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Electrocatalytic Oxidation of Thiols on a TEMPO Modified Electrode

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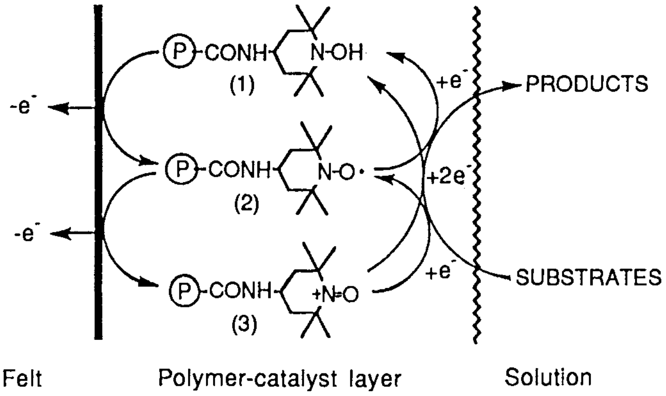
Monothiols were oxidized efficiently and quantitatively to disulfides on graphite felt electrode coated with 4-amino-2,2,6,6-tetramethylpiperidinyl-1-oxyl (4-amino-TEMPO). The 4-amino-TEMPO was immobilized through an amide linkage with poly(acrylic acid). The poly(acrylic acid) was cross-linked with 1,6-diaminohexane, and the residual carboxyl groups were methylated with diazomethane. The electrode was stable and could be used repeatedly.

In the previous work,[1,2] we prepared graphite felt electrodes coated with nitroxides and studied their use in the selective oxidation of alcohols. Semmelhack et al.[3] developed the electrocatalytic oxidation of alcohols using TEMPO as a homogeneous redox catalyst, and Moutet et al.[4] reported the electrocatalytic oxidation of several alcohols on a 2,2,5,5-tetramethyl-3-pyrrolin-1-oxyl modified carbon felt electrode. However, the use of TEMPO in the electrocatalytic oxidation of substrates other than alcohols has not been reported.

TEMPO is a stable organic radical, and both it and its oxidized species, a nitrosonium salt, are known to be specific and useful oxidizing agent.[5] Its catalytic redox mechanism on an electrode surface can involve one of two possibilities. First, the nitroxide (2) can serve as an oxidizing agent and be regenerated by the electrode. Second, the nitroxide can be



Scheme 1. Mechanisum of electrocatalytic oxidations of TEMPO modified electrodes.

oxidized to a nitrosonium salt (3) which is the oxidant. In the process, both nitroxides and nitrosonium salts are probably reduced to hydroxylamines (1) which are reoxidized to complete the catalytic cycle (Scheme 1). The nitroxide-hydroxylamine couple is a one-electron process, and the nitrosonium salt-hydroxylamine couple is a two-electron process. Our alcohol work,$^{1,2)}$ surely involves the nitrosonium salt and is a two-electron reaction.

The graphite felt electrodes (National Carbon WDF) were coated with poly(acrylic acid) (PAA) using a 0.25% solution in methanol, as opposed to the 2.5% previously reported.$^{2)}$ The electrodes were crosslinked with 1,6-diaminohexane and treated with 4-amino-TEMPO. In both cases, dicyclohexylcarbodiimide was used as a coupling reagent. The remaining carboxyl groups were methylated with diazomethane since the carboxyl group is known to catalyze the decomposition of nitrosonium salts.$^{5,6)}$ The density of TEMPO on the electrode was determined to be 0.020 mmol/cm^3. The thickness of the polymer layer was estimated to be about 400 angstroms (based on a surface area of 0.7 m^2/g for the felt).

Preparative, potential-controlled electrolyses were performed in acetonitrile (CH_3CN) solution using an H type divided cell separated by cationic exchange membrane (Nafion 117). The anolyte contained 30 mmol of substrate (15 mmol in the case of 1,3-propanedithiol), 20 mmol of fluorene as a gas chromatographic (GC) standard, 30 mmol of 2,6-lutidine, and 8 mmol of $NaClO_4$ (electrolyte) in a total volume of 40 ml. The addition of 2,6-lutidine to the solution increased the velocity of the reaction, as noted in the oxidation of alcohols.$^{2)}$ The catholyte contained 8 mmol of $NaClO_4$ electrolyte in a volume of 40 ml. Controlled electrolysis was carried out at +0.90 V (vs. SCE). During electrolysis, samples were taken for analysis by GC (Silicon OV-17, raising temp 6 °C/min from 100 to 220 °C, inj. temp 260 °C).

The results from GC analysis of the oxidations of benzyl thiol and benzyl alcohol are shown in Fig. 1. Benzyl alcohol was oxidized to benzaldehyde selectively with a turnover number of 158 during 12 hours of electrolysis. However, the current value gradually decreased, and the electrode was deactivated, as shown in Fig. 2 by cyclic voltammetry. On the other hand, the electrocatalytic oxidation of benzyl thiol proceeded smoothly. The current efficiency was more than 94%, and selectivity for the formation of dibenzyl disulfide was quantitative. The slowing down in the rate of charge transfer in Fig. 1 is due to the decreasing concentration of substrate. After 21.5 hours, the substrate was consumed almost completely, and the turnover number was 375. The unchanged reactivity of the electrode is shown in Fig. 2. The peak current of the used electrode was almost equal to that of an unused one.

The results of electrocatalytic oxidation of other thiols are shown in Table 1 together with that of benzyl thiol. All monothiols were oxidized to the corresponding disulfides, with current efficiencies of more than 94%, no by-products (100% selectivity). In all cases except 1,3-propanedithiol, the turnover number was 375. 1,3-Propanedithiol was oxidized to dithiolane by an intramolecular cyclization with current efficiency of only 68% and a low turnover number of 265 before electrode deactivation. This

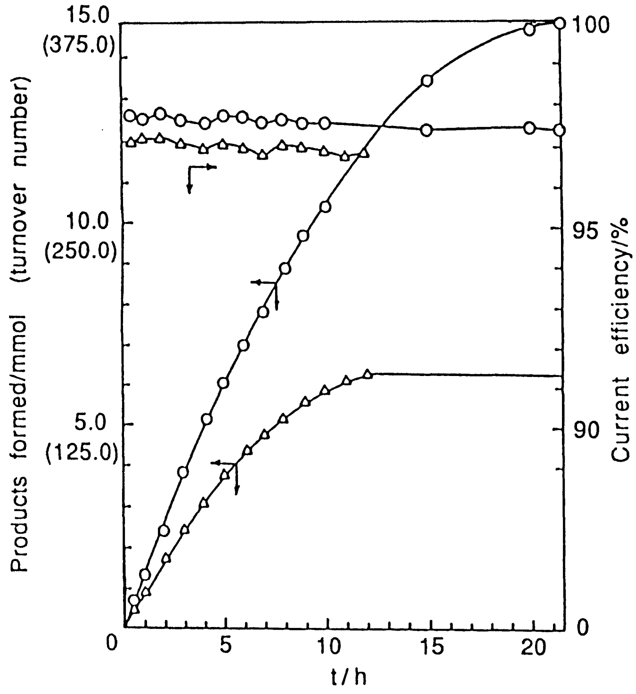


Fig. 1. Macroelectrolysis of benzyl thiol and benzyl alcohol on TEMPO-modified electrode. Turnover number is given by 2 x mol of product /mol of TEMPO. o:benzyl thiol. Δ:benzyl alcohol.

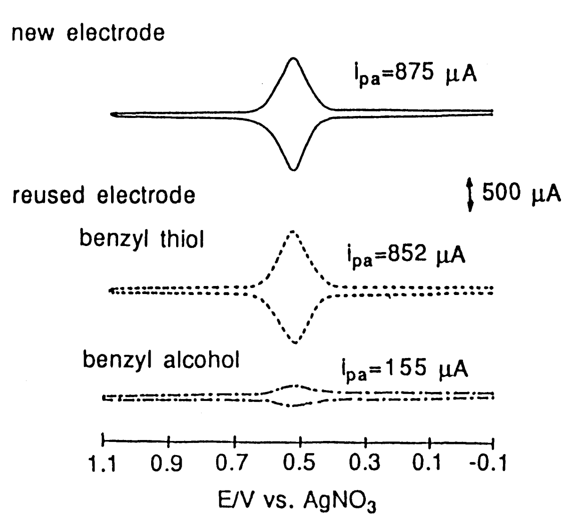


Fig. 2. Cyclic voltammograms of the new and the reused electrodes for oxdation of benzyl thiol and benzyl alcohol in 0.2 M $NaClO_4/CH_3CN$ at the scan rate of 10 mV S^{-1}.

Table 1. Electrocatalytic Oxidation of Thiols on a TEMPO Modified Electrode

Substrate	Product	Charge passed/C	Current efficiency/%	Turnover number	Electrolysis time/h
Butanethiol	dibutyl disulfide	3057	94.7	375	20.5
1-Methyl-1-propanethiol	di-*s*-butyl disulfide	3006	96.3	375	31.3
2-Methyl-2-propanethiol	di-*t*-butyl disulfide	2927	98.9	375	43.5
Benzenethiol	diphenyl disulfide	2936	98.6	375	14.0
2-Pyridinethiol	2,2'-dipyridyl disulfide	2932	98.7	375	17.5
Benzyl thiol	dibenzyl disulfide	3060	94.6	375	21.5
1,3-Propanedithiol	1,2-dithiolane	3084	68.0	265	24.3
N,N-Diethyldithio-carbamic acid	bis(diethyldithio-carbamoyl) disulfide	2969	97.5	375	45.3

appeared to be due to polymer formation. Oxidation rates were estimated from electrolysis times and appeared to be in the order of aromatic < primary < secondary < tertiary. Blank reactions carried out on uncoated felts showed that only 2-pyridinethiol was oxidized below + 0.90 V. The product was the disulfide in low current efficiency, about 65%.

The oxidation of thiols to disulfides is generally considered to be a radical, one-electron process.7) In solution studies, we have shown that both nitroxides and nitrosonium salts oxidize thiols to disulfides. The nitrosonium salt reaction is very fast, and the nitroxide reaction is slow. The oxidation of thiols to disulfides and sulfonic acids with nitroxides has been observed by Liu and his coworkers8,9) and others.10) In view of the slowness of our reactions and the stability of the electrodes, we believe that the reaction described above is a one-electron reaction carried out by the nitroxide.

We are exploring the electrocatalytic oxidation of other substrates and trying to clarify the electrode deactivation observed in the oxidation of alcohols.

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