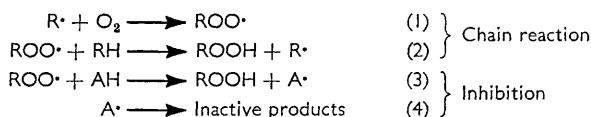


906. *Mechanisms of Antioxidant Action: Sulphur-containing Antioxidants.*

By JOHN D. HOLDSWORTH, GERALD SCOTT, and DEREK WILLIAMS.

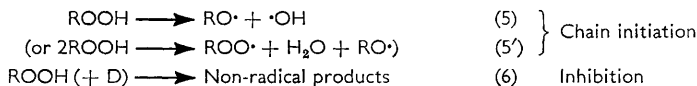
The kinetics of the inhibited oxidation of tetralin are compared with use of two types of initiator and two types of antioxidant. It is established that radical chain-breaking antioxidants (phenols) give an induction period with azodi-isobutyronitrile but a linear rate curve with tetralin hydroperoxide. Peroxide decomposers (*e.g.*, zinc diethyldithiocarbamate) are almost ineffective in a system initiated by azodi-isobutyronitrile but are auto-inhibitive in the presence of tetralin hydroperoxide. These data are consistent with the view that sulphur-containing peroxide decomposers are converted into an effective catalytic non-radical forming hydroperoxide decomposer (probably sulphur dioxide) in a radical-generating reaction.

CONSIDERABLE attention has been devoted recently to the study of the radical-deactivating mechanisms of antioxidant action. In particular the removal of alkylperoxy-radicals by hydrogen (or electron) transfer (3) and (4) has been recognised as the primary function of amines and phenols.¹⁻⁴



where R· is an alkyl radical and AH is a phenol or amine antioxidant.

A second and complementary antioxidant process involving the destruction of chain-initiating hydroperoxides (6) was recognised many years ago by Denison and his co-workers.⁵



where D is a hydroperoxide decomposer.

This type of activity has been found with a variety of sulphur-containing compounds of which the more important are dialkyl monosulphides and zinc dialkyl dithiophosphates⁶ and the metal dithiocarbamates.^{7,8} A notable feature of the antioxidant action of sulphides

¹ Bolland and ten Have, *Discuss. Faraday Soc.*, 1947, **2**, 252; *Trans. Faraday Soc.*, 1947, **43**, 201; Bolland, *ibid.*, 1948, **44**, 669.

² Davies, Goldsmith, Gupta, and Lester, *J.*, 1956, 4926.

³ Boozer, Hammond, Hamilton, and Sen, *J. Amer. Chem. Soc.*, 1955, **77**, 3233, 3238.

⁴ Bickel and Kooyman, *J.*, 1956, 2215; 1957, 2217.

⁵ Denison and Condit, *Ind. Eng. Chem.*, 1945, **37**, 1102; 1949, **41**, 944.

⁶ Kennerly and Patterson, *Ind. Eng. Chem.*, 1956, **48**, 1917.

⁷ Dunn and Scanlan, *Trans. Proc. Inst. Rubber Ind.*, 1958, **34**, 228.

⁸ Imperial Chemical Industries Limited, B.P. 875,601.

is their auto-inhibiting character.⁵ This has been extensively studied by Bateman and his co-workers^{9,10} who have adduced evidence to suggest that sulfoxides and thiosulphates may be the effective antioxidants formed from sulphides and disulphides, respectively.¹⁰

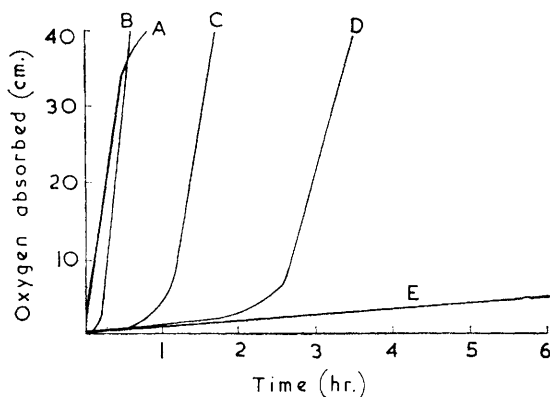


FIG. 1. Effect of phenolic antioxidant [bis-(2-hydroxy-3-1'-methylcyclohexyl-5-methylphenyl)methane] on the oxidation of tetralin in the presence of azodi-isobutyronitrile at 50°.

A, no antioxidant; B, 0.0001 g./2 c.c.; C, 0.0005 g./2 c.c.; D, 0.01 g./2 c.c.; E, 0.025 g./2 c.c.

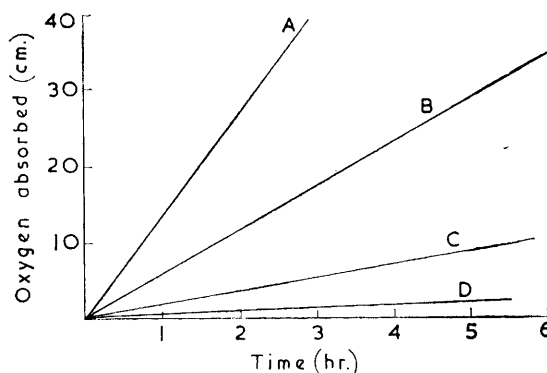


FIG. 2. Effect of phenolic antioxidant (2,4-dimethyl-6-1'-methylcyclohexylphenol) on the oxidation of tetralin in the presence of tetralin hydroperoxide at 50°.

A, no antioxidant; B, 0.00004 g./2 c.c.; C, 0.00008 g./2 c.c.; D, 0.004 g./2 c.c.

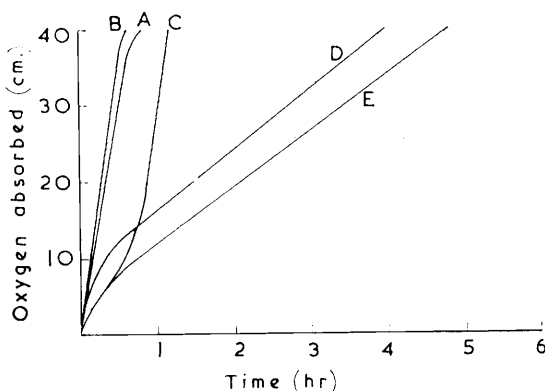


FIG. 3. Effect of peroxide decomposer (zinc diethyldithiocarbamate) on the oxidation of tetralin in the presence of azodi-isobutyronitrile at 50°.

A, no antioxidant; B, 0.0001 g./2 c.c.; C, 0.0004 g./2 c.c.; D, 0.005 g./2 c.c.; E, 0.01 g./2 c.c.

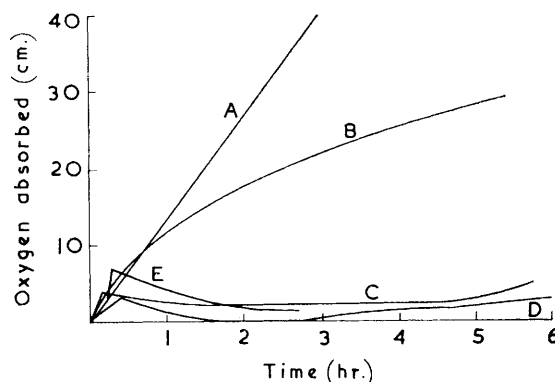


FIG. 4. Effect of peroxide decomposer (zinc diethyldithiocarbamate) on the oxidation of tetralin in the presence of tetralin hydroperoxide at 50°.

A, no antioxidant; B, 0.00004 g./2 c.c.; C, 0.0001 g./2 c.c.; D, 0.0004 g./2 c.c.; E, 0.001 g./2 c.c.

Since peroxide decomposers prevent the autooxidation chain reaction starting by removing the autocatalyst, it should be possible to distinguish this antioxidant mechanism from the chain-breaking mechanism by studying the inhibited autooxidation of tetralin

⁹ Bateman and Cunneen, *J.*, 1955, 1596.

¹⁰ Barnard, Bateman, Cain, Colclough, and Cunneen, *J.*, 1961, 5339.

in the presence of different initiators. Two were chosen. Azodi-isobutyronitrile gives² cyanoisopropyl radicals which react with oxygen to give the chain-initiating peroxy-radical. With a phenolic antioxidant and excess of initiator, typical inhibition of autooxidation was observed (Fig. 1), the induction period increasing with increasing antioxidant concentration. With tetralin hydroperoxide as initiator, no characteristic induction period was evident in the presence of a phenolic antioxidant; instead a steady reduction in the linear rate of oxygen absorption occurred with increasing antioxidant concentration (Fig. 2).

Very different results were obtained with a typical peroxide-decomposing antioxidant, zinc diethyldithiocarbamate, and the same initiators. With the azo-compound (Fig. 3) zinc diethyldithiocarbamate was virtually ineffective up to concentrations at which phenols

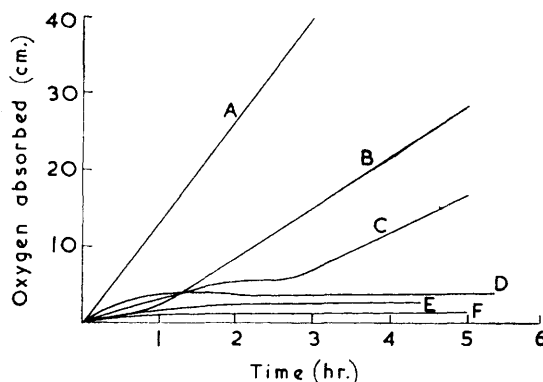
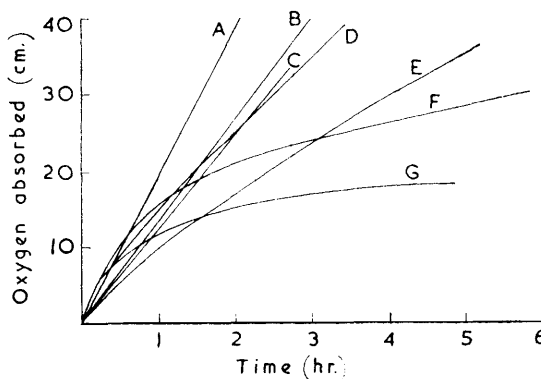


FIG. 5. Effect of peroxide decomposer (zinc dinonyl dithiophosphate) on the oxidation of tetralin in the presence of tetralin hydroperoxide at 50°.

A, no antioxidant; B, 0.0001 g./2 c.c.; C, 0.0005 g./2 c.c.; D, 0.0025 g./2 c.c.; E, 0.005 g./2 c.c.; F, 0.01 g./2 c.c.

FIG. 6. Effect of peroxide decomposer (dilauryl thiodipropionate) on the oxidation of tetralin in the presence of tetralin hydroperoxide at 50°.

A, no antioxidant; B, 0.0001 g./2 c.c.; C, 0.0005 g./2 c.c.; D, 0.001 g./2 c.c.; E, 0.005 g./2 c.c.; F, 0.01 g./2 c.c.; G, 0.05 g./2 c.c.



exert a powerful inhibition. At very much higher concentrations (0.5 w/w) some retardation of oxidation was observed in the later stages of autooxidation. With tetralin hydroperoxide as initiator (Fig. 4) at all concentrations except one (curve D), an initial pro-oxidant effect was observed and in each case the shape of the curve indicated auto-inhibition. At the highest concentration studied, both pro-oxidation and auto-inhibition were more marked than at the lower and the negative absorption curves (C, D, E) indicated gas evolution. On extended oxidation (not shown in Fig. 4, but frequently observed in this and similar systems) there is a sharp end to the complete inhibition which is even more pronounced than that observed in the case of phenolic antioxidants in the autooxidation of tetralin catalysed by azodi-isobutyronitrile.

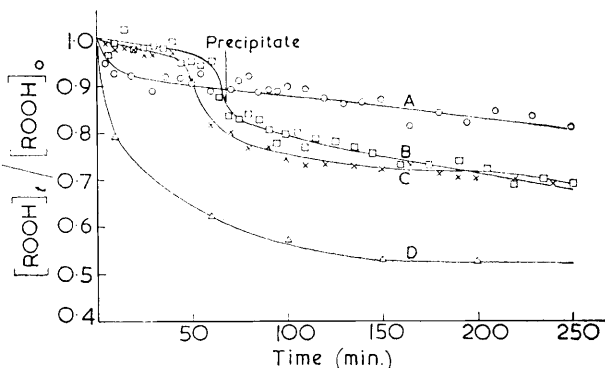
Figs. 5 and 6 show that other sulphur-containing antioxidants behave similarly to zinc diethyldithiocarbamate. Pro-oxidant effects are not evident with zinc dinonyl dithiophosphate (Fig. 5) but the auto-inhibiting characteristic is marked. This antioxidant

is less effective than the diethyldithiocarbamate in tetralin at 50° as measured by the length of the inhibition period. Dilauryl thiodipropionate is much less effective than either zinc diethyldithiocarbamate or dinonyl dithiophosphate and during the early stages of autoxidation or at low concentration is quite an effective pro-oxidant (Fig. 6). However, there can be no question that its general behaviour parallels that of the metal complexes.

The pro-oxidant effects observed during the early stages of hydroperoxide initiated oxidation in the presence of sulphur-containing antioxidants, together with the liberation of a gas from one of them during autoxidation (Fig. 4), suggest that the agent responsible for the non-radical hydroperoxide decomposition may be formed by oxidation of the sulphur compound by hydroperoxide. A detailed study of the early stages of the interaction of hydroperoxide with a variety of metal dithiocarbamates in benzene showed that

FIG. 7. Decomposition of cumene hydroperoxide by metal dithiocarbamates (1 molar-%) in benzene at 25°.

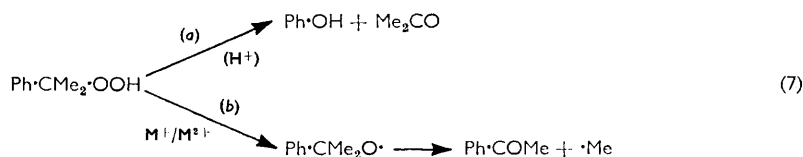
A, nickel dinonyldithiocarbamate;
B, zinc dinonyldithiocarbamate;
C, cobalt dinonyldithiocarbamate;
D, copper dibutyldithiocarbamate.



in each case there occurred a quantitative separation of metal sulphate which was accompanied by a rapid catalytic decomposition of the hydroperoxide (shown typically for cumene hydroperoxide in Fig. 7). In each case the hydroperoxide concentration was ultimately reduced to zero whilst that of the control (without metal complex) remained unchanged.

The products formed by antioxidant-catalysed decomposition of cumene hydroperoxide (see Table 1) were entirely as expected on the basis of a cationic decomposition, namely, phenol and acetone (7a) and not those expected from a transition-metal catalysed decomposition which gives acetophenone as the major product (Table 2) in a radical forming reaction (7b).¹¹

The decomposition of tetralin hydroperoxide was less unambiguous. At a tetralin hydroperoxide-catalyst molar ratio 30 : 1, it gave a mixture of 1-tetralone, γ -o-hydroxy-



phenylbutyraldehyde, and 1,2-dihydronaphthalene, all of which can be formed by cationic decomposition, but radical intermediates cannot be ruled out since 1-tetralone is one of the products formed by the transition-metal catalysed decomposition of tetralin hydroperoxide.¹² At a 100 : 1 molar ratio, 1-tetralone was the only product identified.

Dilauryl thiodipropionate was much less reactive toward cumene hydroperoxide than were the metal complexes. No decomposition was detected under conditions similar to

¹¹ Oberright, Leonardi, and Kozacik, Additives in Lubricants Symposium (A.C.S. Div. Pet. Chem.), Atlantic City, 1956, 115.

¹² Robertson and Waters, *J.*, 1948, 1582.

those used in studying the dithiocarbamates (*viz.*, 1.25 and 0.0125M-solutions of hydroperoxide and catalyst, respectively, at 25°) but at 50° an autocatalytic curve was obtained (Fig. 8) formally similar to that for the dithiocarbamate at 25°. Again, the only products

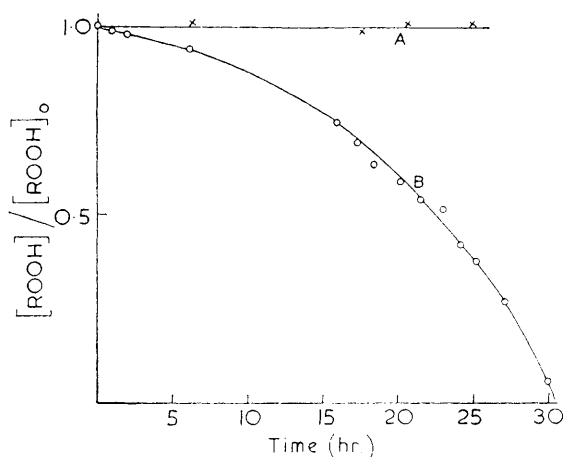


FIG. 8. Decomposition of cumene hydroperoxide by dilauryl thiodipropionate (1 molar-%) in benzene at 50°.

A, no antioxidant; B, dilauryl thiodipropionate.

identified were the heterolytic decomposition products of cumene hydroperoxide (see Table 1).

When the reaction of cumene hydroperoxide with zinc diethyldithiocarbamate took place without temperature control, a copious evolution of sulphur dioxide occurred. The

TABLE 1.

Decomposition of cumene hydroperoxide in benzene at room temperature by sulphur containing antioxidants (at 1 molar %).

Additive	Yields (%) †			Metal sulphate analyses		
	Phenol	Acetone	Hydrated sulphate	After drying S found (%)	Without drying S found (%)	S calc. M·SO ₄ ·nH ₂ O (%)
<i>Dithiocarbamates</i>						
Zinc dinonyl	70	55	60	18.1	—	17.9
Zinc di-isopropyl ...	74	57	89	18.4	—	17.9
Zinc dibutyl	78	61	46	—	—	—
Nickel dinonyl	63	50	79	18.3	—	18.5
Cobalt dinonyl	78	55	59	17.5	—	18.5
Copper dibutyl.....	84	55	92	—	15.0 ^a	12.9 n = 5
<i>Dithiophosphates</i>						
Nickel di-isopropyl	75	53	88	—	12.8	12.2 n = 6
Iron(III) di-isopropyl	81	62	8	—	—	—
Nickel diethoxyethyl	88	61	—	—	—	—
<i>Xanthates</i>						
Nickel isopropyl ...	98	54	—	—	—	—
<i>Non-metal</i>						
Dilauryl thiodipropionate*	72	54	—	—	—	—
Ethanethiol	78	48	—	—	—	—
2-Methylpropane-2-thiol	43	27	—	—	—	—
Tetraethylthiuram disulphide	74	48	—	—	—	—
Sulphur	No reaction		—	—	—	—

^a Analysed without recrystallisation.

* At 50°. † The products were also examined for dimethylbenzyl alcohol and acetophenone but in no case were they detected.

hypothesis that sulphur dioxide might itself be the active peroxide decomposer was supported by further experiments in which catalytic amounts of sulphur dioxide and labile sulphur dioxide generators such as dihydrothiophen dioxide and benzothiazole-2-sulphonic acid caused an immediate and rapid decomposition of cumene hydroperoxide. Phenol and acetone were again the major products.

TABLE 2.
Decomposition of cumene hydroperoxide by metal naphthenates in benzene at room temperature.

Naphthenate	Ratio *	Yields (%)		
		Phenol	Dimethyl benzyl alcohol	Acetophenone
Cobalt	100 : 1	Not detected	100	Small amount
	200 : 1		100	
Iron †	100 : 1	"	Small amount	"
Zinc	100 : 1	Reaction too small to measure		

* Rates of moles of peroxide: g.-atom of metal. † Reaction was incomplete.

EXPERIMENTAL

Materials.—Tetralin was purified by extraction with 2*N*-sodium hydroxide (to remove hydroperoxide) followed by water washing. After being dried, the material was fractionated and immediately before use was passed through activated alumina (to remove traces of hydroperoxide and breakdown products).

The antioxidants, except benzothiazole-2-sulphonic acid, were either commercial materials or made by standard methods. All were recrystallised to constant m. p., except 2,4-dimethyl-6-1'-methylcyclohexylphenol which was distilled, and zinc dinonyl dithiophosphate which could not be distilled but was >95% pure).

Cumene hydroperoxide. Commercial material (75%) was purified by the method of Armstrong *et al.*¹³ in which the pure sodium salt is separated, and the hydroperoxide regenerated by acidification, and finally distilled at 0.1 mm. This material was better than 99% pure.

Tetralin hydroperoxide. Prepared by the method of Knight and Swern¹⁴ and recrystallised several times from light petroleum (b. p. 40–60°), it had m. p. 55–56°.

Benzothiazole-2-sulphonic acid. 2-Mercaptobenzothiazole (8.4 g.) was dissolved in 2*N*-sodium hydroxide (50 ml.) at 80°. Sodium hypochlorite liquor was added slowly with stirring (100 ml.) and the solution was filtered. On cooling the crystals which separated were collected and dried. These were dissolved in a minimum of water and acidified (concentrated hydrochloric acid). The crystallised product was collected and dried (m. p. >260°) (Found: C, 38.3; H, 2.2; N, 7.5; S, 29.5. Calc. for C₇H₅NO₃S₂: C, 39.1; H, 2.3; N, 6.5; S, 29.8%). Attempts to crystallise the sulphonic acid were unsuccessful since sulphur dioxide was evolved on heating in water, and on cooling crystals were obtained (m. p. 30–34°) which was analysed as 2-hydroxybenzothiazole (Found: C, 55.6; H, 3.0; N, 9.0; S, 20.5. Calc. for C₇H₅NOS: C, 55.7; H, 3.3; N, 9.3; S, 21.2%).

Method.—*Autoxidation of tetralin.* The oxygen absorption apparatus was a manometer very similar to that described by Davies and his co-workers.² In each case 2 ml. of tetralin, purified immediately before use, were pipetted into a flask containing 0.06 g. (= 3% w/v) of initiator and this was followed by the antioxidant. In those cases where the antioxidant could not be conveniently added as 100% material, a tetralin solution of the antioxidant was diluted to the required concentration and 2 ml. of this solution used. The apparatus was allowed to equilibrate in the thermostat (approx. 10 min.) before being isolated from the atmosphere. Agitation of the manometer vessel was rapid enough to ensure that solution of oxygen was not rate-controlling. Experimental results are summarised in Figs. 1–6, from which individual manometer readings have been omitted to avoid confusion.

Decomposition of cumene hydroperoxide. To 0.0005 mole of catalyst in dry benzene (20 ml.)

¹³ Armstrong, J., 1950, 666.

¹⁴ Knight and Swern, *Org. Synth.*, **34**, 90.

was added 0.05 mole (7.6 g.) of cumene hydroperoxide in dry benzene (20 ml.) at 25 and 50° for the dithiocarbamates and dilauryl thiodipropionate, respectively. The hydroperoxide remaining was determined at intervals by the method of Swern.¹⁴ At the end of the reaction any precipitated salts were filtered off and washed with acetone, recrystallised from ethanol-water, dried, and weighed. Their composition was determined by sulphate analysis. The filtrate was analysed quantitatively by infrared spectroscopy for phenol, acetone, dimethylbenzyl alcohol, and acetophenone by comparison with standard solutions of these compounds in benzene! Wave numbers were measured in a 0.2 cm. cell on a Unicam S.P. 100 instrument, the following band positions being used for analysis; acetone 1712 cm.⁻¹, phenol 1594 cm.⁻¹, acetophenone 1686 cm.⁻¹, and dimethylbenzyl alcohol 1074 cm.⁻¹.

The results are summarised in Tables 1 and 2 and Figs. 7 and 8.

In a similar experiment, cumene hydroperoxide (0.05 mole) and zinc dinonyldithiocarbamate (0.05 mole) reacted in benzene at room temperature. Sulphur dioxide was evolved rapidly as the peroxide concentration was reduced to zero with concomitant formation of phenol and acetone. Infrared spectral examination of the flash-distilled product indicated the presence of alkyl isothiocyanate.

To test the theory that sulphur dioxide itself may be the catalyst for hydroperoxide decomposition, cumene hydroperoxide (0.05 mol.) in benzene was treated with a catalytic amount (12 ml., 0.0005 mole) of sulphur dioxide. This caused a rapid and quantitative decomposition of the hydroperoxide to phenol and acetone with generation of heat. Sulphur dioxide generators such as dehydrothiophen dioxide and benzothiazole-2-sulphonic acid had a similar effect but in both cases heating to above 50° was necessary to initiate the catalytic decomposition.

Decomposition of t-butyl hydroperoxide. t-Butyl hydroperoxide (27 g., 0.3 mole) in cyclohexane (175 ml.) was added to a solution of zinc dibutyldithiocarbamate (4.7 g., 0.01 mole) in cyclohexane (175 ml.) and after several days at room temperature the mixture was filtered to remove zinc sulphate. The filtrate was flash-distilled at 0.05 mm. The main component of the distillate as indicated by both mass-spectroscopic and infrared analysis was di-t-butyl peroxide. Infrared spectrometry also showed the presence of carbonyl (1714 cm.⁻¹), probably acetone and hydroxyl grouping, probably t-butyl alcohol.

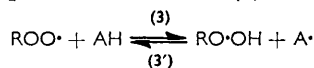
A similar decomposition was carried out in carbon tetrachloride and the same products were identified and additionally a band at 1660 cm.⁻¹ of uncertain origin.

Decomposition of tetralin hydroperoxide. Tetralin hydroperoxide (12.3 g., 0.075 mole) in carbon tetrachloride (40 ml.) was added to zinc dibutyldithiocarbamate (1.18 g., 0.0025 mole) in carbon tetrachloride (40 ml.). After 20 hr. at room temperature, the product was filtered and the filtrate flash distilled. The distillate contained conjugated carbonyl (1675 cm.⁻¹) which was identified by mass-spectrographic examination as 1-tetralone. The latter also showed the presence of dihydronaphthalene and γ -o-hydroxyphenylbutyraldehyde.

The above experiment was repeated at a peroxide-catalyst molar ratio 100 : 1. 1-Tetralone was the only product identified (semicarbazone, m. p. = 220°).

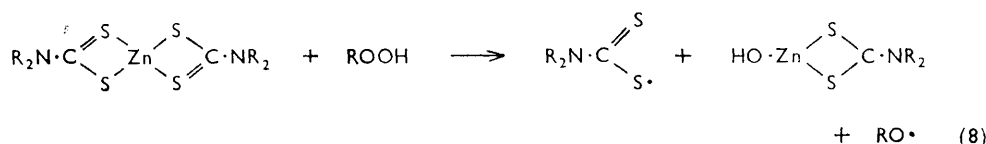
DISCUSSION

The different kinetic behaviour of phenolic and sulphur-containing antioxidants provides clear evidence that the former act primarily by converting alkylperoxy-radicals into alkyl hydroperoxides (reaction 3), whereas the latter antioxidants prevent the initiation of autoxidation chains by removing hydroperoxide. In the initial absence of hydroperoxides (azodi-isobutyronitrile-initiated oxidation), in phenol-inhibited oxidations, an induction period is evident. In the presence of excess of hydroperoxide, however, retardation results and no induction period is evident even at very low antioxidant concentrations. This implies that the antioxidant acts as a chain-transfer agent so that reaction (3) is reversible and reaction (3') competes with reaction (4) for the removal of aryloxy-radicals.



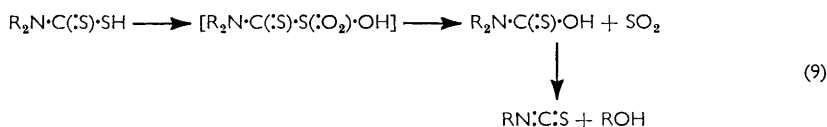
Peroxide-decomposing antioxidants are relatively ineffective in inhibiting azodi-isobutyronitrile-initiated oxidation, indicating that they are unreactive toward alkylperoxy-radicals. On the other hand, they are powerful inhibitors for the tetralin hydroperoxide catalysed oxidation of tetralin, although in each case they become effective

only after an initial period when they are either inactive or pro-oxidant. The pro-oxidant effect is more pronounced the higher the ratio of peroxide decomposer or hydroperoxide. This is reminiscent of the results of Oberright and his co-workers,¹¹ who found that peroxide-decomposing antioxidants (e.g., P_2S_5 -olefin condensation products) reacted with cumene hydroperoxide at 1 : 1 molar ratio to give acetophenone, that is, the reaction involves free-radical intermediates (reaction 7b). At a cumene hydroperoxide-antioxidant molar ratio of 100 : 1 the products were primarily phenol and acetone. This indicates that the effective peroxide decomposer is both an oxidation product formed from the sulphur compound and a catalyst for the non-radical decomposition of hydroperoxide. Kennerly and Patterson have previously suggested⁶ that the thiyl radical may be the responsible agent but the present studies involving the catalytic decomposition of cumene hydroperoxide



in the presence of metal dithiocarbamates (Fig. 7) do not support this view since very extensive oxygenation of the dithiocarbamate occurred before any appreciable peroxide decomposition was evident. It seems more likely on theoretical grounds that the thiyl radical is the transient pro-oxidant species present during the early stages of autoxidation as a result of reaction (8).

In view of the copious evolution of sulphur dioxide under slightly higher temperature conditions and the powerful catalytic effect of this agent on the decomposition of cumene hydroperoxide, it seems likely that the sulphur-containing antioxidants represent a potential reservoir of this peroxide decomposer so that it is liberated over a long period and at the right rate. It seems likely that an intermediate unstable sulphonic acid [similar benzothiazole-2-sulphonic acid] is the immediate precursor of sulphur dioxide. Alkyl isothiocyanate was also identified, indicating that (9) is the overall reaction.



The catalytic effect of sulphur dioxide on the decomposition of hydroperoxides can be accounted for on the basis of the following regenerative scheme:



Of considerable practical importance is the synergism shown by peroxide decomposing antioxidants when used in combination with chain-breaking antioxidants.¹⁵ The present studies suggest a possible explanation in the removal of chain-propagating free radicals (by phenols or amines) during the early stages of decomposer action. This is being investigated.

We thank Mr. S. Ashton for some experiments and Mr. M. St. C. Flett, Mr. A. E. Williams, and Mr. A. Hamer for identifying and estimating the reaction products.

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¹⁵ Scott, *Chem. and Ind.*, 1963, 271.