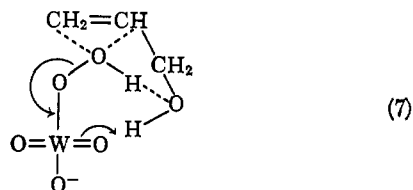


as involving a concerted delivery of the peroxy oxygen with coordination of the hydroxyl hydrogen by one of the W=O bonds (eq. 6).^{10,11}

A precedent for the facile formation of esters from oxides of transition elements could be found in published work on chromic acid oxidations.¹² The ester formation in the present case was preferred over an



(10) P. D. Bartlett was the first to suggest a cyclic concerted mechanism for the epoxidation of olefins with perbenzoic acid; *cf. Record Chem. Progr.* (Kresge-Hooker Sci. Lib.), **11**, 51 (1950).

(11) The polycyclic nature of the transition state pictured receives support from a highly negative entropy of activation (H. C. Stevens and J. C. Cook, Jr., paper presented at the 143rd National Meeting of the American Chemical Society, Atlantic City, N. J., Sept. 1962).

(12) F. Holloway, M. Cohen, and F. H. Westheimer, *J. Am. Chem. Soc.*, **73**, 65 (1951), and references cited therein.

earlier interpretation⁴ postulating merely hydrogen bonding in the intermediate or transition state (eq. 7). Intuitively, an interaction between the peracid hydrogen and the alcohol oxygen would appear to be opposed to the required electron deficiency of the peroxy oxygen. Furthermore, the mechanism would appear to be less consistent with the steric inhibition observed in the case of the tertiary pentenol.

It is concluded that the epoxidation of primary and secondary allylic alcohols involves an interaction of a tungstic acid species with the hydroxyl function prior to a rate-determining delivery of the peroxy oxygen to the olefinic site. Although showing electrophilic character, the reaction appears to be concerted rather than stepwise. Further evidence bearing on the postulated mechanism is contained in the following paper of this series dealing with the effect of hydroxyl group double bond proximity upon substrate reactivity.

Acknowledgment. The writers are indebted to Professor P. Bartlett of Harvard University for much helpful advice.

The Mechanism of Ozonolysis. Formation of Cross Ozonides

L. D. Loan, R. W. Murray, and P. R. Story

*Contribution from the Bell Telephone Laboratories, Incorporated,
Murray Hill, New Jersey. Received September 23, 1964*

The ozonolysis of pure pentene-2 at -70° has been shown to give butene-2 ozonide and hexene-3 ozonide in addition to the normal pentene-2 ozonide. N.m.r. spectra of the ozonides have been obtained and used to show that each ozonide exists as a cis-trans pair. Ozonolyses of pentene-2 in pentane as solvent and in the presence of excess aldehyde have permitted an evaluation of the extent of a cage mechanism.

Introduction

The ozonolysis of olefins is generally interpreted in terms of a mechanism provided by Criegee.¹ This mechanism (Figure 1) postulates that ozone reacts with the unsaturated bond to form an initial unstable ozonide (primary ozonide, I) which readily decomposes to give a zwitterion (II) and a carbonyl fragment (III). These fragments can then combine to give the normal ozonide (IV). Alternatively, the zwitterion may dimerize to a diperoxide (V) or polymerize to a higher molecular weight peroxide (VI). In reactive solvents the zwitterion may react with the solvent to give other products; as an example, a methoxyhydroperoxide (VII) is formed in the presence of methanol. This scheme is consistent with most of the known experimental facts but recent observations of a number of workers suggest that further refinement is required.

(1) For a thorough discussion of the mechanism of ozonolysis see P. S. Bailey, *Chem. Rev.*, **58**, 925 (1958).

The existence of a primary ozonide has been confirmed in the case of *trans*-di-*t*-butylethylene by Criegee and Schröder,² but these authors further found no evidence for the formation of such a primary ozonide from the *cis* compound. Recently, Greenwood³ has found that this difference between *cis* and *trans* isomers with respect to the formation of a primary ozonide may be a general phenomenon, that is, *trans*-olefins give primary ozonides while *cis*-olefins do not give primary ozonides of sufficient lifetime to be characterized. Another important observation from the standpoint of a complete mechanistic picture is that made by Schröder⁴ who found that the *cis*- and *trans*-ozonides obtained from the ozonolysis of the *cis* and *trans* isomers of di-*t*-butylethylene could be separated by gas phase chromatography (g.p.c.). Use of this technique yielded the surprising result that the *trans* isomer gave a single ozonide, which Schröder formulated as the *trans*-ozonide, while the *cis* olefin gave an ozonide distribution of 70:30, which Schröder formulated as the *cis* to *trans* ratio. Taken together the results of Greenwood and Schröder suggest that *cis*-olefins are able to form the normal ozonide *via* a path which may not involve a primary ozonide but which can be largely stereoselective. Another aspect of the Criegee mechanism which is intimately con-

(2) R. Criegee and G. Schröder, *Chem. Ber.*, **93**, 689 (1960).

(3) F. L. Greenwood, *J. Org. Chem.*, **29**, 1321 (1964).

(4) G. Schröder, *Chem. Ber.*, **95**, 733 (1962).

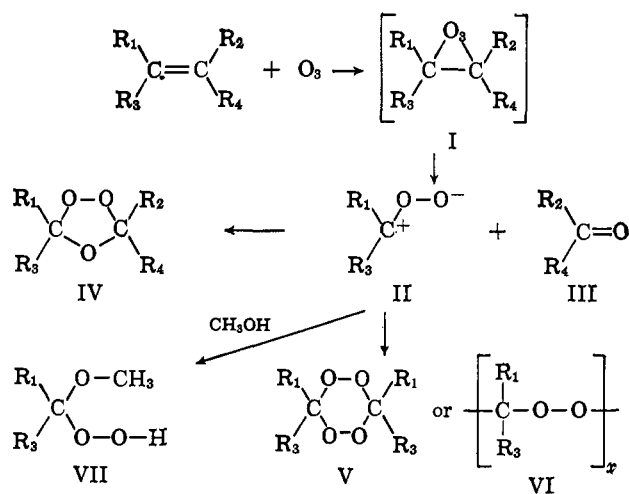


Figure 1.

nected with these observations but which has only recently received attention is the subject of the present paper.

In the case of an unsymmetrical olefin, *i.e.*, $R_1 \neq R_2$, $R_3 = R_4 = H$ in Figure 1, there are two zwitterion and two carbonyl possibilities and, theoretically at least, a total of six ozonide possibilities, that is, three *cis-trans* pairs. Criegee has reported,⁵ however, that 3-heptene gave only its own ozonide and no detectable amounts of the ozonides of hexene-3 and octene-4, while a mixture of hexene-3 and octene-4 gave only two ozonides and no heptene-3 ozonide. Criegee has reconciled this apparent contradiction of his mechanism by postulating a solvent cage⁵ which prevents the cleavage products from participating in "cross" or exchange reactions. On the other hand, addition of an excess of a "foreign" reactive aldehyde, *i.e.*, formaldehyde or acetaldehyde, has been shown⁶ to cause diversion of the zwitterions and formation of ozonides derived from the added aldehyde.

Recently the formation of the theoretically predicted six ozonides from ozonolysis of an unsymmetrical unsaturated compound has been confirmed in the case of methyl oleate.⁷ We have found similar results in the case of a simple, unsymmetrical olefin.

Results and Discussion

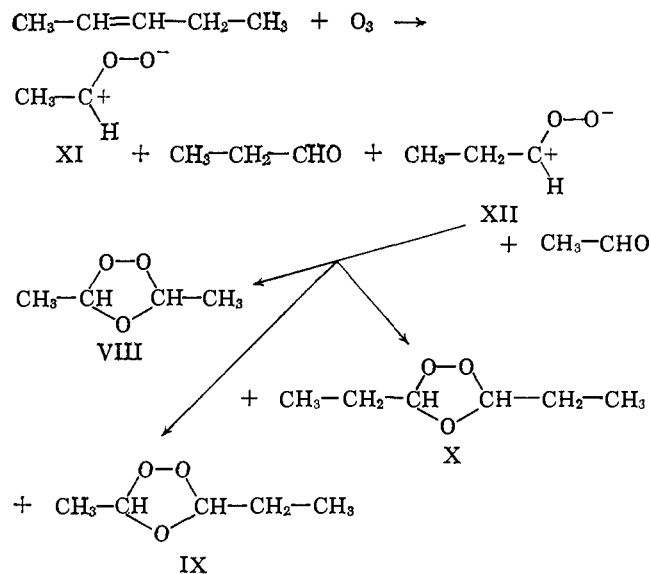
The present paper reports a detailed study of the ozonolysis of pentene-2. The effect and extent of the solvent cage has been investigated and ozonides other than the normal ozonide have been isolated and identified. Pentene-2 was ozonized without solvent at -70° and the reaction mixture subjected to g.p.c. analysis. The g.p.c. trace showed the presence of acetaldehyde and propionaldehyde, which were identified by retention time and infrared spectra, and three other major components. These latter three compounds were identified as the ozonides of butene-2 (VIII), pentene-2 (IX), and hexene-3 (X). The identification rests on oxygen analysis and infrared and

(5) R. Criegee, *Record Chem. Progr. (Kresge-Hooker Sci. Lib.)*, **18**, 111 (1957).

(6) R. Criegee, G. Blust, and H. Zinke, *Chem. Ber.*, **87**, 766 (1954).

(7) G. Riezebos, J. C. Grimmelikhuyzen, and D. A. Van Dorp, *Rec. trav. chim.*, **82**, 1234 (1963); O. S. Privett and E. C. Nickell, *J. Am. Oil Chemists' Soc.*, **40**, 22 (1963).

n.m.r. spectra. Ozonide VIII had the same g.p.c. retention time and infrared and n.m.r. spectrum as those of butene-2 ozonide isolated from the ozonolysis of butene-2. The g.p.c. trace of the pentene-2 reaction mixture also indicated the presence of a number of minor components which presumably are dimers or trimers of the two zwitterions. Analysis of the n.m.r.



spectra and the use of the double resonance technique demonstrated that each of the ozonides exists as a *cis-trans* pair, the isomers being produced in approximately equal amounts. In the case of the butene-2 ozonides the isomers could be partially separated by g.p.c. and the n.m.r. spectra of the individual isomers obtained and analyzed. Despite extensive efforts using a variety of columns the isomeric ozonides of pentene-2 and hexene-3 could not be separated.

The n.m.r. spectrum, taken in CCl_4 , of the butene-2 ozonide pair, shown in Figure 2, contains a pair of overlapping quartets centered at 4.73⁸ and a doublet at 8.65 which are assigned to the methine and methyl protons, respectively. The absorption intensities are in the ratio of 1:3.2 which compares favorably with the expected 1:3 ratio. Irradiation of the methyl protons in a double resonance experiment collapses the two quartets to a doublet. This observation is interpreted to signify that there are two kinds of methine protons which are associated with the *cis-* and *trans-*ozonides. In the absence of the double resonance radiation the methine protons are split by the attached methyl group to give the observed two quartets. Subsequent g.p.c. and n.m.r. measurements have confirmed this explanation, that is, each of the quartets is assignable to a single isomer. Irradiation of the methine protons caused the methyl doublet to collapse to a singlet. The infrared spectrum of all of the ozonides (VIII-X) showed no hydroxyl or carbonyl absorption, but all had a strong absorption at *ca.* 1080-1110 cm^{-1} , which has been associated with the ozonide system.⁹

(8) All n.m.r. results are reported as τ -values with tetramethylsilane as internal standard.

(9) Schröder⁴ has published infrared spectra of the *cis-* and *trans-*ozonides of di-*t*-butylethylene, both of which show strong absorptions at 1080-1100 cm^{-1} . A number of other authors have attributed absorption in this region to the ozonide system.¹⁰

(10) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," John Wiley and Sons, Inc., New York, N. Y., p. 123.

By taking advantage of the partial resolution of the butene-2 ozonide isomers in the g.p.c. analysis it was possible to obtain n.m.r. spectra, which in one case was that of a pure isomer (Figure 2) and in the other showed isomer enrichment. These spectra are assigned so that the *cis* isomer has the longest g.p.c. retention time and the lowest chemical shift for the methine quartet, *i.e.*, 4.72. The *trans* quartet then is at 4.78. This assignment is made by analogy with that of Schröder⁴ who found that the *cis*-ozonide of di-*t*-butylethylene had the longest g.p.c. retention time. In this case the *cis* assignment was made on the basis of the rate of reduction of the two ozonides with lithium aluminum hydride. Thus the *cis* isomer, with less steric hindrance to attack of the reducing agent, reacts faster than the *trans* isomer. A higher g.p.c. retention time for the *cis* isomers is consistent with the expected higher dipole moments for these materials. Using the assignments given, it was possible to use the n.m.r. of the butene-2 ozonide produced in the ozonolysis to show that it consists of a 56% *trans* and 44% *cis* isomer mixture.

The n.m.r. spectrum of IX consists of a multiplet at 5.13, another multiplet at 8.37, a doublet at 8.65, and a triplet at 9.04. These absorptions are assigned to the methine, methylene, ring methyl, and chain methyl, respectively, of the pentene-2 ozonide pair. When the methine protons are irradiated the doublet assigned to the ring methyl group collapses to a singlet. Irradiation of the methylene protons causes the adjacent methyl group triplet to collapse to a singlet. Finally, irradiation of the chain methyl group causes the methylene multiplet to collapse to a doublet which is not as clean as one would expect if a single type of methine proton were responsible for the splitting. Here again it is felt that the presence of both geometric isomers with slightly different methine protons is responsible for the observed spectrum. When an attempt was made to irradiate the entire methyl plus methylene region in order to measure the effect on the methine absorption it was found that this multiplet could not be reduced to a simple absorption but always gave a multiplet whose make-up depended upon the exact position of the double resonance irradiation. When one considers that, given that both isomers are present, there are four possible types of methine protons with very similar chemical shifts, such an observation is not unexpected. The peak area ratios are 4.35:1 for methyl plus methylene to methine which is to be compared with the theoretical 4:1.

The n.m.r. spectrum of X contains two overlapping triplets at 4.95, a multiplet at 8.34, and a triplet at 8.61. These absorptions are assigned to the methine, methylene, and methyl protons, respectively, of the hexene-3 ozonide pair. Their integrated areas are in the ratio 1:2.16:3.29. Irradiation of the methylene plus methyl protons causes the methine triplets to collapse to a doublet which, again, is taken to indicate the presence of both *cis* and *trans* isomers containing methine protons of slightly different chemical shift. Irradiation of the methine protons does not cause the methylene multiplet to collapse to a quartet as expected for a single isomer. The resulting multiplet is believed to consist of two overlapping quartets originating in the *cis* and *trans* isomers whose methyl groups

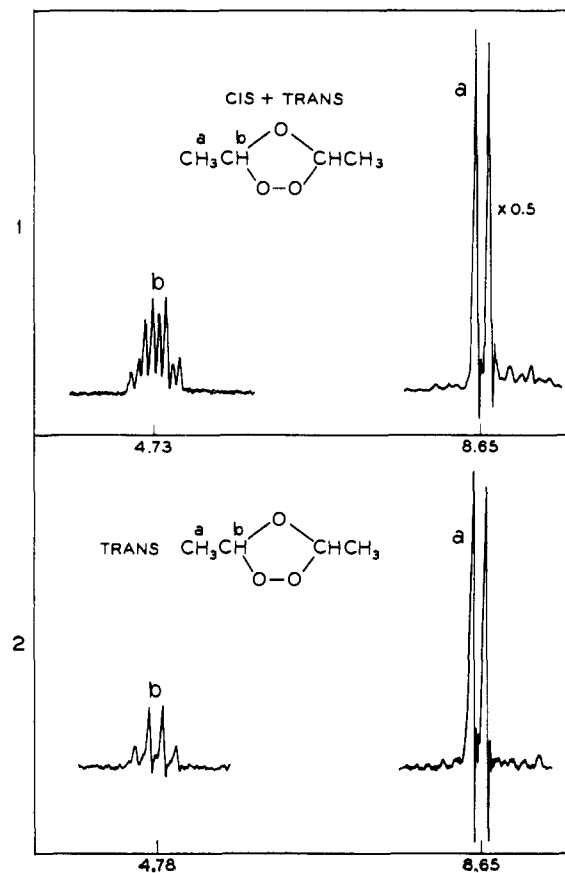


Figure 2. The n.m.r. spectra of the butene-2 ozonide pair (CCl_4). The numbers shown are τ -values using tetramethylsilane as internal standard.

have different environments. If it is assumed that the isomer with the lower chemical shift for the methine protons is the *cis* isomer, following the assignment made in the case of the butene-2 ozonides, then it is possible to show from the n.m.r. spectrum that the hexene-3 ozonide consists of a 58% *cis*, 42% *trans* isomer mixture. This assignment must be considered tentative until n.m.r. spectra of more ozonides are obtained and correlated with stereochemical configuration.

While it is believed that the n.m.r. data provide fair evidence for the presence of isomers in the case of each ozonide it is most definitive in the butene-2 case when g.p.c. separation could be achieved. Efforts to separate other isomer pairs will continue in hopes that individual isomer n.m.r. assignments and correlations can be made.

Effect of Solvent. Having shown that a normal ozonolysis of an olefin can give cross ozonides it became interesting to consider to what extent the results were influenced by a solvent cage. In our work a typical ozonolysis on 143 mmoles of pure pentene-2 produced 13.9 mmoles of VIII, 33.6 mmoles of IX, and 9.3 mmoles of X. The ozonides were therefore produced in a ratio of 1:2.42:0.67. Previous work in which a cage mechanism has been invoked has been usually carried out in dilute solution in an inert solvent and it was therefore of interest to measure the effect of solvent in the present reaction. Figure 3 shows the ratio of pentene-2 ozonide to butene-2 ozonide in the reaction

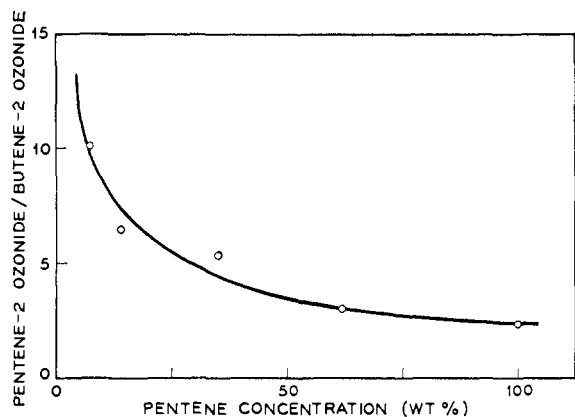


Figure 3. Effect of pentene-2 concentration on ozonide distribution.

products at a number of concentrations in pentane as solvent. As may be seen the ratio approaches the statistical value of two as the solvent is removed. A similar curve is obtained for the ratio of pentene-2 ozonide to hexene-3 ozonide. Criegee has explained the absence of the cross ozonides in his work by postulating an extremely efficient solvent cage⁵ which can only be broken if zwitterion traps such as methanol are present. The present results show that even at very low olefin concentrations escape from the cage occurs. The results also indicate that some reaction probably always occurs within a cage since, even at maximum olefin concentrations, the normal ozonide is formed in greater amount than would be predicted by statistical arguments. It must be remembered, however, that such arguments do not allow for differences in chemical specificity between zwitterions or aldehydes and are therefore not absolutely reliable.

Effect of Excess Aldehyde. To investigate the cage effect in more detail further ozonolyses were performed in the presence of an excess of either acetaldehyde or propionaldehyde. When excess acetaldehyde is present throughout the reaction only a barely detectable amount of hexene-3 ozonide is formed, indicating that almost all free zwitterions are reacting with acetaldehyde. The observed ratio of butene-2 ozonide to pentene-2 ozonide in the product was 1.04. Similarly, in the presence of excess propionaldehyde only a trace of butene-2 ozonide is formed while the ratio of pentene-2 ozonide to hexene-3 ozonide was 1.52. The two ratios obtained for the relative amounts of ozonides formed, VIII:IX in the presence of excess acetaldehyde and IX:X in the presence of excess propionaldehyde, should, on the simplest view, be exact measures of the ratio zwitterion XI:zwitterion XII formed by scission of the initial ozonide. They should, therefore, be equal. The deviation from equality reflects some favorable route to IX and is most easily explained as being a result of the previously postulated cage effect.⁵ If it is assumed that a fixed fraction of zwitterion-aldehyde pairs recombine in a cage, even in the presence of excess aldehyde, then it is possible to deduce from the observed ratios that 9.5% of such recombination occurs and that 51% ozonized molecules give free zwitterion XI and 39.5% give free zwitterion XIII. Such a distribution predicts that at very high pentene (*i.e.*, high aldehyde) concentrations ozonolysis

should lead to the three ozonides VIII, IX, and X in the ratio 1:2.14:0.77, which may be compared with the observed ratio of 1:2.42:0.67 in pure pentene at -70° . The distribution between the zwitterions XI and XII of 51 and 39.5%, respectively, may reflect a difference in stability of the zwitterions due to hyperconjugation stabilization. Further work using other unsymmetrical olefins is necessary before any general conclusions can be drawn regarding this point. Almost no quantitative data are available on the effect of substituents on cleavage path, but Bailey¹¹ has attempted to correlate direction of cleavage with mode of initial ozone attack and found that there is no single mechanism which fits all cases studied. The present work suggests that the measurement of cleavage distribution may be achieved by using excesses of the appropriate aldehydes, and such measurements are necessary for a further understanding of the ozonolysis reaction.

In earlier discussion of the work of Greenwood³ and Schröder⁴ concerning the ozonolysis of *cis* and *trans* isomers, it was shown that the path from olefin to normal ozonide in the case of *cis* isomers, while not involving a primary ozonide or at least one of measurable lifetime, can be stereoselective in some cases. The case of *cis*-di-*t*-butylethylene is one which appears to be largely stereoselective. The use of the n.m.r. technique described here should permit evaluation of this factor in the case of other ozonides even in those cases where g.p.c. separation of isomers cannot be achieved. The results reported here suggest that investigation of the stereochemical aspect of the ozonolysis problem as a function of reaction conditions should prove interesting, and we have initiated work of this nature. Thus, while ozonolysis of *cis*-di-*t*-butylethylene in dilute pentane solution gives mostly *cis*-ozonide⁴ the present results suggest that ozonolysis in more concentrated solution or of the pure olefin might give different stereochemical results. In the case of pentene-2, reported here, where the olefin is a mixture of the isomers, an analysis of the stereochemical make-up of the pentene-2 ozonides is more difficult to correlate with mechanistic arguments. The cross ozonides produced in this case, namely butene-2 and hexene-3 ozonides, whose stereochemical make-up we have reported, should on the simplest grounds be measures of the thermodynamic stabilities of the isomers. The possibility of more complex, stereochemical-sensitive pathways cannot be excluded even in these cases, however. By studying the stereochemical make-up of all three ozonide products produced from ozonolysis of unsymmetrical olefins as a function of stereochemistry of starting olefin, we hope to be able to make more definite statements on this aspect of the ozonolysis problem.

Experimental¹²

Pentene-2 was Matheson Coleman and Bell reagent grade mixed isomers, b.p. $35-37^{\circ}$, and was shown to

(11) P. S. Bailey, S. B. Mainthia, and C. J. Abshire, *J. Am. Chem. Soc.*, **82**, 6136 (1960).

(12) Infrared spectra were measured on a Perkin-Elmer Model 21 Infrared spectrophotometer. N.m.r. spectra were determined using either a Varian Associates Model DP-60 or A-60 n.m.r. spectrometer. G.p.c. analyses were performed on an Aerograph Model A-700 gas chromatograph.

be at least 99% pure by g.p.c. analysis. *Pentane* was Matheson Coleman and Bell highest purity, b.p. 35–36°. *Butene-2* was Phillips Petroleum Co. pure grade *trans*-butene-2.

Ozonolyses were carried out using a Welsbach Model T-23 ozonator. Ozone was supplied at a rate of approximately 0.5 mmoles per minute.

Ozonolysis of Pentene-2. In a typical experiment 10 g. (143 mmoles) of pentene-2 was ozonized to approximately 60% completion at -70° . The resulting reaction mixture was then analyzed by g.p.c. using a 20-ft. 10% Dow 710 silicone grease column at temperatures between 70 and 110° . The chromatogram consisted of six major peaks which were assigned to acetaldehyde, pentene-2, propionaldehyde, VIII, IX, and X in order of increased retention time. The acetaldehyde and propionaldehyde had the same retention times and infrared spectra as the authentic materials. Yields of the aldehydes were 0.15 and 0.22 g. for acetaldehyde and propionaldehyde, respectively. Yields of the ozonides were 1.45, 3.97, and 1.23 g. for VIII, IX, and X, respectively. The yields were determined by weighing the chromatogram peaks followed by calibration of the peak areas. The products isolated account for 64.1 mmoles (75%) of the ozone introduced. The remainder is presumably present as polymeric peroxidic material. Since the ozonides can be shown to be present by g.p.c. analysis *at room temperature*, it is unlikely that they are secondary products arising from cleavage of polymeric materials. The infrared spectra of VIII–X showed no hydroxyl or carbonyl absorption, but a strong absorption at *ca.* 1080–1110 cm^{-1} was present.⁸ Ozonolyses in pentane solution and with excess aldehydes were carried out at -70° to approximately 60% completion. In the excess aldehyde runs 5 g. of pentene and 5 ml. of the aldehyde were used. In the pentane runs the reaction mixtures used were: 5 g. of pentene, 5 ml. of pentane; 2.5 g.

of pentene, 7.5 ml. of pentane; 2.5 g. of pentene, 25 ml. of pentane; and 2.5 g. of pentene, 50 ml. of pentane. Ozonide VIII had the same g.p.c. retention time and infrared and n.m.r. spectrum as those of authentic butene-2 ozonide.

*Anal.*¹³ Calcd. for $\text{C}_4\text{H}_8\text{O}_3$: O, 46.1. Found: O, 45.9. Calcd. for $\text{C}_5\text{H}_{10}\text{O}_3$: O, 40.6. Found: O, 41.4. Calcd. for $\text{C}_6\text{H}_{12}\text{O}_3$: O, 36.4. Found: O, 36.9.

Ozonolysis of trans-Butene-2. The olefin (10 g.) was led from a precooled cylinder into the reaction flask at -70° and ozonized to approximately 60% completion. The reaction mixture was allowed to warm up and the ozonide collected by preparative scale g.p.c.

N.m.r. Spectra. Samples of the individual ozonides were obtained by preparative scale g.p.c. The spectrum of VIII (CCl_4) has a pair of overlapping quartets centered at 4.73 and a doublet at 8.65 with areas of 1:3.2, respectively. The quartets for the individual isomers are at 4.72 and 4.78 (neat). The spectrum of IX (CCl_4) has multiplets at 5.13 and 8.37, a doublet at 8.65, and a triplet at 9.04. The integrated areas are 4.35:1 for (methyl plus methylene):methine. The spectrum for X (CCl_4) has two overlapping triplets at 4.95, a multiplet at 8.34, and a triplet at 8.61 with areas 1:2.16:3.29, respectively.

Acknowledgment. We wish to thank Mr. E. W. Anderson for determining some of the n.m.r. spectra. L. D. L. wishes to thank the Director of the Rubber and Plastics Research Association of Great Britain for a one year leave of absence during which this work was carried out.

(13) Attempts to obtain carbon and hydrogen analyses were discontinued after violent explosions occurred in two analytical laboratories while attempting these analyses. Oxygen analyses were performed by Midwest Microlab, Inc., Indianapolis, Ind.