

Electro-organic Reactions. Part 24.† Preparative and Mechanistic Aspects of the Anodic Oxidation of Dithioacetals and 1,3-Dithianes

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Anodic oxidation of the title compounds is a convenient and efficient method for deprotection, *i.e.* for the regeneration of carbonyl compounds.

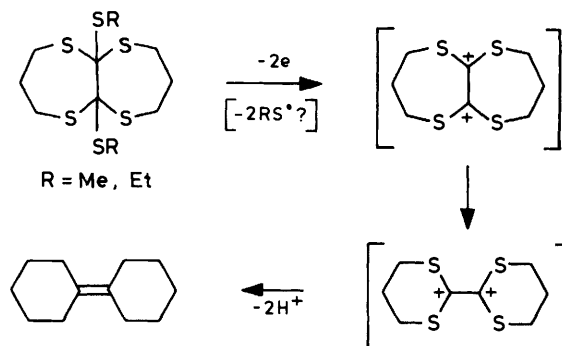
A detailed investigation of the sulphur-containing products confirmed that the initial, 2 F mol⁻¹, products are disulphides which, in aqueous acetonitrile, are oxidised further to alkyl alkanethiosulphinates and the corresponding thiosulphonates. In some cases alkyl polysulphides and *N*-alkylacetamides are important products. Unsymmetrical dithioacetals are oxidised anodically to the three possible disulphides, *i.e.* cross-coupling occurs. Unsymmetrical disulphides are similarly oxidised to a complex mixture of symmetrical and unsymmetrical thiosulphinates and thiosulphonates.

These results, combined with those of cyclic voltammetric and coulometric experiments, suggest a mechanism in which the key step is carbon-sulphur bond cleavage in the initially formed radical cation. The direction of the cleavage is determined by understandable substituent effects.

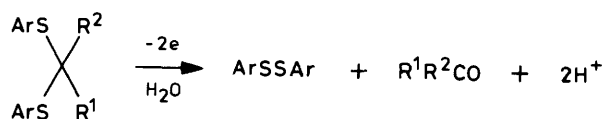
The anodic oxidation of organic sulphides to give mixtures of sulfoxides, sulphones, and sulphonic acids, has been long known but of little synthetic use because of the apparent lack of selectivity.¹ Uneyama and Torii demonstrated² that the pattern of anodic fragmentation of phenyl sulphides was dependent on the structure, *e.g.* thioanisole gave, in wet acetonitrile, phenyl methyl sulfoxide (74%) whereas phenyl triphenylmethyl sulphide gave diphenyl disulphide (48%) as the only sulphur-containing product. Furthermore, it was shown³ that the similar oxidation of diphenyl sulphide gave diphenyl-*p*-(phenylthio)phenylsulphonium perchlorate in dry acetonitrile but increasing amounts of diphenyl sulfoxide as increasing amounts of water were added. In a further development Chambers and co-workers⁴ were able to realise several preparatively interesting anodic cleavages of organosulphur compounds (*e.g.* Scheme 1) and, in the course of this work, cyclic voltammetric experiments pointed to probable rearrangements of cationic intermediates of the sort shown in Scheme 1.

Rearrangements of such intermediates had also come under consideration as possible steps in the efficient anodic production^{5,6} of diaryl disulphides from *gem*-disulphides (Scheme 2).

Most early investigations were mainly concerned with the identification of sulphur-containing products; however, it was well established⁶ that if water were present, carbonyl compounds could be efficiently produced following carbon-sulphur bond cleavage. The preparative possibilities of this aspect of anodic oxidation were demonstrated⁷ by the anodic cleavage, in wet organic solvents, and at a platinum anode, of a number of 1,3-dithianes. The yields of aldehydes and ketones were in the region of 60–70% and the method constitutes an alternative to the chemical removal of the 1,3-dithiane protecting group. It is worth noting that several of the conventional chemical methods are oxidative, using *e.g.* Ce^{IV} salts,⁸ benzeneseleninic anhydride,⁹ or transition metal-ion induced hydrolysis.¹⁰ Because the reactions of cation radicals of many organosulphur compounds are rapid, oxidative redox catalysis is possible. This has been shown^{11,12} to occur for the reaction between disulphides and anodically oxidised mediators



Scheme 1.



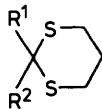
Scheme 2.

[9,10-diphenylanthracene and tris(*p*-bromophenyl)amine]. The electrocatalytic procedure¹¹ involving tris(*p*-bromophenyl)amide or tris(*p*-tolyl)amine is especially useful, giving good yields of carbonyl compounds from 1,3-dithianes in reactions uncomplicated by the electrode fouling which often interferes with the direct anodic method. On the other hand, the mediated electrolysis operates on a small scale (2.5 mmol) and in dilute solution.

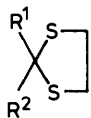
The mechanisms of the anodic chain contraction reaction (Scheme 2) and the related production of carbonyl compounds from 1,3-dithianes has attracted attention.^{6,7} The high efficiency of the cleavage of the dithianes (1) relative to the poor efficiency for the oxidation of the corresponding 2-substituted 1,3-dithiolanes (2) gave rise to the suggestion^{6,7} of bridged dications (3) as key intermediates. These would obviously be formed more readily from dithianes, the reaction proceeding by nucleophilic attack at carbon. Experiments relating to this mechanism have been well summarised and discussed.⁶

In this paper we give a full account of work published in preliminary form⁷ and a report of more recent and

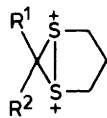
† Part 23, J. D. Hardstone, P. D. Palasz, and J. P. Utley, *J. Chem. Soc., Perkin Trans 2*, 1984, 807.



- (1) a; $R^1 = \text{Ph}, R^2 = \text{H}$
 b; $R^1 = 4\text{-O}_2\text{NC}_6\text{H}_4, R^2 = \text{H}$
 c; $R^1 = \text{Ph}, R^2 = \text{Me}$
 d; $R^1 = 4\text{-O}_2\text{NC}_6\text{H}_4, R^2 = \text{Me}$
 e; $R^1, R^2 = 5\text{-}\alpha\text{-cholestan-3-one}$
 f; $R^1, R^2 = 5\text{-}\alpha\text{-cholest-4-en-3-one}$
 g; $R^1 = R^2 = \text{Me}$



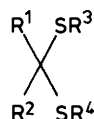
- (2) a; $R^1 = \text{Ph}, R^2 = \text{H}$
 b; $R^1 = R^2 = \text{Me}$



(3)



- (4) a; $R^1 = \text{Ph}, R^2 = R^3 = \text{Et}$
 b; $R^1 = \text{H}, R^2 = R^3 = \text{Et}$
 c; $R^1 = \text{H}, R^2 = R^3 = \text{Pr}^i$
 d; $R^1 = \text{H}, R^2 = R^3 = \text{Bu}^t$
 e; $R^1 = \text{H}, R^2 = \text{Et}, R^3 = \text{Pr}^i$
 f; $R^1 = \text{H}, R^2 = \text{Et}, R^3 = \text{Bu}^n$
 g; $R^1 = \text{H}, R^2 = \text{Et}, R^3 = \text{Bu}^t$
 h; $R^1 = \text{Me}, R^2 = R^3 = \text{Et}$



- (5) a; $R^1, R^2 = \text{-(CH}_2\text{)}_5\text{-}, R^3 = R^4 = \text{Et}$
 b; $R^1 = R^2 = \text{Me}, R^3 = R^4 = \text{Et}$

comprehensive experiments relevant to preparative and mechanistic aspects of the anodic cleavage of 1,3-dithianes (1), 1,3-dithiolanes (2), and thioacetals (4) and (5).

Results and Discussion

Products of Preparative-scale Electrolysis.—Regeneration of carbonyl compounds. The anodic cleavage of *gem*-disulphides, as outlined in Scheme 2, is an efficient method for the regeneration of carbonyl compounds from their dithiane or dithioacetal derivatives. Initial attempts to realise this in dry acetonitrile solution were made difficult by rapid filming of the anode and a concomitant decrease in current. This is a common difficulty for acetonitrile solution electrolysis¹³ and was overcome by the addition of water. A variety of aqueous solvents were explored and the results of preparative experiments are displayed in Table 1. Although no systematic attempt was made to optimise yields, sodium perchlorate was found to be the preferred electrolyte, being easily removed in the aqueous work-up. The reaction clearly tolerates suitable co-solvents, *e.g.* tetrahydrofuran was required to effect solution in the electrolysis of the dithiane derivatives of 5- α -cholestan-3-one and 5- α -cholest-

Table 1. Anodic production^a of carbonyl compounds from the 1,3-dithianes (1), 1,3-dithiolanes (2), and thioacetals (4) and (5)

| Substrate | Electrolyte | Product carbonyl (%) |
|-----------|----------------------------------------------------------------------------|--------------------------|
| (1a) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.1M) | 58 ^b |
| | MeCN-Bu ₄ NClO ₄ (0.25M) | 60 ^b |
| | CH ₂ Cl ₂ -Bu ₄ NClO ₄ (0.25M) | 60 ^b |
| | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.25M) | 77 ^c |
| | HOAc-H ₂ O (5% v/v), NaOAc (0.5M) | 35 ^c |
| (1b) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.25M) | 45 ^d |
| (1c) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.25M) | 66 ^b |
| (1d) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.25M) | 66 |
| (1e) | MeCN-THF (1:1)-H ₂ O (10% v/v), LiClO ₄ (0.1M) | 51 ^d |
| | MeCN-THF (1:1)-H ₂ O (10% v/v), LiClO ₄ (0.1M) | 52 ^d |
| (2a) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.25M) | ca. 5 ^c |
| (4a) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.2M) | PhCHO (76%) ^e |
| | | PhCHO (83%) ^f |
| (5a) | MeCN-H ₂ O (10% v/v), NaClO ₄ (0.2M) | 86 ^g |

^a Platinum gauze anode, divided cell, at or slightly above oxidation peak potential (*ca.* 1.5 V vs. Ag/AgI, see Table 4); to 2 F mol⁻¹. ^b Isolated as the dinitrophenylhydrazone derivative; yields of the free carbonyl compound would be *ca.* 10% higher. ^c Amperostatic electrolysis at 0.03 A cm⁻² to 2 F mol⁻¹. ^d Substrate recovered in 10% yield. ^e At 2 F mol⁻¹ (EtS)₂ *ca.* 29%. ^f At 5 F mol⁻¹. Other major product, EtSO₂SEt (57%); yields by g.l.c. analysis. ^g Other major product, EtSO₂SEt (54%); yields by g.l.c. analysis.

4-en-3-one. The method is practically convenient; electrolysis may be run at constant current and on a several-gram scale. Where anode filming was encountered, even in aqueous solution, brief reversal of polarity or pulsing of the anode to a lower potential restored the electrolysis current. If necessary, scale-up to a much larger scale could be effected.

Although electrolysis was normally terminated at 2 F mol⁻¹, the result for compound (4a), which was electrolysed to 5 F mol⁻¹, suggests that higher yields might be obtained by extended electrolysis. A high current persists well past the 2 F mol⁻¹ point and the implications of this are discussed in detail below.

The dithiolane [Table 1, compound (2a)] is not efficiently oxidised under conditions which give good yields from the other derivatives. The electrochemical behaviour of (2a) and other dithiolanes, is also markedly different from that of the dithianes (Table 4) and these factors are important for the discussion of mechanism.

The sulphur-containing products. These have been examined in detail for the anodic oxidation in aqueous acetonitrile of the thioacetals (4) and (5) and the results are summarised in Table 2. The major conclusion is that only products of chain contraction are observed; no evidence could be obtained for the formation of sulphones or sulphoxides directly produced from the starting materials. The oxygenated materials that were obtained, alkyl alkanethiosulphinates (RSOSR) and the corresponding thio-sulphonates (RSO₂SR), are further oxidation products of the initially formed dialkyl disulphides. Compelling evidence for this is the increased amount of RSO₂SR at high conversion (*e.g.* 2 vs. 4–6 F mol⁻¹). Other products of interest are the *N*-alkylacetamides; these are known to be formed in wet acetonitrile in anodic reactions which involve carbenium ion intermediates.¹⁴ In this case *N*-alkylacetamides were formed only from the isopropyl and *t*-butyl derivatives. The di-*t*-butyl derivative (4d) gives, on oxidation, only traces of the

Table 2. Sulphur-containing products from anodic oxidation^a of the thioacetals (4) and (5)

| Substrate | Potential (V vs. Ag/AgI); consumption (F mol ⁻¹) | Products (%) |
|-----------|-----------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (4a) | 2.1; 2.1 | EtSSEt (22) ^b |
| | 2.04; 4.4 | EtSO ₂ SEt (78) ^c |
| | 1.89; 5.0 | EtSO ₂ SEt (57) ^b |
| (4b) | 1.95; 2.9 | EtSSEt (25) ^d |
| | | EtSOSEt (52) ^d |
| (4c) | 1.95; 5.6 | EtSO ₂ SEt (50) ^d |
| | 1.92; 2.0 | Pr ⁱ SSPr ⁱ (51) ^c |
| | 1.95; 4.6 | [(4c) 15% recovered] Pr ⁱ SSPr ⁱ (11) ^b Pr ⁱ SO ₂ SPr ⁱ (27), CH ₃ CONHPr ⁱ (11) |
| (4d) | 2.18; 2.0 | Bu ⁱ S ₃ Bu ⁱ (31), ^e CH ₃ CONHBu ⁱ (19), [(4d) 22% recovered] |
| | 2.18; 3.6 | Bu ⁱ S ₃ Bu ⁱ (19), ^e Bu ⁱ S ₄ Bu ⁱ (20), ^e CH ₃ CONHBu ⁱ (18) ^e (Bu ⁱ SOSBu ⁱ and Bu ⁱ SO ₂ SBu ⁱ , traces) |
| | | EtSO ₂ SEt (70) ^e |
| (5b) | 2.02; 5.4 | EtSO ₂ SEt (70) ^e |

^a Platinum anode, divided cell, MeCN-H₂O (10% v/v), NaClO₄ (0.1—0.2M), substrate 0.06—0.25M. ^b G.l.c. analysis; some decomposition of alkanethiosulphinates was observed. ^c ¹H N.m.r. analysis. ^d Isolated by t.l.c.; some loss of EtSSEt occurred during work-up. ^e Isolated by column chromatography.

thiosulphinates and thiosulphonates. The major products here, apart from *N*-*t*-butylacetamide, were tri- and tetra-sulphides. It is also worth noting at this point that the last two entries in Table 1 [for compounds (4a) and (5a)] give the results for both the carbonyl and sulphur-containing products; under the preparatively useful conditions the major sulphur-containing product is the thiosulphonate.

Two further preparative results were obtained which are not included in the Tables. The anodic environment is acidic and it is sometimes difficult to assess the importance of acid-catalysed reactions of products initially formed at the anode. Consequently an electrolysis was performed on (4b), at 2.15 V to 4.3 F mol⁻¹, under the conditions described in Table 2 but also in the presence of pyridine (0.68M). The major products were EtSOSEt (*ca.* 20%) and EtSO₂SEt (37%); this is not significantly different from the result obtained in the absence of pyridine (Table 2). A possibly more significant result was obtained from the electrolysis of the sulphoxide, EtSOCH₂SEt. Anodic oxidation of this compound, at 1.98 V to 3.2 F mol⁻¹ in aqueous acetonitrile (as in Table 2), gave the thiosulphonate EtSO₂SEt in 52% isolated yield. This is a clear indication that even if sulphoxides were formed initially they are electroactive and would be converted by further oxidation and chain contraction into thiosulphonates. This route is not considered likely however because sulphoxides and sulphones were not detected at low conversion (2 F mol⁻¹).

The chain contraction outlined in Scheme 2, and observed for the substrates listed in Table 2, invites speculation concerning its intra- or inter-molecular nature. In this context, sulphur-containing products from the anodic oxidation of unsymmetrical thioacetals of the type RSCH₂SR' have been examined. The results are collected in Table 3; for each substrate the products were analysed after *ca.* 2 F mol⁻¹ and after *ca.* 5 F mol⁻¹. At 2 F mol⁻¹ dialkyl disulphides are the predominant product whereas at 5 F mol⁻¹ substantial amounts of

Table 3. Sulphur-containing products from the anodic oxidation^a of the mixed thioacetals (4; R³ ≠ R⁴)

| Substrate | Potential (V vs. Ag/AgI); consumption (F mol ⁻¹) | Products (%) |
|-----------|-----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (4e) | 2.00; 2.0 | EtSSEt (11), ^b EtSSPr ⁱ (26), Pr ⁱ SSPr ⁱ (20) (CH ₃ CONHPr ⁱ detected) ^c |
| | 2.03; 5.1 | EtSO ₂ SEt (25), ^b EtSO ₂ SPr ⁱ and EtSSO ₂ Pr ⁱ (27), ^d Pr ⁱ SO ₂ SPr ⁱ (7), CH ₃ CONHPr ⁱ (21) ^b |
| (4f) | 2.02; 2.1 | EtSSEt (9), ^{b,e} EtSSBu ⁿ (28), Bu ⁿ SSBu ⁿ (16) |
| | 2.04; 5.4 | EtSO ₂ SEt (19), ^b EtSO ₂ SBu ⁿ and EtSSO ₂ Bu ⁿ (32), ^d Bu ⁿ SO ₂ SBu ⁿ (18) |
| (4g) | 2.07; 2.0 | EtSSBu ⁱ (15), ^b EtSSEt (3), ^b CH ₃ CONHBu ⁱ (13) ^f (polysulphides and starting material) ^g |
| | 2.08; 5.1 | EtSO ₂ SEt (27), ^f CH ₃ CONHBu ⁱ (8) (polysulphides) ^h |

^a As for Table 2. ^b G.l.c. analysis. ^c (4e) recovered (10%). ^d Not separated by g.l.c. ^e (4f) recovered (7%). ^f Isolated. ^g Mixture (total 50%) of R¹S_nR² compounds, where *n* = 2, 3, or possibly 4, R¹ = Et, R² = Buⁱ, R¹ = R² or R¹ ≠ R²; analysis by g.l.c., i.r., and ¹H n.m.r. spectroscopy. ^h Probably a mixture (total 31%) of, according to ¹H n.m.r. spectroscopy, diethyl tri- and tetra-sulphides.

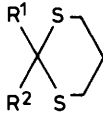
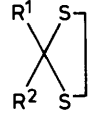

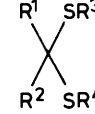
thiosulphonates are obtained. The key feature is that, even at the disulphide stage, the three products of cross-coupling are obtained, *i.e.* RSSR, RSSR', and R'SSR'. Where R or R' is Prⁱ or Buⁱ the corresponding *N*-alkylacetamide is a significant product.

In a related experiment, not included in Table 3, equivalent amounts (0.1M) of (4b) and (4c) were anodically oxidised in aqueous acetonitrile under the conditions listed in Table 2. After reaction to 2.2 F mol⁻¹ at 2.07 V the product distribution according to g.l.c. analysis was: EtSSEt (10%), EtSSPrⁱ (20%), and PrⁱSSPrⁱ (32%). There is therefore some evidence for an intermolecular mechanism but a reliable interpretation hinges upon the starting materials and products being stable to the conditions of electrolysis.

The stability of the starting materials and of the sulphur-containing products. The starting materials do not isomerise under the conditions of the anodic oxidation. In an experiment involving oxidation of EtSCH₂SBuⁿ (4f) under the conditions given in Table 2 the products and starting material were analysed by g.l.c. at intervals (nine) during the passage of 2 F mol⁻¹. No isomerisation of the starting material occurred. The electrolysis was continued to 4.6 F mol⁻¹ at which stage the products were EtSO₂SEt (20%), EtSO₂SBuⁿ-BuⁿSO₂SEt (35%), and BuⁿSO₂SBuⁿ (18%), *i.e.* virtually identical with the result listed in Table 3. The cross coupling occurs therefore at or after the oxidation stage.

The acidic conditions associated with anodic oxidation have been referred to above; it was important therefore to establish that the initial products of oxidation, the disulphides, are stable in acidic solution. Consequently a mixture of EtSSBuⁿ (88%),

Table 4. Oxidation peak potentials by cyclic voltammetry^{a,b}

| Substituents |  |  |  |  |
|----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| R ¹ = R ² = H, R ³ = R ⁴ = Pr ^t | | 2.22 (1.24) ^b | 1.98 | 2.03; ^d 2.20 |
| R ¹ = R ² = H, R ³ = R ⁴ = Bu ^t | | | | 2.14; ^d 2.46 |
| R ¹ = R ² = H, R ³ = R ⁴ = PhCH ₂ | | | | 2.14; ^d 2.23 |
| R ¹ = R ² = H, R ³ = Et, R ⁴ = PhCH ₂ | | | | 2.13; 2.28 |
| R ¹ = R ² = Me | 1.60 | 1.95–2.02 ^c (1.30) ^b | 1.65; ^d 1.95 | |
| R ¹ = Me, R ² = H | 1.72 | 2.01 | 2.01 | |
| R ¹ = Ph, R ² = H | 1.60 | 2.18 (1.32) ^b | 2.00 | |
| R ¹ , R ² = -(CH ₂) ₅ - | 1.58 | 2.04 | 1.65; ^d 1.95 | |
| R ¹ , R ² = H | (1.10) ^b | (1.24) ^b | | |

^a V vs. Ag/AgI, Pt bead anode, 0.3 V s⁻¹, MeCN–NaClO₄ (0.1M), substrate ca. 10⁻³M. ^b Values in parentheses are from ref. 6, vs. Ag/Ag⁺. ^c Broad peak, filming at electrode. ^d Shoulder.

EtSSEt (6%), and BuⁿSSBuⁿ (7%) was stirred for 8 h in the electrolyte with added 70% perchloric acid. The final composition of the mixture was EtSSBuⁿ (79%), EtSSEt (7%), and BuⁿSSBuⁿ (12%). This minor change in composition is to be compared with the result of anodic oxidation, conditions as before, of EtSSBuⁿ which, after 3.7 F mol⁻¹ at 2.1 V gave EtSO₂SEt (19%), EtSO₂SBuⁿ + EtSSO₂Buⁿ (33%), and BuⁿSO₂SBuⁿ (17%). There is, therefore, considerable scrambling during electrolysis and it is perhaps significant that closely similar product mixtures are obtained from the electrolysis of EtSCH₂SBuⁿ (4f) and EtSSBuⁿ.

Electroanalytical Experiments.—Cyclic voltammetry. Anodic oxidation of the compounds under study was irreversible according to cyclic voltammetry; for 2-phenyl-1,3-dithiane (1a) no reverse (reduction) peak was observed on voltammetry at up to 40 V s⁻¹ in dry acetonitrile–LiClO₄ (0.1M). Even in nominally dry conditions the chemical reactions of the oxidised intermediates are fast. There is some indication, however, that a reducible intermediate is formed (see below).

The oxidation potentials, measured by cyclic voltammetry, are included in Table 4. The Table is organised to make easy a comparison between the classes of substrate employed. The lower oxidation potentials (by ca. 0.3–0.4 V) associated with the 1,3-dithianes is well established. When the potential is reversed from the anodic limit a reduction peak is commonly observed at 0.3–0.4 V, provided that the anodic sweep has entered the oxidation region for the substrates. It should be noted at this stage that the major products of preparative electrolysis, the dialkyl disulphides, give oxidation peaks in the region 1.80–2.00 V.

In an experiment aimed at examining the reducible intermediate, (4a) was oxidised to 2.4 F mol⁻¹ in dry acetonitrile–Bu₄NBF₄ (0.1M); the anolyte solution was immediately reduced (on platinum) at –0.6 V (for 1.3 F mol⁻¹) and then at –1.5 V (for 1.1 F mol⁻¹). The reactions were monitored by cyclic voltammetry and it was observed that, after the reduction, an oxidation peak reappeared at the potential associated with the starting material. This result should, however, be treated with caution since the disulphide product oxidises in the same region. Also, it may be significant that only a trace of the starting material was recovered. In other experiments involving (4a), in dry acetonitrile, attempts to isolate and characterise the products failed although it was established that little of the starting material survived the electrolysis.

It is possible to conclude from these experiments that, in dry acetonitrile, a relatively stable reducible intermediate is formed.

Table 5. Controlled potential coulometry^{a,b}

| Compound | <i>n</i> -Values (F mol ⁻¹) | |
|----------|-----------------------------------------|------------------------------------------------------------------|
| | MeCN–NaClO ₄ (0.1M) | MeCN–H ₂ O (10% v/v), NaClO ₄ (0.1M) |
| (4b) | 2.4 | 4.9 (2.2) |
| (4f) | | 4.8 (2.2) |
| (4h) | | 4.9 |
| (5b) | 2.0 | 4.7 |
| (2b) | 2.4 | |
| (1g) | 2.4 | 3.5 |
| (4a) | 2.3 | 4.7 (1.9) |
| (2a) | 2.9 | |
| (1a) | 3.9 | 3.4 |

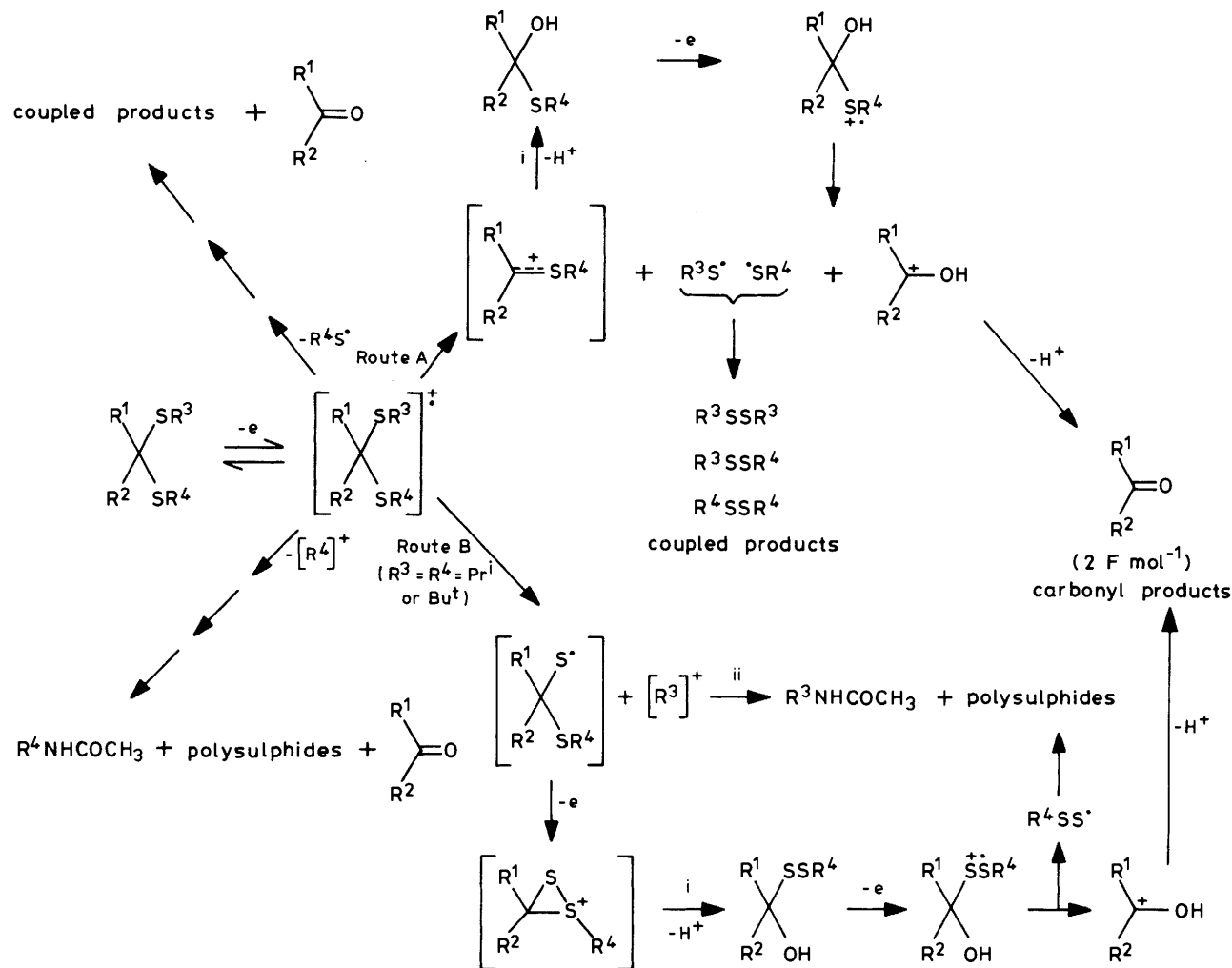
^a By current decay, see Experimental section. ^b Values in parentheses show starting material monitored by g.l.c. analysis.

The restoration of an oxidation peak does not, however, establish the chemical reversibility of the process; the second oxidation peak might well be that of a product and not necessarily that of the starting material. The reducible species could be a nitrilium salt as claimed by Simonet and co-workers.⁶ They refer to the isolation of such an intermediate and propose a structure although the spectroscopic and analytical data have not been published.

Controlled potential coulometry. There is a marked difference between electrolysis in nominally dry acetonitrile and in aqueous acetonitrile. Monitoring of the reaction in the usual way, by current decay, gives *n*-values of ca. 2 F mol⁻¹ under dry conditions but 3–5 F mol⁻¹ in the presence of water. The results of preparative scale experiments (Tables 2 and 3) suggests that in aqueous solution the electrolysis past 2 F mol⁻¹ is associated with oxidation of the disulphides. The results of controlled potential coulometric experiments (Table 5) in which the decay of the starting material is monitored by g.l.c. analysis confirm that even in aqueous solution the starting material is consumed in a 2 F mol⁻¹ reaction.

Rationalisation of mechanism. Uneyama and Torri's early work² points clearly to there being competition between nucleophilic attack at sulphur and cleavage of carbon–sulphur bonds for the radical cations generated anodically from phenyl sulphides (PhSR). Cleavage to PhS⁺ and R⁺ predominates when R⁺ is a relatively stable cation, e.g. R = PhCH₂ and Ph₃C. Sulphoxide formation occurs exclusively when R = Me. Similar factors may be recognised from the results obtained for the oxidation of the dithianes and thioacetals.

Where comparisons can be made there is good agreement



Scheme 3. Reagents: i, H_2O ; ii, $MeCN, H_2O$

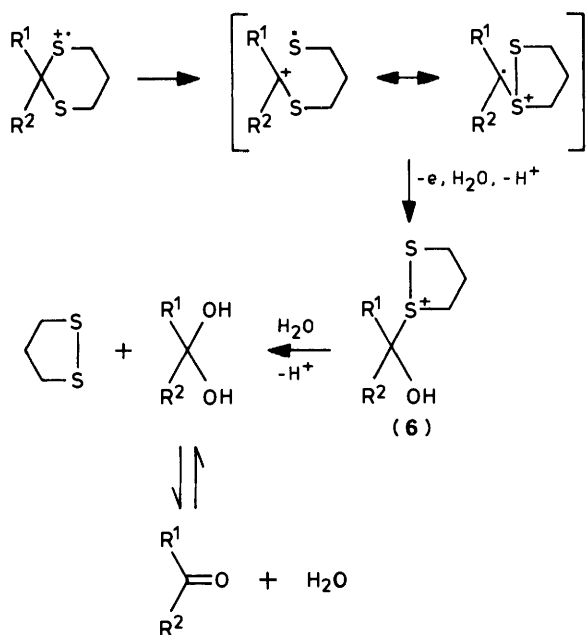
between the results presented in this paper and those of other groups.⁴⁻⁶ In addition we have shown that polysulphide and *N*-alkylacetamide formation is important for compounds of the type $R^1R^2C(SR^3)SR^4$ where R^3 and R^4 are Bu^t or Pr^i . The acetamide formation in particular suggests the formation at some stage of carbocations. Other features of the results which must be accommodated in any explanation include the 2 F mol⁻¹ consumption of starting material in the presence of water, the formation of cross-coupled products, the lower oxidation potentials for the dithianes, and the failure to detect sulphoxides and sulphones which could be formed directly from the starting materials.

Our hypothesis is based on the proposition that the first-formed radical cation, $[R^1R^2C(SR^3)SR^4]^{\cdot+}$, may cleave in each or both of two ways. The possible leaving groups are R^3S^{\cdot} or R^4S^{\cdot} , or $(R^3)^+$ or $(R^4)^+$; the predominant direction of cleavage would be decided, as found by Uneyama and Torii,² by the stabilising nature of the groups R^3 and R^4 . The likely consequence of this are summarised in Scheme 3 which provides a consistent explanation of the facts outlined above.

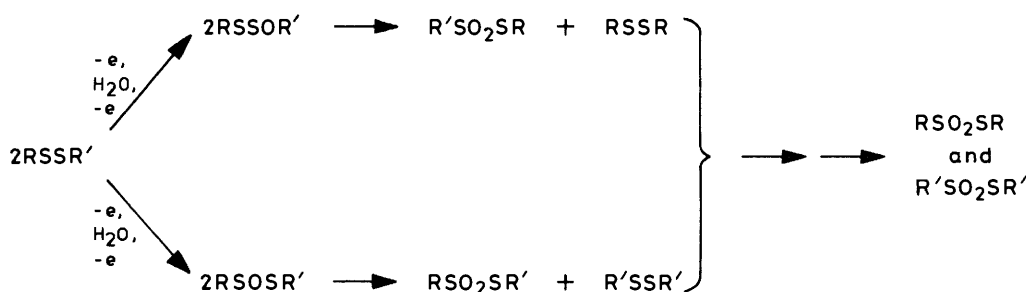
The simplest explanation for the formation of the cross-coupled products is that they arise from dimerisation of the radicals R^3S^{\cdot} and R^4S^{\cdot} ; such coupling, e.g. for MeS^{\cdot} , is known to be diffusion controlled¹⁵ and under electrochemical conditions the sulphur radicals would be formed at the anode at high local concentrations. It is significant that polysulphide formation and

N-alkylacetamide formation go hand in hand. This fact is accommodated in Scheme 3 in which the route involving initial loss of a carbocation $[(R^3)^+ \text{ or } (R^4)^+]$ leads to the formation also of radicals of the type RSS^{\cdot} .

The formation of dicationic species of type (3) has been held⁴⁻⁷ to account for the relatively low potentials for the oxidation of the dithianes; the comparison was with the corresponding dithiolanes for which dication formation will be unlikely as it would involve formation of a four-membered ring. In fact the oxidation potentials for the dithiolanes are similar to those measured for the thioacetals (Table 4); the thioacetals would not be sterically inhibited for dication formation so it would appear that there is a special factor operating for the dithianes. A relatively simple explanation is that the oxidation potentials of the dithianes are decreased because in this case the chemical reactions following electron transfer are especially fast. This is entirely consistent with the relationship between peak potentials and rates of follow-up reactions described first by Nicholson and Shain.¹⁶ A possible reason for especially rapid follow-up reactions in the dithiane oxidation is illustrated by Scheme 4. The second electron transfer would lead to the stabilised cyclic sulphonium ion (6) and the participation of the proximate sulphur atoms in accelerating electron transfer and nucleophilic attack is likely to be more effective for the dithianes than for the other compounds included in this study. A similar lowering of oxidation potential has been observed¹⁷



Scheme 4.



Scheme 5.

for 2-*endo*-methylthiomethyl-6-*endo*-methylthiobicyclo[2.2.1]heptane *vis à vis* the corresponding 2-*exo* isomer. In this case the vertical ionisation potentials for the non-bonding sulphur 3p lone-pair electrons are similar despite the juxtaposition of the sulphur atoms in the *endo* isomer. The difference for solution electron transfer might well arise through rapid follow-up reactions.

The question of the lack of attack at sulphur in the radical cations remains. In all but one of the compounds studied here the pattern of substitution would stabilise carbocationic centres, either of the $R^1R^2C^+$ type or of the $(R^3)^+$ or $(R^4)^+$ type, a factor which in each case would favour C-S bond cleavage. The exception is (4b); from the result given in Table 2 there is an indication from the considerable amount of EtSOSEt formed at 2.9 F mol⁻¹ that oxidation at sulphur had occurred rather earlier in the reaction than for the other compounds. Furthermore it has been established that EtSOCH₂SEt would not survive the conditions of electrolysis. This rather tentative conclusion, concerning the only substrate for which bond cleavage in the radical cations is not especially favoured, may be correct, but, even so, the sulphur-centred radical cations are surprisingly unreactive towards water (or the hydroxide ion). An alternative, and more attractive, explanation is that nucleophilic attack at a sulphur cation by an oxygen nucleophile involves the interaction of 'soft' and 'hard' reagents, respectively. This is an unfavoured interaction¹⁸ and

consequently the rate of nucleophilic attack may be slow relative to bond cleavage in almost all cases.

The consequences of the further oxidation of the initially formed disulphides are more difficult to explain. In summary it was found that, at over 2 F mol⁻¹, increasing amounts of the thiosulphonates and thiosulphinates were formed and that for unsymmetrical disulphides much cross coupling and scrambling occurred (Table 3). Assuming that the oxidation of the disulphide is sequential, and that the thiosulphinates (RSOSR') are the initial products, the formation of the thiosulphonates and the scrambling may be a consequence of disproportionation, well established¹⁹ for mild and acidic conditions (see Scheme 5). In this context it should be remembered that anodic conditions are acidic.

Experimental

Solvents, Electrolytes, and Electrochemical Equipment.—These were essentially as described in earlier papers in this series. The electrolysis cells were of conventional design with sintered glass separators and equipped with platinum gauze or smooth foil anodes.

Dithianes, Dithiolanes, and Dithioacetals.—2-Substituted 1,3-dithianes (1). The general method described by Autenrieth and

Wolff²⁰ was used with little modification. Compounds (1a-f) are known and the physical and spectroscopic data compared well with the literature values.

2-Phenyl-1,3-dithiolane (2a). This was prepared by the method used for the dithianes except that ethane-1,2-dithiol replaced propane-1,3-dithiol.

Dithioacetals (4) and (5). The general method described by Baumann²¹ was used with little modification. Compounds (4a-d) and (5a-b) are known and the physical and spectroscopic data compared well with literature values. The mixed thioacetals (4e-f) were prepared from chloro(ethylthio)methane and the appropriate thiol as described by Bohme and Marx.²² In the case of compound (4g) the sodium thiolate was prepared by treating sodium hydride in dimethyl sulphoxide with 2-methylpropane-2-thiol. *Ethylthio(isopropylthio)methane (4e)* (75%); b.p. 59–60 °C/5 mmHg; $\delta(\text{CCl}_4-\text{SiMe}_4)$ 3.62 (s, 2 H), 3.10 (m, 1 H), 2.63 (q, 2 H), 1.12 (d, 6 H), and 1.10 (t, 3 H); $\nu_{\text{max}}(\text{film})$ 1 450, 1 380, 1 360, 1 260, 1 238, 1 195, 1 150, 1 045, 745, and 722 cm⁻¹ (Found: *M*, 150.0540. C₆H₁₄S₂ requires *M*, 150.0537) (Found: C, 48.0; H, 9.2. C₆H₁₄S₂ requires C, 47.95; H, 9.39%).

t-Butylthio(ethylthio)methane (4g) (75%); b.p. 72 °C/7 mmHg; $\delta(\text{CCl}_4-\text{SiMe}_4)$ 3.62 (s, 2 H), 2.63 (q, 2 H), 1.35 (s, 9 H), and 1.10 (t, 3 H); $\nu_{\text{max}}(\text{film})$ 1 460, 1 365, 1 262, 1 190, 1 160, and 722 cm⁻¹ (Found: *M*, 164.0696. C₇H₁₆S₂ requires *M*, 164.0693) (Found: C, 51.6; H, 10.0. C₇H₁₆S₂ requires C, 51.17; H, 9.81%).

Electrochemical Experiments.—Electroanalytical experiments.

The conditions used for cyclic voltammetry are included in Table 4. Controlled potential coulometry was followed either by the decay in the cyclic voltammetric peak current measured at intervals during an electrolysis or by sampling at intervals and analysing for starting material by g.l.c. The current decay method required the use of specially designed cells and circuitry previously described.²³

Constant current electrolysis. Typically the dithiane (0.2–7.0 g) was dissolved in aqueous acetonitrile (10% H₂O v/v) which was 0.2–0.25M in NaClO₄. This constituted the anolyte in a divided cell equipped with a platinum gauze or foil anode and a carbon rod cathode. The cell current was controlled at 0.03 A cm⁻² for just over 2 F mol⁻¹; this usually took 2–6 h.

The contents of the anode compartment were added to ice-water, and the organic product extracted with chloroform. The chloroform layer was washed (H₂O, aqueous NaOH, H₂O), dried (MgSO₄), and the product isolated after evaporation of the solvent. In some cases the product crystallised, in others it was converted into its 2,4-dinitrophenylhydrazone derivative, and benzaldehyde was isolated by steam distillation.

Constant potential electrolysis. A three-compartment cell equipped with two smooth platinum foil (2 × 2 cm) electrodes and an Ag/AgI reference electrode was used. During the electrolysis the cell was kept in a circulating water-bath at 20 °C. The anolyte was a solution of the dithioacetal (1.0–2.0 g) in aqueous acetonitrile (10% H₂O v/v) which was 0.2M in NaClO₄. After completing the electrolysis two work-up procedures were used. (a) The contents of the anode compartment were poured into ice-water and the organic product extracted with dichloromethane. The organic layer was washed (H₂O, aqueous NaHCO₃, H₂O), dried (MgSO₄), and the solvent evaporated. (b) The anolyte was neutralised with solid NaHCO₃, filtered, the solvent evaporated under reduced pressure, and the organic product extracted with dichloromethane.

Analytical procedures. The crude products were analysed by spectroscopic and chromatographic methods. The components of the reaction mixtures were identified in two ways. (a) By t.l.c. and/or g.l.c. by comparison with the authentic samples, which were prepared by literature procedures. (b) By separation by column chromatography followed by comparison of the spectroscopic data of the isolated components with literature values. The column chromatography was performed on silica gel 50 (Merck Art. 7754). The eluants were hexane, hexane-chloroform mixtures, chloroform, chloroform-ethyl acetate mixtures, and ethyl acetate. ¹H N.m.r. spectra were recorded on a Varian T-60 spectrometer. I.r. spectra were determined with Perkin-Elmer 457 or 283 instruments. Mass spectra were recorded on an AEI MS902 instrument. Gas-liquid chromatography was performed with Hewlett Packard 5830A (column 5% OV-17) or Varian 1860 (columns 3% or 5% QF-1) instruments, either isothermal or temperature programmed. The detector response factors were determined using calibration mixtures or internal standards.

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