Catalytic aerobic oxidation of 2-chloroethyl ethylsulfide, a mustard simulant, under ambient conditions
Effect of solvents, ligands, and transition metals on reactivity

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Abstract

The complexes $Au(III)(Hal)_2(NO_x)(L)$, $Hal = Cl^-$ or Br^-, $NO_x = NO_3^-$ or NO_2^-, $L =$ thioether, catalyze the selective aerobic sulfoxidation of thioethers, including the mustard simulant 2-chloroethyl ethyl sulfide (CEES), by dioxygen (stoichiometry: $CEES + 0.5 O_2 \rightarrow CEESO$) under ambient conditions (25°C, 1 atm O_2) in both homogeneous solution (acetonitrile, trifluoroethanol, nitromethane, 1,2-dichloroethane) or non-toxic perfluoropolyether (PFPE) suspensions. The reaction rate, induction period, and the extent of product inhibition are dependent on the Au(III) ligands, the solvent, and the presence of additional redox active metals. Catalytic aerobic CEES oxidation is 1.8 times faster when NO_3^- is replaced by NO_2^- and 3.3 times faster when Cl^- is replaced by Br^- in acetonitrile. This reaction in trifluoroethanol exhibits no induction period and is 2.8 times faster than in acetonitrile. Addition of 2 equiv. of Cu(II) per Au(III) to the system increases the rate by a factor of 2.7. The $Au(III)/(Br^-)_2/NO_3^-/Cu(II)$ system exhibits high rates for the selective aerobic oxidation of CEES to CEESO under ambient conditions (~68 turnovers per hour), with little if any inhibition by the CEESO product. At low concentrations, sulfoxides reduce the induction period and increase the rate of CEES oxidation in acetonitrile, but at high concentrations they inhibit the reaction. These Au(III) catalysts are extremely efficient for aerobic CEES sulfoxidation when suspended in the PFPE Fomblin® MF-300 (up to 200 turnovers in 10 min). This is a significant improvement from the Au system described in the first study, $Au(III)(Cl)_2(NO_3)(CEES)$ in acetonitrile, which yielded approximately 5 turnovers of CEESO after 10 min. The catalytic reactivity of the $Au(III)(Cl)_2(NO_3)(L)$ in Fomblin® MF-300 for aerobic CEES oxidation was evaluated in the presence of the common amino acids to assess the extent to which the various functional groups in human skin (epidermal polypeptides) might inhibit the catalysis. Some amino acids inhibit the reaction, but the reaction still proceeds even in the presence of 7.5 equiv. of the most inhibitory functional group, indole (tryptophan). © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The development of molecules or materials that catalyze the selective aerobic oxidation of organic molecules under ambient conditions is a major challenge both intellectually and practically [1–4]. "Ambient conditions" means room temperature and

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1.0 atm of air with no additional heat, light, reagents, activators or any other chemical or physical input. Such catalysts could be used to fashion a variety of products that would clean and/or decontaminate the environment by catalyzing the degradation of the toxic agents therein [1,2,4]. These toxic agents include ozone, nitrogen dioxide and volatile organic compounds (VOC). Among the organic pollutants are sulfur compounds (thioethers such as dimethyl sulfide and the chemical warfare agent mustard, abbreviated HD, thiols, and H_2S), nitrogen compounds (amines and pyridine), and aldehydes. [1] Nearly, all these compounds are known pollutants in indoor air.

Only a handful of synthetic molecules or materials are known that catalyze reductant-free O_2 air-based oxidation under mild conditions [6–11]. Abiological aerobic (air/O_2) oxidations usually proceed by radical chain mechanisms which are intrinsically low in selectivity and difficult to control [8,12]. Reduced forms of O_2, including various peroxo species, exhibit chemistry that is generally more selective and controllable than the chemistry of O_2 itself. While there are several biological systems (dioxygenases) [13–15] that can selectively oxidize thioethers to sulfoxides using O_2 without reducing agents, there are only a few synthetic systems that can do this [16–18].

Very recently we reported a Au(III)-based catalyst, Au(III)Cl$_2$NO$_3$(thioether), for the selective and reductant-free O_2-based selective (non-radical chain) oxidation of thioethers to sulfoxides (catalytic aerobic sulfoxidation) that works under ambient conditions (room temperature and 1.0 atm) [18]. [2] While this first study was very thorough and established the mechanism in some detail, the system was not optimized and key issues remained unclear. While there are a number of reports of effective catalysis of mustard or mustard simulant degradation by peroxides [20–22], there are only three that involve O_2 as the oxidant [4,18,23]. [3]

We report here further study of these Au(III)-based selective aerobic sulfoxidation catalysts. The effects of Au(III) ligands, solvent, and additional redox active d-block metals on the rate of reaction, the induction period and product inhibition are established, and these results confirm parts of the mechanism proposed in the first study [18]. For more reactive catalysts that function in homogeneous solution (acetonitrile, trifluoroethanol, nitromethane, 1,2-dichloroethane) or in heterogeneous non-toxic perfluoropolyether (PFPE) media are described. The Au(III)/PFPE/O_2 systems are of considerable interest in context with topical skin protectants (TSPs). These "barrier creams" protect the wearer from mustard and other toxic agents when applied to the skin and are constituted largely by PFPE oils [25,26]. Prior to our recent work [18], there have been no reports, to our knowledge, of the catalytic destruction of mustard, HD, or its simulants under ambient conditions.

2. Experimental

2.1. Materials

HAuCl$_4$, HAuBr$_4$, AgNO$_3$, AgClO$_4$, TBANO$_3$, CuSO$_4$, Cu(ClO$_4$)$_2$ MnSO$_4$, VOSO$_4$, Ti(SO$_4$)$_2$, Fe$_2$(SO$_4$)$_3$, NiSO$_4$, L-methionine, L-asparagine, L-histidine, L-leucine, L-cystine, L-arginine, L-tryptophan, L-serine, L-aspartic acid, L-tyrosine, L-proline, 2-chloroethyl ethyl sulfide (CEES), dimethyl sulfoxide (DMSO), and 1,3-dichlorobenzene were purchased from Aldrich (TBA is an abbreviation for tetra-*n*-butylammonium cation). TBANO$_2$ was purchased from Fluka. TEAAuCl$_2$ was synthesized using a literature procedure (TEA is an abbreviation for tetra-*n*-ethylammonium cation [27]). PFPE surfactant Fomblin MF-300® and PFPE oil Galden D-02® were purchased from Ausimont (Thorofare, NJ).

2.2. General procedures

All gas chromatography analyses were performed on an HP 5890 Gas Chromatograph equipped with an FID detector and a 5% phenyl methyl silicone capillary column. 1,3-Dichlorobenzene was used as an internal standard for GC analyses and added as described below. Mass spectra were obtained using an HP 5890 GC with a 5% phenyl methyl silicone capillary column and a 5971A Mass Selective Detector.

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[1] Review of decontamination [5,47–49].

[2] A key paper on Au-based oxidation catalysts [19]. See also a recent general reference on basic and applied Au chemistry [50].

[3] Recent papers on other modes of mustard or mustard simulant decontamination [24,51–53].

UV–visible spectra were run on an HP 8452A Diode Array Spectrophotometer. The percentages of O_2 in the reaction atmosphere were varied using a Series 810 Mass Trak flowmeter with dried argon as the diluent gas. Stock solutions were prepared in a 20 ml vial, fitted with a PFPE septum, by dissolving the component into anhydrous, argon-purged, CH_3CN. The stock solutions were stored at $-10°C$ and covered in aluminum foil to prevent light exposure.

Throughout the paper, the formulae for the Au(III)-based catalytic systems where the actual active catalyst was not isolated and characterized but generated in situ are written with the catalyst precursors separated by slashes (e.g. Au(III)/ $(Br^-)_2/NO_3^-/Cu(II)$). (In Table 2, colons separate the catalyst precursors in order to emphasize the mole ratios of these precursors.) The formulas for isolated and characterized catalysts are written conventionally (e.g. $Au(III)Cl_2NO_3$(thioether)).

2.3. Initial rate determinations and evaluation of the reaction kinetics

The CEESO product was demonstrated to be quite stable under the reaction conditions. For this reason, the reactions were monitored until at least 10% of the starting CEES had been consumed.

The kinetic data were evaluated and curves fit using the Solver subprogram of Microsoft Excel. The sums of the squares of the difference between experimental and theoretical values were minimized.

2.4. Substituting NO_2^- for NO_3^-

In a 20 ml vial purged with O_2 from stock solutions (all in dry acetonitrile), 0.10 ml (4.8×10^{-6} mol, 1 equiv.) of a 0.048 M $HAuCl_4$ solution, 0.096 ml (9.6×10^{-6} mol, 2 equiv.) of a 0.10 M $AgClO_4$ solution, 0–0.048 ml (0–9.6×10^{-6} mol, 0–2 equiv.) of a 0.2 M $TBANO_2$ solution and 0.083 ml (7.2×10^{-4} mol, 150 equiv.) of 1,3-dichlorobenzene (internal standard) were added by syringe. The volume of the solution was then adjusted to 0.96 ml total volume with dry acetonitrile. After shaking the vial for 1 min, 0.042 ml (3.60×10^{-4} mol, 75 equiv.) of CEES was added. For comparison, the same experiment was performed except that $TBANO_2$ was replaced with $TBANO_3$.

2.5. Assessment of Au(III)/$(Br^-)_2/NO_3^-$ and Au(III)/$(Br^-)_2/NO_3^-$/$(Cu(II))_2$ systems in CH_3CN

In a 20 ml vial purged with O_2, 0.10 ml (4.8×10^{-6} mol, 1 equiv.) of a 0.048 M $HAuBr_4$ solution, 0.035 ml (3.6×10^{-6} mol, 0.75 equiv.) of a 0.10 M $AgNO_3$ solution, 0.060 ml (6.0×10^{-6} mol, 1.25 equiv.) of a 0.10 M $AgClO_4$ solution, and 0.083 ml (7.2×10^{-4} mol, 150 equiv.) of 1,3-dichlorobenzene were added by syringe. After shaking the vial for 1 min, 0.335 ml (2.9×10^{-3} mol, 600 equiv.) of CEES was added. The same procedure was repeated with the addition of 0.20 ml (9.6×10^{-6} mol, 2 equiv.) of a 0.048 M $Cu(ClO_4)_2$ solution in acetonitrile.

2.6. Effect of DMSO concentration on the rate of CEES oxidation

In a 20 ml vial purged with O_2, 0.10 ml (4.8×10^{-6} mol, 1 equiv.) of a 0.048 M $HAuCl_4$ solution, 0.035 ml (3.6×10^{-6} mol, 0.75 equiv.) of a 0.10 M $AgNO_3$ solution, 0.060 ml (6.0×10^{-6} mol, 1.25 equiv.) of a 0.10 M $AgClO_4$ solution, and 0.083 mol (7.2×10^{-4} mol, 150 equiv.) of 1,3-dichlorobenzene were added by syringe. To this solution, 0–0.018 ml (0–3.6×10^{-4} mol, 0–75 equiv.) of DMSO was added by syringe. The solution was adjusted to 1.0 ml in total volume with acetonitrile, factoring in for CEES addition. In the first set of experiments, 0.044 ml (75 equiv., 3.8×10^{-4} mol) of CEES was added by syringe. In the second set of experiments, 0.117 ml (200 equiv., 1.0×10^{-3} mol) of CEES was added.

2.7. Solvent effect on the rate of CEES oxidation

In a 20 ml vial purged with O_2 from stock solutions (all in dry acetonitrile), 0.10 ml (4.8×10^{-6} mol, 1 equiv.) of a 0.048 M $HAuCl_4$ solution, 0.035 ml (3.6×10^{-6} mol, 0.75 equiv.) of a 0.10 M $AgNO_3$ solution, 0.06 ml (6.0×10^{-6} mol, 1.25 equiv.) of a 0.10 M $AgClO_4$ solution and 0.083 ml (7.2×10^{-4} mol, 150 equiv.) of 1,3-dichlorobenzene were added by syringe. In each separate trial, the volume was adjusted to 0.96 ml total volume with various solvents, namely acetonitrile, nitromethane, 1,2-dichloroethane, trifluoroethanol, ethanol, *tert*-butanol, pyridine, and acetone (in all cases the solutions are comprised of 10%

acetonitrile and 90% another solvent). After the vial was agitated for 1 min, 0.017 ml (1.44×10^{-4} mol, 30 equiv.) of CEES was added. Aliquots of 1.0 μl were withdrawn and the organic components were quantified by GC every 15 min.

2.8. Reactions in perfluorinated media

Experiments were conducted using the perfluorinated oil, Galden D-02$^{®}$, or the PFPE oil, Fomblin MF-300$^{®}$ as the solvent in place of acetonitrile. Both Galden D-02$^{®}$ and Fomblin MF-300$^{®}$ are components of the TSP creams. Samples were prepared by adding the components together, dissolving them in a minimal amount of acetonitrile, stirring for 10 min, and then removing the acetonitrile in vacuo.

In all cases, 0.005 g (1.25×10^{-5} mol) of TEAAuCl$_2$ was used. The other components, TBANO$_3$ and CuSO$_4$ were varied in quantities from 1.25×10^{-5} to 1.25×10^{-4} mol. After the mixture was dried in vacuo in a Schlenk flask, the flask was attached to the manometer and the apparatus was purged with O$_2$. After purging, 7.0 ml of the perfluorinated fluid (Galden D-02$^{®}$) was added to the flask. The system was equilibrated to atmospheric pressure and then sealed with a septum stopper. Through the stopper, 0.05 ml (4.2×10^{-4} mol) of CEES was added, and the system was monitored for O$_2$ consumption.

Another experiment (Table 2) was performed using Fomblin MF-300$^{®}$ as the solvent. In this case, 1.0 ml of Fomblin MF-300$^{®}$ and 0.005 g (1.25×10^{-5} mol) of TEAAuCl$_2$ were mixed with varying quantities of CuSO$_4$, MnSO$_4$, VOSO$_4$, Ti(SO$_4$)$_2$, Fe$_2$(SO$_4$)$_3$, NiSO$_4$, ZnSO$_4$, Cr$_2$(SO$_4$)$_3$, MgSO$_4$, CoSO$_4$, Pd(NO$_3$)$_4$, Na$_2$SO$_3$, and TBANO$_3$. The catalyst was prepared and the experiment was performed following the same procedure described above.

In a 10 ml Schlenk flask, 0.005 g (1.25×10^{-5} mol, 1 equiv.) of TEAAuCl$_2$, 0.0038 g (1.25×10^{-5} mol, 1 equiv.) of TBANO$_3$, and an amino acid (9.38×10^{-5} mol, 7.5 equiv.) were stirred in 2 ml of acetonitrile for 3 min. The volatiles were then removed in vacuo. The flask was then connected to a manometer and the system was purged for 5 min with a stream of 100% dry O$_2$. After equilibrating the system to the

atmospheric pressure, 1 ml of PFPE oil was added to the Schlenk flask, followed by 0.110 ml (9.38×10^{-4} mol, 75 equiv.) of CEES. Consumption of O$_2$ was monitored, and aliquots of 0.110 ml of CEES were sequentially added when the existing CEES had been approximately 90% consumed. In order to quantify the amount of CEES and CEESO present at the end of each reaction, an extraction was performed using pentane. In a separatory funnel, 2.0 ml of pentane was added to the reaction mixture. The funnel was shaken, and the top fraction was collected. The bottom fraction was extracted again with 2.0 ml of pentane. An internal standard, 0.177 ml (9.38×10^{-4} mol, 75 equiv.) of 1,2-dichlorobenzene was added and a 1.0 μl aliquot of the solution was analyzed by GC.

Using the same procedure as in the amino acid experiment but omitting the amino acid, 0.005 g of TEAAuCl$_2$ was combined with varying amounts of TBANO$_3$ (1–3 equiv.) and varying amounts of a transition metal sulfate (1–3 equiv.) (see Table 2).

2.9. Measuring O$_2$ consumption in the catalytic oxidation of CEES in a PFPE medium

A 10 ml Schlenk flask fitted with a septum stopper was attached to a manometer and purged with O$_2$. To the flask, 0.005 g (1.25×10^{-5} mol, 1 equiv.) of TEAAuCl$_2$, 0.003 g (1.25×10^{-5} mol, 1 equiv.) of TBANO$_3$, and 0.0015 g (1.25×10^{-5} mol, 1 equiv.) of CuSO$_4$ were added followed by the addition of 1.0 ml of the PFPE surfactant, Fomblin$^{®}$ and 0.166 ml 1,3-dichlorobenzene (7.5×10^{-4} mol) (internal standard for GC). After the system was equilibrated with 1 atm, 0.100 ml of CEES (4.5×10^{-4} mol) was added. The consumption of O$_2$ was recorded, and aliquots were periodically withdrawn, extracted with pentane and analyzed by GC as described above.

2.10. Determining the dependence of O$_2$ on reaction rate in PFPE media

A 10 ml Schlenk flask fitted with a septum stopper was attached to a manometer and purged with O$_2$. To the flask, 0.005 g (1.25×10^{-5} mol, 1 equiv.) of TEAAuCl$_2$, and 0.003 g (1.25×10^{-5} mol, 1 equiv.) of TBANO$_3$ were added followed by 1.0 ml of the PFPE surfactant, Fomblin$^{®}$ and 0.166 ml 1,3-dichlorobenzene (7.5×10^{-4} mol) (internal standard for GC).

This procedure was repeated except that the apparatus was purged with air (20% O_2).

3. Results

3.1. Effect of ligand substitution

In the previous work [18] it was established that a ratio of catalyst components of 1Au(III):2Cl$^-$:1NO$_3^-$ produced the most reactive catalyst for the O_2 (or air)-based oxidation of thioethers to the corresponding sulfoxides. Thus, NO_3^- appears to be necessary for high catalytic activity. To assess the necessity for NO_3^-, it was systematically replaced with other ligands (ClO$_4^-$, HSO$_4^-$, OH$^-$, BPh$_4^-$, CH$_3$CO$_2^-$, H$_2$PO$_4^-$, and NO$_2^-$). Only the stoichiometric substitution of NO_3^- with NO_2^- produced a catalyst with significant activity. In fact, the system with NO_2^- was more active than that with NO_3^- (see Fig. 1). This feature was not thoroughly investigated because NO_2^- is considered to be significantly more toxic than NO_3^-. As a consequence NO_2^- would be less desirable as a component of a catalytically active TSP.

In our previous work, it was noted that the replacement of Cl$^-$ with Br$^-$ increased the initial reaction rate [18]. Significantly, the more thorough investigation here shows that this replacement also reduced the induction period and increased the overall conversion of CEES to CEESO (Fig. 2), both issues of central developmental importance.
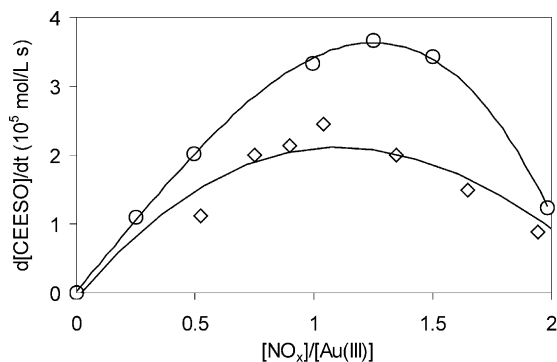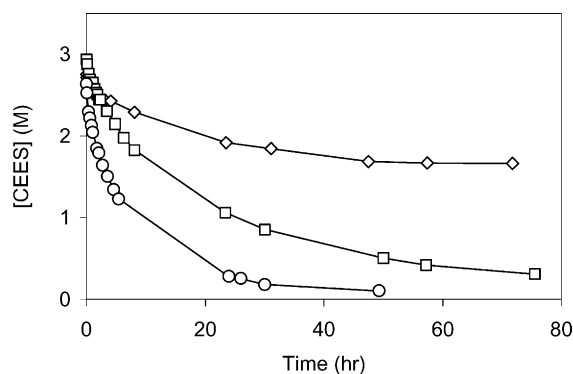

Fig. 2. Effect of Br$^-$ and Cu(II) on the rate of Au(III)-catalyzed O_2 oxidation of CEES. Conditions: 25°C; 1 atm O_2; [CEES] = 3.0 M; [HAuCl$_4$] = 4.8 mM; [AgClO$_4$] = 7.2 mM; [TBANO$_3$] = 3.6 mM ($\diamond$). [HAuBr$_4$] = 4.8 mM; [AgClO$_4$] = 7.2 mM; [TBANO$_3$] = 3.6 mM ($\square$). [HAuBr$_4$] = 4.8 mM; [AgClO$_4$] = 7.2 mM; [TBANO$_3$] = 3.6 mM; [Cu(ClO$_4$)$_2$] = 9.6 mM ($\bigcirc$).

3.2. Solvent effect

Acetonitrile, the solvent used in all the studies on these Au-based aerobic oxidation catalytic systems to date, is toxic (40 ppm is the practical exposure limit (PEL), http://www.msdsonline.com). As such it is not appropriate for use in cosmeceutical applications. Also because it is a polar, non-fluorinated solvent it does not constitute a good model solvent for TSPs. The catalysis exhibits an induction period if acetonitrile is used as the solvent. During the induction period, Au remains in the reduced state, Au(I). Fig. 3 shows the four solvents in which catalysis of CEES oxidation to CEESO occurs. The three solvents, excluding acetonitrile, do not exhibit a measurable induction period because the formed Au(I) intermediate is immediately reoxidized to Au(III) species. The highest rate of CEES oxidation was observed in trifluoroethanol, which is structurally and electronically similar to the PFPE oils that are the principal components of TSPs. Also noteworthy is that in trifluoroethanol, complete conversion of CEES to CEESO can be achieved. In contrast, product-inhibition prevents complete conversion when acetonitrile is the solvent. When ethanol or acetone is used, the Au(III) is immediately reduced to Au(0), in the form of colloidal gold which cannot be reoxidized by O_2. In *tert*-butanol, Au(III) is reduced to Au(I) but reoxidation of Au(I) to Au(III) is
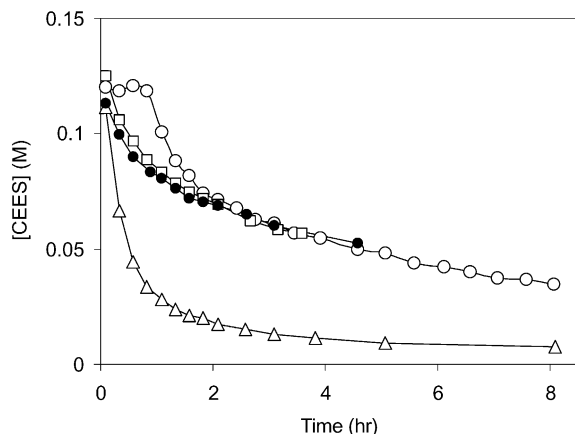

Fig. 1. Effect of NO_2^- substitution on the rate of Au(III)-catalyzed O_2 oxidation of CEES. Conditions: 25°C; 1 atm O_2; [HAuCl$_4$] = 4.8 mM; [AgClO$_4$] = 9.6 mM; TBANO$_3$ ($\diamond$); TBANO$_2$ ($\bigcirc$); [CEES] = 0.38 M.

Fig. 3. Solvent effect on the rate of Au(III)-catalyzed O_2 oxidation of CEES. Conditions: 25°C; 1 atm O_2; [HAuCl₄] = 4.8 mM; [AgClO₄] = 6.0 mM; [AgNO₃] = 3.6 mM; [CEES] = 0.13 M. 10% CH₃CN, 90% CF₃CH₂OH (△). 100% CH₃CN (○). 10% CH₃CN, 90% CH₃NO₂ (□). 10% CH₃CN, 90% ClCH₂CH₂Cl (●).

not observed. In pyridine, CEES does not reduce the initial Au(III) species so catalysis does not occur.

3.3. Effect of transition metal ions

Since three lines of evidence established that the rate-limiting step in the aerobic oxidation of CEES to CEESO catalyzed by Au(III) is reduction

of the Au(III)/(Cl⁻)₂/NO₃⁻(CEES) complex by CEES, it was surmised that transition metal ions in high oxidation states might catalyze the reduction of Au(III). Both Fe(III) and Cu(II) were screened for their activity in conjunction with Au(III)/(Cl⁻)₂/NO₃⁻ and Au(III)/(Br⁻)₂/NO₃⁻, but only Cu(II) resulted in a significant rate enhancement (i.e. co-catalyst activity). The initial rate of CEES oxidation at ∼3.0 M CEES is approximately two times faster for Au(III)/(Br⁻)₂/NO₃⁻ than for Au(III)/(Cl⁻)₂/NO₃⁻, while Au(III)/(Br⁻)₂/NO₃⁻/(Cu(II))₂ is eight times faster than Au(III)/(Cl⁻)₂/NO₃⁻ (Fig. 2).

3.4. Effect of DMSO

As previously noted [18], aerobic oxidation of CEES catalyzed by Au(III)/(Cl⁻)₂/NO₃⁻ in acetonitrile slows down as CEESO accumulates. By using DMSO as sulfoxide model for CEESO, it is clear that high concentrations of sulfoxide inhibit the rate of CEES oxidation (Fig. 4). However, the new Au(III)/(Br⁻)₂/NO₃⁻/(Cu(II))₂ system was able to oxidize CEES to complete conversion (99 ± 5%) without showing significant inhibition by CEESO product (Fig. 2). In the previously investigated Au(III)(Cl)₂NO₃(thioether) system, CEES oxidation proceeds with an induction period. It was observed that at very low concentrations of DMSO

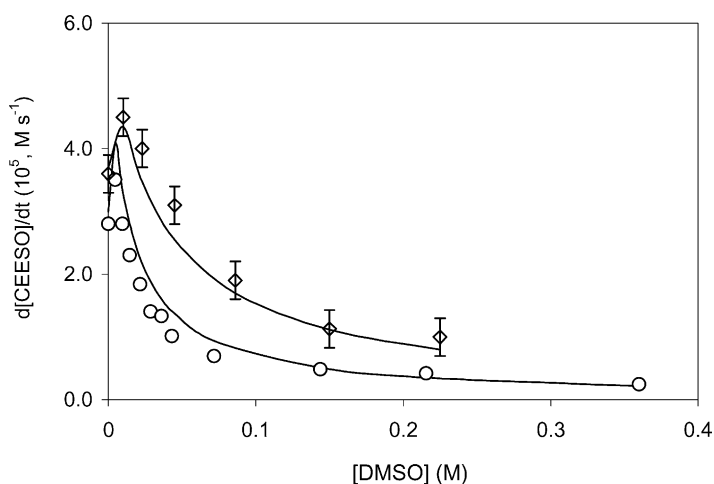Fig. 4. Effect of DMSO concentration on the rate of Au(III)-catalyzed O_2 oxidation of CEES. Conditions: 25°C; 1 atm O_2; [HAuCl₄] = 4.8 mM; [AgClO₄] = 6.0 mM; [AgNO₃] = 3.6 mM; [CEES] = 1.0 (◇) and 0.37 M (○).

(1–2 equiv. relative to the catalyst), the rate of CEES oxidation actually increases, and the induction period disappears. These results suggest that the most active Au(III) catalyst likely contains one CEESO molecule as a ligand.

3.5. Reactions in perfluorinated media

The replacement of acetonitrile with trifluoroethanol gives a highly efficient catalytic system for the aerobic oxidation of CEES to CEESO. It was logical to replace trifluoroethanol with high molecular weight perfluorinated polyethers (PFPE oils) since the TSP creams contain these components. Au(III)/(Cl$^-$)$_2$/NO$_3^-$ appeared to be insoluble in the perfluorinated oil (Galden D-02) but partially soluble in Fomblin MF-300[®], a PFPE surfactant containing terminal carboxylic acid functional groups. In Fomblin[®], the catalyst appears to be dissolved only when CEES is added. As Table 1 indicates, the heterogeneous catalyst system is quite active in Galden D-02. Significantly, the Au-free systems containing Cu(II) and NO$_3^-$ exhibit considerable catalytic activity (Table 1 and Fig. 5).

Also it is noteworthy that the rate-limiting step in perfluorinated media, as in acetonitrile, is the reduction of Au(III) by thioether. Two observations rule out that the O$_2$-reoxidation of Au(I) is the rate-limiting step. First, the yellow chromophore of Au(III) appears at the same time that CEESO appears (Au(I) is colorless). Second, when the atmosphere is changed from 100 to 20% O$_2$, the rate of CEES oxidation remains unchanged.

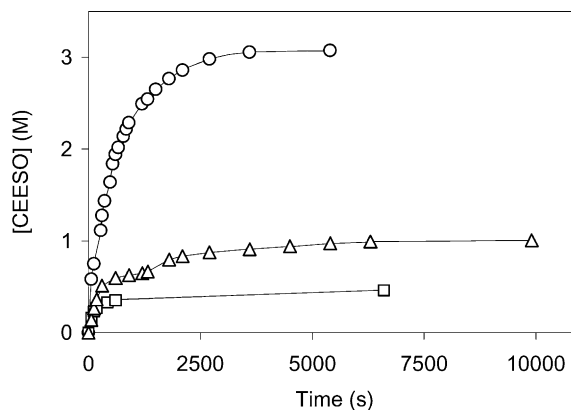The CEES oxidation reactions were also performed in the PFPE surfactant, Fomblin[®], in which

Fig. 5. CEESO formation in the Au(III)-catalyzed O$_2$ oxidation of CEES in a PFPE media. Conditions: 25°C; 1 atm O$_2$; 1.0 ml Fomblin[®] (PFPE surfactant); 0.0125 mmol TEAAuCl$_2$; 0.025 mmol Cu(SO$_4$)$_2$; 0.0375 mmol TBANO$_3$ (○). 0.02 mmol Cu(SO$_4$)$_2$; 0.03 mmol TBANO$_3$ (□). 0.01 mmol TEAAuCl$_2$; 0.03 mmol TBANO$_3$ (△). Additional CEES added in 0.1 ml aliquots, after the initial CEES is 90% consumed. Aliquot addition is repeated until CEES oxidation stops.

the catalyst partially dissolves after CEES addition. Other metal salts were also evaluated as potential co-catalysts. These include the sulfate salts of Fe(III), Cu(II), Mn(II), V(IV), Ti(IV), Co(II), and Ni(II).

From the data in Table 2 and Fig. 5, it is quite clear that there is a synergistic effect when certain redox active metals are added to the Au/(Cl$^-$)$_2$/NO$_3^-$ system. For example, one of the most active systems, Au(III)/(Cl$^-$)$_2$/(NO$_3^-$)$_3$/(Cu(II))$_2$ is 3.8 and 6.5 times more effective after 10 min of reaction time than when only two of the components are used, Au(III)/(Cl$^-$)$_2$/(NO$_3^-$)$_3$ and (Cu(II))$_2$/(NO$_3^-$)$_3$, respectively (in this case chloride is not considered a component since its stoichiometry is determined

Table 1
CEESO formation using a PFPE oil[a]

[TEAAuCl$_2$] (10^{-5} mol)	[TBANO$_3$] (10^{-5} mol)	[CuSO$_4$] (10^{-5} mol)	[CEESO] (10^{-5} mol)
0	1.25	1.25	3.62
1.25	1.25	1.25	5.80
0	2.50	2.50	5.00
1.25	2.50	2.50	8.06
0	5.00	5.00	8.06
1.25	5.00	5.00	16.2
0	7.25	7.25	10.6
1.25	7.25	7.25	18.7

[a] Reaction conditions: 7.0 ml of Galden D-02 (PFPE oil) under 1 atm O$_2$, 25°C, 0.05 ml (4.2 × 10^{-4} mol) CEES, reaction time: 1 h.

Table 2
CEESO formation in PFPE surfactant[a]

Sample[b]	Turnovers of CEESO[c]
$Au:2Cu(II):4NO_3^-$	195
$Au:2Cu(II):3NO_3^-$	181
$Au:2Co(II):3NO_3^-$	177
$Au:3Cu(II):3NO_3^-$	165
$Au:2Mn(II):3NO_3^-$	164
$Au:2V(IV):3NO_3^-$	160
$Au:2Cu(II):2NO_3^-$	155
$Au:Cu(II):3NO_3^-$	155
$Au:Fe(III):3NO_3^-$	142
$Au:2Ti(IV):3NO_3^-$	142
$Au:2Ni^{2+}:3NO_3^-$	140
$Au:Cu(II):2NO_3^-$	115
$Au:3NO_3^-$	50
$Au:2Cu(II):NO_3^-$	28
$2Cu(II):3NO_3^-$	28
$Fe(III):3NO_3^-$	19
$Au:Cu(II):NO_3^-$	17
$Au:2Cu(II)$	1

[a] Reaction conditions: 1.0 ml Fomblin; 25°C; 1 atm O_2; 1.25×10^{-5} mol Au. Additional CEES added: 0.1 ml aliquots, after the initial CEES is 90% consumed. Aliquot addition is repeated until CEES oxidation stops.

[b] Ratio of the catalyst precursor added. Au added in the form $TEAAuCl_2$; Cu(II), Co(II), Mn(II), Fe(III), Ti(IV) and Ni(II) added in the form of sulfate salts. V(IV) added in the form of $VOSO_4$.

[c] mol CEESO per mol Au after 10 min.

by Au). It is also interesting to note that $Au(III)/(Cl^-)_2/$ $(Cu(II))_2$ is not catalytically active. Again NO_3^- appears to be necessary for catalysis in the fluorinated media as well as in acetonitrile. Also the data in Fig. 5 indicate that inhibition by product sulfoxide is less pronounced in the $Au(III)/(Cl^-)_2/(NO_3^-)_3/(Cu(II))_2$ system.

Significantly, oxidation terminates at the sulfoxide oxidation state in these systems (no sulfone is produced within the limits of instrumental detection). This is noteworthy because the sulfoxide of mustard, "HD(O)", is significantly less toxic than the sulfone, "HD(O)$_2$". In consequence, we carefully examined the consumption of O_2 in the catalytic aerobic oxidation of CEES in PFPE medium catalyzed by $Au(III)/(Cl^-)_2/(NO_3^-)/(Cu(II))$. The stoichiometry of O_2 consumption was established by determining the volume of O_2 consumed at a constant pressure while simultaneously monitoring CEESO formation by gas chromatography. It is evident from Fig. 6
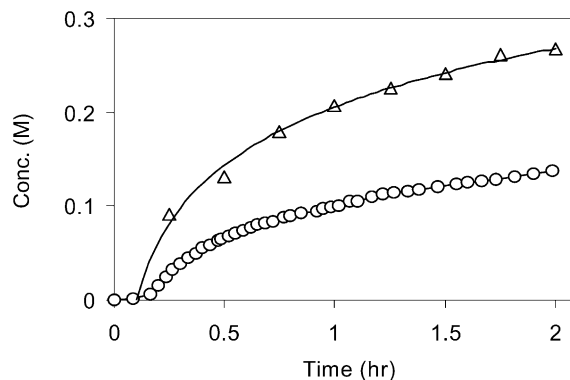

Fig. 6. Consumption of CEES and O_2 in PFPE media. Conditions: 25°C; 1 atm O_2; 1.0 ml Fomblin®; 0.0125 mmol $TEAAuCl_2$, 0.0125 mmol TBANO$_3$, 0.0125 mmol $Cu(SO_4)_2$. O_2 consumption, M (○). CEESO formation, M (△).

that 1 equiv. of CEESO forms per 0.5 equiv. of O_2 consumed ($CEES + 0.5O_2 \rightarrow CEESO$).

3.6. Effect of amino acids

Because a key goal of this work is to develop a catalytic system that can be incorporated in TSPs, we looked at the effect of different amino acids on the catalytic activity for aerobic CEES oxidation. Amino acids, present in cornified layers of skin (epidermal) cells could, in principle, bind to Au and reduce or eliminate its catalytic activity. Amino acids containing different functions (i.e. alkyl, amide, amine, carboxylate, imidazole, indole, alcohol, phenol, disulfide, thioether, and guanidino side chain groups) were evaluated. The inhibitory effect of the amino acids is as follows: tryptophan (indole) (most inhibiting) > methionine (thioether) > tyrosine (phenol) > leucine (alkane) > histidine (imidazole) > arginine (guanidine) > asparagine (amide) > serine (alcohol), aspartate (carboxylate) > cystine (disulfide) (least inhibiting) (Table 3).

4. Discussion

4.1. Reaction mechanism

The effects of various ligands (Br^- versus Cl^-, NO_2^- versus NO_3^-, etc.) and other compounds and

Table 3
Effect of amino acids on the rate of CEES oxidation by the Au:2Cl$^-$:3NO$_3^-$ system[a]

Amino acid	Turnovers of CEESO[b]
None	50
L-Methionine	18
L-Asparagine	44
L-Histidine	31
L-Leucine	25
L-Cystine	50
L-Arginine	37
L-Tryptophan	5
L-Serine	46
L-Aspartic acid	46
L-Tyrosine	21
L-Proline	43

[a] Reaction conditions: 1.25×10^{-5} mol TEAAuCl$_2$; 3.75×10^{-5} mol TBANO$_3$; 9.38×10^{-5} mol amino acid; 9.38×10^{-4} mol CEES; 1.0 ml Fomblin; 1 atm O$_2$; 25°C.

[b] mol CEESO per mol Au after 10 min.

conditions in this study on the selective aerobic oxidation of CEES–CEESO catalyzed by Au(III) complexes is consistent with the mechanism established for the significantly slower Au(III)Cl$_2$NO$_3$(thioether)/O$_2$ system recently reported (Scheme 1) [18].

In this mechanism the active complex, **1**, is formed in rapid ligand exchange reactions, and its concentration is controlled by Eqs. (1) and (2). At higher CEES concentrations one Cl$^-$, or NO$_3^-$ can be replaced to form **2**, a complex with two CEES ligands, and very little catalytic activity is observed. The redox step, the oxidation of thioether/reduction of Au(III), Eq. (3) in Scheme 1, is rate-limiting. This reaction involves bimolecular attack of thioether on a coordinated Cl$^-$ ligand of Au(III). Reoxidation of Au(I) formed in Eq. (3) by dioxygen in a fast subsequent reaction, Eq. (4), regenerates the Au(III) species.

$$Au(I) + 0.5O_2 + 2H^+ \rightarrow Au(III) + H_2O \qquad (4)$$
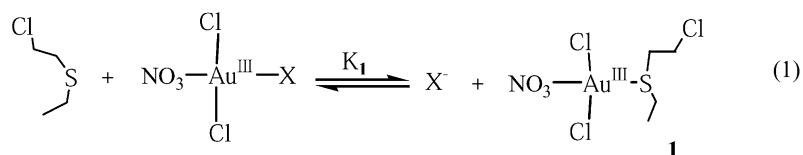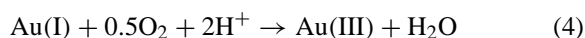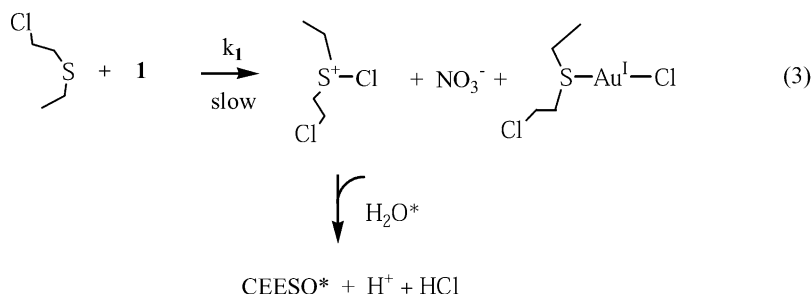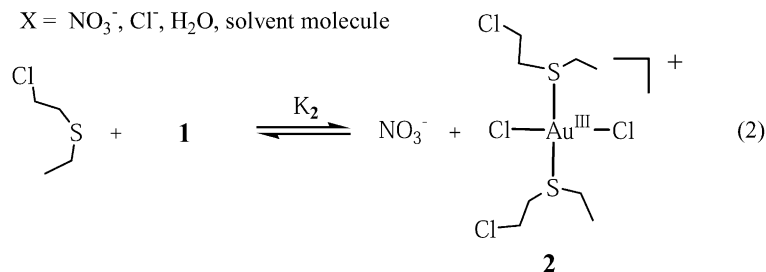
Scheme 1. Mechanism of O$_2$-based oxidation of thioethers catalyzed by Au(III)Cl$_2$NO$_3$(thioether) (**1**).

The overall rate from Scheme 1 is Eq. (5):

$$\text{rate} = (\tfrac{1}{4}k_1[\text{CEES}])(\sqrt{K_2[\text{CEES}] + 4[\text{Au(III)}]_T} - \sqrt{K_2[\text{CEES}]})^2 \qquad (5)$$

where $[\text{Au(III)}]_T$ is a total concentration of Au(III) [18].

4.2. Effect of ligand substitution

The increase in rate when Cl^- is replaced by Br^- under otherwise identical conditions is consistent with a ligand transfer reaction in rate-limiting step, Eq. (3), in the proposed mechanism. Ligand transfer oxidation processes, including reduction of Au(III), are known to be kinetically favored by soft Br^- ligands [28,29]. In water, the reduction of *trans*-$[\text{Au(CN)}_2\text{Br}_2]^-$ by sulfite and hydrogen sulfite is ca. 10 times faster than reduction of *trans*-$[\text{Au(CN)}_2\text{Cl}_2]^-$ [29]. Interestingly, the kinetic preference for the softer bromide ligand is in the opposite direction from the energetics (enthalpy) of the reaction. Clearly the Cl^--ligated metal centers have higher potentials and are stronger oxidants than their Br^--ligated analogs.

In acetonitrile at $[\text{CEES}] > 0.1\,\text{M}$ a considerable part of total Au(III) is in the form of the inactive complex **2**. Therefore, the dependence of initial reaction rate on CEES concentration deviates from linearity as described in Eq. (5). Sequential equilibrium constants for the replacement of Cl^- by Br^- ($4Br^- + \text{AuCl}_4^-$) in water are 240, 98, 49, 17 [30], showing that Br^- ligand binds more strongly than Cl^- to Au(III). This decreases K_2, Eq. (2), for the complex when chloride is replaced with bromide. Nitrite is also a softer ligand than nitrate [31], thus its displacement by CEES from **1** would likely be less favorable than for nitrate. Several gold (III) nitrite complexes have been identified [32–34], but none have been isolated. Octahedral Au(III)EDTA binds NO_2^- even tighter than Cl^-, or Br^- [35]. Thus, NO_2^- and Br^- drive Eq. (2) to the left. Therefore, K_2 should be smaller for bromide than for chloride and smaller for nitrite than for nitrate. A decrease of K_2 results in a dramatic effect on the reaction rate according to Eq. (5). The magnitude of this effect also depends on CEES concentration. For example, Eq. (5) predicts that a 4-fold decrease in the equilibrium constant, K_2, results in a 2-fold increase in the reaction rate at 0.37 M of CEES. Thus, a higher

activity for NO_2^- and Br^- (at least partly)-ligated species can be attributed to a decrease of K_2 for these ligands.

Inhibition of the reaction by the product, CEESO, was noted in the previous work [18] (also see Section 4.4) and proposed to arise from formation of inactive complex **2'** (Scheme 2) with the sulfur ligands, analogous to **2**, but with one of the CEES ligands replaced by a CEESO. The complex with two sulfoxide ligands, **2''**, forms analogously and is also inactive (Scheme 2). If replacement of bromide or nitrite with CEESO in a complex similar to **1** is more difficult than replacement of chloride or nitrite, then product inhibition is less pronounced.

The appearance of an induction period in CEES oxidation is likely to be linked to a slow reoxidation of Au(I) by dioxygen at the beginning of the reaction [18]. However, since reoxidation is not a rate-limiting step during the main catalytic process, it was not possible to assess the effect of ligand or solvent substitution on the rate of Au(I) reoxidation.
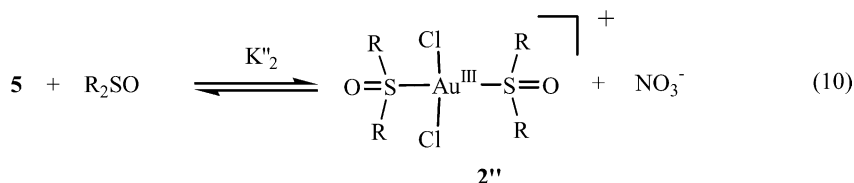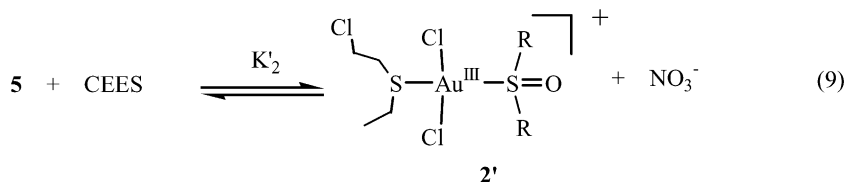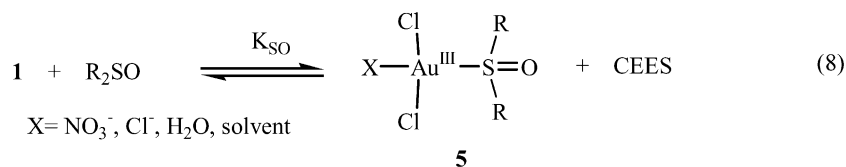
4.3. Solvent effect

The effect of solvent was evaluated for those solvents that produced completely homogeneous Au(III)-based catalytic systems (acetonitrile, trifluoroethanol, nitromethane and 1,2-dichloroethane). The PFPE solvents discussed below result in high rate of catalyst turnover but these systems are heterogeneous (at least one component is insoluble).

Solvent molecules may also bind to Au(III), Eq. (1) in Scheme 1, or shift the equilibrium between a cation **2** and neutral **1** (Eq. (2)). Acetonitrile binding to both Au(III) and Au(I) complexes is well precedented [36–38]. Canovese et al. studied the solvolytic equilibrium, Eq. (6),

$$\text{AuCl}_4^- + \text{MeOH} \overset{K_S}{\rightleftharpoons} \text{AuCl}_3(\text{MeOH}) + Cl^- \qquad (6)$$
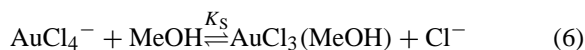
in MeOH–H_2O (95:5, v/v) and found K_S to be $3.4 \times 10^{-4}\,\text{M}^{-1}$ [39] implying that 90% of total Au(III) (at 5 mM) is in the form $\text{AuCl}_3(\text{MeOH})$. In contrast, trifluoroethanol, nitromethane, and 1,2-dichloroethane are likely to coordinate weakly if at all with the Au complexes. The equilibrium constant for the displacement of heterocyclic amines (e.g. pyridine, py)

$$\mathbf{1} + R_2SO \xrightarrow{\ K_{SO}\ } \underset{\mathbf{5}}{\quad X-\overset{\overset{\displaystyle Cl}{|}}{\underset{\underset{\displaystyle Cl}{|}}{Au^{III}}}-\overset{\overset{\displaystyle R}{/}}{\underset{\underset{\displaystyle R}{\backslash}}{S}}{=}O\quad} + \ CEES \qquad (8)$$

X= NO$_3^-$, Cl$^-$, H$_2$O, solvent

$$\mathbf{5} + CEES \xrightarrow{\ K'_2\ } \left[\underset{\mathbf{2'}}{\quad \overset{\overset{\displaystyle Cl}{\backslash}}{\underset{\underset{\displaystyle}{/}}{S}}-\overset{\overset{\displaystyle Cl}{|}}{\underset{\underset{\displaystyle Cl}{|}}{Au^{III}}}-\overset{\overset{\displaystyle R}{/}}{\underset{\underset{\displaystyle R}{\backslash}}{S}}{=}O\quad}\right]^{+} + \ NO_3^- \qquad (9)$$

$$\mathbf{5} + R_2SO \xrightarrow{\ K''_2\ } \left[\underset{\mathbf{2''}}{\quad O{=}\overset{\overset{\displaystyle R}{\backslash}}{\underset{\underset{\displaystyle R}{/}}{S}}-\overset{\overset{\displaystyle Cl}{|}}{\underset{\underset{\displaystyle Cl}{|}}{Au^{III}}}-\overset{\overset{\displaystyle R}{/}}{\underset{\underset{\displaystyle R}{\backslash}}{S}}{=}O\quad}\right]^{+} + \ NO_3^- \qquad (10)$$

Scheme 2. Mechanism of acceleration and inhibition by sulfoxides of O$_2$-based oxidation of thioethers catalyzed by Au(III)Cl$_2$NO$_3$(thioether) (**1**).

in Au(III), Eq. (7):

$$AuCl_3py + Cl^- \underset{K_7}{\rightleftharpoons} AuCl_4^- + py \qquad (7)$$
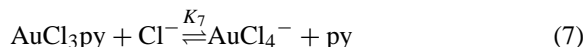
was found to be very sensitive to the nature of the solvent. The equilibrium constant K_7 changes from 25 in C$_6$H$_5$CH$_2$OH to 0.085 in CH$_3$CH$_2$OCH$_2$CH$_2$OH [40]. The equilibrium (Eq. (2) in Scheme 1) between a neutral and positively charged complex, **1** and **2**, respectively, should depend on the solvent polarity. Increasing the solvent polarity drives Eq. (2) to the right, which increases K_2. Thus, the concentration of the active complex **1** and hence the overall reaction rate should correlate with solvent.

In the rate-limiting step, Eq. (3) in Scheme 1, two charged species, chlorosulfonium and nitrate ions, are formed. Their charge separation is also likely to be affected by the solvent polarity. Specifically, k_1 is expected to be larger in more polar solvents. Increasing k_1 would lead to an increase in the overall rate, Eq. (5). Thus, predicting the effect of the solvent on the overall rate could be difficult a priori because K_2 and k_1 impact the rate in opposite directions. Of the solvents leading to completely homogeneous catalytic system, the highest oxidation rate was observed in trifluoroethanol, which is less polar, than acetonitrile.

This high rate is likely due to a shift Eq. (2) to the left (decrease K_2). This assumption is in accordance with the weak product inhibition observed in trifluoroethanol. Formation of the positively charged inactive Au(III)Cl$_2$(CEES)(R$_2$SO) complex (analogous to **2**) is less favorable in less polar solvents and thus the extent of inhibition should be lower. For example, CEES oxidation proceeds easily to almost complete conversion in trifluoroethanol, but significant inhibition occurs in acetonitrile, Fig. 3 (see also Section 4.4 on the DMSO effect).

In this work, we have also found that an induction period, which is observed in CH$_3$CN, is not significant, if it exists at all, in other solvents. In the previous study we reported that the length of this induction period depends on dioxygen concentration and, therefore, is likely to depend on the rate of Au(I) oxidation by dioxygen. As was previously mentioned (Section 4.2), this latter reaction is not rate-limiting in the catalytic process making it impossible to assess a solvent's effect on the rate.

4.4. Effect of Cu(II) ions

The addition of Cu(II) salts markedly increases the reaction rate, eliminates the induction period

and eliminates inhibition by sulfoxide product. Given that Au(III) + CEES is rate-limiting and Au(I) + O_2 is not, an increase in the reaction rate by Cu(II) is likely attributable to the formation of intermediate Au(III)–Hal–Cu(II) complexes, where Hal is Cl^- or Br^-. Additional withdrawal of electron density from Au(III) by Cu(II) makes the electron transfer from CEES to Au(III) more facile, thereby increasing k_1 and accelerating the overall reaction rate. Au(III)–Hal–Cu(II) moieties are precedented. Indeed, a copper(II) chloroaurate(III) complex, $CuAu_2Cl_8 \cdot 6H_2O$, with Au(III)–Hal–Cu(II) unit has been characterized (GMELIN registry number 177659). This complex is formed by neutralization of $HAuCl_4$ with $CuCO_3$ [41]. A withdrawal of electron density from Au(III) by Cu(II) makes the Au(III)–NO_3^- ionic bond stronger, and thus a replacement of nitrate by CEESO is less favorable resulting in less product inhibition.

4.5. Effect of DMSO

DMSO has been used as a model for the CEESO product and found to inhibit the rate of CEES oxidation in the previous study [18]. However, the more thorough evaluation of the DMSO dependence in this work reveals that at low DMSO concentrations (<0.03 M), the initial reaction rate increases and then subsequently decreases with increasing [DMSO] with a maximum observed at ∼10 mM DMSO (Fig. 4).

The following model, based on Scheme 2 alone, has been used to describe this provocative dual effect of DMSO (apparent acceleration followed by inhibition). Equilibria for reactions of DMSO with Au(III) are similar to those of CEES. DMSO forms complexes **5**, **2′** and **2″** (Scheme 2). Complex **5** is an analog of **1**, while **2′** and **2″** are analogous of **2**.

Equilibria and mass balance expressions lead to Eqs. (11) and (12) (the derivations in Appendix A):

where $A = K_2[\text{CEES}] + K_2' K_{SO}[R_2SO] + K_2'' K_{SO} [R_2SO]^2/[\text{CEES}]$.

Eqs. (11) and (12) for [**1**] and [**5**] lead to the reaction rate law in Eq. (13).

$$\frac{d[\text{CEESO}]}{dt} = k_1[\mathbf{1}][\text{CEES}] + k_5[\mathbf{5}][\text{CEES}] \tag{13}$$

In order to simplify the fitting procedure, it was assumed that $K_2' = K_2''$; k_1 was not varied but set at $0.12 \, M^{-1} \, s^{-1}$ based on the fitting of the DMSO inhibition data at high DMSO concentration in the previous paper [18]. The best fit at two different initial CEES concentrations was obtained using the following values: $k_5 = 1.1 \times 10^2 \, M^{-1} \, s^{-1}$ (which is three orders of magnitude higher than $k_1 = 0.12 \pm 0.05 \, M^{-1} \, s^{-1}$); $K_{SO} = 1.1$; $K_2' = K_2'' = 30$. The results of fitting of experimental data d[CEESO]/d*t* versus [DMSO] for initial rates are the solid lines in Fig. 4.

Complex **5** contains a DMSO ligand that withdraws more electron density from the Au center resulting in a higher potential than **1**, and a faster reduction by CEES, $k_5 \gg k_1$. Au(III) is isoelectronic to Pt(II) and both metals tend to form square planar complexes. A study of the *cis*-[PtCl$_2$PPh$_3$L] complexes (where L are different thioethers and their sulfoxides) revealed that the potentials of the sulfoxide complexes are 200–250 mV higher than those the corresponding thioether complexes [42].

From the crystal structures of *cis*-[PtCl$_2$(DMS) (DMSO)], *cis*-[PtCl$_2$(DMS)$_2$] and *cis*-[PtCl$_2$(DMS)$_2$] it is evident that the Pt–S(DMSO) bond distances are 0.02–0.05 Å shorter than the corresponding Pt–S(DMS) bond distances [43–45]. This difference is considered significant for these types of compounds and is attributed to a stronger covalent bond between DMSO and Pt(II) [43–45]. Steric hindrance may be another factor in the preferential binding of DMSO relative to CEES (CEES is more bulky). Thus sulfoxides would be expected to bind more strongly to Au(III) than thioethers, $K_{SO} > 1$ (Eq. (8)). While the above fitting resulted in $K_{SO} = 1.1$, this value was

$$[\mathbf{1}] = \frac{(\sqrt{A + 4[\text{Au(III)}]_T(1 + K_{SO}[R_2SO]/[\text{CEES}])} - \sqrt{A})^2}{4(1 + K_{SO}[R_2SO]/[\text{CEES}])^2} \tag{11}$$

$$[\mathbf{5}] = \frac{K_{SO}[\mathbf{1}][R_2SO]}{[\text{CEES}]} \tag{12}$$

derived from a simplification of the fitting procedure. More detailed analysis reveals that better fitting can

be obtained if $K_2'' > K_2'$ resulting in $K_{SO} \gg 1$.[4] Additional evidence that sulfoxides actually bind more strongly to Au(III) than thioethers comes from an analysis of the kinetics of inhibition by the CEESO formed [18].

At higher DMSO (or CEESO) concentrations the overall reaction slows because inactive complexes **2′** and **2″** form. Since sulfoxides bind to Au(III) more tightly than thioethers, the inhibition is observed at [DMSO] < [CEES]. The formation of inactive complexes is accompanied by a formation of charged nitrate anion and a large Au(III) cation, **2′** or **2″**. The charge separation and the formation of these charged species should be more favorable in a polar solvent such as CH_3CN and less favorable in trifluoroethanol. Therefore, product inhibition is less prevalent in the latter solvent. Au(III)–Br complexes are larger than similar Au(III)–Cl complexes (ionic radii of Cl^- and Br^- in crystals are 1.81 and 1.96 Å, respectively) and the enthalpy of hydration decreases in water in the order $F^- > Cl^- > Br^- > I^-$ [46] resulting in a less favorable formation of the analogous bromide complexes, **2′** and **2″**. As a consequence, product inhibition is less severe in the Au(III)/$(Br^-)_2$/NO_3^-/O_2 than in the Au(III)/$(Cl^-)_2$/NO_3^-/O_2 system.

4.6. Reactions in perfluorinated media

The aerobic oxidation of CEES was then pursued in PFPE media for two reasons: the PFPEs are the principal components of TSPs, and they are effectively non-toxic. To our surprise, the Au(III)-based catalysts are active for selective aerobic sulfoxidation of CEES in the PFPE oil Galden D-02® (representative data in Table 1) and highly active in the PFPE surfactant Fomblin MF-300® (representative data in Tables 2 and 3 and Fig. 5). Making these results even more provocative is the fact that the catalyst components (precursors) are totally insoluble in Galden D-02® and only slightly soluble in Fomblin MF-300®. (Solubility in the latter increases when CEES is present because the Au(III) precursor, $TEAAuCl_2$,

is soluble in Fomblin.) As for the reactions in homogeneous solution (acetonitrile, trifluoroethanol, nitromethane and 1,2-dichloroethane), the reactions in PFPE suspension also require NO_3^- for activity. When NO_3^- is present, the same co-catalytic effect of some d-block metals, particularly Cu(II), that is seen in the homogeneous systems is also seen in the heterogeneous PFPE systems. In short, some of the Au(III)/$(Cl^-)_n$/$(NO_3^-)_n$/PFPE catalysts for selective O_2 oxidation show considerable promise. Since these systems are heterogeneous, a full evaluation of the kinetics is not possible. However, given the similarity of the homogeneous and heterogeneous systems (the same products and selectivity ~100% CEESO, the simultaneous requirement for both halide and NO_3^- for activity, and the co-catalysis by Cu(II), etc.), it is a reasonable inference that the key features of the mechanisms in the two types of media are very similar.

4.7. Effect of amino acids

The results (Table 3) clearly show that while several amino acids inhibit the aerobic sulfoxidation of CEES catalyzed by Au(III) systems, this inhibition is not major. These data and the likely possibility that few Au(III) centers in the actual Au(III)-catalysts in a deployed TSPs would have direct molecular contact with the amino acids in the skin suggest that epidermal polypeptides would probably have little impact on the catalytic aerobic decontamination of mustard by TSPs containing the suspended Au(III)-based catalysts.

5. Conclusions

The most efficient catalytic system for the selective aerobic oxidation of mustard (HD) simulants (CEES oxidation to CEESO) under ambient conditions in non-toxic media (PFPE oil) has been developed.

1. Oxidation of CEES by O_2 can be carried out in a variety of solvents. Some solvents result in a homogeneous catalytic system (acetonitrile, trifluoroethanol, nitromethane and 1,2-dichloroethane) and some result in heterogeneous catalytic systems (PFPE oil). The reaction rate, induction period, and the extent of product inhibition are dependent on the choice of solvent. The reaction has been

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[4] If $K_2'' > K_2'$ the fitting requires a simultaneous change of four independent parameters, which results in several local minima. For these minima the sums of the difference between experimental and theoretical values were very similar. The correct set of varied parameters (K_{SO}, K_2', K_2'' and k_5) could not be specified.

conducted in solvents, which are models for the components present in TSPs.

2. The addition of redox active metals, such as Cu(II) significantly increases the reaction rate, shortens the induction period, and minimizes inhibition by sulfoxide product.

3. Ligand substitution on Au(III) can have a dramatic effect on reaction rate and product inhibition. The replacement of NO_3^- with NO_2^- and Cl^- with Br^- increases the reaction rate. CEES oxidation proceeds to a significantly higher conversion in the $Au(III)/(Br^-)_2/NO_3^-/O_2$ system than in the $Au(III)/(Cl^-)_2/NO_3^-/O_2$ system. The addition of Cu(II) to the former complex results in 99% conversion of CEES to CEESO (not detectable sulfone, $CEESO_2$, forms).

4. Sulfoxides have a dual effect on the reaction rate. The induction period decreases while the oxidation rate increases when some sulfoxide is present. However, higher concentrations of sulfoxide inhibit the reaction.

5. These Au(III)-based catalysts remain active in the presence of most amino acids, which, because they are present in the surface or cornified layers of human skin, could, in principal, affect the aerobic decontamination of mustard (or CEES) by the TSP once it has been applied to the skin. Some amino acids exhibit moderate inhibition of aerobic CEES oxidation.

Acknowledgements

Appendix A

Scheme 2, equilibria and mass balance give:

$$[\mathbf{5}] = \frac{K_{SO}[\mathbf{1}][R_2SO]}{[CEES]}$$

$$[\mathbf{2}] = \frac{K_2'[\mathbf{1}][CEES]}{[NO_3^-]}$$

$$[\mathbf{2'}] = \frac{K_2'[\mathbf{5}][CEES]}{[NO_3^-]}$$

$$[\mathbf{2''}] = \frac{K_2''[\mathbf{5}][R_2SO]}{[NO_3^-]}$$

$$[NO_3^-] = [\mathbf{2}] + [\mathbf{2'}] + [\mathbf{2''}]$$

$$[\mathbf{1}] + [\mathbf{2}] + [\mathbf{2'}] + [\mathbf{2''}] + [\mathbf{5}] = [Au(III)]_T$$

$$[NO_3^-] = [\mathbf{2}] + [\mathbf{2'}] + [\mathbf{2''}] = \left(\frac{1}{[NO_3^-]}\right)$$
$$\times (K_2[\mathbf{1}][CEES] + K_2'[\mathbf{5}][CEES]$$
$$+ K_2''[\mathbf{5}][R_2SO]) = \left(\frac{[\mathbf{1}]}{[NO_3^-]}\right)$$
$$\times \left(\frac{K_2[CEES] + K_2'K_{SO}[R_2SO] + K_2''K_{SO}[R_2SO]^2}{[CEES]}\right)$$

$$[NO_3^-]^2 = [\mathbf{1}]\left(\frac{K_2[CEES] + K_2'K_{SO}[R_2SO] + K_2''K_{SO}[R_2SO]^2}{[CEES]}\right)$$

$$[Au(III)]_T = ([\mathbf{1}] + [\mathbf{5}]) + ([\mathbf{2}] + [\mathbf{2'}])$$
$$= ([\mathbf{1}] + [\mathbf{5}]) + [NO_3^-]$$
$$= [\mathbf{1}]\left(\frac{1 + K_{SO}[R_2SO]}{[CEES]}\right) + ([\mathbf{1}])^{0.5}$$
$$\times \left(\frac{K_2[CEES] + K_2'K_{SO}[R_2SO] + K_2''K_{SO}[R_2SO]^2}{[CEES]}\right)^{0.5}$$

Solving these equations against [**1**] gives Eqs. (11) and (12).

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