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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
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Abstract

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Our research targets an important concept in materials science and protection chemistry: to develop a matrix that entraps undesirable or dangerous molecules, then catalytically decontaminates the entrapped compound(s) using the ambient environment – the O_2 in air at room temperature. Mustard is a highly toxic chemical warfare agent that our group has focused on decontaminating. Recently our group and our collaborators demonstrated that an appropriate mixture of tribromide and nitrogen oxide species, "Br_x/NO_x", selectively oxidizes mustard and its simulant, 2-chloroethyl ethyl sulfide (CEES) using air (O_2). To safely study these air-based oxidations in our laboratory, we used CEES (CEES and mustard have similar structures and properties). One of the fundamental steps in the decontamination of CEES is to find a polymer that has a high affinity for and can entrap high quantities of this sulfide. Swellable hyper-cross-linked polymers (HCP) have been tested for their ability to entrap CEES. We have successfully entrapped CEES in a fluorobenzene-based HCP, HCP-F, and previous co-workers have incorporated the Br_x/NO_x catalytic system into it. Because HCP-F has shown a high affinity to CEES, it is assumed that some of the CEES could be trapped in the pores during CEES oxidation experiments. Therefore, modifications to the CEES oxidation procedure have been explored to account for the lower CEES concentrations. More recently, Br_x/NO_x has been incorporated into HCP-SO_3 (another HCP with a different and strongly acidic functional group), and CEES oxidation experiments have been performed. Both systems selectively produce the most desirable (least toxic) oxidation product, the corresponding sulfoxide, CEESO. The gelation ability of HCP-F and HCP-SO_3 was assessed using common laboratory solvents by measuring the extent of their swellability.

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INTRODUCTION

World War I (WWI) laid the foundation of modern warfare by the use of science to produce mass destruction weapons such as chemical warfare agents (CWA).[1] Bis(2-chloroethyl sulfide) (HD), known as mustard gas, was the most used CWA in WWI, and caused 70% casualties for those exposed to it.[2,3] Even though HD is not as lethal as other CWAs, it was heavily used because of its vesicant properties.[4] Many suffered permanent damage from eye, lung and skin lesions.[5] The threat of the HD release still exists despite treaties restricting the use of CWAs. [6,7] In recent years, there have been reports of the production, use, and storage of HD.[8] Methods such as hydrolysis and oxidation have been suggested for the removal of HD. The effectiveness of hydrolysis is limited because HD is not soluble in water. HD oxidation could potentially produce several products, one of which, bis(2-chloroethyl sulfoxide (HDO) is less toxic than the corresponding sulfone, bis(2-chloroethyl sulfone (HDO_2) and other products.[6] To resolve this issue, catalytic systems have been studied to partially oxidize HD selectively to HDO.[6,10]

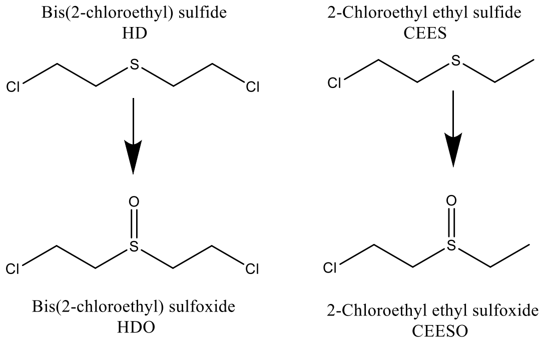


Figure 1. Oxidation of HD and CEES to the least toxic products, the corresponding sulfoxides.

A wide range of oxidants can oxidize HD.[8] It is essential to develop a system that can easily be used by the military in case of HD release.[7] The Br_x/NO_x is an attractive catalyst for HD oxidation because it is inexpensive, environmentally friendly and catalyzes selective sulfoxidation using only air/O_2 as the oxidant.[8-10] It rapidly and selectively converts HD to HDO. Experiments conducted with chloroethyl ethyl sulfide (CEES), a safer analogue of HD, also show selective conversion to the desired product, chloroethyl ethyl sulfoxide (CEESO) in very high selectivity.[8-10] Subsequently, experiments Br_x/NO_x and HD have also shown the very selective air-based (aerobic) conversion of HD to HDO.[10] However, liquid systems are impractical in the field, therefore, researchers have worked on solid heterogenous systems to oxidatively remove CEES.[10] Hyper-cross-linked polymers (HCP-R) are a class of porous materials that have received much attention because of their swelling ability, which enables them to entrap or sequester gases and solvents.[11-15] HCPs have also demonstrated stability in harsh acidic conditions. HCP-R properties, such as swelling, are determined by the functional groups (R), and the number of bonds between the monomers.[12]

Previous co-workers in the Hill group recently incorporated the Br_x/NO_x catalytic system into a fluorobenzene-based HCP (HCP-F) for the entrapment and catalytic removal of CEES. Because HCP-F has shown a high affinity to CEES, it is assumed that some of the CEES could be trapped in the pores during CEES oxidation, resulting in partial oxidation to CEESO. Therefore, modifications to the CEES oxidation procedure have been explored to account for the lower CEES concentrations. Materials, such as the HCP-R derivatives, in which both substrate and product are retained well in the matrix, makes quantitative analysis of CEES oxidation process problematical. As a consequence, the Hill lab recently incorporated Br_x/NO_x into a sulfonic acid HCP (HCP-SO_3) as well. HCP-SO_3 is promising because it does not show lower CEES concentrations due to entrapment, and it does not require the addition of the acidic catalytic component. The latter is a significant point because acid is a co-catalyst in these aerobic oxidations catalyzed by Br_x/NO_x.

The ability of both HCP-SO_3 and HCP-F to swell, thus entrapping various liquids, was evaluated using frequently-used organic solvents.

EXPERIMENTAL (MATERIALS AND METHODS)

HCP-F synthesis

Under the flow of nitrogen, the fluorobenzene monomer (10 mmol) was added to 1,2-dichloroethane (126 mmol), formaldehyde dimethyl acetal, FDA (20 mmol) and iron(III) chloride (20 mmol) to form the fluorobenzene-based HCP (HCP-F). This reaction mixture was heated to 80 ^{o}C for 18 hours under reflux. Afterwards, the product was washed with methanol several times and purified by Soxhlet extraction for 18 hours. When the Soxhlet extraction was finished, the product was dried in a vacuum oven for 18 hours at 60 ^{o}C.[16]

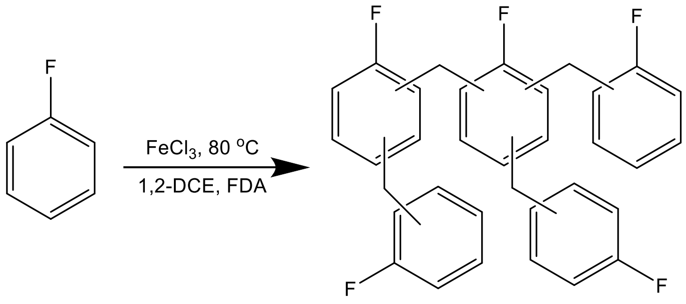


Figure 2. HCP-F synthetic scheme

HCP-SO_3 synthesis

This polymer was prepared in a manner similar to that for HCP-F above. Toluene (20 mmol) was added to FDA (60 mmol), 1,2-dichloroethane (252 mmol) and iron(III) chloride (40 mmol) under a flow of nitrogen. The mixture was stirred and heated to 80 ^{o}C for 24 hours under reflux. The product was washed with methanol several times, then purified by Soxhlet extraction for 24 hours. This partially-purified polymer (2 g) was treated, sequentially, under stirring conditions with DI water (200 mL), ethanol (100 mL), $KMnO_4$ (2.8 g), and NaOH (2 M,15 mL), heated to 80 ^oC for 48 hr under reflux, then washed with HCl, followed by DI water and dried in air.[17] Methylene chloride (150 mL) was added to the product (3 g) in a 250 mL round bottom flask and stirred for 30 minutes. The round bottom flask was placed in an ice-water bath and chlorosulfonic acid (36 mL) was added dropwise. The mixture was left to stir at room temperature for 5 days. Afterwards, the mixture was transferred to a beaker containing water (1L) and stirred for 12 hours. The material was collected by filtration and washed several times with methanol to neutralize the residual acidity.[18]

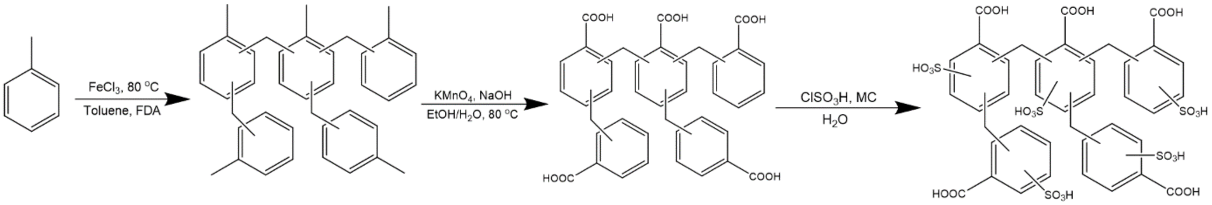


Figure 3. HCP-SO_3 synthetic scheme

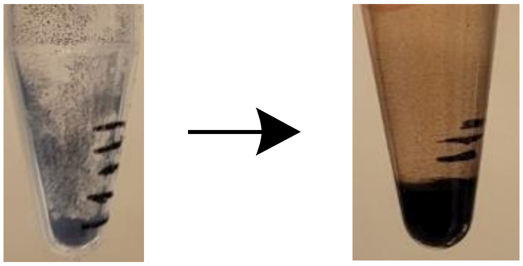
Preparation of the Br_x/NO_x catalyst

Acetonitrile solutions 100 mM in tetrabutylammonium tribromide ($TBABr_3$), 200 mM in tetrabutylammonium nitrate ($TBANO_3$), and *p*-toluenesulfonic acid (*p*-TsOH) were prepared at room temprature.[10] After swirling each component, a pasteur pipette was used to transfer 200µL of these acetonitrile solutions that were equivalent to the following quantities: $TBABr_3$ (0.02 mmol), $TBANO_3$ (0.04 mmol), and *p*-TsOH (0.04 mmol) to HCP-F, and $TBABr_3$ (0.02 mmol) and $TBANO_3$ (0.04 mmol) to HCP-SO_3. After the addition of the catalyst, the HCPs were left overnight at room temperature to enable the acetonitrile to evaporate.

HCP swelling (gelation) studies

Various methods were used to confirm that the degree of solvent-induced swelling (gelation) was measured correctly. The method that produced the most accurate results involved measuring the volume difference of HCP-F before and after swelling. Volumes with an interval of 0.05mL were measured using water and marked on an Eppendorf tube. Samples of ground HCP-F were filled to the 0.025mL mark and were weighed before swelling. Then 1.5 mL of the solvent was added, the Eppendorf tube capped and the system left overnight at room temperature. The final volume of the HCP-F was recorded, and the swelling quotient was calculated using the following equation: (V_f-V_i)/weight and reported in units of mL/g (V_f and V_i are the final and initial volumes of these functionalized polymers).

A modification of these swelling evaluations: Quantitative assessment of the ground HCP-SO$_3$ swelling was difficult using Eppendorf tubes or NMR tubes because the HCP-SO$_3$ powder is attracted to the plastic/glass sides of these tubes. Therefore, HCP-SO$_3$ (20 mg) was added to a glass pipette outfitted with a plug of glass wool. The solvent was added to HCP-SO$_3$ and left for 24 hours at room temperature to allow excess solvent to pass through the glass wool. The pipette and HCP-SO$_3$ were weighed before and after the addition of solvent. The volume of the solvent was found using the density. The swelling quotient was calculated as above.



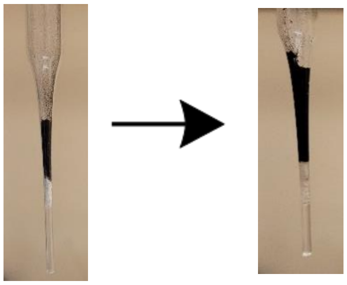


Figure 4. Photographs of the tubes used in quantitative swelling assessments. Top: HCP-F set-up; bottom: HCP-SO_3 set-up.

Swelling of HCP-F containing the Br_x/NO_x *Catalyst*

Swelling tests on HCP-F with Br_x/NO_x used the same method as used for HCP-F without the catalyst. The only difference is that the catalyst was dissolved in the tested solvent (concentration: 100 mM $TBABr_3$, 200 mM $TBANO_3$ and *p*-TsOH). About 300 µL of each catalytic component was added to HCP-F. The mixture was left overnight at room temperature, and the swelling quotient was calculated as shown above.

CEES Oxidation in HCP-F

Ground HCP-F (15 mg) was added to a 2 mL conical vial and 200 µL of each catalytic component added to the ground polymer. The conical vial was placed in the hood uncapped for 24 hours at room temperature to evaporate acetonitrile completely. Six vials were prepared, each to take one time point. After adding 20 µL of CEES to each vial, each was capped, and a balloon filled with O_2 was attached to assure that O_2 was flowing into the system (a positive pressure of O_2 was maintained). When it was time to take a measurement, 1.5 mL of the internal standard (0.12 mM of 1,3-dichlorobenzene in acetonitrile) was added to the vial and the time point was taken using gas chromatography (GC). The time points were taken after reaction times of 30 min, 1 hr, 2 hrs, 3 hrs, 4 hrs, and 5 hrs. At the end of the reaction, HCP-F was washed with acetonitrile and sonicated to remove catalyst and any remaining CEES/CEESO. Subsequently, the FTIR spectrum (2 wt% in KBr pellet) of HCP-F was taken to probe any structural changes possibly induced by the catalytic reaction (see Figure 10).

To see if sonication influenced the concentration of CEES when a timepoint is taken, 15 μL of CEES was added to 10-11mg of ground catalyst-free HCP-F in a conical vial at room temprature. After the polymer absorbed the CEES, 1mL of the internal standard mentioned above was added to the vial. Several timepoints were taken before and after sonicating the vial for different periods of time (see Figure 8).

CEES Oxidation in HCP-SO_3

Ground HCP-SO_3 (15 mg) was added to a 20 mL vial and 200 µL of each catalytic component added to HCP-SO_3 except for *p*-TsOH. The uncapped vial was placed in the hood for 24 hours at room temperature to evaporate acetonitrile completely. Eight vials were prepared, each to take one time point. After adding 20 μL of CEES to each vial, each was capped, and a balloon filled with O_2 was attached to assure that a positive pressure of O_2 was maintained throughout the course of the reaction. When it was time to take a measurement, 5mL of the internal standard (35 µM of 1,3-dichlorobenzene in acetonitrile) was added to the vial and the time point was taken using GC. The time points were taken at 30 min, 1 hr, 2 hrs, 3 hrs, 4 hrs, 5 hrs, 6 hrs, 7 hrs and 8 hrs. At the end of the reaction, HCP-SO_3 was washed with acetonitrile and sonicated to remove catalyst and any remaining CEES/CEESO. Subsequently, the FTIR spectrum (2 wt% in KBr pellet) of HCP-SO_3 was taken to assess the presence of any structural changes possibly induced by the catalytic reaction (see Figure 10).

Figure 5. CEES oxidation in HCP-R set-up

RESULTS

Figures 6–10 below address, respectively, the degree of swelling/gelation (swelling quotient), O_2-based CEES oxidation in the presence of the HCP derivatives, the retention of CEES in HCP-F, ^{13}C NMR spectral evidence of CEES oxidation in the polymers, and the FTIR spectral evidence of CEES oxidation.

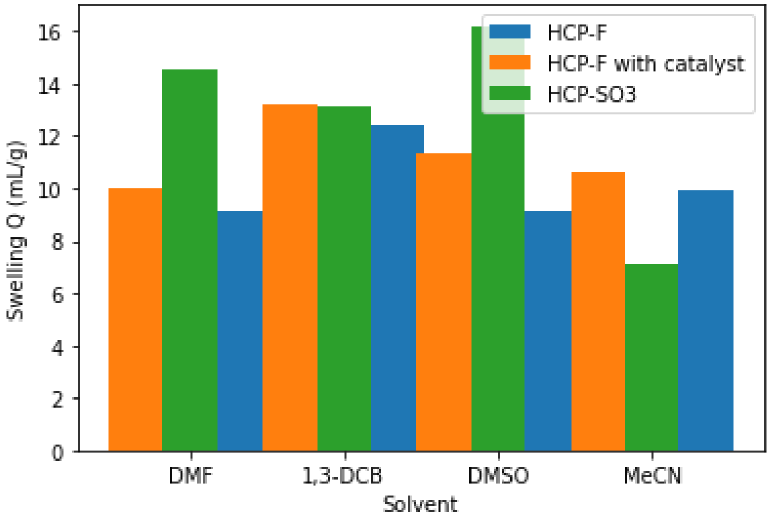


Figure 6. Swelling quotient (defined in text) (mL/g) of four different solvents in HCP-F and HCP-SO_3. Solvents: DMF = dimethylformamide, 1,3-DCB = 1,3-dichlorobenzene, DMSO = dimethyl sulfoxide, and MeCN = acetonitrile

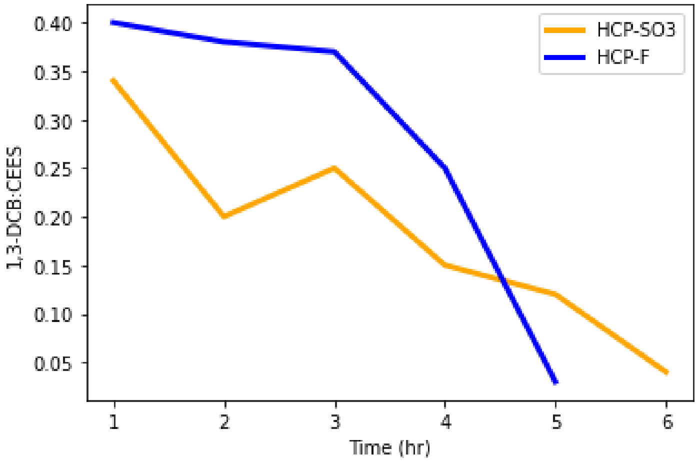


Figure 7. CEES oxidation over time in the presence of HCP-SO_3 and HCP-F containing the aerobic oxidation catalyst, Br_x/NO_x. Conditions: For HCP-SO_3, the sample collected at room temperature after the addition of 5 mL of internal standard, and the mixture was swirled. About 4 μL of the supernatant solution was collected and analyzed by gas chromatography (GC). Each

GC-assessed time point was taken after the addition of 5mL of internal standard. For HCP-F, the same conditions apply, but the internal standard added was 1 mL.

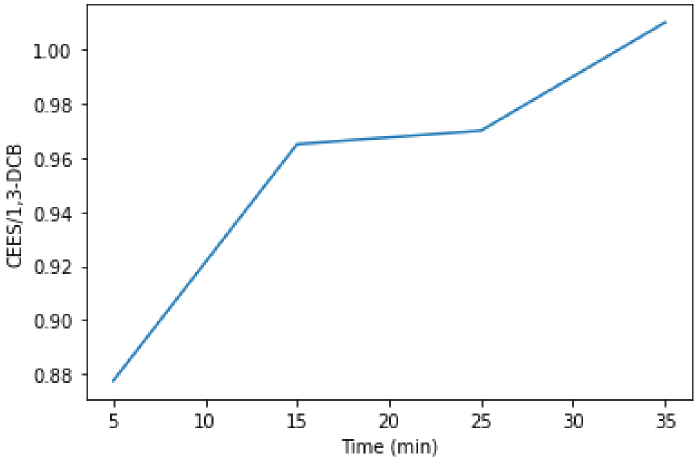


Figure 8. Ratio of CEES/1,3-DCB in HCP-F (without catalyst) after sonicating for different lengths of time. Each sample was collected at room temperature after the addition of 1.5 mL of internal standard and the mixture was sonicated for 30 minutes. About 2 µL of supernatant solution was injected into GC.

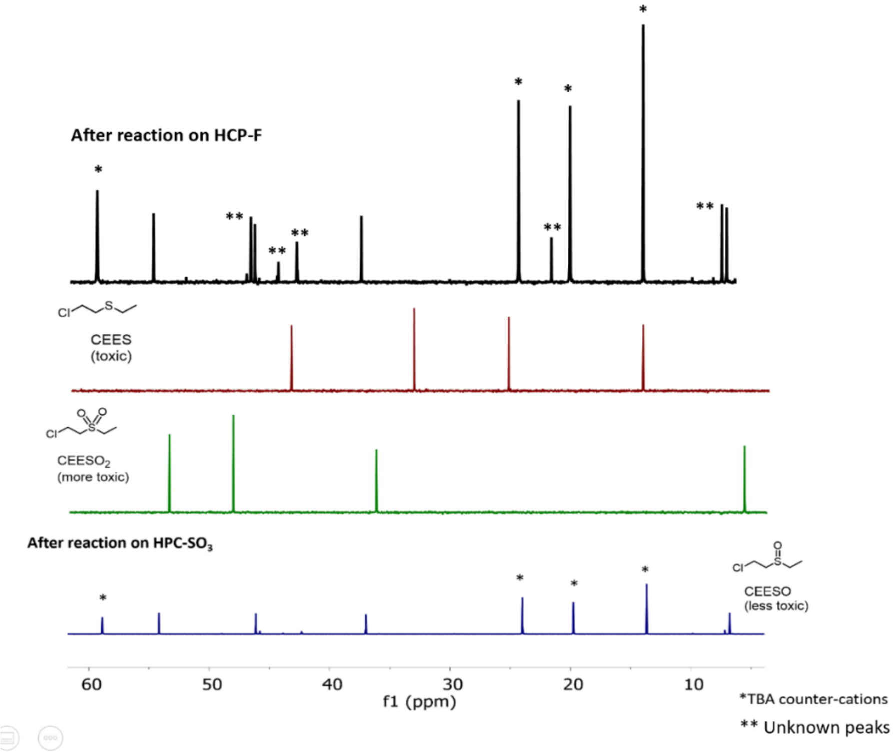
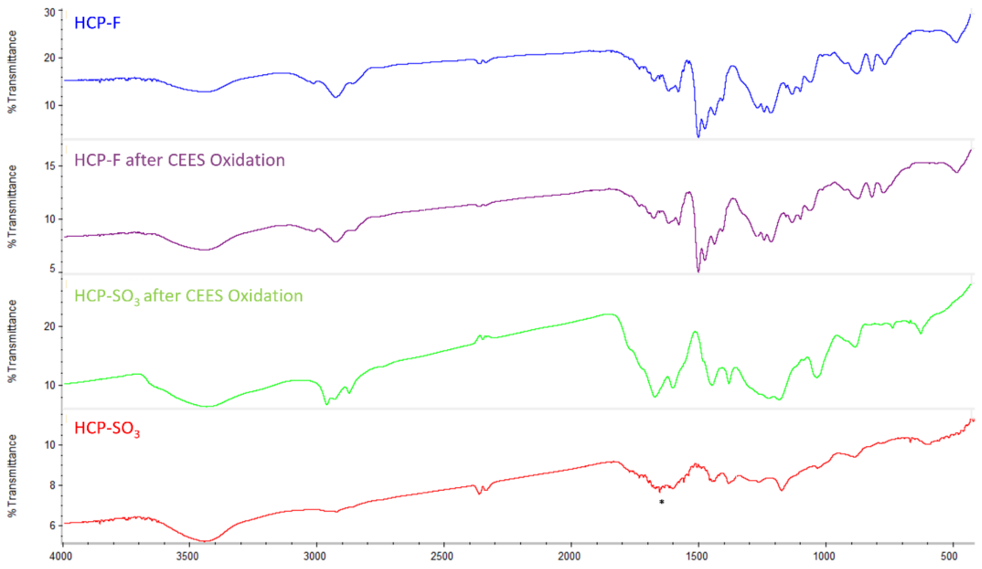


Figure 9. ^{13}C NMR spectra showing that CEES is completely oxidized after reaction in HCP-SO_3, but only partially oxidized in HCP-F. Conditions: HCP-SO_3 sample collected after 8 hours of CEES oxidation at ambient temperature. The mixture was swirled before removal of the aliquot for GC analysis. The same conditions were used for HCP-F except that the sample was collected after 6 hours of CEES oxidation.



*Noise caused by impurity

Figure 10. FTIR spectra for HCP-F and HCP-SO$_3$ before and after CEES oxidation. Conditions: After CEES oxidation, the HCPs were washed with acetonitrile and sonicated 3 times. They were left at room temperature overnight to evaporate the acetonitrile.

DISCUSSION

To create a material that can easily be used in the field to protect against HD by air-based oxidative decontamination of this noxious sulfide, the aerobic (O_2/air-based) catalyst, Br_x/NO_x, was incorporated into the fluorinated hyper-cross-linked polymer, HCP-F. CEES oxidation experiments were performed, and there is a decrease in CEES/1,3-DCB ratio indicating the consumption of CEES (Figure 7). ^{13}C NMR results (Figure 9) show a mixture of CEES and CEESO after six hours of reaction, and a third unknown component that could derive from HCP-F, although FTIR analysis after catalytic reaction showed essentially no change to the HCP-F framework. As a control experiment given the NMR results, CEES was added to HCP-F without the presence of a catalyst, and after absorption, an internal standard was added. Different time points were taken after sonication by GC. With the increase in sonication time, the ratio of

CEES/1,3-DCB increased (Figure 8). This indicates that HCP-F is entrapping CEES and giving inaccurate CEES oxidation data. As a result, the Br_x/NO_x aerobic oxidation catalyst was incorporated into the less hydrophobic polymer, HCP-SO_3. What makes HCP-SO_3 attractive is that its acidity, which speeds up the air-based oxidations catalyzed by Br_x/NO_x (acid functions as a co-catalyst) is already a structural component of the HCP. Aerobic CEES oxidation catalyzed by HCP-SO_3-Br_x/NO_x was conducted (Figure 7), and the CEES concentration is markedly reduced over a few hours at ambient conditions. When ^{13}C NMR was performed (Figure 9) after 8 hours of CEES oxidation in this swellable two-component dual-functional material, only CEESO was found, a very positive result.

After the CEES oxidation reactions in HCP-F and HCP-SO_3, the HCPs were washed with acetonitrile, and FTIR spectra (KBr pellet) of both HCPs were taken to assess the presence of any structural changes in these functional polymers (Figure 10). No changes were observed, which shows considerable stability of the HCPs under conditions of both CEES entrapment and subsequent air-based catalytic oxidation of entrapped CEES to CEESO. These findings indicate that the HCPs can be recycled and reused. Further experiments to study HCP use, isolation and reuse are needed.

Swelling data were also obtained for both HCP-F and HCP-SO_3 without the addition of the catalyst. Because these two functional polymers have different structures, and associated properties to some extent, we ended up using two different methods as each was deemed optimal for that particular HCP. For HCP-F, swelling was measured by volume difference of the HCP-F in an Eppendorf tube. Based on the results (Figure 6), HCP-F swells the most in 1,3-DCB (12 mL/g). Swellability was also assessed after the addition of the catalyst to see if there are any changes in the results. Interestingly, but reproducibly, the HCP-F swells more with the addition of the catalyst, but the trend remains the same with 1,3-DCB (13mL/g) giving the highest swellability of the solvents evaluated. As for HCP-SO_3, swelling was best measured by weighing HCP-SO_3 before and after the addition of the solvent. HCP-SO_3 swells the most in DMSO (16 mL/g). The swellability results observed for the two different HCP derivatives prevents meaningful comparison of the two with each other. Such experiments need to be performed again using the same procedure for both HCPs, and swellability with the addition of the catalyst need to be performed for HCP-SO_3.

CONCLUSIONS

Hyper-crosslinked polymers, HCP-F and HCP-SO_3, containing the highly effective aerobic oxidation catalyst, Br_x/NO_x [8-10] both entrap CEES via swelling (gelation) and catalyze the aerobic (O_2/air)-based selective sulfoxidation of this entrapped CEES producing CEESO (Figure 7). However, the high affinity of HCP-F for CEES makes obtaining accurate rate data (quantitative product analysis) for CEES oxidation a challenge (Figure 8). HCP-SO_3 is an attractive heterogenous system for CEES oxidation because it does not require the addition of *p*-TsOH, as this polymer is already a strong Brønsted acid. ^{13}C NMR data shows complete *and* selective oxidation of CEES after 8 hours. Furthermore, HCP-SO_3 shows high swellability (Figure 6), and stability (Figure 10). Additional CEES oxidation experiments are needed to fully understand and thus optimize the HCP-F and HCP-SO_3 systems. Attractive future experiments include identifying conditions that would facilitate a comparison of the HCP-Br_x/NO_x dual function materials with each other and to collect CEES entrapment (swellability) data for HCP-SO_3 containing the Br_x/NO_x catalyst.

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