STUDIES IN RING - CHAIN POLYMERISATION

BY

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SUMMARY

The synthesis of anhydrosulphite and anhydrocarboxy derivatives of α-hydroxy acids has been examined together with the decomposition of these compounds by routes which lead to α-polyester formation.

The products obtained from the direct reaction of thionyl chloride and several members of the α-hydroxy acid series have been isolated and identified. Possible reaction routes are discussed, together with the effect of α-hydroxy acid structure and reaction conditions on the relative yields of the products obtained.

The polymerisation and related reactions of the anhydrosulphites have been studied kinetically using, principally, gas evolution techniques. Two distinct types of behaviour were observed, typified by the anhydrosulphites of lactic and α-hydroxy isobutyric acids. In the former case the anhydrosulphite ring is susceptible to direct attack by alcohols with resulting regeneration of the α-hydroxy group, this reaction forming the basis of a bimolecular propogation step which leads to polymer formation. α-Hydroxy isobutyric acid shows no such reaction, however, the rate of ring opening being kinetically independent of alcohol concentration. The polymerisation of this anhydrosulphite has been studied with the aid of radioactive tracer techniques.

Both types of decomposition are discussed, together with the observed reluctance of anhydrocarboxy derivatives of α-hydroxy acids to form high molecular weight polyesters, in terms of ring structure and its effect on possible polymerisation mechanisms. The relationship of these compounds to others showing similar behaviour is also discussed.

PREFACE

The work presented in this thesis was carried out between September 1963 and December 1965 at the College of Advanced Technology, Birmingham. It has been done independently and has not been submitted for any other award.

The writer wishes to thank Dr.D.G.H.Ballard for his supervision of this work whilst at the College and his subsequent interest and encouragement. My thanks are also due to Dr.A.V.Golton and Dr.J.Homer for help in obtaining and interpreting infra red and N.M.R. spectra, and to Dr.R.H.Perret and Dr.G.B.Briscoe for advice in the application of gas liquid chromatography and the use of radiochemical counting techniques.

In December 1964 Dr.D.G.Ballard left the department to take up a position with I.C.I. Ltd., Runcorn; Dr. F.J.Hybart was then appointed (internal) research supervisor for the period January - December 1965. Although his concern with this work has been largely administrative, I should like to record my thanks for the help he has given in this respect and in relation to its presentation.

A supporting publication (end cover) reports one aspect of a study of solution properties of polyoxymethylene carried out at the College between January and August 1963 and supervised by Dr. P. F. Onyon (now with B.I.P. Chemicals Ltd., Oldbury). I am grateful to Dr. Onyon both for his guidance in this work and for his initial stimulation of my interest in polymer science.

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1. INTRODUCTION

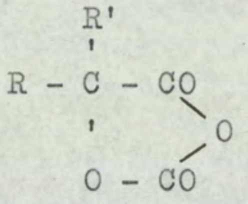
Although linear polyesters have in general been well studied, the simplest members of the group, in which only one main chain carbon atom separates repeat ester units, have received comparatively little attention. These polymers are sometimes referred to as α-polyesters, being related to the α-hydroxy acids from which they may, in principle, be derived by a polyesterification reaction. An illustration of the paucity of published literature on the polymers is found in the fact that a recently published review(1) dealing with linear (saturated) polyesters, contains direct reference to only three members of the α-polyester series.

Perhaps the greatest obstacle to the study of these polyesters has been the lack of a general method of synthesis of high molecular weight polymers, comparatively few of the conventional reactions used in polyester preparation being applicable. Of the polymer forming reactions relying on esterification techniques commonly used in organic chemistry, only the direct self-polyesterification of α-hydroxy acids has been successfully adapted. The reaction is often carried out in an inert solvent, reduced pressure or a flow of nitrogen sometimes being used to remove volatile by-products. An esterification catalyst may be employed (ortho-phosphoric acid, p-toluene sulphonic acid, etc.) or heat alone - temperatures in the region of 250°C being commonly used. An example of the use of this reaction in α-polyester production is found in the du Pont technique for synthesising poly glycollic ester(2). In this case an antimony trifluoride catalyst is used. The self-polyesterification method is unsuitable for acids such as 2-hydroxy propionic acid which are likely to dehydrate or otherwise give rise to undesirable side products. As a result its use in the α-polyester series seems to be limited to formation of the polymers of glycollic and lactic acids.

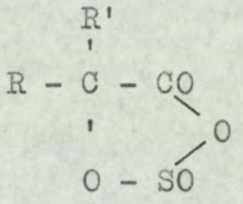
A more satisfactory procedure consists in converting the α-hydroxy acid to the corresponding lactide. This involves an intramolecular cyclisation process which normally takes place in competition with the direct self-polyesterification reaction. The lactide is then isolated and polymerised at elevated temperature in the presence of a suitable catalyst. The method has the virtue that lower temperatures than those necessary for the direct esterification procedure can often be used, depending upon the catalyst, which may be an organic or inorganic acid, a tertiary amine, a Friedel-Crafts catalyst or one of many others which have been successfully employed. Unfortunately the polymerisation of lactides is subject to certain structural limitations. Hall(13) has demonstrated that the presence of four methyl orphenyl substituents (as in 1.1 .4.4.-tetra‿methyl glycollide) inhibits polymerisation. This fact, coupled with the failure of some α-hydroxy acids to cyclise smoothly to the lactide, limits the method in practice to the production of the glycollic and lactic acid polymers.

Techniques based on the reaction of metal salts of dicarboxyl~~l~~ic acids with dihalides have been applied to polyester syntheses, the reaction being accompanied by precipitation of the metal halide. There is apparently only one instance of the principle being extended to α-polyester formation. This involved, notably, the polymerisation of the sodium salt of α-chloro‿benzilic acid(3). The salt was heated in a sealed tube at 110°C-135°C for several hours or until the resultant polybenzilic ester had reached the required degree of polymerisation. Although polymers were also produced from the α-chloro‿lactic and α-chloro α-hydroxy isobutyric acid salts, the method was reported as being too erratic and uncontrollable for general use.

Certain other derivatives of α-hydroxy acids exist which are potentially useful in α-polyester synthesis; these are the so-called anhydrocarboxy acids and acid anhydrosulphites. It is with these compounds that the present work is concerned. The general formulae of the anhydrocarboxy (I) and anhydrosulphite (II) derivatives of α-hydroxy acids are shown below:-



(I)



(II)

Although this trivial nomenclature has by usage become accepted, the anhydrocarboxy derivatives are also named systematically as 1.3-dioxolan-2.4-diones. No attempt has been made in the literature to name the anhydrosulphites on a similar basis; for convenience the trivial nomenclature will hereinafter be adopted.

The first recorded anhydrosulphite synthesis was carried out by Blaise and Montagne. These workers had examined the products of the reaction between thionyl chloride and glycollic acid (4) and, in so doing, isolated the chlorosulphite of glycollyl chloride. On seeking to extend the reaction to lactic and α-hydroxy iso-butyric acids, however, they found that the main products did not contain chlorine and had the empirical formulae $C_3H_4O_4S$ and $C_4H_6O_4S$ respectively (5). They designated these compounds α-hydroxy acid anhydrosulphites. In the course of subsequent investigations into the reactivity of the anhydrosulphites Blaise and Montagne noted that the compounds decomposed under the influence of heat to yield a 'polylactide residue' which could itself be hydrolysed to the parent acid.

Alderson (6) investigated this reaction and developed a technique for the production of a high molecular weight ∝-polyester from ∝-hydroxy iso‿butyric acid anhydrosulphite. The method used by Alderson involved adding an approximately three-fold molar excess of thionyl chloride to the acid and maintaining this below 10°C for some ten hours. The temperature was then allowed to rise to 20°-30°C and hydrogen chloride, together with unreacted thionyl chloride, removed under reduced pressure, the anhydrosulphite being finally purified by vacuum distillation. After a prepolymerisation step, designed to remove chance initiators, the anhydrosulphite was transferred to a predried inert solvent with a boiling point between 60°C and 150°C, aromatic or halogenated hydrocarbons such as benzene or chlorobenzene being preferred. The mixture, contained in a flask fitted with a reflux condenser and vented through a drying tube, was blanketed with nitrogen and refluxed for a period depending on the boiling point of the solvent. The reaction time, which is related to the time taken for the anhydrosulphite to decompose at the temperature of reflux, was found to vary from 52 hours in benzene (b.pt. 80°C) to 18 hours in chlorobenzene (b.pt. 132°C). On cooling the system, the polymer was isolated as a cloudy colourless gel. Alderson recorded the fact that the presence of moisture was found to reduce the molecular weight of polymer formed.

While the present work was in progress Rose and Warren (7) published the results of their attempts to extend Alderson's technique to other ∝-hydroxy acids. Although this publication was valuable in establishing that several other ∝-hydroxy acids would yield polymers by this technique, the results were in some ways unsatisfactory. Thus the degrees of polymerisation obtained by decomposition of the anhydrosulphites varied throughout the series, none of them being as high as that obtained from ∝-hydroxy iso‿butyric acid anhydrosulphite and some so low as to be useless for evaluation. On the data presented it is impossible to assess a reason for this. It is possible that the nature and concentration of impurities produced by the reaction of thionyl chloride and the ∝-hydroxy acids varied and influenced the subsequent polymerisations to different extents. Although each anhydrosulphite was purified by distillation and prepolymerisation, there was apparently no attempt to assess the purity of the final products.

The only publications relating to the synthesis of anhydrocarboxy ∝-hydroxy acids are those of W. H. Davies(8,9). The compounds are formed by interaction of phosgene and ∝-hydroxy acids, the reaction being in many ways analagous to that between thionyl chloride and ∝-hydroxy acids. The technique used involved mixing, at room temperature, a solution of the acid in dioxane or ethyl acetate with a three- to four-fold molar excess of phosgene in the same solvent. The mixture was maintained at 15°-20°C for some three days and the solvent and excess phosgene then removed by distillation at reduced pressure. The residual oil thus obtained was cyclised by heating at 60°C for three hours, the product being purified by vacuum distillation or recrystallisation. Although no attempts to produce high molecular weight polymers from the anhydrocarboxy derivatives are described by Davies, the formation of polymeric residues in reactions with, for instance, amines is mentioned. It is presumably on the work of Davies that Sorenson and Campbell(10) base their remark that 'cyclic carboanhydrides of ∝-hydroxy acids do not polymerise to a high molecular weight.'

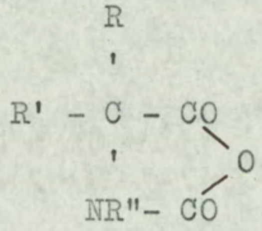
The relationship of anhydrosulphite and anhydrocarboxy derivatives of α-hydroxy acids to other heterocyclics which undergo ring opening polymerisation reactions is not immediately apparent. The compounds are cyclic esters and, in this, bear a superficial resemblance to lactones and lactides. The resemblance extends further for all are derivable from α-hydroxy acids and all, with the possible exceptions of the anhydrocarboxy derivatives, are capable of yielding polyesters by a ring opening process. Lactones and lactides differ from anhydrosulphites, however, in that no structural elements are lost in the polymerisation, whereas the latter compounds polymerise with the evolution of one molecule of sulphur dioxide per repeat unit. Because of this no direct correlation exists between the polymerisibility of anhydrosulphites on one hand and lactides and lactones on the other.

The relationship of ring size of lactides and lactones to ease of polymerisation follows a pattern observed in many cyclic systems susceptible to ring opening polymerisation. Amongst workers in this field the names of Carothers(11) and Hall(12, 13, 14) are noteworthy, particularly in relation to the systems under consideration. In general polymerisibility is observed to be greatest in rings which are strained, either because of size or the presence of bridging groups. Conversely five, and to a lesser extent six, membered rings, being relatively unstrained, polymerise either with difficulty or not at all. The presence of substituents is often found to decrease polymerisibility.

In the lactone series the five membered γ-lactone rings are very resistant to polymerisation, whilst the six membered δ-lactones, except for those substituted by at least one n-propyl or two methyl groups, polymerise readily. A variety of catalysts, especially bases, are found to be effective in promoting the polymerisation (e.g., sodium, sodium hydride, potassium carbonate). The three membered ∝-lactone rings are not known. Attempts to form them by dehydration of the corresponding ∝-hydroxy acids lead to formation of the six membered lactide ring.

The factors affecting polymerisibility of lactides have been briefly mentioned, in particular the observations of Hall that 1.1 .4.4-tetra substituted glycollides do not polymerise. The apparent readiness of the five membered ∝-hydroxy isobutyric acid anhydrosulphite to polymerise, possessing as it does two ∝-methyl substituents, underlines the distinctive nature of this polymerisation reaction. Other cyclic esters such as the cyclic carbonates and oxalates show even less similarity to the anhydrosulphite system.

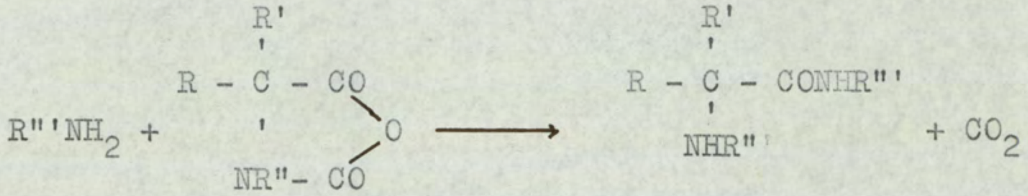
The compounds which undoubtedly show the greatest superficial resemblance to anhydrocarboxy and anhydrosulphite derivatives of ∝-hydroxy acids are the N-carbonic anhydrides of ∝-amino acids (III).



(III)

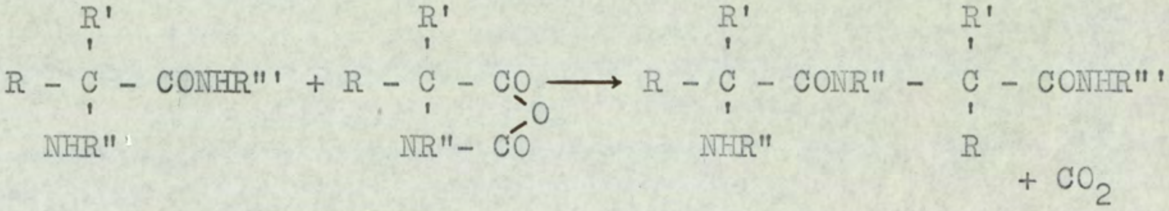
The simplest member of the series, oxazolidine-2.5-dione (R=R'=R"=H), was synthesised by Leuchs in 1906 (15). About one hundred homologues, referred to collectively as Leuchs' anhydrides, have since been prepared. It was Leuchs who first noticed the tendency of the compounds to decarboxylate on heating, a reaction which leads to polypeptide formation. Although mechanisms for this high temperature bulk polymerisation have been suggested, the true nature of the propagation step involved is still obscure.

A more widely studied means of polymerising the Leuchs' anhydrides is based on the ring opening reaction with primary and secondary amines, first reported by Fuchs(16) and Wessely(17). From equimolar quantities of the amine and anhydride the predominant products are an ∝-amino acid amide and carbon dioxide (Equation 1).



Equation 1

In an excess of Leuchs' anhydride the regenerated ∝-amino group reacts with a further molecule of anhydride and produces a dimer possessing a terminal amine group. The reaction is accompanied by liberation of a further molecule of carbon dioxide (Equation 2)



Equation 2

These reactions form the basis of the so-called 'normal' amine propagated polymerisation of the N-carbonic anhydrides. Although amine initiation is probably most commonly used, certain other compounds which contain a labile proton (e.g. alcohols, water, etc.) are capable of initiating the polymerisation reaction.

Kinetic studies of this mode of polymerisation have been carried out by several workers, notable early contributions being those of Waley and Watson(18) and Ballard and Bamford(19). The observed presence of terminal amino groups in the final polymer and the narrow Poisson-type molecular weight distribution obtained, coupled with the effect of initiator concentration on degree of polymerisation, confirmed the postulate that chain transfer and termination processes are absent or negligible. Various apparent anomalies and deviations from the normal scheme of polymerisation have subsequently been observed. Apart from structural effects in the anhydride itself, abnormalities due to heterogeneity in the system(20), the effect of the initiating amine on the rate of the subsequent propagation step(21) and the ability of aprotic bases of various types to initiate the polymerisation(22, 23) are found.

With respect to the effect of structure it is interesting to note the fact that the N-carbonic anhydride of ∝-amino isobutyric acid will not yield high molecular weight polymer by the 'normal' amine propagation mechanism. A study of the stereochemical features of the reaction has indicated that this is due to the shielding effect of the methyl groups(27). It is envisaged that the attacking base approaches the carboanhydride ring along a path which is slightly inclined to it and more or less above (or below) the nitrogen atom on the ring. The reaction proceeds by attack of the base on the $C_{(5)}$ carbonyl group with ensuing ring rupture and evolution of carbon dioxide.

In contrast to the N carbonic anhydrides the anhydrosulphite derivatives of ∝-amino acids have received little attention. It has, however, been stated(24) that these compounds will not polymerise.

1 (i) Scope and Object of the Present Work

The work described in this thesis is primarily a study of the synthesis and ring opening polymerisation of the anhydrosulphites of ∝-hydroxy acids. The main objects in undertaking the work were two-fold; first, to investigate the generality of the reactions reported by Blaise and Montagne(5) and Alderson(6) as a means of producing ∝-polyesters. Second to elucidate the kinetic and mechanistic features of the polymerisation and, in so doing, attempt to resolve apparent anomalies which exist in comparison with the anhydrocarboxy ∝-hydroxy acids and the analogous derivatives of the ∝-amino acids.

It seems relevant in investigating the synthesis of anhydrosulphites to consider the reaction of thionyl chloride with ∝-hydroxy acids in some detail and record not only the varying ease of formation in passing from one member to another of the ∝-hydroxy acid series, but also the nature and relative concentration of the impurities associated with the anhydrosulphite in each case. It was felt that a knowledge of such impurities might well facilitate further purification of the anhydrosulphites and provide information relevant to possible termination reactions in the subsequent polymerisation.

Two further aims in the synthetic work were the development of alternative routes to anhydrosulphites not obtainable from the appropriate hydroxy acid and the preparation of the hitherto unreported anhydrocarboxy derivative of ∝-hydroxy isobutyric acid. This latter compound was required for polymerisation studies in comparison with the analogous anhydrosulphite.

The statements that anhydrocarboxy derivatives of ∝-hydroxy acids do not yield high molecular weight polymer(10) and anhydrosulphites of ∝-amino acids do not polymerise(24) have been referred to. An apparent anomaly exists here in view of the fact that both the α-hydroxy acid anhydrosulphites and the N-carbonic anhydrides of α-amino acids are known to produce polymers of high molecular weight. It is not possible, on existing knowledge, to offer a complete explanation of the situation. Although experimental work involving α-amino acid derivatives is outside the scope of the present work, it seemed appropriate to investigate the anhydrocarboxy α-hydroxy acids and compare their polymerisibility with the analogous anhydrosulphites. The α-hydroxy isobutyric acid derivatives were chosen for initial examination since α-hydroxy isobutyric acid anhydrosulphite has been shown by Alderson to produce high molecular weight polymer. Such investigations were designed to provide definite information both on the behaviour of the two types of compound under identical conditions and on the reasons for any differences that were found to exist.

The bulk of the work presented here is concerned with kinetic and mechanistic aspects of anhydrosulphite polymerisation. Although there are several reasons for suspecting some similarity between these systems and the N-carboxy-α-amino-acid anhydrides, the marked difference in polymerisibility between α-hydroxy isobutyric acid anhydrosulphite and the analagous α-amino acid carboanhydride presents an immediate problem. It is hoped that these studies will resolve apparent anomalies such as this and provide a sound basis for the formation of high molecular weight α-polyesters.

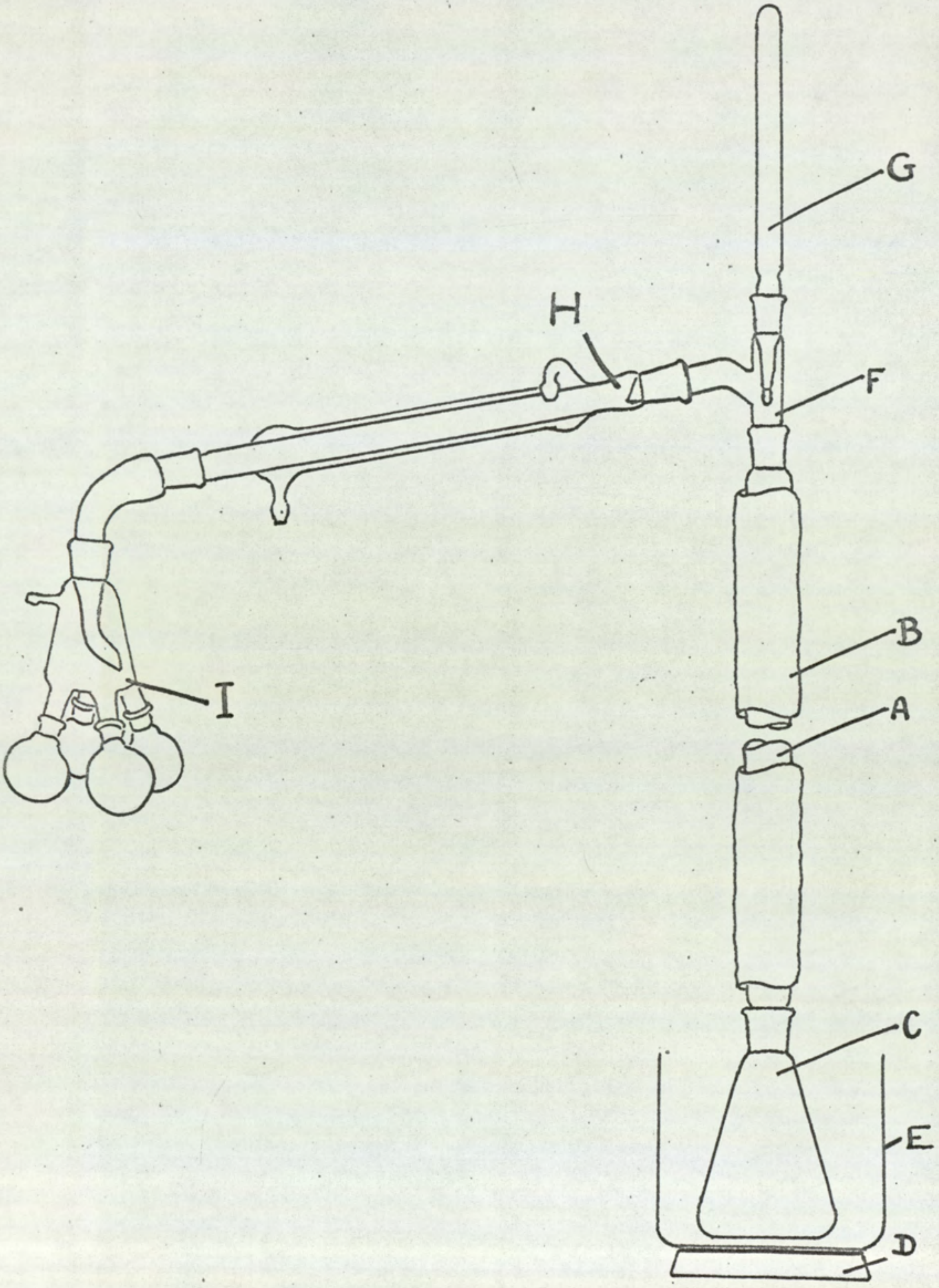


FIGURE 1. Preliminary Distillation Apparatus

2. EXPERIMENTAL METHODS

2:1 Apparatus and Technique

(i) Distillation under reduced pressure

Preliminary fractional distillation at reduced pressure was carried out in the apparatus shown in Figure 1. This consisted of a plain glass column (A) of length 30 cm, which was filled with Raschig rings (4 mm diameter). The column was wound with a heating tape (B) fed via a variable transformer (not shown).

A thermocouple, connected to a dial reading thermometer was used to give some indication of the temperature of the column jacket. The lower end of the column terminated in a B.19 cone by which means the conical flask (C) was attached. The contents of the flask were agitated by a short metal rod encapsulated in glass or polythene, which was actuated by the magnetic stirrer (D). The stirrer was combined with a hot plate; this served to maintain the temperature of the water bath (E) surrounding the conical flask. The upper end of the column was connected by means of a B.19 socket to a stillhead (F) fitted with thermometer (G) and joined to a water condenser (H). The rotating fraction collector (I) led, via a cold trap, to the vacuum pump (not shown).

In distilling the anhydrosulphite derivatives, the technique possessed several advantages over the procedures previously used. The column could be pre-heated to the temperature at which distillation was expected to commence. This, in conjunction with the use of a heated water bath, meant that the compound could be rapidly raised to, and maintained at, the required temperature. This procedure reduced local over-heating in the distillation flask and the delay normally encountered while a temperature equilibrium was established in the column. Raschig rings were employed

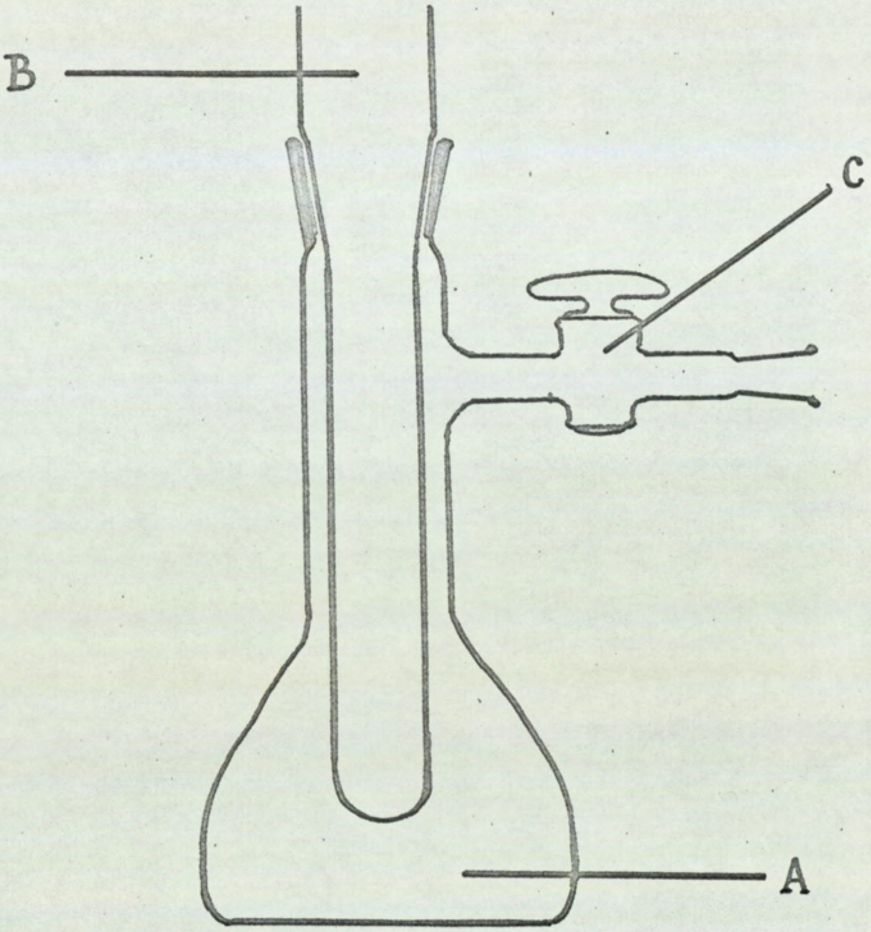


FIGURE 2. Vacuum Sublimation Apparatus

as column packing since, in contrast to, say, Fenske helices, they gave little trouble with flooding. The use of a conical flask with no air bleed minimised pressure leaks in the system.

(ii) Spinning Band Column

Refined fractional distillations at reduced pressure were carried out with the 'Buchi' spinning band column (supplied by Orme Scientific Limited, Manchester).

The spinning band column depends for its high efficiency upon the mechanical mixing of vapour and liquid which occurs. It is well suited to vacuum distillations due to the small pressure drop throughout its length. The 'Buchi' column is claimed to have an efficiency of approximately 30 theoretical plates and a column hold up of 1.5 m l. The efficiency was determined using a mixture of n-heptane/methyl cychlohexane at a throughput of 60 m l per hour. The purification of small quantities (10 m l) of materials which is possible due to the low hold up volume of the column was found to be ideally suited to the type of work described here.

(iii) Vacuum Sublimation

Vacuum sublimation was carried out using the apparatus shown in Figure 2. The apparatus was baked in an oven at 120°C for several hours before use and then transferred to a dry box. The compoundwas placed in the main chamber (A), the cold finger (B) replaced, tap (C) closed and the sublimer placed in a water bath and connected to a vacuum line via the B14 cone (D). The cold finger was filled with a mixture of crushed solid carbon dioxide and acetone and the sublimer evacuated by opening the tap (C). The temperature of the water bath was adjusted to promote fairly ready sublimation.

When the sublimation was judged to be complete, the tap was closed and the sublimer transferred to a dry box where the purified material was removed for further use.

(iv) Liquid/Liquid Extraction

This technique was used for continous ether extraction of ∝-hydroxy acids from concentrated aqueous solution. It was found to be particularly useful for acids such as ∝-hydroxy isobutyric acid which were not readily soluble in ether. The apparatus and technique were based on the description given by Vogel(25).

(v) Glove Box

For manipulations requiring a completely dry environment a Gallenkamp model MA.950 glove box was used. The moisture was removed from the chamber by means of a circulating pump which cycled the air through two glass spirals immersed in a solid carbon dioxide/acetone mixture. An evaporating basin containing phosphorus pentoxide was placed in the dry box, its condition being used as a visual means of detecting the presence of moisture.

(vi) Gas Chromatograms and G.L.C. Separations

These were obtained using the Aerograph Autoprep preparative gas chromatograph (model A.700). Two columns were used:-

(a) 25% squalane on 60/80 mesh Silocel support. Column dimensions 5 ft by 1/4 inch o.d. This was found to be the most suitable of many which were evaluated for use with the anhydrosulphite and anhydrocarboxy derivatives of ∝-hydroxy acids.

(b) 10% polyethleneglycol adipate on 85/100 mesh Silocel support. Column dimensions 5 ft by 1/4 inch o.d. This column was used mainly with ∝-hydroxy acids.

(b) (contd:)

Further details of temperature, carrier gas flow rates, etc., are given, where appropriate, in the text.

(vii) Infra Red Spectra

These were obtained using the Perkin-Elmer infrared spectrophotometer (model 237). Details of the state of the sample, cell dimensions, etc., are given in the text with each recorded spectrum.

(viii) Determination of Chloride ion Concentration

The ionisable chloride concentration of compounds was determined potentiometrically using a method developed by Ingram(26).

The procedure used in the case of products isolated in the reactions described in Sections 3:1 and 3:2 was as follows:-

To a weighed amount of the compound (ca. 0.1 grm) was added a large excess of 3:1(v /v) distilled water: acetone, and a few drops of 1N nitric acid. The solution at this stage was just acid to methyl orange indicator. The solution was warmed slightly in order to decompose the compound, conditions of varying severity being investigated in the case of unknown materials (until replicate analyses were obtained). The solution was then cooled and titrated potentiometrically with 0.01 N silver nitrate solution, the end point being determined graphically in the usual manner.

The electrode system used was silver/silver:silver nitrate, in conjunction with an E.I.L. model 23A pH meter.

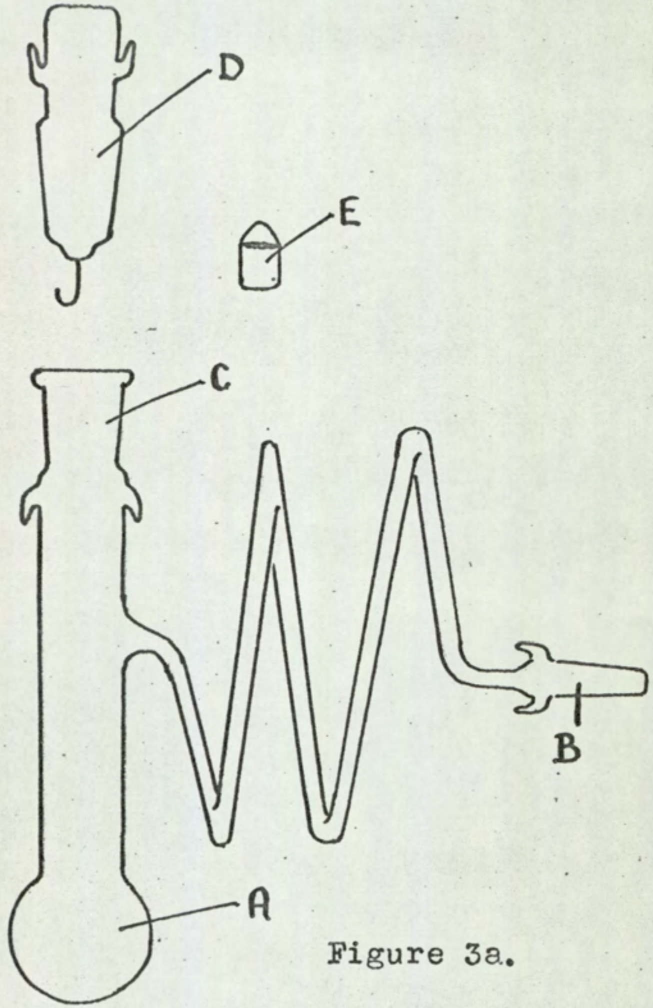


Figure 3a.

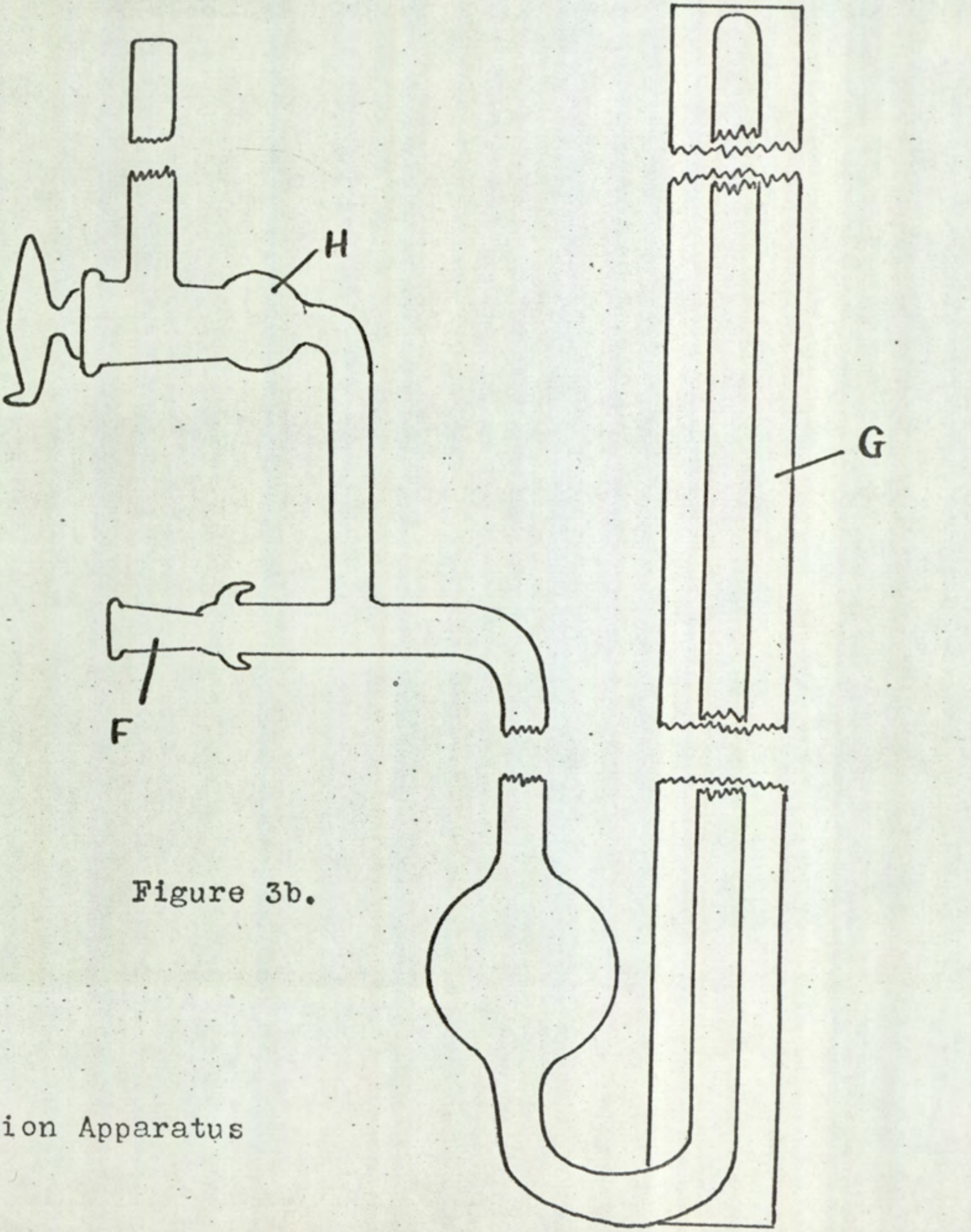


Figure 3b.

FIGURE 3. Low Temperature Gas Evolution Apparatus

(ix) Determination of Carboxyl Group Concentration

Materials were dissolved in Benzene/methanol (3/1), which had been previously adjusted to pH 7, and titrated with standardised sodium methoxide solution. The titration was followed potentiometrically using an E.I.L. model 23A pH meter and a glass/calomel electrode system.

(x) Gas Evolution Measurement at Constant Volume

(a) Low temperature measurement (25°-45°C)

The apparatus, which was developed from that used by Waley and Watson(18) and Ballard and Bamford(19), is shown in Figure 3a. The reaction vessel (A) was connected by means of a glass spiral to a B.10 cone (B). On some models a high vacuum tap was incorporated between the cone and the reaction vessel.

Reactants were introduced in to the reaction vessel through the B.14 socket (C). A modified B.14 cone (D), having a hook attached to the lower end, enabled a glass bucket (E) to be suspended above the reaction medium and released when required. By containing one of the reactants in the bucket the reaction could be initiated at will.

Gas pressure, which increased during the course of the reaction, was measured by connecting the vessel to the manometer unit (Fig. 3b) by means of the B.10 socket (F). The mercury level was measured either directly by reference to the calibrated scale (G) or by means of a cathetometer.

All rate measurements were carried out with the apparatus maintained at constant temperature, normally in a Townson and Mercer E270 Bridge Controlled Thermostat Bath.

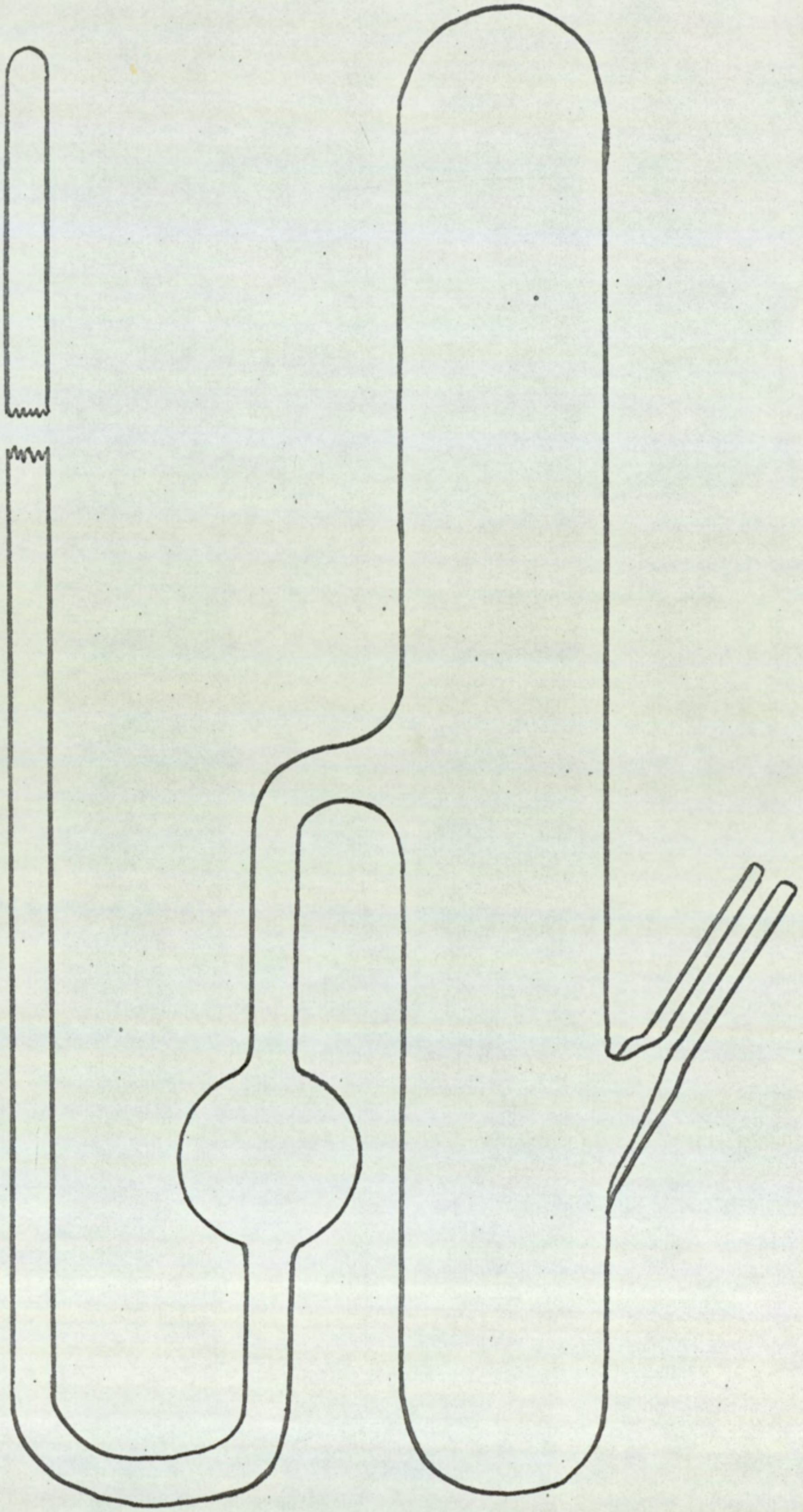


FIGURE 4. High Temperature Gas Evolution Apparatus

(a) (contd:)

Measured quantities of the reactants were introduced into the apparatus using normal manipulative techniques. When complete absence of moisture was required, the reaction vessel was assembled and sealed (by means of the vacuum tap previously described) in the dry box. Weighings were carried out by difference, using containers which were opened only in the dry box itself.

The reaction vessel was then joined to the manometer unit, evacuated by means of tap (H) and placed in the thermostat bath. When the system was judged to have attained the temperature of the bath, the reaction was started (by dislodging the bucket) and readings taken at convenient time intervals.

(b) <u>Temperature Range 50°-150°C</u>

A number of experimental difficulties were encountered when using the gas evolution apparatus, previously described, at temperatures above 45°C. Most of the trouble stemmed from the tendency of the ground glass joints to leak after fairly short periods at the higher temperatures. Several modified types of apparatus containing no ground glass joints were constructed, a typical example being shown in Figure 4.

A further advantage of this design was that due to the much greater volume of the apparatus, larger samples of anhydrosulphite could be employed, thus yielding sufficient polymer for examination after completion of the kinetic measurements.

Thermostats for kinetic studies at temperatures above 65°C were constructed from 8 litre Dewar vessels having a vertical window approximately 3 cm wide.

(b) (contd:)

These were fitted with a contact thermometer/relay/heater system. For temperatures up to 90°C water covered with a layer of liquid paraffin was used as bath fluid, liquid paraffin or silicone oil being substituted at temperatures above this.

(c) Photodecomposition Experiments

These were carried out using apparatus similar to that shown in Figure 4. The reaction vessel was, however, constructed in silica and joined to the manometer by means of a graded silica/Pyrex glass seal.

Agitation

Agitation of all types of reaction vessel was effected by means of a Pifco vibrator. In most cases application of the vibrator to the clamp or stand holding the apparatus was found to provide sufficient agitation for the reaction medium.

Measurement of Reaction Rates by Gas Evolution Techniques

The use of gas evolution techniques to follow the course of chemical reactions is well established. Kinetic studies such as those of Waley and Watson(18) and Ballard and Bamford(19), have consisted essentially in measuring rates of evolution of carbon dioxide and relating these to the rate of decomposition of N-carboxy-α-amino-acid anhydrides. The principles underlying such measurements apply largely to the studies involving anhydrocarboxy α-hydroxy acids presented here. In extending gas evolution studies to the analogous anhydrosulphites, however, two further factors must be taken into account. The first is the volatility of the monomer, which is considerably greater than that of the corresponding anhydrocarboxy derivatives and N-carbonic anhydrides of similar structure. The second is the fact that sulphur dioxide, which is evolved in the decomposition of anhydrosulphites is more soluble than carbon dioxide in the reaction media used in the investigations.

The validity of gas evolution measurements under various conditions will now be considered.

For the general case in which one mole of a monomer decomposes to yield, inter alia, 1 mole of a gas, the initial monomer concentration $[M]_o$ is related to the monomer concentration at any instant $[M]$ and the concentration of gas the decomposition has produced $[G]$, by the equation:

$$[M]_o = [M] + [G] \tag{3}$$

If the reaction proceeds to completion,

$$[M]_o = [G]_\infty \tag{4}$$

For an ideal gas in a system at constant volume and temperature the pressure P is directly proportional to the number of moles of gas produced, i.e.,

$P_\infty \propto [G]_\infty$

introducing a proportionality constant Π:

$$\Pi P_\infty = [G]_\infty = [M]_o \tag{5}$$

If P is the pressure of the gas at any instant, equation (3) gives:

$$\Pi P = [G] = [M]_o - [M] \tag{6}$$

equations (5) and (6) now combine to yield

$$\frac{[M]}{[M]_o} = \frac{\Pi(P_\infty - P)}{\Pi P_\infty} = \frac{P_\infty - P}{P_\infty} \tag{7}$$

Under conditions in which the gas has an appreciable solubility in the reaction medium this derivation must be modified. If $[G]_T$, $[G]_g$ and $[G]_s$ represent the total concentration of gas, the concentration in the gas phase and that in solution respectively,

$$[M] = [M]_o - [G]_T \tag{8}$$

$$[G]_T = [G]_g + [G]_s \tag{9}$$

$$[G]_s = P.A \tag{10}$$

$$[G]_g = P.B \tag{11}$$

$$[G]_T = P(A + B) = \Pi'P \tag{12}$$

Where A is a conversion factor relating the solubility of the gas in the reaction medium to the pressure; and B a similar factor computable from the 'dead space' volume, both being temperature dependent. If the solubility is linearly related to the pressure over the pressure range studied (i.e., the behaviour is consistent with Henry's law) and Boyle's law is obeyed in the gas phase, the use of the combined proportionality constant Π' is valid.

From (8) and (12) we have

$$[M] = [M]_o - \Pi'P \tag{13}$$

$$-\frac{d[M]}{dt} = \Pi'\frac{dp}{dt} \tag{14}$$

Thus for an ideal gas in the absence of any complication from the presence of volatile monomer, the rate of change of monomer concentration is equivalent to the rate of change of pressure with time.

If the monomer has an appreciable volatility, however, a further modification is involved. The subscripts 'g' and 's' denote material in the gas phase and solution respectively. Equations (8) and (9) now become:

$$[M]_o = [M]_g + [M]_s + [G]_g + [G]_s \tag{15}$$

A change in the total monomer concentration with respect to time may now be equated with a similar change in gas concentration,

$$-\frac{d}{dt}([M]_g + [M]_s) = \frac{d}{dt}([G]_g + [G]_s) \qquad (16)$$

i.e. $$-\frac{d\Sigma[M]}{dt} = \frac{d\Sigma[G]}{dt} \qquad (17)$$

In the case of an ideal gas the total pressure P_T is equal to the sum of the partial pressures of monomer (P_M) and gas (P_G)

$$P_T = P_M + P_G \qquad (18)$$

Introducing proportionality constants as before:

$$P_T = \frac{\Sigma[M]}{\Pi''} + \frac{\Sigma[G]}{\Pi'} \qquad (19)$$

then:

$$\frac{\delta P}{\delta t}_T = \frac{1}{\Pi''}\frac{\delta\Sigma[M]}{\delta t} + \frac{1}{\Pi'}\frac{\delta\Sigma[G]}{\delta t} \qquad (20)$$

Therefore, from (15) and (18):

$$\frac{\delta P}{\delta t}_T = \frac{1}{\Pi''}\frac{\delta\Sigma[M]}{\delta t} - \frac{1}{\Pi'}\frac{\delta\Sigma[M]}{\delta t} \qquad (21)$$

$$= \frac{\delta\Sigma[M]}{\delta t}\left(\frac{1}{\Pi''} - \frac{1}{\Pi'}\right) \qquad (22)$$

Thus if the equimolar quantities of monomer and gas exerted equal vapour pressures under the conditions of the reaction, the change in pressure with respect to time would be zero. In the case of an ideal gas which has appreciably greater volatility than the monomer, however, the rate of variation of total pressure will be equivalent to the rate of variation of total monomer concentration.

An assessment of the relative magnitude of Π' and Π" may be obtained from the initial and final pressures (P_o and P_∞) of a system at constant volume in which the monomer is decomposing. Thus if the reaction medium has a negligible vapour pressure at the temperature of the reaction, equations (18) and (19) yield

$$\frac{P_M}{P_G} = \frac{P_o}{P_\infty} = \frac{\Pi'}{\Pi''} \qquad (23)$$

In the systems considered here the ratio $\frac{P_o}{P_\infty}$ did not normally exceed $\frac{1}{20}$. The decrease in sensitivity caused by monomer volatility was, therefore, extremely small. Furthermore, deviations of the monomer vapour from ideal gas behaviour will cause very little error in the use of pressure measurements to determine reaction rates.

The kinetic studies presented in this thesis frequently involve sulphur dioxide as the evolved gas and nitrobenzene as the reaction medium. Although sulphur dioxide has a high solubility in nitrobenzene, it would be expected to follow ideal gas laws since the temperatures involved are high (60^oC-90^oC) and the pressures low (< 300 mm). Furthermore, its critical temperature and pressure (430.3^oK, 77.6 atm.) are not greatly different from those of carbon dioxide (304.2^oK and 72.9 atm.). The kinetic studies of Waley and Watson and Ballard and Bamford have shown that pressure measurements involving this latter gas may be substituted directly in equation (7). This relationship is used in the present work, together with that derivable from equation (14) for initial rates of reaction,

i.e. $$-\left(\frac{\delta[M]}{\delta t}\right)_{t\to 0} = \Pi'\left(\frac{\delta P}{\delta t}\right)_{t\to 0} \qquad (24)$$

the constant Π' being computable from a knowledge of the 'deadspace' volume of the system and the solubility of the evolved gas in the reaction medium.

(xi) Vapour Pressure Osmometer

The Mechrolab model 301 A vapour pressure osmometer was employed in obtaining number average molecular weights below 20,000.

The principle of vapour pressure lowering and its application to determination of molecular weight in instruments of this type has been dealt with by several authors, e.g., (28, 29).

The instrument consists of an insulated thermostatically controlled vapour chamber into which two thermistor probes are placed. By means of two syringes it is possible to place droplets of solvent or solution on one probe and a droplet of solvent on the other. The probes are maintained in an atmosphere of pure solvent vapour above a reservoir of solvent. Since a solution of any solute in a given solvent has a lower vapour pressure than the pure solvent, the resulting differential mass transfer which occurs between the droplets and the solvent vapour phase causes a temperature difference between the probes. The thermistor probes are connected into a Wheatstone bridge circuit, hence any change in temperature causes an imbalance in the system which is measured in the form of a resistance reading.

By calibrating the instrument for the solvent system to be used (employing a suitable solute of known molecular weight, low vapour pressure and high purity), the molecular weight of unknown samples may be determined. The precision and accuracy of the method depend upon various factors (nature and purity of the solvent, molecular weight of sample, etc.). With the systems employed here errors within the limits ± 10% for molecular weights below 10,000 and ± 20% for molecular weights between 10,000 and 20,000 were expected. A comparison of this technique with others (30) indicates that this is not unreasonable.

Further procedural details are included, where relevant, in the text.

(xii) Determination of Carbon 14 Activity by Liquid Scintillation Counting

The use of the scintillation counting technique for weak β-emitters such as C^{14} is now well established. A concise account of the theory and applications of the method is given by Schram(31).

In the present work a commercial liquid scintillation counter was used in conjunction with a head amplifier, discriminator and scaler/timer unit. Samples were initially dissolved in tetrahydrofuran and diluted with a liquid scintillator (Nuclear Enterprises N.E.213) prior to counting, the amount of tetrahydrofuran and scintillator being kept constant for all determinations. Solutions prepared in this manner were transferred to stoppered counting bottles and inserted into the counter. M.S. 200 silicone oil (Midland Silicones Ltd.) was used in the shutter cavity to ensure good optical contact.

The optimum working conditions were determined by recording the count rate of a standard $carbon^{14}$ source plus scintillator and scintillator separately at each of a number of E.H.T. settings for a series of discriminator bias voltages. Plots of count rate vs. E.H.T. voltage at each discriminator bias voltage were made and the working conditions chosen by inspection to give an operating potential on the counting plateau with a minimum background. For the systems employed here an E.H.T. working voltage of 1400 volts and discriminator bias voltage of 10 volts were found most suitable.

2:2 Purification of Solvents and Synthetic Reagents

Diethyl ether

For normal manipulation ether dried over sodium wire was employed. In the synthesis of anhydrocarboxy and anhydrosulphite derivatives, however, the anhydrous grade supplied by May and Baker was used.

Petroleum ether

When required perfectly dry (e.g., for the preparation of anhydrocarboxy mandelic acid) the solvent was allowed to stand over sodium wire.

Ethyl acetate

The material was washed with an equal volume of a 5% sodium carbonate solution, followed by saturated calcium chloride solution, dried over magnesium sulphate and distilled.

Benzene

The solvent was dried over calcium chloride, filtered and stored over sodium wire.

Dioxan

Dioxan was refluxed for eight hours with 10% by volume of a solution consisting of 14 ml concentrated hydrochloric acid in 100 ml water, nitrogen being bubbled through to remove acetaldehyde. After cooling, potassium hydroxide pellets were added until the aqueous layer was saturated; it was then removed. The dioxan was dried at this stage by standing over potassium hydroxide pellets for four hours and then refluxed with an excess of sodium until freshly added sodium remained bright. Finally, the solvent was distilled from sodium and stored away from air and light.

Nitrobenzene

Nitrobenzene was allowed to stand over phosphorous pentoxide for 24 hours and then fractionally distilled under reduced pressure. The middle fraction was collected over barium oxide from which it was redistilled, again at reduced pressure, immediately before use.

o-Nitrotoluene

This was treated in the manner described above for nitrobenzene.

Dekalin (decahydronaphthalene)

The solvent was washed three or four times with dilute (7% W/V) sulphuric acid, once with dilute (10% W/V) sodium hydroxide and, finally, three or four times with water. The washed material was dried over calcium sulphate and fractionally distilled under reduced pressure. The middle fraction was collected over calcium sulphate and redistilled under reduced pressure immediately before use.

α-Methyl naphthalene

This was purified by fractional distillation from calcium sulphate under reduced pressure.

Benzyl alcohol

The material was fractionally distilled at atmospheric pressure, the middle fraction being collected over calcium sulphate and redistilled under reduced pressure immediately prior to use.

Cychohexanol

Cyclohexanol was dried by fractional distillation under reduced pressure. The middle fraction, which solidified on cooling, was collected and stored under vacuum.

Amyl alcohol

The material was allowed to stand over calcium sulphate and fractionally distilled under reduced pressure. The middle fraction was collected and stored over calcium sulphate and redistilled, under reduced pressure, immediately prior to use.

"Cellosolve acetate" (β-ethoxy ethylacetate)

The material was shaken with calcium carbonate, allowed to stand over calcium sulphate, and fractionally distilled under reduced pressure.

Ethyl lactate

The material was shaken with calcium carbonate, allowed to stand over calcium sulphate and fractionally distilled under reduced pressure. The middle fraction was collected over calcium sulphate and redistilled immediately prior to use.

Cyclohexanone

Cyclohexanone was distilled from sodium carbonate under reduced pressure.

Tetrahydrofuran

Tetrahydrofuran was allowed to stand over calcium chloride for 48 hours and fractionally distilled at atmospheric pressure. The material was stored in a dark bottle.

Benzylamine

Benzylamine was allowed to stand over solid potassium hydroxide and fractionally distilled under reduced pressure. The middle fraction was collected over barium oxide and redistilled immediately prior to use.

Pyridine

For the synthesis of anhydrocarboxy acids the anhydrous grade supplied by B.D.H. was employed.

Triethylamine

The material was treated with p-toluene sulphonyl chloride to remove any primary and secondary amines present, distilled, stored over barium oxide or potassium hydroxide and fractionated immediately before use.

Phosgene

Liquid phosgene under pressure was bought in cylinders from I.C.I. Ltd. and distilled from the cylinder when required.

Thionyl Chloride

Thionyl chloride was redistilled at atmospheric pressure. The system was vented to air through a calcium chloride drying tube to prevent entry of moisture.

2:3 Preparation and Purification of Anhydrosulphite and Anhydrocarboxy Derivatives of α-Hydroxy Acids

Note on techniques employed in preparative work

It was found convenient to employ a magnetic stirrer when continuous agitation was required. This facilitated use of an ice or water bath in controlling the temperature of the reaction vessel. Removal of volatile materials (ether, thionyl chloride, phosgene, hydrogen chloride, etc.) was effected by means of an efficient water pump. The diethyl ether used in these syntheses was the anhydrous grade supplied by May and Baker Ltd.

(i) α-Hydroxy Isobutyric Acid Anhydrosulphite

The method is based on that used by Blaise and Montagne(5) and Alderson(6).

1 mole α-hydroxy isobutyric acid (104 g) was dissolved in diethyl ether (500 ml) and slowly mixed with a 50% molar excess (1.5 moles, 180 g) of thionyl chloride in the same solvent. The reaction mixture was stirred continuously and maintained below 5°C during the addition. When this stage was completed the mixture was allowed to warm up to room temperature and stand overnight. The ether and accompanying volatile materials were removed under vacuum. The resultant liquor was roughly purified by distillation at reduced pressure, producing 105 g of the anhydrosulphite (yield 70%). Further purification gives a colourless liquid b.pt. 56°-57°C at 12 mm pressure. (Literature values 63°C/21 mm(5); 58-9°C/13 mm(7))

(ii) Glycollic Acid Anhydrosulphite

1 mole glycollic acid (76 g) was suspended in diethyl ether (500 ml). To the continuously agitated suspension was slowly added a solution of 2 moles thionyl chloride in diethyl ether (250 ml). When the addition was complete, the reaction mixture was refluxed for some ten

hours and allowed to stand overnight. Excess thionyl chloride, together with ether and other volatiles, were removed under vacuum. The resultant oil was roughly purified by distillation under reduced pressure. 90 g of the required material were obtained (yield 74%). Glycollic acid anhydrosulphite is a colourless liquid b.pt. 72°C at 12 mm pressure. (Literature value(7) 71-2°C/11 mm)

(iii) 1-Hydroxy Cyclopentane Carboxyl~~l~~ic Acid Anhydrosulphite

1 mole 1-hydroxy cyclopentane carboxyl~~l~~ic acid (131 g) was suspended in diethyl ether (500 ml). This was reacted with a 50% molar excess (1.5 moles, 180 g) of thionyl chloride in diethyl ether (250 ml) under the conditions indicated for the formation of ∝-hydroxy isobutyric acid anhydrosulphite. 110 g of 1-hydroxy cyclopentane carboxyl~~l~~ic acid anhydrosulphite were obtained (yield 62%). The material is a colourless liquid b.pt. 75°-80°C at 1-2 mm pressure. The synthesis of this compound is not reported in the Literature.

(iv) 1-Hydroxy Cyclohexane Carboxyl~~l~~ic Acid Anhydrosulphite

1 mole 1-hydroxy cyclohexane carboxyl~~l~~ic acid (145 g) was suspended in diethyl ether (500 ml). This was reacted with a 50% molar excess (1.5 mole, 180 g) of thionyl chloride in diethyl ether (250 ml) under the conditions indicated for the formation of ∝-hydroxy isobutyric acid anhydrosulphite.

115 g of 1-hydroxy cyclohexane carboxyl~~l~~ic acid were obtained (yield 60%). The material is a colourless liquid b.pt. 72°-77°C at 1-2 mm pressure. (Literature value(7) 56-8°C/0.7 mm).

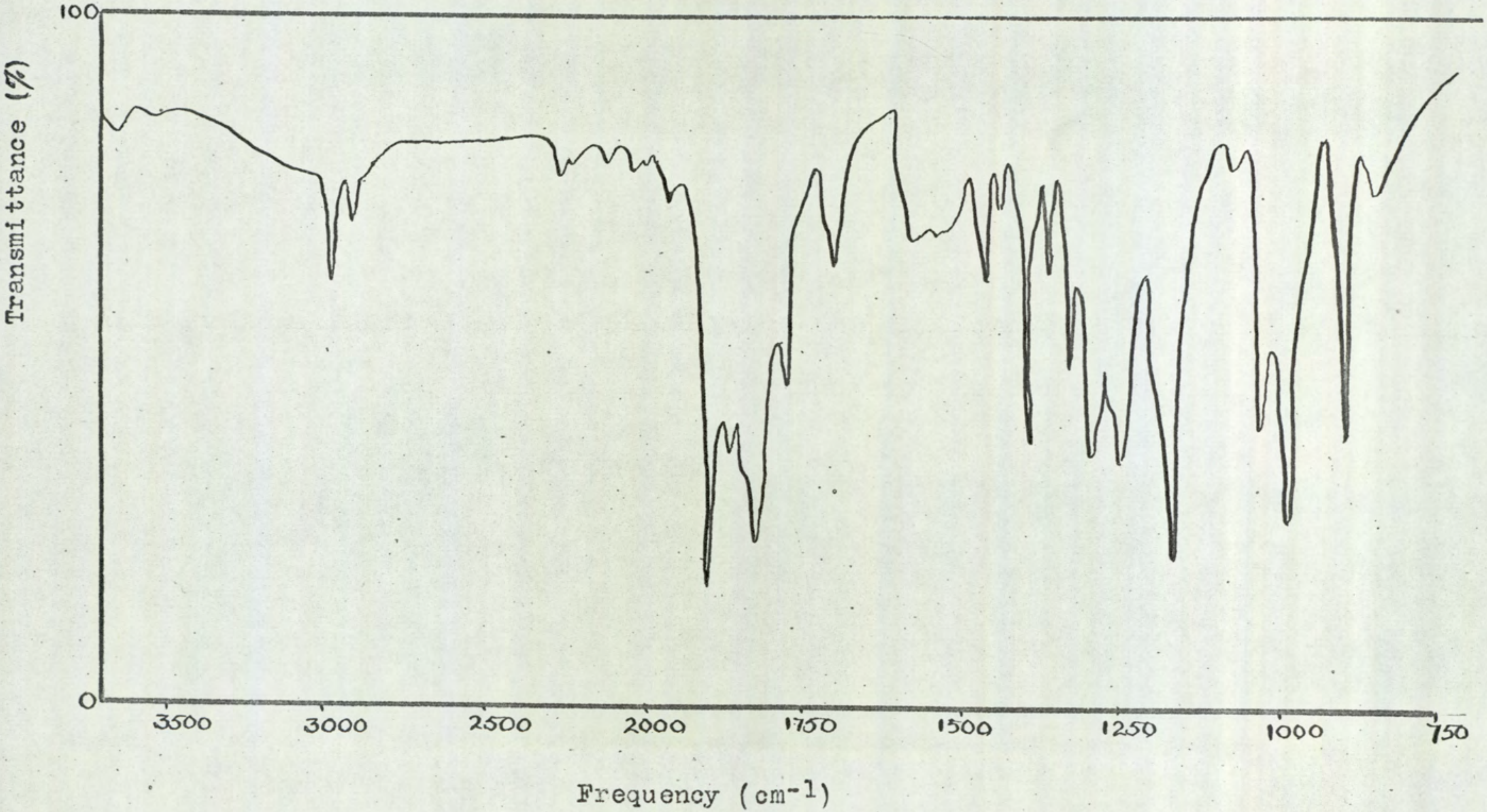


FIGURE 5. Infra red spectrum of anhydrocarboxy α-hydroxy isobutyric acid. Spectrum obtained from CCl_4 soln., cell path 0.5 mm.

(v) Lactic Acid Anhydrosulphite

A slurry of 0.5 mole anhydrous cupric lactate (121 g) in diethyl ether was slowly added to a 100% molar excess (2 moles, 238 g) of thionyl chloride dissolved in 1000 ml of diethyl ether. The reaction mixture was continuously agitated and maintained below 5°C during the addition. The reddish brown precipitate of anhydrous cupric chloride which is formed rapidly in the course of the addition was removed by filtration. Ether and excess thionyl chloride, together with other volatile materials, were removed from the filtrate under vacuum, leaving a colourless liquor. This was distilled under reduced pressure to produce 96.5 g of the desired anhydrosulphite (yield at this stage 67%). Lactic acid anhydrosulphite is a colourless liquid b.pt. 70°C at 17 mm pressure. (Literature value$^{(5)}$ 72-4°C/19 mm)

(vi) Anhydrocarboxy α-Hydroxy Isobutyric Acid

1 mole α-hydroxy isobutyric acid (104 g) was dissolved in diethyl ether (500 ml) and reacted with a 10% molar excess of phosgene (1.2 moles, 110 g) dissolved in the same solvent. 2 moles anhydrous pyridine (158 g) were slowly added. The reaction mixture was maintained below 5°C and continuously agitated throughout the course of the reaction. The precipitated pyridine hydrochloride was removed by filtration and the ether, excess phosgene and other volatiles under vacuum. The resultant oil was roughly purified by distillation under reduced pressure, producing 92 g of the desired product (70% yield).

Anhydrocarboxy α-hydroxy isobutyric acid is a lachrymatory colourless crystalline solid m.pt. 37.5°C; its infra red spectrum is shown in Figure 5.

$C_5H_6O_4$ requires: C = 46.16%, H = 4.65%.

Found: C = 45.9%, H = 4.5%

(vii) Anhydrocarboxy Mandelic Acid

1 mole mandelic acid (152 g) was dissolved in diethyl ether (500 ml) and mixed with a solution of 2 moles pyridine (158 g) in 200 ml of the same solvent. This mixture was added dropwise to a 100% molar excess (2 moles 198 g) of phosgene similarly dissolved in diethyl ether. The reaction mixture was continuously agitated and maintained below 5°C throughout the addition. Pyridine hydrochloride, which precipitates during the addition, was filtered off, leaving a colourless liquid. After removal of ether, excess phosgene and other volatiles, a colourless oil was obtained which was treated with excess 40/60°C petroleum ether and placed in a refrigerator. In this manner a white crystalline solid was obtained melting at 52°-53°C. Further recrystallisation from benzene gave pure anhydrocarboxy mandelic acid m.pt 57°C. (Literature value(8, 9) 57°-58°C)

(viii) Hydroxy Acids

Acids which were not readily obtainable were prepared from the appropriate carbonyl compound by means of a conventional cyanohydrin synthesis.

In the case of glycollic acid the material is normally obtained as a viscous liquid consisting of glycollic acid together with varying amounts of water. Although the water may be removed by drying in a desiccator over, say, phosphorus pentoxide, the process is rather slow and may take several weeks. It was found more convenient, therefore, to use the following method:-

1 mole glycollic acid (76 g) was suspended in diethyl ether (200 ml) and a solution of 0.2 mole thionyl chloride (24 g) dissolved in 50 ml of the same solvent slowly added. The reaction was maintained at a temperature of 0°C and continuously agitated during the addition. When the process was complete, the mixture was pumped down,

using an efficient water pump for a period of three or four hours. During this time a colourless solid was formed which was found on examination to be substantially solid glycollic acid m.pt. 80°C.

Infra Red Spectra

The infra red spectra of the anhydrosulphite derivatives whose preparation has been recorded in this section were examined. The following absorption frequencies, taken together, appear to be characteristic of the anhydrosulphite ring:

$$1020\text{-}1040\ cm^{-1};\ 1065\text{-}1075\ cm^{-1};\ 1165\ cm^{-1};$$
$$1245\ cm^{-1};\ 1305\ cm^{-1};\ 1825\ cm^{-1}$$

Purification Techniques

Four techniques were employed in purifying liquid monomers; these were:-

(a) Preliminary distillation under reduced pressure using the apparatus previously described (Section 2:1(i))

(b) Fractional distillation using the "Buchi" spinning band column (Section 2:1(ii))

(c) Precipitation of impurities containing ionisable chlorine by means of triethylamine. The procedure used was as follows:-

The ionisable chlorine content of the monomer was first determined (Section 2:1(viii)). From this figure an equimolar quantity of triethylamine was calculated. Both the monomer and the triethylamine (purified as described in Section 2:2) were dissolved in anhydrous diethyl ether and cooled to 0°C. The triethylamine solution was then added dropwise to the monomer solution with continuous agitation, care being taken to avoid any rise in temperature. When the addition was complete the reaction mixture was filtered or centrifuged to remove any precipitate and stripped of ether under vacuum. The purified monomer was then distilled under reduced pressure in the normal manner.

(d) Prepolymerisation in a sealed system under reduced pressure. This was carried out immediately prior to a kinetic investigation or polymer synthesis. The monomer was heated under reduced pressure in a system that had been baked at 120°C and flamed out immediately prior to use. When a predetermined amount of the monomer had been converted to polymer, the unconverted monomer was distilled into another part of the system which was sealed off and transferred to a dry box for further use. Fuller details of the technique are given, where appropriate, in the text.

Notes on use of Purification Techniques

The impurities normally encountered in this work were chlorine containing compounds. Thus chloride titration was found to be a rapid and effective method of assessing the purity of samples. The ease with which chloride containing impurities could be removed by distillation techniques varied considerably from compound to compound.

The preliminary fractional distillation technique reduces the ionisable chlorine content to around 5% and the spinning band column improves this figure still further, to a fraction of a percent. Final traces of chloride (one per cent or less) may be removed by the precipitation technique. If the method is used on samples containing appreciably more than 1% chloride a dark oil coupled with considerable decomposition results, due probably to partial solubility of the precipitated chloride in the diethyl ether/anhydrosulphite mixture.

Prepolymerisation was found to be ineffective in completely removing chloride containing impurities, its main use being the removal of possible chance initiators of the anhydrosulphite decomposition.

In the case of solid materials (e.g., anhydrocarboxy ∝-hydroxy isobutyric acid) recrystallisation, followed by the sublimation technique (Section 2:1(iii)) was found to be the most effective method of purification.

3. THE REACTION OF α-HYDROXY ACIDS WITH THIONYL CHLORIDE AND PHOSGENE

3:1 The Reaction with Thionyl Chloride - Experimental Results

In the course of this synthetic work some attempt was made to separate and identify products other than the required anhydrosulphites. The reasons for this have been indicated in Section 1.

The procedure used in separating the reaction products was as follows:-

(i) Volatiles (ether, excess thionyl chloride, etc.) were stripped under vacuum.

(ii) The remaining liquor was cooled. At this stage solid materials having fairly high melting points crystallised out fairly readily. In this way mandelic acid (m.pt. 118°C), benzilic acid (m.pt. 150°C) phenyl chloracetic acid (m.pt. 78°C) and chlorodiphenyl acetic acid (m.pt. 118-119°C with decomposition) were isolated.

(iii) Anhydrosulphites and impurities having similar boiling ranges were distilled off under reduced pressure using the technique described in Section 2:1(i).

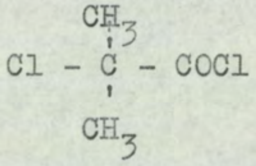
(iv) Materials remaining undistilled were now mainly unreacted acids not recovered in stage (ii) and dimers, together with polymeric residues of low molecular weight.

Identification of compounds was normally achieved using physical constants, ionisable chlorine content, non-aqueous titration with sodium methoxide and infra red spectra.

The ultimate separation and identification of compounds collected in stage (iii) was rather more difficult.

Repeated fractionation, G.L.C. analysis and determination of ionisable chloride content indicated, notably in the case of glycollic, lactic and α-hydroxy isobutyric acids, the presence of a chlorine containing impurity which was difficult to remove by normal methods of distillation. The separation was finally achieved with a preparative gas chromatograph (Section 2:1(vi)). Samples were collected corresponding to both the anhydrosulphite and impurity peaks on the G.L.C. trace, infra red spectra of both samples (in carbon tetrachloride solution) were determined and finally G.L.C. traces of both solutions obtained to ensure that the separation had been effective.

The results obtained in the case of the α-hydroxy isobutyric acid reaction are summarised in Figure 6. On the basis of this information the structure



$$Cl-\underset{CH_3}{\overset{CH_3}{C}}-COCl$$

was assigned to the impurity. (The literature for this compound gave a b.pt. of 126-7°C at 760 mm) The b.pt. of the anhydrosulphite itself at atmospheric pressure had previously been determined as 126°C (although distillations are invariably carried out at reduced pressure to avoid undue decomposition).

The literature data for the analogous compounds derived from glycollic (i) and lactic (ii) acids are given below:

	Formula	Name	B.Pt.
(i)	$ClCH_2COCl$	Chloroacetyl Chloride	108-110°C at 760 mm
(ii)	$ClCH(CH_3)COCl$	Chloropropionyl Chloride	110°C at 744 mm

A summary of further experimental results is given in Table 1. This shows yields of the various products obtained from the reaction of thionyl chloride with a series of α-hydroxy acids. The estimated accuracy of each determined yield is included. Figure 7 indicates possible reaction routes involved.

The chlorosulphites are not listed in the summary of reaction products since in the 'working up' process normally employed they are converted to other compounds (by reactions 26 - 28). With reasonable care, however, it is possible to isolate them at an earlier stage.

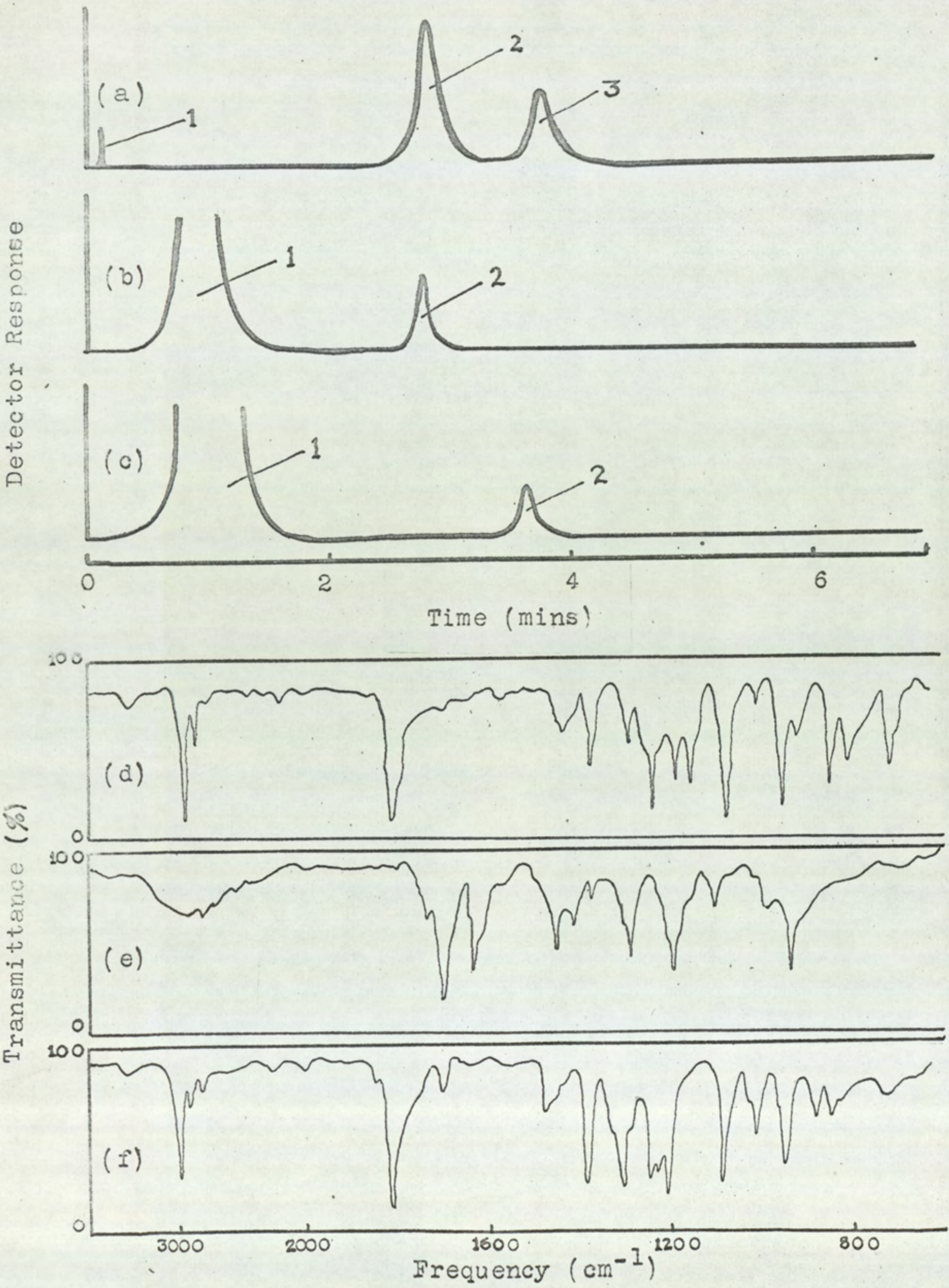

(a)
1
2
3
(b)
1
2
(c)
1
2
Detector Response
0
2
4
6
Time (mins)
100
0
(d)
100
0
(e)
100
0
(f)
Transmittance (%)
3000
2000
1600
1200
800
Frequency (cm-1)

FIGURE 6.

KEY TO FIGURE 6.

a, b, c are gas chromatograms and d, e, f the corresponding infra red spectra (Section 2:1(vi /vii)). The separations were carried out with hydrogen as carrier gas (flow rate 100 ml/min) and a column temperature of 80°C. The spectra were determined in carbon tetrachloride solution using a path length of 0.086 cm.

(a) Gas chromatogram of a sample of the anhydrosulphite of α-hydroxy isobutyric acid prepared as described in the text and roughly fractionated. The peaks are:-

1. Sulphur dioxide
2. The anhydrosulphite
3. A chlorine containing impurity (structure unknown)

(b) Gas chromatogram of a sample of the anhydrosulphite separated from the impurity by G.L.C. and dissolved in carbon tetrachloride. The peaks are:-

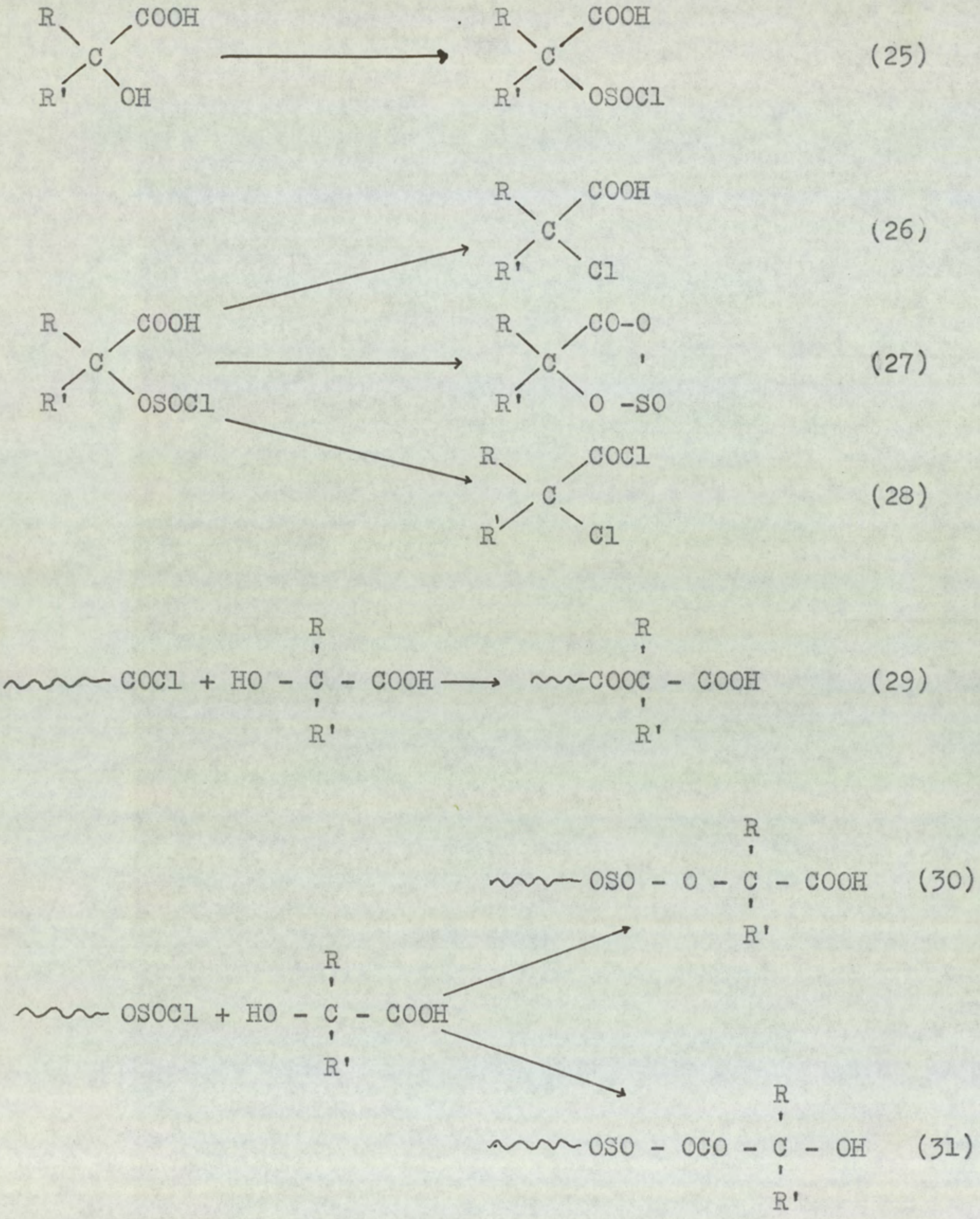
1. Carbon tetrachloride
2. The anhydrosulphite

(c) Gas chromatogram of the impurity obtained and treated in the same way. The peaks are:-

1. Carbon tetrachloride
2. The unknown impurity

(e) I.R. of the sample corresponding to (b). It seems probable that due to the manipulation involved, the sample may have been partially converted to α-hydroxy isobutyric acid by atmospheric moisture.

(f) I.R. spectrum of the sample corresponding to (c).



$$\sim\!\sim\!\sim COCl + HO - \overset{R}{\underset{R'}{C}} - COOH \longrightarrow \sim\!\sim COO\overset{R}{\underset{R'}{C}} - COOH \qquad (29)$$

$$\sim\!\sim\!\sim OSOCl + HO - \overset{R}{\underset{R'}{C}} - COOH \longrightarrow \sim\!\sim OSO - O - \overset{R}{\underset{R'}{C}} - COOH \qquad (30)$$

$$\sim\!\sim\!\sim OSOCl + HO - \overset{R}{\underset{R'}{C}} - COOH \longrightarrow \sim\!\sim OSO - OCO - \overset{R}{\underset{R'}{C}} - OH \qquad (31)$$

FIGURE 7: Possible Routes involved in the Reaction of Thionyl Chloride with ∝-Hydroxy Acids

Hydroxy Acid	Reacn. Conds.	Unreacted Acid (%)	Products of Equation:-			
			(26) (%)	(27) (%)	(28) (%)	(29-31) (%)
Glycollic	a	55±15	?	20±10	<10	<10
Lactic	a	20±10	?	20±10	<10	20±10
α-Hydroxy isobutyric	a			70±10	15±10	<10
1-Hydroxy cyclopentane carboxylic	a			55±15	20±10	?
1-Hydroxy cyclohexane carboxylic	a			50±15	20±10	?
Mandelic	a	70±15	?	< 10	?	<10
Benzilic	a	80±15	10			
Glycollic	b		?	55±15	20±10	20±10
Mandelic	b	50±15	<10	20±10	?	<10
Benzilic	b	70±15	<10			
Mandelic	c	10±5	10±5	50±15	<10	<10
Benzilic	c	50±15	30±10			

TABLE 1.

Reaction of thionyl chloride with various α-hydroxy acids - summary of products obtained (expressed as % of recovered material).

Reaction conditions:

0.5 mole thionyl chloride in 500ml diethyl ether slowly added to 0.25 mole hydroxy acid in the same solvent (250ml). Reaction mixture maintained at 5°C during addition and then allowed to react for: (a) 12 - 15hrs @ 0 - 15°C; (b) 12hrs @ 34°C plus 12 - 15hrs @ 15 - 20°C; (c) 6 hrs @ 34°C plus 100 - 200 hrs @ 15 - 20°C.

? indicates product suspected only.

3:2 The Reaction with Phosgene - Experimental Results

This was found to be rather more complicated than the analogous thionyl chloride reaction for a variety of reasons. The method proposed by W. H. Davies$^{(8, 9)}$ for the formation of anhydrocarboxy derivatives involved the reaction of the acid with an excess of phosgene for periods varying from 3-11 days. Not only were these reaction times inconveniently long, they also promoted side reactions which rendered the products rather impure. Thus, although the desired anhydrocarboxy derivative was formed, separating it in a state of reasonable purity was in many cases virtually impossible.

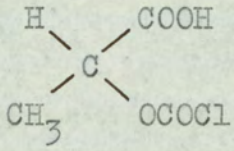
Investigation of modifications of the method led, in the case of α-hydroxy isobutyric acid, to the synthetic procedure indicated in Section 2:3(vi). This had the advantage of involving a much shorter reaction time and yielding the product in a fairly pure state. Attempts to use this modified method in the case of lactic acid were unsuccessful due to decomposition of the anhydrocarboxy derivative under the conditions of the reaction. The reaction of phosgene with lactic acid under various conditions was, therefore, investigated. Lactic acid was reacted with a 100% molar excess of phosgene in various solvents at room temperature for times varying from five hours to ten days. The ether and excess phosgene were removed under vacuum and the resultant oil distilled. The results of a typical distillation are shown in Table 2. Anhydrocarboxy lactic acid has been reported as a solid m.pt. 27-28°C; b.pt. 93°C/ 15 mm$^{(8, 9)}$.

Table 2

Distillation Range of Products obtained from the Reaction of Lactic Acid with Phosgene (100% molar excess) in Dioxan. Reaction Time 72 hours.

Fraction No.	Boiling Range	Pressure	Relative Volume of Fraction
1	38-53°C	3 mm	~10%
2	53-58°C	3mm	~ 5%
3	98-104°C	3 mm	~25%
4	150-160°C	3 mm	~20%
5	> 160°C	3 mm	~40% (including residue)

Since fractions 1-4 contained significant percentages of ionisable chloride, it was presumed that some at least might be due to the uncyclised acid chloride:-



In an attempt to bring about cyclisation two techniques were used:-

(i) heating at 60°C under reduced pressure (~ 20 mm) for several hours.

(ii) addition of a quantity of triethylamine equivalent to the ionisable chlorine content and subsequently filtering and redistilling. The procedure has been described in Section 2:3.

Neither method succeeded in giving appreciable yields of the pure anhydrocarboxy derivative. Both purification techniques recorded by Davies (i.e., recrystallisation from ether and fractional distillation) were then examined but neither gave a satisfactory separation of the small amount of the desired compound that was formed.

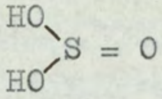
Much effort was expended in attempting to purify lactic acid by methods described in the literature but without appreciable success. This point is discussed in Section 3:3.

This lack of success encountered in synthesising pure anhydrocarboxy and anhydrosulphite derivatives from the acid itself led to the search for an alternative precursor for these compounds. A pure anhydrous material seemed necessary, preferably obtainable in the solid state. These conditions were fulfilled by anhydrous cupric lactate which was subsequently found to provide a fairly ready route to both derivatives.

The reaction between phosgene and mandelic acid was examined and found to be exceptionally slow, unchanged mandelic acid being frequently recovered. Under conditions which were severe enough to induce formation of the chlorosulphite derivative, a marked tendency for this to decompose by inter- rather than intramolecular condensation was noted; thus dimeric products rather than the cyclic anhydrocarboxy derivatives were obtained. A modified technique based on the high dilution principle gave a colourless oil which subsequently crystallised to yield the desired product. Details of this are recorded in Section 2:3(vii).

3:3 The Reaction of ∝-Hydroxy Acids with Thionyl Chloride and Phosgene - Discussion

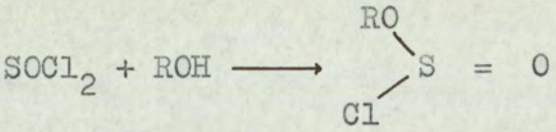
Anhydrosulphites of ∝-hydroxy acids, together with organic sulphites RO·SO·OR' and the anhydrosulphites of carboxyllic acids RCO·O·SO·O·COR', may be regarded as esters of sulphurous acid



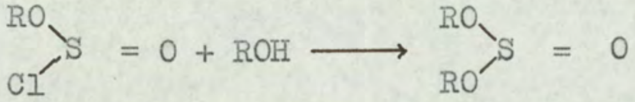
$(HO)_2S=O$

Their synthesis is commonly achieved with thionyl chloride, which may similarly be considered to be the acid chloride of sulphurous acid. On this basis the anhydrosulphites of ∝-hydroxy acids are structurally intermediate between carboxyl~~l~~ic acid anhydrosulphites and organic sulphites. Their behaviour may be reasonably expected, therefore, to show some resemblances to both classes of compound.

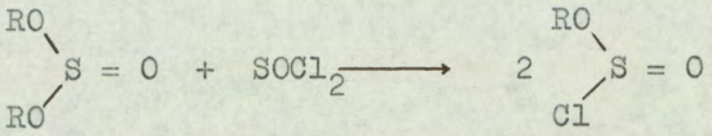
Organic sulphites have been known since 1846 and have aroused considerable interest on both practical and theoretical levels. The literature relating to their synthesis and reactions has been recently reviewed by H. F. van Woerden(32). There are many points of similarity between the synthesis of organic sulphites from thionyl chloride and the reactions considered here in relation to the formation of anhydrosulphites of ∝-hydroxy acids. The main reactions involved in organic sulphite synthesis have been listed by van Woerden. They are shown below, (Equations 32-35).



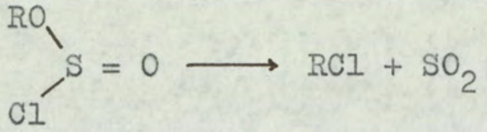
$$SOCl_2 + ROH \longrightarrow (RO)(Cl)S = O \qquad (32)$$



$$(RO)(Cl)S = O + ROH \longrightarrow (RO)_2S = O \qquad (33)$$

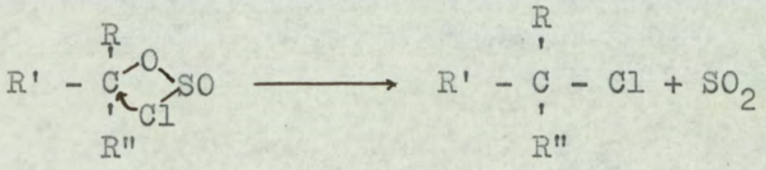


(34)



(35)

These may be compared with those given in Figure 7 for the reaction between ∝-hydroxy acids and thionyl chloride. In both cases the initial step involves the reaction of thionyl chloride with a hydroxyl group. This reaction has been extensively investigated in connection with the formation of alkyl chlorides from alcohols and has been shown to involve the formation of an alkyl chlorosulphite (or chlorosulphinate). Alkyl halide formation proceeds via the decomposition of this chlorosulphite which, in the absence of catalysts, takes place by an "internal SN_2" (SN_i) reaction involving nucleophilic attack of chlorine on the carbon atom(33-37) (Equation 36):



(36)

In both sulphite and anhydrosulphite synthesis a chlorosulphite is similarly obtained (Equations 25 and 32). Organic sulphite formation, however, involves its further reaction with an alcoholic hydroxyl group (Equation 33), whilst the cyclic anhydrosulphite is formed by an intramolecular reaction with a carboxyl group (Equation 27).

The importance of initial concentration and molar ratios of reactants is emphasised by van Woerden; use of excess thionyl chloride inhibits the formation of sulphites in a manner which is apparent from the reaction schemes above.

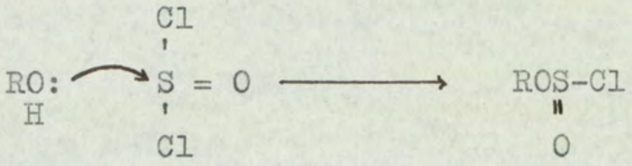
Similarly, in anyhydrosulphite synthesis use of excess thionyl chloride and prolonged reaction times leads to the reaction of carboxylic hydroxyl groups with thionyl chloride to form an acid chloride (Equation 28).

The results presented in Table 1 are most conveniently considered together under a series of headings:

(i) Reactivity of α-Hydroxy Acids with Thionyl Chloride: Chlorosulphite Formation

The main points to be considered in this respect are steric and electronic factors relating to α-substituents in the acid and its initial state and purity. In comparing the ease of attack of thionyl chloride on a series of acids the physical state of the acid and its solubility in the reaction medium are obviously important. Of the acids considered in Table 1 only lactic was not obtainable as a solid in a high state of purity. The particular problems associated with the synthesis of anhydrosulphite and anhydrocarboxy derivatives of this acid will be considered separately (iii). The question of solubility is less critical in the results as presented here that might be suspected, since all the acids dissolved before the addition of thionyl chloride was complete. As the reaction times involved are long (i.e., > 12 hours) relative to the time involved in dissolution of the acid, and since general trends in the acid series rather than specific comparisons between individual members will be considered, differences in solubility will not be taken into account.

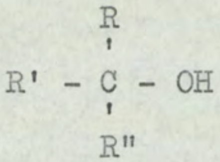
Electronic and steric effects in the reaction are worth considering in some detail. The reaction between hydroxyl groups and thionyl chloride in a solvent of low polarity has been represented (e.g. [38]) as a nucleophilic attack of the hydroxyl oxygen upon the sulphur atom (Equation 37).



$$\underset{H}{RO:}\curvearrowright\overset{Cl}{\underset{Cl}{S}}=O\longrightarrow RO\underset{\overset{\|}{O}}{S}-Cl$$

(37)

If the structure of the attacking hydroxy compound is represented by:



$$R'-\overset{R}{\underset{R''}{C}}-OH$$

(38)

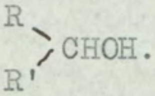
the nature of substituents R, R', R" would be expected to markedly affects its reactivity with thionyl chloride.

Increasing bulk of the substituents will retard the bimolecular reaction. It should be noted that in polar solvents the tendency of the reactants to ionise will be enhanced. In this case a change in mechanism would be anticipated, similar in some respects to that encountered in the hydrolysis of alkyl halides(39).

The presence of electron withdrawing substituents R, R', R" will diminish the nucleophilicity of the hydroxyl group and so retard the reaction of the unionised species. Conversely, the reactivity of the hydroxyl group will be enhanced by substituents which are inductively electron releasing.

An example of electronic and steric effects combining to retard the reactivity of an alcohol with thionyl chloride is seen in 1,1,1, 3,3,3,- hexachloro-2-propanol, which will not react directly with thionyl chloride(40). The reaction will take place, however, (with sulphite formation) in the presence of tertiary bases.

Because of the presence of the carboxyl substituent the hydroxyl group in the α-hydroxy acids would be expected to be less reactive towards thionyl chloride (in non-polar reaction media) than the corresponding secondary alcohols



$$\genfrac{}{}{0pt}{}{R}{R'}\!\!>\!CHOH.$$

This would be predicted from both steric and electronic considerations. Unfortunately no data are available to enable a comparison to be made under idential conditions.

Some indication of the relative reactivity of various α-hydroxy acids can be obtained from Table 1. In the upper section in Table 1 the reactivities of the acids under similar conditions may be judged by comparing the yield of unchanged acid in each case. It will be seen that on this basis the reactivity increases in the order: benzilic $<$ mandelic $<$ glycollic $<$ 1-hydroxy cyclopentane carboxyl~~l~~ic acid $\simeq$ 1-hydroxy cyclohexane carboxyl~~l~~ic acid $\simeq$ α-hydroxy isobutyric acid.

Interpretation of these results must be undertaken with caution. No kinetic data has been obtained on the rates of reaction of the acids with thionyl chloride. The results here merely indicate the extent to which the acid has reacted in a given time under specific conditions. The "reactivities", therefore, are only valid in this context and rest on the assumption that each reaction proceeds in an identical manner. Furthermore, although the dielectric constant of the reaction medium (diethyl ether) was not high enough to promote extensive ionisation of the reactants, the necessary presence of thionyl chloride complicates matters in this respect. The discussion that follows is merely an attempt to correlate the experimental results in terms of mechanisms which might be supposed to operate. It is not intended as an experimental justification of these mechanisms.

The low reactivity of benzilic and mandelic acids may be attributed to the steric hindrance resulting from the bulky phenyl substituents and the diminished nucleophilicity of the hydroxyl group (due to the fact that phenyl substituents are inductively electron withdrawing). The fact that α-hydroxy isobutyric acid is more reactive here than glycollic could be taken as an indication that the tendency of the methyl groups to release electrons (and thus enhance the nucleophilicity of the attacking hydroxyl group) swamps the hindrance caused by their bulk relative to hydrogen atoms. It seems inconceivable, however, that an electronic effect of this magnitude should be observed.

The steric hindrance due to the cyclohexane and cyclopentane rings does not appear to be much greater than that of 2 α-methyl substituents since their reactivities are comparable with α-hydroxy isobutyric acid. Use of Courtaulds Atomic Models also indicates that the hydroxy group in the cycloalkyl derivatives is not subject to much more shielding than that in the dimethyl substituted acid.

(ii) Reaction of Chlorosulphites - Factors affecting Ring Formation

The reaction scheme presented in Figure 7 indicates three major routes by which chlorosulphite derivatives of α-hydroxy acids may react:

(a) Interaction of the carboxyl~~l~~ic hydroxyl group with a further molecule of thionyl chloride which ultimately decomposes to yield an α-chloro acid chloride (Equation 28).

(b) Formation of an α-chloro acid by means of an SNi (internal return) reaction (Equation 26).

(c) Ring closure to form an anhydrosulphite (Equation 27).

The fact that, experimentally, an excess of thionyl chloride is found to be necessary in obtaining high yields of anhydrosulphite inevitably means that reaction (a) will occur to some extent. This view is consistent with the fact that ∝-chloro acid chlorides occur as impurities in almost every case.

Under the conditions of the reactions relating to Table 1 the structure of the acid appears to exert a marked influence on the relative importance of routes (b) and (c). Extremes of behaviour are shown by benzilic acid on one hand (chlorosulphite apparently decomposes exclusively by route (b)) and ∝-hydroxy isobutyric on the other (route (c) predominates).

∝-Chloro acid formation proceeds (in the absence of bases) by a nucleophilic attack of chlorine on the ∝-carbon atom (Equation 36). Anhydrosulphite formation, on the other hand, is probably best envisaged in terms of ion pair formation.

It seems sensible to suggest that inductive effects will primarily affect route (b) (∝-chloro acid formation) and steric effects route (c). Electron withdrawing substituents R, R' will lead to the formation of a partial positive charge on the ∝-carbon atom which will in turn facilitate the SNi attack of the electronegative chlorine atom. Electron repelling groups R, R' would conversely render the ∝-carbon atom less liable to such attack while the bulk of these substituents would not be expected to markedly affect the reaction.

Electronic effects probably exert little effect on anhydrosulphite formation because the substituents are too far removed from the reactive centres. The bulk of attached groups R, R' would, however, seem to be important. Comparisons with similar ring systems and the use of Courtaulds Atomic Models indicats that two phenyl substituents can only be accommodated in the anhydrosulphite ring with extreme difficulty, whereas two methyl substituents form a reasonably compact structure. In the actual cyclisation process two fairly small (say methyl) substituents could well facilitate the reaction by restricting, to some extent, the position which the carboxyl and chlorosulphite group can take up and thus forcing them closer together.

Applying these considerations to the products obtained from benzilic and α-hydroxy isobutyric acid, we find representation of the two extreme cases. Benzilic acid is quite unique in having two α-phenyl substituents which will promote the establishment of a resonance stabilised positive charge on the α-carbon atom. Thus the formation of α-chlorobenzilic acid is facilitated. Conversely the bulk of the phenyl substituents makes cyclisation a much less favoured process. Mandelic acid with one α-phenyl and one α-hydrogen substituent forms an anhydrosulphite with difficulty as might be expected, together with a comparable yield of α-chloromandelic acid.

In passing through glycollic and lactic acid chlorosulphites to that of α-hydroxy isobutyric acid, considerably less α-chloro acid formation is noticed. The chlorosulphites of α-hydroxy isobutyric and the 1-hydroxy cycloalkane carboxylic acids studied decompose predominantly (under the reaction conditions used) to yield anhydrosulphites. The electron repelling alkyl substituents here render the α-carbon atom a less favourable site for nucleophilic attack, the anhydrosulphite rings being predominantly formed in these cases.

(iii) The Formation of Dimeric and Polymeric Products: Syntheses from Lactic Acid

Reference to Table 1 indicates that especially in the case of acids whose chlorosulphites yield both αchloro acids and anhydrosulphites (i.e. neither process is favoured to the virtual exclusion of the other) an appreciable proportion of dimeric and polymeric products are obtained. Whilst it is true that the anhydrosulphites, when formed, are susceptible to thermal decomposition, yielding polymeric products, the conditions involved here were not sufficiently severe to make this process more than partially responsible. The reactions listed in Figure 7 are only representative of those capable of yielding such products. Others (such as the reaction of an acid chloride with an anhydrosulphite ring) undoubtedly exist.

Lactic acid was found to yield an abnormally high proportion of impurities in its reaction with thionyl chloride. This is apparent from Table 1. The primary reason for this abnormal behaviour is the composition of the lactic acid. (It has been noted that lactic acid was not obtainable in a pure solid condition prior to reaction.) The composition and purification of this acid has been discussed and reviewed by several writers (e.g.(41, 42, 43)). From the conclusions of these and other authors it is apparent that lactic acid, as normally encountered, is a mixture of lactic acid, lactyl lactate, lactide, polylactyl lactic acids and water in proportions that approach equilibrium very slowly. Because of the tendency of lactic acid molecules to condense together, eliminating water, conventional purification techniques do not remove the other components of the mixture but simply alter their relative proportions. Thus in the reaction with phosgene and thionyl chloride, the hydroxyl groups of all compounds present are attacked, resulting in a mixture of products more diverse than those obtained with other ∝-hydroxy acids.

Because of the low yield and impurity of lactic acid anhydrosulphite obtained by direct reaction of the acid with thionyl chloride, alternative precursors were examined. The most successful of these was anhydrous cupric lactate, which when reacted with excess of thionyl chloride in the manner described in Section 2:3 gave a much improved yield of the anhydrosulphite. Insufficient evidence was obtained to suggest a mechanism for the reaction; it seems fairly clear, however, that α-chloro lactyl chloride is the main impurity.

(iv) The Overall Reaction : Summary

It is necessary to bear in mind the two distinct steps involved in the formation of both α-chloro acids and anhydrosulphites and, also, the fact that the mechanism of each step may change in passing from a non-polar to a polar reaction medium. For these reasons comparisons with results obtained under different conditions must only be made with due recognition of the fact.

An example of the difficulties involved is found in comparing phenyl substituted hydroxy compounds. Van Woerden's review(32) relates the observation that on reacting with thionyl chloride primary and secondary alcohols with α-phenyl substituents form chlorides rapidly. The impression obtained from the work of Davies(8, 9), however, is that considerably longer times are necessary for the reaction between mandelic acid and phosgene than for that between, say, glycollic acid and phosgene. Under the conditions used in the present work mandelic and benzilic acids were observed to be less active than alkyl substituted α-hydroxy acids in reacting with thionyl chloride.

The apparent discrepancy is probably due to the two stages involved in the reaction. The chlorosulphites of the phenyl carbinol series have not been isolated, although circumstantial evidence for their formation has been obtained(44). Thus the second stage of the reaction, i.e., chloride formation, is very much more rapid in phenyl than in alkyl substituted carbinols. This is consistent with the reasoning applied to the analogous α-hydroxy acid reactions in the text.

The effect of introducing a phenyl substituent into an α-hydroxy acid would be to reduce even further the nucleophilicity of a hydroxyl group already affected by the presence of an α-carboxyl substituent. Since phenyl carbinols contain only one electron withdrawing substituent the hydroxyl group is less markedly affected.

The overall change in passing from alkyl to phenyl substituted carbinols in the reaction with thionyl chloride is, therefore, a slight retardation of the first step and a very considerable facilitation of the second, to such an extent that the intermediate is not isolated.

The analogous effect in the α-hydroxy acid series is the further retardation of an already relatively sluggish first step and an acceleration of one of two alternative second stages, together with a retardation of the other (anhydrosulphite formation). Seen in this light the observed effects are consistent with the electronic and steric factors involved.

Two further facts are noteworthy in connection with phenyl substituted α-hydroxy acids. The first is the extreme reluctance of mandelic acid to form the anhydrosulphite, high dilution techniques ultimately proving successful. The second is that during the course of this work a communication from Rose and Warren(6) indicated that they had also attempted unsuccessfully to synthesise benzilic acid anhydrosulphite, α-chlorobenzilic acid only being obtained. Both of these observations are consistent with the views expressed in this discussion. An apparent anomaly arises, however in the successful synthesis by Rose and Warren of the 2,2, (bis chloromethyl) 2-hydroxy acetic acid anhydrosulphite. It seems that the inductive effect of the two chlorine atoms does not exert as marked an effect as might be anticipated. It must be borne in mind, however, that thionyl chloride itself was used as the reaction medium; thus greater ionisation of the carboxyl group would be encountered and further facilitated by the chloromethyl groups. Anhydrosulphite formation is enhanced by this ionisation. Therefore predictions based on behaviour in non-polar media are not valid.

No attempt has been made to compare in detail the formation of anhydrocarboxy and anhydrosulphite derivatives. Differences in the physical nature of phosgene and thionyl chloride immediately present a problem in comparing experimental results. The work with phosgene presented here was carried out in different solvents and at different concentrations from the thionyl chloride syntheses. It is noticeable, however, that the synthesis of many anhydrocarboxy derivatives is facilitated by the use of a tertiary base to remove the hydrogen chloride formed in the course of the reaction, whereas attempts to use this technique with anhydrosulphite derivatives lead to considerable decomposition of the product. This accords with the results of Gerrard and Schild(45) on the interaction of chloroformates and chlorosulphinates with tertiary bases and tertiary base hydrochlorides.

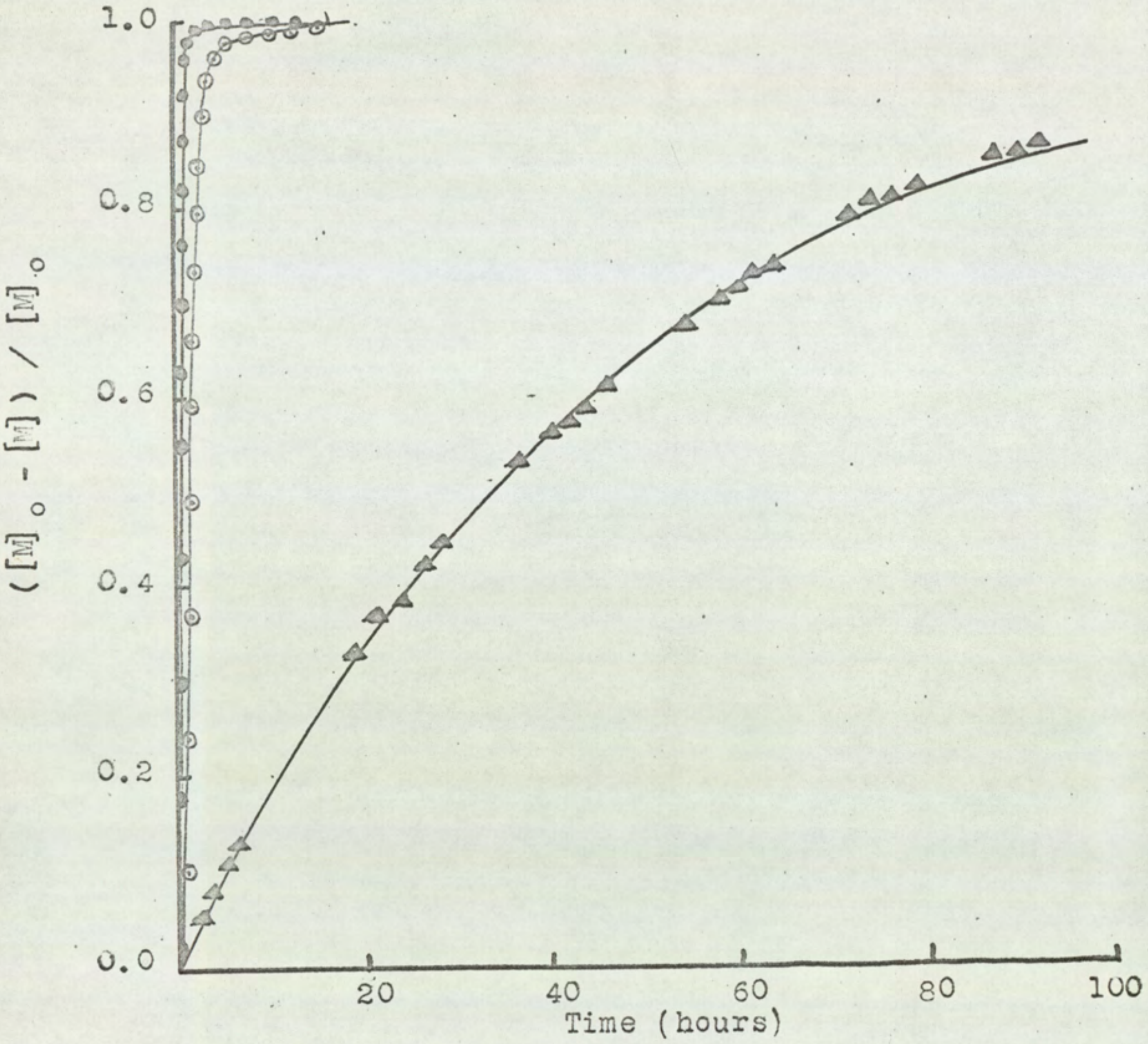


FIGURE 8. Decomposition of lactic acid anhydrosulphite in the presence of various reagents at 40°C. Reaction medium; dioxan (in each case).

● ,(a) $[\varnothing CH_2NH_2]$,2.0 m.l^{-1}.; $[M]_o$,0.5 m.l^{-1}.

⊙,(b) $[H_2O]$,2.0 m.l^{-1}.; $[M]_o$,0.5 m.l^{-1}.

▲,(c) $[\varnothing CH_2OH]$, 2.0 m.l^{-1}.; $[M]_o$,0.5 m.l^{-1}.

4. POLYMERISATION OF LACTIC AND GLYCOLLIC ACID ANHYDROSULPHITES

EXPERIMENTAL RESULTS AND DISCUSSION

4:1 Ring Opening by Aliphatic Amines (primary and secondary) Alcohols and Water - Kinetic Observations

Unless otherwise stated the rates of reaction presented in this and subsequent sections were determined by gas evolution techniques. The validity of these techniques and the relationship of pressure measurements to reactant concentrations has been considered in Section 2:2. The terminology and derivations presented there will be adopted, in particular Equations 7 and 24.

Qualitative observations indicated that at room temperature the reaction of these anhydrosulphites was vigorous with amines, less so with water and fairly slow with alcohols. The rates of decomposition of lactic acid anhydrosulphite with 2 molar solutions of benzylamine, benzyl alcohol and water in dioxan at 40°C are presented in Figure 8. Problems such as interaction of sulphur dioxide with reactants, solubility, etc., present some difficulty in undertaking detailed kinetic analysis in the case of amines and water. Furthermore, the attack of alcohols has has a greater relevance to polymerisation studies involving this series of compounds because of the possibility of a regenerated hydroxyl group being involved in the propagation step. A detailed kinetic study was therefore limited to the ring opening reaction with alcohols.

Kinetic Order of the Reaction with respect to Monomer Concentration

The form of the plot of $\frac{[M]_o-[M]}{[M]_o}$ vs. time normally obtained for this type of reaction has been shown in Figure 8.

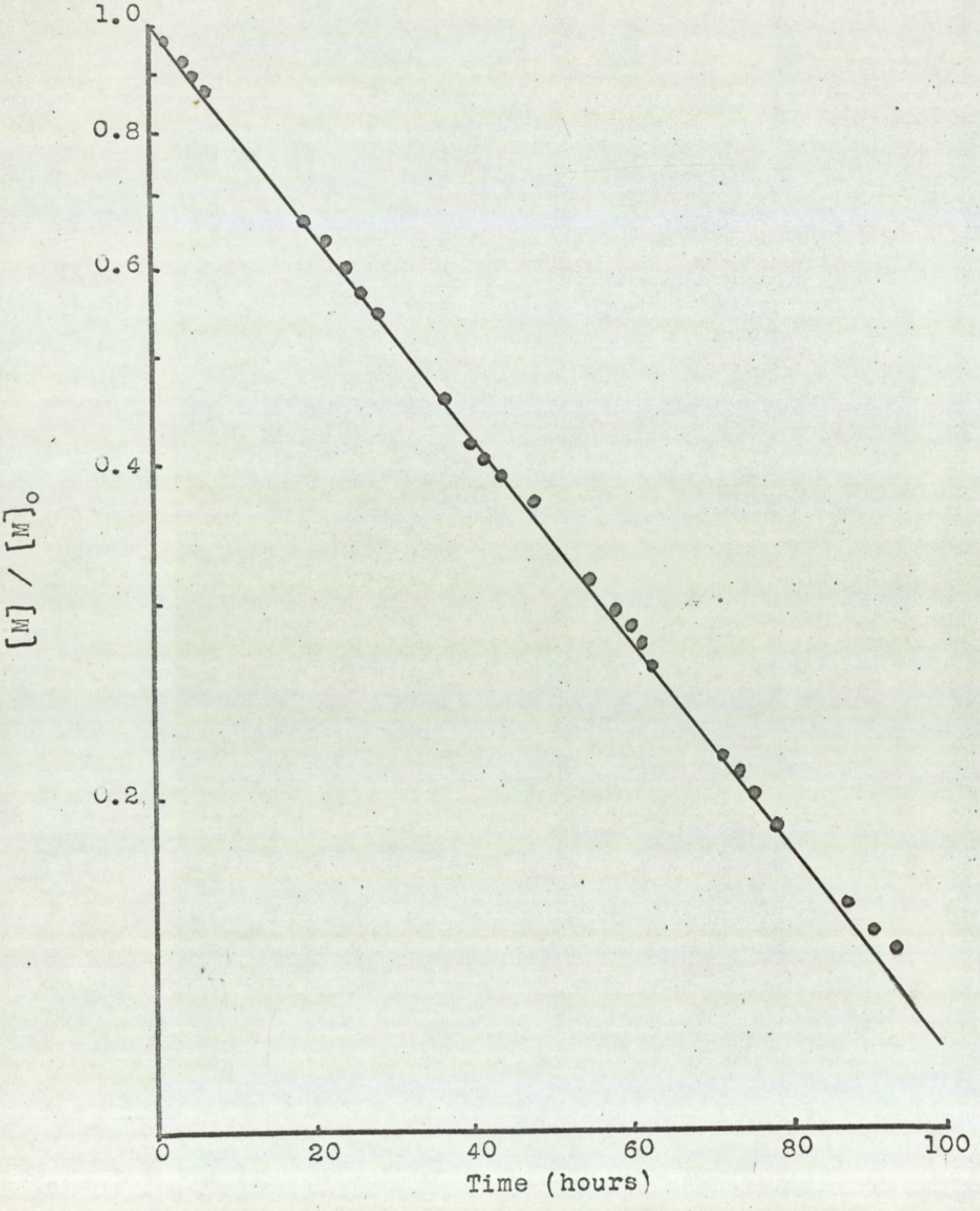


FIGURE 9. Decomposition of lactic acid anhydrosulphite in dioxan at 40°C in the presence of benzyl alcohol. Fraction of monomer remaining (undecomposed) plotted logarithmically as a function of time (data from Figure 8c).

$[M]_o$, 0.5 m.l^{-1}.; [ϕCH_2OH], 2.0 m.l^{-1}.

The decomposition of anhydrosulphite obeys a first order kinetic decay law as evidenced by Figure 9, which shows the data from Figure 8(c) plotted in the form of log $\frac{[M]}{[M]_o}$ vs. time.

The first order relationship was confirmed at higher temperatures by measuring initial rates of sulphur dioxide evolution ($\left(\frac{\delta P}{\delta t}\right)_{t=o}$) in systems containing various initial concentrations of anhydrosulphite and a fixed concentration of hydroxyl groups, benzyl alcohol being used both as a solvent and source of hydroxyl groups. Measurements were carried out at the same initial pressure in each case in order to avoid possible effects due to sulphur dioxide catalysis.

The results obtained at 90°C are shown graphically in Figure 10 in which the initial rate of sulphur dioxide evolution for the above-mentioned systems is plotted against the initial concentration of lactic acid anhydrosulphite.

Catalytic Effects of Sulphur Dioxide on the System

The reaction was examined for signs of catalysis by sulphur dioxide. This precaution was taken because carbon dioxide catalysis has been observed in certain N-carbonic anhydride systems(19). Rates of decomposition of lactic acid anhydrosulphite-benzyl alcohol systems, with a fixed initial concentration of both the anhydrosulphite and hydroxyl groups, were examined at a series of initial sulphur dioxide pressures. The results indicated that between 40° and 90°C, within the range of initial pressures studied (10 - 400 mm), sulphur dioxide exerted no catalytic effect on the reaction.

Kinetic Order of the Reaction with respect to Hydroxy Group Concentration

Systems in which the initial anhydrosulphite concentration was fixed and the initial hydroxyl group concentration

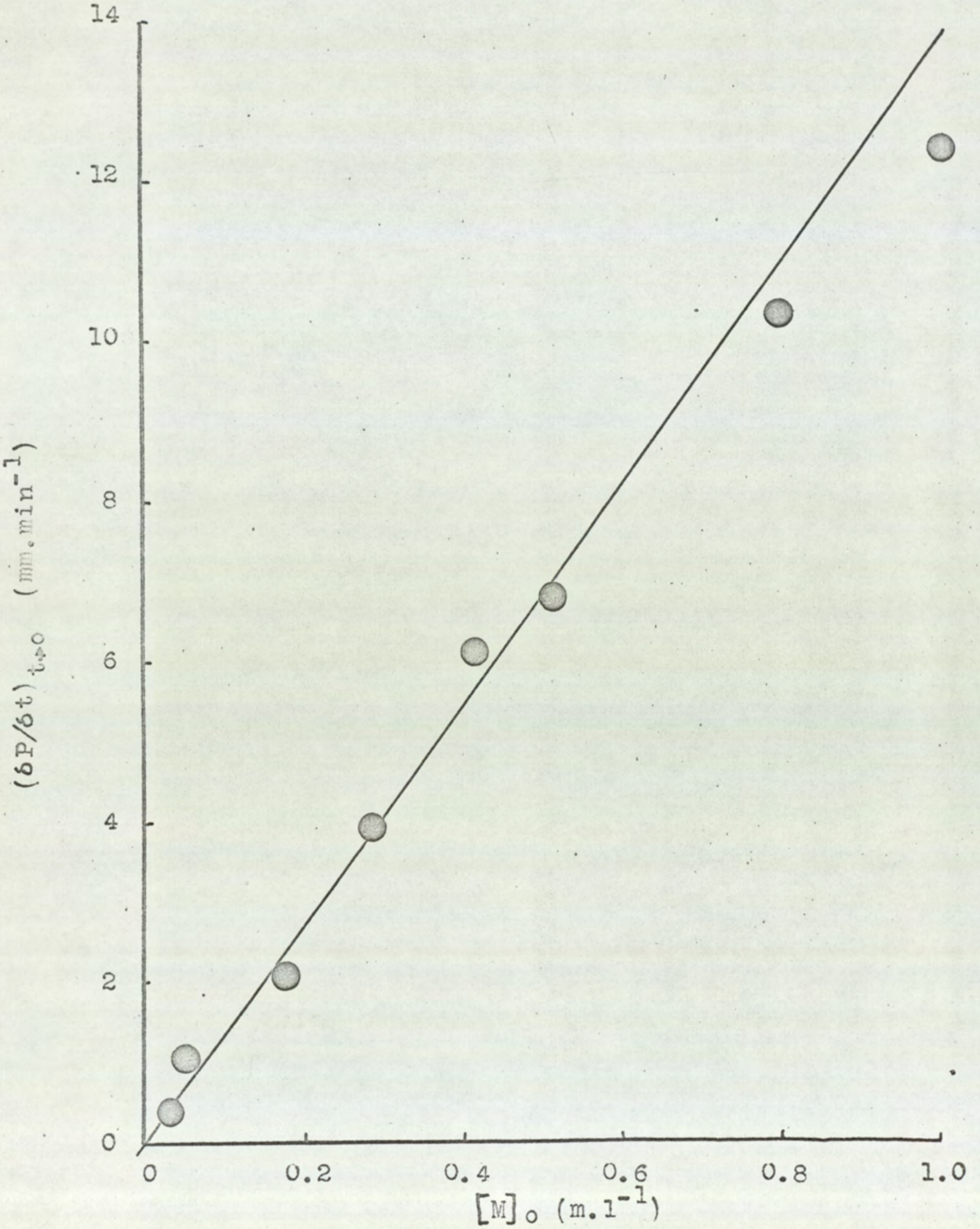


FIGURE 10. Decomposition of lactic acid anhydrosulphite in benzyl alcohol at 90°C. Variation in initial rate of sulphur dioxide evolution $(\delta P/\delta t)_{t\to o}$ plotted as a function of initial anhydrosulphite concentration $[M]_o$. Some departure from linearity is observed at higher values of $[M]_o$ due to the effective reduction in hydroxyl concentration.

varied were examined. The variation of initial rate of sulphur dioxide evolution with changing hydroxyl group concentration at 90°C is shown graphically in Figure 11, nitrobenzene being used as solvent and benzyl alcohol as source of hydroxyl groups. The results indicate a first order dependence on hydroxyl group concentration. The results show that even at zero hydroxyl group concentration the anhydrosulphite has a finite rate of decomposition. This is negligible in comparison with the initiated decomposition if the initial hydroxyl and anhydrosulphite concentrations are of the same order but appreciable if the latter is in, say, a ten-fold excess. For this reason experimental observations related to this 'uninitiated decomposition' are presented in Section 4:2.

Effect of Temperature on the Reaction

The decomposition of lactic acid anhydrosulphite in benzyl alcohol was studied over the temperature range 45°-90°C. Values of the bimolecular velocity coefficient k_2 are given in Table 3. These are calculated on the assumption that the uninitiated decomposition (to which is allotted the velocity coefficient k_1) is negligible in comparison with that due to the hydroxyl initiated decomposition. This fact, together with the first order dependence of the rate of reaction on both anhydrosulphite and hydroxyl group concentration has been established by the results presented above. Values for the Arrhenius activation energy (E) over the temperature range and collision number (A) at 65°C are also shown in the table.

Effect of Dielectric Constant of Reaction Medium on the Reaction

The rate of reaction of benzyl alcohol with lactic acid anhydrosulphite was studied in reaction media of higher and lower dielectric constant than benzyl alcohol. The results are presented in Table 4.

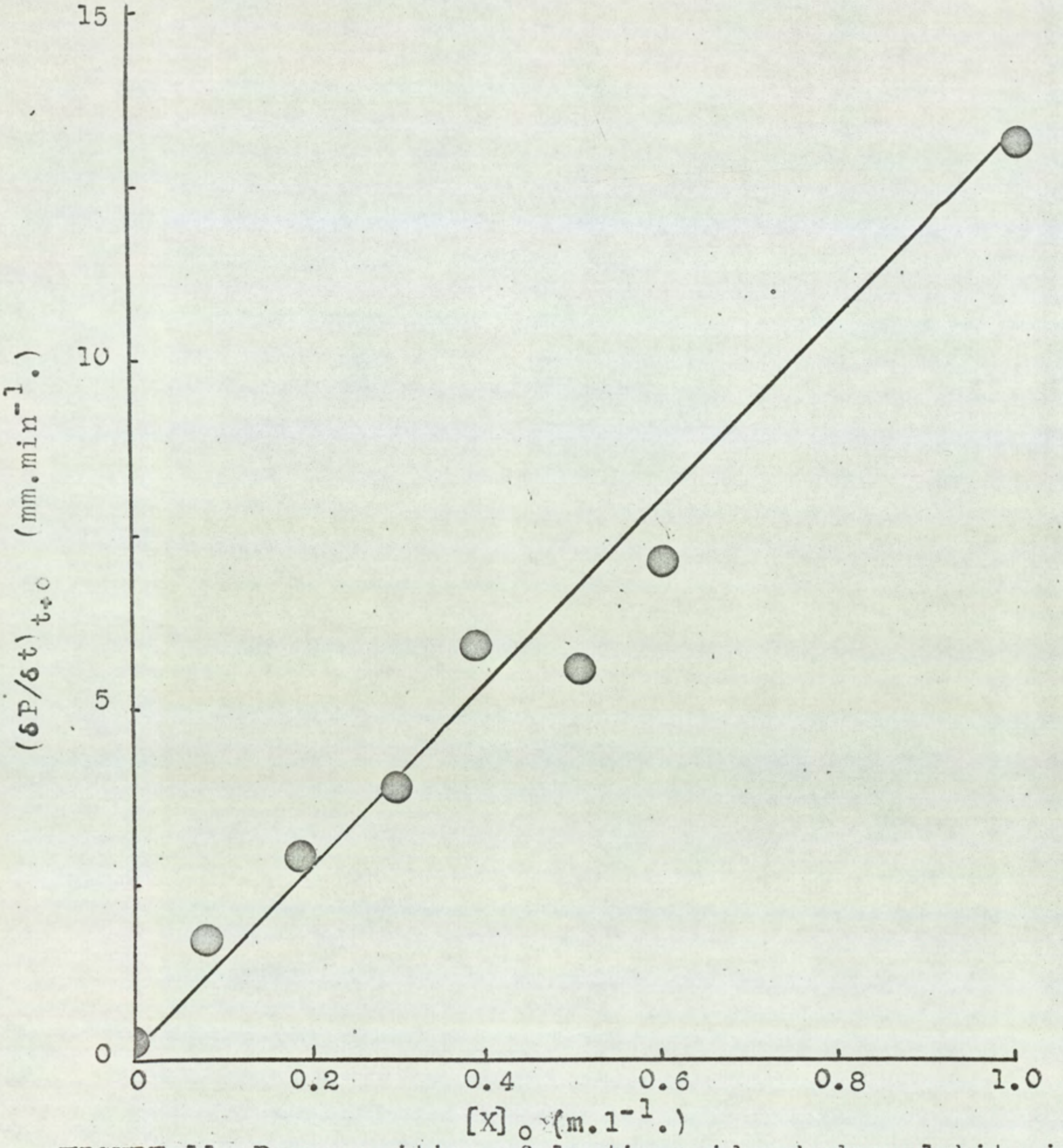


FIGURE 11. Decomposition of lactic acid anhydrosulphite in nitrobenzene at 90°C. Effect of added benzyl alcohol. Variation in initial rate of SO_2 evolution plotted as a function of initial alcohol concentration $[X]_o$, ie. $(\delta P/\delta t)_{t\to o}$ vs. $[X]_o$ $[M]_o$, 1.87 m.l^{-1} (in each case)

TABLE 3

Kinetic data for the reaction of lactic acid anhydrosulphite (initial concentration 1.0 moles/litre) with benzyl alcohol. Reaction medium: benzyl alcohol (Dielectric Constant 9.8 at 65°C)

Temperature (°C)	Velocity Coefficient(k_2) ($l\ mole^{-1}\ s^{-1}$)	Activation Energy(E) ($kcal.mole^{-1}$)	Collision Number(A) ($l.mole^{-1}s^{-1}$)
45	1.0×10^{-5}	-	-
65	2.5×10^{-5}	12.4	2.7×10^{3}
90	8.5×10^{-5}	-	-

TABLE 4

Kinetic data for the reaction of lactic acid anhydrosulphite with benzyl alcohol in nitrobenzene (Dielectric Constant 27 at 65°C) and dioxan (Dielectric Constant ~ 2 at 45°C)

Temperature (°C)	Reaction Medium	Velocity Coefficient ($l.mole^{-1}s^{-1}$)	Activation Energy ($kcal.mole^{-1}$)	Collision Number ($l.mole^{-1}s^{-1}$)
45	Dioxan	3.8×10^{-6}	-	-
65	Nitrobenzene	1.5×10^{-4}	9.9	2.3×10^{2}
90	Nitrobenzene	4.0×10^{-4}	-	-

Steric Effects in the Reaction

In order to assess the importance of steric factors in the addition of alcohols to the anhydrosulphite ring, the bulk of the attacking reagent was varied. The effect of replacing the methyl group in lactic acid anhydrosulphite by an α-hydrogen atom as in glycollic acid anhydrosulphite was also examined. Results are collected in Table 5.

TABLE 5

Reaction of lactic and glycollic acid anhydrosulphites with various hydroxy compounds. In each case the hydroxy compound was used as reaction medium.

Temperature (^oC)	Anhydrosulphite	Hydroxy Compound	Velocity Coefficient ($l.mole^{-1}s^{-1}$)
65	Lactic	Ethyl lactate	$\sim 3 \times 10^{-6}$
65	Lactic	Benzyl alcohol	2.5×10^{-5}
65	Lactic	Amyl alcohol	9.0×10^{-5}
90	Lactic	Ethyl lactate	$\sim 1 \times 10^{-5}$
90	Lactic	Benzyl alcohol	8.5×10^{-5}
90	Glycollic	Benzyl alcohol	3.7×10^{-4}

4:2 The Propagation Reaction - Formation of Polymer - Kinetic Observations

The studies applied above to the ring opening reaction were extended to the polymerisation of lactic acid anhydrosulphite.

It was observed that in non-hydroxylic solvents or in bulk lactic acid anhydrosulphite decomposed to yield a white polymeric material. The decomposition was extremely slow at temperatures around 20°-25°C but relatively rapid in the temperature range 80°-90°C.

The decomposition and polymer formation was accompanied by a steady evolution of sulphur dioxide, manometric measurement of this being used, as before, to follow rates of reaction.

Kinetic Dependence of the Reaction on Monomer Concentration

The form of the plot of sulphur dioxide pressure time was identical to that obtained with anhydrosulphite/ alcohol reactions; the rate of decomposition of monomer exhibiting the characteristics of a first order reaction throughout the range of conditions studied. Systems varying in initial anhydrosulphite concentration from 0.1 - 8.0 moles/litre were examined at temperatures from 45°-95°C. In each case the relationship

$$[M] = [M]_0 e^{-kt}$$

was obeyed, consistent velocity coefficients being obtained for runs at the same temperature with the same initial hydroxyl group concentration.

Catalytic Effects of Sulphur Dioxide on the System

The system was examined, as in the case of the ring opening reaction, for sulphur dioxide catalysis. Rates of decomposition at 65° and 90°C for systems with a fixed initial concentration of both anhydrosulphite and hydroxyl

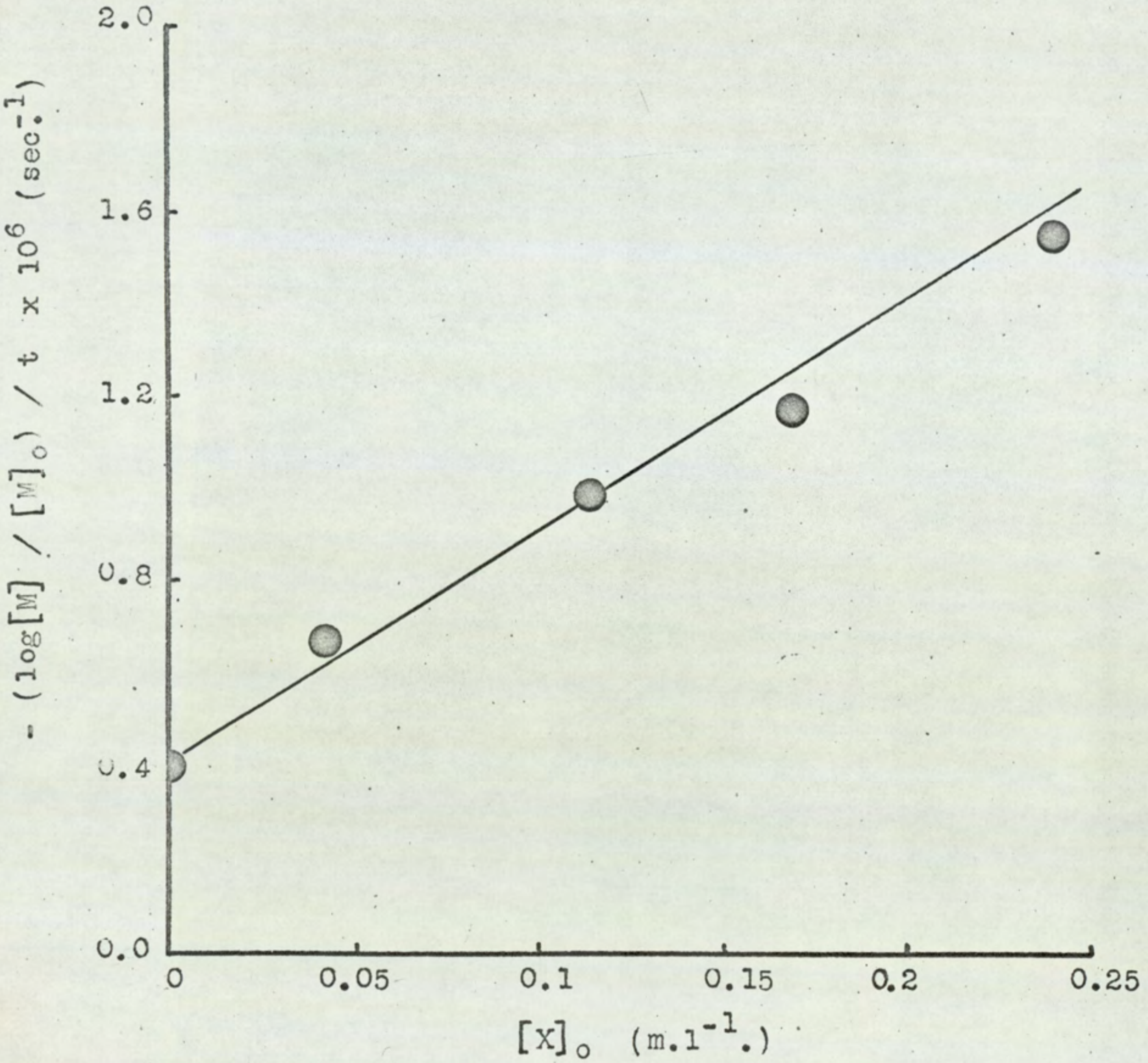


FIGURE 12. Effect of initial hydroxyl group concentration on rate of polymerisation of lactic acid anhydrosulphite in nitrobenzene at 65°C. Separation of 'uninitiated' and hydroxyl initiated contributions. Rates of polymerisation (corresponding to slope BC in Fig.13b, ie. $(\log[M]/[M]_o)/t$,) are expressed as a function of initial hydroxyl group concentration $[X]_o$. The values are plotted as $-(\log[M]/[M]_o)/t$ vs. $[X]_o$.
$[M]_o$, 1.87 m.l^{-1}. in each case.

groups were determined at various initial sulphur dioxide pressures. The results indicated that within the range of pressure studied (10 - 400 mm) sulphur dioxide exerted no catalytic effects on the reaction.

Kinetic Dependence of the Reaction on Hydroxyl Group Concentration

Systems in which the initial anhydrosulphite concentration was fixed and the initial hydroxyl group varied were studied, the former being in excess. Because the reaction of the anhydrosulphite with the initiating alcohol was faster than the subsequent polymerisation, plots of $\log \frac{[M]}{[M]_0}$ vs. time of the form shown in Figure 13a were obtained. Studies involving the propogation reaction were concerned with the slope of the portion B C. A further complication arose from the fact that the monomer had been observed to decompose in the absence of added initiating species (Section 4:1). For this reason the results were processed by plotting minus the slope BC, i.e., $-(\log\frac{[M]}{[M]_0} / t)$, against initial hydroxyl group concentration.

The resultant slope (Figure 12) is of the form y = mx + c, i.e.,

$$-\log\frac{[M]}{[M]_0} / t = k_2'[OH] - \left(\log\frac{[M]}{[M]_0} / t\right)_{[OH]=0} \qquad (39)$$

$$\therefore \quad \log\frac{[M]}{[M]_0} = -\left(k_2'[OH] - (\log\frac{[M]}{[M]_0} / t)_{[OH]=0}\right)t \qquad (40)$$

Where k_2' is a bimolecular velocity constant and $\log\frac{[M]}{[M]_0} / t)$ has the dimensions of a first order coefficient.

Having established that lactic acid anhydrosulphite decomposed at 65°C at a finite rate even in the absence of added hydroxyl groups, a more sophisticated prepolymerisation technique was used to remove other initiating species and the experiment repeated. It was thus established that repeated prepolymerisation failed to affect the rate of uninitiated decomposition.

In view of the fact that the rates of hydroxyl initiated polymerisation were themselves extremely slow at 65°C it was not considered feasible to study rates at lower temperatures (thereby reducing the effects of thermal decomposition on the system). An attempt was made, therefore, to characterise the kinetic behaviour of the initiated polymerisation and thus evaluate $\left(\log\frac{[M]}{[M]_0}/t\right)_{[OH]=0}$

The uninitiated decomposition was therefore studied and found to show first order kinetic dependence on monomer concentration, i.e.,

$$-\left(\frac{d[M]}{dt}\right)_{([OH]=0)} = k_1.[M] \qquad (41)$$

$$\therefore \qquad -\left(\log\frac{[M]}{[M]_0} / t\right)_{[OH]=0} = k_1 \qquad (42)$$

Kinetic data showing the effect of temperature and dielectric constant on the rate constant k_1 are presented in Table 6.

TABLE 6

The decomposition of lactic acid anhydrosulphite in the absence of added initiating species. Reaction media nitrobenzene (Dielectric Constant ~25 at 90°C) and dekalin (Dielectric Constant ~2 at 90°C)

Temperature (°C)	Reaction Medium	Velocity Coefficient(k_1) (Sec^{-1})	Activation Energy (kcal/mole)
65	Nitrobenzene	0.4×10^{-6}	-
90	Nitrobenzene	6.0×10^{-6}	27
90	Dekalin	$\sim 4 \times 10^{-6}$	-

Equation 40 now becomes:

$$\log\frac{[M]}{[M]_0} = -(k_2'[OH].t + k_1 t)$$

$$= -(k_1 + k_2'[OH])t \qquad (43)$$

and Figure 11 may be expressed as:

$$-\frac{d[M]}{dt} = (k_1 + k_2[OH])[M] \qquad (44)$$

Because of the magnitude of the thermal decomposition, evaluation of kinetic data relating to the hydroxyl initiated polymerisation was difficult. The data presented in Table 7 were calculated on the basis of Equation (43), the validity and significance of the results being discussed in Section 4:4. The table shows the effect of temperature and dielectric constant on the second order velocity coefficient (k_2').

TABLE 7

Kinetic data relating to the hydroxyl initiated polymerisation of lactic acid anhydrosulphite. Reaction media nitrobenzene (Dielectric constant ~ 25 at 90°C) and dekalin (Dielectric Constant ~ 2 at 90°C)

Temp. (°C)	Reaction Medium	Velocity Coefficient(k_2') ($l.mole^{-1}s^{-1}$)	Activation Energy (E) ($kcal.mole^{-1}$)	Collision Number(A) ($l.mole^{-1}s^{-1}$)
65	Nitrobenzene	4.8×10^{-6}	-	-
90	Nitrobenzene	1.5×10^{-5}	11.9	1.2×10^{2}
90	Dekalin	$\sim 5.5 \times 10^{-6}$	-	-

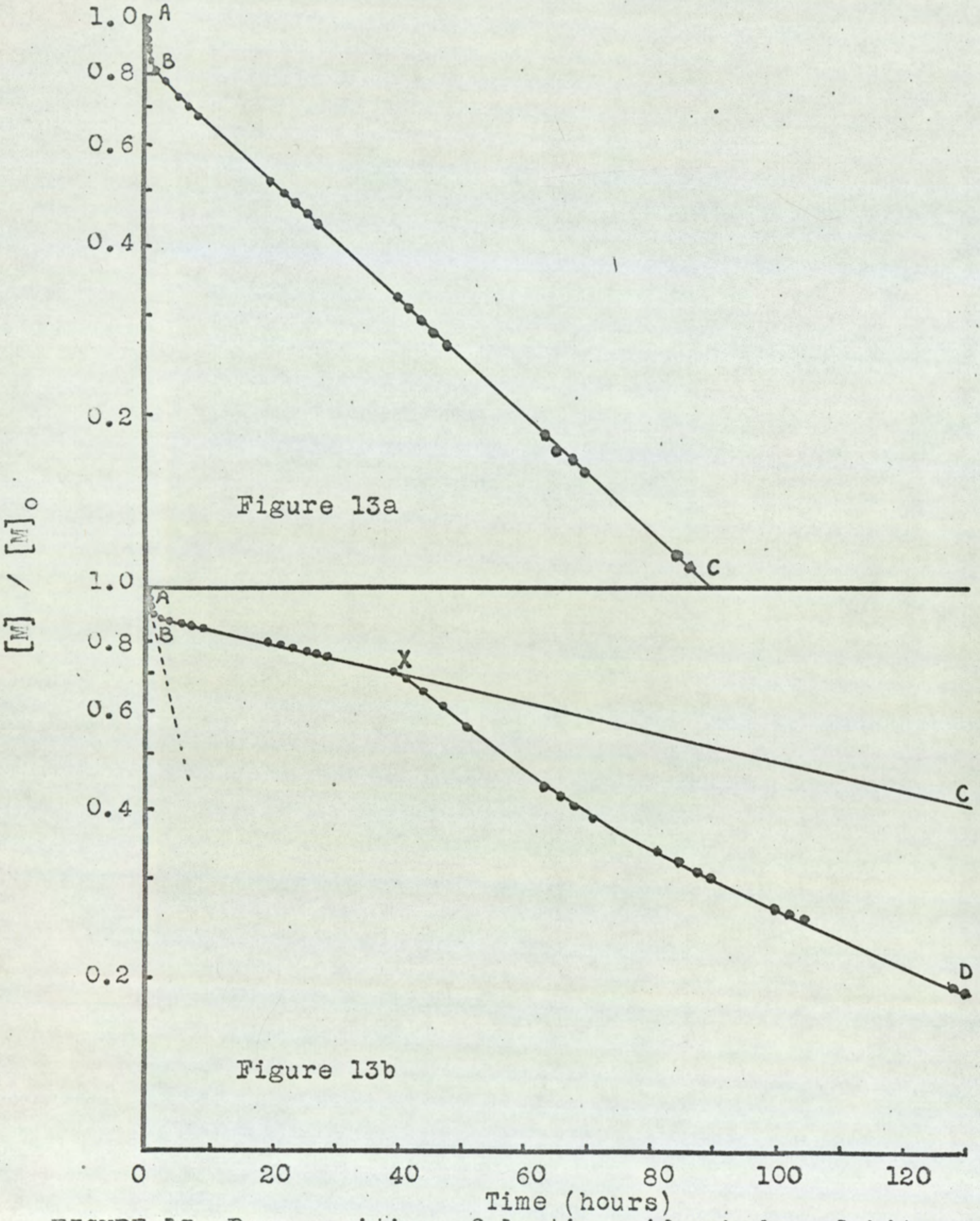


FIGURE 13. Decomposition of lactic acid anhydrosulphite in nitrobenzene initiated by benzyl alcohol. Fraction of monomer remaining (undecomposed) plotted logarithmically as a function of time.
(a) at 90°C, $[M]_0$, 1.87 $m.l^{-1}$; $[\phi CH_2OH]$, 0.24 $m.l^{-1}$
(b) at 65°C, $[M]_0$, 1.87 $m.l^{-1}$; $[\phi CH_2OH]$, 0.24 $m.l^{-1}$

Heterogeneous Polymerisation

Under conditions in which the polymer formed during the reaction precipitated from solution, abnormal kinetic behaviour was shown. Figure 13 shows the relationship $\log \frac{[M]}{[M]_0}$ vs. time for a solution of lactic acid anhydrosulphite in nitrobenzene at 90°C (Figure 13a) and 65°C (Figure 13b). In both cases the initial concentration of anhydrosulphite was 1.87 moles/litre and that of initiator (benzyl alcohol) 0.24 moles/litre.

The portion A - B on these curves represents the initial addition of benzyl alcohol to the anhydrosulphite and the linear portion B - C the subsequent rate of decomposition due to both hydroxyl initiated and thermal decomposition. In the case of curve (b), however, a discontinuity appears at point X: this corresponds to the precipitation of polymer from solution. The acceleration in the portion X - D being associated with the heterogeneity of the system.

This phenomenon leads to difficulties in carrying out kinetic studies below 80°-90°C. The situation is most marked in the non-polar solvents which are used to provide reaction media of low dielectric constant. Thus accurate rate constants for the hydroxyl initiated polymerisation of lactic acid anhydrosulphite in dekalin at 65°C are virtually impossible to obtain.

4:3 Examination of Reaction Products

(i) The Ring Opening Reaction

The products obtained from the reactions corresponding to Figure 8 were examined, together with those obtained when a larger excess of the alcohol, amine, and water were employed. In the case of benzyl alcohol and benzylamine the products were largely benzyl lactate and N-benzyl lactamide respectively, infra red spectra and classical analytical techniques being used to identify the materials. In the reaction with water lactic acid was isolated following, presumably, the formation of the intermediate noted by Blaise and Montagne(5). All the above results are consistent with the findings of these workers.

(ii) The Propogation Reaction

Complete characterisation of the polymers obtained from lactic and glycollic acids was not undertaken, although infra red spectra were consistent with those obtained from α-hydroxy isobutyric acid polymers which were examined in some detail (Section 5). It was presumed, therefore, that the polymers were, in fact, true α-polyesters probably terminated by carboxyl and hydroxyl groups, in the case of those initiated by moisture, or hydroxyl and benzyl ester groups in the case of polymers initiated by benzyl alcohol.

The molecular weights of a series of polymers prepared from lactic acid anhydrosulphite and corresponding to the monomer and initiator concentrations of Figure 12 were determined. The results are presented in Table 8.

TABLE 8

Polymerisation of Lactic Acid Anhydrosulphite Initiated by Benzyl Alcohol. Reactions carried out in nitrobenzene at 65°C.

Anhydrosulphite Concentration (mole.l^{-1})	Benzyl Alcohol Concentration (mole.l^{-1})	Molecular Weight ($\overline{M}n$) of Polymer (VPO)
1.87	0.05	2500
1.87	0.12	1400
1.87	0.163	1200
1.87	0.225	900

4:4 Discussion

The kinetic results presented in Sections 4:1 and 4:2 show that although the rate of decomposition of this class of compounds is affected by the presence of hydroxyl groups, there is a finite rate of decomposition even in their absence. The rate of decomposition of anhydrosulphites of this type has been related to the molar concentration of the anhydrosulphite [M] and hydroxy compounds [OH] by the following expression:

$$-\frac{d[M]}{dt} = [M](k_1 + k_2[OH]) \qquad (45)$$

The constant k_1 has the dimensions of a first order velocity coefficient (sec^{-1}) and k_2 those of a second order constant ($litre.mole^{-1}sec^{-1}$).

At zero hydroxyl group concentration the expression reduces to:

$$-\frac{d[M]}{dt} = k_1[M] \qquad (46)$$

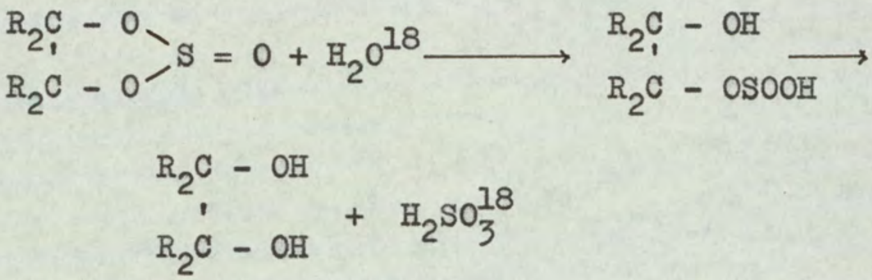
Values of k_1 for lactic acid anhydrosulphite in nitrobenzene at 65°C and 90°C were given in Table 6 together with that obtained in dekalin at 90°C. The magnitude of these values and the nature of the decomposition in the absence of hydroxyl groups is discussed in Section 6.

The Hydroxyl Group Initiated Decomposition - Features of the Ring Opening Reaction

There are several points of resemblance between the decomposition of this class of anhydrosulphites in the presence of hydroxyl groups and the decomposition of N-carbonic anhydrides of α-amino acids (hereinafter referred to as NCA's) in the presence of primary and secondary amines. It is relevant to compare the reactions involved.

Mono and unsubstituted anhydrosulphite rings are susceptible to attack by water, primary and secondary aliphatic amines and alcohols. The reaction with water leads to the regeneration of the hydroxy acid and liberation of sulphur dioxide, probably by nucleophilic attack of the water molecule on the carbonyl carbon atom, since this is the site of lowest electron density in the molecule.

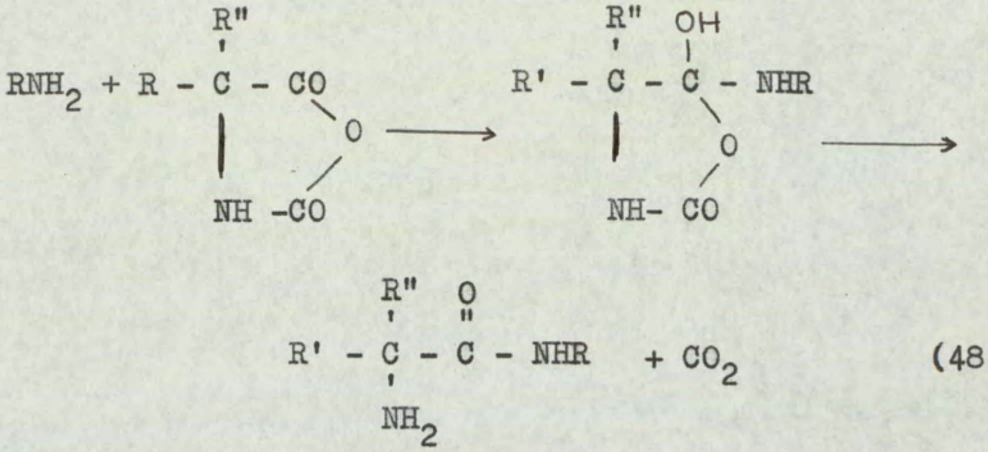
Nucleophilic attack at the sulphur atom is much less favoured, although organic sulphites undergo hydrolysis by water in which the sulphite group is the seat of attack. Reaction rates and mechanisms of sulphite hydrolysis have been extensively studied by various workers (46-52). The use of isotopically enriched water has indicated that for both open chain and cyclic sulphites the hydrolysis takes place with sulphur-oxygen bond fission (52).



(47)

The mechanism in acid solution has been shown to proceed by a fast proton addition followed by a rate determining bimolecular attack involving a solvent molecule or nucleophilic anion. In alkali a direct nucleophilic attack by hydroxyl ion on the sulphur atom takes place, followed by sulphur-oxygen bond fission. It is presumed, however, that in the hydrolysis of anhydrosulphites such reactions play little if any part.

The reaction of amines with anhydrosulphites probably resembles the hydrolysis with water. This would be consistent with decomposition of NCA's in the presence of amines which proceeds predominantly by the following route, e.g. (18, 53, 54).



(48)

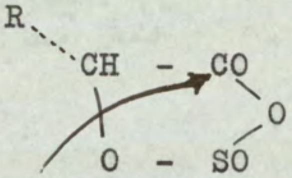
The rate of addition of water and benzylamine to the anhydrosulphite of lactic acid in dioxan at 40°C are compared in Figure 8. The amine addition is noticeably more rapid in spite of its greater size due, probably, to its greater nucleophilicity under the conditions of the reaction.

Alcohols will also react directly with the class of anhydrosulphites under consideration, although the rates of addition are much slower than those obtained with amines or water. This is again illustrated in Figure 8 where the rates of addition of benzylamine and benzyl alcohol to lactic acid anhydrosulphite in dioxan at 40°C are compared. The similarity in overall size of the alcohol and amine indicate that steric hindrance is not the primary cause of the effect, difference in the nucleophilicity again being responsible. A similar difference in reactivity to alcohols and amines is observed in the NCA's; benzyl alcohol is relatively slow in its attack on NCA's whereas amines in general react rapidly.

It should be noted that the attack of water on NCA's is especially sensitive to pH of reaction medium(55) as in the case of organic sulphites previously mentioned. Care must be exercised, therefore, in making generalisations about the relative rates of attack summarised here.

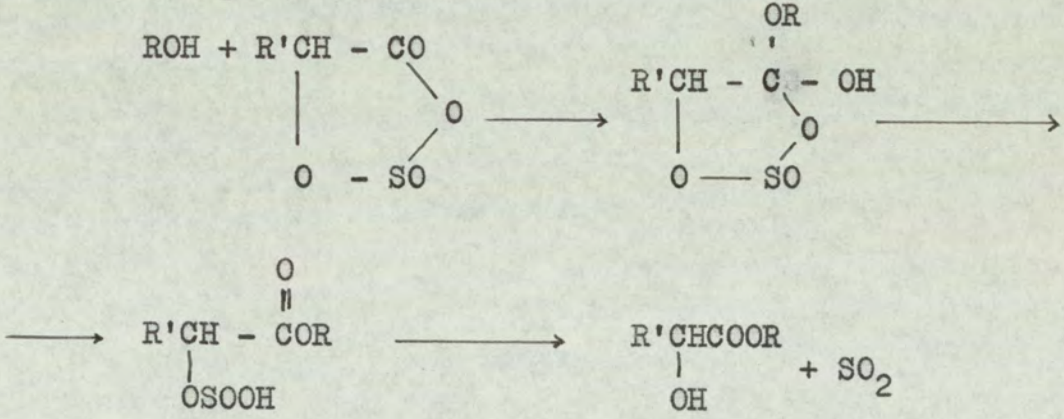
Within a given class of compounds - for instance alcohols - both steric and electronic factors must be considered in relation to the ease of attack of individual members of the series on a given anhydrosulphite. Electronic factors will be largely responsible for variations in nucleophilicity of the alcohol group while steric factors will govern the physical ease with which the reagent can approach the site of attack.

The most probable path for the attack of an alcohol would seem to be across the ring to the back side of the carbonyl group in the manner shown:



This is analogous to the path by which the NCA's are attacked by amino compounds(27). It is to be expected, therefore, that substituents which tend to withdraw electrons from the hydroxyl group, and those which by their bulk offer hindrance to the carbonyl group, will diminish the effectiveness of the alcohol in this reaction. Such an effect can be seen by comparing the attack of amyl alcohol, benzyl alcohol and ethyl lactate on lactic acid anhydrosulphite at 65°C (Table 5). Even allowing for the fairly small differences in dielectric constant involved, the rate of attack increases markedly in the order ethyl lactate, benzyl alcohol, amyl alcohol. The results are most readily understood as reflecting the greater ease with which less bulky reagents can attack the ring. The steric hindrance caused by substituents in the ring itself is illustrated (in Table 5) by the difference in rates of attack of benzyl alcohol on the glycollic and lactic anhydrosulphites. This point is discussed further in relation to the anhydrosulphite of ∝-hydroxy isobutyric acid.

Addition reactions involving the carbonyl group, of the type under discussion, are quite markedly affected by the dielectric constant of the reaction medium. This effect is well characterised in the case of the NCA's (19,56) although comparison of results is not valid unless the reactions are known to be completely homogeneous. In the case of the addition of benzyl alcohol to the anhydrosulphites the relevant experimental evidence is presented in Tables 3 and 4. These results show a change in the second order velocity coefficient from 1.5 x 10^{-4} $\text{litre.mole}^{-1}.\text{sec}^{-1}$ in nitrobenzene (dielectric constant ~ 27) at 65°C to 2.5 x 10^{-5} $\text{litre.mole}^{-1}.\text{sec}^{-1}$ in benzyl alcohol (dielectric constant ~ 9) at the same temperature. A change of this magnitude is consistent with the bimolecular reaction involved, falling as it does into the category of dipole - dipole reactions. The results are further suggestive of a di-polar transition state and some rearrangement and separation of change involved in formation of the final product. Such conditions are fulfilled in the mechanism for the addition presented below.



(49)

The kinetic data for the reaction between benzyl alcohol and lactic acid anhydrosulphite yield collision numbers (Tables 3 and 4) somewhat lower than those associated with the reaction of amines and NCA's. The former are of the order of $10^2 - 10^3$ while typical results for the latter give values between 10^3 and 10^4.

The collision number (A) is normally factorised into a collision frequency (Z) and a steric factor (p). Both theoretical arguments and direct experimental comparison between gas and liquid phase reactions indicate that the order of magnitude of Z in solution is that calculated from the kinetic theory of gases viz., of the order of 10^{11}. The effect of the solvent in impeding diffusion is to promote repeated collisions between pairs of molecules rather than fresh encounters. For the purpose of ordinary slow chemical reactions these processes are equally effective. Thus changes in pZ over several powers of 10 are normally attributed to changes in p, although changes within a given order of magnitude may equally well be due to variations in Z. Following this reasoning Fairclough and Hinshelwood(57), studying the esterification of a series of fatty acids in ethyl alcohol, accounted for the low pZ values obtained in terms of the magnitude of the steric factor p. The range of values obtained at 100°C were: $k = 3.0 - 5.7 \times 10^{-6}$ litre.mole^{-1}.sec^{-1};

$E = 14.8 - 15.1$ kcal.mole^{-1};

$\log pZ = 3.18 - 3.69$

Similarly low pZ values have been encountered in several reactions including the esterification of cyclohexane dicarboxylic acids(58).

It has been suggested that in the case of the NCA series, low collision numbers are obtained as a result of the greater polarity of the transition state compared with that of the initial reactants(19, 59).

It seems probable in the reaction between benzyl alcohol and lactic acid anhydrosulphite that shielding effects in the anhydrosulphite ring, together with the bulk of the alcohol molecule, will render many collisions ineffective, leading to a considerable reduction in the value of p and thus A. Low collision numbers such as those discussed here are inevitably coupled with large negative entropies of activation. The effects involving interaction of solvent with reacting species are more readily understood in terms of this quantity.

The inter-relation between the entropy of activation ($\Delta S^{\mp}$) and collision number (A) is given by:

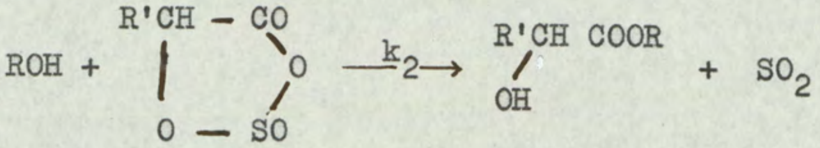
$$A = \left(\frac{kT}{h}\right) e^{\frac{\Delta S^{\mp}}{R}}$$

where k is Boltzman's constant (1.380×10^{-16} erg, deg^{-1})
h is Plancks constant (6.624×10^{-27} erg sec)
R is the Gas constant (1.986 cal.deg^{-1} mole^{-1})
and T is the absolute temperature.

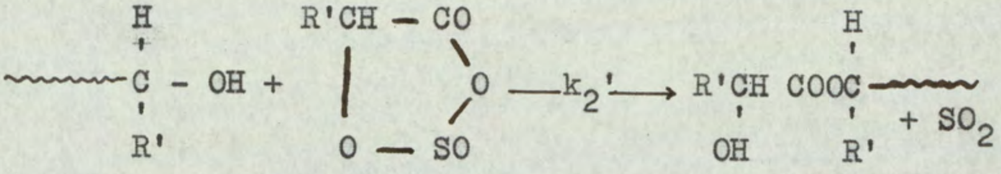
In both reaction schemes (48) and (49) an intermediate more polar than the initial reactants is postulated. In reactions of this type the complex formed tends to bind solvent molecules more strongly than do the reactant molecules. This effect results in a considerable negative entropy of activation and a correspondingly low frequency factor.

The Hydroxyl Initiated Decomposition - Chain Propagation

The mode of addition normally encountered in the reaction between NCA's and primary or secondary aliphatic amines leads to the regeneration of an amino group. This, in turn, is capable of attacking another NCA molecule, thus providing the basis of the propagation reaction (refs 18, 19). In an analogous manner addition of an alcohol to an anhydrosulphite leads to the regeneration of a terminal hydroxyl group, which should in principle be capable of a similar propogation step.



(50)



(51)

The kinetic results obtained for the benzyl alcohol/ lactic acid anhydrosulphite system (Section 4:1) are consistent with such a bimolecular propagation step, although simultaneous uninitiated decomposition has also been demonstrated to occur. If the initial molar concentration of anhydrosulphite is represented by $[M]_o$ and that of the alcohol by [OH] the overall rate of decomposition during the initial ring opening reaction will be:

$$-\frac{d[M]}{dt} = [M](k_1 + k_2[OH]) \qquad (45)$$

which on rearrangement and integration yields

$$\log\frac{[M]}{[M]_o} = -(k_1 + k_2[OH])t \qquad (52)$$

(where [M] is the anhydrosulphite concentration at time t)

Similarly for the subsequent reaction the overall rate of decomposition will be:

$$-\frac{d[M]}{dt} = [M](k_1 + k_2'[OH]) \qquad (53)$$

or in its integrated form,

$$\log\frac{[M]}{[M]_o} = -(k_1 + k_2'[OH])t \qquad (54)$$

Values for both k_1 and k_2' can be obtained for the polymerisation of lactic acid anhydrosulphite in nitrobenzene at 65°C, initiated by benzyl alcohol, from Figure 13b. Here the initial slope $\log\frac{[M]}{[M]_o}$ in the portion AB is equal to

$-(k_1 + k_2[OH])$ and the slope of BX (produced to C) corresponds to $-(k_1 + k_2'[OH])$.

By substituting $k_1 = 4.0 \times 10^{-7}$ sec.$^{-1}$ and $[OH] = 0.24$ moles.l^{-1}, the approximate values $k_2 = 1.2 \times 10^{-4}$ litre.mole.$^{-1}$sec.$^{-1}$ and $k_2' = 4.2 \times 10^{-6}$ litre.mole.$^{-1}$sec.$^{-1}$ are obtained. These may be compared with values from other determinations previously presented in Tables 4 and 7 (which have been summarised in Table 9 below).

Effects of a similar nature are found in the NCA series(19,20). The differences in basisity of the initiating amine and the terminal amino group of the growing chain are often sufficient to cause quite large differences in velocity coefficient. Consequently changes in the slope of $\log\frac{[M]}{[M]_0}$ vs. time analogous to those presented here are observed. In studies of the kinetics of NCA polymerisation small preformed polymers are often used as initiators. In this case no change in velocity coefficient and slope is observed.

The velocity coefficients, activation energies and collision numbers determined for the bimolecular propogation reaction involved in lactic acid anhydrosulphite polymerisation are not greatly dissimilar from those obtained for the attack of benzyl alcohol in the same solvents and at the same temperatures. The values obtained in nitrobenzene at 65°C are compared for convenience below (Table 9).

TABLE 9

Comparison of the kinetic data relating to the initiation and propagation reactions involved in the polymerisation of lactic acid anhydrosulphite initiated by benzyl alcohol. The data (collected from Tables 4 and 7) refer to reactions in nitrobenzene at 65°C.

Reaction Involved	Velocity Coefficient ($l.mole^{-1}sec^{-1}$)	Activation Energy (65-90°C) ($kcal.mole^{-1}$)	Collision Number ($l.mole^{-1}sec^{-1}$)
Alcohol Addition	1.5×10^{-4} (k_2)	9.9	2.3×10^2
Propagation Step	4.8×10^{-6} (k_2')	11.9	1.2×10^2

The values are reasonably consistent with the reactions postulated, such differences as exist being due to the steric and electronic differences in the environment of the hydroxyl groups.

It is apparent that the molecular weight of the polymer produced by the polymerisation of lactic acid anhydrosulphite does not bear a direct relationship to the inverse of the initial [OH] concentration (Table 8). It seems certain, however, that the ratio $\frac{[M]}{[OH]}$ is the controlling factor in determining the molecular weight of polymer formed. In view of the fact that two apparently distinct mechanisms are operative in the polymerisation, it is not surprising that such a position exists. Further discussion will depend on some elucidation of the mechanism of the 'thermal polymerisation' associated with the constant k_1. Such discussion, together with observations on the nature of the heterogeneous polymerisation (Figure 13b) will be presented in Section 6.

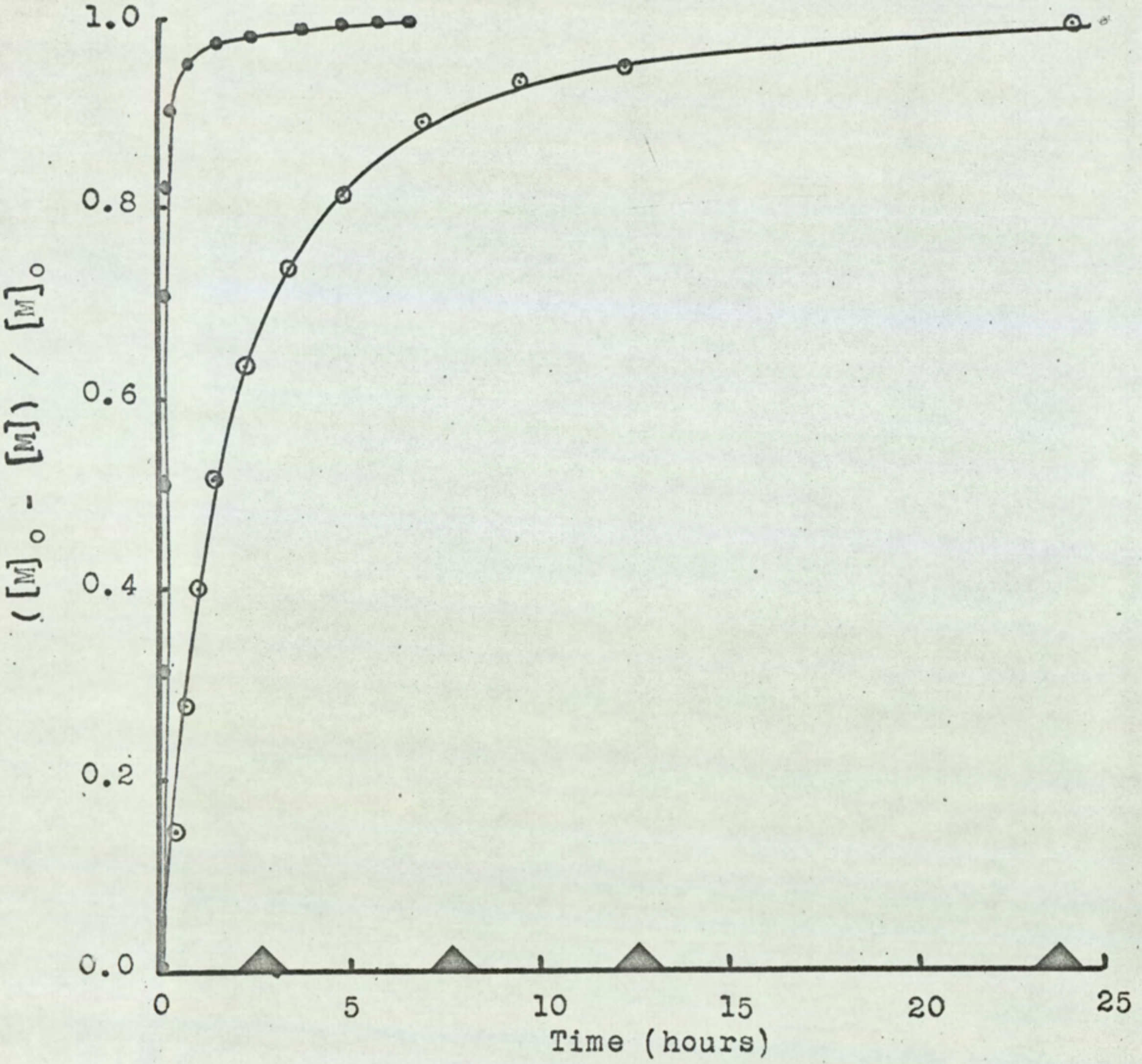


FIGURE 14. Decomposition of AHIBAS in the presence of various reagents at 40°C. Reaction medium; dioxan (in each case).

● ,(a) [ØCH$_2$NH$_2$] ,2.0 m.l^{-1}.; [M]$_o$,0.5 m.l^{-1}.

⊙ ,(b) [H$_2$O] ,2.0 m.l^{-1}.; [M]$_o$,0.5 m.l^{-1}.

▲ ,(c) [ØCH$_2$OH], 2.0 m.l^{-1}.; [M]$_o$,0.5 m.l^{-1}.

5. THE POLYMERISATION OF ∝-HYDROXY ISOBUTYRIC ACID ANHYDROSULPHITE - EXPERIMENTAL RESULTS

5:1 Ring Opening by Aliphatic Amines (primary and secondary) Alcohols and Water - Kinetic Observations

Qualitative observations indicated that although the reaction of this anhydrosulphite was fairly rapid at room temperature with amines and water, the reaction with alcohols was infinitesimally slow. The rate of decomposition of ∝-hydroxy isobutyric acid anhydrosulphite (abbreviated in this and subsequent Figures and Tables to AHIBAS) with 2 molar solutions of benzylamine, benzyl alcohol and water in dioxan at 40°C is shown in Figure 14. This was followed, as in previous studies, by manometric measurement of sulphur dioxide evolved.

For reasons outlined in Section 2:3 detailed kinetic studies of the ring opening reaction were restricted to the attack of alcohols. Experimental results indicated that benzyl alcohol did not react directly with the anhydrosulphite of ∝-hydroxy isobutyric acid. Figure 15 shows the effect of alcohol concentration on the initial rate of decomposition of the anhydrosulphite at various temperatures. Measurements were carried out in nitrobenzene at 40°, 65° and 90°C using an anhydrosulphite concentration of 1 mole/litre. All studies at a given temperature were carried out using reaction vessels of identical volume.

In order to assess the effectiveness of other alcohols in opening the anhydrosulphite ring the experiments were repeated using cyclohexanol and amyl alcohol in place of benzyl alcohol. In both cases the results were similar to those obtained with the latter.

The effect of a much larger hydroxyl group concentration was studied by employing benzyl alcohol as both reaction medium and source of hydroxyl groups. In this

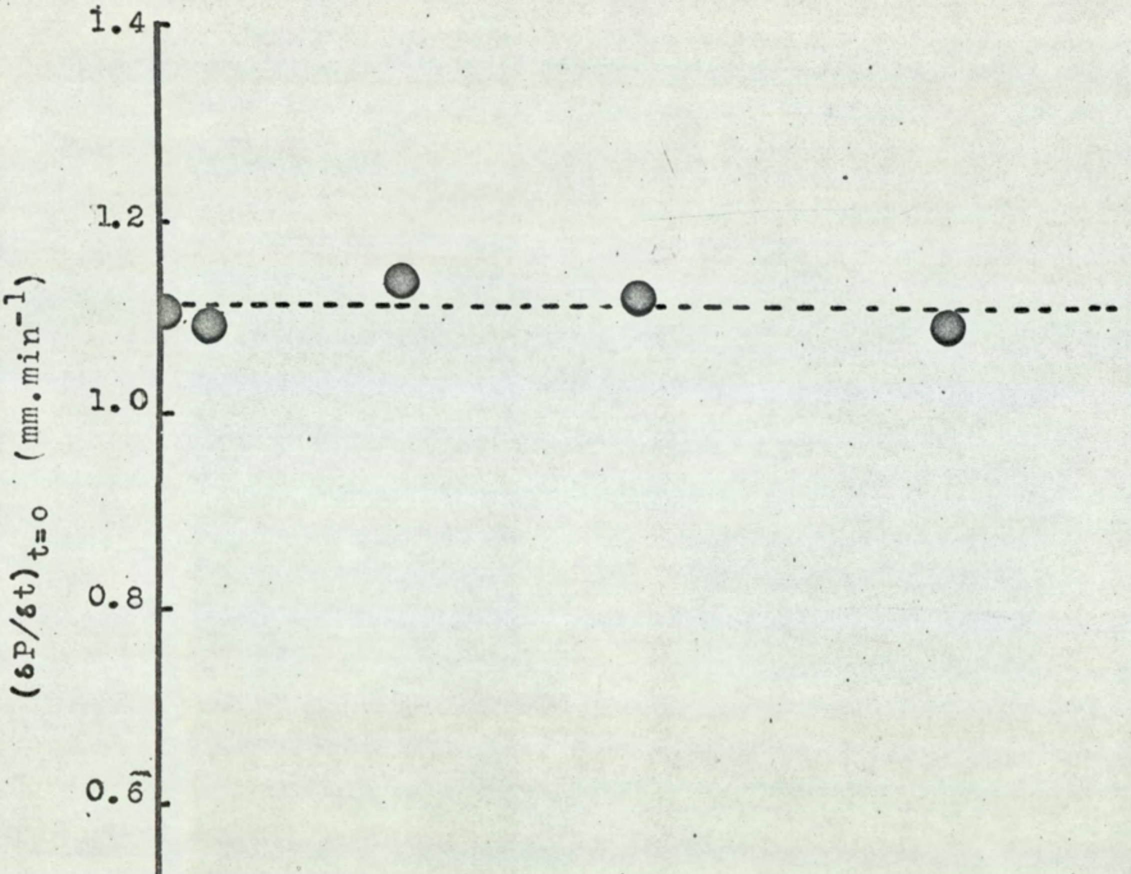


FIGURE 15. Decomposition of AHIBAS in nitrobenzene at various temperatures. Effect of added benzyl alcohol (X). Variation in initial rate of AHIBAS decomposition plotted as a function of initial alcohol concentration $[X]_o$. Decomposition expressed as initial rate of SO_2 evolution $(\delta P/\delta t)_{t=o}$. $[M]_o$, 1.0 m.l^{-1}.(at each temp.); ▲ (40°C); ◆ (65°C); ● (90°C).

case the hydroxyl group concentration was in the region of 8.5 moles/litre, the exact value depending upon the temperature of the alcohol. Figure 16(a) shows the rate of decomposition of α-hydroxy isobutyric acid anhydrosulphite in benzyl alcohol at 90°C and Figure 16(c) the rate at 40°C. Figures16(b) and 16(d) show the rate of decomposition at 90°C and 40°C respectively in the absence of hydroxyl group containing compounds; nitrobenzene being used as reaction medium. In both cases the initial anhydrosulphite concentration was 0.5mole/litre.

The decomposition of anhydrosulphite was found to obey a first order kinetic decay law. The relationship $\log\frac{[M]}{[M]_0}$ vs. time corresponding to decomposition in both benzyl alcohol and nitrobenzene at 90°C (i.e. Figure 16(a) and 16(b)) is shown in Figure 17(a) and 17(b). These results confirm the observation that alcoholic hydroxyl groups exert little or no influence on the rate of decomposition of α-hydroxy isobutyric acid anhydrosulphite.

5:2 The Propagation Reaction - Formation of Polymer - Kinetic Observations

The reports of previous workers indicated that the formation of polymer from α-hydroxy isobutyric acid is accompanied by an apparently quantitative evolution of sulphur dioxide. In view of this and the ineffectiveness of alcohols in the ring opening reaction (and therefore, presumably, as initiators for the polymerisation), the validity of gas evolution measurements in following rates of polymerisation was examined. The results are described below.

Kinetic Dependence on Monomer Concentration

In all solvents and over the whole range of concentration and temperature studied (o - 8 moles/litre and 65° - 95°C) the decomposition of anhydrosulphite obeyed a

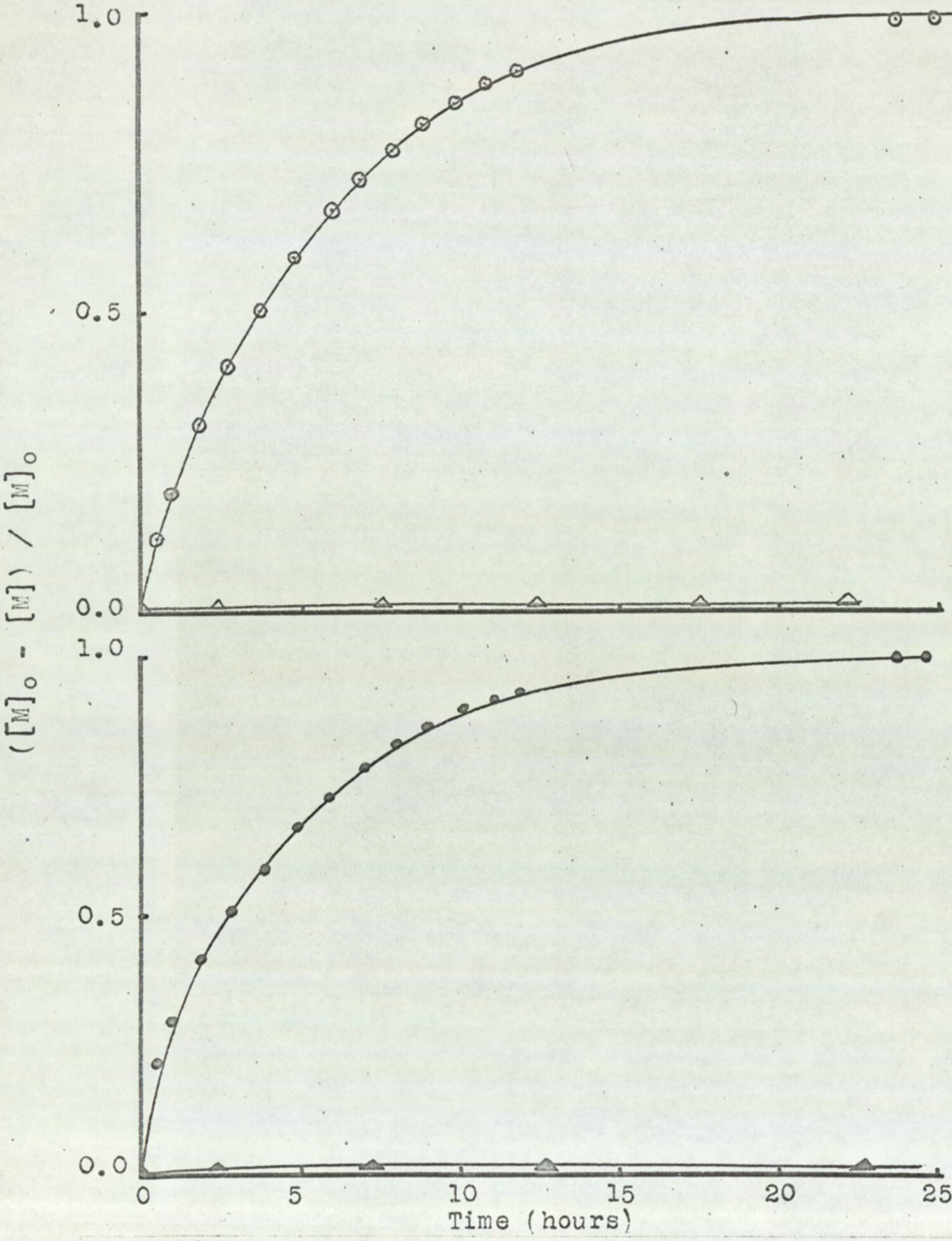


FIGURE 16. Rate of decomposition of AHIBAS under various conditions.

⊙ (a), in benzyl alcohol at 90.8°C; $[M]_o$, 0.5 m.l^{-1}.
● (b), in nitrobenzene at 90.8°C; $[M]_o$, 0.5 m.l^{-1}.
△ (c), in benzyl alcohol at 40.0°C; $[M]_o$, 0.5 m.l^{-1}.
▲ (d), in nitrobenzene at 40.0°C; $[M]_o$, 0.5 m.l^{-1}

first order kinetic decay law. Typical $\frac{[M]_0 - [M]}{[M]_0}$ vs. time and the relevant plots of $\log\frac{[M]}{[M]_0}$ vs. time have been shown in Figures 16 and 17. The first order velocity coefficients obtained for a given temperature and solvent were found to be constant over the whole concentration range.

Kinetic Dependence on Hydroxyl Group Concentration

The fact that the concentration of hydroxyl group containing compounds (with the exception of water) does not affect the rate of decomposition of this class of anhydrosulphites has been demonstrated experimentally in Section 5:1.

The effect of hydroxyl group concentration on molecular weight of the resultant polymer is described elsewhere (Sections 5:5 and 5:6).

Catalysis by Sulphur Dioxide

The system was examined for signs of sulphur dioxide catalysis using the method which has previously been described (Section 4:1). No evidence of any such effect was observed in the pressure range studied (10 - 400 mm) at temperatures between 65° and 95°C.

Correspondence of Sulphur Dioxide Evolution with Polymer Formation

A solution of α-hydroxyisobutyric acid anhydrosulphite in nitrobenzene (concentration 1.5 moles/litre) was prepared and a sample transferred to a reaction vessel with manometer attached. Measured quantities of the same solution were transferred to reaction vessels of similar volume but without manometer attachments. The vessels were evacuated, sealed and transferred to a 90°C thermostat. The rate of anhydrosulphite decomposition was measured manometrically and, in addition, at suitable time intervals, the amount of polymer formation was determined by removal of a sealed

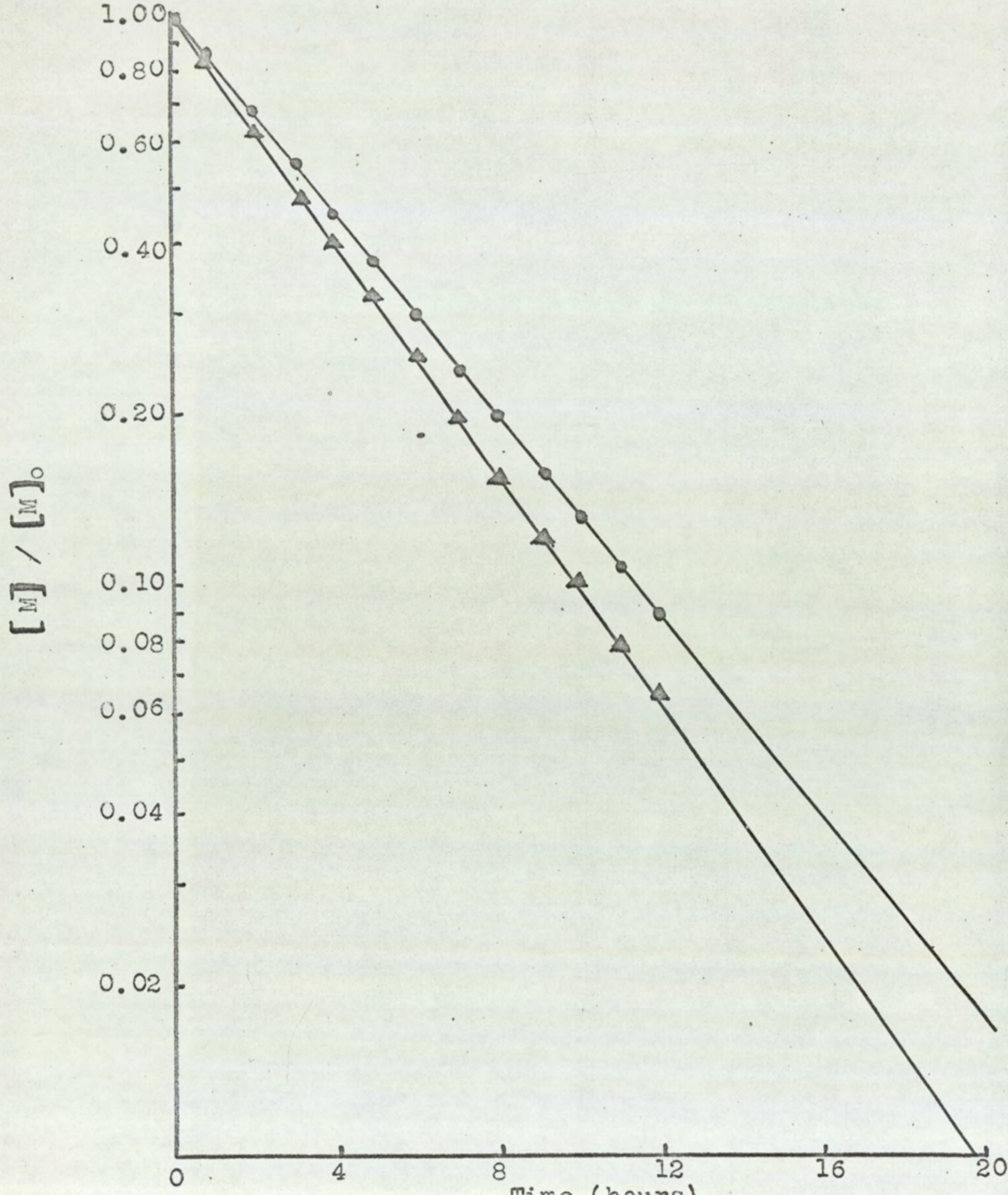


FIGURE 17. Decomposition of AHIBAS under various conditions. Data from Figure 16a and 16b plotted logarithmically as a function of time.

(a), in benzyl alcohol at 90.8°C; $[M]_o$, 0.5 m.l^{-1}.

(b), in nitrobenzene at 90.8°C; $[M]_o$, 0.5 m.l^{-1}.

vessel and precipitating, filtering, washing, drying and finally weighing the polymer formed. The final tube was not removed until some 48 hours after gas evolution measurements had indicated that the reaction was complete.

The results of both gas evolution and gravimetric measurements (shown graphically in Figure 18) indicate that the rate of evolution of sulphur dioxide corresponds to the rate of polymer formation.

Effect of Dielectric Constant of Reaction Medium

The effect of dielectric constant of the reaction medium on the rate of decomposition of ∝-hydroxy isobutyric acid anhydrosulphite at 90°C was investigated. The solvents used were purified as previously described (Section 2:2) to avoid the presence of chance initiators and other impurities. In each case the decomposition showed first order kinetic dependence on anhydrosulphite concentration.

Table 10 shows the first order velocity coefficient corresponding to the rate of decomposition in each solvent at 90°C.

TABLE 10

Polymerisation of AHIBAS in various reaction media. Dependence of velocity coefficient on dielectric constant

Reaction Medium	Dielectric Constant (at 90°C)	Velocity Coefficient (Sec^{-1})
Nitrobenzene	~25	6.1×10^{-5}
o-Nitrobenzene	~16	5.5×10^{-5}
Benzyl Alcohol	~8.5	5.5×10^{-5}
AHIBAS(undiluted)	-	5.0×10^{-5}
∝-Methyl napthalene	~2.5	3.5×10^{-5}
Dekalin	~2.1	2.2×10^{-5}

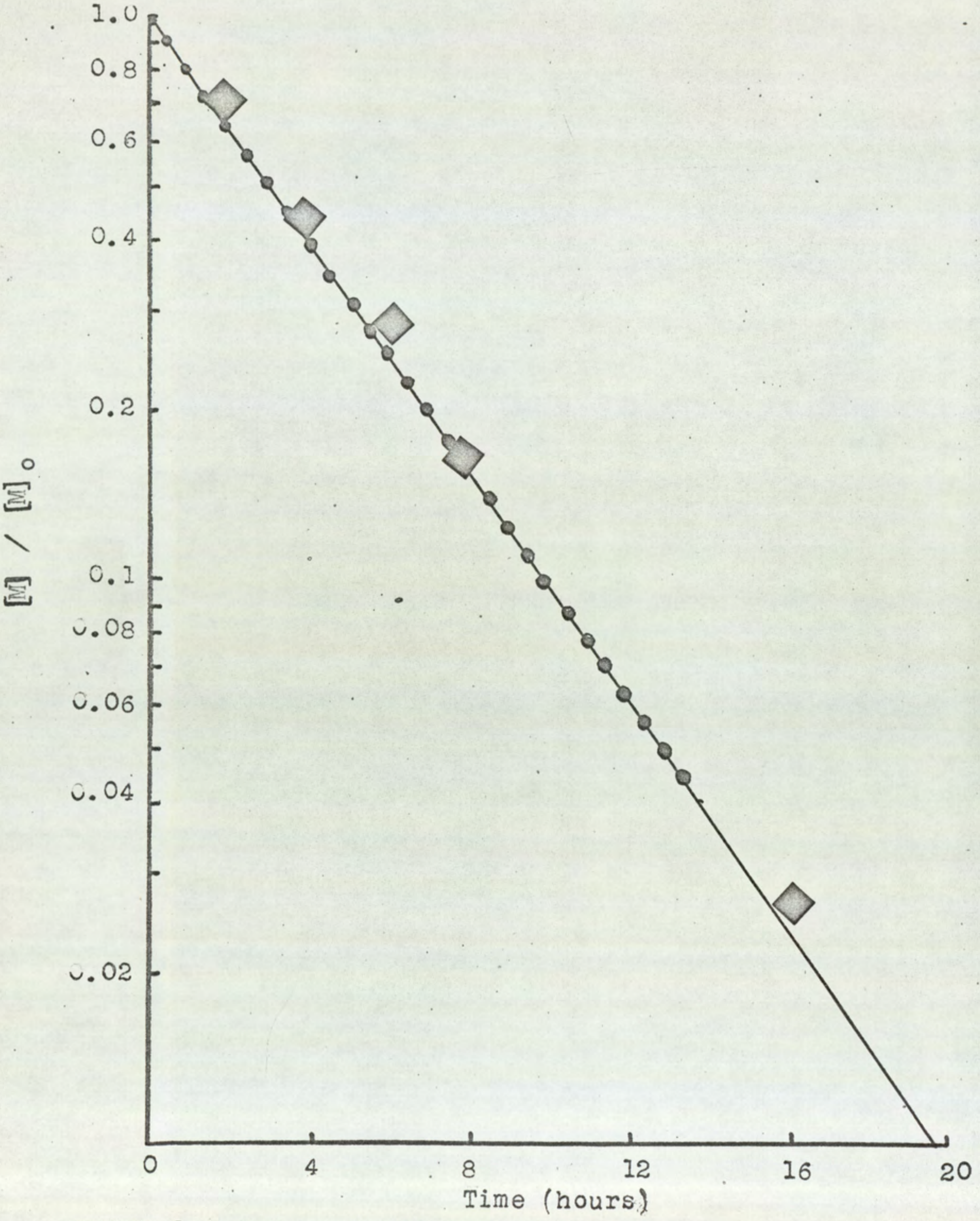


FIGURE 18. Polymerisation of AHIBAS in nitrobenzene at 90.8°C. Comparison of gas evolution measurements with gravimetry. $[M]_o$, $1.5 m.l^{-1}$. Ffaction of monomer remaining plotted logarithmically vs. time. Gas evolution measurements (●); Gravimetry (◇).

Effect of Temperature on the Reaction

The rate of decomposition of the anhydrosulphite was studied in nitrobenzene and benzyl alcohol at temperatures between 65° and 95°C, first order kinetic behaviour being shown throughout the range. The relevant first order velocity coefficients are collected in Table 11, together with the Arrhenius activation energy(E) calculated over the temperature range and collision number(A) at 90°C.

TABLE 11

Kinetic data relating to the polymerisation of AHIBAS in nitrobenzene and benzyl alcohol.
Dependence of velocity coefficient on temperature.

Temperature (°C)	Reaction Medium	Velocity Coefficient (sec^{-1})	Activation Energy ($kcal.mole^{-1}$)	Collision Number ($l.mole^{-1}sec^{-1}$)
65	Nitrobenzene	3.9×10^{-6}	-	-
90	Nitrobenzene	6.1×10^{-5}	27.5	2.2×10^{12}
95	Nitrobenzene	10.0×10^{-5}	-	-
85	Benzyl Alcohol	2.8×10^{-5}	-	-
90	Benzyl Alcohol	5.5×10^{-5}	25.0	5.5×10^{10}
95	Benzyl Alcohol	8.0×10^{-5}	-	-

Heterogeneous Polymerisation

In the course of studies of the decomposition of α-hydroxy isobutyric acid anhydrosulphite, the reaction of the material in bulk was examined. During the decomposition a marked acceleration was noticed at a point corresponding

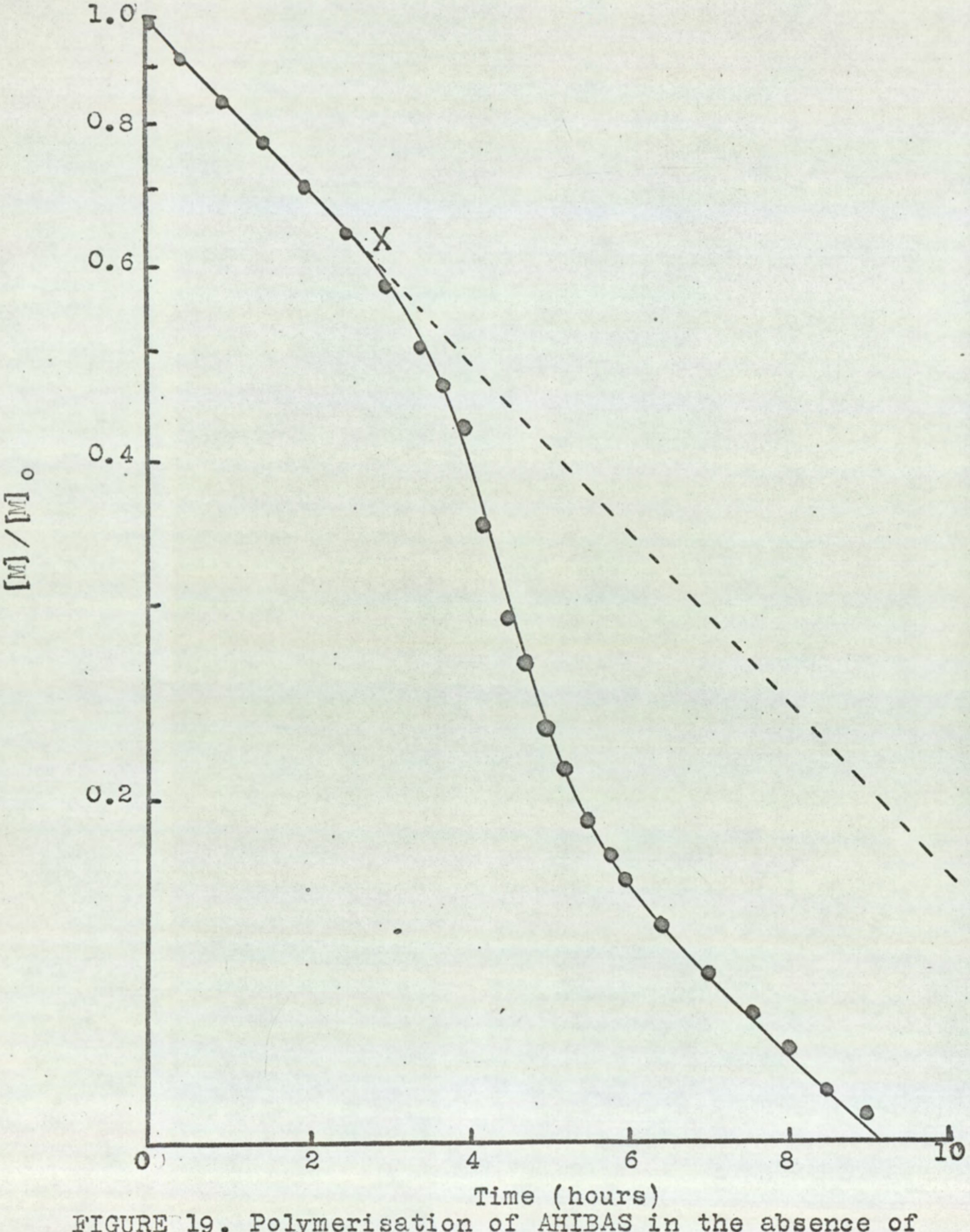


FIGURE 19. Polymerisation of AHIBAS in the absence of added solvent at 90°C. Fraction of monomer remaining (undecomposed) plotted logarithmically as a function of time.

$[M]_o \simeq 7 \text{ mole.l}^{-1}$

to precipitation of polymer from solution. Figure 19 shows a typical example of this type of behaviour. The figure presents the relationship $\log\frac{[M]}{[M]_o}$ vs. time for the decomposition of α-hydroxy isobutyric acid anhydrosulphite, in the absence of added material, at 90°C.

The point X, at which a sudden acceleration occurs, corresponds to the precipitation of polymer from solution. Similar behaviour was encountered when non-polar liquids such as dekalin and α-methyl naphthalene were used as reaction media.

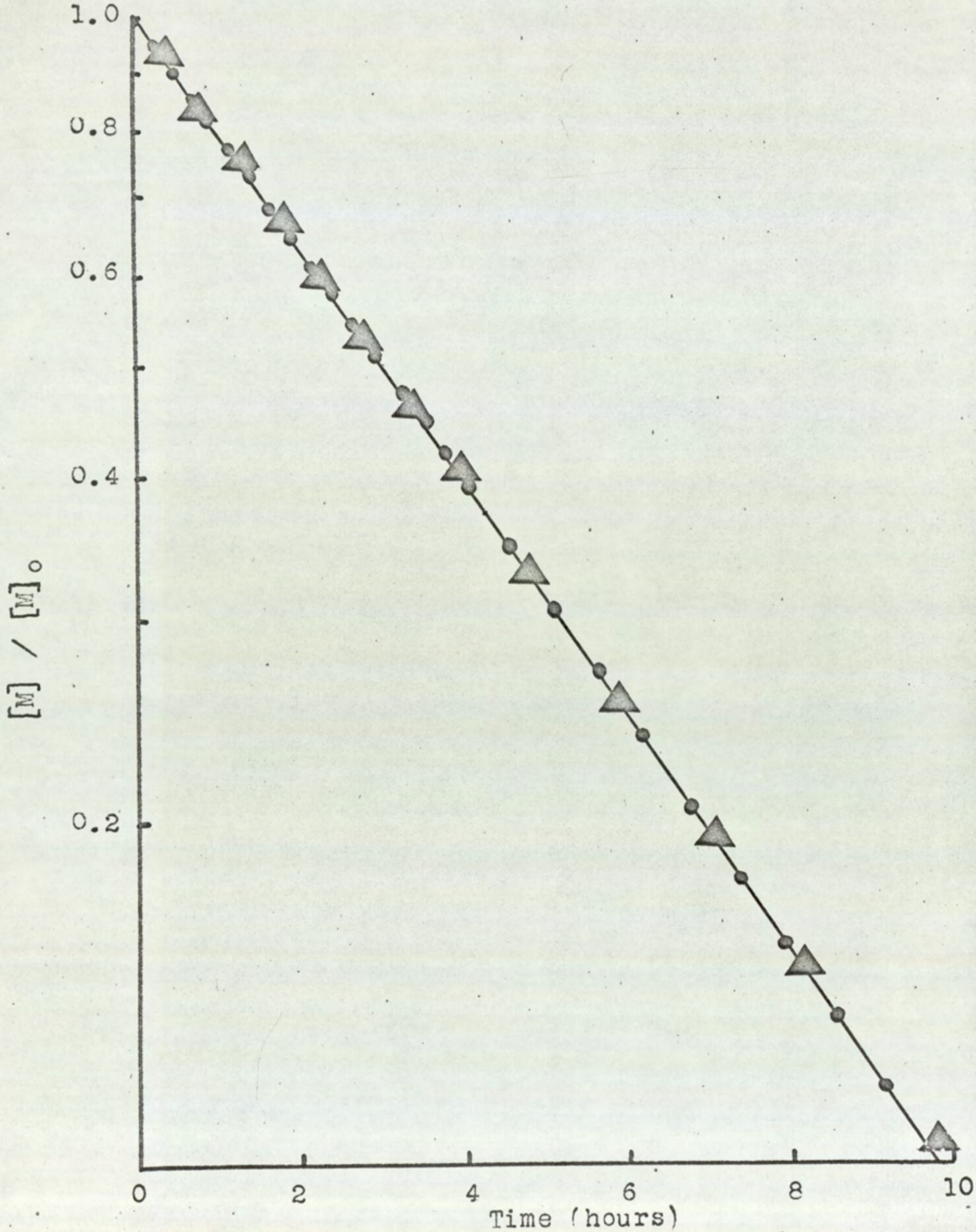


FIGURE 20. Decomposition of AHIBAS in nitrobenzene at 90°C. Effect of added benzoyl peroxide (B.P.). Fraction of monomer remaining (undecomposed) plotted logarithmically as a function of time.
(●) $[M]_o$, 1.0 m.l^{-1}. no added peroxide.
(▲) $[M]_o$, 1.0 m.l^{-1}. [B.P.], 0.05 m.l^{-1}.

5:3 Reaction with Miscellaneous Compounds - Experimental Observations

In an attempt to find alternative methods of initiation, the reaction of the anhydrosulphite with a wide variety of substances was studied. Compounds within the general classes of free radical and anionic initiators appeared to exert no marked influence on the rate of decomposition of the monomer. Cationic initiators of certain types, however, accelerated the decomposition considerably.

The rapid reaction of amines and water with the anhydrosulphite has been previously mentioned. In the reaction with water ∝-hydroxy isobutyric acid was formed. If excess anhydrosulphite is used the acid produced is found to exert no effect on the subsequent rate of decomposition. Similarly, in the case of amines, although the rate of the initial reaction between amine and anhydrosulphite depends on the nature and concentration of the amine, when excess anhydrosulphite is present, its subsequent rate of decomposition is not affected.

Further experimental data are included, where relevant, below.

Reaction with Peroxides

Several kinetic investigations of the effect of methyl ethyl ketone peroxide on the rate of decomposition of ∝-hydroxy isobutyric acid anhydrosulphite in the temperature range 25° - 60°C were made. The results indicated that the rate of decomposition was not affected.

Experiments were carried out using benzoyl peroxide in the higher temperature range (i.e. 65°-90°C). The rate of decomposition of the anhydrosulphite in nitrobenzene (1 mole/litre) in the presence of benzoyl peroxide (0.05 mole/litre) was determined at 90.8°C. The relevant plot of $\log\frac{[M]}{[M]_0}$ vs. time is shown in Figure 20.

Comparison of the first order velocity coefficient with that obtained for pure anhydrosulphite in nitrobenzene at the same temperature indicates that the presence of peroxide did not affect the rate of decomposition.

Reaction in the Presence of Cationic and Anionic Initiators

It is known that lithium chloride in N.N dimethyl formamide and sodium methoxide will initiate NCA polymerisation. These, together with various other compounds, were examined as potential initiators for ∝-hydroxy isobutyric acid polymerisation. Qualitative investigations indicated that lithium bromide in dimethyl formamide and sodium methoxide in benzene did not affect the rate of decomposition of the anhydrosulphite. Anhydrous aluminium trichloride and other compounds which show activity as cationic initiators for the polymerisation of various vinyl monomers were found to exert a marked effect, however. A fairly detailedinvestigation of such systems was carried out, the main object being to find conditions which favoured the rapid formation of high molecular weight polymer from ∝-hydroxy isobutyric acid anhydrosulphite.

Strong acids such as sulphuric, orthophosphoric and trichloracetic brought about rapid decomposition of the anhydrosulphite, especially in the presence of moisture. In each case the rate of sulphur dioxide evolution increased with increase in temperature and initiator concentration. In all cases only low molecular weight products were formed, a fair proportion of which was found to be ∝-hydroxy isobutyric acid. The nature of the reaction products varied to some extent with the initiating system used, but high molecular weight polymer was not formed with any of those examined.

Anhydrous ferric chloride, aluminium trichloride, aluminium tribromide and antimony pentachloride were examined,

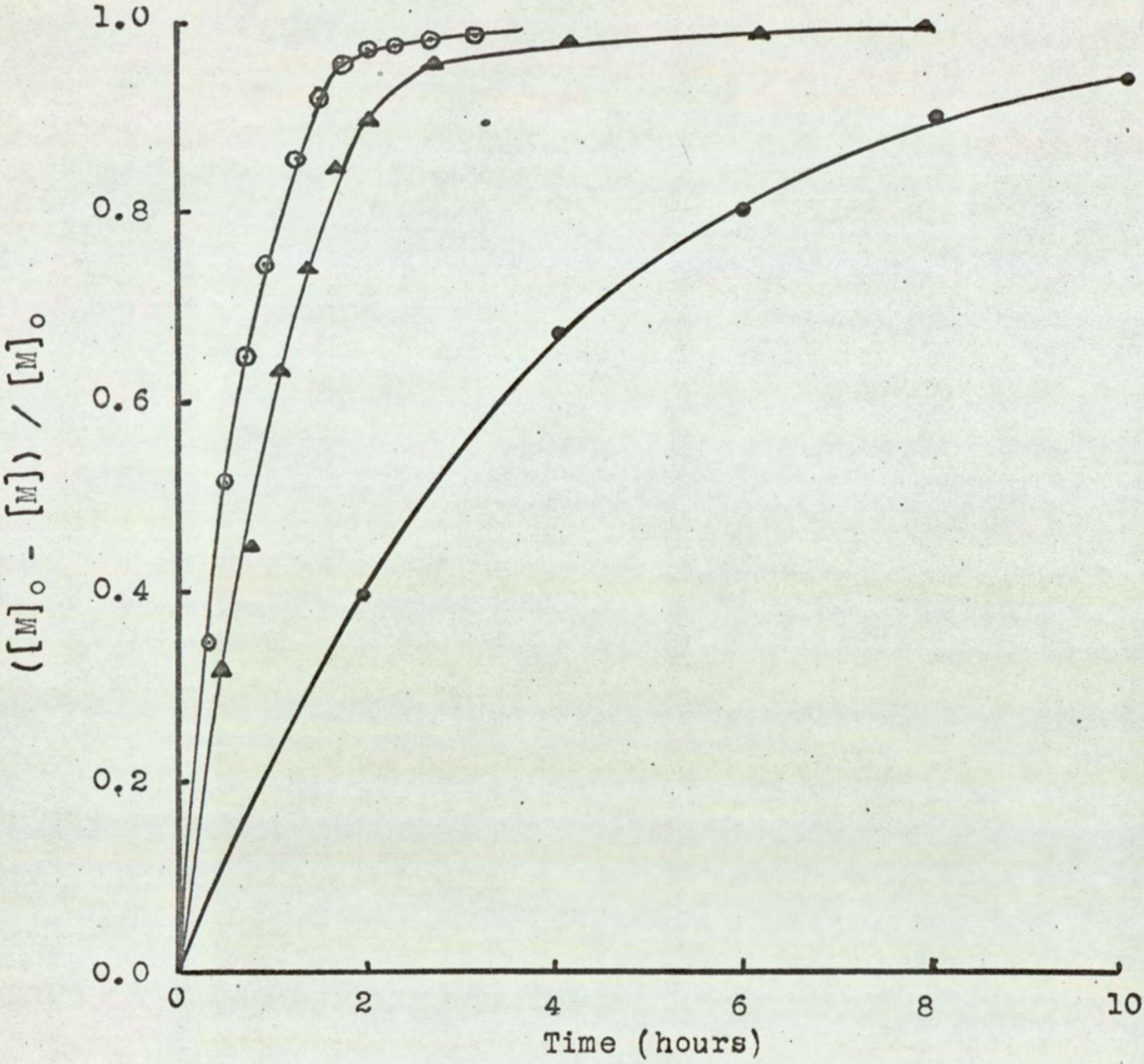


FIGURE 21. Rate of decomposition of AHIBAS in nitrobenzene at 90°C. Effect of added anhydrous aluminium chloride.

⊙, $[M]_o$, 0.25 $m.l^{-1}$.; $[Al_2Cl_6]$, 0.05 $m.l^{-1}$.

▲, $[M]_o$, 0.25 $m.l^{-1}$.; $[Al_2Cl_6]$, 0.033 $m.l^{-1}$.

●, $[M]_o$, 0.25 $m.l^{-1}$.; $[Al_2Cl_6]$, nil.

each being used both alone and together with a co-catalyst, such as water or acetyl chloride. Results were similar for most systems used, those involving aluminium trichloride or ferric chloride were, however, noticeably more effective in the rapid formation of solid products. The rate of decomposition of the anhydrosulphite increased with temperature and catalyst/co-catalyst concentration.

The effect of anhydrous aluminium trichloride concentration on a solution of α-hydroxy isobutyric acid anhydrosulphite in nitrobenzene at 90°C is demonstrated in Figure 21. Experimental observations relating to the effect of aluminium chloride on the anhydrosulphite in bulk at 0°C are shown in Table 12.

In each case the aluminium chloride was resublimed before use, all further manipulations being carried out in the dry box. Reaction products were precipitated by addition to excess benzene/methanol (2:1 v/v) at room temperature.

Examination of the reaction products obtained at 0°C (Table 12) showed that their properties were quite different from Alderson's polymer. The material showed quite marked thermal stability, tending to decompose at temperatures above 350°C without a distinct melting point. It was only barely soluble in chlorophenols even at temperatures in the region of 100°C. Furthermore, all samples had a chloride content of approximately 5%. The infra red spectrum of the material was determined by the potassium bromide disc technique and is shown in Figure 22(a) with the spectrum of Alderson's polymer for comparison (Figure 22b). The spectrum of material produced from the ferric chloride/anhydrosulphite system was determined and found to be similar.

Chemical analysis showed the presence of iron in ferric chloride catalysed reaction products and aluminium

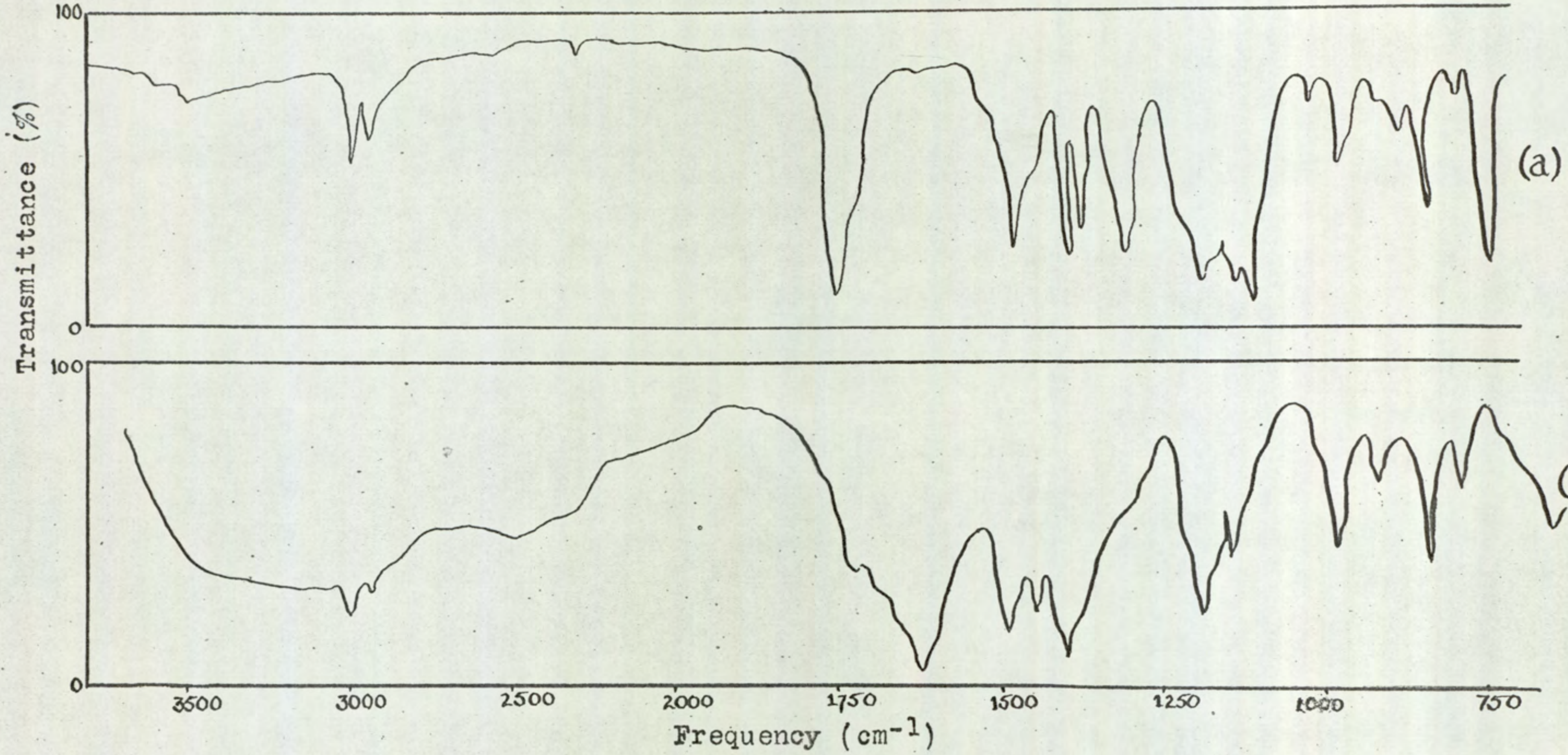


FIGURE 22. Infra red spectra (KBr disc) of AHIBAS 'polymers'. (a) Produced by Alderson's technique. (b) Prepared at 0°C (reaction time 10 hrs.) in the presence of anhydrous aluminium chloride.
$[Al_2Cl_6]$, 0.25 m.l^{-1}.; AHIBAS undiluted.

in those formed in the presence of aluminium chloride. It was decided that the products were organo-metallic complexes and, as such, outside the scope of the present work. Further examination of these systems was, therefore, not undertaken.

TABLE 12

Reaction of (undiluted) AHIBAS with anhydrous aluminium chloride at 0°C. Reaction time 70 hours*.

AHIBAS (grm)	Aluminium Chloride (grm)	Aluminium Chloride (%)	Weight of Solid Products (grm)	Conversion (%)
2.0	-	-	-	-
2.0	0.010	0.5	0.034	1.7
2.0	0.024	1.2	0.086	4.3
2.0	0.048	2.4	0.170	8.5
2.0	0.090	4.5	0.300	15.0

* By this time all samples containing aluminium chloride were completely gelatinous.

5:4 Evidence Relating to the Formation of Radicals

Reaction with Styrene

The effect of adding small amounts (0.5 - 5% by weight) of α-hydroxy isobutyric acid anhydrosulphite to redistilled styrene on the rate of polymerisation of the latter was studied by dilatometry. Experiments were carried out in the presence and absence of benzoyl peroxide; the observed effects, although not marked, were reproducible.

Table 13 shows the % conversion of styrene to polymer at 75°C in the presence of benzoyl peroxide and the anhydrosulphite. Polymerisations were carried out in bulk.

TABLE 13

Polymerisation of (undiluted) styrene at 75°C in the presence of benzoyl peroxide and AHIBAS

Benzoyl Peroxide Concentration ($mole.l^{-1}$)	Anhydrosulphite Concentration ($mole.l^{-1}$)	Reaction Time (hrs)	Conversion to Polymer (%)
nil	nil	1	2.5
nil	6.6×10^{-2}	1	3.6
4.13×10^{-2}	nil	1	15.8
4.13×10^{-2}	6.6×10^{-2}	1	16.8
nil	nil	2	5.1
nil	6.6×10^{-2}	2	7.2
4.13×10^{-2}	nil	2	32.5
4.13×10^{-2}	6.6×10^{-2}	2	34.7

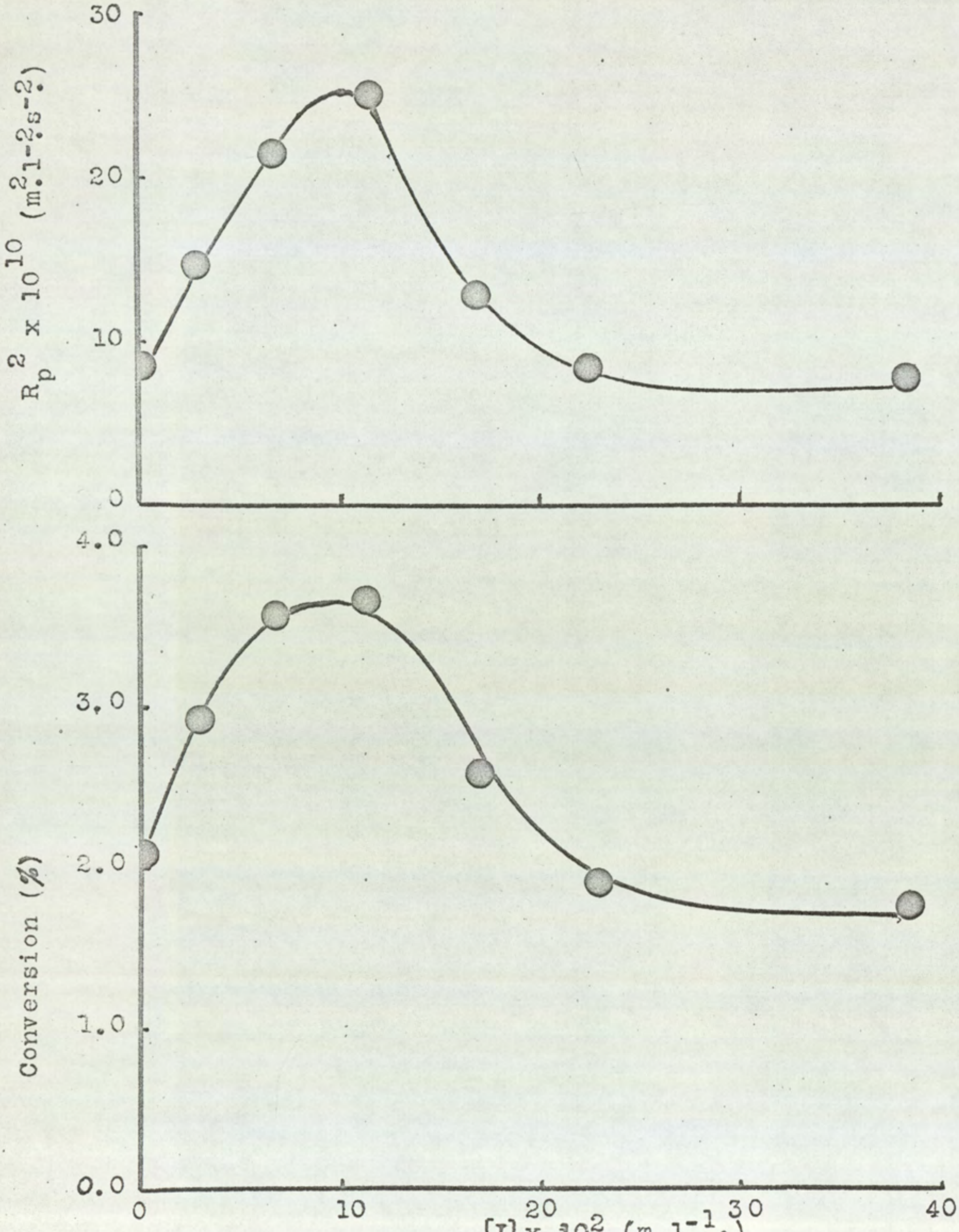


FIGURE 23. Bulk polymerisation of styrene at 80°C in the presence of AHIBAS.
(a)-upper diagram - Variation in rate of polymerisation (R_p) with AHIBAS concentration [I], $(R_p)^2$ being plotted as a function of [I].
(b)-lower diagram - Extent of conversion (%) in 2hr. plotted as a function of [I].

Figure 23(a) shows the variation in rate of polymerisation of (undiluted) styrene with changing ∝-hydroxy isobutyric acid anhydrosulphite concentration at 80°C and Figure 23(b) relates the extent of conversion after two hours under the same conditions.

Effect of U.V. Light on the Anhydrosulphite

The use of a manometer with quartz reaction vessel attached enabled the effect of U.V. radiation on the rate of decomposition of the anhydrosulphite to be investigated. A 250 watt Mazda mercury vapour lamp was employed with samples normally placed 30 cm away from the source.

The effect of a five minute exposure period on the rate of decomposition at 25°C, 65°C and 90°C was examined by observing the rate before exposure, placing the apparatus in front of the light source for five minutes and finally replacing it in the thermostat and observing the rate after allowing thermal equilibrium to be attained.

At 25°C the rate of decomposition was infinitesimally slow both before and after irradiation and in the experiments at 65°C no marked effect was observed. At 90°C, however, a fairly substantial increase in rate (nearly two-fold) was noticed subsequent to irradiation. The products of the reaction appeared to be of abnormally low molecular weight, suggesting that the mode of anhydrosulphite decomposition was in some way affected.

The fact that, judged by other photochemical reactions, the effect of U.V. light was not great, coupled with the possibility of abnormal decomposition and the difficulty of providing adequate temperature control during irradiation, suggested that detailed experimental investigation would be of little value in the present work.

Effect of Benzoquinone and 2.2-Diphenyl - 1-Picryl Hydrazyl

It has been noted that addition of benzoquinone to systems containing α-hydroxy isobutyric acid anhydrosulphite resulted in diminished yield and molecular weight of final product. This effect had, however, been observed with a variety of other impurities and could not, in itself, be taken as necessarily significant.

The stable free radical 2.2-diphenyl-1-picryl hydrazyl has been frequently used in detecting and counting radicals, although the results are not always susceptible to unequivocal interpretation. The reagent, which is violet in colour, reacts with radicals and in so doing is converted to a form which is yellow.

In the course of preliminary trials, D.P.P.H. was added to a solution of the anhydrosulphite under normal polymerisation conditions at 90°C; a fairly rapid loss of colour was noted.

Further experiments would be necessary in order to determine whether radical formation is responsible, especially in view of the fact that thionyl chloride and certain sulphoxides were observed to effect a similar decolourisation.

5:5 Examination of Reaction Products

Alderson reported that scrupulously anhydrous conditions were necessary in the formation of high molecular weight polymer from the anhydrosulphite. This, and other factors influencing the characteristics and yield of polymer were examined, the results being presented below and in Section 5:6. This Section (5:5) is concerned with the use of chemical and physico-chemical techniques and Section 5:6 with radiochemical studies.

Effect of Initial Hydroxyl Group and Anhydrosulphite Concentration on Resultant Polymer

Having established that traces of moisture react rapidly with the anhydrosulphite to form ∝-hydroxy isobutyric acid and that the acid formed had no effect on the subsequent rate of decomposition of the material, an investigation of the effect of added ∝-hydroxy isobutyric acid on the intrinsic viscosity and melting point of the polymer formed in the reaction was undertaken. Table 14 presents data for the polymerisation of the anhydrosulphite in nitrobenzene (concentration 1.65 moles/litre) in the presence of added hydroxy acid. Other hydroxy compounds were examined and found to exert a similar effect. It is relevant to compare the product of polymerisation carried out in nitrobenzene with that in benzyl alcohol. Although the kinetic data relating to the decomposition (Table 11) are comparable the products of the reaction are not. Thus polymer is formed in the first case and benzyl ∝-hydroxy isobutyrate in the second.

TABLE 14

Polymerisation of AHIBAS in nitrobenzene at 90°C. Effect of added ∝-hydroxy isobutyric acid on the intrinsic viscosity [η] and melting point (T_m) of the final polymer. Reaction time 24 hours.

∝-Hydroxy Isobutyric Acid Concentration (mole.l^{-1})	Anhydrosulphite Concentration (mole.l^{-1})	T_m (°C)	[η] dl.g^{-1}
0.200	1.65	Oil	-
0.150	1.65	93/8	-
0.100	1.65	120/5	0.05
0.075	1.65	135/9	0.09
0.050	1.65	170/4	0.11
0.025	1.65	175/9	0.14

Effect of Other Impurities on Polymerisation Products

Impurities other than water were observed to affect the molecular weight of polymer formed in anhydrosulphite polymerisations. The chlorine containing impurity associated with the anhydrosulphite of ∝-hydroxy isobutyric acid has been shown (Section 3:1) to be ∝-chloro isobutyryl chloride. Its presence was demonstrated to prevent the formation of high molecular weight polymer (Table 15).

Polymerisations were carried out in bulk in sealed vessels, the anhydrosulphite being prepolymerised under reduced pressure (approximately 10% conversion) and distilled into the reaction vessel which was then sealed off. The entire operation was carried out with the system attached to a vacuum line to avoid inclusion of atmospheric moisture. After polymerisation (to about 40% conversion) a portion of the undecomposed anhydrosulphite was removed by distillation at reduced pressure and the experiment repeated twice.

Chlorine contents were determined on the anhydrosulphite before polymerisation and on the resultant polymer (after hydrolysis with alcoholic potassium hydroxide). Their relative magnitude is obviously more reliable than the absolute values obtained. The results provide further confirmation of the ineffectiveness of prepolymerisation as a means of completely removing chloride containing impurities.

TABLE 15

Effect of chloride containing impurities on the polymer produced from the polymerisation of undiluted AHIBAS at 90°C.

AHIBAS Chlorine Content (%)	AHIBAS Conversion to Polymer (%)	Polymer-Chlorine Content (%)	Polymer T_m (°C)	Polymer M_n(V.P.O)
2.2	~40	~0.2	165/9	1,000
1.0	~40	~0.09	172/6	2,300
0.5	~80	~0.06	176/9	4,200

Effect of Reaction Time on Molecular Weight of Polymer

An investigation of the effect of reaction time on conversion of the anhydrosulphite to polymer has been described (Section 5:2). The results show that rate of polymer formation parallels the rate of sulphur dioxide evolution. The variation of molecular weight with time during the polymerisation reaction was also investigated using the same technique. Polymerisations carried out in solvents (nitrobenzene and dekalin) and undiluted anhydrosulphite (i.e. bulk polymerisation) indicated that the molecular weight changed by less than a factor of two after 30% conversion. More precise experiments were performed using radiotracer techniques. These are presented in Section 5:6.

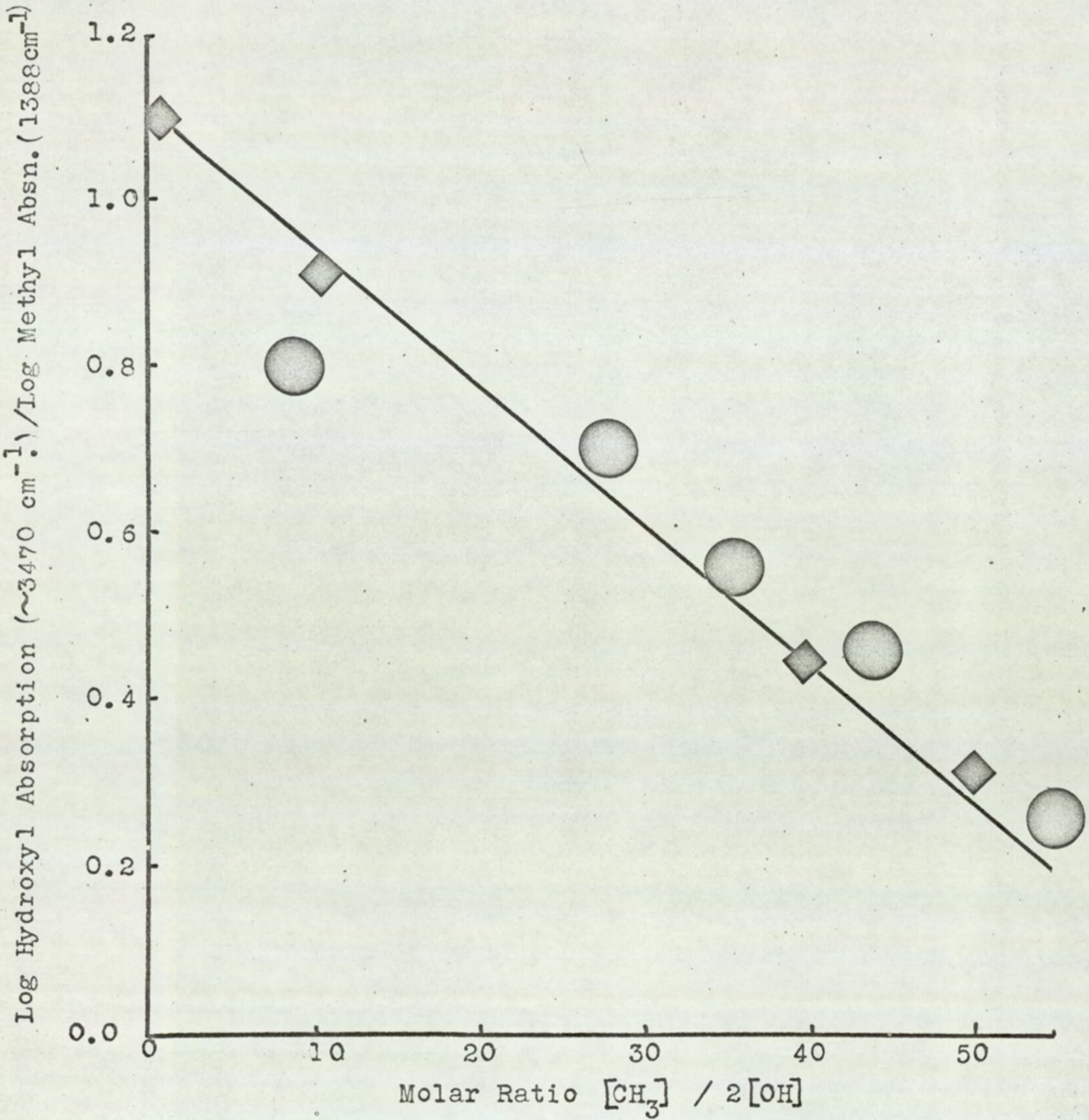


FIGURE 24. Variation in intensity of hydroxyl (~3470 cm.$^{-1}$) absorption peak relative to methyl (1388 cm.$^{-1}$) for a series of AHIBAS polymers of known $\overline{M}_n$ (VPO). The molecular weights are expressed in terms of the molar ratio $[CH_3]/2[OH]$. The results obtained with mixtures of a polymer of known molecular weight ($\overline{M}_n$, 5.5×10^3) and α-hydroxy isobutyric acid are presented for comparison.

●, Polymer samples

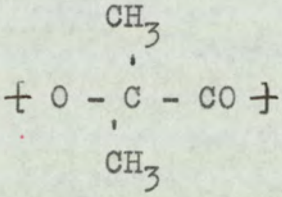
◆, Mixtures of hydroxy acid and polymer

The stability of the ∝-hydroxy isobutyric acid polymer to molecular weight changes was investigated under normal reaction conditions,(i.e. 50 hours at 90°C). Samples of polymer were heated in the various solvents used in polymerisation experiments, in the presence and absence of added hydroxyl group containing materials. Even when the reaction time was increased to 250 hours no evidence of molecular weight change was encountered.

The Structure of the Polymer : Infra Red Spectrum

The infra red spectra obtained from various polymer samples (e.g. Figure 22b) are consistent with the expected structure of the repeat unit

i.e.



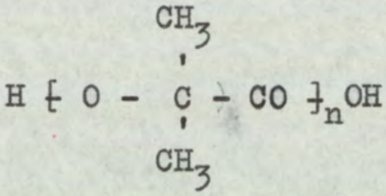
$$\left[O - \underset{CH_3}{\overset{CH_3}{C}} - CO \right]$$

The evidence concerning the nature of the end groups is, however, less conclusive. The variation in intensity of the hydroxyl absorption peak (3470 cm^{-1}) with polymers of various molecular weights (VPO) is qualitatively consistent with the presence of hydroxyl end groups.

An estimation of the variation in intensity of the hydroxyl absorption relative to one of the methyl absorption peaks (1388 cm^{-1}) was made for several polymers of known molecular weight. The figures were compared with those for intimate mixtures of ∝-hydroxy isobutyric acid and a polymer of $\bar{M}n = 5.5 \times 10^3$ in varying quantities. The result of both series are shown graphically in Figure 24 in which $\frac{\log(-OH\ absorption)}{\log(-CH_3\ absorption)}$ determined from infra red spectra is plotted against the molar ratio $\frac{[-CH_3]}{2[-OH]}$ calculated from molecular weights of polymers and composition of mixtures. The results are also included, for comparative purposes, in Table 16.

Nuclear Magnetic Resonance Studies

Solutions of the polymer in β-ethoxy ethyl acetate were studied at 60 Mc/sec. The methyl absorption shift observed was characteristic of the environment:



$$H\left[O-\overset{CH_3}{\underset{CH_3}{C}}-CO\right]_nOH$$

One further proton absorption was observed which was attributed to total hydroxyl resonance. On the basis of the relative intensities of the methyl and hydroxyl absorption and assuming (for the purposes of calculation) that all chains are hydroxyl and carboxyl terminated, a number average molecular weight was assigned to each polymer studied. The results are compared with those obtained by other methods in Table 16.

Determination of Carboxyl Concentration - End Group Titration

Several techniques were examined, the requirement being: a non-acidic solvent which was miscible with the titrant; a titrant which did not cause precipitation of the polymer and a sharp and distinct end point.

Most satisfactory results were obtained with β-ethoxy ethyl acetate or tetrahydrofuran as solvent and dilute alcoholic potassium hydroxide as titrant. End points were determined with phenolphthalein or potentiometrically. Results, based on the assumption that each chain has one carboxyl end group, are presented in Table 16.

Molecular Weight Determination - Vapour Pressure Osmometer

Determinations were carried out in β-ethoxy ethyl acetate solution at 37°C and tetrahydrofuran solution at

25°C. Each solvent/temperature system was calibrated using recrystallised benzil. Solutions of known molar concentration (m) were made up, ΔR values being determined for each by the method mentioned in Section 2:1 and fully described in the manufacturer's literature. A plot of $\frac{\Delta R}{m}$ vs. m gave an intercept, $\left(\frac{\Delta R}{m}\right)_{m=o}$, corresponding to the calibration factor (or 'k' value). Polymer samples of unknown molecular weight were treated similarly (the concentration, c, being expressed in grams/litre). Values of $\left(\frac{\Delta R}{c}\right)_{c=o}$ were obtained and the molecular weight calculated $\left(\bar{M}n = \frac{k}{\left(\frac{\Delta R}{c}\right)_{c=o}}\right)$

The values of $\bar{M}n$ obtained for a series of polymers are compared with those given by other methods in Table 16.

TABLE 16

Low molecular weight polymers of AHIBAS: comparison of molecular weight and end-group data. Relevant data given in text.

V.P.O. ($\bar{M}n \times 10^{-3}$)	N.M.R. ($\bar{M}n \times 10^{-3}$)	[COOH] Titration ($\bar{M}n \times 10^{-3}$)	Infra Red $\left(\frac{\log(OH)abs.}{\log(CH_3)abs.}\right)$
0.1	0.1	0.1	1.1
0.9	0.8(8)	0.9(2)	0.79
1.1	-	1.4	-
2.7	-	-	0.65
3.5	3.3	3.7	0.56
4.4	-	4.2	0.45
5.5	-	-	0.27

5:6 The Role of Hydroxyl Groups in the Reaction : Radio-Chemical Studies

The size of polymers studied by the techniques referred to in Section 5:5 was to some extent limited by the sensitivity of the methods involved. More detailed evidence concerning the extent and efficiency of incorporation of traces of moisture in the polymerisation was required particularly in relation to higher molecular weight polymers. The radio-tracer studies described here were designed to supply this evidence.

It has been established (Section 5:1) that traces of moisture react rapidly with the anhydrosulphite to regenerate ∝-hydroxy isobutyric acid. This in turn is involved in the subsequent polymerisation of anhydrosulphite in a manner which does not affect its rate of decomposition (Section 5:2) but controls the molecular weight of polymer formed (Section 5:5).

To enable this reaction to be studied in more detail a sample of ∝-hydroxy isobutyric acid in which the carbonyl carbon atom was partially replaced by the C^{14} isotope was prepared. The acid was synthesised by the conventional cyanohydrin route from acetone and labelled potassium cyanide. The activity of samples containing labelled acid and the acid itself were determined by the liquid scintillation counting technique described in Section 2:1.

In the subsequent polymerisation reactions involving the acid, the following experimental procedures were adopted:

All glass apparatus to be used was baked for several hours at 120°C, transferred to the dry box and allowed to cool. All solvents were rigorously dried and distilled at reduced pressure before use, as was the anhydrosulphite, on the Buchi spinning band column. The rotating fraction collector was connected to the volumn via a 10 mm

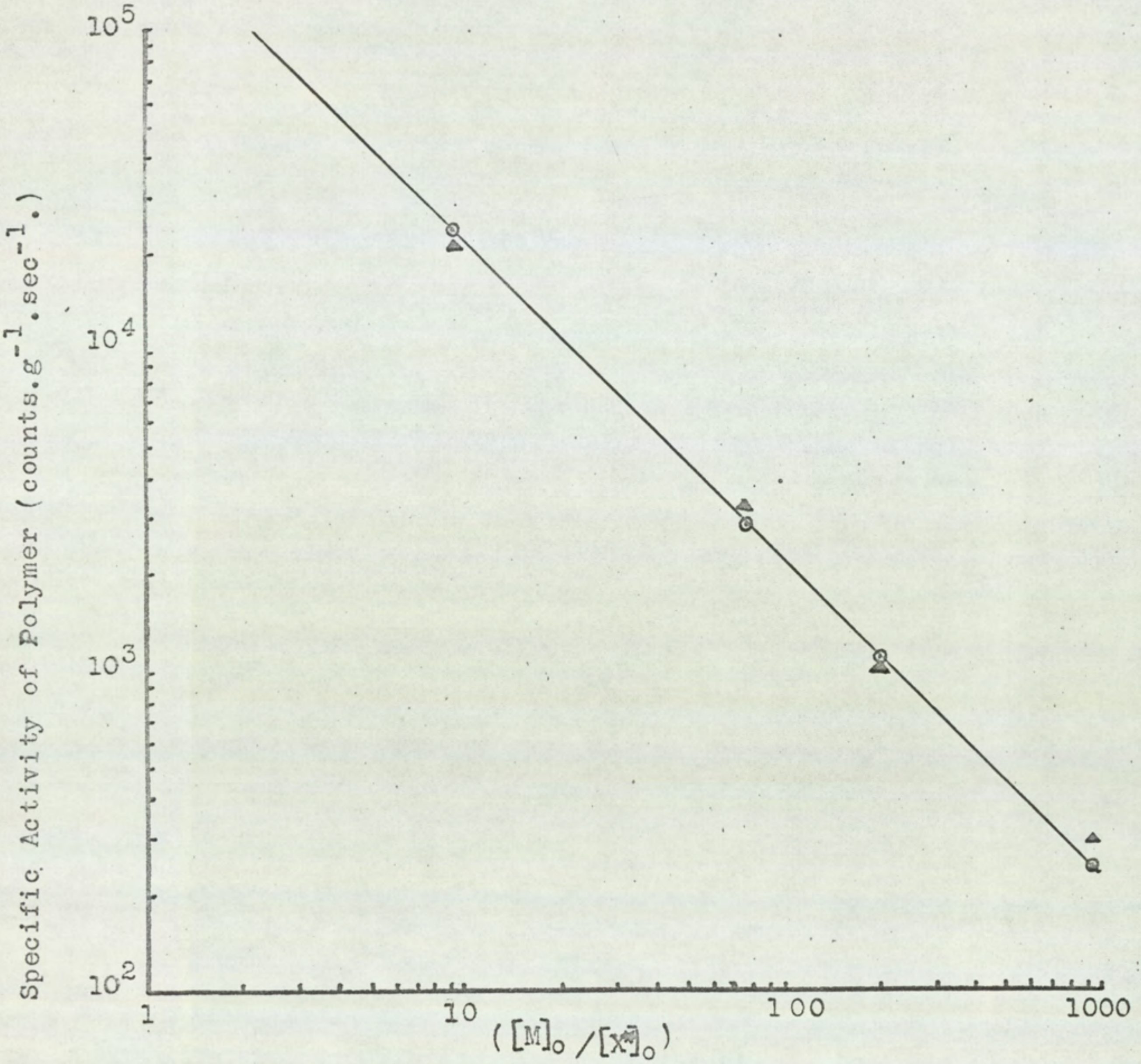


FIGURE 25. Polymerisation of AHIBAS in nitrobenzene at 90°C in the presence of active α-hydroxy isobutyric acid (X^*). Effect of initial $[M]/[X^*]$ ratio on specific activity of the final polymer.
$[M]_o$ 3.25 m.l^{-1}.; Sp. Acty. of added acid , 2.12 x 10^5 counts.g^{-1}.sec^{-1}.
▲, Experimental results
⊙, Theoretical values assuming all acid incorporated into polymer.
All data presented ,for convenience, on a log/log basis

vacuum tap which enabled it to be removed and transferred to the dry box without introducing atmospheric moisture. Weighings of the active acid, etc., were carried out by difference-containers being opened and material transferred only in the dry box.

Polymerisations were carried out in Carius tubes. These were removed from the dry box, evacuated and sealed on the vacuum line without contamination of the contents by the atmosphere. This was achieved by stoppering in the dry box with small cone /socket units interconnected by a vacuum tap.

Details of particular experiments and the results obtained are presented below:

Effect of Initial Concentration of Acid on Activity and Degree of Polymerisation of Final Polymer

Carius tubes containing solutions of the anhydrosulphite in nitrobenzene (3.25 moles/litre) and various (known) amounts of added acid were prepared. These were polymerised for 24 hours at 90°C and one (a duplicate) for 200 hours. The polymers were precipitated into excess methanol and washed with hot water to avoid occlusion of unreacted acid. Activities and molecular weights (V.P.O.) of the polymers were determined. The results are presented in Figures 25 and 26. It is apparent that in the range of acid concentration studied (3.5×10^{-3} - 0.35 moles/litre) the acid is quantitatively incorporated into the polymer during the course of the anhydrosulphite decomposition.

Furthermore the molecular weights of the resultant polymers were consistent with the view that when polymerisations are carried out in the presence of acid the chains are predominantly hydroxyl/carboxyl terminated.

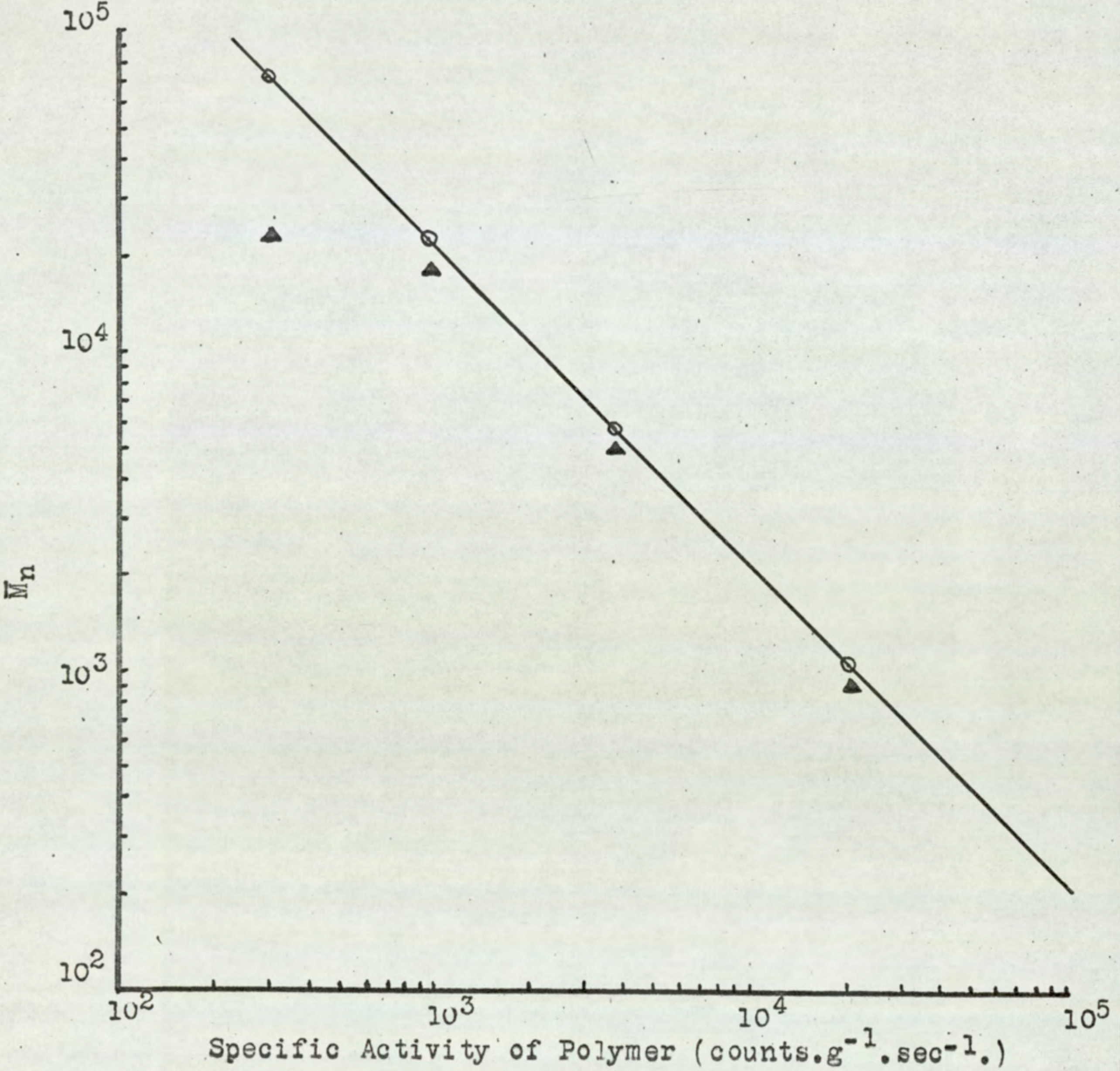


FIGURE 26. Polymerisation of AHIBAS in nitrobenzene at 90°C in the presence of active α-hydroxy isobutyric acid. Relationship of the specific activity of polymers produced to their number average molecular weight (VPO). Sp. Acty. of added acid, 2.12×10^5 counts.g^{-1}.sec^{-1}.

▲, Experimental results

⊙, Calculated values (based on the assumption that each polymer chain contains one active acid residue)

Note : The highest molecular weight recorded (2.3×10^4) was at the limit of the range of the VPO, the true value may have been somewhat higher.

Kinetic Studies involving Labelled Acid

Carius tubes containing identical samples of a solution of the anhydrosulphite and active acid in a dry solvent were prepared. The tubes were transferred to a 90°C thermostat and removed, individually, after various time intervals. The contents of the tube were made consolute with ethanol and precipitated into an excess of boiling water (the solution being introduced beneath the surface). The unreacted anhydrosulphite was thus converted to α-hydroxy isobutyric acid, occluding with it any unreacted active acid.

In this way the specific activity of the polymer and its cumulative activity, together with the total activity of uncombined acid at various times were obtained. Because of chemical quenching and the greater experimental difficulties in isolating α-hydroxy isobutyric acid, results based on determination of the activity of unreacted acid are less reliable than those relating to the activity of the polymer itself.

The former are plotted in the form $\log\frac{[X^*]}{[X^*]_0}$ vs. time and the latter $\log\frac{[P^*]_\infty - [P^*]}{[P^*]_\infty}$ vs. time

where $[X^*]$ is the total activity of unreacted acid at any time (t) and $[X^*]_0$ the initial activity. Similarly $[P^*]$ is the total activity of polymer formed at any time (t) and $[P^*]_\infty$ the final activity. It has been demonstrated in the preceding experiments (Figures 25 and 26) that in a closed system $[X^*]_0 = [P^*]_\infty$

Figure 27 shows plots of $\log\frac{[P^*]_\infty - [P^*]}{[P^*]_\infty}$ vs. time for polymerisations carried out in nitrobenzene and dekalin and Figure 28 a graph of $\log\frac{[X^*]}{[X^*]_0}$ vs. time for the reaction in dekalin.

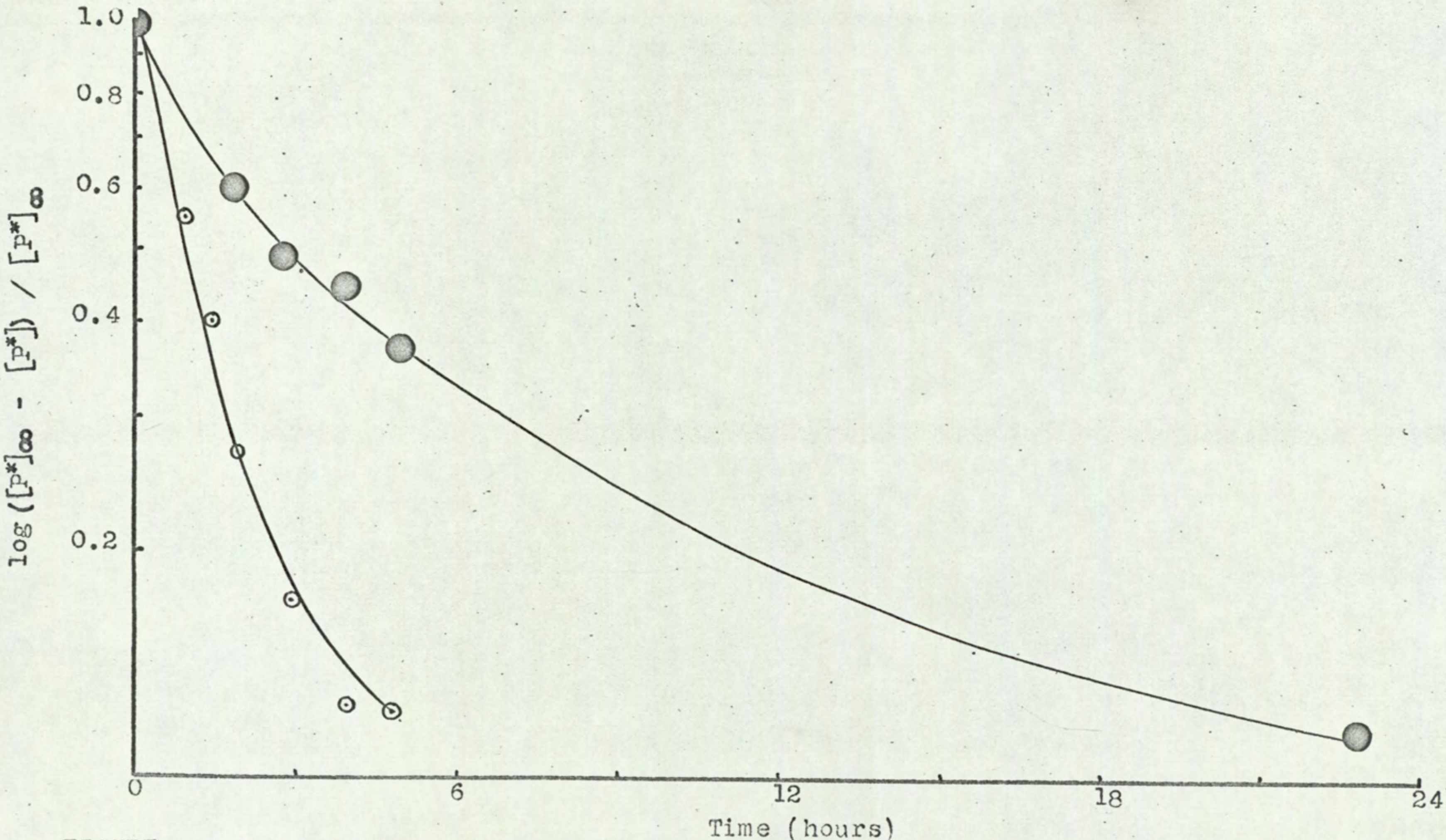


FIGURE 27. Polymerisation of AHIBAS at 90°C in the presence of labelled α-hydroxy isobutyric acid. Fraction of acid remaining uncombined - determined from total activity(P^*) of polymer formed - plotted logarithmically as a function of time.
⊙, in nitrobenzene, $[M]_o$, 3.3 $m.l^{-1}$.; $[X^*]_o$, 4.9×10^{-2} $m.l^{-1}$., sp. acty., 2.1×10^5 $cts.g^{-1}.s^{-1}$.
●, in dekalin, $[M]_o$, 4.0 $m.l^{-1}$.; $[X^*]_o$, 2.0×10^{-2}.

From a knowledge of the initial activity of the acid, and the specific activity of polymer formed at various times throughout the polymerisation, the variation in mean degree of polymerisation ($\overline{DP}$) with time can be calculated. The results pertaining to polymerisation in nitrobenzene and dekalin are presented in Tables 17a and 17b.

TABLE 17

Solution polymerisation of AHIBAS in the presence of labelled α-hydroxy isobutyric acid at 90°C. Variation in ($\overline{DP}$) with time conversion.

(a) In Dekalin: Initial AHIBAS Conc. 4.0 mole.l^{-1}
initial acid* conc. 2.0×10^{-2} mole.l^{-1}
sp.acty. 2.1×10^{5} counts $g.^{-1}$ $sec.^{-1}$

Time (hr)	Conversion (%)	Sp.Acty. of Polymer (Counts $g.^{-1}$ $s.^{-1}$)	$\overline{D.P.}$ of Polymer
2	14	2,900	72
3	21	2,600	81
4	27	2,200	95
5	33	2,100	100
23	80	1,200	175
80	100	1,100	190

Note: System became heterogeneous between 33% and 80% conversion.

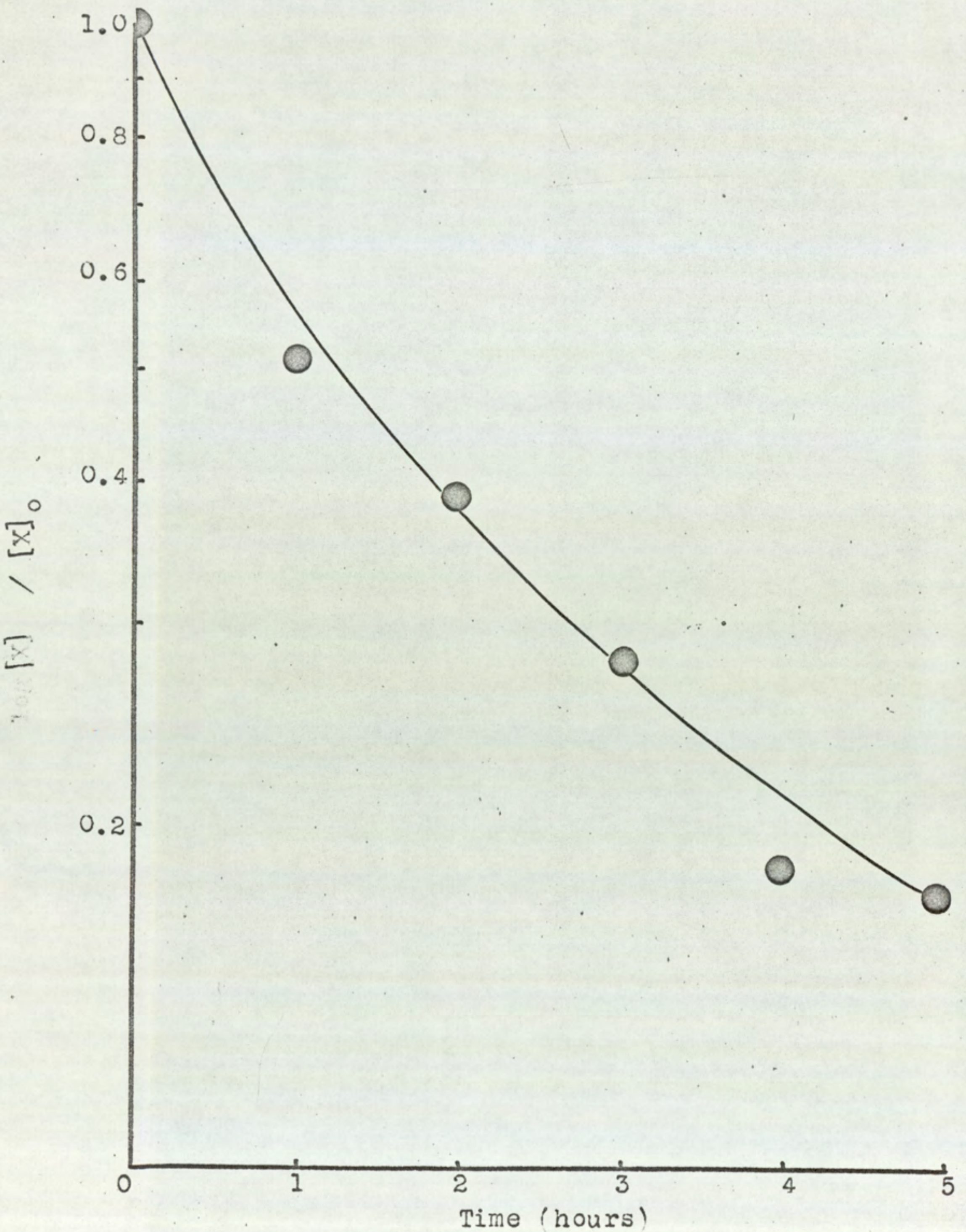


FIGURE 28. Polymerisation of AHIBAS in dekalin at 90°C in the presence of labelled α-hydroxy iso-butyric acid (X^*). Fractionof acid remaining (uncombined) - determined directly - plotted logarithmically as a function of time.
$[M]_o$, 4.0 $m.l^{-1}$.; $[X]_o$, 2.0 x 10^{-2} $m.l^{-1}$.
Sp. Acty. of added acid, 2.1 x 10^5 $cts.g^{-1}.s^{-1}$.

(b) <u>In Nitrobenzene</u>: Initial AHIBAS conc. 3.3 mole.l.$^{-1}$
initial acid* conc. 4.9 x 10^{-2}mole.l.$^{-1}$
sp.acty. 2.1 x 10^{5} counts g.$^{-1}$sec^{-1}

Time (hr)	Conversion (%)	Sp.Acty. of Polymer (Counts g.$^{-1}$ s.$^{-1}$)	$\overline{\text{D.P.}}$ of Polymer
1.0	17	9.600	22
1.5	24	9,000	23
2.0	30	8,500	25
3.0	42	7,000	30
5.0	60	5,500	38
24	100	3,560	59

6. POLYMERISATION OF α-HYDROXY ISOBUTYRIC ACID ANHYDROSULPHITE - DISCUSSION OF RESULTS

In the discussion of ring opening and polymerisation reactions of anhydrosulphites developed in Section 4:4 the rate of decomposition of the anhydrosulphite in the presence of hydroxy compounds was expressed as:

$$-\frac{d[M]}{dt} = (k_1 + k_2[OH])[M] \qquad (45)$$

Values of k_2 relating to bimolecular ring opening and propogation reactions of lactic acid anhydrosulphite were discussed but the magnitude of k_1 and the nature of the decomposition in the absence of hydroxyl groups were reserved for consideration here. The factors relating to this "thermal decomposition" will be discussed, together with the apparent absence of a bimolecular propogation reaction in $\alpha\alpha$-disubstituted anhydrosulphites.

Kinetic Features of the Bimolecular Ring Opening Reaction

Figures 8 and 14 show the rates of decomposition of lactic and α-hydroxy isobutyric acid anhydrosulphites respectively in the presence of benzyl alcohol, water and benzylamine under identical conditions. A qualitative comparison indicates that whereas the reaction of benzylamine and water is somewhat slower with the α-hydroxy isobutyric acid derivative than with the lactic, the reaction of benzyl alcohol is moderately slow in the latter case but apparently infinitesimally slow or completely non-existent in the former. The complexity of hydrolysis by water of similar compounds has been alluded to in Section 4:4. It is pertinent to note that even $\alpha\alpha$-disubstituted anhydrosulphites are attacked fairly rapidly, but more detailed conclusions from the data would be unwise. In comparing the rates of attack of benzylamine and benzyl alcohol on the two anhydrosulphites, it is interesting to note that the more nucleophilic amine is little affected by the introduction of a second methyl substituent into the substrate. The alcohol on the other hand, although of comparable overall size to the amine, is hindered to such an extent that carbonyl attack is apparently completely inhibited, the value of k_2 in this case approaching zero.

The reaction between benzyl alcohol and glycollic, lactic and α-hydroxy isobutyric acid anhydrosulphites at 90°C illustrates the susceptibility of this hydroxyl attack to steric hindrance. The results have been presented in Table 5 and Section 5.

The second order velocity coefficients (k_2) for the bimolecular reaction decrease in the order:

glycollic (3.7×10^{-4} litre.mole.$^{-1}$sec.$^{-1}$),
lactic (8.5×10^{-5} litre.mole.$^{-1}$sec.$^{-1}$),
α-hydroxy isobutyric ($\ngtr 5 \times 10^{-7}$ litre.mole.$^{-1}$sec.$^{-1}$).
In each case benzyl alcohol was used as the reaction medium.

The exact value of k_2 for α-hydroxy isobutyric acid anhydrosulphite is difficult to compute for the conditions indicated above. This is apparent from a comparison of the value of $(k_1 + k_2[OH])$ for the system with that obtained for lactic acid anhydrosulphite under the same conditions. In the former case $(k_1 + k_2[OH])$ is found experimentally to be 5.5×10^{-5} sec.$^{-1}$ where the value of k_1 (allowing for the effect of dielectric constant) is approximately 5.1×10^{-5} sec.$^{-1}$, while for the lactic acid derivative the values are 7.0×10^{-4} sec.$^{-1}$ and 0.06×10^{-4} sec.$^{-1}$ respectively. Uncertainties in the determinations and assessments involved in evaluating k_2 for α-hydroxy isobutyric acid anhydrosulphite make it impossible, from the present data, to state the value of k_2 more precisely than $\ngtr 5 \times 10^{-7}$ litre.mole.$^{-1}$sec.$^{-1}$.

It is important to notice, however, that this is merely an indication of the maximum value of k_2 that the data will allow; the absolute value may well be very much smaller, possibly zero. It is certainly true that at the level of hydroxyl concentration normally employed (i.e. below 0.5 mole/litre) $k_2[OH]$ is so small as to be kinetically undetectable (by the techniques employed here) in the presence of the thermal decomposition associated with k_1. Since polymerisation of anhydrosulphites by a bimolecular propogation reaction of the type discussed in Section 4 involves the attack of a hydroxyl terminated anhydrosulphite residue, it is clear that successive introduction of ∝-methyl substituents in the series glycollic, lactic, ∝-hydroxy isobutyric acid affects not only the substrate but also the bulk of the attacking reagent. Thus the polymerisation of ∝-hydroxy isobutyric acid anhydrosulphite takes place exclusively by the thermal initiation mechanism associated with k_1.

This absence of a hydroxyl initiated decomposition, be it complete or virtual, is seen here as a consequence of steric hindrance, a conclusion substantiated by experimental observations on the ring opening behaviour of lactic and glycollic acid anhydrosulphites.

Kinetic Features of the First Order 'Thermal Decomposition'

Experimental results presented in Section 5 demonstrated that the decomposition of α,α-disubstituted anhydrosulphites is kinetically first order and independent of the initial hydroxyl group concentration. Furthermore, the products of this decomposition are polymeric, the molecular weight of the material being in some way controlled by the concentration of moisture and certain other compounds which may be present. The nature of this reaction is in many ways distinct from the bimolecular ring opening and propagation reactions that have been previously discussed. The difference between the two processes (whose velocity coefficients are designated by k_1 and k_2 respectively) will now be considered in some detail.

The fact that the initial concentration of hydroxyl groups is not rate controlling in the decomposition of ∝-hydroxy isobutyric acid anhydrosulphite is illustrated by comparing the rate of reaction in benzyl alcohol with that in nitrobenzene. The velocity coefficient at 90°C in the latter solvent is 6.0×10^{-5} $sec.^{-1}$, whilst in benzyl alcohol at the same temperature it is somewhat lower (5.5×10^{-5} $sec.^{-1}$). These constants, together with those for other solvents, have been presented in Table 10.

The velocity coefficient observed in benzyl alcohol is consistent with the general trend in effect of dielectric constant on the reaction, although the possibility that its magnitude is in part due to a bimolecular decomposition has been previously mentioned. This decrease in velocity coefficient in passing from nitrobenzene to benzyl alcohol as reaction medium contrasts markedly with the behaviour observed for lactic acid anhydrosulphite. Here the comparable figures are 6.0×10^{-6} $sec.^{-1}$ (nitrobenzene) and 7.0×10^{-4} $sec.^{-1}$ (benzyl alcohol), this latter figure being the sum of a first order decomposition and a bimolecular hydroxyl attack. These figures have been considered previously; their relevance at this point is in emphasising the distinct nature of the reaction under discussion.

The energies of activation associated with the decomposition of ∝-hydroxy isobutyric acid anhydrosulphite are around 25 kcal/mole. The experimental results are contained in Section 5. It is interesting to note that the value obtained in benzyl alcohol (Table 11) is very similar to that in nitrobenzene over the same temperature range. Both contrast markedly with the much lower values (around

10 kcal/mole/ obtained for the bimolecular reactions associated with the mono or unsubstituted anhydrosulphites.

A similar contrast is found in the magnitude of the collision numbers and associated entropies of activation for the reactions. The collision numbers observed for the first order decomposition are around 10^{12} (Table 11) compared with values of $10^2 - 10^3$ for the bimolecular reaction (Table 9). The entropies of activation, associated with the former reaction, are small and generally positive whereas for the latter they are large and negative.

The effect of dielectric constant of the reaction medium has already been alluded to. Table 10 illustrates the fact that the rate of decomposition of α-hydroxy isobutyric acid anhydrosulphite is little affected by even large changes in dielectric constant. This contrasts markedly with the bimolecular addition reaction discussed in Section 4, which is fairly sensitive to such changes.

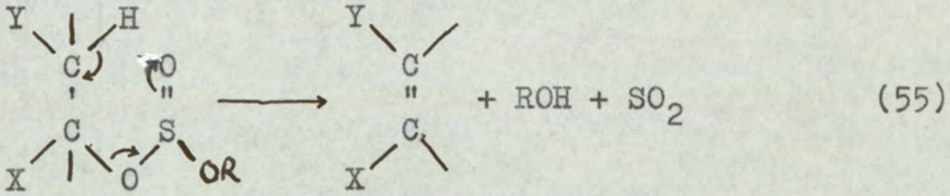
Quite clearly there is a fundamental difference in the nature of the two reactions. The bimolecular decomposition shows many similarities to the reaction of NCA's with amines and is in some ways analogous to the classic work of Gold(60-63) and others, e.g. (64-69) on the hydrolysis and alcoholysis of acetic anhydride. The significance of the large negative entropy of activation and marked effect of dielectric constant of the reaction medium have been discussed, together with the other factors involved, in Section 4:4. The postulate of an intermediate addition complex of fairly polar nature was presented. The first order decomposition encountered here is quite distinct. The entropy of activation, collision numbers and lack of sensitivity to dielectric make it highly improbable that the collision between reactant molecules need to take place in a particular steric sense in order to be effective. Similarly the formation of any sort of polar addition complex seems unlikely.

The reaction is similar in some respects to the decomposition of organic peroxides. These reactions, together with many others, come into the general category of 'thermal decompositions'. Their rates of reaction are, typically, similar to those expected on the basis of the simple collision theory, this being in part due to the fact that the collision numbers for the reaction are generally similar to collision frequencies predicted from gas phase studies (i.e., the steric factors are around unity). The decomposition seems, then, on this basis to be thermally initiated. The precise nature of the decomposition will be discussed subsequently in the light of system showing similar behaviour. The preceding discussion, however, especially in relation to the results obtained in benzyl alcohol, leaves little doubt that, whatever the role of hydroxyl groups in the reaction, they are not involved in the primary ring opening step.

Comparison with Other Systems

The contrast between the hydroxyl initiated and 'thermal' decomposition of anhydrosulphites has been emphasised. There exist, however, other systems whose behaviour on decomposition is, in some way, similar to that of the disubstituted anhydrosulphite. These will now be discussed, together with the thermal decomposition of other anhydrosulphites. Some reference will be made to the anhydrocarboxy derivatives of ∝-hydroxy acids whose behaviour is discussed in more detail elsewhere (Section 7).

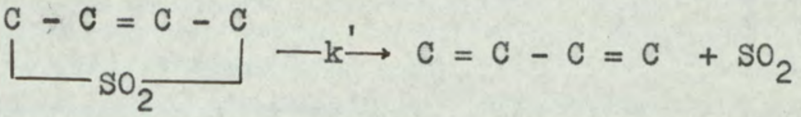
The similarities which exist between anhydrosulphites and organic sulphites have been previously mentioned. It is also seen in some aspects of the thermal decomposition of these compounds. Thus Rose and Warren(7) have noted a similarity in the decomposition of 2.2 - bis(chloromethyl) 1.3 - propylene sulphite reported by Matlack and Breslow(70) and the analogous anhydrosulphite of 2.2 - bis(chloromethyl-2 - hydroxyacetic acid, both being subject to pyrolytic fragmentation processes. In general organic sulphites decompose to yield alcohols and olefines as the primary products together with elimination of sulphur dioxide, as shown in Equation 55(32).



The nature of the groups X and Y determining the ratio of olefine to alcohol in the products. Reports of other modes of decomposition are noted in van Woerden's review, including the formation of ethers and oxides. Apparently, no kinetic data has been collected on the thermal decomposition of organic sulphites.

The sulphur-oxygen bond in anhydrosulphites of ∝-hydroxy acids is quite similar to that in alkyl sulphoxides. The pyrolysis of these compounds has been studied by several workers in recent years. Most workers have reported the formation of olefines as primary products(71-74) although evidence of aldehyde formation and other decomposition products had been noted(75-77). It is apparent from these results that the structure of the sulphoxide affects the nature of the products. In a kinetic study of the decomposition of di n-butyl sulphoxide Barnard-Smith and Ford(76) observed first order kinetic behaviour, the velocity coefficient at 180°C being 4.1×10^{-4} $sec.^{-1}$ and the activation energy 32 kcal/mole. Although there is no immediate parallel in the actual mode of decomposition of anhydrosulphites it is interesting to note the similarity in kinetic behaviour.

Systems which show a quite striking similarity of behaviour to disubstituted anhydrosulphites are the conjugated diene sulphones. Drake and Stowe(78) have studied the formation and thermal decomposition of these compounds. The decomposition is represented by Equation 56, the diene being shown in skeletal form only.



$$C-C=C-C\,(\text{ring closed by }SO_2) \xrightarrow{k'} C=C-C=C + SO_2 \qquad (56)$$

First order kinetic behaviour was observed with quite wide variation in the values of kinetic constants between the individual members of the series. Thus the activation energy (Ea) varied with substitution at the ∝-carbon in the following manner:

unsubstituted (E_a = 27.3 kcal/mole)
monosubstituted (E_a = 19.5 kcal/mole)
disubstituted (E_a = 32.9 kcal/mole)

The actual values of the first order velocity coefficients (k') were quite similar to those obtained with the anhydrosulphite. For example:

butadiene sulphone	$k' = 2.0 \times 10^{-4}$ sec.$^{-1}$ at 120°C
isoprene sulphone	$k' = 1.65 \times 10^{-5}$ sec.$^{-1}$ at 100°C

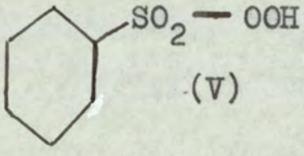
The mixed carboxylic-carbonic anhydrides(RCOO·COOR') are worthy of some consideration at this point due to their structural similarity to the anhydrosulphite and anhydrocarboxy derivatives of ∝-hydroxy acids. The thermal decomposition of many members of this series has been examined, notably by Tarbell and his co-workers(79-82). The decomposition normally involves carbon dioxide evolution together with ester, anhydride and alkyl carbonate formation. In the case of formic acid derivatives, however, both carbon monoxide and carbon dioxide formation was noted. An interesting tracer study of secondary and tertiary butyl benzoic anhydrides demonstrated that the presence or absence of an ∝-hydrogen atom in the alcoholic component affects the mode of decomposition(83). No alkyl-oxygen fission was observed in the former case but it occurred quite freely in the second. These points are quite pertinent to a consideration of the decomposition products of anhydrocarboxy derivatives of ∝-hydroxy acids (Section 7).

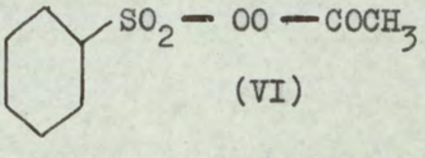
¶ The decomposition of aroyl and acyl peroxides (RCO·O·O·COR) is kinetically very similar to that of anhydrosulphite and anhydrocarboxy derivatives of ∝-hydroxy acids. In view of the fact that further similarities exist both in the structure and actual mode of decomposition of these compounds they are obviously relevant to the present discussion. Since peroxides provide a classic example of the thermal dissociation of an organic molecule in solution into reactive free radicals they have received considerable attention in the last forty years. Much of the data relating to their decomposition has been collected in texts dealing with free radical reactions (e.g.84, 85). The most widely studied compound of this series is undoubtedly benzoyl peroxide, whose primary decomposition follows a first order law although induced decomposition is observed, especially at higher concentrations. The velocity coefficients obtained at 80°C in various solvents (87) are all around 4×10^{-5} sec.^{-1} and the activation energies of the order of 30 kcal/mole. The dielectric constant has little effect on the primary decomposition and, although the induced decomposition is more marked in some solvents than in others, this is not attributable to the variation in dielectric constant.

Studies of acetyl peroxide by Levy, Steinberg and Szwarc(88) indicate that no marked difference exists in the magnitude of the rate constant and activation energy relating to decomposition in the gas phase and various solvents at the same temperatures. The studies were carried out at 85°C, the values of k_d (the first order velocity coefficient for the process) being around 1.5×10^{-4} sec.$^{-1}$, and that of the activation energy around 31 kcal/mole.

Another peroxide which is of interest in the present discussion is the cyclic monomeric phthaloyl peroxide which produces a diradical on decomposition(89-91), the kinetics of the decomposition being similar to those observed for the other peroxides. Finally in this section the existence of certain sulphur containing peroxides which are reported to decompose into radicals(92,93) might be mentioned. They are bis(methyl sulphonyl) peroxide (IV), cyclohexyl persulphonic acid (V) and cyclohexyl sulphonyl acetyl peroxide (VI).

$$CH_3 — SO_2 — O — O — SO_2 — CH_3 \qquad (IV)$$


(V)


(VI)

The unitiated decomposition of NCA's of ∝-amino acids has not received much attention, probably due to the magnitude of the "normal" bimolecular propogation which makes such studies difficult. Heyns and Brockman(94) have established by means of tracer techniques, however, that thermal decarboxylation of NCA's involves the 2 carbonyl group of the oxazolidine-2.5-dione ring.

Sulphur derivatives of ∝-amino acids analogous to the anhydrosulphites of ∝-hydroxy acids do not appear to have been studied in any detail. Certain other sulphur analogues of the NCA's do exist, however, some of these decomposing to yield polymers (e.g., 2-thio-5-thiazolidone(95) thiazolidine-2.5-dione(96)) but none by a mechanism showing kinetic similarity to the disubstituted anhydrosulphites.

On the basis of the kinetic behaviour of the various systems discussed in this section certain tentative conclusions are possible. There is a considerable similarity between the decomposition of the anhydrosulphite of α-hydroxy isobutyric acid and some of the compounds mentioned here, both in respect of kinetic behaviour and the modes of decomposition involved. Many of these decompositions involve the thermal cleavage of covalent bonds that have a dissociation energy of around 30 kcal/mole. In some cases, notably the organic peroxides, the dissociations are known to be homolytic and the products to include free radicals. It is very probable, therefore, that the decomposition of disubstituted anhydrosulphites proceeds similarly by the thermal rupture of a covalent bond; certainly the observed kinetic characteristics are consistent with such a view. Furthermore, it is possible, although by no means certain, that free radicals are formed in the decomposition.

It was noted that monosubstituted anhydrosulphites (Section 4) and the disubstituted anhydrocarboxy derivatives (Section 7) show an analogous uninitiated decomposition, although their stability is much greater. There is insufficient experimental evidence to say at present how similar the decomposition of these compounds is to that of the disubstituted anhydrosulphite. If an unequivocal mechanism for the uninitiated decomposition and subsequent polymerisation of the disubstituted anhydrosulphites can be deduced, its applicability to these other classes of compound will be discussed.

The Nature of the Decomposition and Subsequent Propagation Reaction

The possibility of an initial bimolecular attack on the anhydrosulphite ring, involving regeneration of a hydroxy group which could in turn attack a fresh anhydrosulphite molecule, thus forming the basis of a chain propogation reaction, is precluded on the kinetic evidence. This has been established in the preceding discussion. Similarly the fact that added ∝-hydroxy isobutyric acid does not influence the rate of decomposition of the anhydrosulphite implies that carboxyl groups are not the propogating species. Undoubtedly, however, hydroxyl groups play an important part in determining the chain length of the resultant polymer, conceivably through being involved in chain transfer or termination processes during the polymerisation. Alternatively, an active intermediate may be formed (by the initial decomposition of the anhydrosulphite) which is susceptible to hydroxyl attack. The whole question of the role of hydroxyl groups in the reaction will be discussed in some detail separately.

The effect of dielectric constant of the reaction medium on the rate of anhydrosulphite decomposition is so small that any process which involves the reaction of a charged species with the ring, or the decomposition of the ring to yield ionic products, must also be precluded. Such processes, together with others which involve the separation or combination of very polar or charged species in the rate determining step, show marked sensitivity to changes in dielectric constant of the reaction medium. It is conceivable on the kinetic evidence, however, that some process takes place which involves the decomposition of the anhydrosulphite to yield products of similar polarity; these subsequently rearranging to a more charged form which couple with others of the same type to yield polymer. In this case the rate of anhydrosulphite decomposition would not necessarily be influenced greatly by the dielectric constant of the reaction medium.

The observed effect of reaction medium on polymer formation argues against such a mechanism, however. The propagation step outlined above would be largely inhibited in solvents such as dekalin or benzene which have very low dielectric constants, thus markedly affecting yield and molecular weight of the reaction products. In fact the yield and molecular weight of polymers produced from such solvents are, if anything, slightly higher than those in, for instance, nitrobenzene. In addition to this difficulty such a mechanism would have to account for the somewhat obscure behaviour of hydroxyl groups, which become involved at some stage in the propagation or termination process.

The reaction of α-hydroxy isobutyric acid anhydrosulphite with cationic initiators is at first sight suggestive of a cationic mechanism for the polymerisation. A more detailed consideration reveals the fact that, although the anhydrosulphite ring is very reactive towards certain compounds of this type, a charged species, capable of chain propagation, is not regenerated in the reaction. Although it may be possible, given the appropriate conditions, to polymerise anhydrosulphites by a cationic propagation mechanism, it is certain that such a process is not involved in the systems used in the main bulk of the work presented here, or the original work of Alderson.

The kinetic features of $\alpha.\alpha$-disubstituted anhydrosulphite decomposition are in many ways similar to those of reactions known to involve free radical products. Some such systems have been considered, perhaps the most notable example being that of the organic peroxides. The order of reaction, activation energies, collision numbers and response to solvents of differing dielectric constant of such compounds show a marked resemblance to the behaviour of the anhydrosulphites. Further, the effects observed with benzoquinone, DPPH and styrene (Section 5:4) are consistent with the existence of radicals in the reaction products, although their reactivity and/or concentration appears to be very low. The role which any radicals which may be produced in the decomposition play in the subsequent polymerisation reaction is difficult to determine. It has been established that the concentration of radicals in the system does not influence the rate of anhydrosulphite decomposition (Figure 20). The chain propagation mechanism does not, then, involve the attack of a terminal free radical on an unreacted anhydrosulphite ring (and subsequent evolution of a molecule of sulphur dioxide) together with radical transfer to the end of the growing chain.

The alternative to this type of mechanism is one in which the anhydrosulphite ring decomposes to yield sulphur dioxide and a diradical which may rearrange, fragment into monoradical products, or couple with other diradicals. This alternative seems much more feasible on the basis of the experimental evidence, since diradicals, being very prone to cyclisation, show very weak activity with conventional radical acceptors such as styrene and DPPH. Of the possible types of mechanism considered, then, one involving an initial ring opening yielding principally diradical products, which subsequently rearrange or react, seems most consistent with the experimental evidence presented in Section 5. Possible propagation mechanisms which may result from such a preliminary step will now be considered in some detail.

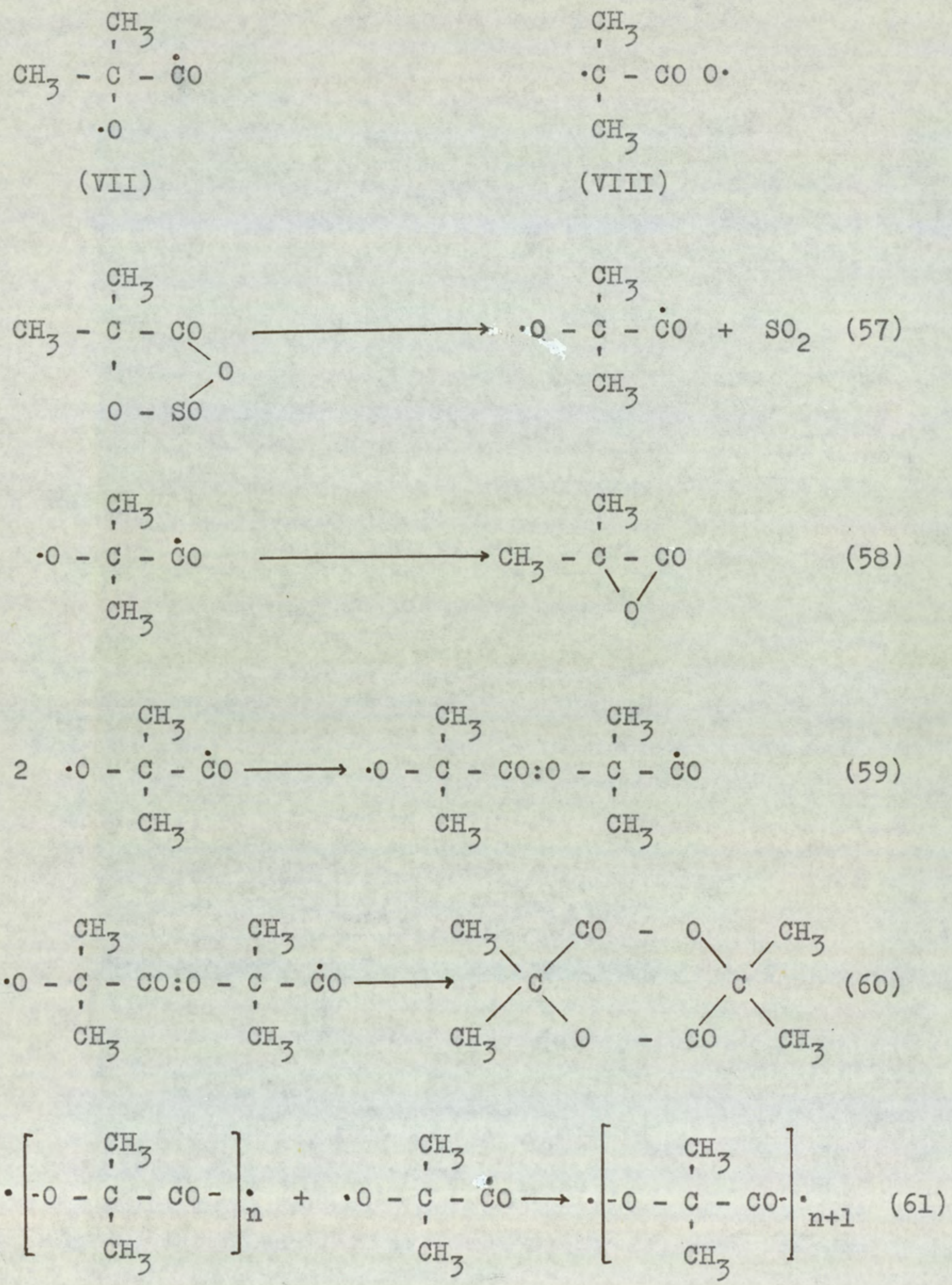


FIGURE 29: Possible Reactions of AHIBAS involving Diradical Formation

Possible Propagation Reactions Resulting from Initial Diradical Formation

On the evidence of such bond energies as are available and the products of the reaction of ∝-hydroxy isobutyric acid anhydrosulphite with benzyl alcohol, it seems probable that the diradical produced from this anhydrosulphite would have the structure (VII) rather than (VIII). A set of equations representing its formation and possible reactions relating to polymerisation are presented in Figure 29 (Equations 57 - 61). Two types of propagation process could be envisaged on the basis of these reactions:

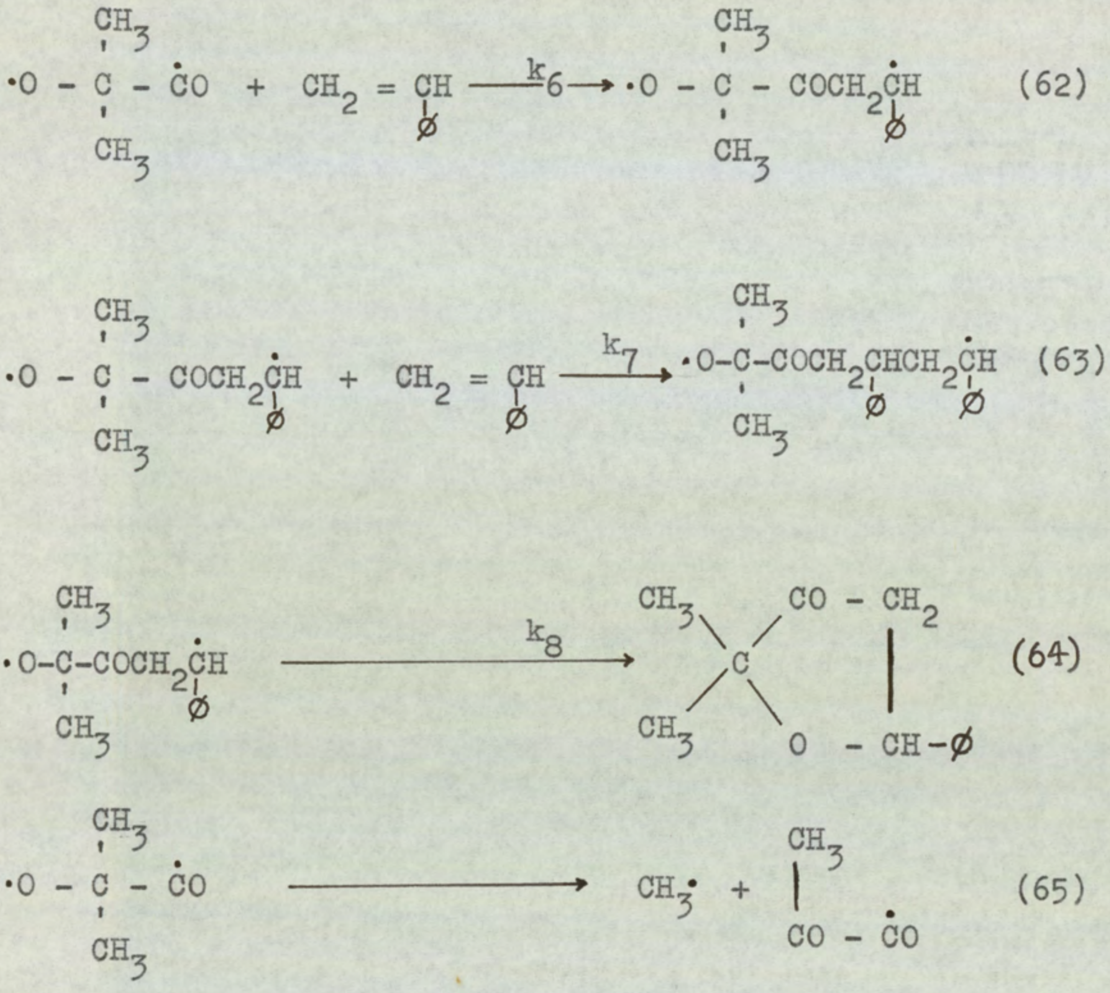
(i) A diradical coupling process (Equation 61)

(ii) Formation of a cyclic intermediate (Equations 58 and 60) followed by a ring opening propagation step.

The two possibilities will be discussed separately.

Although diradical coupling is not a common chain propagation mechanism it has been shown to occur in some systems, for example the copolymerisation of bicyclo (2.2.1) hept-2-ene and sulphur dioxide$^{(97)}$. As might be expected, however, most attempts to produce chain propagation by diradical coupling mechanisms are frustrated by the tendency of such species to cyclise. The observation that diradicals are very inefficient initiators of vinyl polymerisations has been attributed to this fact$^{(98)}$.

On the basis of this evidence it seems apparent that even if the diradical coupling process were to proceed to the dimer stage (Equation 59) the rate at which this species cyclised to form a six membered ring (Equation 60) would be so great that further addition of diradical units (Equation 61) would be virtually, if not completely, nonexistent. Studies of intramolecular relaxation processes do indicate, however, that the energy barrier to rotation about carbon-carbon single bonds may be markedly increased



$$\cdot O-\overset{CH_3}{\underset{CH_3}{C}}-\dot{C}O + CH_2=\underset{\phi}{CH} \xrightarrow{k_6} \cdot O-\overset{CH_3}{\underset{CH_3}{C}}-COCH_2\underset{\phi}{\dot{C}H} \qquad (62)$$

$$\cdot O-\overset{CH_3}{\underset{CH_3}{C}}-COCH_2\underset{\phi}{\dot{C}H} + CH_2=\underset{\phi}{CH} \xrightarrow{k_7} \cdot O-\overset{CH_3}{\underset{CH_3}{C}}-COCH_2\underset{\phi}{CH}CH_2\underset{\phi}{\dot{C}H} \qquad (63)$$

$$\cdot O-\overset{CH_3}{\underset{CH_3}{C}}-COCH_2\underset{\phi}{\dot{C}H} \xrightarrow{k_8} \qquad (64)$$

$$\cdot O-\overset{CH_3}{\underset{CH_3}{C}}-\dot{C}O \longrightarrow CH_3^{\bullet} + \overset{CH_3}{\underset{CO-\dot{C}O}{|}} \qquad (65)$$

FIGURE 30: Possible Reactions relating to the Polymerisation of Styrene in the Presence of AHIBAS

by the introduction of bulky or polar substituents. Examination of the dimeric diradical species under consideration suggests that the barrier to rotation, and thus cyclisation, may be quite high. If the relaxation time for the cyclisation process were longer than the average lifetime of a diradical in a system containing other radical species, propagation by diradical coupling would take place in preference to cyclisation.

Attempts to interpret the detailed experimental results, especially those relating to styrene polymerisation, in the light of such a mechanism are faced with several problems. The results presented in Table 13, for instance, show that the efficiency of the radicals produced is very low in comparison to those obtained from benzoyl peroxide, even when the faster rate of decomposition of the latter is taken into account. It seems probable, however, that although cyclisation of the dimeric diradical shown in Equation 60 may be hindered, the energy barrier to rotation of the styrene plus initiator dimeric diradical shown in Equation 62 (Figure 30) will be much lower. A crude verification of this suggestion is obtained by use of Courtaulds Atomic Models to construct and compare the two species. If this is the case, then the cyclisation process represented in Equation 64 will occur more frequently than the propogation step shown in Equation 63, thus accounting for the observed inefficiency of the anhydrosulphite as a free radical initiator.

Although these hypotheses lack direct proof, they do offer some explanation of the experimental results presented in Figure 23a which relates the rate of polymerisation of styrene to the initial concentration of α-hydroxy isobutyric acid anhydrosulphite.

The rate of polymerisation (R_p) of vinyl monomers in the presence of free radical initiators is given by the well-known expression

$$R_p = (f \frac{k_d}{k_t})^{0.5} \quad k_p [M] [I]^{0.5} \qquad (66)$$

where [I] is the initiator concentration, f its efficiency and k_d the first order velocity coefficient governing its rate of decomposition. [M] represents the concentration of monomer, k_p the velocity coefficient for the propagation and k_t that relating to termination. Thus the variation of R_p with $[I]^{0.5}$ should be linear.

In the system under consideration (Figure 30), however, the initiator fragments are also involved in a bimolecular diradical coupling reaction (Equation 61). If the concentration of the diradical anhydrosulphite fragment is represented by [·I·] and that of the undecomposed anhydrosulphite by [I], the rate of polymer formation by diradical coupling (R_p') is given by:

$$R_p' = k_4[\cdot I \cdot]^2 = k_4(k_1[I])^2 \qquad (67)$$

The modified rate of styrene polymerisation ($R_p - R_p'$) will then be given by:

$$R_p - R_p' = \left\{\frac{fk_d}{k_t}\right\}^{0.5} k_p[M][I]^{0.5} - k_4 \ (k_1[I])^2 \qquad (68)$$

Some of the constants may now be evaluated:

A value for $\frac{k_p}{(k_t)^{0.5}}$ for styrene at 80°C may be obtained by interpolation in the data collected by Flory(99). This procedure gives, $\frac{k_p}{(k_t)^{0.5}} = 5{\cdot}5 \times 10^{-2}$ $\text{mole}^{0.5} . \text{l}^{-0.5} . \text{sec}^{-0.5}$

$k_d = k_1$, the first order velocity coefficient for anhydrosulphite decomposition. At 80° C in styrene $k_1 = 1.0 \times 10^{-5} \text{sec}^{-1}$.

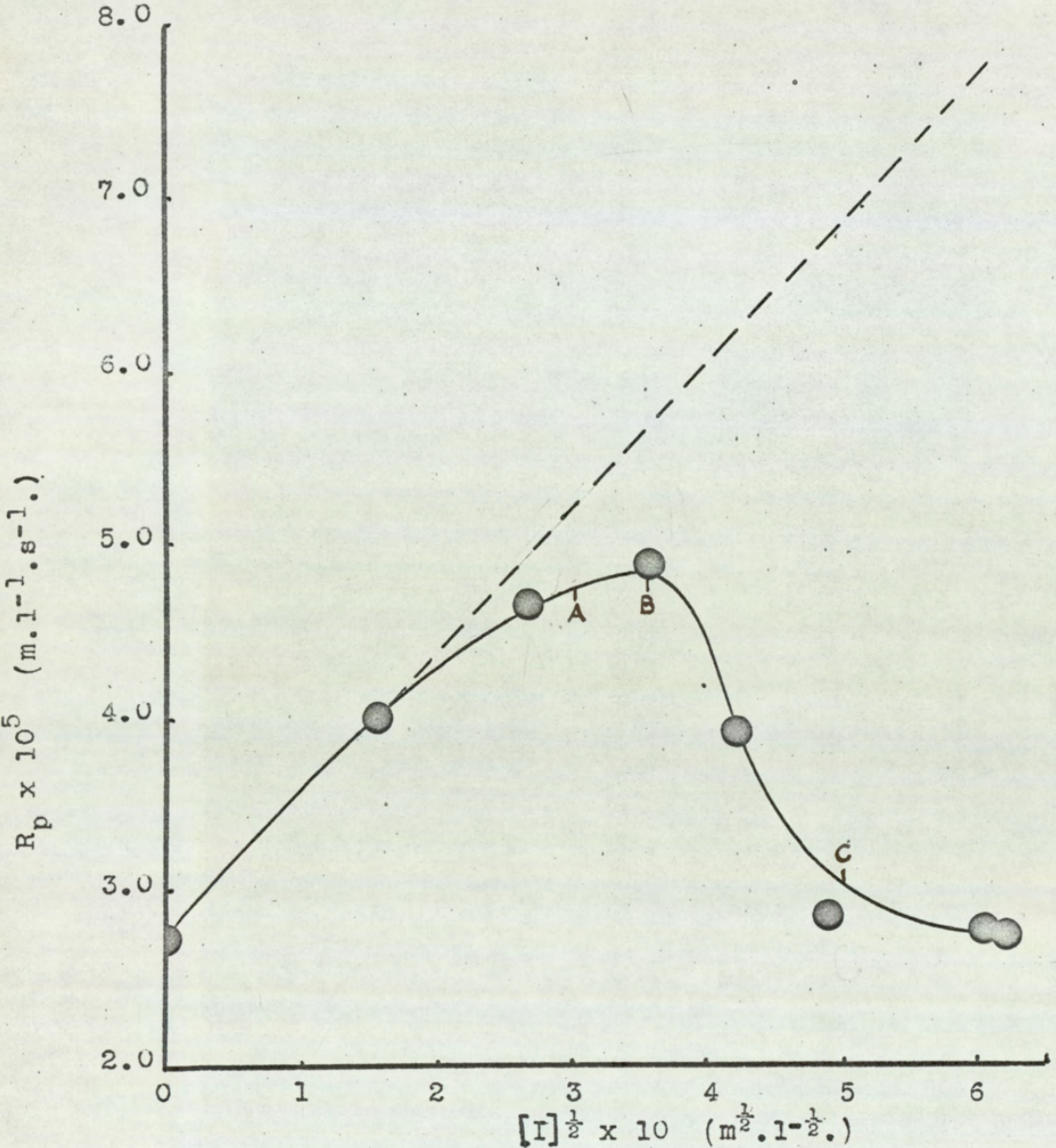


FIGURE 31. Polymerisation of styrene (in bulk) at 80°C in the presence of AHIBAS (I). Variation in rate of polymerisation (R_p) with $[I]^{\frac{1}{2}}$. Construction of limiting slope ($[I] \rightarrow 0$).

The value of R_p' will become negligible in comparison with R_p at very low values of [I], thus the limiting slope of $(R_p - R_p')$ vs. $[I]^{0.5}$, as $[I]^{0.5}$ approaches zero, will be equal to $\left(\frac{f_{kd}}{k_t}\right)^{0.5} \cdot k_p[M]$. Using the experimental results presented in Figure 23a, construction of the limiting slope enabled a value for f to be obtained:

$$\frac{1.75}{0.2} \times 10^{-5} = f^{0.5} \times 5.5 \times 10^{-2} \times 8.25 \times 3.3 \times 10^{-3}$$

$$\therefore \quad f = 3.4 \times 10^{-3}$$

This implies that the cyclisation process shown in Equation 64 occurs some three hundred times as frequently as the propagation step (Equation 63). It is interesting to note that similar 'f' values have been obtained with phthaloyl peroxide/methyl methacrylate systems(90).

The value of R_p' corresponding to various initiator concentrations may be evaluated by taking the difference between the straight line produced from the initial slope (R_p) and the experimental curve $(R_p - R_p')$ at the appropriate points. Figure 31 shows three values of $[I]^{0.5}$ (A, B, C), at which this operation has been performed. The values obtained for R_p' and thus k_4 are indicated below:

At point A:

$$R_p' = k_4(k_1[I])^2$$

$$0.5 \times 10^{-5} = k_4\ (0.09 \times 1.0 \times 10^{-5})^2$$

$$k_4 = 6.2 \times 10^6 \text{ litre.mole}^{-1} \text{ sec}^{-1}$$

At point B:

$$0.8 \times 10^{-5} = k_4\ (0.12 \times 1.0 \times 10^{-5})^2$$

$$k_4 = 5.9 \times 10^6 \text{ litre.mole}^{-1} \text{ sec}^{-1}$$

At point C:

$$3.95 \times 10^{-5} = k_4 \, (0.25 \times 1.0 \times 10^{-5})^2$$

$$k_4 = 6.3 \times 10^6 \text{ litre.mole.}^{-1} \text{ sec.}^{-1}$$

The mean value of a series of such determinations was:

$$k_4 = 6.1 \times 10^6 \text{ litre.mole.}^{-1} \text{ sec.}^{-1}$$

Insertion of the values of f and k_4 obtained in this manner into Equation (68) produces a curve which fits the experimental points quite satisfactorily. It is perhaps noteworthy that the value of k_t for most vinyl polymerisations at temperatures around 80°C is of the order of $10^6 - 10^7$, this being very similar to the value of k_4 obtained above. The point that seems significant about this similarity is that both constants refer to radical coupling reactions.

Although some explanation of the anhydrosulphite ring opening reaction and subsequent chain propogation step is possible in terms of the processes outlined above, the ~~extremeløy~~ extremely efficient way in which moisture acts as a chain regulator is not easily understood. It seems certain that inclusion of moisture in this scheme must take place by a termination or transfer reaction involving α-hydroxy isobutyric acid, but inexplicable that such processes should involve this acid in so efficient a manner. Thus, although it is understandable that α-hydroxy isobutyric acid is capable of acting as a chain transfer agent, it is not credible (on the basis of other investigations involving similar compounds in free radical systems) that its transfer constant should be so much greater than that of the many solvents which have been successfully used to produce polymer from the anhydrosulphite. Further doubt is cast on the possibility of a transfer process of this nature by the fact that all hydroxy group containing compounds examined (e.g. benzyl alcohol) behave as 'chain stoppers' in a similar manner. For this reason the reactions by which hydroxyl groups might be incorporated will be considered in more detail under a separate heading.

In biradical propagation reactions chain termination by bimolecular coupling of the growing chains is not possible since the resultant molecule is also a diradical. Propagation and termination processes in diradical systems have been considered from a statistical standpoint by Haward(100), and in relation to the "thermal" polymerisation of styrene by Russel and Tobalsky(101). The low probability of propagation occurring in diradical systems has been referred to in this discussion; Russel and Tobalsky, in relation to diradical species producing a propagation step in styrene polymerisation suggest: "A high proportion, perhaps all, undergo self termination to form small rings". In the case of a system in which macro diradicals have been formed, however, the conclusions of Haward suggest that termination will occur predominantly by intra- rather than intermolecular combination.

Other termination processes for the anhydrosulphite system could be envisaged. These would involve fragmentation or dismutation processes, e.g. Equation 65, Figure 30, and subsequent combination of the monoradicals produced, with the diradical chains. Fragmentation of α-hydroxy isobutyric acid into two monoradical species would seem to be very improbable under the reaction conditions involved.

It must, therefore, be concluded that although the postulated diradical propagation mechanism offers an apparent interpretation of the kinetic data, it is unable to account for the highly efficient inclusion of hydroxy compounds which occurs. Neither, it must be admitted, does the behaviour of the anhydrosulphite seem truly characteristic of a radical-producing thermal dissociation. It is common for such dissociations to show great sensitivity to ultra violet light. The effect with α-hydroxy isobutyric acid anhydrosulphite was very small by comparison. Evidence of induced decomposition in such solvents as dioxan was also lacking. This latter phenomenon is, however, by no means universal amongst such compounds, being very marked in benzoyl peroxide(87, 102) and non-existent in azobis-isobutyro nitrile(86).

The possibility of copolymerisation of sulphur dioxide and styrene being responsible for the kinetic results presented in Figure 23a and discussed here must be considered. A detailed examination of styrene-sulphur dioxide copolymerisation and resulting polysulphone formation has been carried out by Barb(103,104) and others. It must be concluded that the concentrations of sulphur dioxide involved in the work presented here are too low to present serious difficulties in the form of copolymerisation, although the possibility that the sulphur dioxide may act as a retarder is worthy of consideration.

A second type of propagation process involving the initial formation of a diradical has already been mentioned. Following sulphur dioxide evolution the diradical might possibly cyclise to form an active intermediate which would be subject to a further ring opening step resulting in chain propagation. Only two types of intermediate could be readily envisaged. They are the six membered 'lactide' (1.1.4.4-tetramethyl glycollide) shown in Equation 60 and the three membered α-isobutyro lactone shown in Equation 58.

There are several facts which suggest that the substituted glycollide cannot be an intermediate in the polymerisation. The work of Carothers(11) on the polymerisibility of such compounds was continued by Hall(13) who has shown that glycollides with four phenyl or methyl substituents do not polymerise even at temperatures up to 250°C. Various catalysts were used. It is, therefore, inconceivable that 1.1.4.4-tetramethyl glycollide would polymerise under the relatively mild conditions employed in the anhydrosulphite polymerisations described here. This conclusion was confirmed experimentally. Furthermore all attempts to isolate the glycollide from reaction mixtures containing α-hydroxy isobutyric acid anhydrosulphite failed, as did the attempts to prepare the glycollide by heating the anhydrosulphite in bulk at a variety of temperatures and pressures. In the light of this evidence 1.1.4.4-tetramethyl glycollide cannot reasonably be postulated as an intermediate in the polymerisation of α-hydroxy isobutyric acid anhydrosulphite.

The ease with which α-hydroxy isobutyro lactone can be formed depends on the tendency of the unpaired electrons in the diradical (VII) - Figure 29 - to become coupled. In considering the possibility one must balance the probability of such a coupling process against the inherent instability of three membered rings of this type. Because of this instability α-lactones have not been isolated, attempts to form them from α-hydroxy acids invariably resulting in glycollide formation. If an α-lactone were formed then, it would be extremely unstable, this being in accord with the requirements of the postulated intermediate, provided that its decomposition led to polymer formation.

The effect of ring size on the polymerisibility of lactones has been examined by Carothers and subsequently by Hall. It is concluded that although four and six membered rings polymerise, five membered do not, the presence of substituent groups in general tending to stabilise the ring against polymerisation. The behaviour of the four membered lactone rings is particularly interesting; β-propiolactone, being unsubstituted, polymerises spontaneously on formation(105) while the disubstituted α α-bis chloromethyl propiolactone, although polymerising readily is less reactive(106). Since polymerisibility is related to ring strain the three membered α-lactone ring should polymerise spontaneously even with two methyl substituents.

A wide variety of catalysts have been found to be successful in accelerating the polymerisation of lactones, amongst them sodium, sodium hydride, sulphonic acids, tetra isopropyl titanate, litharge, potassium carbonate and water(13). A recent paper has described the ring opening of lactones by radicals(107).

On the basis of this evidence, then, it seems possible that α-butyro lactone is an intermediate in the decomposition of α-hydroxy isobutyric acid anhydrosulphite, being subject itself to further decomposition, thus forming an α-polyester. The mechanism of the subsequent polymerisation must now be considered in the light of this possibility, with particular reference to the mode of hydroxyl group inclusion.

The Role of Hydroxyl Groups in the Reaction

The postulated existence of an intermediate of the type under discussion demands that the kinetic requirements considered previously be viewed in a new light. Although the arguments raised against propogation by diradical coupling are still applicable, the objections to a bimolecular hydroxyl initiated process need not apply. Such a propagation step would not be kinetically involved in the initial decomposition of the anhydrosulphite but would, on the other hand, account for the inclusion of hydroxyl groups in the polymer. The mechanism of lactone hydrolysis is, admittedly, complex and has been shown to vary with ring size (see, for instance, reference 39, p.776 et. seq.). Any attempt to discuss the behaviour of the α-lactone intermediate postulated here in the light of this would be beyond the limits of the available experimental data.

The evidence presented in Section 5 demonstrates that certain chlorine containing compounds are capable of taking part in the polymerisation reaction, acting as molecular weight regulators. In the absence of such impurities, however, moisture (and thus α-hydroxy isobutyric acid) was shown to be responsible for limiting the degree of polymerisation, the resultant chains being predominantly 91 hydroxyl/carboxyl terminated (Section 5:5). The radiochemical work demonstrated more clearly that within the limits of experimental error, any such hydroxy acid present is quantitatively incorporated into the polymer chain by the time the anhydrosulphite decomposition is complete. Further, up to moderate molecular weights the degree of polymerisation predicted on this basis is observed (Figure 26), demonstrating the virtual absence, under these circumstances, of termination by other species.

The fact that benzyl alcohol is as efficient a chain regulator as the hydroxy acid and that benzyl α-hydroxy isobutyrate is formed when the anhydrosulphite is decomposed in benzyl alcohol, suggest that the hydroxyl group (as distinct from the carboxyl) is the active species in the polymerisation. This postulate is further supported by 100 Table 17 and Figure 27 which present dielectric effects more appropriate to the attack of an -OH nucleophile than a carboxyl group. Similarly the efficiency of hydroxy acid incorporation in dekalin would seem to indicate that carboxylate ions are not involved in the process. For ease of interpretation, then, the simplest case will be considered - that in which hydroxyl groups are the only foreign species present in the system capable of initiating or terminating the propogation step. Although this undoubtedly represents a gross simplification, the results relating to the production of polymer of moderate molecular weight (DP $\leqslant$ 200) in the presence of moisture or added hydroxyl compounds seem to merit such a treatment.

Results relating to the rate of hydroxy acid disappearance and incorporation into the polymer are presented in Figures 27 and 28. The apparent discrepancy between Figures 27a and 28 must not be overemphasised because of the sources of error inherent in the latter. Complete (gravimetric) recovery of the polymer is difficult at low conversions, however, and the difference between the Figures does substantiate the view that it is low molecular weight (and hence highly active) polymer that is lost. Figures 27(a) and (b) consideredin relation to the rates of anhydrosulphite decomposition in nitrobenzene and dekalin are qualitatively consistent with the view that an intermediate, probably susceptible to hydroxyl attack, is formed and rapidly converted to polymer, the hydroxy compounds being incorporated by a propogation or termination step.

The results in benzyl alcohol and dielectric effects previously mentioned are more consistent with a mechanism involving direct hydroxyl attack on the intermediate than the combination of hydroxyl groups with a growing chain to yield an inactive hydroxyl terminated species. A bimolecular process of this nature is readily visualised in terms of a nucleophilic attack at the carbonyl group. The steric hindrance of the α-methyl groups to such a process would be fairly small and the resultant ring opening markedly facilitated by release of the strain energy associated with the three membered ring. It must be remembered, however, that this evidence is purely circumstantial and

$$M \xrightarrow{k_1} L + SO_2 \tag{69}$$

$$L + X_1 \xrightarrow{k_9} X_2 \tag{70}$$

$$L + X_2 \xrightarrow{k_{10}} X_3 \tag{71}$$

$$L + X_n \xrightarrow{k_{11}} X_{n+1} \tag{72}$$

$$-\frac{d[M]}{dt} = \frac{d[SO_2]}{dt} = k_1[M] \tag{73}$$

$$-\frac{d[X_1]}{dt} = k_9[L][X_1] \tag{74}$$

$$-\frac{d\,\Sigma_2^n\,[X_n]}{dt} = k_{10}[L]\,\Sigma_2^n\,[X_n] \tag{75}$$

$$\frac{d[L]}{dt} = k_1[M] - k_9[L][X_1] - k_{10}[L]\Sigma_2^n\,[X_n] \tag{76}$$

$$[X_1]_\circ = [X_1] + \Sigma_2^n\,[X_n] \tag{77}$$

FIGURE 32: Kinetic Scheme relating to Anhydrosulphite Polymerisation via a Reactive (∝-lactone) Intermediate.

Symbols: Anhydrosulphite monomer (M);
∝-Lactone intermediate (L);
Hydroxyl terminated residue of
the form $H\left[O - C(CH_3)_2 - CO\right]_n OH$, ($X_n$).

does not demonstrate the existence of such a mechanism. It is concerned rather with its feasibility.

A quantitative evaluation of the radiochemical evidence, in particular the apparent curvature encountered in Figure 27 presents several problems. A possible interpretation will now be considered, based on the kinetic scheme presented in Figure 32.

The observed curvature in Figure 27 would be explicable in terms of Equation 74 if the effective concentration of lactone [L] diminished with time. This might be due to an actual variation, or to an increase in magnitude of k_{10} as compared with k_9. Because the intermediate is formed relatively slowly and is, itself, very reactive, application of a stationary state approximation $(\frac{d[L]}{dt}) = 0$ would appear to be valid. This enables an expression for the magnitude of k_{10} relative to k_9 to be derived (Figure 33).

The radiochemical and gas evolution data relating to the polymerisation of α-hydroxy isobutyric acid anhydrosulphite in nitrobenzene and dekalin at 90°C (Tables 10 and 17)(Figure 27) enable the ratio k_{10}/k_9 to be evaluated for these systems. The relevant data were inserted into Equation 83, the results being presented in Table 18. (p.129)

The magnitude of the k_{10}/k_9 ratios calculated in this manner are surprising. Some increase in reactivity might be anticipated when the terminal carboxyl group ceases to be in the α position relative to the hydroxyl group, since in its unionised form it will tend to withdraw electrons from the hydroxyl nucleophile. In solvents which promote the formation of a carboxylate ion, however, the reverse effect would be expected - the magnitude depending on the extent of ionisation. Although these considerations are qualitatively similar to those observed, Equations (76) and (77) yield,

$$[L] = \frac{k_1[M]}{[X_1](k_9-k_{10}) + k_{10}[X_1]_o} \qquad (78)$$

Insert (74) and rearrange:

$$-\frac{\left([X_1](k_9 - k_{10}) + k_{10}[X_1]_o\right)}{k_9[X_1]} d[X_1] = k_1[M]dt = -d[M] \qquad (79)$$

Integrating:

$$\int_{[X_1]_o}^{[X_1]} \left(\frac{k_9 - k_{10}}{k_9} + \frac{k_{10}}{k_9} \frac{[X_1]_o}{[X_1]} \right) d[X_1] = \int_{[M]_o}^{[M]} d[M] \qquad (80)$$

$$\left[\frac{k_9 - k_{10}}{k_9} [X_1] + \frac{k_{10}}{k_9} [X_1]_o \log[X_1] \right]_{[X_1]_o}^{[X_1]} = \Big[[M] \Big]_{[M]_o}^{[M]} \qquad (81)$$

$$\frac{k_9 - k_{10}}{k_9} \left([X_1]_o - [X_1] \right) + \frac{k_{10}}{k_9} [X_1]_o \log\frac{[X_1]_o}{[X]} = [M]_o - [M]$$
$$= [SO_2] \qquad (82)$$

Division throughout by $[X_1]_o$ yields:

$$\left(1 - \frac{k_{10}}{k_9}\right)\left(1 - \frac{[X_1]}{[X_1]_o}\right) + \frac{k_{10}}{k_9} \log\frac{[X_1]_o}{[X_1]} = \frac{[SO_2]}{[X_1]_o} \qquad (83)$$

FIGURE 33: Application of Stationary State Approximation to the Kinetic Scheme of Figure 32.

the magnitude of the effects encountered experimentally are far too high to be accounted for in this manner. Similarly the possibility of hydroxy acid association in solvents of low polarity might explain fairly small effects but is little help in rationalising the observed data.

Before attempting consideration of the actual calculated values of k_{10}/k_9 some observation on their constancy is necessary.

In both nitrobenzene and dekalin the values obtained at around 15% conversion are somewhat higher than those relating to higher conversions (which are apparently farily constant). The fact that low molecular weight (highly active) polymer is difficult to recover has been mentioned. Since the degree of polymerisation increases with conversion it is apparent from Equation (83) that errors due to incomplete recovery of polymer will be more marked at low conversion and will lead to erroniously high values of k_{10}/k_9. It is not unjustified, on this basis, to regard k_{10}/k_9 as being (approximately) constant for the greater part of the reaction.

Because the ratio k_{10}/k_9 is so large it seems likely that the magnitude of the velocity coefficients k_{10}, k_{11} (Equations 71 and 72) will be markedly different. Thus the use of k_{10} to represent the attack of all hydroxy terminated species except the hydroxy acid itself is hardly valid. Fortunately, however, (Cf. Table 17) the D.P.s of the polymers considered in Table 18 are all $\gg$ 20 so that although k_{10} represents a composite coefficient it has reached a steady value.

The constancy of the ratio k_{10}/k_9 in both systems studied provides an apparent justification for the application of a stationary state approximation to the problem. The unexpected values of the computed ratio may well have brought to light an aspect of the polymerisation mechanism which would otherwise have been overlooked. This feature and its effect on the magnitude of k_{10} relative to k_9 will be considered.

TABLE 18

Solution polymerisation of AHIBAS in the presence of α-hydroxy isobutyric acid at 90°C. Calculation of k_{10}/k_9 from Equation (83) in conjunction with the data of Tables 10 and 17 and Figure 27.

(a) <u>In Dekalin</u>: $[M]_o = 4.0$ mole.l.$^{-1}$;
$[X_1]_o = 2.0 \times 10^{-2}$ mole.l.$^{-1}$

Time (hrs)	Conversion (%)	$[X_1]_o/[X_1]$	$[SO_2]$ (mole.l.$^{-1}$)	k_{10}/k_9
0	0	1.0	0	-
2	14	1.75	0.56	212
3	21	2.15	0.84	180
4	27	2.4	1.08	178
5	33	2.8	1.32	182
23*	80	9.0	3.2	123

* System Heterogeneous

(b) <u>In Nitrobenzene</u>: $[M]_o = 3.3$ mole.l.$^{-1}$;
$[X_1]_o = 4.9 \times 10^{-2}$ mole.l.$^{-1}$

0	0	1.0	0	-
1.0	17	2.02	0.56	54.6
1.5	24	2.85	0.79	38.7
2.0	30	3.7	0.99	33.7
3.0	42	5.3	1.4	37.4
5.0	60	8.0	2.0	32.5

Adsorption Effects in Anhydrosulphite Polymerisation

The marked acceleration in anhydrosulphite decomposition which accompanies the precipitation of the polymer from solution has been noted in the case of both lactic (Section 4:2 Figure 13b) and α-hydroxy isobutyric acids (Section 5:2 Figure 19). The explanation of Ballard and Bamford(20) in relation to effects of heterogeneity in NCA systems seems applicable. Thus the anhydrosulphites (like the α-polyesters) are highly polar substances and it is reasonable to suppose that they are preferentially soluble in a phase consisting of swollen polyester in contact with a poor solvent for the polymer. In this way precipitation followed by adsorption of the anhydrosulphite will increase the effective concentration of the latter and, therefore, its rate of decomposition.

Ballard and Bamford point out that 'the mechanism of heterogeneous polymerisation has analogies with the chain effect encountered in homogeneous polymerisation initiated by poly-sarcosine(108), the adsorption of anhydride by the precipitated polymer taking place of the attachment of anhydride molecules to polysarcosine by hydrogen bonds'. The same authors in their account of the chain effect suggest (ref. 108 p.396) that the effect 'would be expected to be of general occurrence in reactions involving polymers under conditions which favour association between the reactants'.

The chain effect was observed in the polymerisation of D.L. phenylalanine NCA by the 'normal' amine propogation mechanism, the use of preformed polysarcosine dimethylamide as initiator leading to rates of decomposition very much (e.g., 100 times) faster than expected. The rate was shown to be dependent on the degree of polymerisation of the iniator (below D.P. $\simeq$ 20) and the effect less marked in highly polar solvents. The results were explained in terms of adsorption of the monomer by the polysarcosine chain and consequently high rate of reaction between the terminal base group on the chain and the absorbed NCA.

It seems not unreasonable to extend this explanation to the anhydrosulphite system, in particular the calculated k_{10}/k_9 ratios presented in Table 18. The observed effects of heterogeneity in anhydrosulphite system have been referred to; these imply that adsorption of monomer onto swollen polymer takes place quite markedly. Similarly in non-polar solvents such as dekalin the environment of the (polar) polymer chain could even in apparently homogeneous solution lead to locally high concentrations of the intermediate, resulting in a higher collision frequency between the reactants (lactone and terminal hydroxy group). The effect should be markedly less in solvents of greater polarity - a trend observed in Table 18. Furthermore, the fact that the k_{10}/k_9 ratios in the table are practically constant for a given system is consistent with the degrees of polymerisation involved (Table 17), since in order to be effective, adsorption sites must be accessible to the terminal hydroxyl group (Cf.[108]).

The absolute values of k_{10} and k_9 are not obtainable from the present information. The arguments developed above imply that k_{10} is abnormally high; it does not, however, necessarily render invalid the previous suggestions relating to the reactivity of α-hydroxy isobutyric acid, since both mechanisms may operate.

7. THE POLYMERISATION OF ANHYDROCARBOXY DERIVATIVES OF ∝-HYDROXY ACIDS

7:1 Experimental Observations

(a) The Ring Opening Reaction with amines, alcohols and water

From a qualitative point of view the ring opening reaction of anhydrocarboxy derivatives of ∝-hydroxy acids bears great similarity to the corresponding anhydrosulphite derivatives. Thus anhydrocarboxy lactic acid was found to react directly with alcohols whereas anhydrocarboxy ∝-hydroxy isobutyric acid did not. On the other hand, amines and water reacted with both the lactic acid and the ∝-hydroxy isobutyric acid derivative.

(b) The Propogation Reaction

Both gravimetric and gas evolution techniques were used to examine the rate of polymer formation in comparison with the rate of decomposition of the anhydrocarboxy derivatives. Particular attention was paid to decomposition and polymer formation under Alderson's conditions in order that a direct comparison with the anhydrosulphite derivatives could be made.

Anhydrocarboxy ∝-Hydroxy isoButyric Acid

A fairly crude gravimetric technique was employed in order to determine the rate of polymer formation under the conditions used by Alderson in the case of the anhydrosulphite of this acid (i.e., chlorobenzene at reflux temperature - reaction time 18 hours). Great care was taken not to introduce moisture when samples were removed. The results are shown in Table 19.

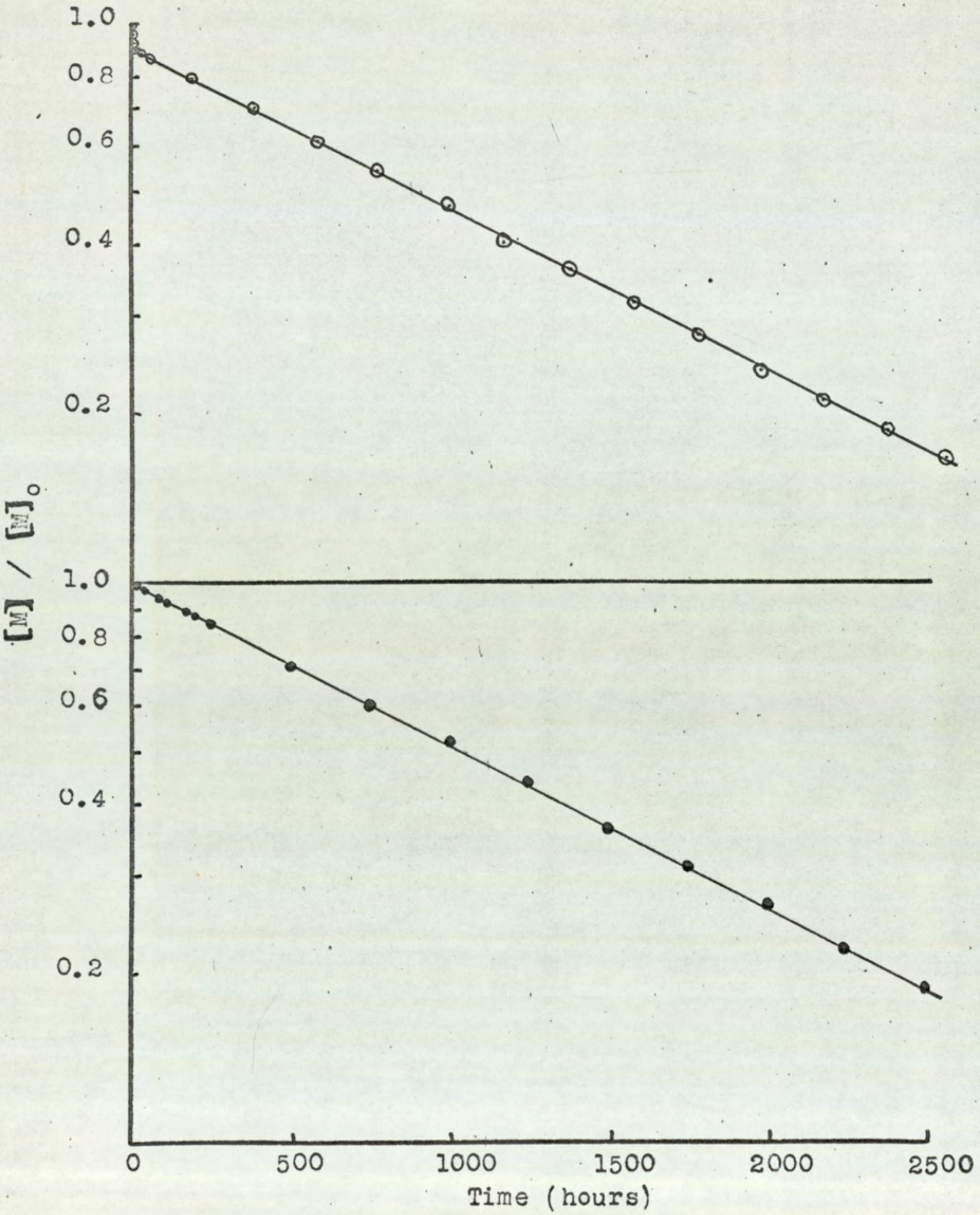


FIGURE 34. Decomposition of anhydrocarboxy α-hydroxy isobutyric acid in nitrobenzene at 90°C. Fraction of monomer remaining (undecomposed) plotted logarithmically as a function of time.

●,(a) $[M]_o$, 1.0 m.l^{-1}.; no added initiator.

⊙,(b) $[M]_o$, 1.0 m.l^{-1},; Cyclohexylamine, 0.1m.l^{-1}.

TABLE 19

The reaction of anhydrocarboxy α-hydroxy isobutyric acid (3 moles/litre) in refluxing chlorobenzene.

Reaction Time (hours)	Conversion to Polymer
0	Nil
20	Nil
30	Nil
40	Tracial
100	$< 5\%$

It was concluded from these results that the rate of polymer formation was much slower with this derivative than with the corresponding anhydrosulphite. It was not clear at this stage, however, if this was due to a slower ring opening or to formation of non-polymeric products.

In order to facilitate direct comparison with the anhydrosulphite, the rate of decomposition in nitrobenzene at 90°C was measured, using the gas evolution technique described previously. In the absence of added initiating species the decomposition followed a simple first order kinetic decay law, shown graphically in the form $\log \frac{[M]}{[M]_0}$ vs. time, for the conditions stated in Figure 34(a).

In the presence of tracial quantities of primary and secondary amines or water, an initial rapid addition to the ring was observed but the subsequent rate of decomposition of the cyclic compound was unaffected. Figure 34(b) shows the relationship $\log \frac{[M]}{[M]_0}$ vs. time for a solution of anhydrocarboxy α-hydroxy isobutyric acid in nitrobenzene solution (concentration 1 mole/litre) containing a small quantity of cyclohexylamine (concentration 0.1 mole/litre). The portion AB represents the initial reaction of the anhydrocarboxy derivative with cyclohexylamine and portion B - C the subsequent decomposition (which is seen to proceed at an identical rate to that in the absence of amine as shown in Figure 34a).

An examination of other systems which were thought to be possible initiators or catalysts for the polymerisation was carried out, using the gravimetric technique mentioned earlier.

The point of interest was to find, if possible, a method of forming polymer fairly rapidly at reasonably low temperatures (i.e., 25° - 50°C). The results of the investigation are presented in Table 20.

The initial concentration of anhydrocarboxy α-hydroxy isobutyric acid was 2.0 moles/litre in each case, the nature of the solvent being dependent on the particular catalyst or initiator system in use.

In view of the lack of success in producing polymer from this material at temperatures in the range 25° - 130°C the use of higher temperatures was investigated. Exploratory studies at temperatures between 150° and 200°C were carried out using the gas evolution technique. In view of the high vapour pressure of nitrobenzene at this temperature, the manometer design previously employed was of little use. Furthermore, a tendency for abnormal decomposition of the anhydrocarboxy derivative with consequent production of non-polymeric material was suspected. Because of this difficulty, studies along these lines were discontinued.

TABLE 20

Reaction of anhydrocarboxy α-hydroxy isobutyric acid (concentration 2.0 moles/litre) in various initiator/solvent systems.

Nature of Initiating System and % Concentration of Initiator	Temp. (^{o}C)	Reaction Time (hrs)	% Conversion to Polymer
LiBr/Dimethylformamide (0.1%)	25	100	Nil
LiBr/Dimethylformamide (1%)	25	100	Nil
LiBr/Dimethylformamide (5%)	25	250	Nil
LiBr/Dimethylformamide (0.1%)	50	100	Nil
LiBr/Dimethylformamide (5%)	50	250	Nil
Na O Me/Benzene (0.1%)	25	100	Nil
Na O Me/Benzene (1%)	25	100	Nil
Na O Me/Benzene (5%)	25	250	Nil
Na O Me/Benzene (0.1%)	50	100	Nil
Na O Me/Benzene (5%)	50	250	Nil
M.E.K.P./Nitrobenzene (0.1%)	50	100	Nil
M.E.K.P./Nitrobenzene (1%)	50	250	Nil
M.E.K.P./Benzene (1%)	50	250	Nil
BF_3etherate/Nitrobenzene(1%)	25	100	)Trace of)viscous)fluid formed
BF_3etherate/Nitrobenzene(5%)	25	250	
BF_3etherate/Nitrobenzene(1%)	50	100	)5% conversion)to viscous)fluid
BF_3etherate/Nitrobenzene(5%)	50	250	
Al_2Cl_6/Nitrobenzene (1%)	25	100	Approx. 5% solid
Al_2Cl_6/Nitrobenzene (1%)	50	250	Aluminium complex formed

(M.E.K.P. = Methyl ethyl ketone peroxide)

Anhydrocarboxy Lactic Acid

Kinetic examination of anhydrocarboxy lactic acid decomposition indicated that it behaved in a similar manner to the anhydrosulphite of lactic acid.

The rate of decomposition showed first order dependence on monomer and was quite markedly affected by the presence of hydroxyl groups. The rates encountered were, however, noticeably lower than those exhibited by the anhydrosulphite under similar conditions. In view of this a detailed kinetic examination was not undertaken.

Anhydrocarboxy Mandelic Acid

The rate of formation of polymer from this derivative under Alderson's conditions was found to be considerably slower than that encountered with anhydrocarboxy α-hydroxy isobutyric acid. Bearing in mind the scope of the present work and the anomalous behaviour of the N-carbonic anhydride of C-phenyl glycine in the analogous amino acid series, no further kinetic studies involving this compound were undertaken.

7:2 Discussion

It is quite apparent from the experimental results presented in this chapter that anhydrocarboxy ∝-hydroxy isobutyric acid does not decompose to form polymer under the reaction conditions successfully employed by Alderson for its anhydrosulphite counterpart. It is also clear that the kinetic behaviour of the compound is quite distinct from that of the N-carboxy-∝-amino-acid-anhydrides. It is in this latter respect that the two ∝-hydroxy acid derivatives behave similarly. The discussion developed in Section 6 shows that there is no kinetic evidence for a bimolecular propogation step in the polymer forming decomposition of ∝-hydroxy isobutyric acid anhydrosulphite. The limited kinetic studies presented in this chapter show a similar type of behaviour; the anhydrocarboxy ring reacts readily with added initiating species (e.g. amines) but the resultant hydroxyl terminated residue exerts no influence on the rate of decomposition of the remaining anhydrocarboxy acid (Figure 34).

Although it is outside the scope of this work to investigate in detail the mechanism of the decomposition of the anhydrocarboxy derivatives, it was the stated intention at the outset of the studies to examine the relationship of these compounds to the anhydrosulphites. It seems fairly clear that both the anhydrocarboxy and anhydrosulphite derivatives of ∝-hydroxy isobutyric acid undergo an uninitiated 'thermal' decomposition. It is further apparent that at temperatures in the region of 90°C the anhydrosulphite yields a polymer offairly high molecular weight while the anhydrocarboxy derivative produces none in a comparable time. Attempts to produce polymer from the latter derivatives at higher temperatures were also unsuccessful.

A partial explanation, at least, of the difference observed at 90°C is found in the comparative rates of decomposition of the anhydrosulphite and anhydrocarboxy derivatives. Both derivatives show first order kinetic behaviour, but the half lives differ by a factor of three hundred. The appropriate figures for the decomposition in nitrobenzene at 90°C are found in Figures **17** and 34a, i.e., anhydrocarboxy α-hydroxy isobutyric acid ($t_{0.5}$ = 1050 hours), α-hydroxy isobutyric acid anhydrosulphite ($t_{0.5}$ = 3.5 hours). It is quite clear from these figures that the formation of polymer from the anhydrocarboxy derivatives at 90°C is not practicable.

The lack of success in producing polymer from this compound at higher temperatures (i.e. 150° - 200°C) was thought to be due to the tendency of the anhydrocarboxy ring to fragment. A crude verification of this fact was obtained using a polymer pyrolysis unit, of the type described by Robb and Lehrle(109), coupled to a gas chromatograph.

Traces corresponding to the decomposition of both anhydrosulphite and anhydrocarboxy derivatives were obtained at filament temperatures which were judged to be around 400°C. The results demonstrated that while the anhydrosulphite decomposed to yield sulphur dioxide as the only volatile component, the anhydrocarboxy derivatives produced mainly carbon dioxide but also carbon monoxide and acetone.

These results are not presented formally in the experimental section because of the (necessary) high filament temperature and difficulty in measuring its exact value. It is felt, however, that they do offer some support for the suggestion that the anhydrocarboxy derivative is prone to fragmentation at higher temperatures.

Whilst it is true that the anhydrosulphite derivative of α-hydroxy isobutyric acid is much more readily polymerised than the anhydrocarboxy acid (under the conditions used by Alderson) this does not permit generalisations to be made about either the mechanism of polymerisation or other members of the series. It is conceivable that the anhydrosulphite and anhydrocarboxy derivati~~on~~ves decompose thermally to form a common intermediate which polymerises spontaneously. Since further propagation and termination steps would presumably take place at a rate which was independent of the origin of the intermediate, the slow formation of the intermediate might preclude the formation of high molecular weight polymer from the anhydrocarboxy derivative. It is conceivable, on the other hand, that the anhydrocarboxy derivatives are susceptible to polymerisation in the presence of a catalyst which is ineffective for the anhydrosulphites. There are many alternatives: a considerable amount of experimental work would be necessary to offer convincing evidence for any one.

With respect to other members of the anhydrocarboxy series: reference to Section 4 shows the possibility of a bimolecular propogation reaction occurring with the anhydrocarboxy derivatives of lactic and glycollic acid. It is quite possible that the 'uninitiated' decomposition of these compounds would be exceedingly slow in comparison with that of the corresponding anhydrosulphites. Although this in itself would make studies of the bimolecular reaction less complicated, it seems hardly likely that the bimolecular rate constants would be appreciably higher than those of the corresponding anhydrosulphites.

8. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK.

8:1 Conclusions

The stated objects (Section 1:1) of the work described here have largely been achieved.

Thus the synthetic work (Section 3) has not only produced new compounds and improved routes to existing ones, but the information it has provided relating to impurities associated with the anhydrosulphite (Blaise and Montagne's observations (5) in this respect being substantiated), has facilitated their purification and polymerisation. The failure of low conversion prepolymerisation to completely remove such impurities is understandable in terms of the mechanism of polymer formation discussed in Section 6.

The somewhat surprising difference in the polymerisibility of α-hydroxy isobutyric acid anhydrosulphite and the NCA of α-amino isobutyric acid in relation to the behaviour of their respective homologues has been considered. The mechanism proposed here (Section 6) for the former reaction is quite distinct from the 'normal' amino propagated polymerisation of the NCA's, which does, however, have some analogies with the relatively slow hydroxyl propagated polymerisation observed in the case of unsubstituted and monosubstituted anhydrosulphites (Section 4). The effects of steric hindrance (relating to these bimolecular processes) are not dissimilar in the anhydrosulphite (Sections 4,5,6) and NCA series (27). The 'uninitiated' thermal polymerisation observed in the former compounds, however, seems to be a more efficient means of preparing polymers than the thermal decarboxylation of the latter. Thus while recorded attempts to polymerise the NCA of α-amino isobutyric acid have produced only low molecular weight polymer, the anhydrosulphite of the analagous hydroxy acid is capable of polymerising to D.Ps of around 1000. Although the amino propagated polymerisation of NCA's is a much more rapid and efficient process than the bimolecular hydroxyl initiated decomposition of the anhydrosulphites, it must be concluded on the basis of evidence currently available that polymerisation resulting from thermal decomposition occurs more readily with the anhydrosulphites than NCA's.

Of the mechanisms considered in relation to the 'thermal' polymerisation of anhydrosulphites (Section 6), propogation via an α-lactone intermediate is undoubtedly the most viable. The α-lactone is structurally acceptable; its suggested role as an intermediate is not without precedent (110,111); its reactivity should be of the right order and its formation from other α-hydroxy acid anhydrosulphites could equally well be envisaged. It is possible, therefore, to consider this mechanism as applying to the thermal polymerisation of the anhydrosulphite series in general, rather than to α-hydroxy isobutyric acid anhydrosulphite in particular.

The results presented in relation to the anhydrocarboxy derivatives might also be considered on this basis; it must be emphasised however that such extensions of what is, at best, an attractive possibility, are without kinetic or analytical evidence to justify them.

The (relative) thermal stability of the anhydrocarboxy acids, the adsorption phenomena encountered in certain anhydrosulphite systems and the reactivity of the compounds with aluminium chloride have been considered in the text, although not in great detail. They serve to illustrate the varied and interesting chemistry associated with these somewhat obscure α hydroxy acid derivatives.

8:2 Suggestions for Further Work.

The mechanism associated with the 'thermal' polymerisation of the anhydrosulphites merits further attention, in particular the question of the α-lactone intermediate. Controlled decomposition in the vapour phase coupled with spectroscopic techniques, particularly the use of a mass spectrometer, might well yield usefull information in this respect. Analytical evidence relating to the presence or absence of cyclic products in styrene/anhydrosulphite systems would also be valuable.

A more complete characterisation of the mode and rate of incorporation of (various) hydroxy compounds into the polymer and the effect of reaction medium on this could well be undertaken using radio-tracer techniques. This, together with a study of the effects of added preformed polymers on the ratio k_9 / k_{10} (Section 6) and further studies on the variation of D.P. with time would provide a useful basis for computations relating to molecular weight distributions.

Studies relating to the α-polyesters themselves are obviously important. The preparation of various members of the series via the anhydrosulphites and a comparative examination of their properties (T.G.A., D.T.A., crystallisation studies etc.) is worthy of consideration. The anhydrosulphites should provide a ready route to α-polyester copolymers, a possibility which is of interest both from the point of view of the polymers themselves and the polymerisation reactions involved. Molecules containing two ketonic functions might conceivably (via cyanohydrin syntheses etc.) be converted into 'di-anhydrosulphites which would in effect be potentially tetrafunctional and thus provide a route to branched and cross linked structures.

Anhydrocarboxy derivatives of the α-thio acids are known.(8,9) The polymerisibility of these compounds and the analagous anhydrosulphites could well make an interesting study in the light of the results presented here. Similarly preparation of substituted β-hydroxy acid anhydrosulphites if this were possible and an examination of their degradation products might provide circumstantial evidence of relevance to the α-hydroxy acid series.

The high temperature polymerisation of NCAs has been referred to (Section 1) a further examination of this aspect of their chemistry in the light of the results obtained here would be interesting. A direct comparison of the NCA of α-amino isobutyric acid with the analagous α-hydroxy acid anhydrosulphite might be made, paying particular attention to its behaviour in styrene and the possibility of α-lactam formation.

BIBLIOGRAPHY.

1. Goodman I., and Rhys J.A: Polyesters. Vol.1., Saturated Polymers. (Iliffe) (1965).
2. U.S. Patent: 2,585,427 (1952).
3. Bezzi S., Gazz. Chim. Ital. 79, 219, (1949) Chem. Abs. 44, 1022e, (1950).
4. Blaise E.E., and (Mlle) Montagne: Compt. Rend. 174 1173, (1922); Chem. Abs. 16, 2480, (1922).
5. Blaise E.E., and (Mlle) Montagne: Compt. Rend. 174 1553, (1922); Chem. Abs. 17, 3163, (1923).
6. Alderson T: U.S.P. 2, 811, 511, (1957).
7. Rose J.B., and Warren C.K: J.Chem. Soc. 791, (1965)
8. Davies W.H: J.Chem. Soc. 1357, (1951).
9. Davies W.H: British Patent, 650, 003, (1951).
10. Sorenson W.R., and Campbell T.W: Preparative Methods of Polymer Chemistry, p 242, Interscience, (1961).
11. Carothers W.H: The Collected Papers of W.H. Carothers, Ed. Mark and Whitby, Interscience, (1940).
12. Hall H.K: J.Amer. Chem. Soc. 80, 6404, (1958).
13. Hall H.K., and Schneider A.K: J.Amer.Chem.Soc. 80, 6409, (1958).
14. Hall H.K., Brandt M.K., and Mason R.M: J.Amer. Chem.Soc. 80, 6420, (1958).
15. Leuchs H., Ber. 39, 857, (1906).
16. Fuchs F., Ber. 55, 2943, (1922).

17. Wessely F: Z.Physiol Chem. 146, 72, (1925).

18. Waley S.G., and Watson J: Proc.Roy.Soc. A199, 499, (1949).

19. Ballard D.G.H., and Bamford C.H: Proc.Roy.Soc. A 223, 495, (1954).

20. Ballard D.G.H, and Bamford C.H: J.Chem.Soc. 1039, (1959).

21. Blout E.R., and Karlson R.H: J.Amer.Chem.Soc. 78,941, (1956).

22. Ballard D.G.H., and Bamford C.H: J.Chem.Soc. 381, (1956).

23. Bamford E.H., and Block H: J.Chem.Soc. 4989, (1961).

24. Stille J.K: Introduction to Polymer Chemistry, p. 117. Wiley (1962).

25. Vogel A.I: A Textbook of Practical Organic Chemistry. 2nd Ed. p 151. Longmans (1951).

26. Ingram G: Michrochim. acta 877, (1956). Methods of Organic Chemical Microanalysis. Chapman and Hall. (1962).

27. Ballard D.G.H and Bamford C.H: J.Chem.Soc. 355, (1958)

28. Mueller R.H., and Stolten H.J: Anal. Chem. 25,1103, (1953).

29. Higuchi W.I., Schwartz M.A., Rippie E.G., and Higuchi J. J.Phys.Chem. 63,996, (1959).

30. Billemeyer F.W, J.Poly. Sci.(C),No.8, 161, (1965)

31. Schram E: Organic Scintillation Detectors, Elesvier, (1963).

32. van Woerden H.F: Chemical Reviews, 63,557, (1963).

33. Lewis E.S., and Boozer C.E: J.Amer.Chem.Soc. 74,308, (1952).

34. Lewis E.S., and Boozer C.E: J.Amer.Chem.Soc. 75,3182, (1953).

35. Bartlett P.D., and Herbrandson H.F: J.Amer.Chem. Soc. 74,5971, (1952).

36. Cowdrey W.A., Hughes E.D.,Ingold C.K., Masterson S., and Scott A.D: J.Chem.Soc. pt 2, 1252, (1937).

37. Whitmore F.C., and Rothrock H.S: J.Amer.Chem.Soc. 54,3431, (1952).

38. Noeller C.R: Chemistry and Organic Compounds, 3rd. Ed. p 147 Sanders, (1965).

39. Ingold C.K: Structure and Mechanism in Organic Chemistry, p 318, and refs. cited therein. Cornell, (1951).

40. Gerrard W., and Howe B.K:J.Chem.Soc. 505, (1955).

41. Watson P.D: Ind.Eng.Chem. 399, 32, (1940).

42. Chudzynski S: Przemysl Chem. 28,211, (1949). Chem. Abs. 43, 9032h, (1949)

43. Weiser R.B., and Geankoplis C.J: Ind.Eng.Chem. 47,858, (1955).

44. Gerrard W., and Shepherd B.D: J.Chem.Soc. 2069,(1953)

45. Gerrard W., and Schild F: Chem. and Ind.1232, (1954).

46. Bunton C.A.,de la Mare P.B.D., Greasely P.M., Llewellyn D.R., Pratt N.H., and Tillett J.G: J.Chem.Soc. 4751,cf.4754,cf.4761, (1958).

47. Bunton C.A., de la Mare P.B.D., and Tillett J.G: J.Chem.Soc. 1766, (1959).

48. Davies E.D., and Tillett J.G: J.Chem.Soc. 4766,(1958)

49. de la Mare P.B.D., Tillett J.G., and van Woerden H.F. Chem. and Ind. 1533, (1961).

50. de la Mare P.B.D., Tillett J.G., and van Woerden H.F. J.Chem.Soc. 4888, (1962).

51. Tillett J.G: J.Chem.Soc. 37 and 5138, (1960).

52. Bunton C.A.,de la Mare P.B.D., Llewellyn D.R., Pearson R.B., and Pritchard J.G: Chem.& Ind.490,(1956)

53. Wessely F., and Sigmund F: Z.Physiol.Chem. 157, 91, (1926).

54. Hanby W.E.,Waley S.G., and Watson J: J.Chem.Soc. 3009, (1950).

55. Bartlett P.D., and Jones R.H: J.Amer.Chem.Soc. 79, 2153, (1957).

56. Katchalski E., and Sela M: Advances in Protein Chem. 13,243, (1958).

57. Fairclough R.A., and Hinshelwood C.N: J.Chem.Soc. 593. (1939).

58. Smith H.A., and Byrne F.P: J.Amer.Chem.Soc. 72,4406, (1950).

59. Szwarc M: Fortschritte der Hochpolymeren Forschung, 4,1, (1965).

60. Gold V: Trans. Farad. Soc. 44,506, (1948).

61. Gold V., and Bafna S.L: J.Chem.Soc. 1406, (1953).

62. Gold V., and Jefferson E.G: J.Chem.Soc. 1409,(1953).

63. Gold V., and Jefferson E.G: J.Chem.Soc. 1416,(1953).

64. Phillips J.C: Proc.Chem.Soc. 28,259, (1912).

65. Rivett A.C.D., and Sidgwick N.V: J.Chem.Soc. 732, (1910).

66. Wilsdon B.H., and Sidgwick N.V: J.Chem.Soc. 1959, (1913).

67. Moelwyn Hughes E.A., and Hinshelwood C.N: J.Chem.Soc. 230, (1932).

68. Moelwyn Hughes E.A., and Rolfe A.C: J.Chem.Soc. 241, (1932).

69. Kilpatrick M: J.Amer.Chem.Soc. 50,2891, (1928).

70. Matlack A.S., and Breslow D.S: J.Org.Chem. 22, 1723, (1957).

71. Bateman L., Cain.M.,Colclough T., and Cuneen J.I: J.Chem.Soc. 3570, (1962).

72. Kingsbury C.A., and Cram D.J: J.Amer.Chem.Soc. 82,1810, (1960).

73. Walling C., and Bollyky L: J.Org.Chem. 29,2699,(1964).

74. Entwhistle I.D., and Johnstone R.A.W: Chem.Comm. 29, (1965).

75. Fromm E., and Achert O: Ber. 36,534, (1903).

76. Barnard Smith D.G., and Ford J.F: Chem.Comm. 121, (1965).

77. Caruthers W., Entwhistle I.D., Johnstone R.A.W., and Millard B.J: Chem.and Ind. 342, (1966).

78. Drake L.R., Stowe S.C., and Partansky A.M: J.Amer.Chem.Soc. <u>68</u>,2521, (1946).

79. Tarbell D.S., and Leister N.A: J.Org.Chem. <u>23</u>,1149, (1958).

80. Tarbell D.S., and Leister N.A: J.Org.Chem. <u>23</u>,1152, (1958).

81. Tarbell D.S., and Longosz E.J: J.Org.Chem. <u>24</u>,774, (1959).

82. Tarbell D.S., and Parasaran T: J.Org.Chem. <u>29</u>,3422, (1964).

83. Michejda C.J: Diss.Abs. <u>25</u>,1576, (1964).

84. Bamford C.H., Barb W.G., Jenkins A.D., and Onyon P.F: "The Kinetics of Vinyl Polymerisation", Butterworths(1958).

85. Walling C: "Free Radicals in Solution", Wiley, (1957).

86. Reference 84. Page 220.

87. Bartlett P.D., and Nozaki K:J.Amer.Chem.Soc.<u>68</u>,2686,(1946).

88. Levy M., Steinberg M., and Szwarc M: J.Amer.Chem.Soc. <u>76</u>,5928, (1954).

89. Kleinfeller H., and Rastadler K: Angew.Chem. <u>65</u>,543, (1953).

90. Russel K.E: J.Amer.Chem.Soc. <u>77</u>,4814, (1955).

91. Greene F.D: J.Amer.Chem.Soc. <u>78</u>,2246, (1956).

92. Jones G.D., and Friedrich R.E: U.S.Pat. 2,619,507, (1952).

93. Graf R: Ann. 578,50, (1952).

94. Heyns K., and Brockman R: Z.Naturforsch.9b,21,(1954).

95. Cook A.H., and Levy A.L: J.Chem.Soc. 637, (1950).

96. Aubert P., Jeffreys R.A., and Knott E.B: J.Chem. Soc. 2195, (1951).

97. Zutty N.L.,Wilson C.W., Potter G.H.,Priest D.C., and Whitworth C.J: J.Poly.Sci. (A) 3,2781, (1965).

98. Overberger C.G., and Lapin M: J.Amer.Chem.Soc. 77, 4651, (1955).

99. Flory P.J: Principles of Polymer Chemistry, p122, Cornell, (1953).

100. Haward R.N: Trans. Farad.Soc. 46, 204, (1950).

101. Russel K.E., and Tobalsky A.V: J.Amer.Chem.Soc. 75,5052, (1953).

102. Swain C.G., Stockmeyer W.H., and Clarke J.T: J.Amer.Chem.Soc. 72, 5426, (1950).

103. Barb W.G: Proc.Roy.Soc. A 212, 66 and 177, (1952).

104. Barb W.G: J.Poly.Sci. 10,49, (1953).

105. Zaug H. in "Organic Reactions". Vol.V111 ed. Adams, Wiley, (1954).

106. Reynolds R.J.W., and Vickers E.J: Canadian Pat. 549,347. (1957).

107. Ohse H., Cherdron H.,and Korte F: Macromol Chem. 86,312, (1965).

108. Ballard D.G.H., and Bamford C.H: Proc.Roy.Soc. A 236, 384, (1956).

109. Robb J.C., and Lehrle R.S: Polymer 2,27, (1961).

110. Winstein S., and Lucas H.J. J. Amer. Chem. Soc. 61, 1576, (1939).

111. Grünwald E., and Winstein S: J. Amer. Chem. Soc. 70, 841, (1948).