in sample color intensity as shown in Figure 5. In the more intensely absorbing UV region at 375.28 nm (yet still well below saturation), the data in the inset of Figure 4 indicates that a plateau conversion is reached as TMA exposure approaches 100 ppm, suggesting a maximum response rate of roughly 1 ambient TMA molecule for every 2 resorcinol molecules in 15 min for this immobilized resorcinol concentration. Most significantly, we note from Figures 4 and 5 that the membrane remains responsive down to 3 ppb TMA exposure or less, indicating a high degree of accessibility to sensitized sites, despite resorcinol's immobilization within the acidic clusters of the PSA membrane.

The color change was found to be irreversible when the membrane was removed from TMA exposure for as long as three months. Interestingly, no spectral response whatsoever was observed when the membrane did not contain resorcinol under the same TMA exposure conditions. Such behavior suggests that TMA diffuses much more rapidly within the membrane than does resorcinol, despite the substantially larger size of the TMA molecule (see Scheme 1). One explanation for this behavior may be the presence of twice as many hydroxyl groups on resorcinol

that enhance the polar interactions with the membrane that were previously linked to changes in the resorcinol spectrum when immobilized.

Identification of Product and Selectivity versus TMLA.

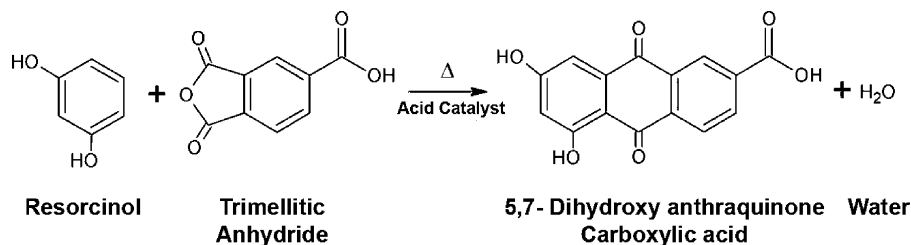
FTIR spectra complementary to the UV/vis results shown in Figure 2 are provided in Figure 6. The unexposed dye-impregnated PFSI membrane background has been subtracted from these spectra.

From Figure 6, we note a substantial increase in the presence of carbonyl groups with increased TMA exposure. Such data, combined with the color change observed, suggests that membrane optical activity results from the acid-catalyzed Friedel–Crafts acylation of resorcinol with the anhydride to form the product (5,7- dihydroxyanthraquinone-2-carboxylic acid) according to Scheme 1. From the literature, the para form of this compound is an orange brown color,³⁸ which coincides with a red color shift in the spectra. Product concentrations in the membrane are too low to permit validation using solid-state NMR. Direct chemical confirmation of the product in Scheme 1 could hypothetically be achieved by extraction from the membrane. However, this entails the risk of product degradation, and efforts along these lines are ongoing. In lieu of product isolation, we have conducted homogeneous solution-phase syntheses utilizing dissolved Nafion (1100 EW) as the acid catalyst and confirmed that the spectral response (both UV/vis and FTIR) observed in the membrane could only be obtained under similar conditions when *both* resorcinol and TMA are present.

To provide additional indirect evidence for Friedel–Crafts acylation as the optical response mechanism, dye-impregnated membrane was exposed to TMLA by first hydrolyzing the anhydride in water. According to Scheme 1, membrane-immobilized resorcinol should not yield any color response in the visible region of the electromagnetic spectrum due to the presence of (transparent) TMLA. An acetone/water mixture was used for

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Scheme 1. Friedel–Crafts Acylation with Trimellitic Anhydride



series dilutions in place of pure acetone. Figure 7 depicts the FTIR spectra of 50 g/L anhydride in a 50/50 acetone/water mixture versus pure acetone (with the solvent used as background). We note clearly in the figure the appearance of carboxylic acid groups

indicating anhydride ring-opening to form TMLA in the presence of water. Exposure of dye-impregnated membrane to as high as 3000 ppm TMLA did not yield any color response in the visible region of the electromagnetic spectrum, consistent with Scheme 1.

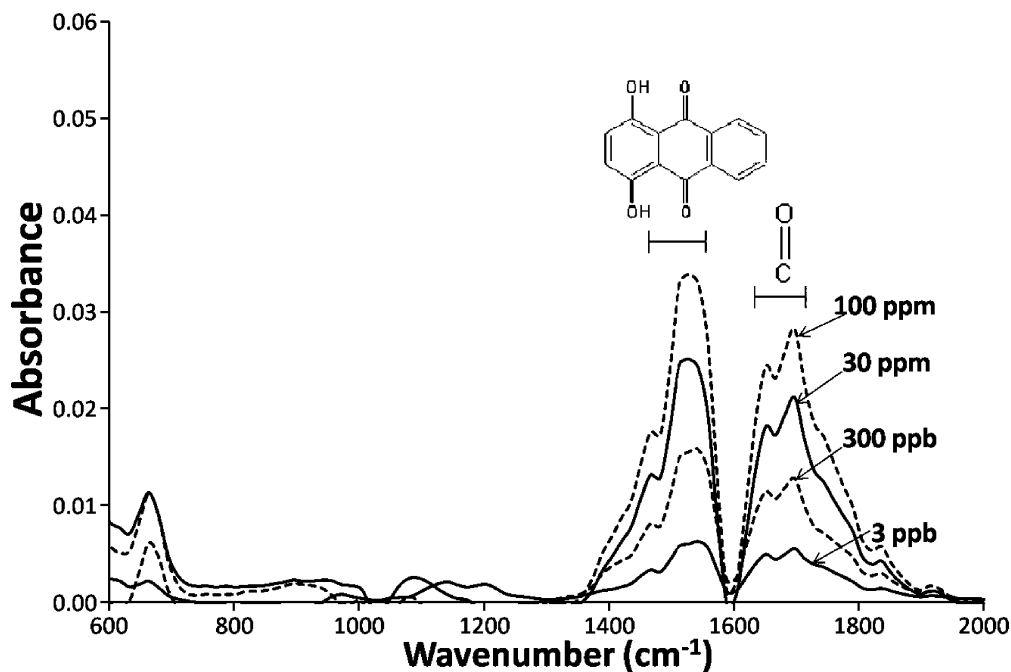


Figure 6. FTIR spectra of resorcinol-dyed PSA membranes after exposure to various concentrations of TMA (resorcinol-imbibed PSA background subtracted).

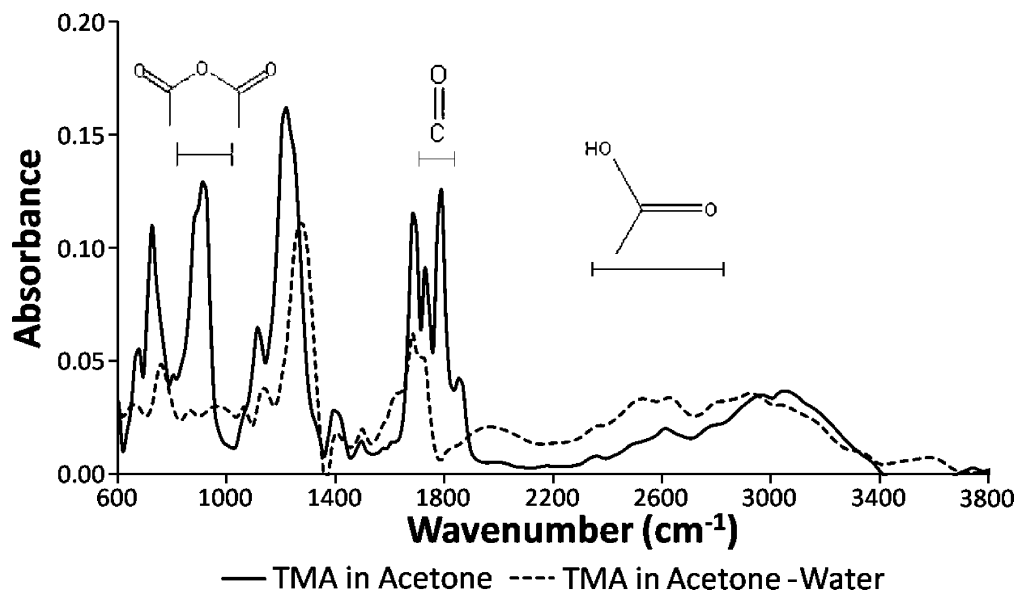


Figure 7. FTIR spectra of TMA in acetone/water mixture (dashed line) versus pure acetone (solid line).

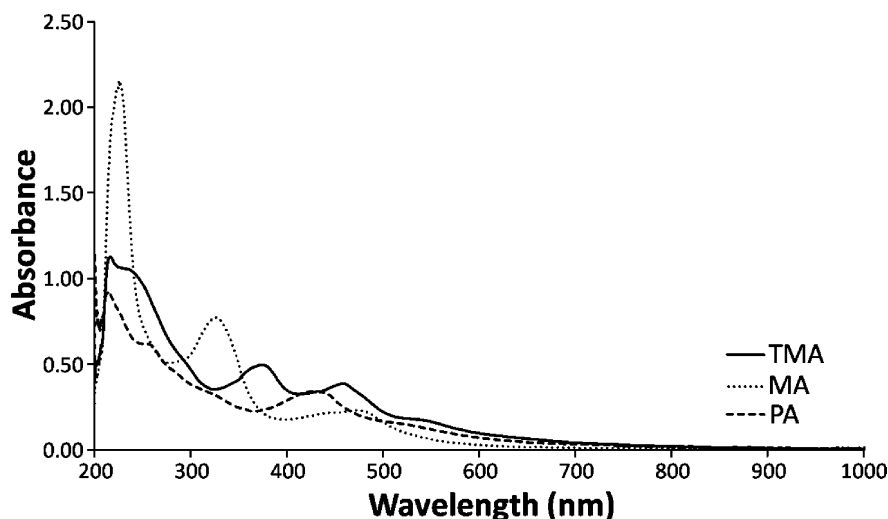
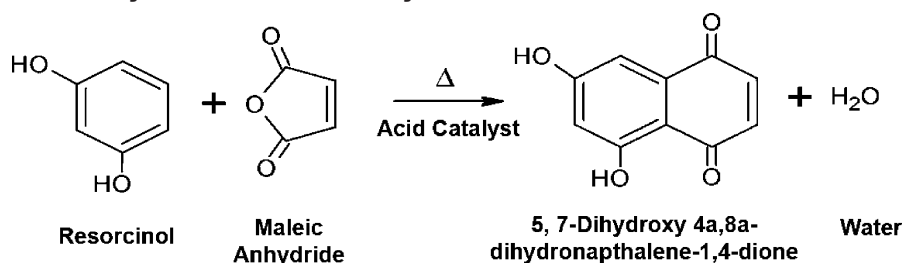
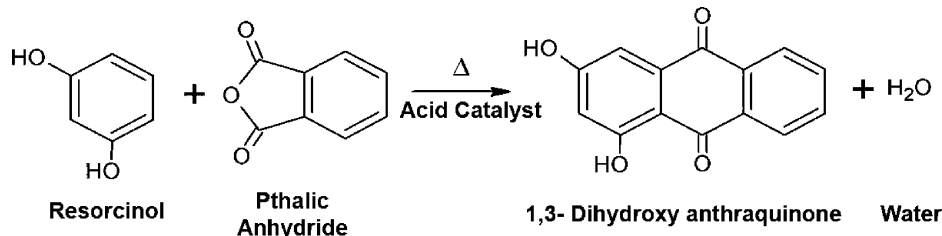


Figure 8. UV-vis spectra resorcinol-dyed PSA membranes after exposure to various anhydrides (resorcinol-imbibed PSA background subtracted).

Scheme 2. Friedel-Crafts Acylation with Maleic Anhydride



Scheme 3. Friedel-Crafts Acylation with Phthalic Anhydride



Selectivity versus Other Anhydrides. The selectivity of this unique sensing approach was next evaluated by comparing the dyed membrane exposure to 30 000 ppm of maleic anhydride (MA) vapor, 230 ppm of phthalic anhydride (PA) vapor, and 100 ppm of TMA vapor, all at 170 °C. The selectivity comparison was made at a high concentration for MA since acetone has a boiling point close to the melting point of MA. Thus, series dilutions could not be employed with this solvent in the case of MA, and exposure was instead achieved by melting the solid MA directly in the flask. A comparison of the resultant UV/vis spectra is shown in Figure 8. Despite the functional group similarity of TMA, MA, and PA, a distinct difference in optical response is observed, suggesting the formation of a unique product according to the Friedel-Crafts acylation reactions proposed in Schemes 2 and 3.

Tentative identification of the MA-resorcinol and PA-resorcinol reaction products based on FTIR and UV/vis are 5,7-dihydroxy-4a,8a-dihydronaphthalene-1,4-dione and 1,3-dihydroxyanthraquinone.³⁸ In occupational settings, neither PA nor MA are present simultaneously with TMA. Only TMLA convolutes the standard off-line analysis using HPLC. We have previously shown that immobilized resorcinol is insensitive to TMLA, consistent with

Friedel-Crafts acylation being the optical response mechanism. PA and MA are evaluated in this work primarily to demonstrate the unique color response that may be achieved using membrane-catalyzed reactions of dyes.

Practical Considerations. A membrane color response to TMA exposure as low as 1 ppb has been detected using the catalytic membrane approach described in this study. However, the spectra were not sufficiently reproducible utilizing our experimental procedure to include in Figure 4. Nevertheless, the intensity of the color response at 3 ppb (Figure 5), coupled with a relative absorbance of 0.172 at 443.05 nm (Figure 4), suggests the potential for sub-ppb sensitivity using this approach. Future work must use HPLC or GC analyses of TMA in ambient air in order to calibrate the sensor response from sub-ppb to ppb levels as opposed to the successive dilution scheme we used in the present study. Furthermore, the impact of imbibed resorcinol concentration on the TMA conversion rate must be more closely investigated to determine whether TMA sensitivity may be enhanced. For now, we can only confirm that the detection limit of this approach is 24 $\mu\text{g}/\text{m}^3$, or just below the recommended NIOSH and ACGIH exposure (40 $\mu\text{g}/\text{m}^3$). Whereas this limit

is higher than that of existing methods ($0.623 \mu\text{g}/\text{m}^3$ for 480 L of air at 2.0 L/min in the case of HPLC³⁹ and $0.6 \mu\text{g}/\text{m}^3$ for 12 L of air at a sampling rate of 0.2 L/min in the case of GC⁴⁰), the catalytic membrane approach offers portability, continuous monitoring, and the advantage of TMA versus TMLA discrimination.

It is important to also note that any practical device using this catalytic membrane approach to monitor occupational TMA exposure must be able to heat ambient air to the elevated temperature required to volatilize the TMA aerosol (170 °C) before passing it over the resorcinol-imbibed membrane. However, prolonged exposure of the membrane to this temperature causes discoloration that interferes with TMA detection, and therefore the device must also be capable of accurately limiting exposure time (not more than 30 min). Since membrane discoloration is also observed even at room temperature after one week, any practical device must further incorporate a reference signal with which to screen out membranes that have exceeded their useful lifetime. Refrigeration of the resorcinol-imbibed membranes is found to extend their lifetime. Despite these limitations, miniature resistive heating elements and fans, light-emitting diodes (LEDs: red, green, blue, and white), charge-coupled imaging devices (CCDs), carousel-type membrane holders, and microprocessors are available to fabricate small devices suitable for personal monitoring applications using this new technology.

CONCLUSIONS

In this paper, optical activity in the visible region of the electromagnetic spectrum utilizing an acid-catalyzed reaction between an immobilized dye molecule and an ambient gas-phase hazard has for the first time been demonstrated using PSA membranes. Sensitivity to 3 ppb TMA exposure has been observed

with high selectivity relative to TMLA, PA, and MA. Resorcinol was used as the dye molecule, and immobilization within the hydrophilic clusters of the membranes was associated with a hypsochromic wavelength shift from 275.01 nm for the low intensity peak in ethanol–water solution to 271.22 nm in the membrane. This shift was accompanied by a reduction in the Beer–Lambert Law extinction coefficient from $2010 \text{ m}^2/\text{g}$ in ethanol–water solution to $1210 \text{ m}^2/\text{g}$ in the membrane, suggesting substantial interaction between the dihydroxybenzene and the PSA clusters. The proposed product of the reaction, 5,7-dihydroxyanthraquinone-2-carboxylic acid, is found to be consistent with a combination of FTIR and UV/vis spectra, TMLA response studies, and homogeneous synthesis data in the case of the TMA–resorcinol reaction, indicating Friedel–Crafts acylation as the optical response mechanism. However, extraction studies for direct chemical confirmation without damaging the product are ongoing. At a resorcinol concentration of 0.376 g/L in the membrane, a partition coefficient of nearly unity is obtained between the membrane and solution concentrations, and the maximum conversion rate observed was one ambient TMA molecule for every two membrane-immobilized resorcinol molecules in 15 min.

We are currently in the process of applying this methodology to develop cost-effective, compact devices for personal health monitoring of anhydride exposure at worksites as well as to measure surrogate chemical markers for diabetes, chronic obstructive pulmonary disease (COPD), and asthma.

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