NORTHEASTERN UNIVERSITY

GRADUATE DIVISION

Thesis Title: Triple Bond Participation in The Oxy-Cope Rearrangement.

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Approved for Thesis Requirements of the Doctor of Philosophy Degree

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TRIPLE BOND PARTICIPATION IN THE OXY-COPE REARRANGEMENT

A Thesis Presented

by

John Harry MacMillan

to

The Department of Chemistry

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

in the field of

Chemistry

Northeastern University
Boston, Massachusetts

May, 1970

ACKNOWLEDGMENTS

I wish to express my deepest appreciation to my advisor, Dr. Alfred Viola, for the help and guidance which I received in the course of my research and in the writing of this thesis.

I wish to thank Dr. E. J. Iorio for his assistance in the early stages of the experimental work.

Also, I should like to thank Miss Noralee Barnett for an excellent job in drawing the numerous formulas and graphs with which this thesis is illustrated; to Miss Dianne O'Keefe and my mother, Mrs. Enid MacMillan, for help in the typing of this thesis. I also wish to acknowledge the financial support of Northeastern University for the period June, 1968, to June, 1970.

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Abstract

As a part of the study of oxy-Cope systems in this laboratory, some examples of triple bond participation in these reactions have been investigated.

In general, the experimental results indicate that acetylenes and allenes participate readily in cyclic six membered transition states and that triple bond participation in electrocyclic reactions leads to increased rates in comparison with the corresponding olefinic structures.

1-Hexen-5-yn-3-ol was subjected to vapor phase thermolysis in a flow system over the range of 350-90° and under various pressures. The extent of β-hydroxyolefin cleavage, which leads to formation of acrolein and allene, is independent of residence time in the thermolysis zone but increases with temperature, indicative of a higher activation energy than for the competing rearrangement processes. One of these processes affords 4,5-hexadienal via an acetylenic analog of the oxy-Cope reaction. Also produced is Δ^3-cyclopentenecarboxaldehyde in amounts increasing with increasing temperature and/or residence time. The data is consistent with an electrocyclic reaction involving the enolic progenitor of the oxy-Cope product, which ketonizes only upon condensation in the product trap.

The thermolysis of 3-methyl-1-hexen-5-yn-3-ol was reinvestigated due to conflicting literature reports concerning product formation. The production of both vinyl acetylcyclopropane and 4-acetylcyclopentene has been verified in this laboratory. The effect of the methyl group upon product composition is interpreted on the basis of a torsional effect in the transition state.

Thermolysis of 5-hexen-1-yn-3-ol affords Δ^2- and Δ^3-cyclopentene-carboxaldehydes, trans-2,5-hexadienal and sorbaldehyde in varying amounts dependent upon temperature and contact time. Since the competing β-hydroxyolefin cleavage is completely absent, kinetic parameters could be determined. The Arrhenius energy of 30 ± 2 kcal/mol and ΔS^* of -14e.u. are indicative of a concerted mechanism. The kinetic data, the effects of temperature and contact time upon product distribution and the results of a deuterium tracer indicate the intermediacy of the primary oxy-Cope product in the formation of all observed products. These reactions constitute the chemistry of an allenol intermediate, 1-hydroxy-1,2,5-hexatriene.

Thermolysis of 1-phenyl-3-butyn-1-ol and 1-phenyl-2-methyl-3-butyn-2-ol gave no trace of oxy-Cope rearrangement products, indicating the unwillingness of the phenyl group to participate in the oxy-Cope rearrangement.

Thermolysis of 1,5-hexadiyn-3-ol at 350° gives 4-methylene-2-cyclobutene-1-carboxaldehyde and phenol. The hydroxy group greatly facilitates the aromatization pathway. Phenol production increases with increasing temperature or residence time. 3-Methyl or 4,4-dimethyl substitution blocks the pathway leading to aromatization. 4-Methyl substitution gives o-cresol as the only aromatic product. The data indicate the absence of hydroxy migration or carbon skeletal rearrangements in the formation of phenol. Prismane or benzvalene intermediacy is ruled out on the basis of this data. A mechanism for phenol formation is presented involving the intermediacy of the primary oxy-Cope product.

Thermolyses of 5-hexyn-3-ol and 2-methyl-4-pentyn-2-ol afford quantitative conversions to cleavage products. Kinetic studies show

both reactions to be first order and to possess highly negative entropies of activation, indicative of concerted mechanisms with cyclic transition states. Both alcohols gave faster cleavage rates and lower activation energies than the corresponding literature values of their olefinic analogs.

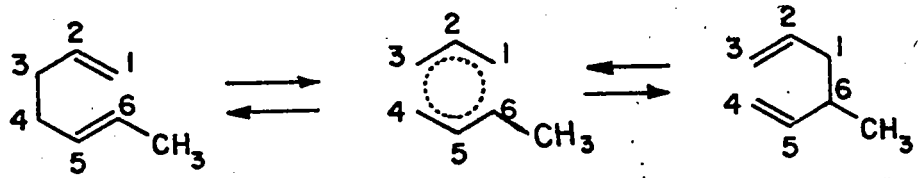
Grignard reagents are found to add to the internal carbon atom of the triple bond in propargylic alcohols to yield 2-methylene substituted alcohols. The presence of a carbinol function bonded to the internal alkyne carbon atom is necessary for the addition to occur.

HISTORICAL REVIEW

The last ten years have seen an increased interest in thermal reactions passing through cyclic six membered transition states. These reactions are exemplified by the Cope rearrangement and by β -hydroxyolefin cleavage.

The Cope Rearrangement

The classical Cope rearrangement has been reviewed by Rhoads,[1] Vogel,[2] and more recently by Frey[3]. Since this reaction was thoroughly discussed in a previous thesis presented to this department,[4] only the essentials of the reaction will be considered here. It may be described as a thermal, uncatalyzed reaction of a diallylic molecule (1) to give an isomeric diallylic molecule (2) via a cyclic transition state.

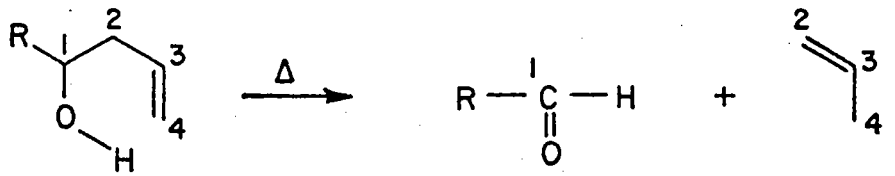


1 2

The reaction has been shown to be intramolecular,[5] to proceed with inversion of the migrating group[5], and to possess a large negative entropy of activation[6]. Since these reactions are unimolecular and insensitive to solvent polarity, they are usually termed "concerted" processes.

The β-Hydroxy Olefin Cleavage

This thermal decomposition, described by Arnold and Smolinsky[7], was also reviewed in a previous thesis.[4] The reaction consists of a concerted 1,5-hydrogen shift in a β-hydroxy-olefin (3) with concurrent breakage of the 1,2-carbon-carbon bond.



3

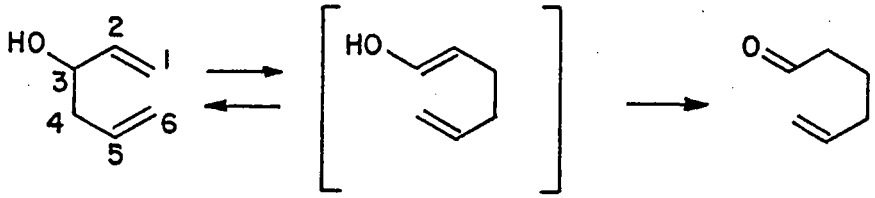
The products of the reaction are a carbonyl compound and an olefin. Smith and Yates[8], showed that phenyl substitution in the 2 position had little effect on the reaction rate. Phenyl substitution in the 4 position retarded the rate since the double bond moved out of conjugation during the reaction. Substitution at position 3 accelerated the rate. The authors believed this acceleration to be due to the phenyl group stabilizing a partial positive charge developing at position 3 in the transition state for the reaction.

Both of the reactions described above seem to be operative in the oxy-Cope system. This reaction has been defined[9] as the rearrangements of 1,5-hexadienes bearing a 3-hydroxy substituent.

The Oxy-Cope Rearrangement

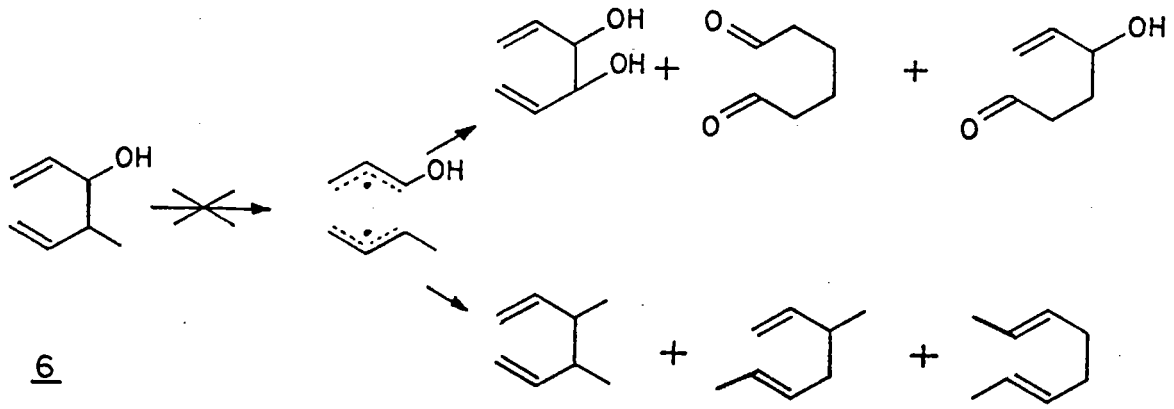
Berson and Jones[10] studied the oxy-Cope rearrangement in rigid bicyclic systems. This work was fully described in the earlier thesis[4]. A diradical mechanism was postulated to account for the products.

Viola and Levasseur[9] showed that the thermal rearrangement of 1,5—hexadien—3—ol (4) gave 5—hexenal (5),presumably via an enolic intermediate.



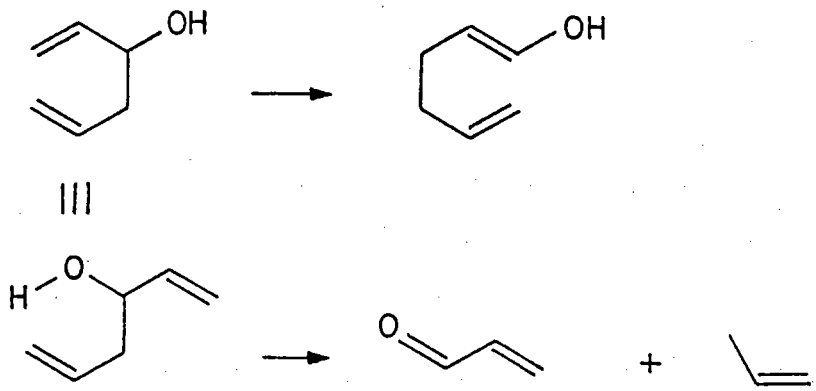
4 5

Viola et al.[11] studied the mechanism of the oxy-Cope reaction in a linear, unconstrained system. Ten methyl derivatives of 1,5—hexadien—3—ol were prepared and thermolyzed. All gave the expected oxy-Cope products in addition to the compounds resulting from β-hydroxyolefin cleavage. In no instance could any product resulting from radical cleavage, followed by recombination of like fragments be observed. For example, in the 4—methyl substituted compound (6) the following products can be anticipated from a diradical mechanism.



6

In view of these results the reaction was interpreted as involving two competing concerted electrocyclic reactions. The relative rates depend on the relative activation energies for the respective cyclic six membered transition states. Methyl substitution in the 1 position favored the cleavage reaction due to steric factors. Substitution of a methyl group in the 5 position favored the cleavage reaction due to stabilization of a transient positive charge by the electron donating methyl group. Methyl substitution in the 2,3 and 4 positions had only minor effects, if any, upon the ratio of Cope to cleavage products.

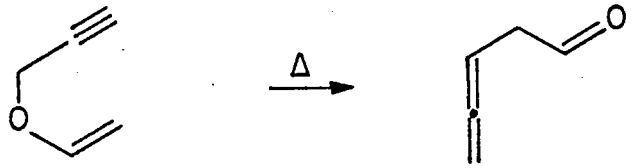


Since this investigation dealt with the participation of acetylenic bonds in the oxy-Cope process, previously reported examples of triple bond envolvement in six membered cyclic transition states will be reviewed.

Acetylenic Claisen and Cope Rearrangements

In comparison to the host of studies undertaken on olefinic Cope and Claisen rearrangements, reports involving triple bond participation are few in number.

Black and Landor[12] reported the vapor phase thermolysis of propargyl vinyl ether (7) to yield 3,4—pentadienal (8) in a process analogous to the nonaromatic Claisen rearrangement.



7 8

Several methyl substituted derivatives were also thermolyzed and the results are presented on plate I. Since much polymer was formed in the rearrangements the authors postulated a free radical mechanism involving a "1 electron shift" with partial radical formation at C_1 and C_3 .

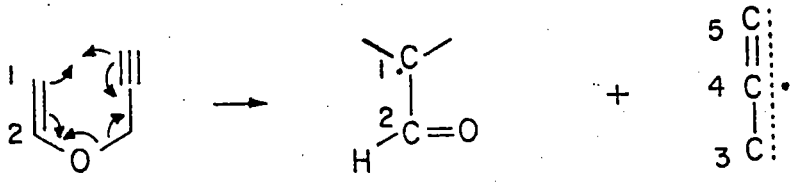
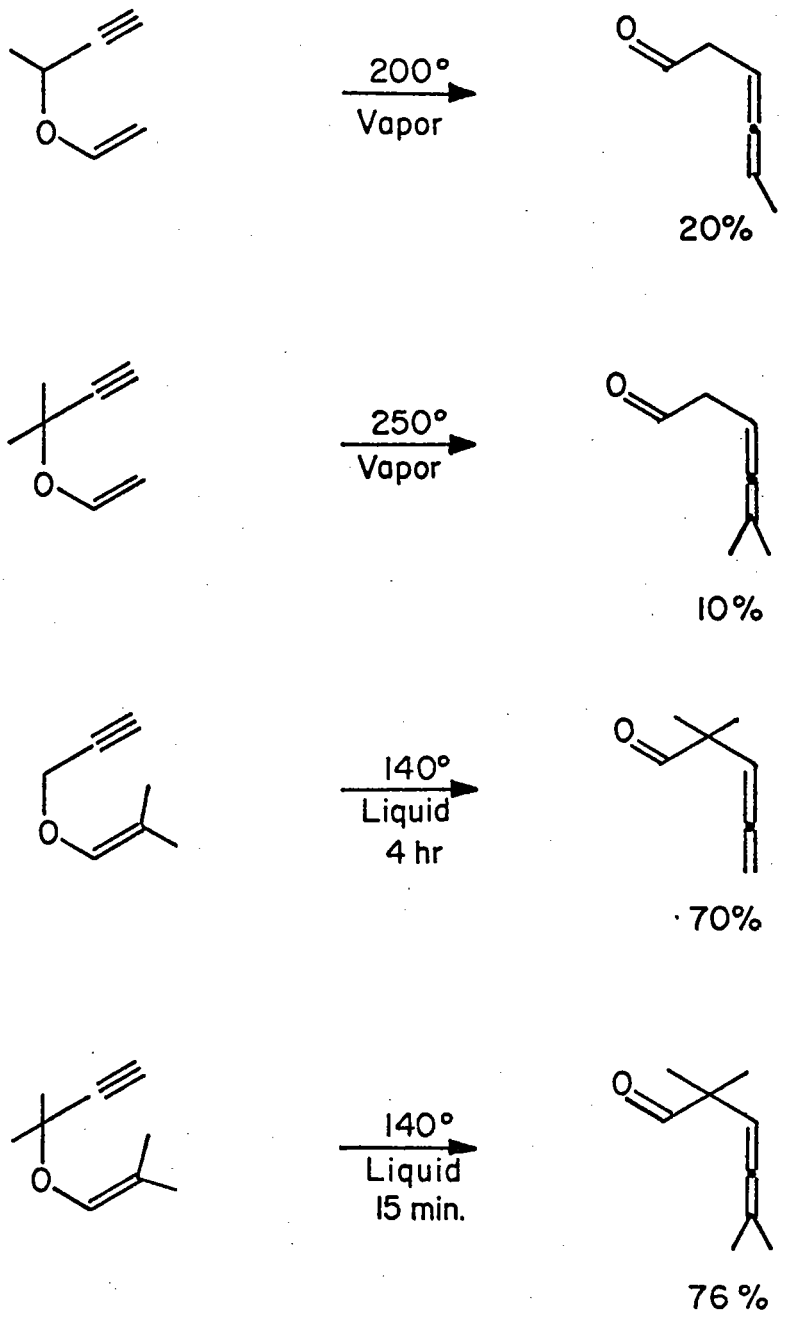
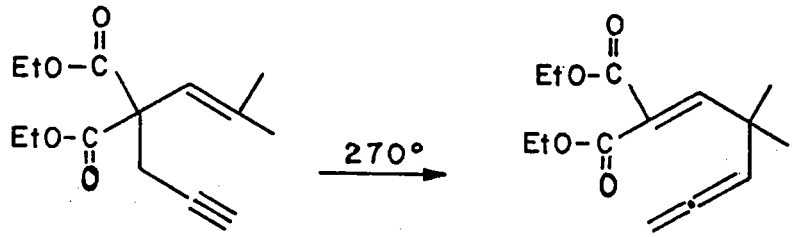


PLATE I


200°
Vapor
20%
250°
Vapor
10%
140°
Liquid
4 hr
70%
140°
Liquid
15 min.
76 %

The fact that methyl substitution accelerated the reaction was taken as additional evidence for this mechanism.

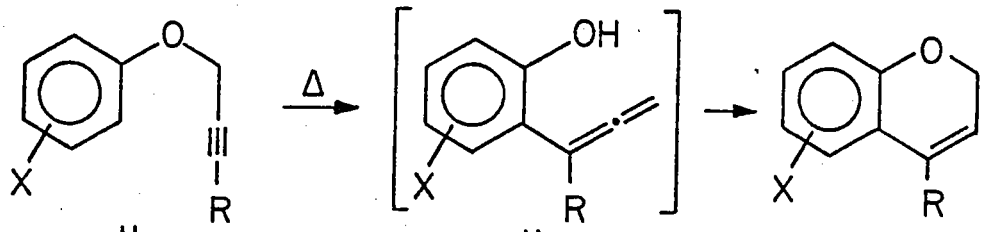
In addition, these authors reported the thermolysis of diethyl isobutenylpropargylmalonate (9) to yield diethyl -2,2—dimethylpent—3,4— dienylidene—malonate (10). This reaction is a Cope rearrangement involving an acetylenic link.



9 10

Much polymer was also formed in this reaction.

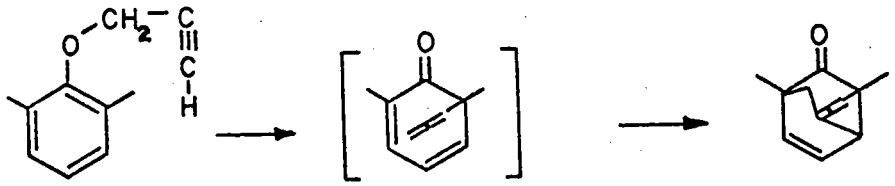
Iwai and Ide[13] attempted aromatic Claisen reactions of substituted phenyl propargyl ethers (11) but were only able to isolate the isomeric chromene (12).



11 11a 12

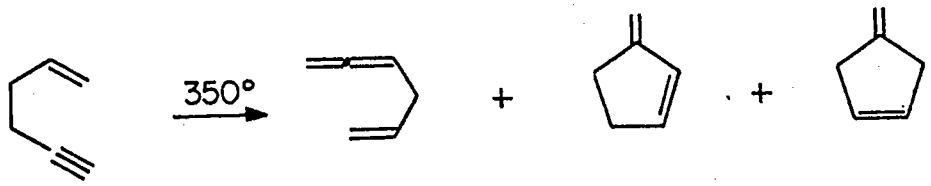
The authors proposed direct cyclization without an intermediate. However it has been shown that o—allenyl phenol(11a) on heating is converted to chromene.[14]

Zsindely and Schmid[14] showed that the rearrangement of 2,6 —dimethylphenylpropargyl ether (13) resulted in the formation of a tricyclic ketone (14). It was believed that an allene -dienone intermediate was formed via a Claisen rearrangement, which subsequently underwent an internal Diels Alder reaction.



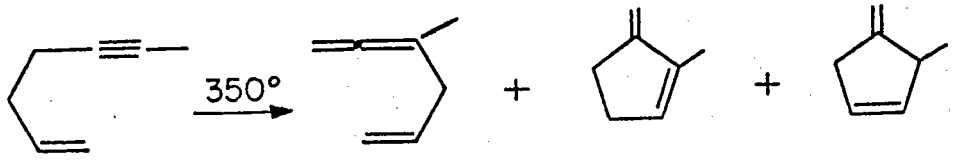
13 14

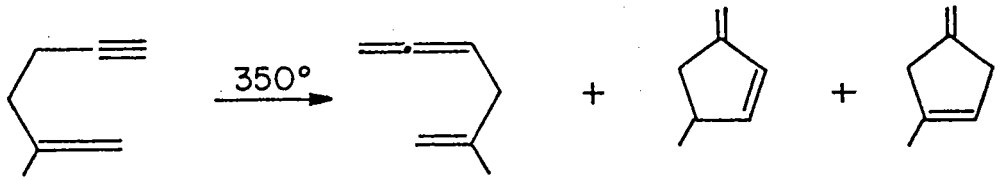
Huntsman et al[15] thermolyzed 5—hexen—1—yne (15) and found it to yield 1,2,5 —hexatriene (16), 3—methylene cyclopentene (17) and 4—methylenecyclopentene (18).



15 16 17 18

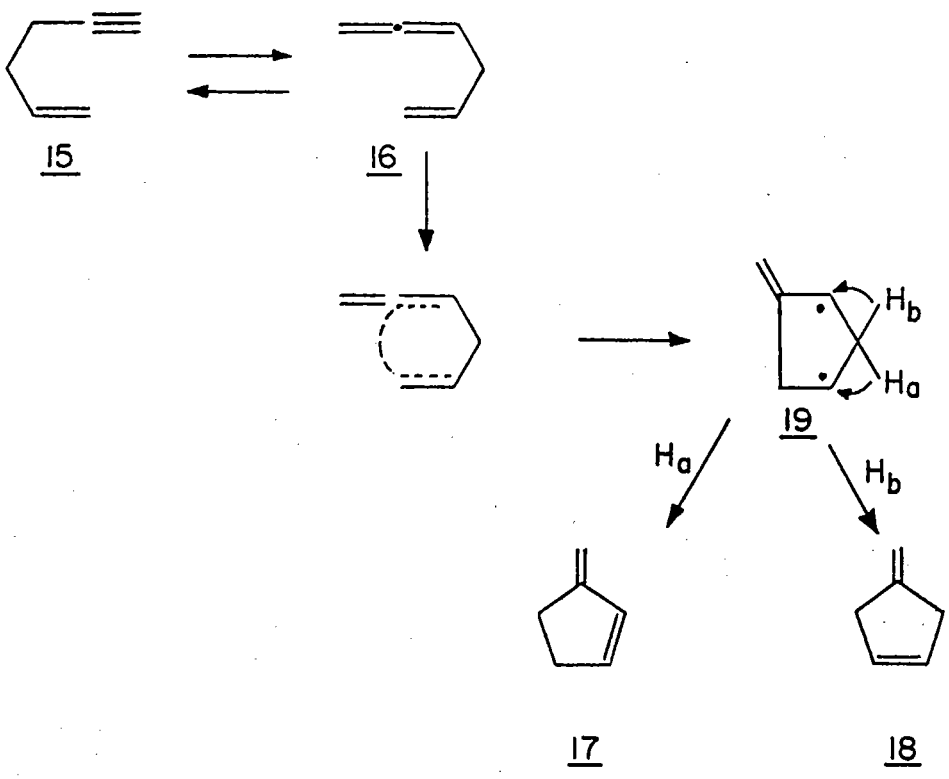
Two methyl substituted derivatives were also thermolyzed and the results are given below.



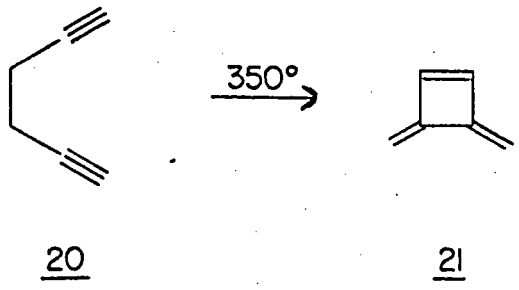


It was found that the longer the reaction mixture was maintained in the thermolysis zone, the more cyclic product formed at the expense of the allenic product. The conjugated isomer was always the major cyclic product. Methyl substitution at the terminal acetylenic position resulted in a decreased rate of disappearance of starting material. Both methyl substituted derivatives showed increased rates of formation of cyclic products compared to the unsubstituted system. Reversibility of the initial Cope process was demonstrated with 1,2,5—hexatriene (16) which, when thermolyzed, afforded 5—hexen—1—yne (15)in addition to the cyclic products.

The above considerations lead the authors to propose the following mechanism. The mechanism involves a reversible Cope rearrangement followed by an irreversible cyclization of the hexatriene to form a diradical intermediate. Rapid 1,2—hydrogen shifts then give the cyclic products. Methyl substitution results in one of the radical centers becoming tertiary, thus resulting in a lower activation energy for the cyclizations.

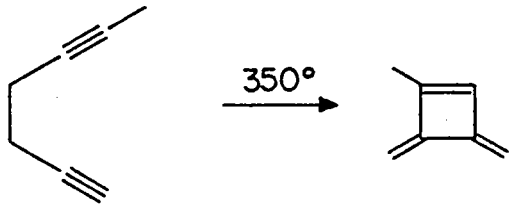


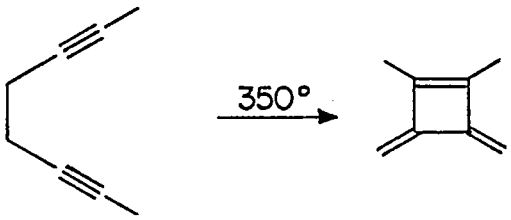
Huntsman and Wristers[16] reported the thermal rearrangement of 1,5—hexadiyne (20) to yield 3,4—dimethylene cyclobutene (21) as the sole product.



20 21

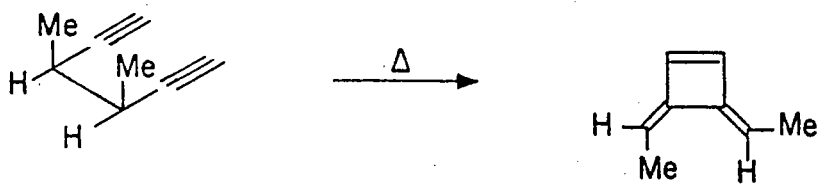
Kinetic data on the rearrangement gave an activation energy of 34.4 kcal/mole and an entropy of activation of -9.4 e. u. These values were considered consistent with a concerted reaction involving a cyclic transition state. Similarly, the following methyl derivatives were thermolyzed.



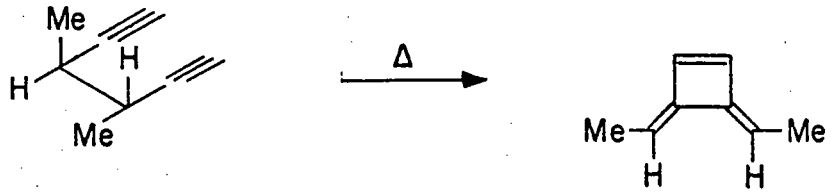


The terminal methyl substituted derivatives reacted at slower rates than the unsubstituted compound.

In order to gain insight into the stereochemistry of the rearrangement, meso-3,4—dimethyl—1,5—hexadiyne (22) was thermolyzed to give syn, anti-3,4—diethylidene cyclobutene (23) while rac—3,4—dimethyl—1,5—hexadiyne (24) gave the anti, anti isomer (25).



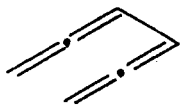
22 23



24 25

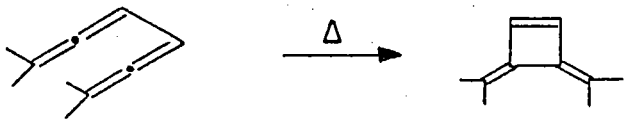
Thus it appears that the methyl groups rotate in the same direction during the cyclization, i.e. a conrotary[17] process occurs.

A possible mechanism considered by the authors involves an initial Cope rearrangement yielding a tetraene (26)



26

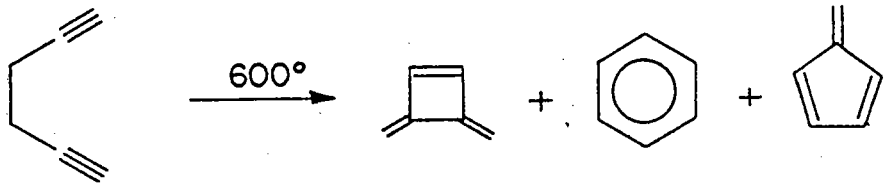
which then rapidly undergoes an internal cyclization to the observed product.



26a

Such a process is predicted to result in conrotary motions of the methyl groups[17]. In support of this mechanism is the observation of Skattebol[18] that 26a does undergo facile thermal rearrangement to diisopropylidenecyclobutene.

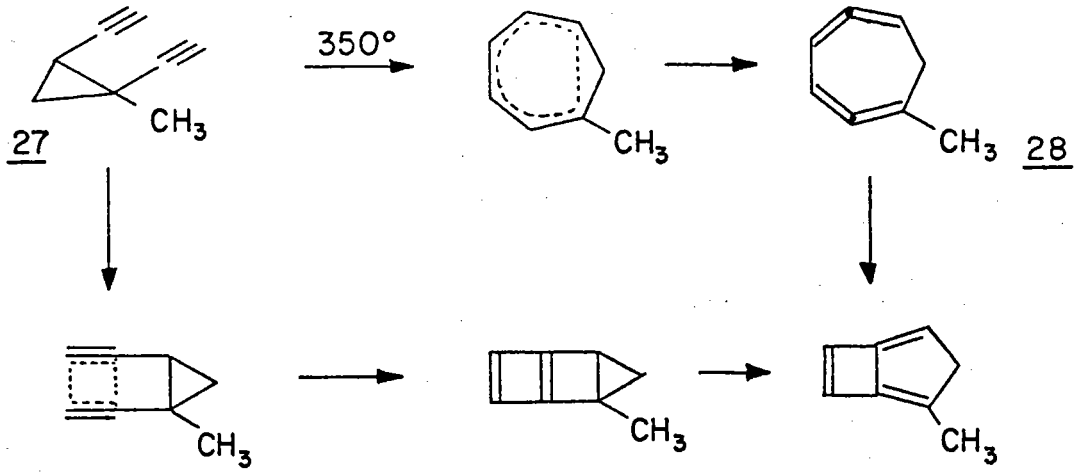
However, since Huntsman found no trace of allenic products in his reaction mixtures he did not favor the above mechanism. Since carbon atoms 1 and 6 appeared to be too far apart for bonding, he favored a one step mechanism in which bonding arises between carbon atoms 2 and 5 concurrent with rupture of the 3,4 bond. Coller et al[19], in a more recent theoretical treatment, reject the one step process on molecular orbital grounds and prefer the intermediacy of the tetraene. Coller also showed that thermolysis of 20 at 600°yielded benzene and fulvene in addition to 21.



20 21

Bergman[20] has found that 1—methyl—1,2—diethynyl cyclopropane (27) upon thermolysis gave 2—methylbicyclo (3.2.0) hepta—1,4,6—triene (30) as the only isolable product.

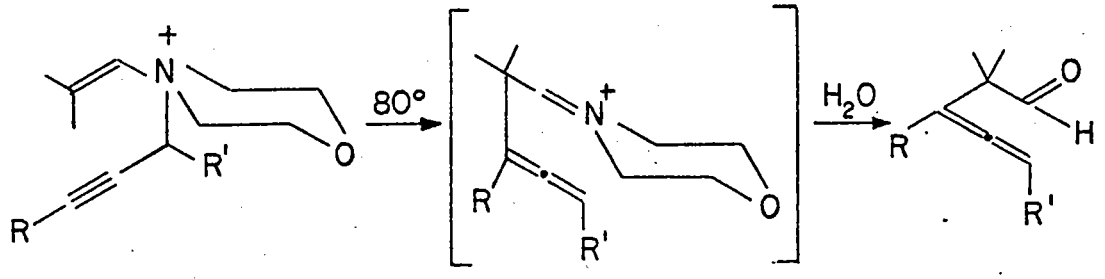
The results were interpreted as possibly involving a bis-allene (28) or cyclobutadiene (29) intermediate.



27 28 29 30

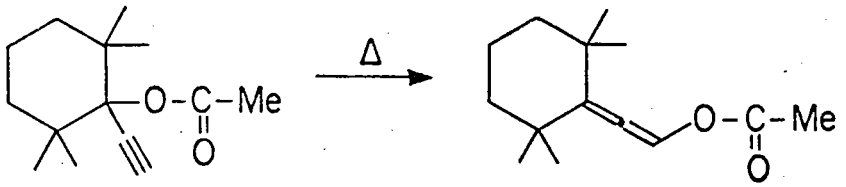
Miscellaneous Examples of Triple Bond Participation in Cyclic Six Membered Transition States.

Cresson and Corbier[21] showed that the quaternary ammonium species 31 on hydrolysis at 80° gave allenic aldehyde 33. They postulated an initial Claisen like rearrangement to 32 followed by hydrolysis.



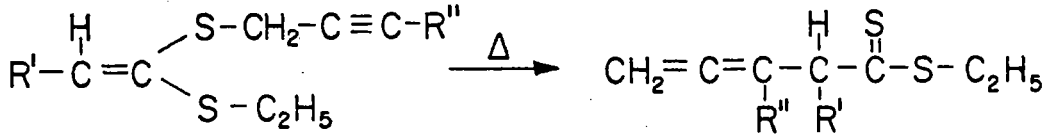
31 32 33

Landor[22] described a novel rearrangement of the acetylenic ester 34 which thermally isomerized to the allenic ester 35



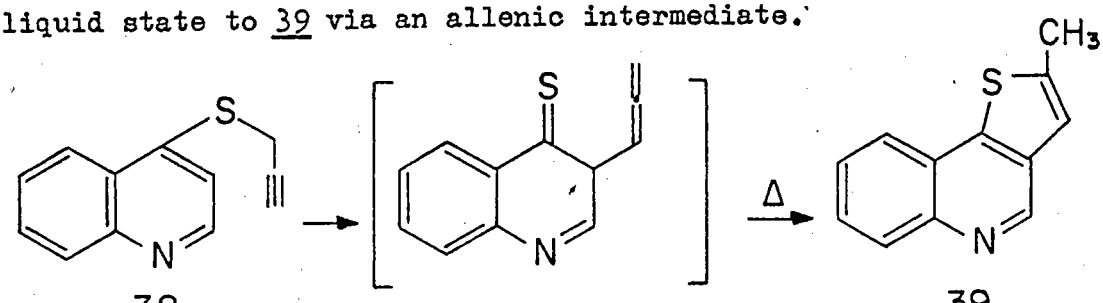
34 35

An example of a thio-Claisen rearrangement involving triple bond participation was described by Schuizl et al.[23] who found 36 to rearrange thermally to 37



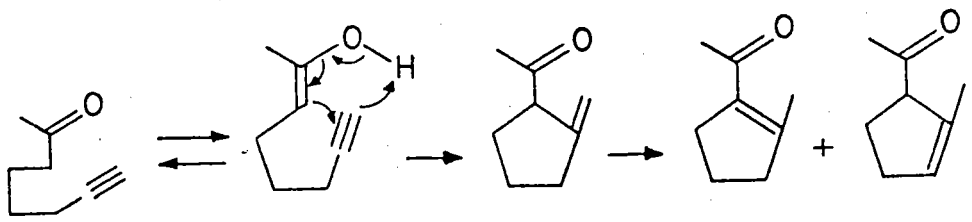
36 37

Another example was described by Makisumi[24] who found propargyl 4-quinolyl sulfide (38) to rearrange thermally in the liquid state to 39 via an allenic intermediate.



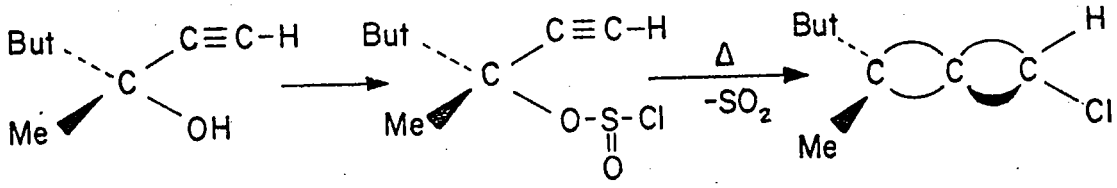
38 39

Bloch et al.[25] described a thermal cyclization of the acetylenic ketone 40 to various cyclopentenes. The reaction was believed to involve a thermal rearrangement of the enol from 40.



40

Evans et al[26] gave an example of triple bond participation in a cyclic six membered $S_N i'$ reaction. Enantiomeric alcohol 41 on treatment with thionyl chloride and heat gave a chloro-allene with retention of optical activity.

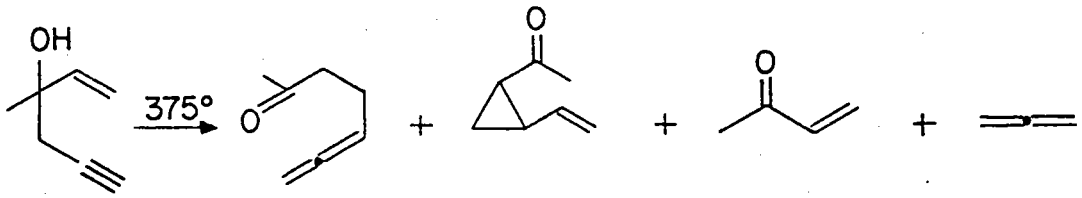


41

Acetylenic Oxy-Cope Rearrangements

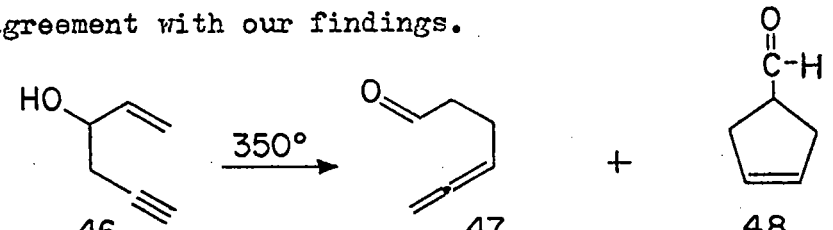
During the course of this thesis work, two papers appeared which are closely related to the research reported here. Wilson and Sherrod[27] reported the thermolysis of 3-methyl-1-hexen-5-yn-3-ol (42) to yield 5,6-heptadien-2-one (43), 1-acetyl-2-vinylcyclopropane (44), methyl vinyl ketone(45) and allene. The authors postulate 43 as arising through an oxy-Cope process while 45 and allene arise via an acetylenic analog of a β-hydroxyolefin cleavage. Compound 44 was believed to arise via an electrocyclic reaction of the enolic precursor to

the Cope product. This system will be treated more fully in the discussion section.



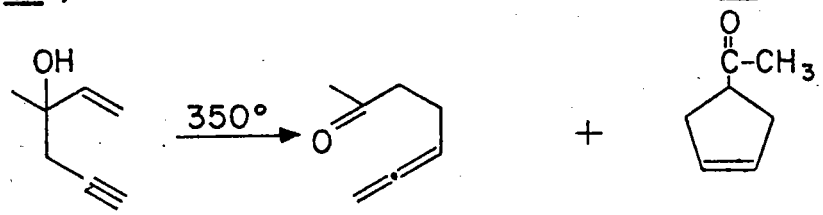
42 43 44 45

After publication of the first portion of this thesis work, a paper by Chuche and Manisse[28] appeared which dealt with similar systems. They reported 1—hexen—5—yn—3—ol (46) to give 4,5—hexadienal (47)and Δ^3—cyclopentene carboxaldehyde (48) in agreement with our findings.



46 47 48

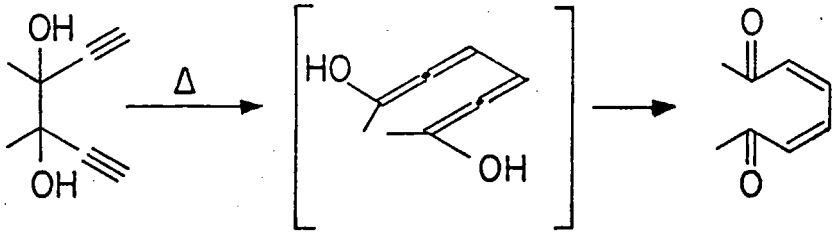
However, they also reported 42 to yield 4—acetylcyclopentene (49) in addition to the oxy-Cope product, 43.



42 43 49

No 44 was reported by these authors. The discrepancy in the results between the two sets of authors will be considered in the discussion section.

In addition, Chuche and Manisse thermolyzed 3,4 —dimethyl 1,5 —hexadiyn —3,4 —diol (50) to yield 3,5 —octadien —2, —7- -dione (51),presumably through a bis-enolic intermediate.

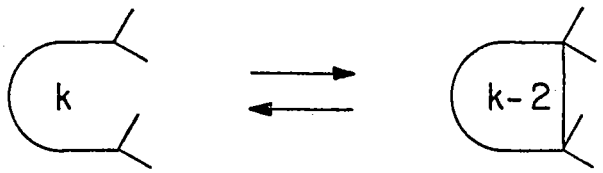


50 51

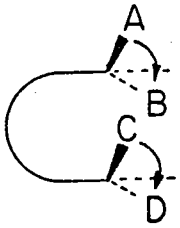
The Woodward-Hoffman Rules

Few theories have had an impact upon organic chemistry comparable to the Woodward-Hoffman rules[17,29] for orbital symmetry control of concerted processes. Since these rules have been extensively reviewed,[29,30] only those facets pertinent to the work in this thesis will be briefly presented. It must be emphasized that these rules apply only to concerted reactions.

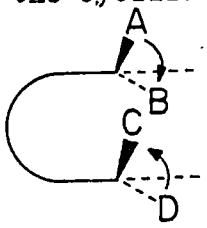
Electrocyclic reactions are defined as the formation of a single bond between the termini of a linear system containing k π electrons or the converse process.



A conrotary process is one in which the terminal groups rotate in the same clockwise or counterclockwise direction during the cyclization.

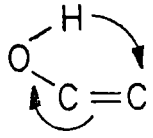


In a disrotary process the terminal groups rotate in opposite directions during the cyclization.

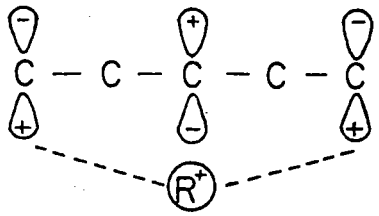


For thermal reactions (only the thermal case will be considered here) the cyclization is conrotary for k = 4Q where Q= 0,1,2,3,... ∞. Thus the Cope rearrangement, where four π electrons are involved in the bond reorganization, should be a conrotary process.

A sigmatropic rearrangement of order (i,j) is defined as the migration of a σ bond, flanked by a π system, to a new position which is i-1 and j-1 atoms separated from the original bond. For example, the ketonization of an enol is a sigmatropic rearrangement of order (1,3).

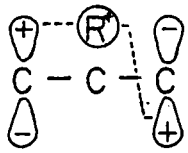


For a suprafacial process the migrating nucleus remains at all times on the same side of the π electron plane. For example:



The above migration is order (1,5) and suprafacial.

For an antarafacial process the migrating nucleus is transferred from one side of the plane of the unsaturated framework to the other. For example:



The above migration is order (1,3) and antarafacial.

The migrations of pertinence to the work reported in this thesis are hydrogen shifts. For thermal uncatalyzed rearrangements, the rules state that (1,3) hydrogen shifts are antarafacial,(1,5)hydrogen shifts suprafacial and (1,7)hydrogen shifts antarafacial. A (1,3)antarafacial hydrogen shift is extremely unfavorable, sterically, and no concerted (1,3) hydrogen transfer has ever been reported. All (1,3)hydrogen

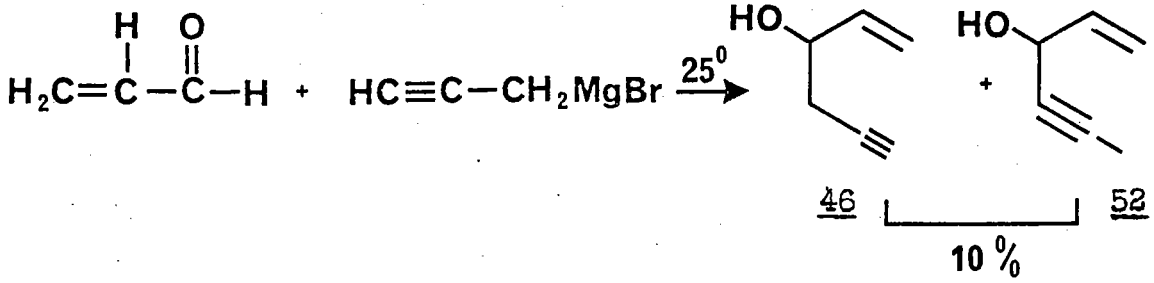
shifts are non-concerted and catalyzed. A (1,5) hydrogen shift, being suprafacial, is a facile process sterically and may proceed in a concerted manner. A (1,7) hydrogen shift, although an antarafacial process, is not sterically prohibitive and concerted (1,7) hydrogen transfers are possible.

DISCUSSION

As a part of the study of the oxy-Cope reaction and β-hydroxyolefin cleavage in this laboratory, the following compounds were synthesized and thermolyzed.

Investigation of vinyl propargyl carbinols

1-Hexen-5-yn-3-ol (46) was initially prepared by the method of Gaudemar[31], which consisted of the addition of acrolein to propargylmagnesium bromide at room temperature, followed by hydrolysis.



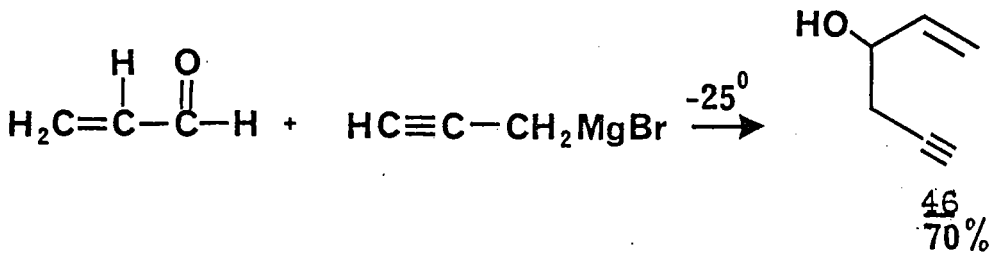
The yield of volatile product was quite poor. Although physical constants for the resulting material agreed with the literature[31], v.p.c.* of the material showed two components of nearly equal concentration.

The compounds were separated by preparative v.p.c. One compound was identified as 46 while the second component was assigned the 1-hexen-4-yn-3-ol (52) structure on the bases of infrared, n.m.r. and hydrogenation data. The spectral data for 52 are given in the experimental section, page 123. The infrared spectrum of 52 showed absorption at 2200 cm^{-1} but

---

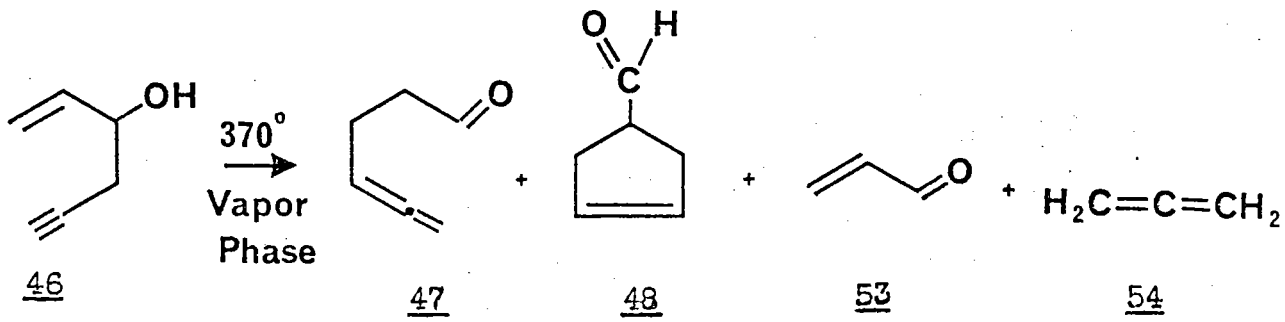
*The term v.p.c. will be used throughout this thesis for vapor phase chromatography.

no "spike" in the spectrum corresponding to a terminal acetylenic hydrogen. Hydrogenation of 52 gave 3-hexanone due to the now well documented[32] hydrogen transfer reaction of allylic alcohols on palladium catalysts. The formation of 52 is in accord with the results of Sondheimer[33] who reported formation of internal acetylenes in the "normal" reaction of propargylmagnesium bromide with propargylaldehyde. He suggested a low temperature Barbier synthesis to give a high yield of product uncontaminated with internal acetylene. This procedure, described in the experimental section, page 114, gave 46 in 70% yield with no trace of 52.



The elementary analysis and spectral data for 46 are consistent with the structure and are given in the experimental section, page 115. Hydrogenation of 46 gave 3-hexanol as the major and 3-hexanone as the minor product. The 3-hexanol was identified as its acid phthalate derivative.

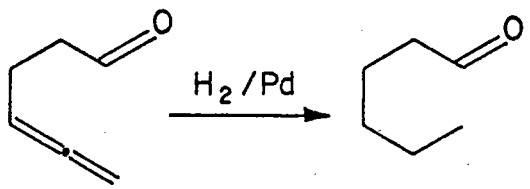
Thermolysis of 46 produced four products, shown to be 4,5-hexadienal (47), Δ^3-cyclopentenecarboxaldehyde (48), acrolein (53) and allene (54).



Acrolein (53) was identified by its characteristic odor, v.p.c. retention time, infrared spectrum and 2,4-dinitrophenylhydrazone derivative.

Allene (54) was identified only as a small peak near the air peak, in the v.p.c. The mass balances of the thermolyses require a three carbon hydrocarbon to be present although the possibility of formation of propyne could not be excluded.

4,5-Hexadienal (47) was identified by its infrared and n.m.r. spectra and hydrogenation to hexanal.



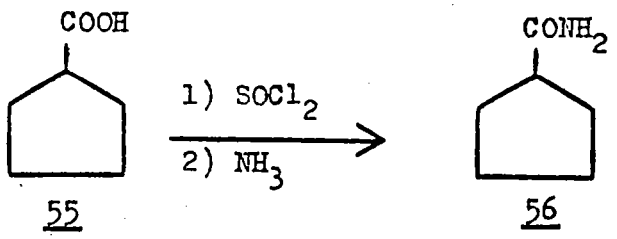
47

The spectra are described in the experimental section, page 121. Hexanal was identified by its infrared spectrum and 2,4-dinitrophenylhydrazone derivative.

Δ^3-Cyclopentenecarboxaldehyde (48) gave infrared and n.m.r. spectra consistent with the assigned structure. They are detailed in the experimental section, page 118. The n.m.r. spectrum closely parallels that reported for Δ^3-cyclopentenecarboxylic acid in which the olefinic protons also appear as a singlet at a chemical shift value very close to that found for 48.

Hydrogenation of 48 was quantitative for one double bond and gave a saturated aldehyde. The aldehyde was quantitatively air oxidized to a saturated acid whose infrared spectrum was totally identical to that

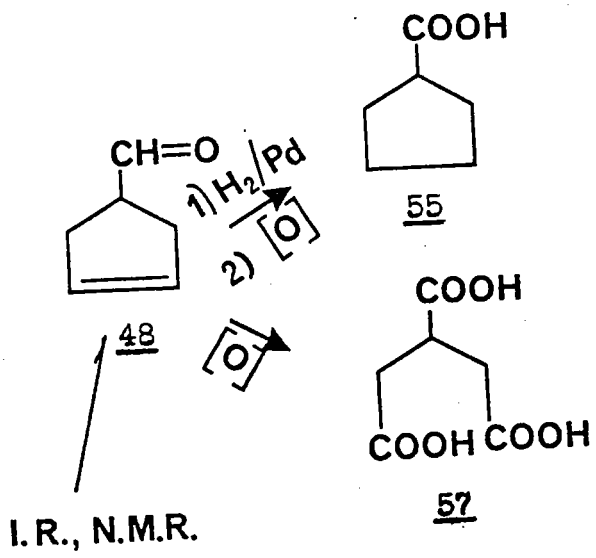
published[35] for cyclopentanecarboxylic acid (55). The acid was converted into its amide derivative (56) whose melting point was in exact agreement with the literature value.[61]



55 56

Although the skeleton of 48 had been rigorously established and the n.m.r. was consistent with the postulated structure, chemical evidence was sought for the postulated position of the double bond. Consequently, 48 was oxidized with alkaline permanganate to give a solid acid of melting point 158-159°, in close agreement with the literature value of 160-161° for 1,2,3-tricarballylic acid (57). This acid can arise only from the double bond in the Δ^3-position. The Δ^1-isomer is ruled out by the n.m.r. spectrum while oxidation of the Δ^2-isomer would yield 1,1,3-tricarballylic acid. This acid has a reported[37] melting point of 125° and any conceivable degradation products from this acid melted at a still lower temperature. Therefore the Δ^3-position of the double bond in 48 is unambiguously established.

The structure proof for 48 is summarized below.



An investigation was undertaken on the effect of temperature and residence time in the heated zone upon product composition. The data is given in Table I and the conclusions may be summarized as follows.

a) Higher pressure → more 48, less 47.

b) Acrolein and allene are not pressure dependent.

c) Higher temperature → more 48 relative to 47.

d) Higher temperature → more acrolein and allene.

Table I Effect of Temperature and Residence Time[a] on Product Composition (in %)[b]

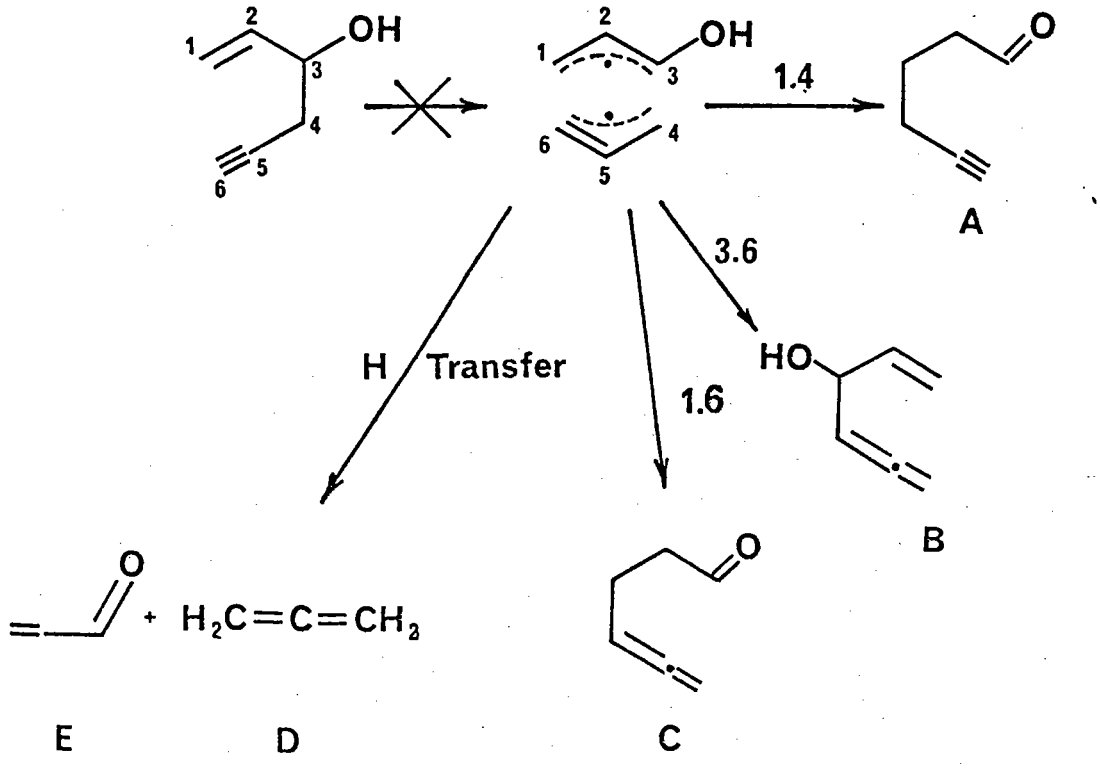
Run	t °C	P[a] mm	cleavage[b] 53 + 54	Rearrangement		Ratios[b]	
				Cope 47	Cyclic 48	47 / 48	(47 + 48) / (53 + 54)
1	350	1	39	46	12	3.8	1.5
2	370	1	48	36	15	2.4	1.1
3	370	8	49	28	23	1.2	1.1
4[c]	390	1	50[c]	28	22	1.3	1.0[c]
5	390	8	54	20	26	.77	.85
6	390	15	54	7	38	.18	.83

a) Pressure was regulated at the trap end of the flow system and is not therefore a true measure of pressure within the thermolysis zone but, at constant drop rate, reflects the relative residence time.

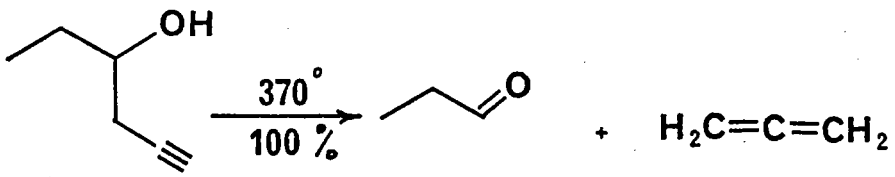
b) Percentages are based on integrated v.p.c. peak areas of condensed products and the weight loss. The assumption that non-condensation of the more volatile cleavage products accounts for all weight losses may lead to a small error in the ratio of rearrangement to cleavage products.

c) Run 4 represents a single small sample. Cleavage percentage is therefore not reliable since mechanical losses were not negligible.

The data in Table I show that the extent of the cleavage reaction is a function only of the temperature, increasing with increasing temperature. This finding is analogous to the observation of Viola, et al[11] who found β-hydroxyolefin cleavage and oxy-Cope rearrangement to be competetive concerted processes. The products of the thermolyses of 46 indicate that acetylenic systems may participate in cyclic six membered transition states even though the acetylenic group is linear in the ground state. Participation of allenes and acetylenes in transient six membered ring intermediates has recently been demonstrated, as described in the "Historical" section. The possibility remains that the observed oxy-Cope product (47) or the cleavage products arose through a tight radical pair mechanism, as presented schematically below. This limiting case for a diradical process is discounted by the fact that no trace of A or B, the single inversion products, produced by bond formation as indicated below, could be detected.



The observed acrolein and allene therefore appear to arise via a concerted reaction analogous to the β-hydroxyolefin cleavage. The term β-hydroxyacetylene cleavage will be used for this new reaction. Additional support for the existence of a β-hydroxyacetylene cleavage arises from the fact that 5-hexyn-3-ol (58) is cleaved quantitatively into propanal and allene at 370°.



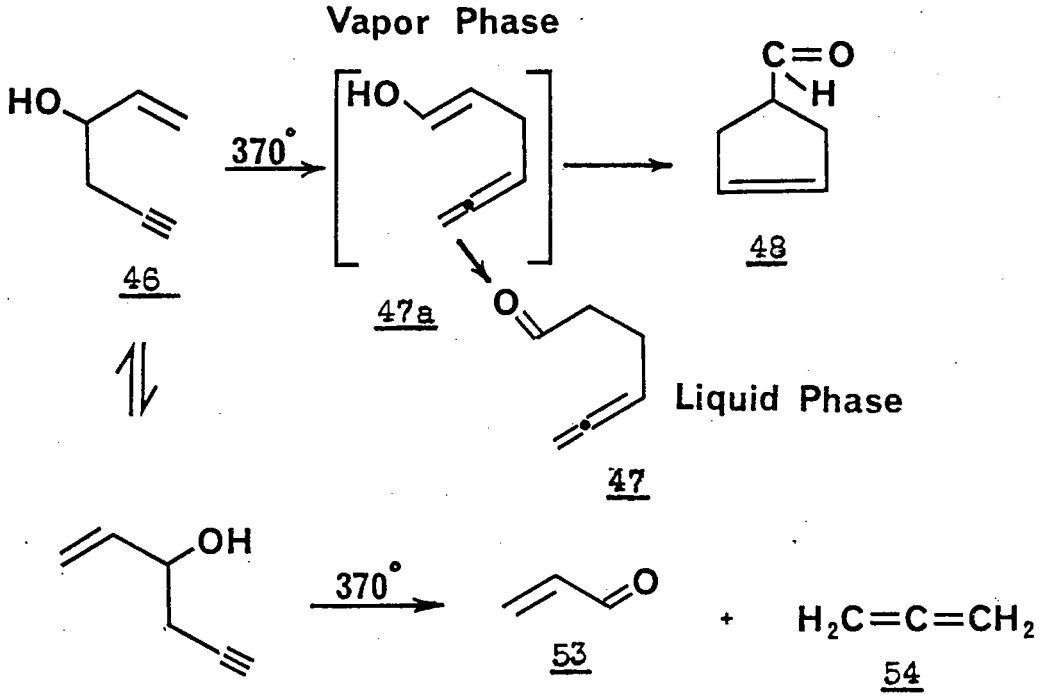
58

This reaction will be extensively discussed later in this thesis.

The rearrangement to cleavage ratio for 46 is 1.1 at 370° compared to 1.5 for 1,5-hexadien-3-ol[11] at 370°. Therefore it would appear that ΔF* for the acetylenic rearrangement is increased relative to ΔF* for the cleavage reaction when compared with the same parameters in the olefinic system. A possible explanation involves the fact that although the acetylenic system must bend to form both cyclic transition states, less distortion is operative in the cleavage reaction due to the mobility of the hydroxyl proton.

The fact that the amount of oxy-Cope product 47 decreases and 48 increases with increasing pressure (i.e. residence time) indicates the probable formation of 48 from 47 or a common precursor. The formation of 48 from 47 is inconsistent with the fact that thermolysis of a 1:1 mixture of 47 + 48 resulted in quantitative recovery of 48 while about 40% of 47 was converted to fragmentation products. The fact that these fragmentation products were not observed on the initial thermolysis

indicates that 47 was not in its keto form when first formed in the thermolysis column. This behavior parallels that reported for the thermolysis of 5-methyl substituted 1,5-hexadien-3-ols[11] wherein the ketonic product was found to undergo subsequent thermal rearrangements which were not present in the initial thermolysis. All of the above evidence suggests that it is the enol form of 47 which undergoes cyclization to 48. Furthermore, the above evidence indicates that enol 47a does not ketonize in the gas phase. The ketonization occurs in the liquid phase after condensation. The mechanistic scheme is presented below.



The fact that 47a does not ketonize to 47 in the gas phase is consistent with the Woodward-Hoffman rules for sigmatropic rearrangements previously discussed. The ketonization step is a 1,3-hydrogen transfer which cannot proceed thermally in a concerted fashion. Therefore intramolecular catalyzed processes must operate to affect the hydrogen transfer. These intramolecular catalyzed processes require bi- or poly-molecular aggregates with definite conformational requirements. In the gas phase

molecular collisions are both less probable and nearly elastic, thus preventing the intermolecular ketonization from occurring. In the liquid state catalyzed processes quickly convert the enol to the thermodynamically more favorable keto form.

A limited amount of kinetic data is also available for the 47a to 48 cyclization. This data offers additional evidence for the existence of 47a in the heated zone. The data from runs 1, 2 and 4 Table I were obtained with the same pressure, i.e. residence time. Therefore if one assumes that contact time under the three temperature conditions is nearly constant and that reaction 46 → 47a is fast compared to reaction 47a → 48, then a modified Arrhenius plot may be constructed for reaction 47a → 48.*

The latter assumption is justified by the fact that only traces of starting alcohol were found to survive under conditions where over 80% of the six carbon species in the hot zone existed as the enol (see run 1, Table I, page 27).

The kinetic treatment is given mathematically below.

$$\text{Log } {}^{C_o}/_{C} = (k/2.3)t \quad \text{but} \quad [47a] = 47 + 48$$

and C final = 47, i.e. the surviving 47a which ketonizes in the liquid state.

$$\text{Therefore, } k = \frac{2.3 \log \left[\frac{47 + 48}{47}\right]}{t}$$

---

*We wish to thank Professor J. L. Roebber for suggesting this kinetic treatment.

Since t is assumed constant we have: $$k_{1/k_2} = \frac{\text{Log}\left[\frac{47 + 48}{47}\right]_1}{\text{Log}\left[\frac{47 + 48}{47}\right]_2}$$

Then: $$\text{Log}\ k_{1/k_2} = \frac{-Ea}{2.3R}\left[\frac{1}{T_1} - \frac{1}{T_2}\right] = \text{Log}\ \frac{\left[\text{Log}\frac{47 + 48}{47}\right]_1}{\left[\text{Log}\frac{47 + 48}{47}\right]_2}$$

Therefore: $$\frac{\text{Log}\left[\text{Log}\ \frac{47 + 48}{47}\right]_1}{\text{Log}\left[\text{Log}\ \frac{47 + 48}{47}\right]_2} = \frac{-Ea}{2.3R}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]$$

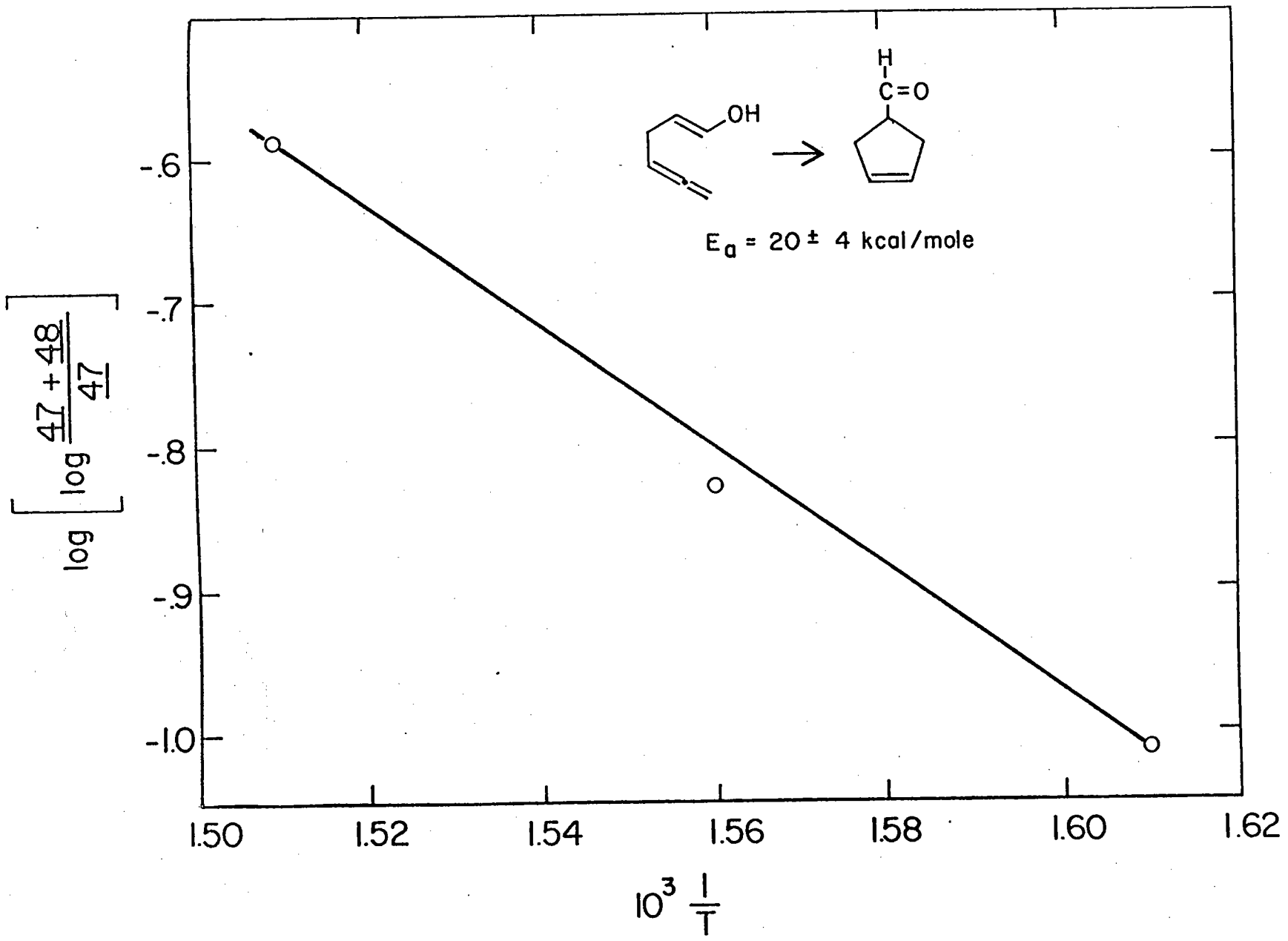
Therefore a plot of $\text{Log}\left[\text{log}\ \frac{47 + 48}{47}\right]$ vs 1/T should be linear with a slope equal to -Ea/2.3R. The plot is shown in Fig. I, page 33. Good linearity was found although the fact that only three points are available makes the data tenuous at best. An activation energy for the cyclization of 20 ± 4 kcal/mole was computed from the slope of the line. Of particular interest is the fact that gross distortions from linearity are found if the above treatment is applied assuming some ketonization (approx. 10%) to occur in the gas phase. Therefore the kinetic data is also consistent with ketonization occurring only in the liquid state.

The mechanism of the 47a → 48 cyclization was next considered. For this purpose, 1-hexen-5-yn-3-ol-O-d (58) was prepared by stirring

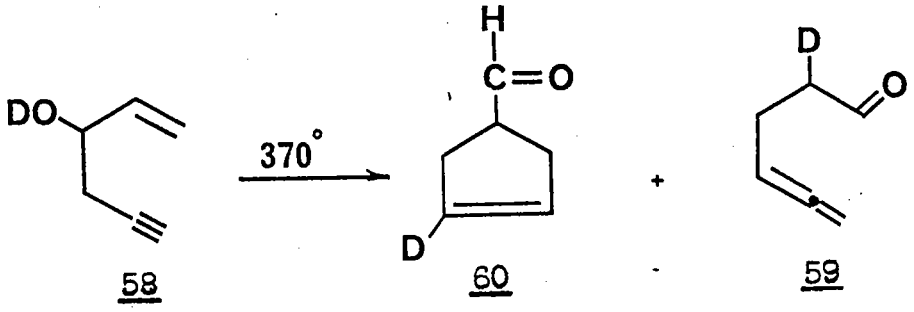
FIGURE I

Plot of Log $\left[\text{Log } \frac{\underline{47} + \underline{48}}{\underline{47}}\right]$

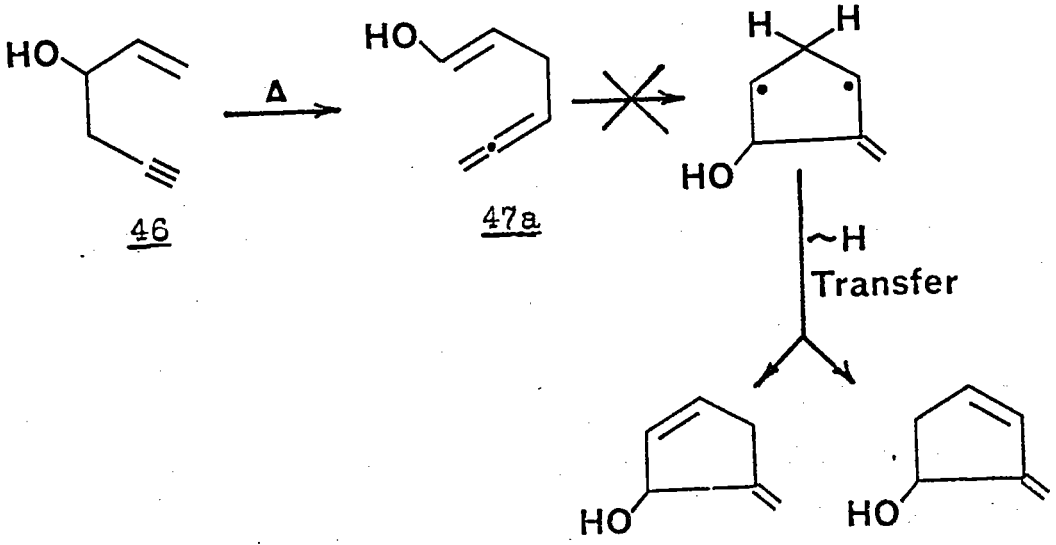
vs 1/T


H
C=O
OH
E_a = 20 ± 4 kcal/mole
$\log\left[\log\frac{47+48}{47}\right]$
-.6
-.7
-.8
-.9
-1.0
1.50
1.52
1.54
1.56
1.58
1.60
1.62
$10^3\,\frac{1}{T}$

46 with a large excess of deuterium oxide. The 58 was thermolyzed and the products separated by preparative v.p.c. The deuterated oxy-Cope product was shown to be 4,5-hexadienal-2-d (59) by its n.m.r. spectrum. The evidence consisted of the aldehydic triplet at 9.73δ in 47 collapsing to a doublet with the area of the 2.40δ aliphatic multiplet being reduced to one proton. The cyclic product was shown to be Δ^3-cyclopentenecarboxaldehyde-3-d (60) by the fact that in its n.m.r. spectrum the integral of the olefinic singlet was reduced in intensity to one proton.

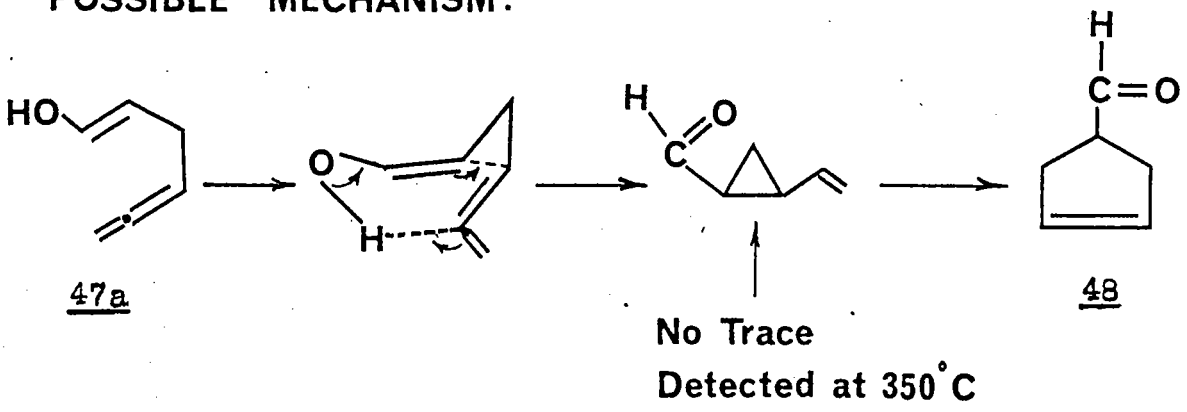


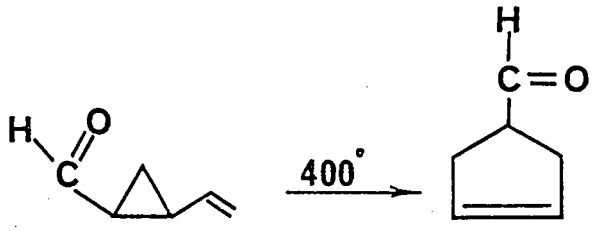
In view of these kinetic and deuterium labeling experiments, two possible mechanisms for the cyclization were considered. It is of interest to note initially that the Huntsman diradical intermediate cannot be invoked in this system since no trace of the products from such an intermediate was detected.



A possible mechanism would involve 47a proceeding through a [4.1.0] bicyclic transition state to form a cis or trans-2-vinylcyclopropane-carboxaldehyde (61). This process represents the enolene rearrangement[39]. Vogel[40] has shown that 61 does thermally isomerize to 48. Although this mechanism is consistent with the deuterium labeling experiment it is inconsistent with the kinetic data and the known thermal stability of vinylcyclopropanes. For example, in the vinylcyclopropane to cyclopentene isomerization nearly 20% of the starting material was recovered[41] even at 510°. Vogel[40] has stated that 61 "possesses remarkable thermal stability" and that 61 isomerized to 48 slowly even at 400°. In our investigations no trace of 61 could be detected even at 350° and very short contact times under pump vacuum.

POSSIBLE MECHANISM:





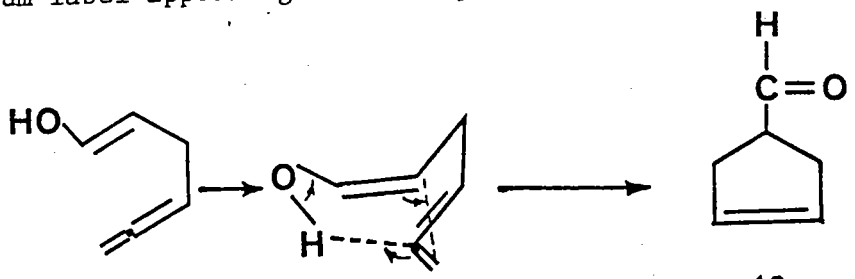
61 cis or trans

48 Incomplete Conversion

Also, the observed activation energy of 20 ± 4 kcal/mole for the 47a → 48 isomerization is inconsistent with a vinylcyclopropane inter-

mediate. All known vinylcyclopropane rearrangements are free radical reactions with activation energies of 40-50 kcal/mole[3].

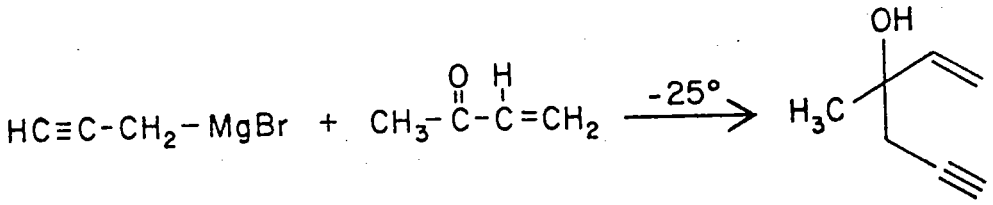
The proposed mechanism involves a [3.2.1] bicyclic transition state arising directly from 47a. This process is consistent with the deuterium label appearing in the 3-position.



47a 62 48

Also, it has previously been stated that the 46 → 47a isomerization appears to be much faster than the 47a → 48 cyclization. All known Cope processes have activation energies of between 25-36 kcal/mole[42]. Since 47a cyclizes to 48 with an activation energy of 20 ± 4 kcal/mole we should expect the cyclization reaction to be faster than the oxy-Cope rearrangement, solely on the basis of activation energy. The slower rate of the 47a → 48 cyclization can only be rationalized by attributing a much more negative entropy of activation to the 47a → 48 cyclization than for the primary oxy-Cope process. A highly negative activation entropy is consistent with the rigid bicyclic transition state 62.

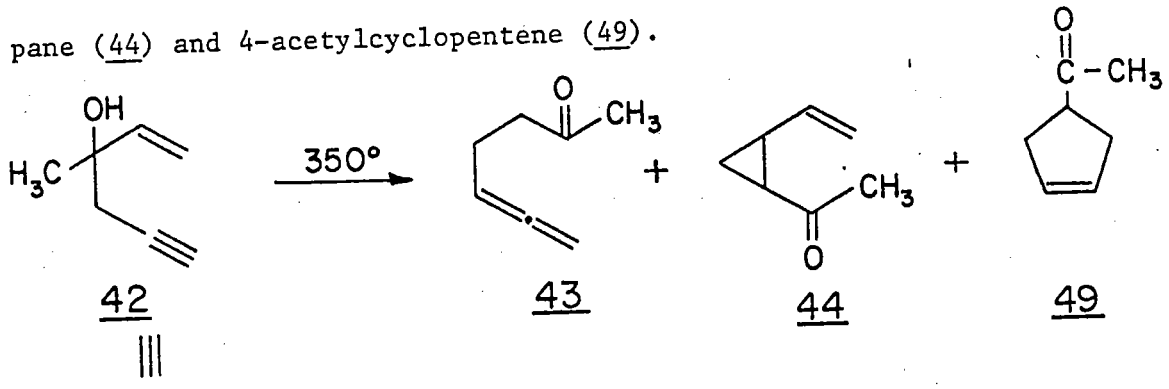
In order to resolve the previously discussed anomalous results of Wilson[27] and Chuche[28], 3-methyl-1-hexen-5-yn-3-ol (42) was prepared and thermolyzed. 42 was prepared by the low temperature Barbier reaction of propargylmagnesium bromide with methyl vinyl ketone, followed by hydrolysis.



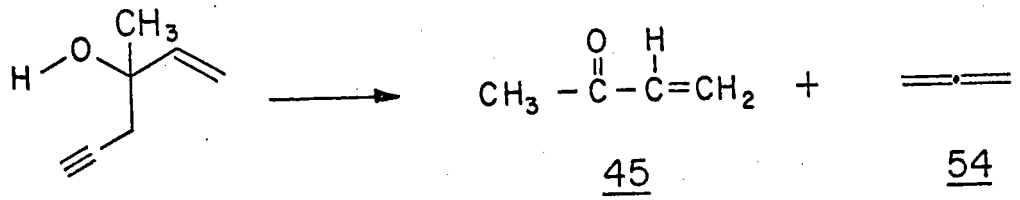
42

The material appeared homogeneous on v.p.c. and gave physical constants consistent with a seven carbon alcohol. The infrared and n.m.r. spectra, given in the experimental section, were entirely consistent with structure 42 and showed no trace of an internal acetylene. Since this material had previously been reported[27,28], no further structure proof was undertaken.

Thermolysis of 42 produced five products in amounts depending on reaction conditions. The products were shown to be methyl vinyl ketone (45), allene (54), 5,6-heptadien-2-one (43), 1-acetyl-2-vinylcyclopropane (44) and 4-acetylcyclopentene (49).



42 43 44 49



45 54

Allene (54) was identified only as a small peak near the air peak in the v.p.c. The mass balance of the thermolyses indicated a three carbon

species to be produced although propyne formation could not be excluded.

Methyl vinyl ketone(45) was identified by its characteristic odor and v.p.c. retention time. This product had previously been characterized by Wilson and Sherrod[27].

5,6-Heptadien-2-one (43) was identified by its infrared and n.m.r. spectra, described in the experimental section, page 127. This material also has been identified by Wilson and Sherrod[27]. The spectra were entirely analogous to those for 4,5-hexadienal obtained from the thermolyses of 46.

4-Acetylcyclopentene (49) was identified by its infrared and n.m.r. spectra which were entirely analogous to those previously obtained for Δ^3-cyclopentenecarboxaldehyde (48). This material had previously been reported by Chuche and Manisse[28].

1-Acetyl-2-vinylcyclopropane (44) was identified by its infrared and n.m.r. spectra which were entirely consistent with structure 44. The infrared spectrum showed aliphatic absorption at approximately 3090 cm^{-1} characteristic of a cyclopropane ring[43]. The n.m.r. spectrum also contained the characteristic high field cyclopropane absorption[44]. A 100 MHz n.m.r. spectrum of 44 was obtained.* See page 189a.

Although detailed analysis was still difficult due to the complex spin-spin interactions, the chemical shift values for the ring protons indicated the compound to be largely in the trans form with a minor cis constituent. The assignment is based on a comparison of chemical shift

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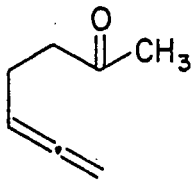
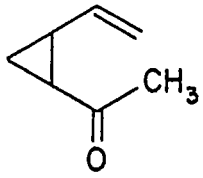
*We wish to thank Prof. R. D. Stolow of Tufts University for obtaining this spectrum.

values with the literature values for cis-2-vinylcyclopropanecarboxaldehyde[45]. The ring protons of the latter were consistently upfield from those found in 44. One would expect the ring protons in trans 44 to be downfield relative to cis 44, since in trans 44 both the vinyl and acetyl groups deshield the ring protons from both sides of the ring. In cis 44 steric hindrance to rotation makes this deshielding less effective.

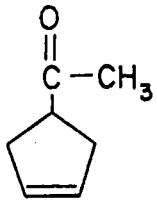
The above investigation shows that both 44 and 49 are produced in the thermolysis of 42. Since Wilson[27] identified only 44 while Chuche[28] identified only 49, it would appear that both authors missed one product.



43



44



49

The literature disagreement was resolved by investigating the thermolytic behavior of 42 over a wider range of experimental conditions than were utilized in either of the conflicting reports. The data is summarized in Table II. As in previous studies, the ratio of cleavage to rearrangement products is residence time independent. However, the distribution of the various rearrangement products is not. The decreasing amount of 43 produced with increasing temperature or residence time indicates the formation of 43 from its enolic precursor (43a). The pressure dependence of the 44:49 ratio shows that 43a → 49 cannot be the only pathway for formation of 49, since both products would then be formed from a common precursor by competing processes. A sample of pure 44

Table II Product Distribution In Thermolysis of 42.

t °C	P (mm)	Product Formation (%)		Composition of Rearranged Fraction (%)		
		Cleavage	Rearrangement	43	44	49
330	1	31	69	61	39	0
	22	29	71	56	32	11
350	1	32	68	59	31	10
	22	33	67	44	27	29
380	1	38	62	53	15	32
	22	37	63	39	9	52

upon re-thermolysis at 380° and 22mm gave a product found to consist of 13% 44 and 87% 49. This experiment demonstrated the formation of 49 from 44 by a vinylcyclopropane rearrangement as described by Vogel[40] and Rhoads[45].

The data of Table II may be treated similarly to that described in the thermolyses of 46. The three data points at 22mm and the three at 1mm may be used to construct two plots of Log $[\text{Log } \frac{43 + 44}{43}]$ vs $\frac{1}{T}$. If pathway 44 → 49 is the only source of 49 then the two plots as described above should be linear. If pathway 43a → 49 makes a contribution, then the two plots should show deviations from linearity and the "best" straight lines should be non-parallel. The plots, shown in Figure II, show both deviations from linearity and non-parallel slopes, tending to indicate that process 43a → 49 does contribute. This argument should not be taken as unequivocal, however, due to the tenuous nature of the three data points available at each pressure.

On the basis of the above discussion, a mechanistic scheme for formation of the seven carbon species is given below.

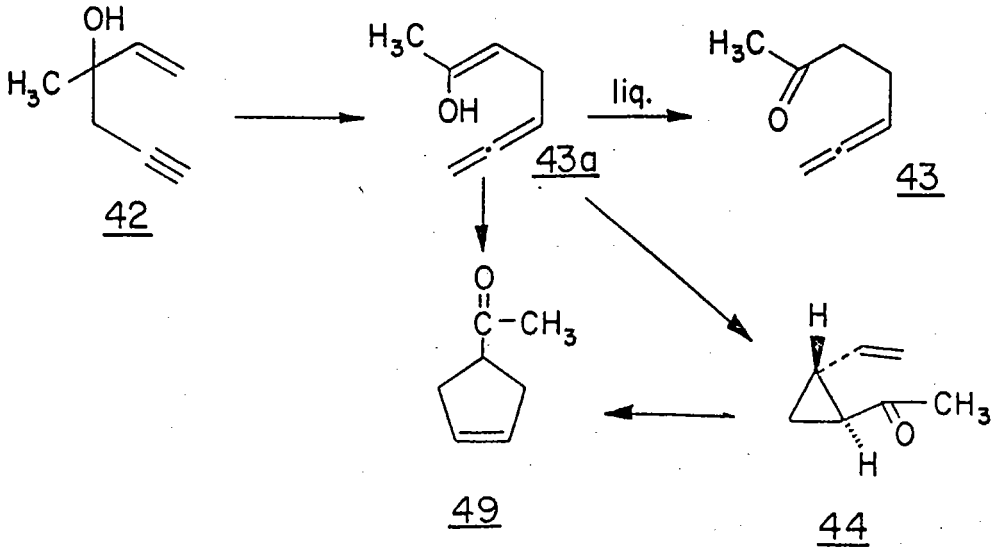
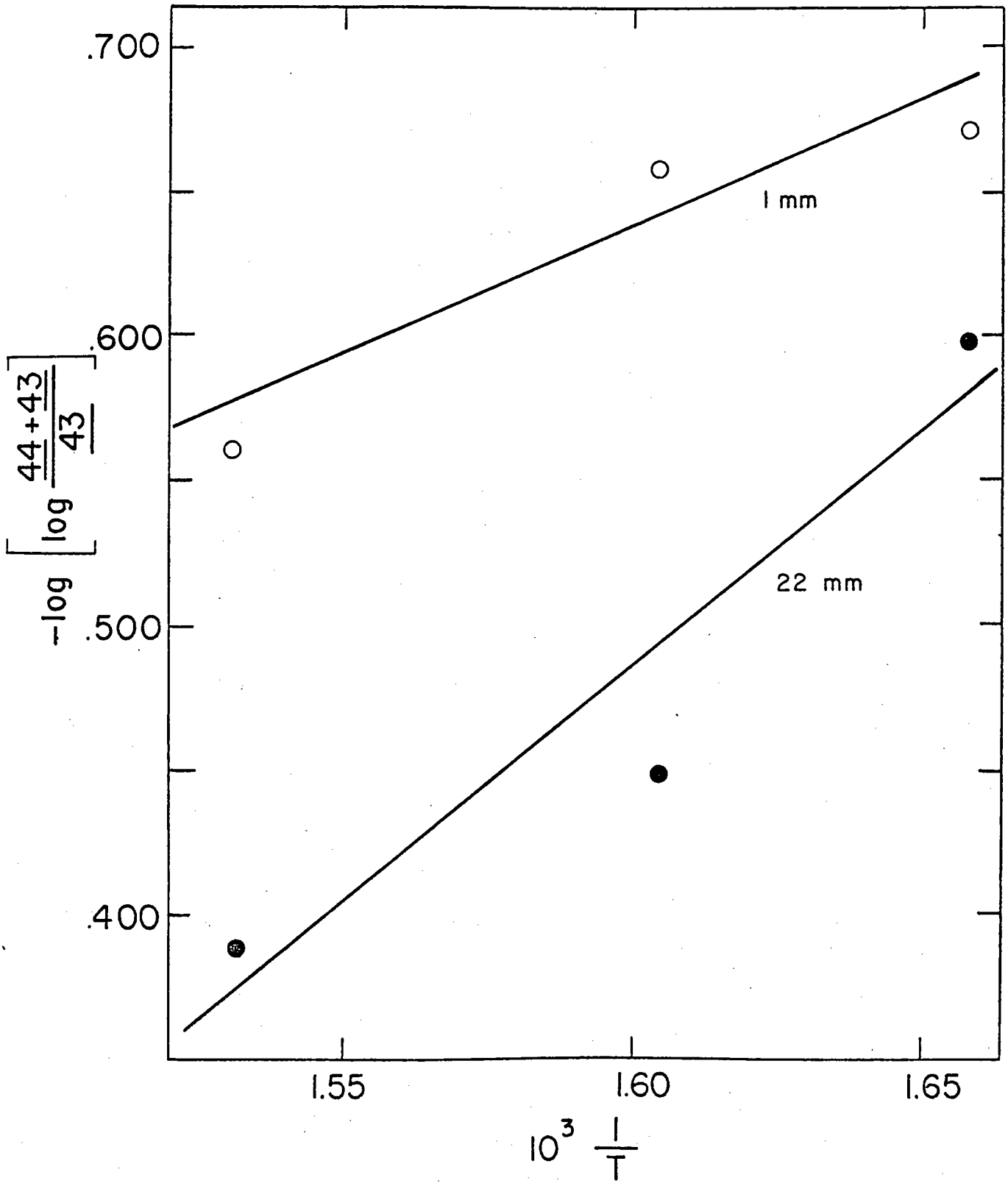


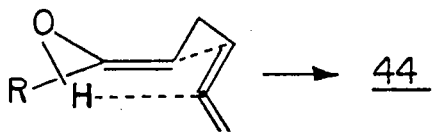
FIGURE II

Plots of Log $\left[\text{Log } \frac{43 + 44}{43}\right]$

vs $1/T$

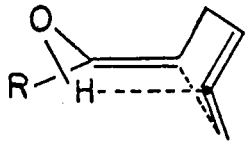

.700
.600
.500
.400
1 mm
22 mm
1.55
1.60
1.65
$10^3 \frac{1}{T}$
$-\log\left[\log\frac{44+43}{43}\right]$

The 43a → 44 transformation would pass through a [4.1.0] bicyclic transition state 44a while the 43a → 49 process would involve a [3.2.1] bicyclic transition state 49a as in the previously discussed thermolysis of 46.



→ 44

44a



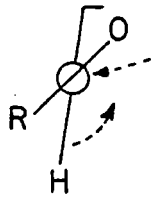
→ 49

49a

The quantitative data in Table II resolves the literature disagreement. Both previous reports[27,28] represent extreme experimental conditions. At 370-430° and 30mm as utilized by Chuche[28] no 44 survives. Wilson[27], by contrast, appeared to use an exceedingly short residence time (i.e., the only report where starting material survives) and thus was able to detect only 44.

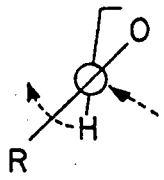
The data of Table II indicate that the process 43a → 49 is a higher energy process than 43a → 44. However, in the absence of the 3-methyl group, as in the thermolyses of 46, no cyclopropane derivative was detected even at 350° and 1mm. The subtle steric influence of the methyl group, far removed from the reaction site, becomes apparent upon consideration of the requisite transition states 44a and 49a for the two intramolecular cyclizations. The transfer of the hydroxyl proton to the central atom of the allene requires a cis configuration of the enol. The structure of the product then depends upon the choice of C_2-C_4 vs C_2-C_6 bond formation. During these processes a slight twist of the enolic double bond seems inevitable before re-hybridization to sp^3 at C_2 is completed. The consequence is seen in the corresponding pro-

jections, taken along the $C_1 - C_2$ bond axis.



44a

$R = CH_3$, $R = H$



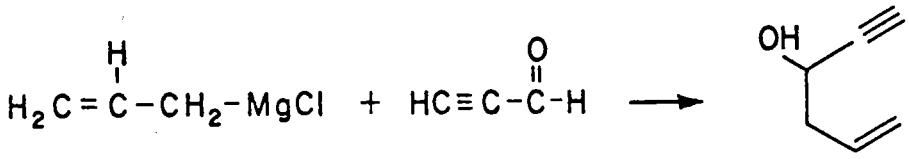
49a

$R = CH_3$, $R = H$

For pathway 49a → 49, leading to the cyclopentene derivative, with $R = CH_3$ additional energy is required due to eclipsing with the adjoining proton. The alternate pathway 44a → 44 now can compete successfully and a cyclopropane derivative is produced. With R = H, this effect is smaller, the more strained state 44a cannot compete and only a cyclopentene derivative can be detected. This explanation has some precedence in the torsional effect invoked by Schleyer in the norbornanes[46].

Investigation of 5-hexen-1-yn-3-ol (63)

This compound, previously unreported, was synthesized in 60% yield by the reaction of allylmagnesium chloride with propargylaldehyde.



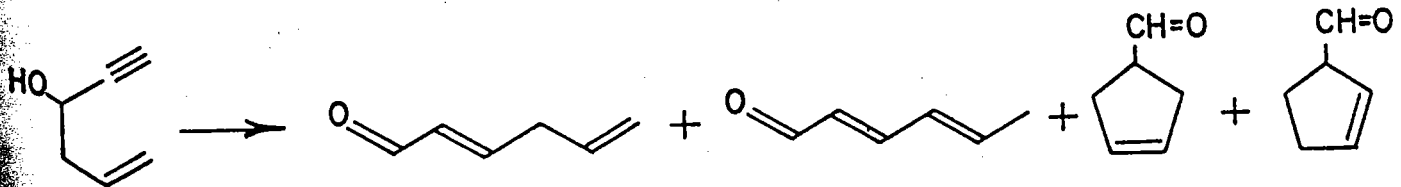
63

In addition a high boiling byproduct was obtained which will be discussed on page 99.

The physical constants of 63 were in accord with a six carbon alcohol and its carbon-hydrogen analysis was consistent with the formula C_6H_8O. Upon hydrogenation with Pd/C, 63 gave 3-hexanone as the major product and 3-hexanol as the minor product. The 3-hexanone was identified by its infrared spectrum, v.p.c. retention time, and 2,4-dinitrophenylhydrazone derivative.

The infrared and n.m.r. spectra of 63 were entirely in accord with the proposed structure and are described in the experimental section, page 130.

Vapor phase thermolysis of 63 produced four main products, shown to be trans-2,5-hexadienal (64), various configurational isomers of 2,4-hexadienal (sorbaldehyde) (65), Δ^2-cyclopentenecarboxaldehyde (66) and Δ^3-cyclopentenecarboxaldehyde (48).



63 64 65 48 66

The thermolyses were accompanied by fragmentation, which ranged from a small percentage at 350° to as much as 25% at 390°. The main products were separated by preparative v.p.c. and identified as follows.

The oxy-Cope product (64) gave an elementary analysis consistent with the formula C_6H_8O. The ultraviolet spectrum showed an absorption maximum at 220 mμ , ε 11,000, consistent with an α,β-unsaturated aldehyde. On catalytic hydrogenation 64 absorbed 100% of the theoretical quantity of hydrogen and yielded hexanal. Hexanal was identified by its v.p.c. retention time, infrared spectrum, and 2,4-dinitrophenylhydrazone, which showed no melting point depression on admixture with an authentic sample.

The infrared and n.m.r. spectra for 64 were entirely consistent with the proposed structure and are detailed in the experimental section, page 134. The trans configuration was assigned to 64 due to the strong infrared band[43] at 975 cm^{-1} and the observed n.m.r. coupling constant, $J\alpha\beta$ = 18cps[44].

64 formed a 2,4-dinitrophenylhydrazone whose melting point was in agreement with the literature[47]. The derivative gave elementary analysis consistent with the composition $C_{12}H_{12}N_4O_4$. Although 64 was reported in the literature by Ward et al.[47], their product was stated to be contaminated by 20% sorbaldehyde. The compound obtained in this research appeared to be homogeneous (v.p.c.). Consequently, the physical constants obtained for 64 did not agree with those reported, but the DNPH melting point did, since Ward et al.[47] separated and purified their derivative by column chromatography.

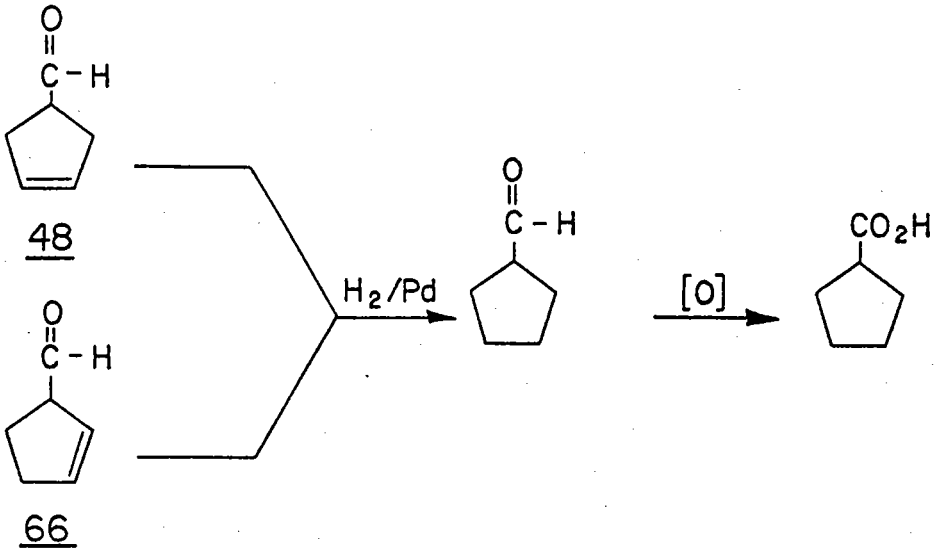
Sorbaldehyde (65) was identified by its characteristic odor, v.p.c. retention time and infrared spectrum. All four geometric isomers appeared to be present, since four overlapping peaks were observed on v.p.c., whose retention times coincided with those observed from a commercial sample. The relative abundance of the isomers differed from that of the commercial material although the all trans form was the major isomer in both samples.

65 formed a 2,4-dinitrophenylhydrazone whose melting point was in agreement with the literature and which showed no depression on admixture with an authentic sample.

A fraction containing only a mixture of Δ^2- and Δ^3-cyclopentenecarboxaldehydes, 66 and 48, was obtained by preparative v.p.c. However, the two isomers could not be completely separated on a variety of column packings. On 10 ft analytical columns, 66 appeared as a bump[illegible] on the 48 peak. The presence of both isomers was established as follows. The major Δ^3-component had v.p.c. retention times, on three stationary phases, identical to the known Δ^3-isomer obtained previously from the thermolyses of 1-hexen-5-yn-3-ol. Mixtures of 48 and 66, enriched by preparative v.p.c. to a Δ^3-isomer concentration of over 80%, gave infrared spectra essentially identical to that of the known Δ^3-isomer. Also, n.m.r. spectra of mixtures of 48 and 66 clearly showed all the peaks previously assigned for the Δ^3-isomer in addition to new peaks for the Δ^2-isomer.

Since the Δ^2-isomer could not be isolated in a pure state, its presence could be proven only indirectly. Ultraviolet spectra of an enriched 50:50 mixture of the two isomers, showed only end absorption above

220 mμ, thus precluding the presence of the Δ^1-isomer. Hydrogenation of the same 50:50 mixture gave a single product which was identified as cyclopentanecarboxaldehyde by oxidation to the saturated acid. The infrared spectrum of the acid was superimposable with that published in the literature[35].



Further evidence for the presence of the Δ^2-isomer was obtained from the n.m.r. spectrum of a 50:50 mixture of the two isomers since fortunately, there was essentially no overlap between the peaks due to the two isomers. Therefore the n.m.r. spectrum for 66 could be obtained by subtraction. The spectrum was entirely in accord with structure 66 and is described in the experimental section, page 133.

Therefore the assignment of structure 66 is based upon quantitative hydrogenation of the mixture to cyclopentanecarboxaldehyde, upon the absence of the Δ^1-isomer, and upon a consistent n.m.r. spectrum.

Since formation of propargylaldehyde via the β-hydroxyolefin cleavage had been anticipated, the origin of the low boiling fragmentation products was examined carefully. Propargylaldehyde was not among these substances since it had a v.p.c. retention time longer than any of the fragmentation

products. A sample of propargylaldehyde, upon thermolysis at 370°, was found to yield no fragmentation. Also, both 2,5-hexadienal and a mixture of the cyclopentenecarboxaldehydes were recovered unchanged upon thermolysis at 370°. A sample of commercial sorbaldehyde, however, upon thermolysis at 370° not only produced the fragmentation products but also resulted in formation of a different isomer ratio from that initially present.

All oxy-Cope processes previously reported were accompained by the competing β-hydroxyolefin cleavage, which prevented direct kinetic measurement of the oxy-Cope process. Since the cleavage reaction appeared to be totally absent in the thermolysis of 5-hexen-1-yn-3-ol (63), the disappearance of 63 in small sealed tubes was measured over the temperature range of 186 - 210°. The technique employed is described in detail in the experimental section. Rate constants and Arrhenius parameters were calculated using the method of least squares to obtain best straight lines. The kinetic data, shown in Figure III, clearly show the reaction to obey the first order rate law. Intermolecular processes for the disappearance of 63 are thereby ruled out as they would cause deviations from first order kinetic behavior. The Arrhenius plot, shown in Figure IV, gives an excellent linear relationship. This linearity excludes the possibility that the four main products produced are formed from 63 by competing first order processes. For the Arrhenius plot to remain linear, competing first order processes would require equal free energies of activation at all temperatures studied. This situation is extremely unlikely.

In view of the above discussion, it was assumed that the reaction step whose kinetics were measured was the oxy-Cope rearrangement of 63 to

FIGURE III

Kinetic Data for

Disappearance of

5-Hexen-1-yn-3-ol

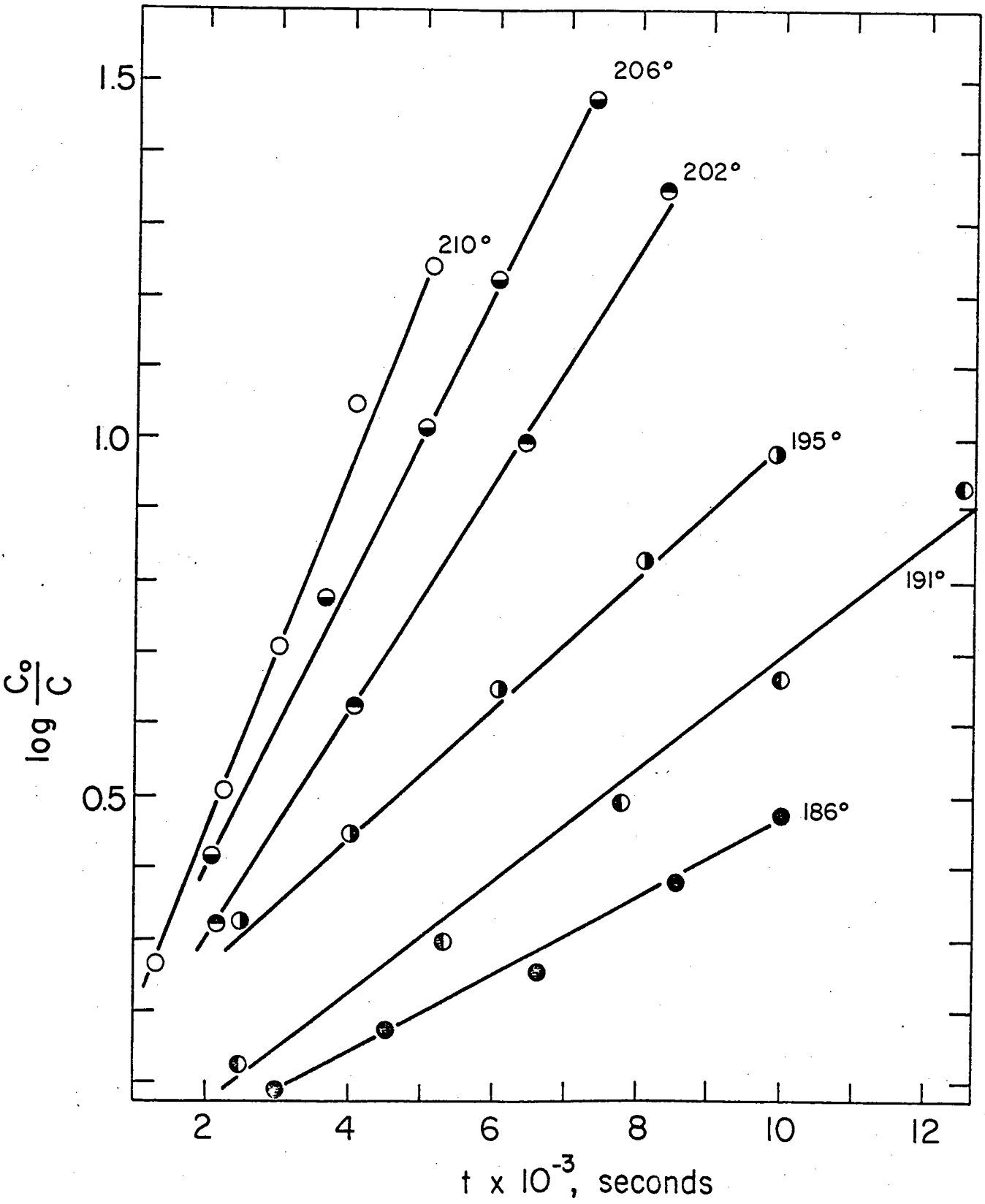

206°
202°
210°
195°
191°
186°
1.5
1.0
0.5
log C°/C
2
4
6
8
10
12
t x 10^-3, seconds

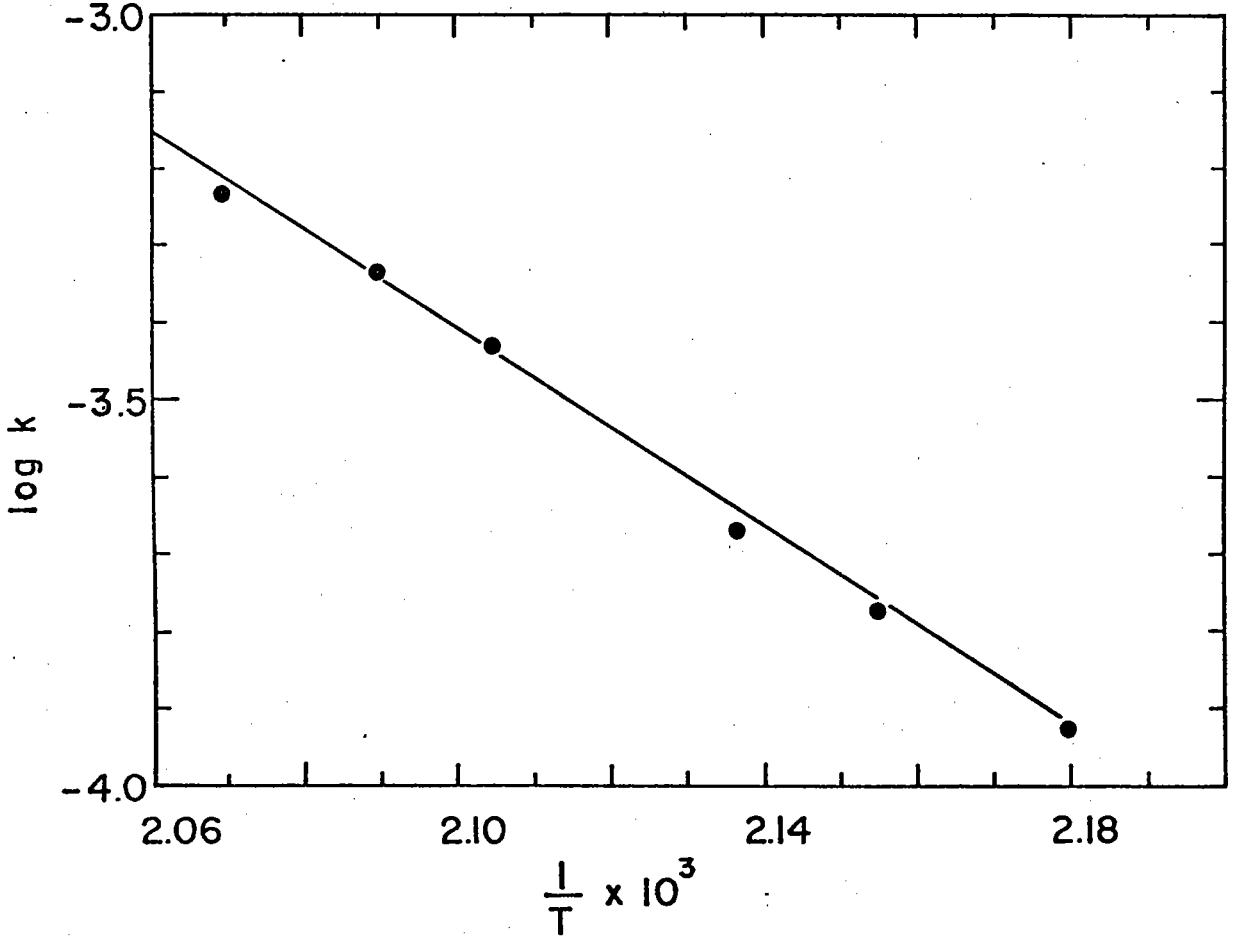
FIGURE IV

Arrhenius Plot of

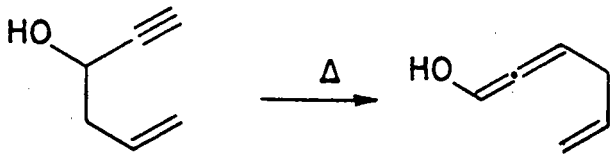
Kinetic Data for

Disappearance of

5-Hexen-1-yn-3-ol


-3.0
-3.5
-4.0
log k
2.06
2.10
2.14
2.18
1/T x 10^3

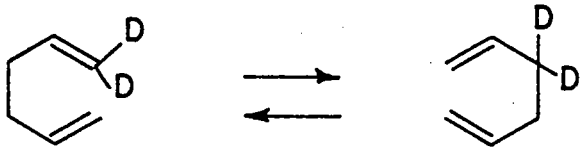
form the "allenol" 64a.[i]



63 64a

This assumption is further verified by the consideration of temperature and pressure effects on product distribution, discussed on page 54.

The activation parameters obtained from the Arrhenius plot were Ea = 30 ± 2 kcal/mol and ΔS* = -14 e.u.[ii] These parameters are strongly indicative of a concerted reaction possessing a cyclic transition state. To our knowledge the above are the first activation parameters obtained for an oxy-Cope process. Reported activation energies for concerted Cope processes range from 23 to 36 kcal/mol[42]. The lower end of this range represents contributions of relief of ring strain as in divinylcyclobutane[48]. Doering and Toscano[49] have reported a value of 36 kcal/mol for the pure unperturbed Cope rearrangement of 1,1-dideuterio- → 3,3-dideuterio-1,5-hexadiene.



Berson[50] has estimated that the activation energy of a diradical Cope process should be lowered some 3 kcal/mol by a hydroxyl group. However, Martin[51] has estimated that a propargylic radical is some 3-4 kcal/

i The term "allenol" is here proposed for a 1-hydroxy-1,2-diene.
ii See footnote on page 86.

mol less stable than an allyl radical. Therefore, it would seem that the oxygen perturbation in 63 is counterbalanced by the effect of the triple bond, if these considerations based upon radical stabilization are apropos to a concerted reaction.

The experimental activation energy of 30 kcal/mol seems surprisingly low. Initially it was thought that electrocyclic reactions involving acetylenic links would possess higher activation energies than their olefinic counterparts, due to the necessity for bending the triple bond in forming a cyclic six membered transition state. Although it is not possible to unequivocally state the reasons for the unexpectedly low activation energy, three possible factors have been considered. The acetylenic π system is actually a symmetrical cylinder of electron density. Therefore, an attacking olefinic bond could overlap effectively with the acetylenic bond at all positions in space surrounding the acetylenic link. Such is not the case for nonacetylenic Cope processes in which two π lobes must each rotate into a rigid conformation in order for bonding to occur. This consideration, however, most likely represents an entropy factor.

Another consideration is that in the olefinic Cope process a change of hybridization from sp^2 to sp^3 occurs in the interaction at the 1-6 positions, counterbalanced by the reverse process at the 3-4 positions. For the acetylenic system, however, the hybridization at carbon -1 changes from sp to sp^2 while carbon -4 changes from sp^3 to sp^2. Although the energy differences corresponding to these hybridizations are readily calculable, the effects on transition states, unfortunately, are not.

A third factor could be the higher ground state energy of a molecule containing an acetylenic link as compared to the olefinic link. If the transition state for the acetylenic Cope process is increased in energy less than the increase of the ground state, then the higher ground state energy for the acetylenic molecule would result in a lower activation energy for the process.

Since the acetylenic link appears to be more reactive than the olefinic in electrocyclic processes, the lack of β-hydroxyolefin cleavage in the thermolysis of 5-hexen-1-yn-3-ol is readily explainable. Only the oxy-Cope process involves participation of the more reactive acetylenic link. By contrast, in the thermolysis of 1-hexen-5-yn-3-ol both the oxy-Cope and cleavage reaction involve triple bond participation.

The effect of temperature and pressure upon product composition is given in Table III. The data suggest complex interrelationships in the formation of the observed products. The concentration of oxy-Cope product 64 was found to decrease with increasing temperature and contact time. This fact demonstrated the intermediacy of the allenol precursor 64a in the formation of other products, in agreement with the assumption made previously on the basis of kinetic data. The sorbaldehyde (65) concentration also decreased with increased residence time but passed through a maximum with increasing temperature. This observation was taken as evidence for multiple involvement of 65 in the reaction sequence. The concentration of cyclopentenecarboxaldehyde products, 48 and 66, also passed through a temperature maximum but increased with increasing residence time. This effect demonstrates that 48 and 66 are formed from a precursor or precursors whose concentration is temperature dependent. The fact that the amount of fragmentation increases with

TABLE III

EFFECT OF TEMPERATURE AND RESIDENCE TIME[a] ON YIELDS (%)[b,c] IN THERMOLYSIS OF 63

t, °C	P,[a] mm	2,5-hexadienal 64	2,4-hexadienal 65	cyclopentenecarboxaldehydes 48 + 66	fragmentation[c]
390	20	28	15	31	26
	0.5	46	21	24	10
370	20	32	15	38	15
	0.5	48	37	6	9
350	20	46	16	23	15
	0.5	62	24	6	8

a) Pressure was monitored at the trap end of the flow system and is not, therefore, a true measure of pressure within the thermolysis zone, but, at constant drop rate, reflects the relative residence time.

b) Percentages are based on integrated vpc peak areas of condensed products and the weight loss.

c) Fragmentation includes the highly volatile products and the weight loss.

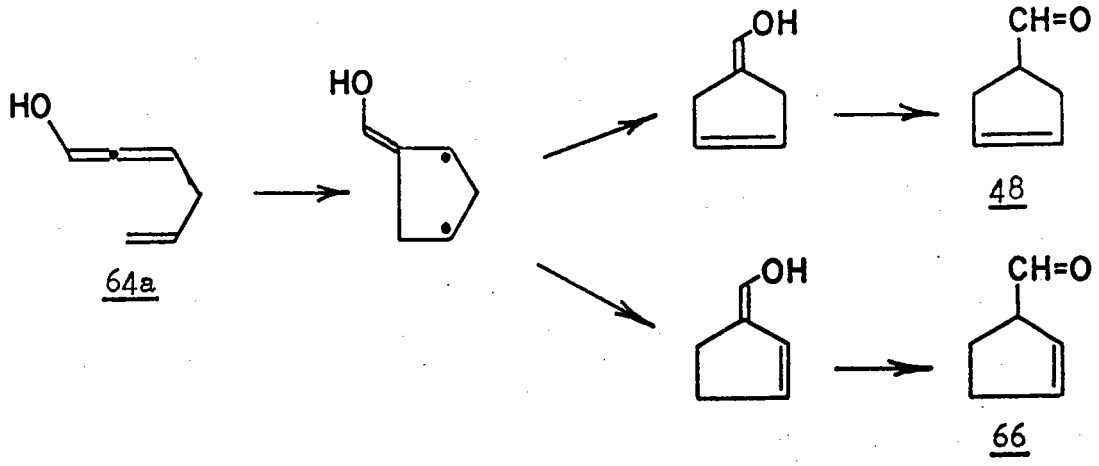
increasing residence time indicates that its origin cannot be entirely from starting material 63. The recycling experiments previously described indicated that fragmentation results from 65 but not from any other thermolysis end-product. The possibility remains, however, that one of the respective enolic precursors may be responsible for some fragmentation. This latter possibility is considered unlikely since none of the enolic precursors previously encountered[11] have undergone fragmentation while some of the resulting carbonyl compounds have.

The participation of free radicals in the oxy-Cope reaction of 63 is disproven by the highly negative entropy of activation and low activation energy. Also, no evidence for formation of intermolecular coupling products was found.

The fact that 63 follows a first order rate law for its disappearance indicates that the observed products are formed from a common intermediate, the allenol 64a. The survival of 64a in the gas phase is consistent with the Woodward-Hoffman rules as previously described. Since ketonization of 64a occurs only in the liquid state, the formation of thermolysis products other than 64 indicates intramolecular reactions of the allenol 64a.

The diradical mechanism proposed by Huntsman[15] for the formation of 17 and 18, page 8, accounted for the production of the conjugated cyclic

diene, 17, as the major product. In the reaction of 64a, this mechanism should lead to an excess of the conjugated enolic precursor of 66.



64a 48 66

However, such was not the case. Table IV shows the ratio of 48 to 66. This ratio was greater than unity in all thermolyses. In addition, increased contact time, i.e. higher pressure, was found to increase the amount of 48 relative to 66. An alternate mechanism, in addition to the diradical intermediate, is therefore indicated for formation of 48. A lower activation energy than the diradical pathway is required for such an alternate path to account for the decrease in the ratio of 48:66 with increasing temperature.

In order to further study the mechanism of the reaction, 5-hexen-1-yn-3-ol-O-d (67) was prepared, thermolyzed and the products isolated by preparative v.p.c. An indication of deuterium scrambling in each fraction was achieved through mass spectral analysis*.

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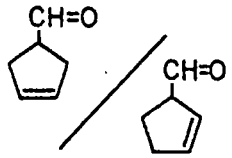
*We wish to thank Dr. Philip L. Levins, of the Arthur D. Little Co., Inc., for the Mass Spectral analysis.

TABLE IV

EFFECT OF TEMPERATURE AND RESIDENCE TIME[a] ON COMPOSITION[b] OF CYCLOPENTENECARBOXALDEHYDE FRACTION

t, °C	P(mm)	
390	20	5.5
	0.5	2.5
370	20	6.2
	0.5	2.9
350	20	7.1
	0.5	5.0
370[c]	20	1.3

a) At constant drop rate, pressure reflects the relative residence time.

b) Data was obtained from partially resolved vpc peak areas.

c) From deuterium tracer study involving thermolysis of 67.

The data is presented in Table V. The expected intensity of the 98 m/e peak is 6.6% of the molecule-ion at 97. The dideuterium content, the excess percentage of the M + 1 peak over the normal value, is an indication of the degree of deuterium scrambling.

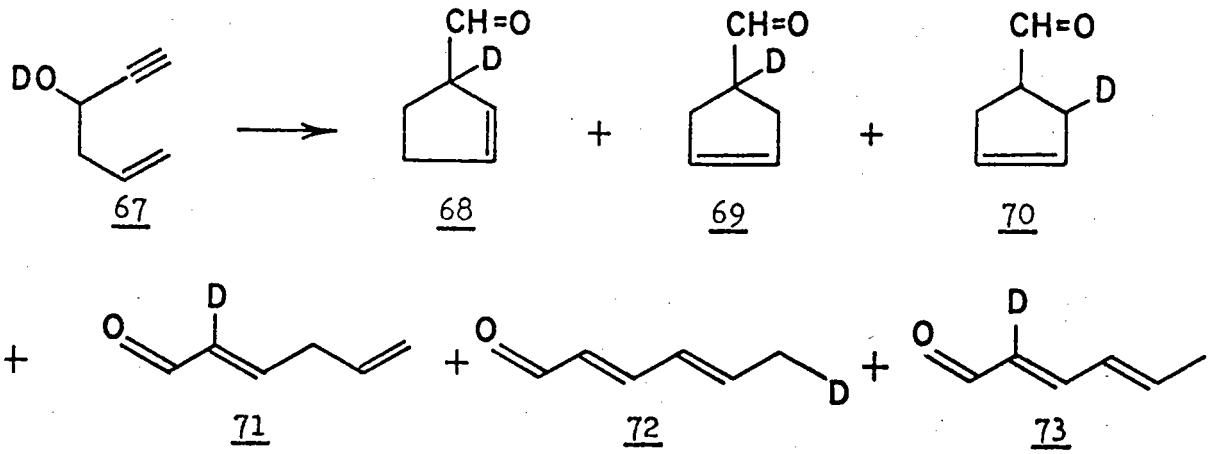
Table V. Mass Spectral Analysis of Fractions From Thermolysis of 67. Relative Peak Intensities.

m/e	Cyclopentenecarbox-aldehydes	2,5-Hexadienal	Sorbaldehyde
95	27	31	12
96	100	100	55
97	100	82	100
98	9	13	23
99	1	3	5

The amount of dideuterated species was negligible in the cyclic fraction, slightly more in the oxy-Cope product and moderate in the sorbaldehyde fraction. It is of interest to note that the dideuterium content increases with increasing v.p.c. retention time. Therefore deuterium scrambling may occur in the preparative v.p.c. separation process and not in the gas phase during the thermolysis.

The position of the deuterium in the thermolysis product was determined by means of the n.m.r. spectra (see page 187). The following

distribution was found.



67 68 69 70 71 72 73

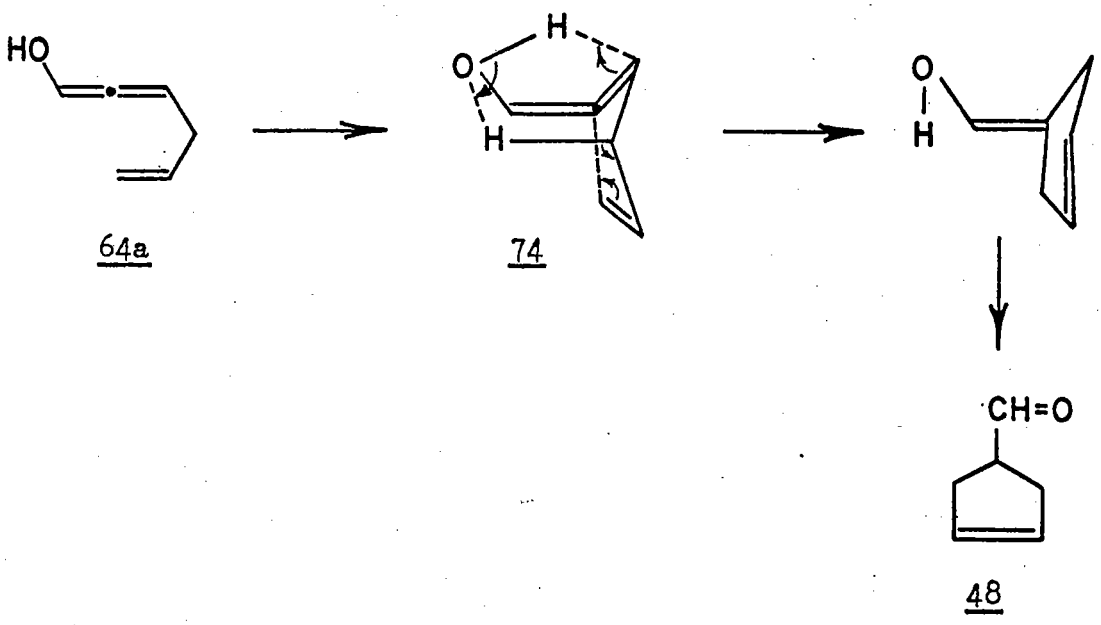
In the cyclic fraction, the aldehydic doublet of the Δ^2-component had collapsed to a characteristic deuterium triplet ($J \angle 1$ cps). A deuterium triplet appeared in the center of a diminished doublet in the Δ^3-component. The multiplets from the two alpha protons were greatly reduced in intensity for both components. The spectra indicated that approximately equal amounts of the α-deuterated species 68 and 69 were produced. Also, the 2.68δ multiplet from the Δ^3-component showed significantly reduced integral intensity and an altered multiplicity pattern, thus indicating the remainder of the deuterium to be in the 2-position (70).

In the oxy-Cope product, the aldehydic doublet had collapsed to a characteristic deuterium triplet, ($J \angle 1$ cps) and the absorption at 6.08δ was considerably reduced. The major deuterated species was therefore α-d-trans-2,5-hexadienal (71), in line with simple ketonization of the enol.

The deuterated sorbaldehyde consisted of mostly 72 with some 73. An altered pattern and decreased integral area for the 1.9δ methyl group in-

dicated formation of 72. A decreased integral area at 6.06δ and the appearance of a weak deuterium triplet in the center of each of the aldehydic doublets of the four geometric isomers was evidence for the formation of 73.

The formation of two labeled species for the Δ^3-cyclopentenecarboxaldehyde is consistent with two mechanisms operating in the formation of the Δ^3-isomer as was previously suggested. The α-labeled Δ^2- and Δ^3-components are consistent with Huntsman's diradical mechanism. The 2-labeled Δ^3-species, 70, could be formed in a concerted fashion from the allenol via a tricyclic transition state 74.



64a 74 48

Although this mechanism results in deuterium in the 2-position and could account for the effect of temperature on the Δ^3/Δ^2 isomer ratio, it cannot explain the increased amounts of the Δ^3-isomer formed with increased residence time. Since both the diradical mechanism and 74 involve reactions of the allenol by two competitive reactions, the Δ^3/Δ^2 isomer ratio should be independent of residence time. An additional pathway to

the Δ^3-isomer, consistent with all data, is presented in the discussion of sorbaldehyde formation.

Table VI shows the geometric isomer distribution in commercial sorbaldehyde, thermolyzed commercial sorbaldehyde and sorbaldehyde from the thermolysis of 5-hexen-1-yn-3-ol (63). The assignments are based upon isomeric abundance in the commercial sample and are in accord with diamagnetic anisotropy effects[44]. The thermolysis of commercial material led to fragmentation and resulted in increased amounts of cis isomers 65c and 65d at the expense of the all-trans form 65a. The sorbaldehyde produced from thermolysis of 63 contained a still greater concentration of the cis isomers. The data is in accord with a mechanism for sorbaldehyde formation from 64a involving a cyclic transition state 75. Two conforma-

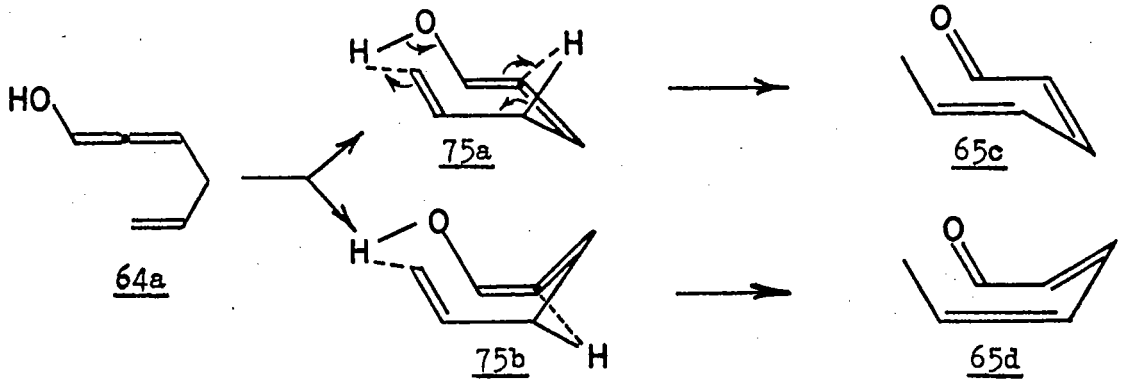
Table VI. Distribution (%)[a] of Geometric Isomers in Various Sorbaldehyde Samples

Source	trans-trans 65a	trans-cis 65b	cis-trans 65c	cis-cis 65d
Commercial sample	77	19	4	trace
Thermolyzed[b] commercial	66	18	11	4
From thermolysis[b] of 63	51	36	11	2

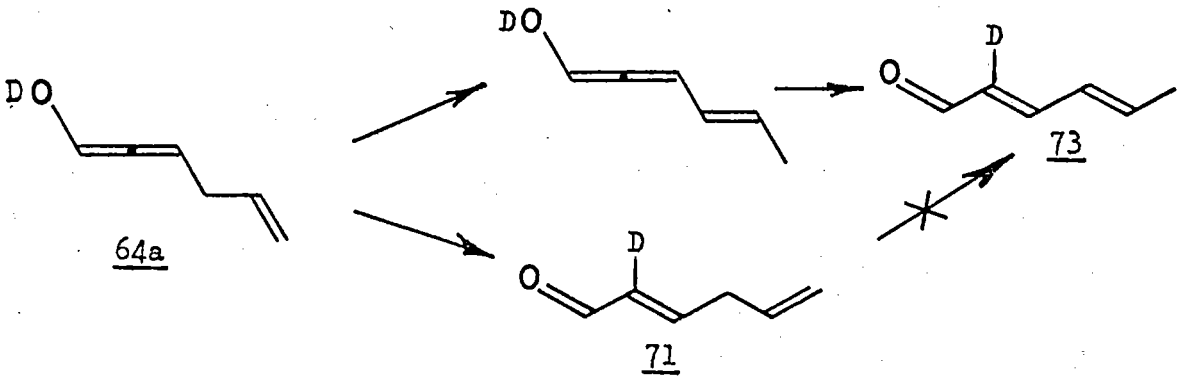
a) Percentages are based on relative areas of the corresponding aldehydic proton n.m.r. peak. Doublets are centered at δ = 9.53, 9.63, 10.19 and 10.23 for the 65a, b, c and d isomers respectively.

b) Thermolysis at 370°.

tions of 75 would result in the cis-trans and cis-cis isomers 65c and 65d. The thermolysis of commercial sorbaldehyde demonstrated the occurrence of thermal cis → trans isomerizations in the gas phase. These processes then can account for the formation of the trans-cis and trans-trans isomers.

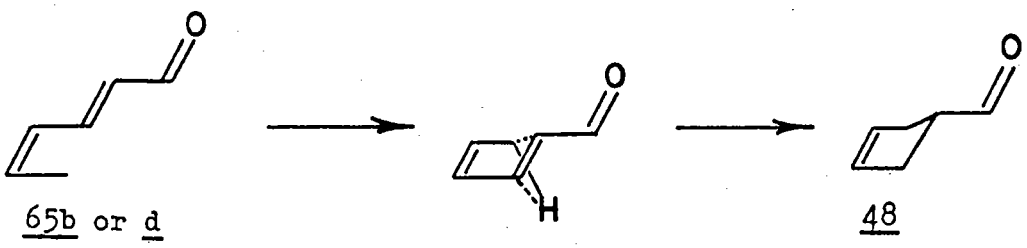


This mechanism accounts for the appearance of 72, with deuterium in the terminal methyl position of sorbaldehyde. Also, an allylic shift in 64a, in the liquid phase, competitive with ketonization, would give 73 with the deuterium label in the α position.



A direct isomerization of 2,5-hexadienal (64) to 2,4-hexadienal (as in 71 → 73) does not occur since 64 is recovered unchanged upon re-thermolysis.

If the above mechanism applies, then the thermolysis of 5-hexen-1-yn-3-ol results in the formation of considerable Δ^4-cis-sorbaldehyde in the gas phase. Δ^3-Cyclopentenecarboxaldehyde (48) could then arise from the following process.



65b or d 48

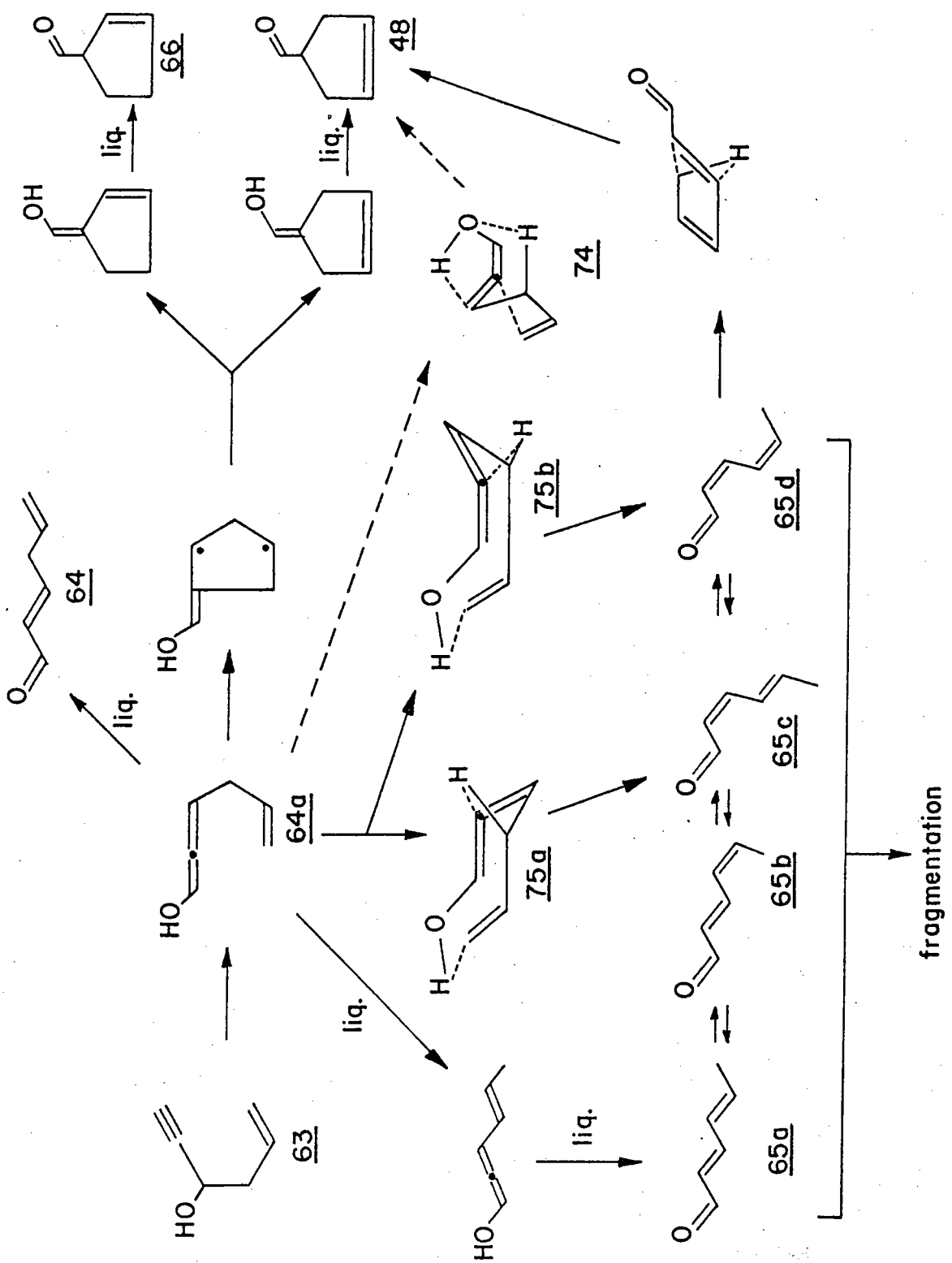
This process involves a thermal 1,2-cycloaddition from Δ^4-cis-sorbaldehydes 65b or d. The above mechanism would account for the deuterium label appearing in the 2-position of 48 since deuterium was originally contained in the methyl group of 65. The increasing amount of 48 formed with increased contact time is also consistent with this mechanism, since the longer the contact time, the more 65 may convert to 48. Also, Table IV, page 58, shows that there is an isotope effect, retarding formation of the Δ^3-cyclopentenecarboxaldehyde, when the deuterated alcohol 67 is thermolyzed. The rate of formation of sorbaldehyde via transition state 75 should be retarded for the deuterated allenol. Therefore a decreased concentration of sorbaldehyde results in a decreased amount of 48 by this pathway. The presence of deuterium on the terminal methyl group of sorbaldehyde (72) would also retard the cycloaddition, but to a lesser extent since only one methyl hydrogen is replaced by deuterium.

Both 65b and 65d are sterically favorable for formation of the cyclic transition state leading to 48. The cis-cis isomer 65d arises directly from 75b and is then converted to the other isomers through thermal isomerization. The recycling of commercial sorbaldehyde indicated that all four

isomers are thermally interconvertible. It appears likely that the majority of the fragmentation observed during the thermolyses of 5-hexen-1-yn-3-ol (63) and of commercial sorbaldehyde occurs through the cis isomers. The fact that more fragmentation occurs during the thermolysis of 63 than for commercial sorbaldehyde is an indication of the greater quantity of cis isomers of sorbaldehyde initially produced during the thermolysis of 63. It appears that the sorbaldehyde, after production by thermolysis, may undergo internal cycloaddition, geometric isomerization, or fragmentation.

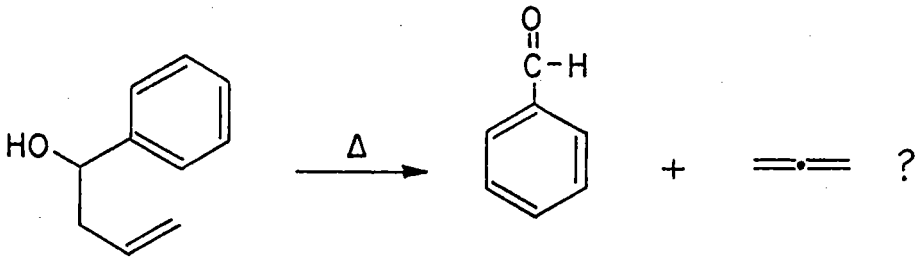
The complete mechanistic scheme suggested in this discussion is given in Chart I. The allenol intermediate 64a serves as a precursor to 48, 66 and 65. This reaction therefore constitutes the first reported chemistry of an "allenol". The existence of the tricyclic transition state 74, which leads to 48, is considered highly speculative. All 1,3-hydrogen shifts occur in the liquid after condensation, in accord with the previously discussed Woodward-Hoffman rules.

CHART I



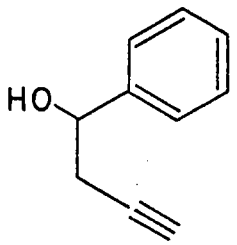
Investigation of Possible Phenyl Participation in the Acetylenic Oxy-Cope Rearrangement.

Glover[52] thermolyzed 1-phenyl-3-buten-1-ol (77) and isolated benzaldehyde as the only condensed product.

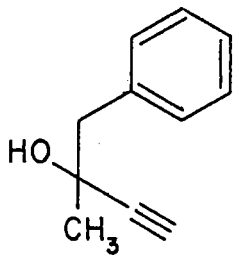


77

No oxy-Cope rearrangement product could be detected. The kinetic parameters obtained for 5-hexen-1-yn-3-ol(63) suggested that triple bond participation lowers the activation energy required for the oxy-Cope process. Therefore attempts were made to observe phenyl participation for 1-phenyl-3-butyn-1-ol (76) and 1-phenyl-2-methyl-3-butyn-2-ol (78).

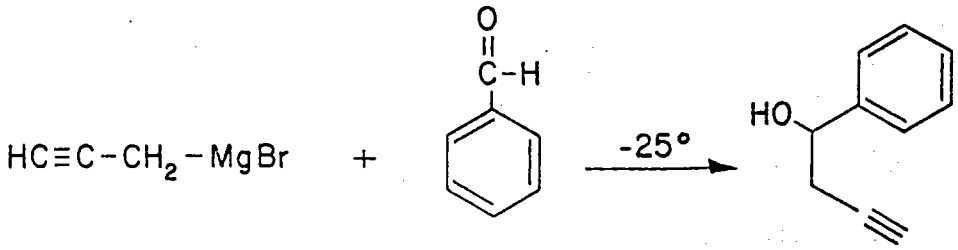


76



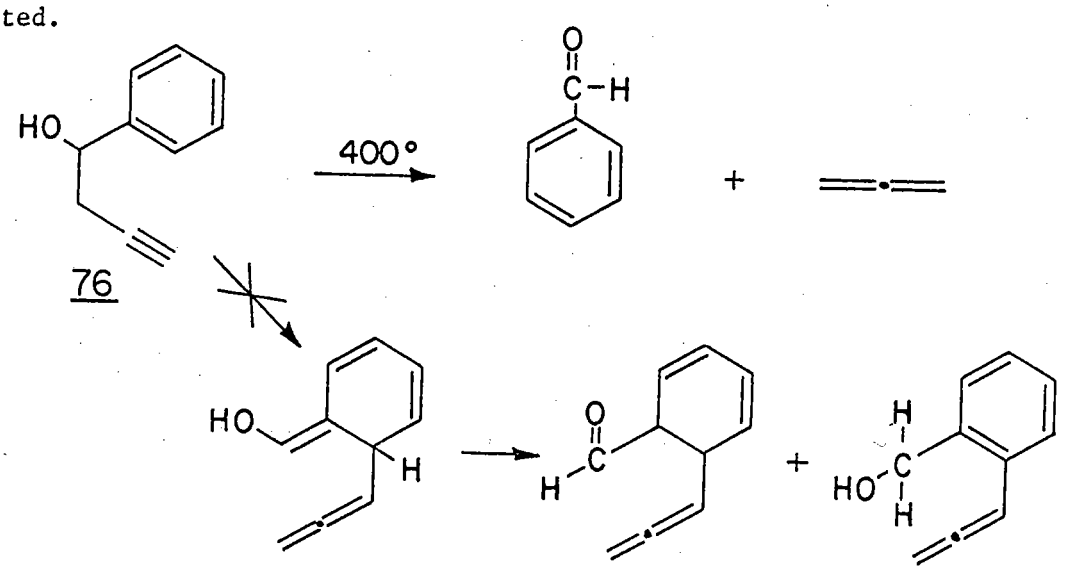
78

1-Phenyl-3-butyn-1-ol (76) was synthesized by the Grignard reaction of benzaldehyde with propargylmagnesium bromide, followed by hydrolysis.



The physical constants of 76 were in agreement with the literature[65] values and the infrared and n.m.r. spectra were consistent with the proposed structure. Hydrogenation of 76 gave phenyl n-propyl ketone as the major product, identified by its 2,4-dinitrophenylhydrazone derivative, which showed no melting point depression on admixture with authentic material.

Thermolysis of 76 produced benzaldehyde and a low boiling material believed to be allene. No trace of any oxy-Cope product could be detected.

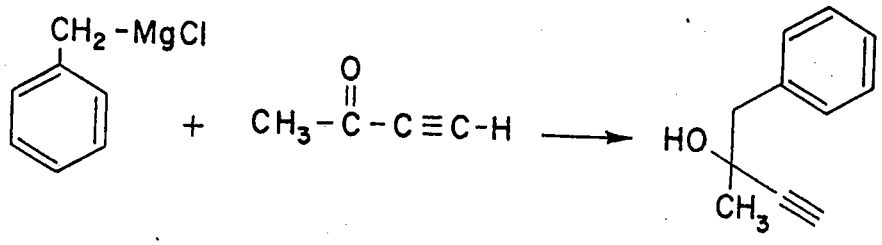


The benzaldehyde produced was identified by its characteristic odor, infrared spectrum and 2,4-dinitrophenylhydrazone derivative. The derivative showed no melting point depression on admixture with authentic material.

The absence of oxy-Cope rearrangements in these systems may be due to the fact that in the rearrangement pathway the aromatic ring must be attacked with resulting loss of aromatic resonance energy. Since the activation energy of the rearrangement pathway is greatly increased by this effect, the lower energy cleavage pathway dominates to the complete exclusion of the oxy-Cope pathway.

Another factor is that even if the oxy-Cope pathway possessed an activation energy sufficiently low to proceed at 400°, the resulting enol could restore the aromaticity of the benzene ring in the gas phase only via a symmetry forbidden 1,3 hydrogen shift. Therefore the reverse reaction, to give starting material, 76, would occur preferentially since this reaction restores the aromaticity in a symmetry allowed fashion.

1-Phenyl-2-methyl-3-butyn-2-ol (78), previously unreported, was prepared by the reaction of benzylmagnesium chloride with methyl ethynyl ketone.



78

The yield of 78 was low, but sufficient quantity was obtained for the following experimental work. The physical constants and elementary analysis of 78 were consistent with the proposed structure as were the infrared and n.m.r. spectra. They are detailed in the experimental section, page 156. Hydrogenation of 78 was quantitative and gave 1-phenyl-2-methyl-2-butanol, identified by comparison of its v.p.c. retention time and infrared spectrum with authentic material.

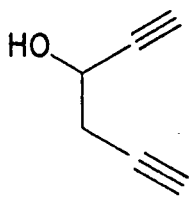
Thermolysis of 78, even at temperatures as high as 430°, gave only some low boiling fragmentation products and large quantities of unreacted material. No trace of any oxy-Cope product could be detected in the thermolyzed products. The reasons for the lack of any oxy-Cope rearrangement in this compound are probably similar to those discussed for the thermolysis of 1-phenyl-3-butyn-1-ol. In 78, the cleavage reaction also

would involve phenyl participation therefore both oxy-Cope and cleavage processes are unfavorable. In view of these results it would appear that phenyl participation in oxy-Cope or cleavage reactions is energetically an unfavorable process. The possibility remains, however, that phenyl participation in the oxy-Cope process could occur if a symmetry allowed 1,5 hydrogen transfer were possible to restore the aromatic system. Phenyl participation in the Cope rearrangement has been reported by Doering and Bragole[68] but under base catalysis where intermolecular hydrogen shifts can occur.

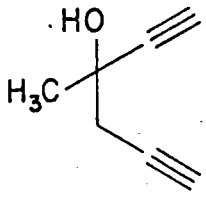
The above results are surprising since the Claisen rearrangement[1], which involves phenyl participation, is a facile process at 300 - 400°. The reasons for the comparative ease of the Claisen rearrangement are not within the scope of this thesis.

Investigation of 1,5-Hexadiyn-3-ols

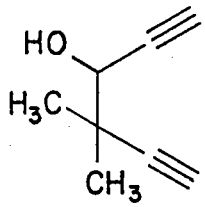
The effect of two triple bonds upon the oxy-Cope rearrangement was next investigated. For this purpose, the following compounds were synthesized and thermolyzed: 1,5-hexadiyn-3-ol (79), 3-methyl-1,5-hexadiyn-3-ol (82), 4,4-dimethyl-1,5-hexadiyn-3-ol (84) and 4-methyl-1,5-hexadiyn-3-ol (86).



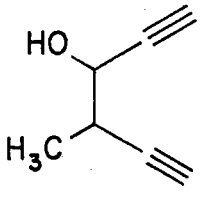
79



82



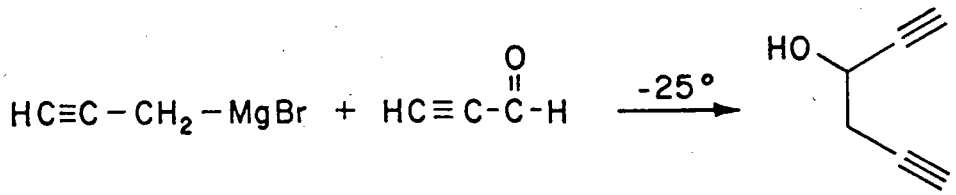
84



86

The preparations and thermolysis products obtained will be discussed first.

1,5-Hexadiyn-3-ol (79) was synthesized by the Barbier reaction of propargyl bromide with propargylaldehyde, as described by Sondheimer[33].

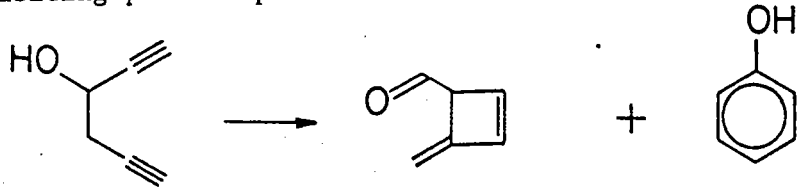


79

The physical constants, infrared and n.m.r. spectra of the compound were consistent with the proposed structure. They are detailed in the experimental section. The compound contained no allenic or internal acetylenic functionalities. Since this compound was fully characterized by Sondheimer[33], no further structure proof was undertaken on it.

Thermolysis of 79 afforded viscous mixtures containing much polymeric material. V.p.c. analysis indicated two volatile constituents. The lower boiling product proved quite unstable, polymerizing rapidly. It could be isolated in impure form by trap to trap distillation as described in the experimental section. Due to the compound's extreme instability the 4-methylene-2-cyclobutene-1-carboxaldehyde structure (80) was assigned solely on the basis of its n.m.r. spectrum. The spectrum is described in the experimental section. The structure assignment rests on the similarity of the n.m.r. data to that reported for the model compound dimethylene-cyclobutene[16]. See page 189a.

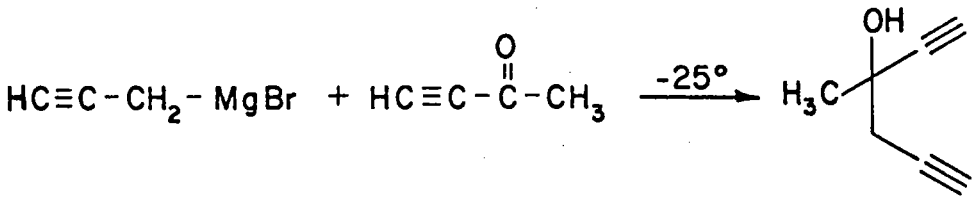
The higher boiling product was identified as phenol by its odor, v.p.c. retention time, infrared spectrum and tribromo derivative, which showed no melting point depression on admixture with an authentic sample.



79 80 81

No trace of any allenic products or of any propargylaldehyde could be detected in the thermolysis of 1,5-hexadiyn-3-ol.

3-Methyl-1,5-hexadiyn-3-ol (82), previously unreported, was prepared by the low temperature Barbier reaction of propargyl bromide with methyl ethynyl ketone, followed by hydrolysis.



82

The physical constants, elementary analysis, infrared and n.m.r. spectra of 82 were consistent with the proposed structure and are described in the experimental section. Hydrogenation of 82 was quantitative and gave 3-methyl-3-hexanol, identified by comparison of v.p.c. retention time and infrared spectrum with authentic material.

Thermolysis of 82 afforded only one volatile product, in addition to surviving starting material. In addition considerable polymeric material was always present in the crude thermolysis product. The volatile product was extremely prone to further polymerization upon standing or heating, necessitating spectral analysis immediately after isolation. The 3-acetyl-4-methylenecyclobutene (83) structure was assigned to the thermolysis product solely on the basis of its infrared and n.m.r. spectra due to rapid polymerization of the compound. The spectra are described in the experimental section. The infrared spectrum contained bands at 1710 and 875 cm^{-1} ascribable[44] to carbonyl and olefinic methylene absorption respectively. The n.m.r. spectrum is in agreement with the model compound 1,2,3-trimethyl-3-acetyl-4-methylenecyclobutene.[69]

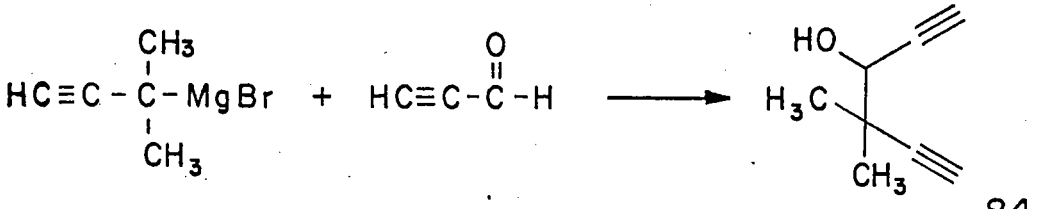
See page 189a.

Hydrogenation of the compound gave a saturated ketone which gave a positive iodoform test. The thermolysis product formed a stable 2,4-dinitrophenylhydrazone derivative whose elementary analysis was consistent with the proposed structure.

82 83

No trace of any allenic, aromatic or cleavage products could be detected in the thermolysis of 82.

4,4-Dimethyl-1,5-hexadiyn-3-ol (84), previously unreported, was prepared by the Barbier reaction of 3-bromo-3-methyl-1-butyne with propargylaldehyde, followed by hydrolysis.

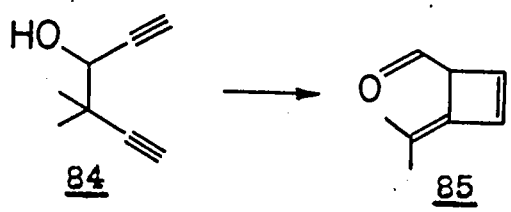


84

The physical constants, elementary analysis, infrared and n.m.r. spectra of 84 were consistent with the proposed structure and are detailed in the experimental section. The compound appeared homogeneous (v.p.c.) and no traces of allenic or internal acetylenic products were detectable.

Thermolysis of 84 afforded mixtures containing much polymeric material. V.p.c. analysis showed one major thermolysis product constituting 70-80% of the volatile material. Small quantities of two other products were produced but were present in insufficient quantities for isolation and characterization. The major product was isolated, free of polymer, in

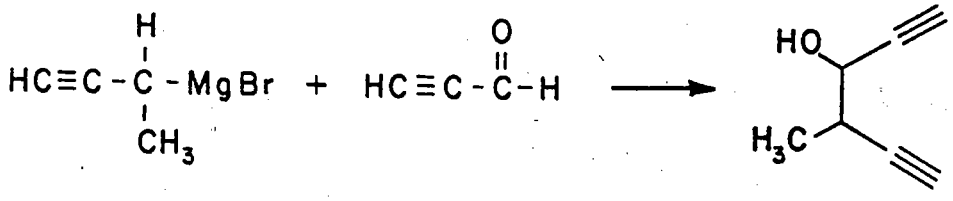
about 90% purity as described in the experimental section, page 147. The 4-isopropylidene-2-cyclobutene-1-carboxaldehyde (85) structure was assigned to the major product on the basis of its infrared and n.m.r. spectra as detailed in the experimental section. The compound polymerized extremely rapidly on standing, thus precluding further structure proof. The infrared spectrum of 85 showed bands at 1725 and 1630 cm^{-1}, indicative[44] of carbonyl and olefinic functionalities respectively. The n.m.r. spectrum was quite similar to that reported for the model compound di-isopropylidenecyclobutene.[18] See page 189a.



84 85

The product formed a stable 2,4-dinitrophenylhydrazone whose elementary analysis and n.m.r. spectrum were consistent with the structure. Infrared spectra of crude thermolyses mixtures from the thermolysis of 84 indicate no trace of any allenic or aromatic products.

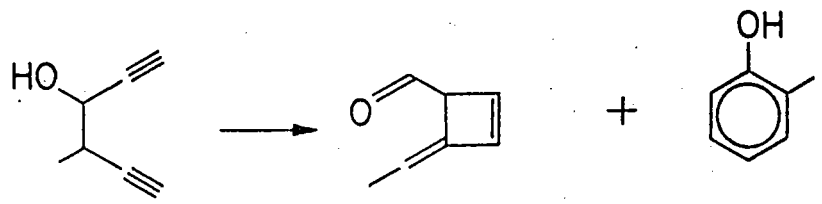
4-Methyl-1,5-hexadiyn-3-ol (86), previously unreported, was prepared by the Barbier reaction of 3-bromo-1-butyne with propargylaldehyde, followed by hydrolysis.



The physical constants, elementary analysis, infrared and n.m.r. spectra of 86 were consistent with the proposed structure. They are detailed in the experimental section, page 149. The material appeared homogeneous (v.p.c.) and no trace of allenic or internal acetylenic products could be detected. Hydrogenation of 86 gave a mixture of 4-methyl-3-hexanone and 4-methyl-3-hexanol, identified by comparison of v.p.c. retention times with authentic materials[4].

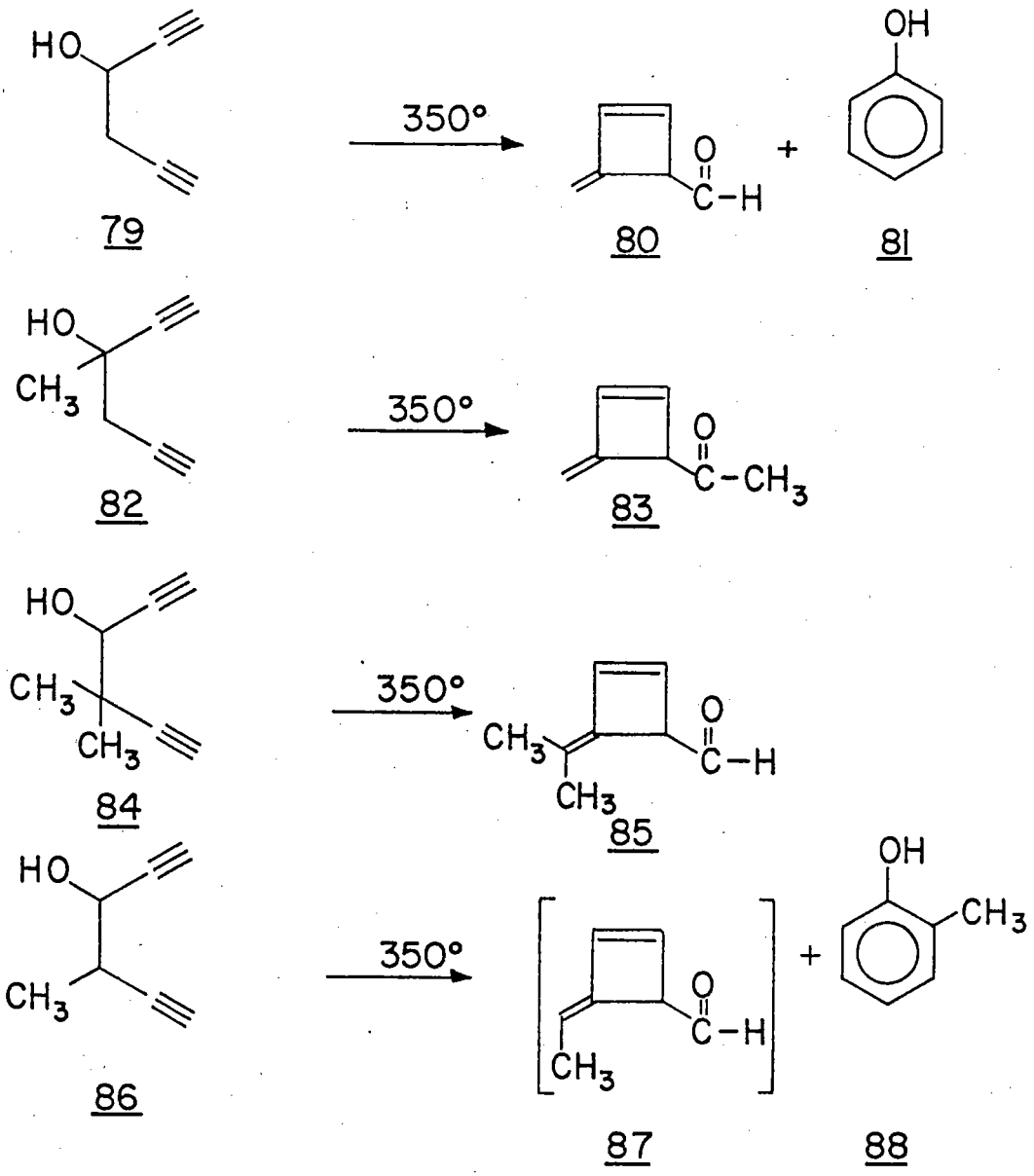
As with the thermolysis of the previously described diacetylenic alcohols, thermolysis of 86 yielded a viscous product containing much polymeric material. V.p.c. showed the volatile constituent to consist of two components in a 7:3 ratio. The minor product is believed to be the corresponding 4-ethylidene-2-cyclobutene-1-carboxaldehyde (87) on the basis of its v.p.c. retention time and by analogy with the other systems studied. Due to the small amount of material available and its tendency to polymerize, this component could not be isolated.

The major component, isolated by distillation under aspirator pressure, was shown to be o-cresol by its v.p.c. retention time and infrared spectrum, both of which were identical to those of authentic o-cresol but quite different from those of the m- and p-isomers. The major component formed a bromo derivative which showed no melting point depression on admixture with an authentic sample.



86 87 88

PLATE II


HO
350°
O
C-H
+
OH
79
80
81
HO
CH3
350°
O
C-CH3
82
83
HO
CH3
CH3
350°
CH3
O
C-H
CH3
84
85
HO
CH3
350°
O
C-H
CH3
+
OH
CH3
86
87
88

The reactions discussed in the thermolyses of the above diacetylenic alcohols are summarized on plate II page 76.

Table VII indicates the dependency of phenol production, from 79, on temperature and residence time.

Table VII

Temperature and Residence Time Effects on Phenol Formation

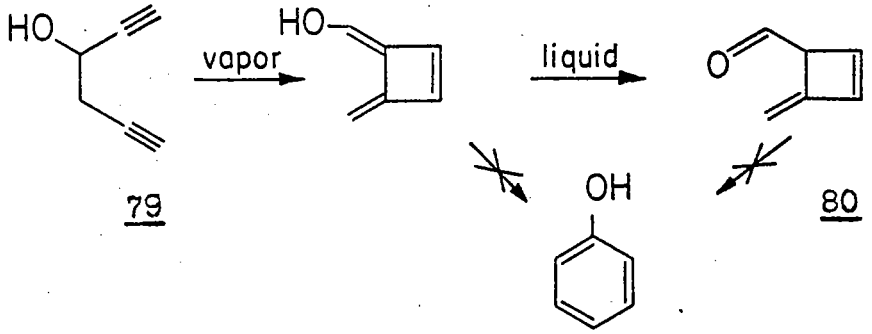
t°C	Pmm	% Phenol
350	0.5	detonation
"	3	8
"	25	43
370	3	6
"	5 H_2O trap	10
"	20	48

At shorter residence time (lower pressure) the amount of polymeric material increased as phenol formation fell off. The amount of phenol produced was measured using an internal standard as described in the experimental section, page 141. The percentage of cyclobutene product, 80, could not be measured quantitatively due to its extreme instability.

A thermolysis of 79, performed at 350° and 0.5 mm, afforded a product mixture which decomposed explosively upon warming to near room temperature. Consequently, the possibility of a phenol precursor such as cyclohexadienone which could either produce phenol or polymerize in the liquid phase, after condensation, was considered. To test this hypothesis, a thermolysis was performed at 370° and 5 mm and the vapors were condensed in traps containing cold water. Although these conditions

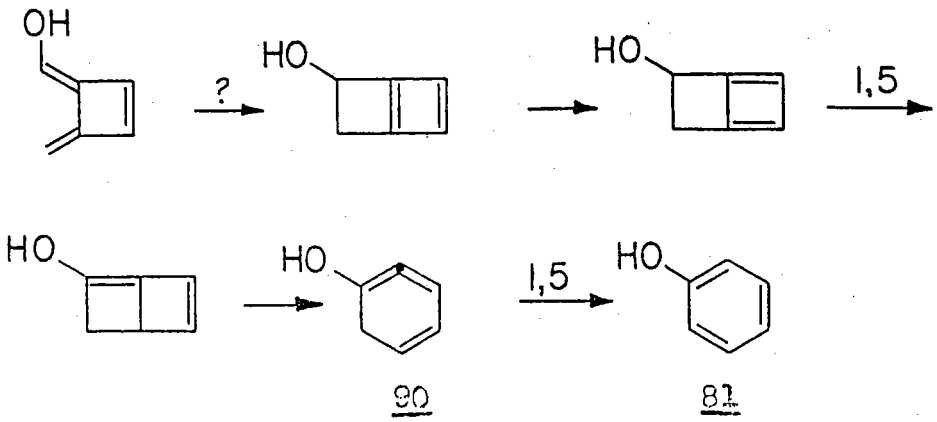
should greatly facilitate any intermolecular, liquid phase, hydrogen shifts required for phenol formation, only the expected amount of phenol, about 10%, was obtained.

By analogy with the results reported from the thermolysis of 1,5-hexadiynes[16], the primary products expected from the diacetylenic alcohols 79, 82, 84 and 86 are the enolic precursors of the observed carbonyl products 80, 83, 85 and 87. The fact that thermally produced enols survive in the gas phase with ketonization occurring only in the liquid state has previously been explained. The carbonyl components of the above product mixtures were shown not to be precursors to the aromatic products, since a sample of 80 in dilute deuterochloroform solution showed no n.m.r. spectral changes after standing for five days.



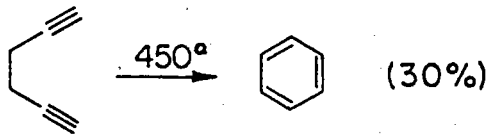
79 80 81

Another possible mechanism considered for formation of the aromatic products involves the enolic precursor of 80 by a reaction sequence such as the following.

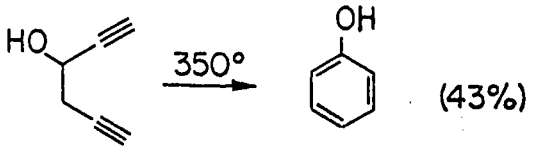


90 81

However, such mechanisms are discounted by the following argument. It appears that formation of the aromatic ring is greatly facilitated by the presence of the hydroxy function. For example, thermolysis of 1,5-hexadiyne at 450° produced 30% benzene[19] while thermolysis of 79 produced 43% phenol at only 350°.



20



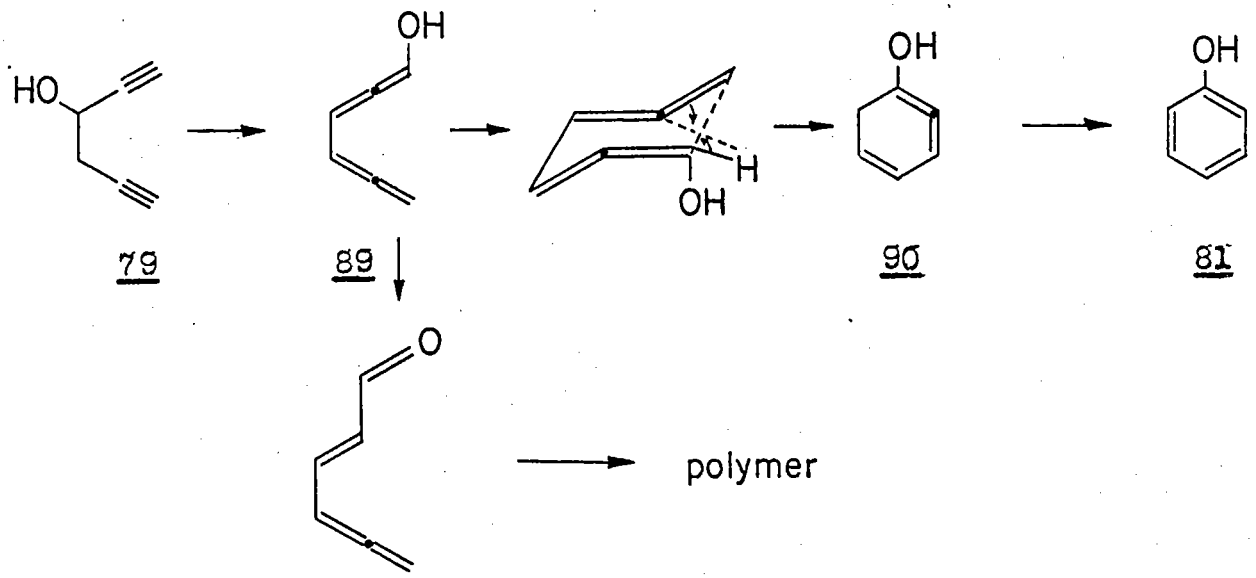
79 81

Although it is difficult to compare reaction conditions as reported by different investigators, it would appear that residence times in this work were considerably less than in the work of Coller[19]. It may be concluded then, that under conditions of identical length of exposure, the differences between amounts of benzene and phenol formation would be even greater.

Now the first step in the above mechanism is a butadiene-cyclobutene isomerization to form a cyclobutadiene in the fused ring. This step should require an activation energy which is increased by the presence of the hydroxyl function since it involves a disruption of the oxygen lone pair interaction with the ethylenic π system. Berson[50] has shown that a perturbation due to an oxygen on an ethylenic function stabilizes the system relative to the unsubstituted molecule. Therefore the enolic precursor should possess a lower ground state energy than the corresponding unsubstituted dimethylenecyclobutene. Since aromatization is facilitated by the hydroxyl group, the above sequence is not in accord with the observed data.

The fact that increased residence time in the thermolysis zone leads to increased phenol formation is indicative of an intermediate whose rate of formation is fast compared to its rate of decay along the pathway leading to phenol. The formation of o-cresol, as the only phenolic product from 86, eliminates any prismane or benzvalene intermediates since such structures should result in some m- or p-cresol formation. The complete absence of phenolic products in the thermolyses of 82 and 84 indicates that phenol formation requires hydrogen migration from both carbons 3 and 4 and also renders unlikely any potential hydroxyl migration or carbon skeletal rearrangements.

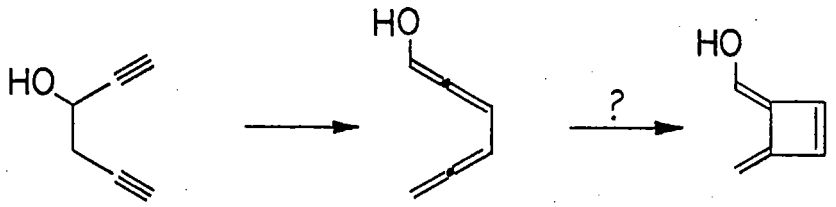
A mechanism which seems to fit all the above considerations is phenol formation via the oxy-Cope pathway.



The cyclic allenol intermediate 90, which represents a more stabilized cyclic allene than the similar intermediate suggested by Bergmann[20], can arise from the oxy-Cope product 89 by means of a 1,2-cycloaddition of the terminal hydrogen as indicated. The cyclic allenol can undergo a 1,5

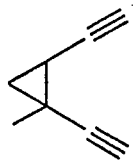
hydrogen shift and thus produce phenol in the vapor state. This step is in accord with the fact that there was no increase of phenol formation by condensation into a prototropic medium. As pointed out earlier, the intermediate 89 should form rapidly, via the low energy oxy-Cope pathway, compared with its decay rate to phenol, via the higher energy cycloaddition. Polymer would result from ketonization of 89, after condensation, since the resulting hexatrienal cannot be expected to survive in an acidic medium.

Whether cyclobutene formation occurs directly from the starting alcohol or proceeds through the Cope product remains conjectural. An internal allene dimerization[53] of 89, a pathway considered by Huntsman, can account for cyclobutene formation.

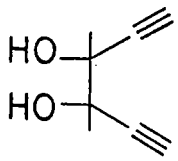


79

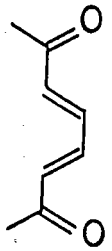
Disubstitution as in compounds 27 or 50 would prevent formation of benzene derivatives from the primary Cope product.



27



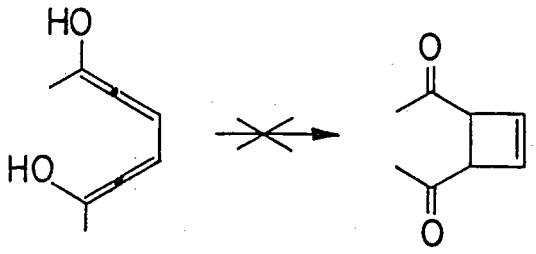
50



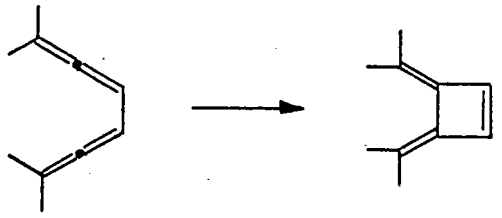
51

However, the report of Chuche[28] is not in agreement with this scheme. Since the results of Skattebol[18] show that tetra substitution at the termini of the 1,2,4,5-hexatetraene system does not block cyclobutene formation,

Chuche's terminal Cope product seems to require an alternate path for cyclobutene formation.



Chuche & Manisse

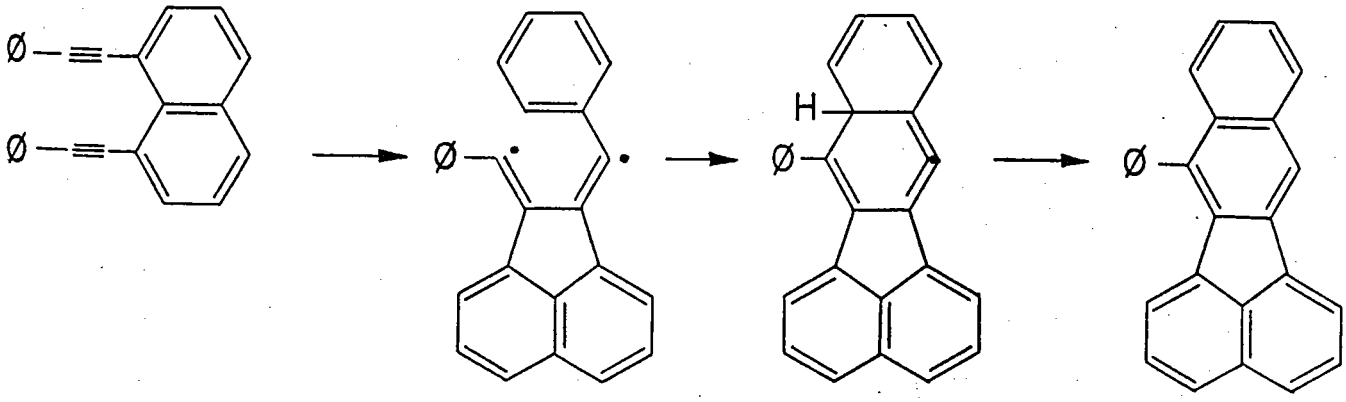


Skattebol & Solomon,

26a

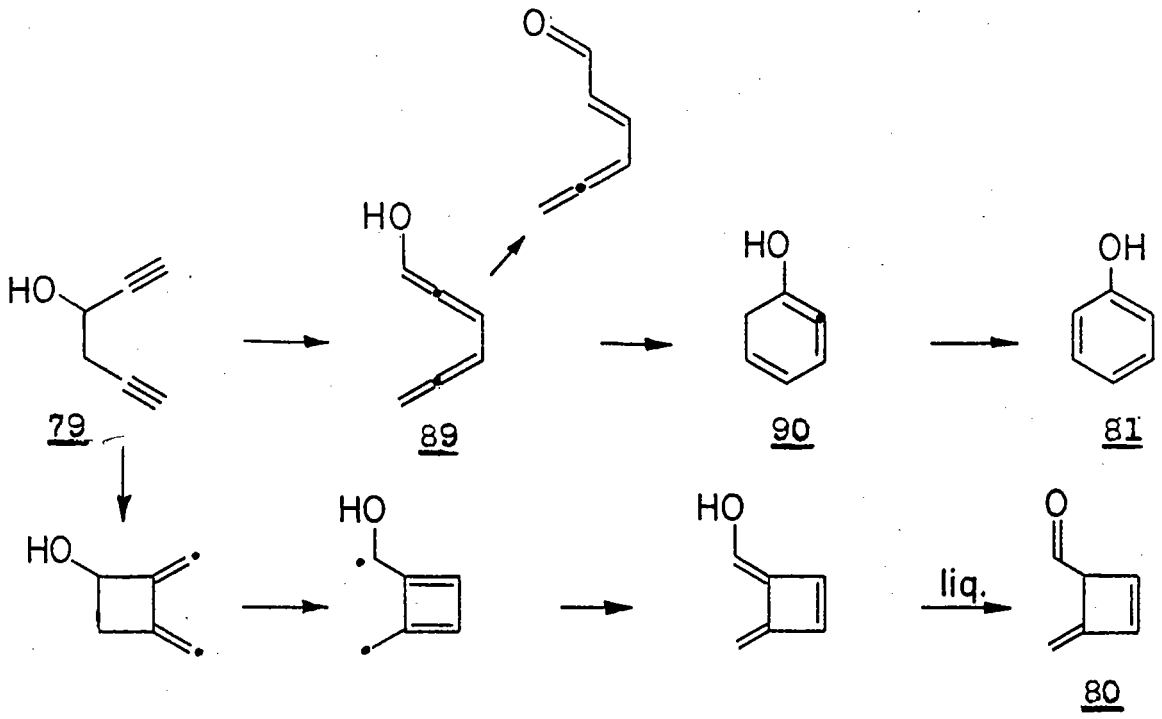
Olefin stabilization by the two hydroxyl functions in the enolic precursor to 51 cannot account for lack of cyclization since only the inner double bonds of the allenic systems would be involved.

Schechter[54] has proposed the following scheme in a similar system.



The possible formation of the cyclobutenes by a diradical pathway

analogous to that above is here proposed.



A concerted ring closure-ring opening of the initially produced diradical results in a diallylic resonance stabilized diradical which collapses to the final product. This pathway avoids the necessity of invoking the various highly strained, fused ring cyclobutadienyl systems[19,20] that plague alternate mechanistic suggestions. The diradical pathway is actually a multistep version of the concerted 10 electron one-step mechanism originally proposed by Huntsman[16] but rejected by Coller et al.[19] on molecular orbital grounds. Stereospecificity is maintained by the diradical pathway since, following the concerted ring opening-ring closure step, geometry is maintained by the necessity of π orbital overlap in the forming allylic radical and the rotational restraint inherent in the cyclic system. Tetrasubstitution as in 50 would result in substantial steric

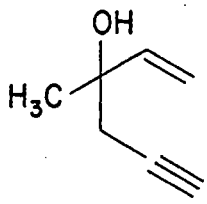
crowding in the initial diradical produced and could render this pathway incapable of competition with the Cope process.

The fact that Chuche[28] did not observe cyclobutene formation from the bis-allenol intermediate, as might be expected from the results of Skattebol[18], could be the result of intramolecular H-bonding which must be disrupted in any cyclization process.

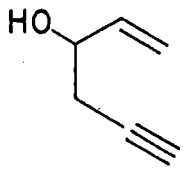
It is worthy of note that only in the thermolysis of 50 is the concurrent formation of β-hydroxyacetylene cleavage products reported. It was demonstrated earlier in this thesis that the latter reaction can compete with the acetylenic Cope process. The absence of this reaction in the thermolyses of the diacetylenic alcohols here reported is indicative of a more facile reaction with which the cleavage cannot compete and only in the absence of cyclobutene formation is it observable. This fact is also in accord with the proposed low energy pathway for cyclobutene formation.

Investigation of the β-hydroxyacetylene cleavage.

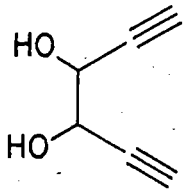
The results thus far presented in this thesis indicate a ready participation of triple bonds in electrocyclic reactions. In particular, the cleavage of β-hydroxyacetylenes seemed promising for direct determination of kinetic parameters. This reaction has now been reported by Wilson and Sherrod[27] (42), by Chuche and Manisse[28] (46 and 50) and in an earlier portion of this thesis (42 and 46).



42



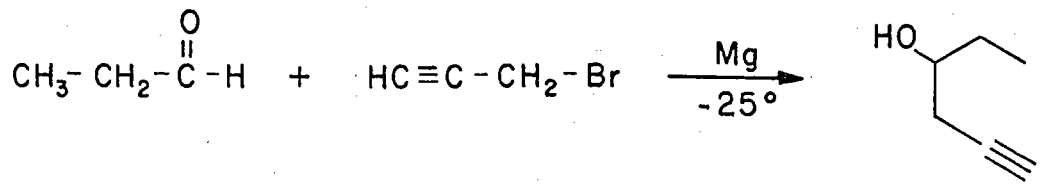
46



50

It was therefore decided to investigate this reaction further in some compounds where no competing reactions could obscure the kinetic determinations. As this study was in progress it was learned that Dr. Brian Yates[70] was also investigating this system independently. A joint project was initiated and is continuing at this writing. Only those aspects of the work directly pertinent to this thesis will be presented here.

5-Hexyn-3-ol (58) was synthesized by the low temperature Barbier reaction of propargyl bromide with propionaldehyde.



58

The physical constants of 58 were in agreement with those reported in the literature. The elementary analysis, infrared and n.m.r. spectra were consistent with the structure. No trace of internal acetylenic impurity was detected. Hydrogenation of 58 gave 3-hexanone, identified as its 2,4-dinitrophenylhydrazone derivative.

Thermolysis of 58 in the flow system at 350° gave a quantitative conversion to propionaldehyde and allene as previously stated, page 29. The propionaldehyde was identified by its characteristic odor, v.p.c. retention time and 2,4-dinitrophenylhydrazone derivative, which gave no melting point depression on admixture with an authentic sample.

Allene was identified only as a small peak near the air peak in the v.p.c. The mass balance of the reaction indicated that a three carbon species had been produced.

Since the cleavage reaction appeared to be quantitative, the rate of the reaction was followed in sealed tubes over the temperature range 227 to 258°. The experimental procedures and calibration techniques employed are described in detail in the experimental section, page 167. The results, presented in Figure V, show the reaction to follow the first order rate law at all temperatures studied. No surface or pressure effects were detectable. Individual rate constants were obtained for six temperatures by standard least squares analysis. An Arrhenius plot of the rate constants, shown in Figure VI, gave an excellent linear relationship. Least squares analysis was employed to yield the best slope and intercept. The Arrhenius parameters were E_a=35.0 kcal/mol, $\log_{10}A$=10.29, ΔS^*=-14.5e.u.[i]

[i] All ΔS^* values calculated in this thesis are based on the formula urged by Frey[3]:

$$A = e(k/h)Tm\ e^{\Delta S^*/R}$$

Figure V
Kinetic Data for
Disappearance of
5-Hexyn-3-ol

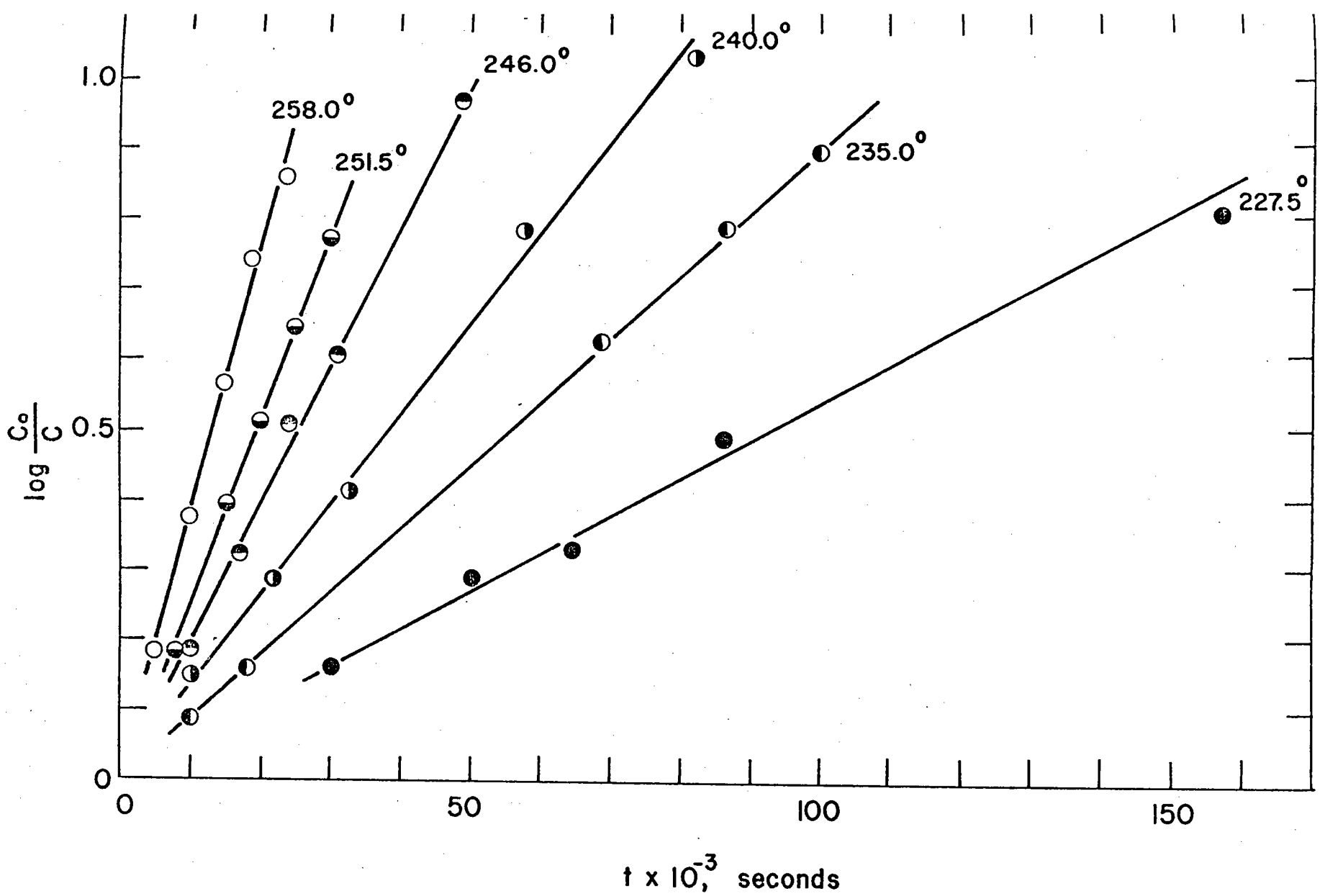
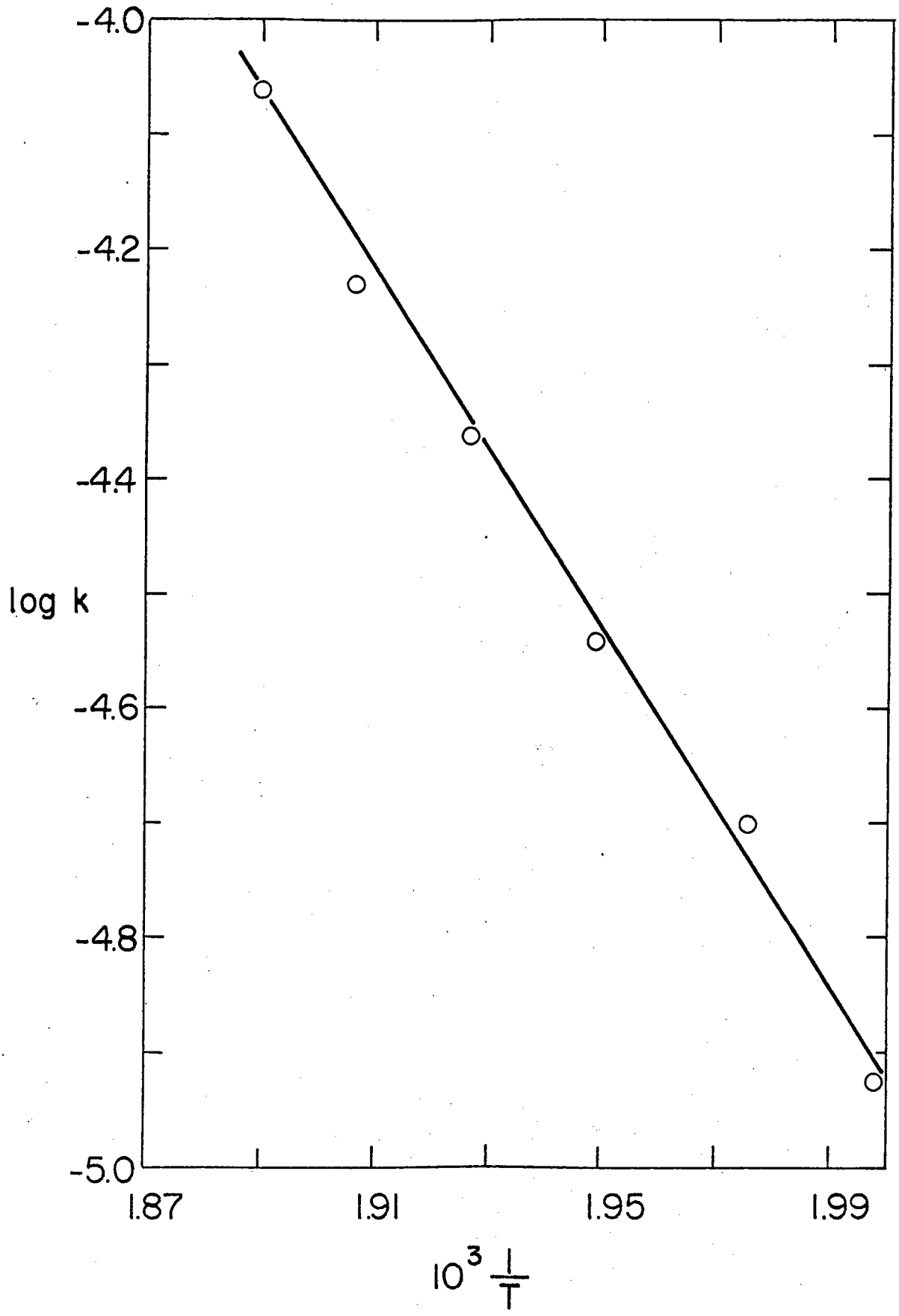
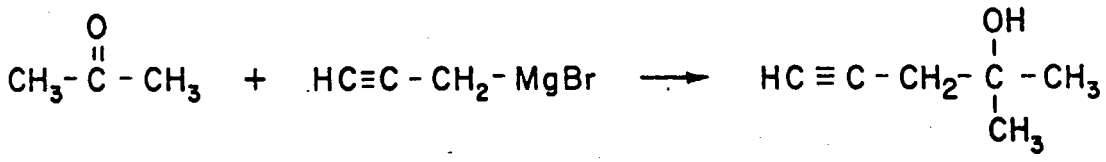

1.0
0.5
0
log C°/C
258.0°
251.5°
246.0°
240.0°
235.0°
227.5°
0
50
100
150
t x 10,-3 seconds

Figure VI
Arrhenius Plot of
Kinetic Data for
Disappearance of
5-Hexyn-3-ol


-4.0
-4.2
-4.4
-4.6
-4.8
-5.0
log k
1.87
1.91
1.95
1.99
$10^3 \frac{1}{T}$

The estimated error limits for the activation energy and entropy are ±2 kcal/mol and ±3e.u. respectively. These activation parameters are considered strongly indicative of a concerted mechanism with a rigid transition state.

2-Methyl-4-pentyn-2-ol (91) was prepared by the low temperature Barbier reaction of propargyl bromide with acetone.



91

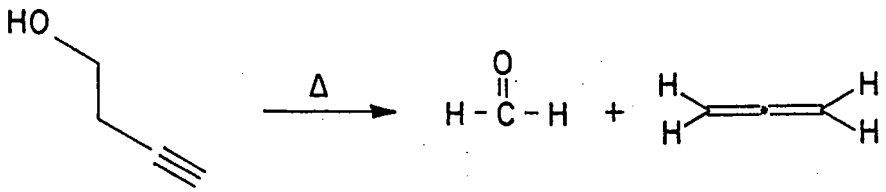
The physical constants of 91 were in agreement with the literature values and the infrared and n.m.r. spectra were in accord with the structure. No internal acetylenic impurity was detectable.

Thermolysis of 91 gave quantitative cleavage to acetone and a low boiling constituent believed to be allene. The acetone was identified by its characteristic odor and 2,4-dinitrophenylhydrazone derivative which showed no melting point depression on admixture with authentic material. Allene again was identified only as a small peak near the air peak in the v.p.c. However, Yates[70] has established allene to be a product of this reaction by means of its characteristic gas phase infrared spectrum.

A kinetic study of the cleavage of 91 was undertaken by the same procedure as for 5-hexyn-3-ol. Rates were measured over five temperatures from 234 to 256°. The reaction followed the first order rate law at all five temperatures. The data is presented in Figure VII. The individual rate constants, obtained by least squares analysis, were used to construct

the Arrhenius plot, shown in Figure VIII. An excellent linear relationship was again observed. Least squares gave E_a=37 ± 2 kcal/mol, $Log_{10}A$= 11.13, ΔS^*= -10.6±3 e.u. These values again suggest a cyclic transition state for the β-hydroxyacetylene cleavage.

Commercial 3-butyn-1-ol (92) upon thermolysis also gave quantitative conversion to cleavage products.



92

The formaldehyde component was trapped as its 2,4-dinitrophenylhydrazone derivative which showed no melting point depression on admixture with authentic material. A kinetic study of this reaction has been completed in this laboratory.[i] The reaction was first order and gave Arrhenius parameters of E_a=37.1 kcal/mol and ΔS^*= -12.7 e.u.

Thus the primary alcohol (92), the secondary (58) and the tertiary (91) all gave activation parameters consistent with cyclic six membered transition states.

Professor Yates[70] has studied the kinetics of the β-hydroxyacetylene cleavage for 3-butyn-1-ol (92), 4-pentyn-2-ol (93) and 2-methyl-4-pentyn-2-ol (91).

These results are tabulated in Table VIII along with the results from this laboratory. Also given are the activation parameters for the corresponding β-hydroxyolefin as published by Smith and Yates[8].

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[i] Robert Proverb, unpublished results.

Figure VII
Kinetic Data for
Disappearance of
2-Methyl-4-Pentyn-2-ol

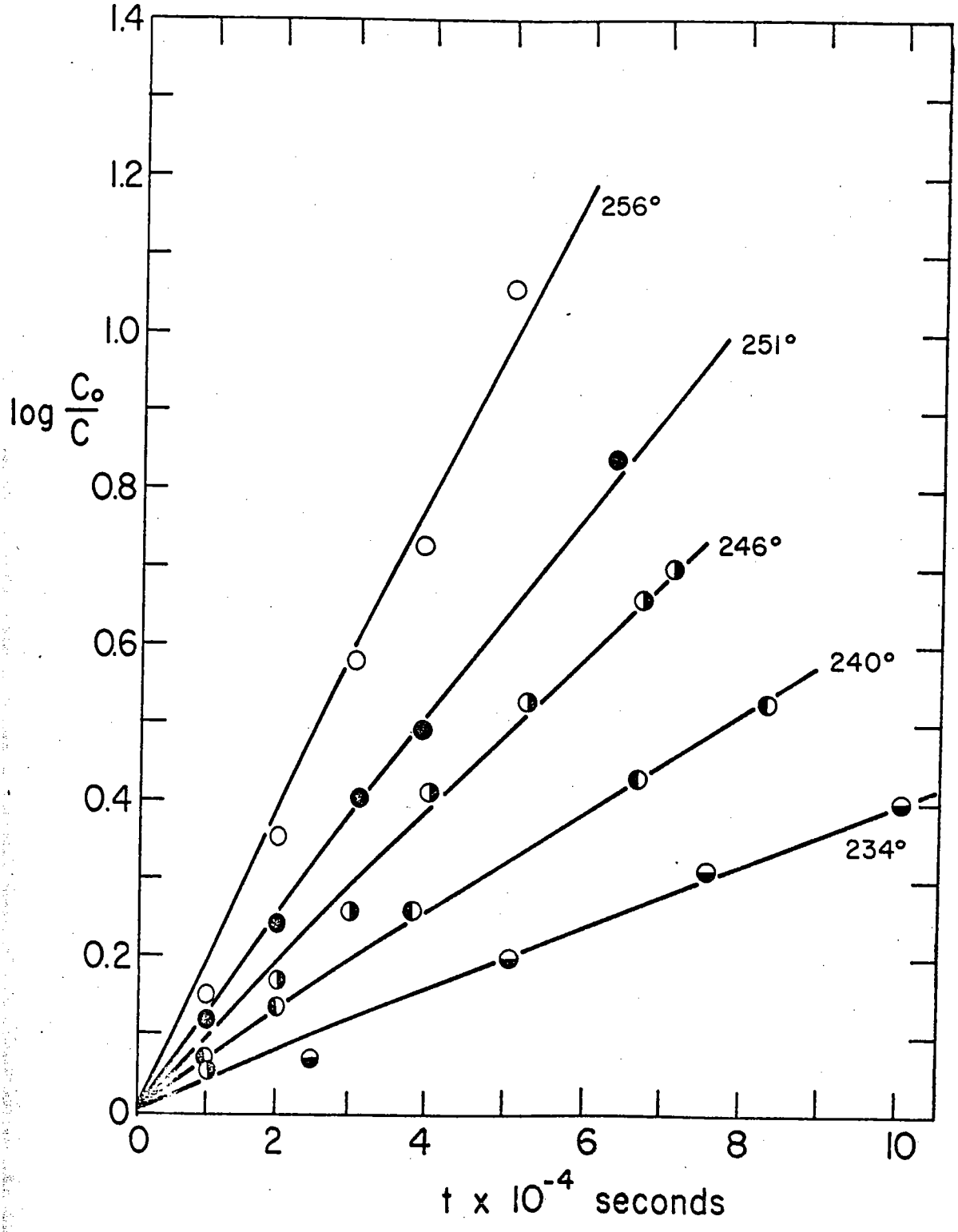

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
log Co/C
256°
251°
246°
240°
234°
0
2
4
6
8
10
t x 10-4 seconds

Figure VIII
Arrhenius Plot of
Kinetic Data for
Disappearance of
2-Methyl-4-Pentyn-2-ol

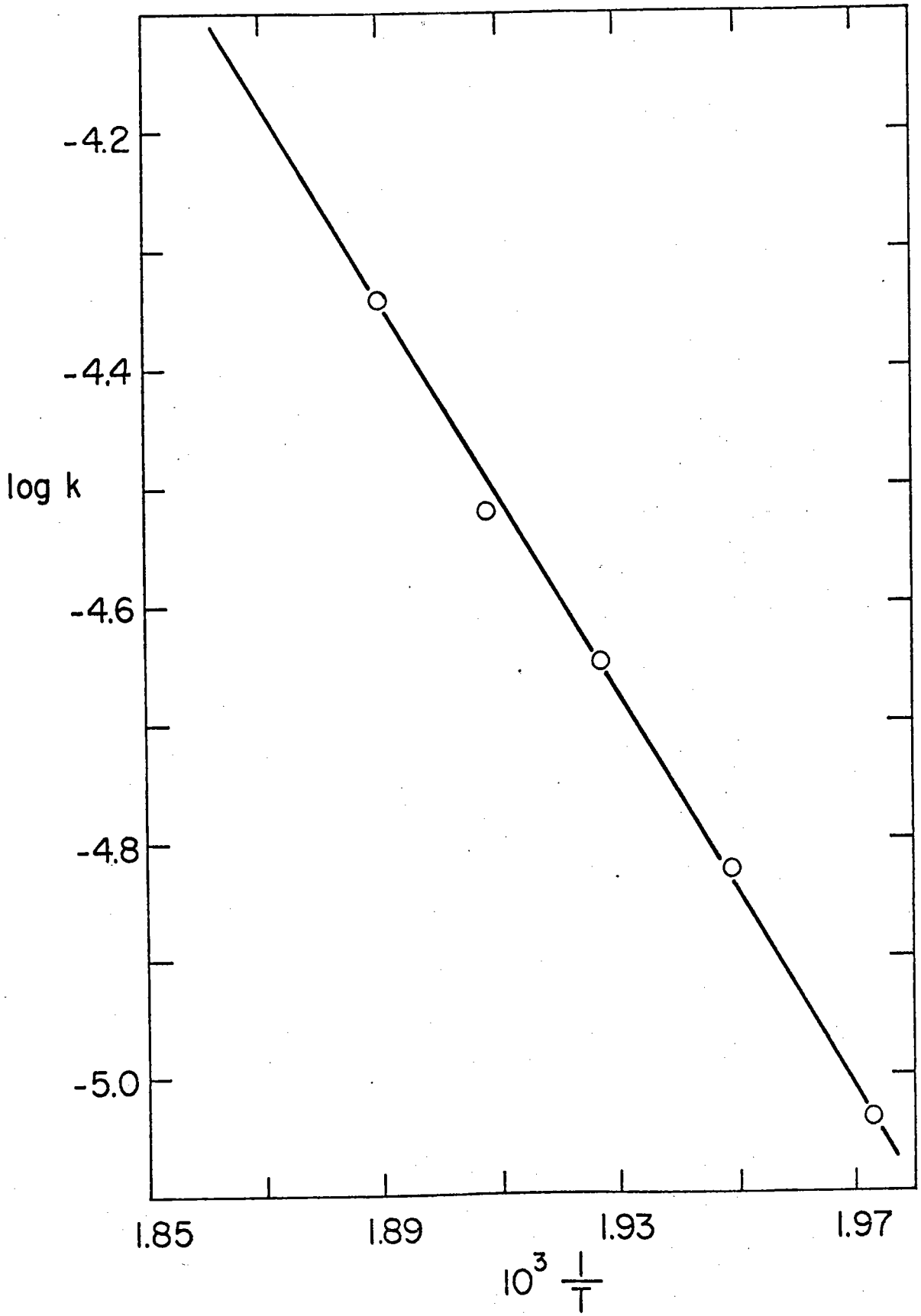
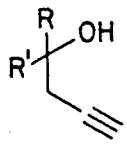
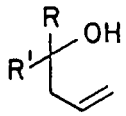

-4.2
-4.4
log k
-4.6
-4.8
-5.0
1.85
1.89
1.93
1.97
$10^3 \frac{1}{T}$

Table VIII. Comparison of activation parameters in β-hydroxyolefin and β-hydroxyacetylene cleavage.





	Source	Ea	ΔS^*	Source	Ea	ΔS^*
$R=R^1=H$	A	39.6	-10.6	B	41.0	-8.8
"	C	37.1	-12.7			
$R=H$, $R^1=CH_3$	A	39.7	-9.3	B	40.9	-7.5
$R=H$, $R^1=C_2H_5$	C	35.0	-14.5			
$R=CH_3$, $R^1=CH_3$	A	39.7	-9.3	B	40.7	-6.3
"	C	37.7	-10.6			

A, Professor Yates[70], personal communication.

B, Smith and Yates[8]

C, This laboratory

This table indicates that the data from this laboratory and those of Yates are within experimental error for 3-butyn-1-ol (92) and 2-methyl-4-pentyn-2-ol (91). The secondary alcohol 5-hexyn-3-ol (58), however, gave a substantially lower activation energy and more negative activation entropy than the secondary alcohol 4-pentyn-2-ol. The source of this discrepancy is not known as of this writing.

Comparison of the activation energies of the acetylenic alcohols with their olefinic counterparts seems to indicate a slight trend toward lower activation energies for the acetylenic alcohols, however this trend could be fortuitous since most of the energy differences noted are probably within experimental error (±2kcal). With the present data all that should be

stated is that β-hydroxyolefin and acetylene cleavages possess activation energies of comparable magnitude. Also, the slight differences between the primary (92), secondary (58 and 93) and tertiary (91) activation parameters for the acetylenic compounds do not permit elucidation of relative thermolysis rates by inspection. Therefore, the Arrhenius parameters calculated by Smith and Yates[8] were used to compute rate constants at temperatures where an experimental value was available for an acetylenic alcohol. The data in Table IX indicate that at any particular temperature each of the acetylenic alcohols does undergo cleavage substantially faster than its olefinic counterpart. Furthermore, the acetylenes cleaved at the faster rate at all temperatures studied as illustrated for the case of compounds 58 and 94 in Table X.

Table IX. Comparison of relative cleavage rates between acetylenic and olefinic alcohols at arbitrary temperatures.

$t^{o}C$	Compound	$10^{5}ksec^{-1}$	k acet./k olef.
240.0	3-Buten-1-ol	.135[a]	6.0
"	3-Butyn-1-ol	.806	
227.5	4-Penten-2-ol	.10[a]	11.9
"	5-Hexyn-3-ol	1.19	
256.0	2-Methyl-4-penten-2-ol	1.00[a,b]	4.57
	2-Methyl-4-pentyn-2-ol	4.57	

a. Calculated from data of Smith and Yates[8].

b. Result duplicated by Fred Garafolo, this laboratory.

Table X. Comparison of relative cleavage rates between 5-hexyn-3-ol (58) and 4-penten-2-ol (94) at different temperatures.

t°C	10^5k acet. sec^{-1}	10^5k olef. sec^{-1}	k acet./k olef.
227.5	1.19	.10	11.9
233.0	1.99	.16	12.4
240.0	2.88	.32	9.1
246.0	4.40	.50	8.8
256.0	8.66	1.15	7.5

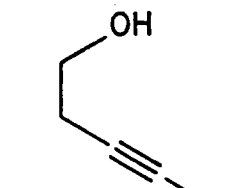
The above comparison involved experimental acetylenic cleavage data and calculated rates for the olefinic analogs. It seemed desirable to verify these comparisons, and also the smaller rate differences between primary, secondary, and tertiary acetylenic alcohols by direct experimental means.

The competitive thermolyses are described in detail in the experimental section, page 162. Qualitatively, the relative cleavage rates for the acetylenic alcohols were secondary (58) > tertiary (91) > primary (92) at 370°. Yates[70] has conducted similar competitive thermolyses and found the order to be tertiary (91) > secondary (95) > primary (92). The discrepancy appears to lie with 5-hexyn-3-ol (58) which, in our hands, gave an anomalously low activation energy and high rate of cleavage compared to 4-pentyn-2-ol (95)*.

Also, we have found qualitatively that 1-phenyl-3-butyn-1-ol (76) underwent cleavage at a faster rate than 1-phenyl-3-buten-1-ol (77) at

* The thermolysis of 58 is currently under investigation in the laboratory of Prof. Yates[70] as well as that of Prof. G. G. Smith, Utah State University, Logan, Utah. Since the techniques in the three laboratories differ, it is hoped that in this manner the anomaly can be either verified or disproven. The interpretation of this effect of structure on reactivity must await the experimental results from these other laboratories.

270°. Thus all the available results indicate triple bond participation in the β-hydroxyolefin cleavage to lead to substantial increases in the rate compared to the olefinic counterparts. Also, Yates[70] has found that 4-phenyl-3-butyn-1-ol (114) cleaved at a rate of 0.4 times that of 3-butyn-1-ol (92) at 300° while 1-phenyl-3-butyn-1-ol (76) cleaved 31 times faster than 92.



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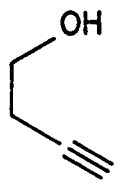

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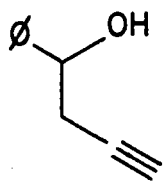


76

Further evaluation of this data is not warranted until activation parameters are obtained for 114 and 76.

Competitive thermolyses were also undertaken in this laboratory between 1-hexen-5-yn-3-ol (46), 5-hexen-1-yn-3-ol (63) and 1,5-hexadien-3-ol (4). Qualitatively, these results indicated acetylenic alcohols 46 and 63 to undergo thermal reaction faster than 4 at 350°. By thermolysis of a mixture of 63, which does not cleave, and 4 which gives both oxy-Cope rearrangement and cleavage, we may write:

$$\frac{(\log {}^{C}o/C)\ 4}{(\log {}^{C}o/C)\ 63} = \frac{(k\ \text{cope} + k\ \text{cleav.})\ 4}{(k\ \text{cope})\ 63}$$

Since activation parameters for 63 have been determined, a rate constant may be extrapolated at 350°. The Cope to cleavage ratio for 4 at 350° has also been determined[11]. Therefore one may substitute a value for k cleav. in terms of k cope. Thus by experimentally determining the initial and final concentrations of 4 and 63 one may obtain Cope and cleavage rate constants for 4 at 350°. Also, after these constants have been computed, a competitive thermolysis between 4 and 1-hexen-5-yn-3-ol

(46) can yield k cope and k cleavage for 46 at 350°, since the Cope to cleavage ratio for 46 is known (see Table I, page 27).

$$\frac{(\text{Log } C_o/C)\,4}{(\text{Log } C_o/C)\,46} = \frac{(k \text{ cope} + k \text{ cleav.})\ 4}{(k \text{ cope} + k \text{ cleav.})\ 46}$$

The results of these computations are given in Table XI. The estimated accuracy of the rate constants is ±10%.

Table XI

Oxy-Cope and cleavage rate constants at 350°

	10^2k cleav.	10^2k cope	Cleavage k/k93	oxy-Cope k/k4
3-buten-1-ol(93)	.147*	---	1	---
5-hexyn-3-ol(58)	1.0	---	6.8	---
1,5-hexadien-3-ol(4)	5.9	7.4	40	1
1-hexen-5-yn-3-ol(46)	13.5	20	92	2.7
5-hexen-1-yn-3-ol(63)	---	50	---	6.8

*Calculated from data of Smith and Yates[8].

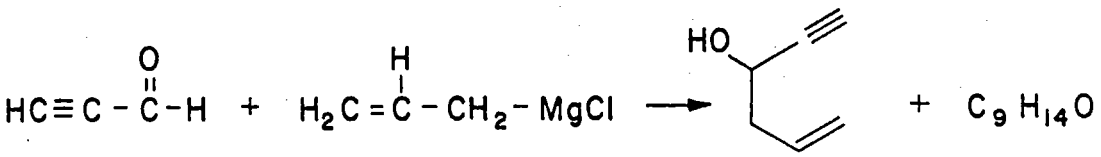
The data readily indicate substantial rate increases in both the oxy-Cope rearrangement (compare 46 with 4), and the β-hydroxyolefin cleavage (compare 58) with 93) with triple bond participation. Possible reasons for these rate accelerations have previously been discussed (see page 53). In addition, the data from Table XI show substantial rate accelerations for the β-hydroxyolefin and -acetylene cleavages when a vinyl group is substituted at carbon 1 (compare 4 with 93 and 46 with 58). This acceleration probably results from the vinyl group weakening the 1-2-carbon-carbon bond which breaks during the cleavage reaction.

Probably the most unexpected and striking result of this thesis work is the faster rates of triple bond participation in electrocyclic reactions as compared to their olefinic analogs.

Investigation of Grignard additions to acetylenes

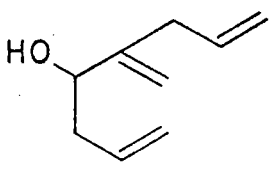
This investigation was undertaken only as a side project since it is not pertinent to the main objectives of this thesis.

During the synthesis of 5-hexen-1-yn-3-ol (63) by the reaction of propargylaldehyde with allylmagnesium chloride, a higher boiling constituent (97) was isolated in addition to the desired 63. For this reaction, an excess of Grignard reagent was used beyond that theoretically required to react with the aldehyde.



.2 mole .7 mole 63 97

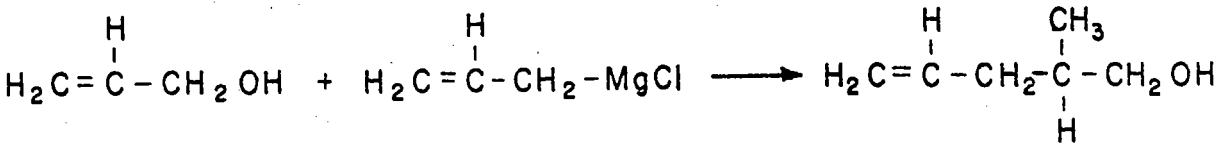
The physical constants and elementary analysis of the higher boiling compound were consistent with the formula $C_9H_{14}O$. The infrared spectrum indicated an olefinic alcohol with no acetylenic functionality. The n.m.r. spectrum consisted of olefinic multiplets corresponding to eight protons, a bis-allylic two proton doublet, an allylic two proton triplet and a carbinol proton triplet. The ultraviolet spectrum showed only end absorption thus precluding conjugation. On the basis of the analytical and spectral data the most likely structure for the higher boiling compound would appear to be 5-methylene-1,7-octadien-4-ol (97).



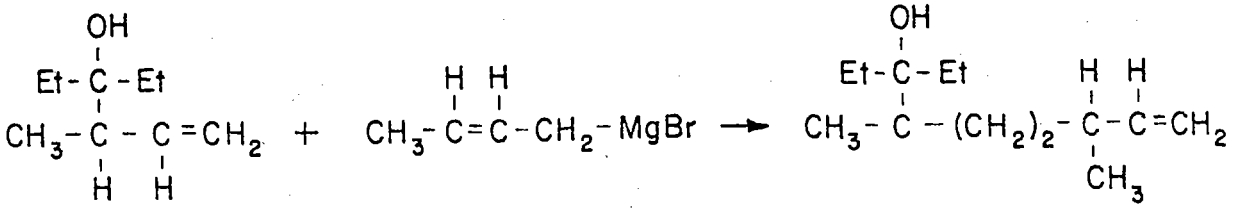
97

The proposed structure was confirmed by hydrogenation with Pd/C. The hydrogenation was nonquantitative and gave a saturated hydrocarbon a saturated ketone and a saturated alcohol. This mode of hydrogenation is characteristic of allylic alcohols[32]. The ketone and alcohol were isolated by preparative v.p.c. and identified as 5-methyl-4-octanone and 5-methyl-4-octanol respectively. The v.p.c. retention times, infrared spectra, indices of refraction and boiling points of the hydrogenation products were identical to those of authentic 5-methyl-4-octanone and 5-methyl-4-octanol.

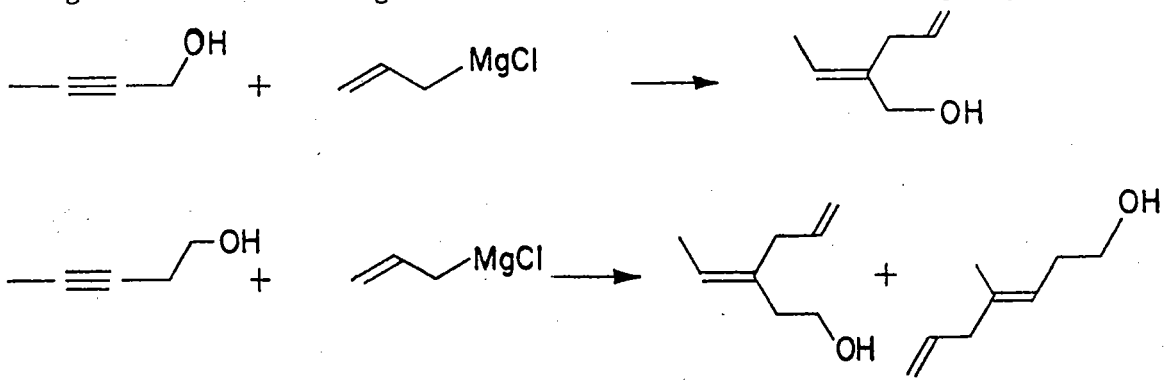
The above reaction appears to be an example of a Grignard reagent adding to an acetylenic group of a propargylic alcohol. The addition of Grignard reagents to allylic alcohols such as allyl alcohol has been reported. These reactions were reviewed in the Ph.D. thesis of Iorio[4]. As an example, Cherest[55] has reported the addition of allyl and benzyl Grignard reagents to the internal carbon atom of allyl alcohol to give branched compounds.



Benkeser and Broxterman[56] have recently reported addition of the crotyl Grignard reagent to an isolated double bond (a homoallylic alcohol).

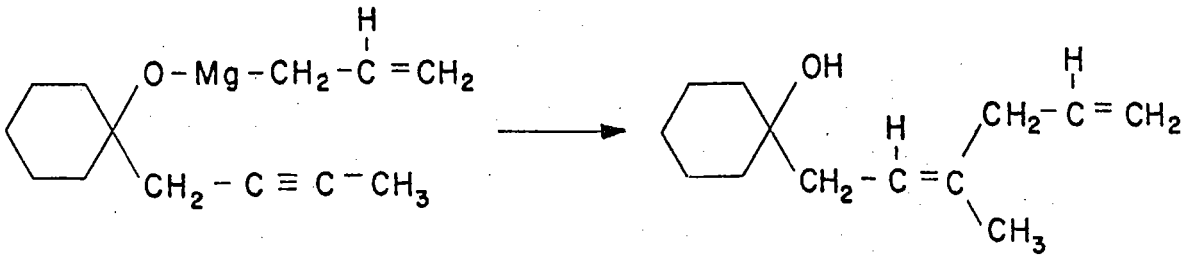


After completion of this investigation, two papers appeared giving examples of Grignard additions to triple bonds of propargylic alcohols. Richey and VonRein[58] have reported the allyl and vinyl Grignard reagents to add to the alkyne carbon nearer to the OH group in 2-butyn-1-ol. The allyl Grignard was found to give both modes of addition with 3-pentyn-1-ol.



These results for 2-butyn-1-ol were in general agreement with our findings. The authors believed <u>trans</u> addition of R and of magnesium to occur for the reactions where R becomes attached to the alkyne carbon nearer the hydroxyl group.

Eisch and Merkley[57] reported stereospecific addition of allylmagnesium bromide to 1-(2-butynyl) cyclohexanol (<u>110</u>). In this reaction the R group became attached to the alkyne carbon farthest removed from the hydroxyl group.



The authors consider this <u>cis</u> addition strongly indicative of an intramolecular mechanism for Grignard addition.

In order to investigate the generality of the addition of Grignard reagents to propargylic alcohols, the reaction of propargyl alcohol with several Grignard reagents was investigated. All reactions were carried out using a 3:1 molar ratio of appropriate halide to alcohol. The same reaction volumes and approximately the same reaction times were used. No attempts were made to maximize yields as it was desired only to ascertain relative reactivity. The results are given in Table XII.

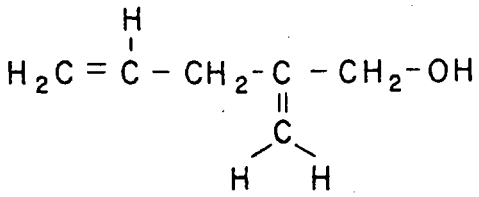
Table XII

Summary of Grignard Addition Data

Alcohol	R-Mg-X	React. Time	Adduct	Yield
5-Hexen-1-yn-3-ol(63)	Allyl-	3 Hr.	97	10%
Propargyl-	"	15	2-Methylene-4-penten-1-ol (98)	35
"	Methallyl-	18	2-Methylene-4-methyl-4-penten-1-ol(99)	28
"	Propargyl-	15	2-Methylene-4-pentyn-1-ol (100)	27
"	Benzyl-	18	2-Methylene-3-phenyl-1-propanol (101)	12
"	n-Propyl	15	2-Methylene-1-propanol (102)	5
3-Butyn-2-ol(103)	Allyl-	18	3-Methylene-5-penten-2-ol(104)	22
2-Methyl-3-butyn-2-ol(107)	"	15	-------	N.R.
3-Butyn-1-ol(108)	"	18	-------	N.R.
1-Hexyne (109)	"	35	-------	N.R.
Allyl-	"	15	2-Methyl-4-penten-1-ol(106)	13
"	n-Propyl-	"	-------	N.R.

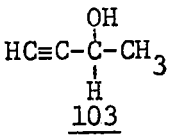
It is seen that allyl, methallyl, propargyl, benzyl and n-propyl Grignard reagents all added to the internal carbon of the triple bond in propargyl alcohol to give the corresponding allylic alcohols. All compounds gave physical constants, elementary analyses, infrared and n.m.r. spectra and hydrogenation data consistent with the proposed structures and inconsistent with the corresponding product in which the Grignard reagent added to the terminal carbon of the triple bond. All yields were low, with propargyl alcohol always being recovered. The data for these reactions is detailed in the experimental section.

In a typical structure elucidation, the Grignard adduct obtained from the reaction of propargyl alcohol with allylmagnesium chloride was isolated by preparative v.p.c. The physical constants and elementary analysis were consistent with the formula $C_6H_{10}O$. The infrared spectrum indicated an olefinic alcohol with no acetylenic functionality. The n.m.r. spectrum showed olefinic and allylic absorption in the integral ratio 5:4 and contained a two proton allylic singlet plus a two proton bis-allylic doublet. The ultraviolet spectrum showed only end absorption. Hydrogenation with Pd/C gave a saturated aldehyde as the major product and a saturated alcohol as a minor product. The v.p.c. retention time and infrared spectrum of the aldehyde were identical to those for authentic 2-methylpentanal. The 2,4-dinitrophenylhydrazone melted in agreement with the literature and showed no melting point depression on admixture with an authentic sample. The saturated alcohol gave a v.p.c. retention time and infrared spectrum identical to authentic 2-methylpentanol. On the basis of the above data the 2-methylene-4-penten-1-ol (98) structure is assigned to the Grignard adduct.

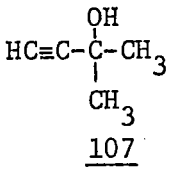


98

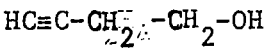
The compound 3-butyn-2-ol (103) was also found to add the allyl Grignard internally, however, 2-methyl-3-butyn-2-ol (107), 3-butyn-1-ol (108), and 1-hexyne (109) failed to give Grignard addition products under these conditions. Allyl alcohol (105) was found to add the allyl Grignard internally in agreement with the report of Cherest, however, the n-propyl Grignard reagent failed to add to allyl alcohol under these conditions.



103



107



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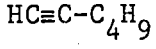
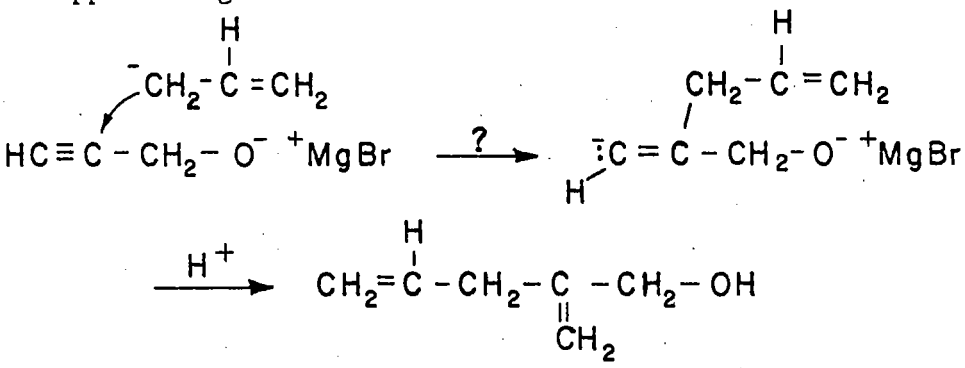


109

Although the amount of data for this new reaction is limited, the following constraints seem to be operative in the addition. The fact that 1-hexyne (109) fails to add the allyl Grignard reagent even after prolonged stirring indicates that the hydroxyl function is necessary for the addition to occur. The failure of the tertiary alcohol 2-methyl-3-butyn-2-ol (107) to react indicated a possible steric retardation of the addition. The failure of 3-butyn-1-ol (108) to add a Grignard reagent shows that the carbinol function must be alpha to an alkyne carbon

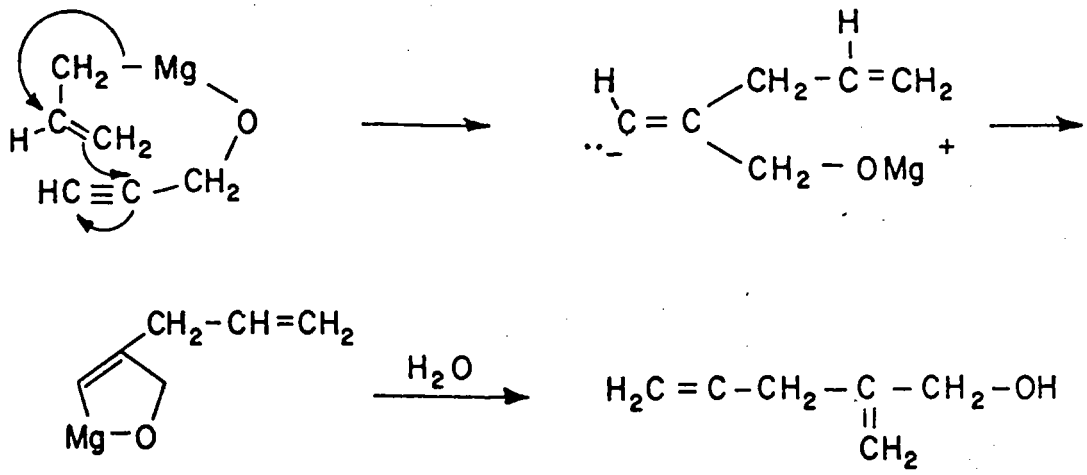
for an addition to occur. This result is in apparent disagreement with Richy[58] and Eisch[57] although their reactions were run for considerably longer periods. Also, it appears that saturated Grignard reagents (i.e. n-propylmagnesium chloride) react at slower rates than the unsaturated Grignard reagents.

Due to the limited data available and the complex nature of the Grignard reagent, any mechanistic interpretation seems tenuous at best. A direct nucleophilic attack at the internal acetylenic carbon would be a possibility. However, since the neighboring oxygen bears a negative charge in its complexation with the magnesium, it should electrostatically repel an approaching carbanion.

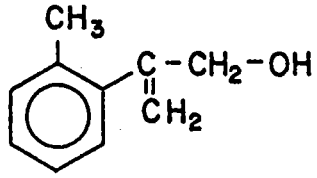


Since the presence of the oxygen is required for the reaction to proceed, this mechanism does not explain the data. 1-Hexyne would be expected to react faster than propargyl alcohol by this mechanism.

Another possible mechanism would involve a cyclic seven membered transition state in which the magnesium is complexed to one oxygen and an allylic carbanion. This mechanism is favored by Eisch and Merkley[57].

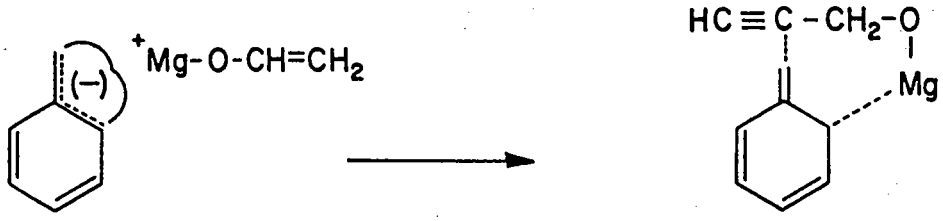


However this mechanism does not explain the addition of the n-propyl Grignard reagent to propargyl alcohol. The addition of the benzyl Grignard reagent to propargyl alcohol by this mechanism might be expected to yield 112.



112

However, the product of the reaction was rigorously shown to be 2-methylene-3-phenyl-1-propanol (101). It is conceivable that the benzyl Grignard reacts through its ortho resonance form via the above mechanism.

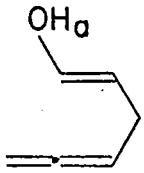


It is evident that further study of this reaction is necessary in order to establish its mechanistic pathway. The reaction has potential synthetic utility for the production of 2-methylene substituted alcohols.

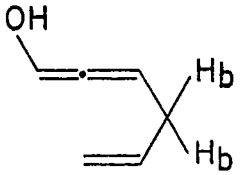
Conclusions

Several general conclusions may be summarized from the results discussed in this thesis. The acetylenic link is found to readily participate in electrocyclic reactions despite its linear geometry in the ground state (see pages 30, 41, 66). Triple bond participation in both the oxy-Cope rearrangement and β-hydroxyolefin cleavage appears to lead to increased rates as compared to the corresponding olefinic structures (see page 53). The higher ground state energy of the acetylenic link as compared to the olefinic link is suggested to be a major factor for these rate accelerations (see page 54). Phenyl participation appeared to be an unfavorable process in the oxy-Cope rearrangement for the systems studied to this point (see page 68).

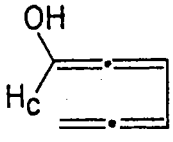
Enolic intermediates produced in the gas phase at reduced pressures do not ketonize until condensed in the liquid state (see pages 30, 32). These intermediates undergo further electrocyclic reactions in the gas phase with the allenic groups (see pages 36, 43, 63, 80). The central carbon of the allenic link is the site preferentially attacked during these reactions (see pages 36, 43, 57, 63, 80). From the products produced during these studies of electrocyclic reactions involving allenic groups, one may obtain a reactivity scale for the hydrogens in these molecules.



47a

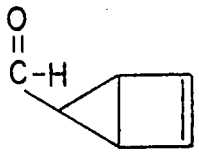


64a



89

For 47a the hydroxyl hydrogen (H_a) is most reactive, transferring itself to the central carbon of the allenic group via a [3.2.1] bicyclic transition state (page 36). This pathway possesses a low activation energy (20±4 kcal/mol) thus preventing a contribution from the diradical pathway of Huntsman (page 34). For the "allenol" 64a the reactive hydroxyl hydrogen could attack the central allenic carbon only via a symmetry forbidden 1,3 shift. Therefore the higher energy Huntsman pathway makes a contribution (page 57). Also, the less reactive bis-allylic hydrogens (H_b) now attack the internal allenic carbon via a 1,7 shift to produce sorbaldehyde (page 63). For the tetraenol 89, the reactive hydroxyl hydrogen can attack the central carbon of the allenic group via a [3.2.1] bicyclic transition state. However the product of this reaction would be cyclopentadienecarboxaldehyde, a species which could not be expected to survive under our acidic conditions, and may well be responsible for some of the observed polymer formation. The Huntsman mechanism cannot be operative in this system since there are no available hydrogens for the requisite 1,2 shifts in the intermediate diradical. Only highly strained 113 could result, which would be expected to be thermally labile.



113

Since bis-allylic hydrogens are not present in 89, the next most reactive hydrogen appears to be H_c, which undergoes a 1,2-cycloaddition involving hydrogen attack at the central allenic carbon of the other

allenic linkage (page 80). Thus the reactivity scale for these hydrogens appears to be $H_a > H_b > H_c$.

Finally, Grignard reagents added to the internal carbon atom of propargylic alcohols to produce 2-methylene-substituted alcohols.

EXPERIMENTAL SECTION

Melting points and boiling points are uncorrected. Infrared spectra were determined with Beckmann IR-5A or IR-8 spectrophotometers on neat liquid samples. N.M.R. spectra were determined with a Varian A-60A spectrometer on neat liquid samples or in deuterated chloroform solutions with an internal tetramethylsilane standard. N.M.R. spectral interpretations were based upon "Spectrometric Identification of Organic Compounds" by Silverstein and Bassler.[44] Ultraviolet spectra were determined with a Bausch and Lomb Spectronic 505 on spectro grade "Isooctane" solutions. Vapor phase chromatographic analyses were obtained with a F and M Model 500 using 2-or 5-ft. columns packed with 10% SE-30 on acid washed Chromosorb- P or 20% Triton X-305. Relative peak areas were determined with a disc integrator. Preparative vapor phase chromatography was accomplished with a F and M Model 776 using 8 ft. X 1 inch columns packed with silicone grease or Triton-X as described above. Elementary analyses were performed by Dr. Stephen M. Nagy, Belmont, Mass.

Fractional distillations were accomplished by means of a "tantalum wire column" or a spinning band column. The "tantalum wire column" was a 45 cm X 7 mm column packed with a spiral of tantalum wire. The column was enclosed in a glass jacket wound with Nichrome wire by which external heat was applied as needed. The spinning band column was a Nester Faust Model No. NF-120, 8 mm X 61 cm., equipped with a dual temperature controller and

a #306 duo set timer for automatic control of the reflux ratio.

The technique of "flash distillation" was often employed to remove non volatile materials from crude reaction mixtures. The procedure consisted of slowly dropping the material into a 3-neck flask heated to a temperature well above the expected distilling temperature while maintaining the system under appropriate reduced pressure. The volatile constituent was trapped with a water condenser and collected. Non volatile materials accumulate in the still pot.

Thermal Vapor Phase Rearrangements

The apparatus used, see diagram I , consisted of a vertical Pyrex column, 22 mm o.d., packed with 1/16 inch i.d. Pyrex helices for a length of about 45 cm. The packed portion of the column was divided into three equal sections, each individually wrapped with resistance wire connected to a variac, and in the center of each section was a well containing a 500° thermometer. A dropping funnel attached to the top of the column admitted the sample, usually at a rate of four to ten drops per minute, and a capillary inlet just below the funnel maintained an atmosphere of dry nitrogen. The vapors were condensed at the bottom of the tube by means of one or two flasks in series cooled with a Dry Ice -acetone bath. The system was evacuated, by means of a water aspir--ator or vacuum pump, through a drying tube in the vacuum line to protect the system from water vapor. Pressures were regulated

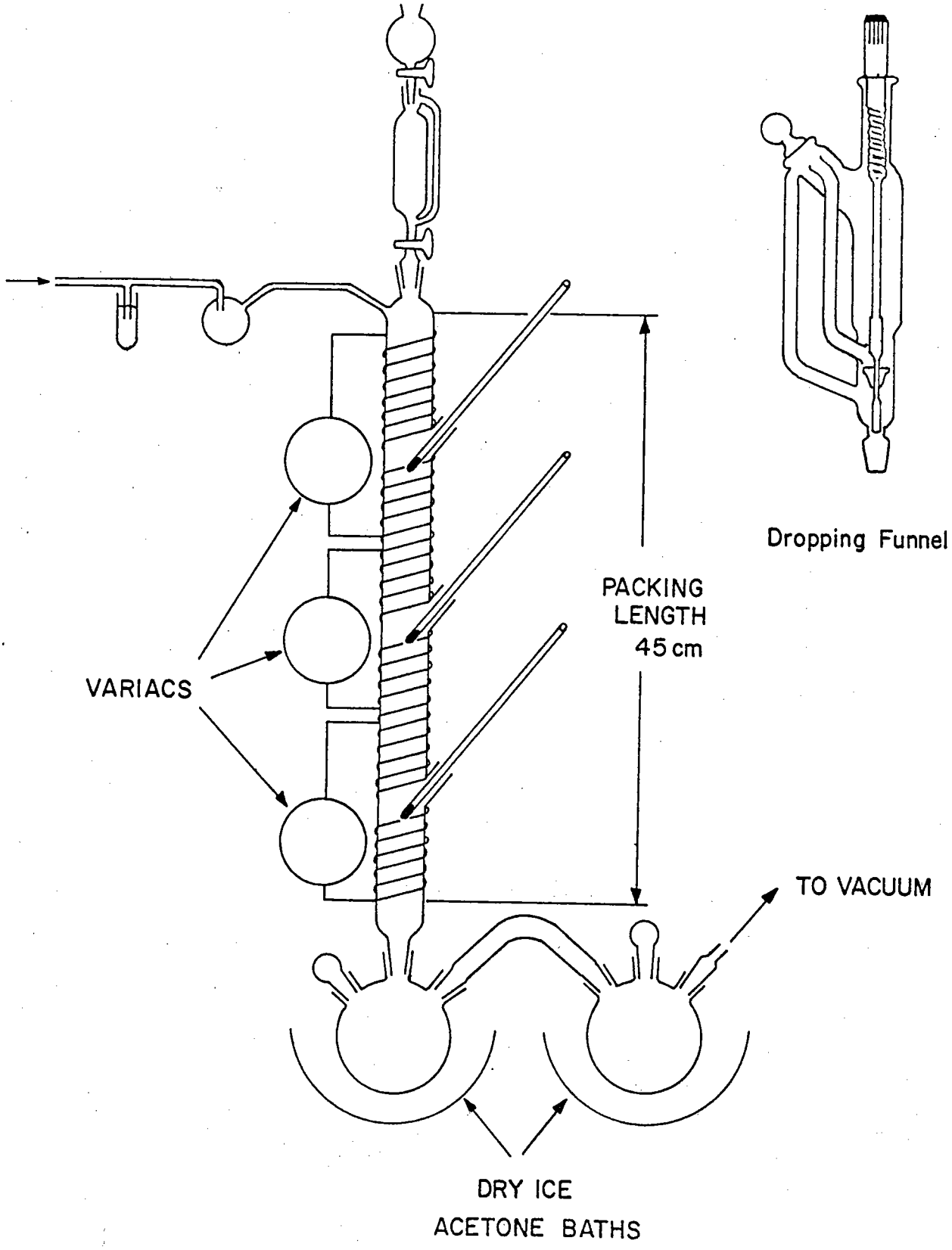


Diagram I

Thermolysis Apparatus

by means of a bleed valve attached to the stopcock opening on the safety trap attached to the aspirator. The condensed products, usually representing a recovery of 70-90%, were subjected to analyses by vapor phase chromatography. Low boiling hydrocarbon components condensed only partially under these conditions and appeared as minor peaks in the vapor phase chromatograms. The condensed products were separated by fractional distillation or preparative vapor phase chromatography. Each of the compounds reported was thermolyzed numerous times and a typical experiment is given for each compound along with the structure proofs for the thermolysis products.

preparation of 1—hexen-5-yn-3-ol(46)

a) Attempted normal Grignard procedure.

To a 1 liter three neck flask equipped with mechanical stirrer, dropping funnel, and condenser was added 0.1g of mercuric chloride, 20 g. (0.83 mol) magnesium turnings, 4 g redistilled propargyl bromide and 200 ml dry ether. The mixture was warmed, with stirring, until reaction commenced. Then a solution of 56 g redistilled propargyl bromide (total 0.5 mol) in 150 ml dry ether was added dropwise, with stirring, over a period of three hours. The reaction was stirred for one hour, after which a solution of 21 g redistilled acrolein (0.38 mol) in 150 ml ether was added dropwise over a period of two hours. After standing for a half hour, the mixture was decomposed with

ice/ammonium chloride. The ether and aqueous layers were separated and the aqueous layer shaken with two 50 ml ether portions. The combined ether layers were shaken with 50 ml water and then dried with magnesium sulfate. Evaporation of the ether yielded a viscous dark brown oil. The oil was flash distilled, under aspirator pressure, yielding only 3.5 g of volatile material (9% based upon the acrolein used). Considerable nonvolatile material remained in the still pot. V.p.c. analysis of the volatile product showed two products in approximately a 1 : 1 ratio. Preparative v.p.c. afforded the pure compounds. One product was shown to be the desired 1-hexen--5-yn-3-ol while the other proved to be the isomeric 1-hexen-4-yn--3-ol. Several modifications of the above procedure, involving reaction times or changing amounts of one or more reactants, failed to increase the amount of volatile product. The undesired internal acetylenic isomer was also always present. Therefore this procedure was abandoned.

b) Barbier Synthesis.

In order to avoid possible internal rearrangement of the propargyl Grignard reagent, a modification of the Barbier procedure, reported by Sondheimer,[33] was utilized.

To 200 ml dry ether in a 1 liter three neck flask equipped with mechanical stirrer, dropping funnel, and water condenser, was added 4 g redistilled propargyl bromide. A 0.1 g sample of mercuric chloride and 24 g (1 mol) magnesium turnings were then added. The mixture was stirred, then gently warmed with a heating

mantle, until the reaction commenced as evidenced by vigorous boiling of the ether. The flask then was immersed in a Dry Ice/acetone bath maintained at -30°. A solution of 67 g redistilled propargyl bromide (total 0.60 mol) and 25 g freshly distilled acrolein (0.45 mol) in 200 ml dry ether was then added, with vigorous stirring, over a period of three hours. During the addition, the bath was maintained at -25°. The mixture was stirred for an additional half hour, let come to room temperature, and then decomposed with ice/ammonium chloride. The ether layer was separated and the aqueous layer extracted with ether. The combined ether layers were shaken with several small portions of deionized water then dried with magnesium sulfate. Evaporation of the ether yielded a dark brown oil. Flash distillation of the oil, under aspirator pressure, afforded 29.2 g of crude distillate, b.p. 53-4° (20 mm), containing about 5% low boiling impurities. Careful fractionation yielded 24 g of product (56% based on the amount of acrolein used) which gave only a single v.p.c. peak and which contained no isomeric internal acetylene; b.p. 53-4°/20 mm, n_D^{25} 1.4670 (lit.[31]: b.p. 49°/12 mm, n_D^{17} 1.4650).

Anal.	Calcd. for C_6H_8O :	C,74.97;	H,8.39.
	Found:	C,75.10;	H,8.61.

The infrared spectrum showed bands at 3400(s),3300(spike), 3120(w),3070(w),2950(m),2140(w),1650(m),1440(s),1130(s), 1040(s), 990(s), and 930(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a triplet at 2.05 (1H, acetylenic), a doublet of doublets at 2.45 (2H,aliphatic), a broad singlet at 2.75 (1H,hydroxyl), a quartet at 4.25 (1H,methine), multiplet at 5.25 (2H,terminal vinyl),and a multiplet at 5.90 (1H, internal vinyl).

Hydrogenation of 1-hexen-5-yn-3-ol (46)

A 0.506 g (5.27 mmols) sample of the alcohol, in pentane, over Pd/C, was found to absorb 370 ml of hydrogen at 297°K, which corresponded to 97% of the 382 ml theoretically required to saturate three double bonds. The catalyst was filtered off and the pentane was evaporated to yield a colorless liquid. V.p.c. analysis showed two hydrogenation products. The major product (80%) had a v.p.c. retention time equal to that of authentic 3-hexanol while the 20% component had a retention time equal to that of authentic 3-hexanone.

Preparation of the acid phthalate of 3-hexanol.

A 0.12 g sample of the above hydrogenation mixture containing 0.096 g of alcohol (0.94 mmol), was mixed with 0.2 g (1.35 mmols) of phthalic anhydride in a 10 ml distilling flask equipped with a water condenser. The mixture was heated for 48 hours at 110-120° and then the resulting solid was shaken with 10 ml of 20% sodium carbonate solution until it dissolved. The solution was shaken twice with 5 ml portions of ether which were then discarded. The aqueous solution was treated dropwise with concentrated hydrochloric acid until acid to litmus. At this point a colorless oil

separated from the solution. The solution was shaken twice with 5 ml portions of chloroform which were combined. The chloroform extract was shaken with 2 ml of water then dried over anhydrous calcium chloride. The chloroform was removed on a steam bath yielding a white powder, m.p. 70-75°. Recrystallization from 60-80° petroleum ether gave white crystals, m.p. 74-5° (lit.[59]: m.p. 76-7°) which gave no melting point depression on admixture with an authentic sample of 3-hexanol acid phthalate.

Vapor phase thermolyses of 1-hexen-5-yn-3-ol (46)

This compound was thermolyzed at temperatures ranging from 350° to 390° and at various pressures. The data is summarized in Table 1 page 27. The condensed products, usually representing a 85 to 90% recovery, were subjected to v.p.c. analyses and found to consist of the following components in amounts which depended upon reaction conditions: unreacted starting alcohol, allene, acrolein, Δ^3-cyclopentenecarboxaldehyde, and 4,5-hexadienal. The component believed to be allene condensed only partially under these conditions and always appeared as a minor component in the appropriate region of the v.p.c. Its structure was not established further.

In a typical experiment, a 24.9 g sample of pure 1-hexen-5-yn--3-ol was passed through the thermolysis column at a temperature of 390-5° and a pressure of 15 mm. A uniform drop rate of four drops per minute was maintained. The condensed product weighed

21.1 g (85% recovery). V.p.c. analysis showed it to contain 36% acrolein, 45% Δ^3-cyclopentenecarboxaldehyde, 12% 4,5-hexadienal, and 7% of a very low boiling constituent believed to be allene. The three main constituents were identified as follows.

Acrolein (53)

This component was isolated from the mixture by distillation and identified by its characteristic odor, and by comparison of its v.p.c. retention time and infrared spectrum with those of an authentic sample of freshly distilled acrolein. The component formed a 2,4-dinitrophenylhydrazone derivative by the procedure of Shriner and Fuson.[60] Recrystallization from 50/50 ethanol/ethyl acetate gave orange crystals m.p. 164-166° (lit.[60] m.p. 165°), which showed no melting point depression on admixture with an authentic sample.

Δ^3-Cyclopentenecarboxaldehyde (48)

This component was isolated by preparative v.p.c. All samples used for structure determinations were v.p.c. homogeneous. B.p. 148-150°.

The infrared spectrum showed pertinent bands at 3020(m), 2900 (s), 2800(s), 2700(m), 1720(s), 1610(w), 1440(m), 1340(m), 1270(w), 1170(m), 895(w), 805(w), and 685(s) cm^{-1}.

The n.m.r. spectrum (δ scale) consisted of a doublet at 9.63 (1H, aldehydic), a singlet at 5.67 (2H, olefinic), complex multiplets at

3,05 (1H,methine), and 2.60 (4H,aliphatics). The spectrum parallels that reported for Δ^3-cyclopentenecarboxylic acid.[34]

Attempted carbon-hydrogen analyses of the compound were unsatisfactory due to sensitivity to oxidation and explosive decomposition in the combustion tube. Consequently, a sample of the compound was converted to its semicarbazone by the Shriner and Fuson[60] procedure. Repeated recrystallization from water gave white crystals m.p. 174-175°.

Anal. Calcd.for $C_7H_{11}N_3O$: C, 54.80 ; H, 7.25.
Found: C, 54.40 ; H, 7.40.

Hydrogenation of Δ^3-cyclopentenecarboxaldehyde (48)

A 0.48 g (5 mmols) sample of the aldehyde was hydrogenated in pentane over Pd/C. The mixture absorbed 109 ml (corrected) of hydrogen which corresponded to 98% of the 112 ml theoretically required to saturate one double bond. The catalyst was removed by filtration and the pentane evaporated. The product was analyzed by v.p.c. and found to consist of a single component. The material was quite sensitive to air oxidation and therefore was converted to the saturated acid.

Oxidation of cyclopentanecarboxaldehyde

Since the aldehyde obtained from the above hydrogenation was so sensitive to oxidation, a small sample of the aldehyde in a test tube was gently warmed for three hours while passing a slow stream of oxygen through the solution. V.p.c. analysis of

the oxidized product indicated greater than 95% conversion of the aldehyde. The infrared spectrum of the oxidized material was found to be totally superimposable on that published for cyclopentanecarboxylic acid.[35]

The acid was derivatized as the amide by a modification of the Shriner and Fuson[60] procedure. A 0.3 g sample of cyclopentanecarboxylic acid was mixed with 2 ml of thionyl chloride in a 20 ml flask. A condenser was attached and the mixture gently refluxed for thirty minutes. The mixture was cooled to room temperature and was then poured cautiously into 5 ml of ice cold concentrated ammonia water. The resulting solution was evaporated to dryness and the solid residue extracted twice with 5 ml portions of hot chloroform. The combined chloroform layers were quickly filtered while hot, to remove suspended material, and were then evaporated to a volume of 1 ml. Cooling in ice yielded pure white, shiny plates of amide, m.p. 178° (lit.[61] m.p. 178°).

Permanganate oxidation of Δ^3-cyclopentenecarboxaldehyde (48)

A 0.16 g (1.7 mmols) sample of the aldehyde was mixed with 3 ml of 1 N sodium hydroxide in a 100 ml standard taper one neck flask. The flask was immersed in ice and a solution of 1.3 g (8.5 mmols) of potassium permanganate in 30 ml of water was added dropwise over a period of fifteen minutes, while shaking the flask in the ice bath. A condenser was attached and the mixture was refluxed for fifteen minutes. The manganese dioxide precipitate

was filtered off and the solution acidified with concentrated HCl. Excess permanganate was removed by bubbling sulfur dioxide through the solution. The colorless solution was evaporated to dryness and the solid extracted three times with 50 ml portions of hot acetone. The combined acetone extracts were evaporated to dryness yielding a small quantity of brownish material. The material was dissolved in 5 ml of 1:1 acetone-toluene, treated with decolorizing charcoal, and then the solution was concentrated to a volume of 1 ml. Cooling in an ice bath precipitated a small quantity of white crystals, m.p. 157-158°. Repeated recrystallization from acetone failed to raise the melting point above 158° (lit.[36] m.p. 160-161° for tricarballylic acid).

4,5-Hexadienal (47)

This component was isolated by preparative v.p.c. B.p. 156-9° (dec), n_D^{25} 1.4727.

The infrared spectrum showed pertinent bands at 3050(w), 2900(m),2800(m),2700(m),1950(m),1710(s),1440(m),1410(m),1395(m), 1060(m), and 850(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a triplet at 9.73 (1H, aldehydic),complex multiplets at 5.15 (1H, internal allenic), 4.7 (2H, terminal allenic), and 2.4 (4H, aliphatics).

The compound proved too sensitive to oxidation for reproducible C-H analyses. Therefore it was converted, by the Shriner and Fuson[60] procedure, to its 2,4-dinitrophenylhydrazone derivative.

Recrystallization from ethanol yielded yellow orange crystals, m.p. 91-92°.

Anal.	Calcd. for	$C_{12}H_{12}N_4O_4$:	C,52.17;	H,4.38.
	Found:		C,51.88;	H,4.67.

Hydrogenation of 4,5-hexadienal (47)

A 0.115 g (1.2 mmols) sample of the aldehyde was dissolved in pentane, over 10% Pd/C. The material absorbed 54 ml of hydrogen at 295°K which corresponds to 94% of the 58 ml theoretically required to saturate two double bonds. The catalyst was removed by filtration and the pentane by evaporation. The hydrogenated product showed a v.p.c. retention time and infrared spectrum identical to those of an authentic sample of hexanal. The hydrogenated product was converted to its 2,4-dinitrophenylhydrazone derivative by the method of Shriner and Fuson.[60] Recrystallization from ethanol yielded yellow crystals, m.p. 101-103° (lit.[60]: m.p. 104°). The derivative showed no melting point depression on admixture with an authentic sample.

Characterization of 1-hexen-4-yn-3-ol (52)

This compound, produced during the "normal" propargyl Grignard reaction with acrolein, was isolated by preparative v.p.c., b.p. 147-9°, n_D^{29} 1.4695.

The infrared spectrum showed bands at 3400(s), 3080(m), 2970(w), 2900(m), 2200(m), 1650(m), 1400(s), 1265(s), 1150(s), 1010(m), 985(s), 920(s), and 800 cm^{-1}.

The n.m.r. spectrum (δ scale) showed a doublet at 1.85 (3H, J=2 -cps, methyl), a singlet at 2.95 (1H, hydroxyl), a multiplet at 4.8 (1H, methine), a multiplet at 5.3 (2H, terminal vinyl) and a multiplet at 5.9 (1H, internal vinyl).

Hydrogenation of 1-hexen-4-yn-3-ol (52)

A 0.986 g sample of the alcohol, in pentane, over Pd/C, absorbed 800 ml of hydrogen at 298° K, which corresponded to 106% of the 754 ml theoretically required to saturate three double bonds. The catalyst was filtered off and the pentane evaporated to yield a colorless liquid. V.p.c. of the material showed two high boiling hydrogenation products. The major product, (70%), had a v.p.c. retention time equal to that of authentic 3-hexanone. The 30% product had a retention time equal to that of authentic 3-hexanol. Treatment of the hydrogenated product with 2,4-dinitrophenylhydrazine solution gave a precipitate. The derivative was recrystallized twice from ethanol, yielding yellow crystals, m.p. 131-4° (lit.[60]: m.p. 130°) which showed no melting point depression on admixture with authentic 3-hexanone-2,4-dinitrophenylhydrazone.

Rethermolysis of mixture of Δ^3-cyclopentenecarboxaldehyde (48) and 4,5-hexadienal (47).

A 1.42 g sample of a thermolysis mixture containing 0.72 g of Δ^3-cyclopentenecarboxaldehyde and 0.70 g of 4,5-hexadienal was thermolyzed at 395° and 10 mm pressure. The condensed product weighed 1.24 g (87% recovery). V.p.c. analysis showed the material to contain 0.71 g Δ^3-cyclopentenecarboxaldehyde, 0.39 g 4,5-hexadienal, and 0.14 g low boiling fragmentation products. The fragmentation products were not observed in any alcohol thermolyses.

Preparation of 3-methyl-1-hexen-5-yn-3-ol(42)

This compound was prepared by the low temperature Barbier reaction of propargylmagnesium bromide with methyl vinyl ketone. The general procedure was analogous to that described for the synthesis of 1-hexen-5-yn-3-ol(see page 114).

24 g (1 mol) magnesium was reacted with 59 g redistilled propargyl bromide (0.7 mol) and 27 g (0.39 mol) redistilled methyl vinyl ketone. Workup as previously described yielded 26.5 g (62%) of v.p.c. pure material, b.p. 54-55°/25 mm, n_D^{22}1.4576, d_4^{25}0.8930.

The infrared spectrum showed bands at 3400(s),3300(s),3040(m), 2950(m),2930(m),2910(m),2120(w),1640(m),1450(m),1410(s),1370 (s), 1270(m),1240(m),1170(m)1110(s),995(m),920(s),870(m),760(m),750(m), and 650(v.s.)cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.40 (3H, methyl), a doublet at 2.45 (2H, aliphatics), a broad singlet at 3.35

(1H, hydroxyl), a doublet of doublets centered at 5.10 and 5.30 (total 2H, terminal vinyl), and a doublet of doublets at 6.10 (1H, internal vinyl).

Vapor phase thermolyses of 3-methyl-1-hexen-5-yn-3-ol (42)

This compound was thermolyzed at temperatures ranging from 330° to 380°and at various pressures. The data is summarized in table II page 40. V.p.c. of the thermolyzed material indicated four products. The low boiling product was identified as methyl vinyl ketone by its characteristic odor and v.p.c. retention time. The higher boiling products were identified as 1-acetyl-2-vinylcyclopropane, 4-acetylcyclopentene and 5,6-heptadien-2-one in order of increasing v.p.c. retention times.

In a typical experiment, a 3.47 g sample of alcohol was thermolyzed at 380°and a pressure of 22 mm. The recovered product weighed 2.92 g which represented a 84% recovery. V.p.c. analysis showed the alcohol to have undergone 37% cleavage and 63% rearrangement. The seven carbon components were found to consist of 9% cyclopropane species, 52% cyclopentene species and 39% allenic species.

1-Acetyl-2-vinylcyclopropane (44)

This compound was isolated by preparative v.p.c. and identified by its infrared and n.m.r. spectra, which are in accord with those reported in the literature.[45]

The infrared spectrum showed bands at 3090(w),3010(w),1700(s),

1640(m), 1430(m), 1390(s), 1360(m), 1330(w), 1290(w), 1260(w), 1210(m), 1175(s), 1110(w), 1090(w), 1030(w), 995(m), 970(m), 910(s), 840(m), and 810(m)cm^{-1}.

The n.m.r. spectrum (δ scale) showed a complex multiple pattern spread between 0.9 and 1.60 (2H, methylene on ring), a complex pattern centered at 2.0 (2H methine protons on ring), a singlet at 2.25 (3H, methyl) and multiplets at 5.0 (1H, internal vinyl), and at 5.40 (2H, terminal vinyl).

4-Acetylcyclopentene (49)

This component was isolated by preparative v.p.c. and identified by comparison of its infrared and n.m.r. spectra with those previously obtained for Δ^3-cyclopentene carboxaldehyde and with those reported in the literature.[28]

The infrared spectrum showed bands at 3050(w), 2900(m), 2850(m), 1710(v.s.), 1620(w), 1580(w), 1430(m), 1360(s), 1270(w), 1190(m), 1170(m), 1040(w), 850(w), 700(m), and 665(m)cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 2.10 (3H, methyl), broad multiplets centered at 2.45 and 2.60 (4H, aliphatics), a triplet split into triplets at 3.20 (1H, methine) and a singlet at 5.45 (2H, olefinics).

5,6-Heptadion-2-one (43)

This compound was isolated by preparative v.p.c. and identified

by comparison of its infrared and n.m.r. spectra with those previously obtained for 4,5-hexadienal and with those reported in the literature.[28]

The infrared spectrum showed bands at 2900(m),1950(m),1720(s), 1420(m),1360(s),1260(w),1230(w),1190(m),1170(s),1060(w),and 850(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 2.10 (3H, methyl), a distorted triplet at 2.50 (2H,aliphatic), a multiplet at 2.25 (2H,aliphatic), a multiplet at 4.60 (2H, terminal allenic) and a multiplet at 5.0 (1H, internal allenic).

Rethermolysis of 1-acetyl-2-vinylcyclopropane (44)

A small sample of the pure compound was recycled through the thermolysis column at 385°and a pressure of 20 mm. The thermolyzed product was analyzed by v.p.c. and found to consist of 13% unchanged 1-acetyl-2-vinylcyclopropane and 87% 4-acetylcyclopentene.

Preparation of propargyl aldehyde

This material was prepared by a modification of the Organic Syntheses procedure.[63]

In a 2 liter three neck flask, equipped with a mechanical stirrer, was placed 120 g redistilled propargyl alcohol and 240 ml of water. To this mixture was then added a cooled solution of 135 ml concentrated sulfuric acid in 150 ml of water. A "Y" tube was inserted in one neck of the flask and a dropping funnel was

placed in one neck of the "Y" tube. The other neck of the "Y" tube lead to two traps, in series, which in turn were connected to a pressure gauge and vacuum pump. The third neck of the flask was connected to a broken thermometer which served as a nitrogen inlet. A cooled solution of 210 g chromium trioxide, 200 ml of water and 100 ml concentrated sulfuric acid was then added to the dropping funnel. One trap was cooled to -10° with an ice/salt mixture and the second trap was cooled with Dry Ice/acetone. The exterior of the 2 liter flask was cooled to -10° with ice/salt. Nitrogen was introduced through the capillary and the pressure of the system was reduced to 15 mm. The chromium trioxide-acid solution was added, with stirring, over a three hour period, while the temperatures in the baths were maintained as mentioned. After the addition was complete, the pressure of the system was reduced to 5 mm for fifteen minutes. The vacuum was released and the material in the traps allowed to reach room temperature. The liquids in the traps were combined and the material saturated with sodium chloride. At this point an organic layer separated from the solution. The upper organic layer was separated, dried over magnesium sulfate, then carefully fractionated at atmospheric pressure. The material boiling between 54-58° was collected and shown to be homogeneous by v.p.c. Yields varied from 20 g to 35 g depending upon the efficiency of the vacuum system. A 2,4-dinitrophenylhydrazone was prepared by the Shriner and Fuson[60] procedure. Recrystallization from ethanol yielded yellow crystals, m.p. 121-123° (lit.[62] m.p. 122.5-127.5°).

Preparation of 5-hexen-1-yn-3-ol (63)

This compound, previously unreported, was prepared by addition of propargyl aldehyde to a cooled solution of allylmagnesium chloride in ether.

In a 1 liter three neck flask, equipped with mechanical stirrer, dropping funnel and water condenser, were placed 300 ml of dry ether and 34 g (1.4 mols) of magnesium turnings. A crystal of iodine was added, followed by a solution of 54 g (0.7 mol) of redistilled allyl chloride in 100 ml ether, which was added dropwise, with stirring, over a period of two hours. During the course of the addition a thick white Grignard complex precipitated which was redissolved by addition of 1 ml dry tetrahydrofuran. After the addition was complete, the flask was immersed in a Dry Ice/acetone bath at -25° to -30°. Then 11 g (0.2 mol) of freshly distilled propargyl aldehyde in 100 ml ether was added, dropwise, over a period of one hour, while the bath temperature was maintained as above. After the addition the mixture was allowed to warm to room temperature and was decomposed with ice-ammonium chloride. The ether and aqueous layer were separated and the aqueous layer was extracted twice with 50 ml ether portions. The combined ether extracts were shaken with 20 ml of water and then were dried with magnesium sulfate. Removal of the ether on a steambath yielded a light yellow oil. The oil was first flash distilled, under aspirator pressure, and then was carefully fractionated. The fraction boiling at 67-69° (35 mm) was collected and appeared to be homogeneous by v.p.c.

A higher boiling material was also isolated and is described on page 171. The yield of 5-hexen-1-yn-3-ol was 11 g (57% based upon the amount of propargyl aldehyde used); n_D^{21} 1.4580, d_4^{25} 0.8953.

Anal. Calcd. for C_6H_8O: C, 74.97; H, 8.39.

Found: C, 74.93; H, 8.42.

The infrared spectrum showed bands at 3400(s), 3300(spike), 3080(m), 2900(m), 2130(w), 1650(m), 1435(m), 1300(m), 1260(w), 1220(w), 1120(m), 1030(s), 990(s), 955(m), 920(s), 880(w), 865(w), 800(w), and 640(s) cm^{-1}.

The n.m.r. spectrum (δ scale) contained a complex multiplet centered at 2.5 (4H, allylic, acetylenic and hydroxylic), which collapsed to a simpler multiplet (3H, allylic and acetylenic), on D_2O exchange, and multiplets centered at 4.43 (1H, methine), 5.2 (2H, terminal vinyl) and 5.9 (1H, internal vinyl).

Hydrogenation of 5-hexen-1-yn-3-ol (63)

A 0.915 g sample of pure alcohol in pentane, over 10% Pd/C, was found to absorb 575 ml (corrected to S.T.P.) of hydrogen which corresponds to 90% of the 640 ml theoretically required to saturate three double bonds. The catalyst was removed by filtration and the pentane evaporated to yield a colorless oil. V.p.c. of the oil indicated two high boiling hydrogenation products. The major constituent had a v.p.c. retention time equal to that of authentic 3-hexanone while the minor high boiling product had a retention time equal to that of 3-hexanol. Two low boiling

constituents also were observed, one was suspected to be residual pentane while the other was believed to be n-hexane resulting from hydrogenolysis. The hydrogenated mixture was dissolved in 10 ml ethanol and was then treated with 2,4-dinitrophonylhydrazine solution. The resulting precipitate was recrystallized from ethanol to yield yellow crystals, m.p. 135-6°(lit.[60] m.p. 130°). The compound gave no melting point depression on admixture with an authentic sample of the DNPH of 3-hexanone.

Vapor phase thermolyses of 5-hexen-1-yn-3-ol (63)

This compound was thermolyzed at temperatures ranging from 350°to 390° and various pressures. The data is summarized in table III, page 55. The condensed products, usually representing a recovery of 85-90%, were analyzed by v.p.c. and found to contain the following: low boiling fragmentation products, Δ^2- and Δ^3-cyclopentenecarboxaldehydes, trans-2,5-hexadienal, and various geometric isomers of sorbaldehyde. Only trace quantities (less than 2%) of propargyl aldehyde were detected by comparison of the v.p.c. retention time of authentic propargyl aldehyde with those of the low boiling components in the chromatograms. The other low boiling products eluted prior to the propargyl aldehyde and were presumed to result from thermal fragmentation of the rearrangement products. They were not identified.

In a typical experiment, 2.99 g of the alcohol was thermolyzed at a temperature of 390-5°and a pressure of 0.5 mm. The recovered

material weighed 2.77 g (91%). V.p.c. analysis showed the material to consist of 3% fragmentation products, 26% Δ^2— and Δ^3—cyclopentenecarboxaldehydes, 49% trans-2,5-hexadienal, and 22% 2,4-hexadienal (sorbaldehyde).

Δ^2- and Δ^3- Cyclopentenecarboxaldehydes (66) and (48).

These products were isolated as a mixture of the two isomers by preparative v.p.c. The two isomers were not completely separable from each other on either analytical or preparative columns and therefore the components were characterized in the form of mixtures. The Δ^3—isomer was always the major cyclic thermolysis product. A ten foot Triton—X column was required to partially separate the components whereon the Δ^2—isomer could be observed as a hump on the front of the peak due to the Δ^3—isomer. The presence of the Δ^3—isomer was established in the following manner. Infrared spectra of mixtures containing greater than 80% of the major cyclic component were essentially superimposable on the spectrum obtained for Δ^3—cyclopentenecarboxaldehyde formed from the thermolyses of 1-hexen-5-yn-3-ol. V.p.c. retention times of the major cyclic thermolysis product were identical to those of the authentic Δ^3-isomer on three different substrates (2-ft. silicone grease, 2-ft. Triton-X, and 10 ft. Apiezon). The n.m.r. spectrum of the mixture clearly showed all the peaks previously found in the spectrum of the Δ^3—isomer (see page118) as well as those due to the Δ^2-isomer.

Since the Δ^2—isomer was never obtained pure, its presence could be proven only indirectly. For this purpose, a mixture of the two isomers was enriched in the Δ^2—isomer by preparative v.p.c. A 1:1 mixture of the Δ^2- and Δ^3—isomers was obtained in this manner.

A sample of this mixture upon hydrogenation (see next section) yielded only one product, identified as cyclopentanecarboxaldehyde. The ultraviolet spectrum of the mixture showed only end absorption above 220 mμ which precludes the presence of the Δ^1—isomer. The n.m.r. spectrum of the mixture fortunately showed little overlap between peaks due to the Δ^2— and Δ^3— isomers; therefore n.m.r. assignments for the Δ^2—isomer can be given.

The spectrum (δ scale) showed a doublet at 9.52 (1H, aldehydic), a multiplet at 6.05 (1H, vinyl proton at position 2), a multiplet at 5.7 (1H, vinyl proton at position 3), a complex at 3.52 (1H, methine proton) and a complex centered at 2.2 (4H, aliphatic protons).

Hydrogenation of mixture of Δ^2— and Δ^3— cyclopentenecarboxaldehydes

A 0.650 g (6.65 mmols) sample of a 1:1 mixture of the two aldehydes was placed in pentane over Pd/C. The mixture absorbed 172 ml of hydrogen, at 298°K, which corresponded to 110% of the 154 ml theoretically required to saturate one double bond. After filtering off the catalyst, the pentane was evaporated yielding a colorless liquid. V.p.c. analysis showed only one peak on both 2 ft. and 10 ft. Triton-X columns. The product gave an infrared

spectrum identical to that previously obtained for cyclopentanecarboxaldehyde, see page 119. Air oxidation as previously described gave an acid whose infrared spectrum was identical to that published for cyclopentanecarboxylic acid.[35]

Trans—2,5-Hexadienal (64)

This component was separated from the thermolysis mixture by preparative v.p.c., b.p. 141-3°(dec); n_D^{20} 1.4725.

Anal. Calcd. for C_6H_8O: C, 74.97; H, 8.39.

Found: C, 74.79; H, 8.54.

The infrared spectrum showed bands at 3075(w),2990 (w),2900(w), 2800(m),2700(m),1720(shoulder),1690(v.s.),1635(s),1430(m),1310(w), 1280(w),1230(w),1130(s),1085(w),995(s),975(s),950(w)and 920(s)cm^{-1}.

The ultraviolet spectrum showed λ max = 219 mμ ε = 11000.

The n.m.r. spectrum (δ scale) consisted of a doublet at 9.51 (1H, aldehydic, J=7), a doublet of triplets at 6.82 (1H, β vinylic, $J_{\alpha\beta}$ = 16, $J_{\beta\gamma}$ = 6.5), a doublet of doublets with long range triplet splitting centered at 6.08 (1H, α vinylic, J=7, 16), a typical terminal vinyl pattern at 4.9-5.3 and 5.82 (3H, the latter multiplet consists of a series of triplets, J=6.5) and a triplet with long range quartet splitting at 3.08 (2H, methylene).

The compound formed a 2,4—dinitrophenylhydrazone by the Shriner and Fuson[60] procedure. Recrystallization from 1:1 ethanol/ethyl acetate gave red crystals m.p. 140-142°(lit.[47] m.p. 140-142°).

Anal. Calcd. for $C_{12}H_{12}N_4O_4$: C, 52.17; H, 4.38.
Found: C, 52.23; H, 4.51.

Hydrogenation of trans-2,5-hexadional

A 0.450 g sample of the aldehyde in pentane, over Pd/C, was found to absorb 230 ml of hydrogen, at 298°K, which corresponded to 100% of the theoretical amount required to saturate two double bonds. The catalyst was filtered off and the pentane evaporated. The hydrogenated product was analyzed by v.p.c. and found to consist of a single entity whose v.p.c. retention time and infrared spectrum were identical to those of authentic hexanal. A 2,4-dinitrophenylhydrazone was prepared by the method of Shriner and Fuson.[60] Recrystallization from ethanol yielded yellow crystals, m.p. 105-6°(lit.[60] m.p. 104°) which showed no melting point depression on admixture with an authentic sample of hexanal-2,4-dinitrophenylhydrazone.

Sorbaldehyde (2,4-hexadienal) (65)

A mixture of various configurational isomers of sorbaldehyde was separated from the thermolysis mixture by preparative v.p.c. Pure configurational isomers could not be obtained as all four isomers closely overlapped on a variety of column packings. This thermolysis component was identified as sorbaldehyde by its characteristic odor and by comparison of its v.p.c. retention time and infrared spectrum with those of a commercial sample.

The commercial sample was found to contain all four isomers but in differing proportions than the thermally produced material (see page 62). A 2,4-dinitrophenylhydrazone of the thermolysis product was prepared by the Shriner and Fuson[60] procedure. Recrystallization from 1:1 ethanol/ethyl acetate gave red-violet crystals. m.p. 187- 188° (lit.[64] m.p. 192°), which showed no melting point depression upon admixture with authentic sorbaldehyde-2,4-dinitrophenylhydrazone.

The n.m.r. spectrum (δ scale) of sorbaldehyde consisted of a methyl doublet at 1.9, multiplets in the region of 5.8-6.6 (3H)and 6.9-7.7 (1H), and a series of doublets in the aldehydic region. Complete analysis of the spectrum is difficult due to the mixture of geometric isomers always present. The aldehydic region,however, contains four sets of doublets readily assignable to the four isomers (see table VI).

Thermolysis of propargyl aldehyde.

A small sample of v.p.c. pure propargyl aldehyde was thermolyzed at 370°and a pressure of 20 mm. V.p.c. of the thermolyzed product showed only recovered aldehyde with no detectable fragmentation products.

Thermolysis of mixture of Δ^2-and Δ^3-cyclopentenecarboxaldehydes.

A 1.09 g sample of a thermolysis mixture containing 19%(0.21 g) of cyclic product was rethermolyzed at 350°and 20 mm pressure.

The condensed product weighed 0.89 g and contained 22% cyclic product (0.20 g) as determined by v.p.c.

Thermolysis of trans-2,5-hexadienal (64)

Several small samples of v.p.c. pure trans-2,5-hexadienal were rethermolyzed at 370° and 10 mm pressure. V.p.c. of the condensed products showed only pure aldehyde with no trace of any other thermolysis product.

Thermolysis of sorbaldehyde (65)

Small samples of redistilled commercial sorbaldehyde were thermolyzed at temperatures from 350° to 390° and pressures from 20 mm to 10 mm. V.p.c. analyses of the condensed products showed low boiling fragmentation products and the n.m.r. spectrum showed altered geometric isomer ratios.

In a typical experiment, 2.19 g of redistilled commercial sorbaldehyde was passed through the thermolysis column at 370° and 15 mm. The recovered product weighed 2.0 g (91% recovery). The commercial sample was analyzed by n.m.r. integration of the aldehydic proton areas prior to thermolysis (see table VI., page 62) and was found to consist of 77% trans-trans, 19% trans-cis, 4% cis-trans and a trace of the cis-cis isomer. The thermolyzed sorbaldehyde was analyzed by both v.p.c. and n.m.r. V.p.c. of the product showed it to contain approximately 5% low boiling fragmentation products of the same retention times as those found in the product

from the thermolyses of 5-hexen-1-yn-3-ol. In addition the closely overlapping sorbaldehyde isomer peaks appeared to show different relative areas from the commercial material. Nitrogen was bubbled through the thermolyzed material to remove the fragmentation products and it was then analyzed by n.m.r. Integration of the aldehydic region showed the material to contain 66% trans-trans, 18% trans-cis, 11% cis-trans and 4% of the cis-cis isomer.

Preparation of 1,5-hexadiyn-3-ol (79)

This compound was prepared by the Sondheimer procedure.[33] In a 1 liter three neck flask, equipped with mechanical stirrer, dropping funnel and condenser, were placed 24 g (1 mol) Mg turnings, 150 ml dry ether, 3 g redistilled propargyl bromide, and 0.1 g $HgCl_2$. The mixture was warmed, with stirring, until a reaction commenced as evidenced by vigorous boiling of the ether.The flask was then immersed in a Dry-Ice-acetone bath at -35°and a solution of 57 g redistilled propargyl bromide(total 0.5 mol)and a 14 g propargyl aldehyde (0.26 mol) in 150 ml ether was added over a period of 3.5 hours, while the bath temperature was maintained at -30°to -40°. The mixture was allowed to warm to room temperature,decomposed over ammonium chloride-ice, and the ether layer was separated. The aqueous layer was extracted twice with 50 ml of ether and the combined ether extracts were then washed several times with 10 ml portions of water. After drying with magnesium sulfate, the ether was

evaporated to yield a dark brown oil. Flash distillation followed by careful fractionation under aspirator pressure yielded 11.7 g (48%) of v.p.c. pure material. B.p. 79-80°/25 mm, n_D^{25} 1.4728 (lit.[33] b.p. 73-75°/20 mm, n_D^{25} 1.4728).

The infrared spectrum showed bands at 3400(s),3300(spike), 2900(w),2130(w),1420(m),1395(m),1300 (m),1220(w),1190(w),1050(s), 980(w),955(m),935(w),880(w),850(m),810(w),790(w),705(m),and 650(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a triplet at 2.2 (1H, acetylenic),a broad singlet at 3.4 (1H,hydroxyl), overlapping doublets at 2.75 and 2.63 (total 3H, aliphatic and one acetylenic), and a triplet split into doublets at 4.6 (1H,methine proton).

Vapor phase thermolyses of 1,5-hexadiyn-3-ol (79)

This compound was thermolyzed at temperatures ranging from 300° to 370° and at various pressures. Complications and hazards were encountered during the thermolyses of this compound not found in other thermolyses. Appreciable polymerization and carbonization were observed in the thermolysis column at all temperatures employed. Another complication was the tendency of the thermolyzed material to solidify in the cooler regions of the column before reaching the cold trap. Also, the thermolyzed material was extremely unstable upon warming, even to room temperature. In one experiment, as the thermolysis mixture was being weighed on a Mettler balance, the mixture suddenly warmed, and then

exploded, disintegrating the container and shattering the glass sides of the balance. The thermolyses mixtures obtained were thick syrups containing polymeric material. V.p.c. of the crude thermolyses mixtures indicated a major volatile thermolysis product which proved to be phenol. A lower boiling constituent was also detected which proved to be 4-methylene-2-cyclobutene-1-carboxaldehyde. This compound could not be isolated by micro distillation since it polymerized when heated in the presence of phenol. Its isolation is described later.

In a typical experiment, 3.08 g of 1,5-hexadiyn-3-ol was passed through the thermolysis column at 370°and 15 mm pressure. A drop rate of four drops/minute was employed. 2.37 g of thick oily product was recovered (77%). V.p.c. of the crude product showed two volatile constituents the major of which was phenol. The product was micro distilled under 0.1 mm pressure until rapid polymerization began in the distilling pot, whereupon distillation was discontinued. Approximately 1 g of volatile product was obtained which partially solidified on standing. V.p.c. of the material showed it to be about 80% phenol. Therefore the phenol was obtained in a yield of 0.8 g (26%).

The volatile thermolysis product had an infrared spectrum superimposable on that of authentic phenol. The product gave a positive test for phenol with bromine water. On treatment with excess bromine water, the thermolysis product gave a white solid,

which, when recrystallized from 50/50 water-ethanol, melted at 95-96° (lit.[60] m.p. 95°). The derivative gave no melting point depression on admixture with an authentic sample of 2,4,6-tribromophenol.

4-Methylene-Δ^2-cyclobutenecarboxaldehyde (80)

The low boiling minor component obtained in addition to phenol was identified via n.m.r. spectroscopy, by comparison with literature reports of similar compounds.[69] The material was obtained free of polymer but contaminated with phenol. The thermolyzed product was collected in the first of two traps set in series. The trap was let come to room temperature and the second trap cooled to -78°. Trap to trap distillation was then accomplished by heating the first trap gently with a warm water bath while the pressure was reduced to 1 mm. After one half hour the contents of the second trap were analyzed by v.p.c. and n.m.r. V.p.c. indicated an approximately 1:1 mixture of the low boiling product and phenol. The n.m.r. (δ scale) showed in addition to the phenol multiplet at 7.0, the following peaks: a doublet (J=5 cps) with long range splitting at 3.95 (1H, methine), multiplets at 4.70 and 4.95 (2H, olefinic), a singlet at 6.65 (2H, ring olefinics), and a doublet (J=5 cps) at 9.41 (1H. aldehydic).

Thermolyses of 1,5-hexadiyn-3-ol employing an internal standard.

Several small samples of 1,5-hexadiyn-3-ol, diluted with

benzene and n-hexyl alcohol, were thermolyzed at 350°and 370°and at high and low pressures. The benzene served as an inert diluent and the hexyl alcohol as an internal standard. The integral ratio of acetylenic alcohol to hexyl alcohol was determined initially by v.p.c. After thermolysis, the product was analyzed by v.p.c. and the integral ratio of hexyl alcohol to phenol was computed. By this procedure the absolute percentage of phenol produced was calculated as a function of temperature and pressure. The results are summarized in table 7 page 77.

The following methyl substituted 1,5-hexadiyn-3-ols were synthesized, using procedures analogous to that employed in the above synthesis of 1,5-hexadiyn-3-ol.

3-Methyl-1,5-hexadiyn-3-ol. (82)

24 g (1 mol) magnesium, 0.1 g mercuric chloride and 56 g (0.5 mol) propargyl bromide were treated with 23 g (0.34 mol) of methyl ethynyl ketone (Farchan Laboratories). The yield was 36.8 g(66%) b.p. 50°(10 mm), n_D^{25} 1.4628, d_4^{23} 0.9288.

Anal.	Calcd. for C_7H_8O:	C, 77.95;	H, 7.46.
	Found :	C, 77.59;	H, 7.30.

The infrared spectrum showed bands at 3400(s),3300(spike), 2980(m),2900(w),2120(w),1450(m),1420(m),1380(s),1360(s),1290(m), 1260(m),1160(m),1130(s),1090(s),950(m),940(m),910(w),875(m), and 650(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.65 (3H, methyl), a triplet at 2.25 (1H, acetylenic), a singlet at 2.65 (1H, acetylenic), a doublet centered at 2.65 (2H, methylene), and a broad singlet at 3.30 (1H, hydroxyl).

Hydrogenation of 3-methyl-1,5-hexadiyn-3-ol (82)

A 1.14 g sample of the alcohol, in methanol, over Pd/C, was found to absorb 1030 ml of hydrogen at 298°K, which was 101% of the 1020 ml theoretically required to saturate four double bonds. The methanol was evaporated, yielding a colorless liquid, which was analyzed by v.p.c. A single peak was observed whose retention time was equal to that of authentic 3-methyl-3-hexanol. The infrared spectrum of the hydrogenated material was also identical to that of authentic 3-methyl-3-hexanol.

Vapor phase thermolyses of 3-methyl-1.5-hexadiyn-3-ol (82)

This compound was thermolyzed at temperatures ranging from 320° to 380° and at various pressures. At all temperatures substantial polymerization occurred in the cooler regions of the thermolysis column, resulting in a viscous, dark brown thermolysis product. Since the product slowly solidified on standing to a polymeric material, it was necessary to analyze the material immediately after recovery. V.p.c. of the crude thermolyses mixtures showed them to contain a single volatile product in addition to surviving starting alcohol. Increase in temperature or

pressure of the system resulted in less recovered starting material and increased polymerization. At higher temperatures, a small amount of another volatile constituent was detected, but was present in insufficient quantity for characterization. The 3-acetyl--4-methylenecyclobutene structure was assigned to the thermolysis product. Infrared spectra of the crude thermolyses mixtures showed no trace of aromatic or allenic products.

In a typical experiment, 1.59 *g* of the alcohol was thermolyzed at a pressure of 5 mm and a temperature of 330°. The condensed product was dark yellow and weighed 1.23 *g* (77% recovery). V.p.c. of the product showed it to contain 80% 3-acetyl-4-methylene-cyclobutene and 20% unreacted starting alcohol, in its volatile constituency.

3-Acetyl-4-methylenecyclobutene (83)

The thermolysis product could be isolated by rapid distillation under aspirator pressure. Usually only a small forerun of the material could be collected before the remaining material in the pot rapidly polymerized to a dark mass. The colorless distillate rapidly turned brown and polymerized. However, infrared and n.m.r. spectra could be obtained on the compound immediately after its isolation.

The infrared spectrum showed bands at 3080(w), 2980(w), 2930(w), 1710(s), 1670(s), 1600(w), 1420(m), 1360(s), 1320(m), 1280(m), 1230(s), 1165(m), 1130(m), 1000(w), 950(w), 875(m), 820(m) and 770(m) cm^{-1}.

The n.m.r. spectrum (δ scale) showed 2 doublets with fine splitting at 6.55 and 6.75 (2H, J=3 cps, ring olefinics), multiplets at 4.65 and 4.85 (2H, terminal methylene), a broad singlet at 4.05 (1H, methine), and a singlet at 2.15 (3H, methyl).

The compound formed a 2,4-dinitrophenylhydrazone by the procedure of Shriner and Fuson.[60] Three recrystallizations from 50/50 ethanol/ethyl acetate yielded yellow crystals, m.p. 117-118°.

Anal.	Calcd. for $C_{13}H_{12}N_4O_4$:	C, 54.17;	H, 4.25.
	Found:	C, 54.14;	H, 4.76.

The n.m.r. spectrum of the derivative (δ scale) showed a broad singlet at 11.05 (1H, N-H), doublets at 9.08, 8.20 and 7.90 (3H, aromatics), two doublets at 6.55 and 6.75 (2H, ring olefinics, J=3 cps), a broad singlet at 4.20 (1H, methine), broad singlets at 4.83 and 4.60 (2H, terminal methylene), and a singlet at 2.0 (3H, methyl).

Hydrogenation of crude 3-Acetyl-4-methylenecyclobutene.

A crude thermolysis mixture was placed in pentane, over Pd/C, immediately after thermolysis. The crude mixture was hydrogenated until gas absorption ceased. After filtering the catalyst and evaporating the pentane, the crude product was micro distilled and was then analyzed by v.p.c. A single hydrogenation product was observed, whose infrared spectrum indicated it to be a saturated ketone. The ketone gave a positive iodoform test. Attempts to convert the saturated acid from the haloform reaction to its amide derivative were unsuccessful.

4,4—Dimethyl-1,5-hexadiyn-3-ol (84)

24 g (1 mol) magnesium, 0.1 g mercuric chloride and 42 g (0.31 mol) 3-bromo-3-methyl-1-butyne were reacted with 15 g (0.28 mol) of propargyl aldehyde. The bromide was synthesized by the reaction of phosphorous tribromide with 2-methyl-3-butyn-2-ol (Airco Chemical Co.). The yield of 4,4-dimethyl-1,5-hexadiyn-3--ol was 7.55 g (22%). B.p. 57-8°(10 mm), n_D^{28} 1.4613.

Anal. Calcd. for $C_8H_{10}O$: C, 78.65; H, 8.25.

Found : C, 78.80; H, 8.24.

The infrared spectrum showed bands at 3400(m), 3300(spike), 2980(m),2940(w),2900(w),2120(w),1470(m),1390(m),1370(m),1310(w), 1260(m),1210(w),1140(w),1060(s),1020(m),970(w),940(w),860(w), and 650(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.35 (6H, methyl), a singlet at 2.25 (1H, acetylenic), a doublet (J=2 cps) at 2.55 (1H, acetylenic), a doublet at 2.85 (J=7 cps,1H, hydroxyl, collapses with D_2O), and a doublet of doublets at 4.23 (J_1=7 cps, J_2=2 cps, 1H, methine), which collapsed to a doublet (J=2 cps) on shaking the sample with D_2O.

Vapor phase thermolyses of 4,4-dimethyl-1,5-hexadiyn-3-ol(84)

This compound was thermolyzed at 350°and at various pressures. Substantial polymerization occurred in the cooler regions of the thermolysis column and in the recovery pot. The thermolyzed

products were dark brown and quite thick. Since the thermolyzed material rapidly hardened to a brown solid upon standing, it was necessary to work up and analyze the material immediately. V.p.c. of the crude product showed it to contain three constituents, the major of which was always present in a 70-80% concentration. No significant amount of aromatic or allenic products could be detected in the crude product by infrared spectroscopy. Starting material was not detected in any of the recovered products from the various thermolyses. The major thermolysis product could be isolated by rapid micro distillation of the product at aspirator pressure. Although hydroquinone was always added to the still pot to inhibit polymerization, usually only about 25% of the material would distill before the remainder would harden to a dark polymeric mass. This procedure afforded the major thermolysis product, free of polymer, in about 90-95% purity. The material was contaminated by a high boiling minor thermolysis product. Neither the low nor high boiling minor thermolysis products could be isolated and identified. The 4-isopropylidene-Δ^2-cyclobutenecarboxaldehyde structure was assigned to the major product solely on the basis of its infrared and n.m.r. spectra, due to rapid polymerization of the compound.

In a typical experiment, 1.91 *g* of 4,4-dimethyl-1,5-hexadiyn-3-ol was thermolyzed at 350-5° and a pressure of

22 mm. The recovered material weighed 1.19 g (63% recovery). V.p.c. analysis showed that 75% of the volatile material consisted of 4-isopropylidene-Δ^2-cyclobutenecarboxaldehyde, 15% of a very low boiling cleavage product and 10% of a higher boiling product.

4-Isopropylidene-Δ^2-cyclobutenecarboxaldehyde (85)

This material was isolated in about 90% purity by the procedure described above. Since it polymerized to a brown solid rapidly upon standing, spectral analyses were undertaken immediately after isolation.

The infrared spectrum showed bands at 3030(w),2950(m), 2900(m),2850(m),2800(m),2700(m),1725(s),1700(s)1670(m),1630(m), 1450(m),1380(m),1300(m),1270(m),1240(w),1205(m),1170(m),1090(m), 1060(m),785(m),750(s), and 715(m) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.60 (3H, methyl), a singlet with long range quartet splitting at 1.80 (3H, methyl), a doublet (J=6 cps) at 3.85 (1H, methine proton), a doublet (J=2.5 cps) with long range splitting at 6.40 (1H, ring olefinic), a doublet (J=2.5 cps) at 6.83 (1H, ring olefinic),and a doublet (J=6 cps) at 9.25 (1H, aldehydic).

A 2,4—dinitrophenylhydrazone was prepared by the method of Shriner and Fuson.[60] Repeated recrystallization from 50/50 ethanol/ ethyl acetate yielded yellow crystals, m.p. 146-7°.

Anal. Calcd. for $C_{14}H_{14}N_4O_4$: C, 55.63; H, 4.67.
Found: C, 55.70; H, 5.05.

The n.m.r. spectrum (δ scale) of the dinitrophenylhydrazone showed singlets at 1.70 and 1.85 (6H, methyl), a doublet (J=8 cps) at 4.20 (1H, methine), a doublet with additional fine splitting at 6.45 (1H, ring olefinic, J=3 cps), a doublet at 6.70 (J=3 cps, 1H, ring olefinic), a doublet (J=8 cps) at 7.40 (1H, -CH=N), doublets at 7.95, 8.40 and 9.17 (3H, aromatics), and a broad singlet at 11.17 (1H, N-H).

4-Methyl-1,5-hexadiyn-3-ol (86)

12 g (0.5 mol) magnesium, 0.1 g mercuric chloride and 27 g (0.2 mol) 3-bromo-1-butyne were reacted with 10 g (0.18 mol) of propargyl aldehyde. The bromide was synthesized by the reaction of phosphorous tribromide with 3-butyn-2-ol (Farchan Chemical Co.). The yield of 4-methyl-1,5-hexadiyn-3-ol was 4.70 g (24%), B.p. 86-7°(40 mm), n_D^{24} 1.4653.

Anal. Calcd. for C_7H_8O: C, 77.95; H, 7.46.
Found: C, 78.26; H, 7.70.

The infrared spectrum showed bands at 3400(s), 3300 (spike), 2980(m), 2940(m), 2900(m), 2880(m), 2120(w) 1460(m), 1380(m), 1290(m), 1120(m), 1080(m), 1065(m), 1030(s) 975(m), 880(w), 835(w), 795(w), 755(w), and 650(v.s.) cm^{-1}.

The n.m.r. spectrum (δ scale) showed two doublets (J=7 cps) approximately 2 cps apart, centered at 1.30 (3H, diastereomeric

methyl protons), a doublet (J=3 cps) at 2.25 (1H, acetylonic), a doublet (J=2 cps) at 2.60 (1H, acetylenic), a multiplet at 2.80 (1H, methine), a broad singlet at 3.50 (1H, hydroxyl, collapses with D_2O), and a multiplet at 4.50 (1H, carbinol proton), which collapsed into two overlapping sets of doublet of doublets upon shaking the sample with D_2O.

Hydrogenation of 4—methyl-1,5-hexadiyn-3-ol (86)

A 0.598 g (5.56 mmol) sample of the alcohol, in pentane over 10% Pd/C, absorbed 495 ml of hydrogen at 299°K, which corresponded to 91% of the 545 ml theoretically required to saturate two triple bonds. V.p.c. of the hydrogenated material indicated two main products. The major product (70%) had a v.p.c. retention time equal to that of authentic 4-methyl-3-hexanol on three different v.p.c. columns (2 ft SE-30, 2 ft Triton-X, and 10 ft Apiezon). The minor (30%) product had a v.p.c. retention time equal to that of authentic 4-methyl-3-hexanone on the three different v.p.c. columns.

Vapor phase thermolysis of 4-methyl-1,5-hexadiyn-3-ol (86)

This compound was thermolyzed at 370°and a pressure of 25 mm. Considerable polymerization and carbonization in the cooler regions of the thermolysis column was observed. o-Cresol was the only isolable product from the thermolyzed mixture. V.p.c. showed the cresol to be the major product of the reaction, although a lower

boiling product, believed possibly to be a cyclobutenecarboxaldehyde, was also present. This product polymerized upon distillation preventing its characterization. The data follows.

A 1.41 g sample of the alcohol was thermolyzed at 370-5° and a pressure of 25 mm. The condensed product, 0.743 g (53% recovery) was dark brown and viscuous. V.p.c. analysis showed a minor (30%) and a higher boiling major (70%) volatile thermolysis product. The major product had v.p.c. retention time identical to that of authentic o-cresol, but shorter than that of authentic m-or p-cresol.

The major thermolysis product was isolated free of polymeric material by distillation under aspirator pressure. It gave an infrared spectrum superimposable on that of authentic o-cresol but different from those of m-and p-cresol. The product was converted to its dibromo derivative by the procedure of Shriner and Fuson.[60] Recrystallization from ethanol/water yielded white crystals, m.p. 53° (lit.[60] 56°) which showed no melting point depression on admixture with an authentic sample.

Preparation of 1-phenyl-3-butyn-1-ol (76)

To a 1 liter three neck flask, equipped with condenser, mechanical stirrer and dropping funnel, were added 24 g (1 mol) Mg turnings, 1 g propargyl bromide, 200 ml dry ether and 0.1 g of mercuric chloride. The mixture was warmed with stirring until a reaction commenced as evidenced by vigorous ether reflux. The flask was then immersed in a Dry Ice/acetone bath maintained at -20°, and a solution of 46 g redistilled propargyl bromide (total 0.4 mol) in 150 ml ether was added dropwise over a period of three hours while the bath temperature was maintained at -20°. After the addition was complete, a solution of 26 g redistilled benzaldehyde (0.25 mol) in 150 ml ether was added over a period of two hours, while the bath temperature was maintained between -10° and 0°. The mixture was allowed to reach room temperature and then was decomposed with ice/ammonium chloride. The ether and aqueous layers were separated and the aqueous layer extracted twice with 50 ml ether portions. The combined ether layers were washed twice with 25 ml water and were then dried with magnesium sulfate. The ether was evaporated, yielding a light yellow oil. Careful fractionation of the oil under reduced pressure yielded 28 g (77%) of material which proved to be v.p.c. homogeneous. B.p. 80° (0.5 mm), n_D^{26} 1.5457, d_4^{29} 1.0265, (lit.[65] b.p. 89°/1 mm, n_D^{20} 1.5470).

Anal. Calcd. for $C_{10}H_{10}O$: C, 82.16; H, 6.90.

Found: C, 82.10; H, 6.92.

The infrared spectrum showed bands at 3400(s),3300(spike), 3030(m),2900(m),2120(w),1600(w),1490(m),1450(m),1420(m),1390(m), 1320(m),1205(m),1085(m),1050(s),1015(s),945(m),915(m),865(m),830(w), 775(m), 755(s), and 700(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a triplet at 1.95 (1H, acetylenic), a doublet of doublets at 2.50 (2H,aliphatic), a broad singlet at 3.50 (1H,hydroxyl), a triplet at 4.70 (1H,methine), and a singlet at 7.25 (5H,phenyl).

Hydrogenation of 1-phenyl-3-butyn-1-ol.

A 1.04 g (7.1 mmols) sample of the alcohol in pentane, over Pd/C, was found to absorb 365 ml of hydrogen at 298°K, which corresponded to 105% of the 347 ml theoretically required to saturate a triple bond. After filtering off the catalyst and evaporating the pentane, the product was analyzed by v.p.c. and found to consist of a major product of 95% purity. The v.p.c. retention time and infrared spectrum of the hydrogenated alcohol were identical to those of an authentic sample of 1-phenyl-1-butanol, prepared by the action of a n-propyl magnesium bromide on benzaldehyde by standard procedures. Dichromate oxidation of the hydrogenated alcohol gave a ketone whose 2,4—dinitrophenylhydrazone was prepared by the Shriner and Fuson[60] procedure. Recrystallization from ethanol gave orange red crystals, m.p. 189-91°(lit.[62]:m.p.190°) which showed no melting point depression on admixture with an authentic sample. The authentic derivative was prepared from

n-propyl phenyl ketone obtained by dichromate oxidation of the above authentic alcohol.

Vapor phase thermolyses of 1-phenyl-3-butyn-1-ol (76)

This compound was thermolyzed at temperatures from 370° to 430°. V.p.c. analyses of the thermolyzed products always showed a very low boiling constituent, believed to be allene, and a single higher boiling constituent, shown to be benzaldehyde, resulting from the cleavage reaction. No traces of any component resulting from an oxy-Cope rearrangement could be detected in the thermolyses products even when large injections and high sensitivities were employed with the analytical gas chromatograph.

In a typical experiment, 12.16 g of the alcohol was passed through the thermolysis column at a temperature of 430-5°, a pressure of 10 mm, and a drop rate of three drops per minute. The condensed product, 8.69 g (72% recovery), was analyzed by v.p.c.and found to consist of 3% of a very low boiling constituent, believed to be allene, and 97% high boiling constituent shown to be benzaldehyde as follows.

The cleavage product was obtained nearly pure from the thermolysis. After bubbling nitrogen through the product to remove the suspected allene, the material was easily identified by its characteristic odor, v.p.c. retention time and infrared spectrum superimposable on that of authentic redistilled benzaldehyde.

The thermolysis product was converted to its 2,4-dinitrophenyl-

hydrazone by the method of Shriner and Fuson.[60] Recrystallization from ethyl acetate yielded orange crystals, m.p. 238-40° (lit.[60]: 237°) which showed no melting point depression on admixture with an authentic sample.

Preparation of 1-phenyl-2-methyl-3-butyn-2-ol (78)

This compound, previously unreported, was prepared by the addition of an ethereal solution of methyl ethynyl ketone to benzylmagnesium chloride.

In a 2-liter three neck flask, equipped with mechanical stirrer, dropping funnel and condenser, were placed 48 g (2 mols) magnesium turnings, 400 ml dry ether and several iodine crystals. Then 10 ml of a solution of 102 g (0.8 mol) redistilled benzyl chloride in 200 ml ether was added directly to the solution. After five minutes a reaction commenced as evidenced by vigorous boiling. The stirrer was started and the remainder of the benzyl chloride was added dropwise over a period of six hours. The solution was stirred for one hour and then a solution of 37 g (0.55 mol) redistilled methyl ethynyl ketone in 100 ml dry ether was added, dropwise, over a period of two hours. After stirring for one half hour the mixture was decomposed with ice/ammonium chloride. The aqueous layer was extracted with two 150 ml ether portions and the combined ether extracts washed four times with 100 ml portions of water, dried with magnesium sulfate and the ether was evaporated. The remaining thick brown oil was flash distilled under reduced pressure

to remove non-volatile material. Careful fractionation under reduced pressure yielded 8.40 g (10%) of pure material, b.p. 94-96° (4 mm), n_D^{23} 1.5320.

Anal. Calcd. for $C_{11}H_{12}O$: C, 82.47; H, 7.55.
Found: C, 82.59; H, 7.48.

The infrared spectrum showed bands at 3400(s),3300(spike), 3030(m),2990(m),2940(m),2120(w),1610(w),1500(s),1460(s),1380(s), 1360(s),1290(m),1240(m),1160(s),1120(s),1090(s),1060(s),1035(m), 935(s),875(m),760(m) and 700(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.50 (3H, methyl), a broad singlet overlapping another singlet at 2.45 (2H, acetylenic and hydroxyl protons) which collapses to a singlet (1H, acetylenic) on addition of D_2O, a singlet at 2.95 (2H,benzylic) and a singlet at 7.3 (5H,phenyl).

Hydrogenation of 1-phenyl-2-methyl-3-butyn-2-ol

A 0.854 g (5.34 mmols) sample of the alcohol in methanol, over Pd/C absorbed 265 ml of hydrogen, at 297°K, which corresponded to 102% of the theoretical quantity for saturating a triple bond.The product was identified as 1-phenyl-2-methyl-2-butanol by comparison of v.p.c. retention time and infrared spectrum with authentic material. The authentic material was synthesized by the reaction of benzylmagnesium chloride with 2-butanone followed by hydrolysis.

Vapor phase thermolyses of 1-phenyl-2-methyl-3-butyn-2-ol (78)

This compound was thermolyzed at temperatures from 370° to 410° and at various pressures. The product, usually representing a recovery of 85-90% was analyzed by v.p.c. and found to consist of some low boiling fragmentation products and large quantities of unreacted starting material. The amount of fragmentation products, which were not identified, increased with increasing temperature or residence time but never exceeded 25% of the recovered product. No trace of any oxy-Cope product could be detected in the thermolysis mixture. The recovered starting material was identified by its v.p.c. retention time and its infrared spectrum.

In a typical experiment, 1.81 g of the alcohol was thermolyzed at 410-15° and a pressure of 22 mm. A drop rate of four drops/minute was employed. The recovered product weighed 1.55 g (86% recovery). V.p.c. analysis indicated the thermolysis product to consist of 25% low boiling fragmentation products and 75% unreacted starting alcohol.

In an attempted liquid phase Cope rearrangement of this alcohol, 1.37 g was heated in a distilling flask for 30 hours at 210°. The product was dark brown and polymeric. V.p.c. indicated the only volatile product to be unreacted starting alcohol.

Preparation of 5-hexyn-3-ol (58) *

This compound was prepared by the low temperature Barbier procedure also used for 1-hexen-5-yn-3-ol (see page 114). The major modification was the extension of the addition time of the aldehyde/bromide solution to nine hours.

4 g propargyl bromide, 24 g (1 mol) Mg turnings, 200 ml ether and 0.1 g mercuric chloride were reacted by warming, then cooled to -25°. A solution of 67 g (total 0.6 mol) redistilled propargyl bromide and 26.5 g redistilled propionaldehyde (0.145 mol) in 300 ml dry ether was then added over a nine hour period with bath temperatures maintained at -25°. Workup as previously described gave a brownish liquid which was flash distilled to remove non volatile material. Careful fractionation under aspirator pressure gave v.p.c. homogeneous material. The yield was 6.5 g (45%). B.p. 44°/10 mm, n_D^{23} 1.4435, d_4^{25} 0.8555, (lit.[66]: b.p. 58-9°/25 mm, n_D^{20} 1.4437, d_{20} 0.8918).

Anal. Calcd. for $C_6H_{10}O$: C, 73.43; H, 10.27.
Found: C, 73.48; H, 10.25.

The infrared spectrum showed bands at 3400(s), 3300(spike), 2900(s), 2850(m), 2120(w), 1460(m), 1420(m), 1335(m), 1240(m), 1100(s), 1060(m), 1030(s), 990(s), 950(m), 930(w), 900(w), 875(w), 845(w) and 770(w) cm^{-1}.

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* We wish to thank Mr. Robert Proverb for synthesizing this compound.

The n.m.r. spectrum (δ scale) showed a triplet at 0.9 (3H, methyl), a quartet split into doublets at 1.55 (2H, methylene), a triplet at 2.05 (1H, acetylenic), a complex at 2.4 (3H, methylene and hydroxyl), which collapsed to a doublet of doublets (2H), on D_2O exchange, and a quintet at 3.67 (1H, methine).

Hydrogenation of 5-hexyn-3-ol.

A 1.32 g (1.35 mmols) sample of the alcohol in pentane, over Pd/C, was found to absorb 600 ml of hydrogen at 295°K which corresponded to 92% of the 655 ml theoretically required to saturate a triple bond. V.p.c. analysis of the recovered product showed a low boiling constituent believed to be pentane or hexane and two higher boiling products. The major product, (65%), had a v.p.c. retention time equal to that of authentic 3-hexanol. The remaining constituent was believed to be 3-hexanone. The mixture was dissolved in ethanol and treated with 2,4—dinitrophenylhydrazine reagent. Two recrystallizations of the precipitate from ethanol/water gave yellow crystals, m.p. 129.5-133°, (lit.[60] m.p. 130°), which showed no melting point depression on admixture with an authentic sample.

Vapor phase thermolyses of 5-hexyn-3-ol

This compound was thermolyzed at 350° and 370° and at various pressures. V.p.c. of the thermolyzed product showed three peaks corresponding to unreacted starting alcohol, propionaldehyde, and

a very low boiling component believed to be allene. No trace of any other product could be detected.

In a typical experiment, 1.57 g of pure 5-hexyn-3-ol was thermolyzed at 370° and a pressure of 30 mm. A constant drop rate of three drops per minute was always maintained. The thermolyzed product, 0.940 g (60% recovery) was analyzed by v.p.c. and found to consist of 75% propionaldehyde 21% unreacted starting alcohol and 4% of a low boiling material believed to be allene.

The propionaldehyde resulting from the cleavage reaction was identified by its characteristic odor, its v.p.c. retention time which was identical to that of authentic propionaldehyde and by its 2,4—dinitrophenylhydrazone, prepared by the Shriner and Fuson[60] procedure. Repeated recrystallization from alcohol/water yielded yellow orange crystals, m.p. 149-153° (lit.[60] m.p. 154°) which showed no melting point depression on admixture with an authentic sample.

Vapor phase thermolysis of 3-butyn-1-ol (92)

A 6.5 g sample of v.p.c. pure alcohol (Farchan Labs) was thermolyzed at 370° and a pressure of 20 mm. Into each of two collecting traps, set in series, was placed approximately 20 ml ethanol and the traps were then cooled to -78° with Dry Ice/acetone before evacuating the system. At the end of the thermolysis, the Dry Ice traps were removed and the contents of each trap treated with about 20 ml of dilute 2,4—dinitrophenylhydrazine solution. Copious yellow precipitate formed in each trap as the contents warmed to

room temperature. Recrystallization of the material from the ethanol/ethyl acetate gave yellow crystals, m.p. 166.5-168° (lit.[60] m.p. 167° for formaldehyde-2,4—dinitrophenylhydrazone). The derivative gave no melting point depression on admixture with authentic material.

Preparation of 2-methyl-4-pentyn-2-ol (91)

This compound was synthesized by the Barbier reaction of propargylmagnesium bromide with acetone. The procedure was as described in the preparation of 5-hexyn-3-ol (see page 158).

24 g (1 mol) Mg and 0.1 g $HgCl_2$ were reacted with 71 g (0.60 mol) propargyl bromide and 26 g (0.44 mol) acetone. The yield was 23 g (52%), b.p. 124°, n_D^{24} 1.4375, d_4^{25} 0.8729 (lit.[67] b.p. $_{756}^{124-7°}$, n_D^{21} 1.4381).

The infrared spectrum showed bands at 3400(s),3300(spike), 2950(s),2920(m),2120(m),1470(m),1420(w),1380(s),1370(m),1300(w), 1240(m),1210(m),1140(s),1010(w),985(m),950(m),900(s),870(w), and 760(m) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.25 (6H, methyl), a triplet (J=2.5 cps) at 2.05 (1H,acetylenic), a doublet (J=2.5 cps)at 2.25 (2H,aliphatics), and a singlet at 3.35 (1H, hydroxyl).

Vapor phase thermolysis of 2-methyl-4-pentyn-2-ol (91)

A 1.04 g sample of the alcohol was thermolyzed at 375-80° and a pressure of 10 mm. V.p.c. of the condensed product, 0.64 g (62% recovery), showed it to contain 39% acetone and 61% recovered starting material. The acetone was identified by its v.p.c. retention time, characteristic odor, and 2,4—dinitrophenylhydrazone derivative, m.p. 124-126° (lit.: m.p. 126°), which showed no melting point depression on admixture with an authentic sample.

Competition Experiments

Direct competition experiments were conducted between several mixtures of alcohols in order to determine relative thermolysis rates. The technique consists of thermolyzing mixtures containing known integral ratios of alcohols under conditions sufficiently mild that some quantity of both alcohols survives the thermolysis. From the relative v.p.c. areas before and after the thermolysis the relative rates of the thermal reactions were ascertained.

A 1,5-Hexadien-3-ol (4) and 1-hexen-5-yn-3-ol (46)

A 0.940 g. sample of a mixture containing 53.5% 1,5-hexadien-3-ol and 46.5% 1-hexen-5-yn-3-ol was thermolyzed at 350° and a pressure of 1 mm. The initial olefinic to acetylenic alcohol

integral ratio was 1.15. The thermolyzed material weighed 0.741 g (79% recovery). V.p.c. analysis showed the material to contain 39.4% 1,5-hexadien-3-ol and 14.6% 1-hexen-5-yn-3-ol. The final olefinic to acetylenic alcohol integral ratio was therefore 2.70 and the acetylenic alcohol underwent thermal reaction at a faster rate than did the 1,5-hexadien-3-ol at 350°. From the mass balance, mechanical weight loss (weight loss due to other than non condensed cleavage products) was calculated to be 6% and resulted in negligible differences in the computed values.

In another experiment, a 0.862 g sample of a mixture containing 72.5% 1,5-hexadien-3-ol and 20.8% 1-hexen-5-yn-3-ol was thermolyzed at 370° and a pressure of 1 mm. The condensed product weighed 0.610 g (71% recovery). V.p.c. analysis of the thermolyzed product showed it to contain 22.5% recovered 1,5-hexadien-3-ol and only 1.4% recovered 1-hexen-5-yn-3-ol. Therefore the 1,5-hexadien-3-ol underwent thermal reaction slower than the 1-hexen-5-yn-3-ol at 370° also.

B 1,5-Hexadien-3-ol (4) and 5-hexen-1-yn-3-ol (63)

A 0.398 g sample of a mixture containing 48.5% 1,5-hexadien-3-ol and 51.5% 5-hexen-1-yn-3-ol was thermolyzed at 350° and a pressure of 1 mm. The initial olefinic/acetylenic alcohol integral ratio was 0.94. The thermolyzed material weighed 0.310 g (78% recovery). V.p.c. analysis showed it to contain 28% 1,5-hexadien-3-ol and 5.0% 5-hexen-1-yn-3-ol. The new integral ratio of

olefinic to acetylenic alcohols was therefore 5.65 and the acetylenic alcohol underwent thermal reaction faster than the 1,5-hexadien-3-ol at 350°. From the mass balance, mechanical weight loss (weight loss due to other than non-condensed cleavage product), was calculated to be 7% of the initial weight and resulted in negligible differences in the computed values.

C 5-Hexyn-3-ol (58) and 1-phenyl-3-butyn-1-ol (76)

A small sample of a mixture of the two above alcohols was thermolyzed at 375-80° and 1 mm pressure. The initial ratio of peak areas of 5-hexyn-3-ol to 1-phenyl-3-butyn-1-ol was 0.288. The condensed thermolyzed product was analyzed by v.p.c. and the new ratio of peak areas was computed to be 1.85. Therefore 1-phenyl--3-butyn-1-ol cleaved at a faster rate than 5-hexyn-3-ol at 375-80°.

D 1-Phenyl-3-butyn-1-ol and 1-phenyl-3-buten-1-ol (77)

A 1.80 g sample of a mixture containing 1-phenyl-3-buten-1-ol and 1-phenyl-3-butyn-1-ol was thermolyzed at 370-5°, and 1 mm pressure. The initial ratio of the peak areas of the olefinic to acetylenic alcohols was 1.20. The condensed product weighed 1.46 g (81% recovery). Analysis of the thermolyzed material by v.p.c. showed the new integral ratio of the olefinic to acetylenic alcohol peak areas to be 1.53. Therefore the 1-phenyl-3-butyn-1-ol cleaved at a faster rate than 1-phenyl-3-buten-1-ol at 370-5°.

E 5-Hexyn-3-ol (58) and 2-methyl-4-pentyn-2-ol (91)

A mixture containing 54.5% 2-methyl-4-pentyn-2-ol (tertiary alcohol) and 45.5% 5-hexyn-3-ol (secondary alcohol) was prepared. Tert./Sec. integral ratio therefore was initially 1.21.

A 1.73 g sample of the mixture was thermolyzed at 380° and a pressure of 10 mm. The condensed material weighed 1.21 g (70% recovery). V.p.c. analysis showed the new Tert./Sec. alcohol ratio to be 1.16. Therefore the tertiary alcohol underwent cleavage at a faster rate at 380° than did the secondary alcohol.

F 5-Hexyn-3-ol (58) and 3-butyn-1-ol (92)

A 0.550 g sample of a mixture containing 76% 3-butyn-1-ol (primary alcohol) and 24% 5-hexyn-3-ol (secondary alcohol) was thermolyzed at 380-5° and a pressure of 17 mm. The initial primary/secondary integral ratio was therefore 3.14. The thermolyzed material weighed 0.270 g (49% recovery). V.p.c. of the material showed 80% of the unreacted alcohol to be the primary while 20% was the secondary. The new primary/secondary integral ratio was 4.00. Therefore the secondary alcohol underwent cleavage at a faster rate than the primary at 380-5°.

G 3-Butyn-1-ol (92) and 2-methyl-4-pentyn-2-ol (91)

A 2.88 g sample of a mixture containing 37% 2-methyl-4-pentyn--2-ol (tertiary alcohol) and 63% 3-butyn-1-ol (primary alcohol)

was thermolyzed at 360° and a pressure of 10 mm. The initial integral ratio of primary to tertiary alcohol was therefore 1.69. The thermolyzed material was analyzed by v.p.c. Integration of the peak areas showed the new primary to tertiary alcohol ratio to be 2.17. Therefore the tertiary alcohol underwent cleavage at a faster rate than did the primary at 360°.

General procedure for deuterium tracer studies

Approximately 1 *g* of pure alcohol (v.p.c.) was stirred magnetically, for two hours, with 3 ml of 99.9% deuterium oxide. The solution was then saturated with sodium chloride whereupon the alcohol salted out. The upper alcohol layer was separated and the above procedure repeated. The final product was dried with magnesium sulfate. After thermolysis, the deuterated thermolysis mixture was immediately subjected to preparative v.p.c. The products were then dissolved immediately in deuterochloroform and packed in ice until analyzed by n.m.r. spectroscopy. The spectral changes seen for the deuterated thermolyses products are described in the discussion section, pages 34,60. The 1-hexen-5-yn-3-ol-O-d was thermolyzed at 360° and 10 mm pressure. The 5-hexen-1-yn-3-ol-O-d was thermolyzed at 370° and 20 mm pressure. N.M.R. spectral changes due to deuterium substitution in the products of the thermolyses are shown on pages 185-86 for 1-hexen-5-yn-3-ol-O-d and on pages 187-89 for 5-hexen-1-yn-3-ol-O-d.

Procedure for kinetic studies

A) Thermolysis of 5-hexen-1-yn-3-ol (63)

The kinetic studies were undertaken using a Colora HT-13 temperature bath with a temperature constancy rating of $\pm 0.15^{\circ}C$. Dow Corning 210-H fluid was employed as the bath oil. A precision Scientific Co. time was used. Bath temperatures were recorded with a 360° thermometer calibrated at 0° with ice water, at 100° with boiling water, and at 216° with sublimed anthracene. A series of standard solutions, containing known weights of the alcohol in the inert hydrocarbon nonane, were prepared at high, medium and low nonane to alcohol ratios. The ratio of nonane to alcohol was then determined from v.p.c. integral areas, which showed a deviation of no more than $\pm$ 2% from the known weight ratios. The v.p.c. detection gave a nearly linear response to concentration over nonane/alcohol ratios ranging from 0.2 to 20.

Glass capillaries about four inches long and 7 mm O.D. with a 1 mm bore were sealed at one end and about ten µl of analyzed nonane/alcohol solution was injected into the bottom of each capillary. The bottom 5-cm portion of each capillary was then immersed in a Dry Ice/acetone bath at -78° and evacuated by a vacuum pump. Each capillary was then sealed one inch from its top while still under vacuum in the dry ice bath. Five capillaries were prepared in this manner for each temperature utilized. The capillaries were placed in copper casings and immersed in the oil bath at recorded times. The

reactions were quenched by quickly removing the samples from the bath and plunging them into water. The contents of each capillary were then analyzed by v.p.c. and the new nonane/alcohol ratios computed. From this data, log C_o/C was calculated. Rate constants at each temperature were obtained by least squares analyses from the log C_o/C vs time plots. The plots showed fairly good linearity (see fig.III, page 50). An Arrhenius plot of the data also gave a good linear relationship (see fig.4 page 51).

The validity of the above kinetic procedure has been demonstrated by a study of the cleavage of 2-methyl-4-pentene-2-ol. Rate constants and activation parameters obtained for this alcohol were in close agreement with the literature values.[a] Variation of the ratio of capillary size to the amount of material in the capillaries did not affect the linearity of the plots. Also, use of capillaries washed with base, prior to kinetic use, did not affect plot linearity when these capillaries were randomly interspersed with non-washed capillaries.[b]

B) Thermolysis of 5-hexyn-3-ol. (58)

The general procedure was as described above, except that decane rather than nonane was used as the internal standard. Five kinetic points were obtained at each of six temperatures from 227° to 258°. The rate appeared to follow first order kinetics at all temperatures although some scatter was encountered,

a) Fred Garafolo, unpublished results, this laboratory.

b) Robert Proverb, unpublished results, this laboratory.

especially at the lower temperatures (see fig V , page 87). An Arrhenius plot of the data displayed fairly good linearity (see fig VIpage 88). Estimated error in the rate constants was 5-10%. The best rate constant was obtained at each of the six temperatures by the method of least squares. Least square analysis was also employed in finding the best slope and intercept for the Arrhenius plot.

C) Thermolysis of 2-methyl-4-pentyn-2-ol. (91)

The general procedure was that described in the above kinetic studies. Nonane was used as the internal standard. Five points were obtained at each of five different temperatures. Good linearity was observed for both the kinetic runs and Arrhenius plot. Individual rate constants and Arrhenius parameters were computed by least squares analysis. (See figure VIIpage 91 and Figure VIII page 92).

Competitive thermolyses, in capillary tubes, between 5-hexyn--3-ol and 2-methyl-4-pentyn-2-ol.

A standard solution containing nonane, 5-hexyn-3-ol, and 2-methyl-4-pentyn-2-ol was prepared. The initial integral ratio of nonane/sec. alcohol was 0.392, while the initial ratio of nonane/tert. alcohol was 0.380. Approximatoly ten microliters of the material was sealed in a capillary tube by the technique

described previously. The material was reacted at 246°c for 50,000 seconds. V.p.c. analysis showed the new nonane/sec.alcohol ratio to be 1.82 while the new nonane/tert.alcohol ratio was 1.34. Using the relationship:

$$\frac{\text{Log } (C_o/C)_{sec.}}{\text{Log } (C_o/C)_{tert.}} = \frac{k_{sec.}}{k_{tert.}}$$

it was computed that the secondary alcohol underwent cleavage 1.22 times faster than the tertiary alcohol at 246°.

In another experiment a capillary containing the above solution was heated at 240° for 86,000 seconds. The new nonane/tert. alcohol ratio was 1.50. The new nonane/sec. alcohol ratio was 2.48. From this data it was computed that the secondary alcohol cleaved 1.34 times faster than the tertiary at 240°.

Kinetic Data for Cope Rearrangement of 5-Hexen-1-yn-3-ol.

T°C	t sec.	C_o/C	log C_o/C	k sec^{-1}
186	3000	1.25	.097	
"	4500	1.50	.176	
"	6620	1.83	.263	1.24×10^{-4}
"	8500	2.49	.346	From Slope
"	10,000	3.00	.477	
191	2500	1.35	.130	
"	5325	2.00	.301	
"	7780	3.15	.498	1.86×10^{-4}
"	10,000	4.65	.668	From Slope
"	12,460	8.65	.937	
195	2520	2.13	.328	
"	4000	2.82	.450	2.38×10^{-4}
"	6030	4.50	.653	From Slope
"	8100	6.85	.836	
"	9900	9.65	.985	
202	2170	2.12	.326	
"	4040	4.25	.628	3.66×10^{-4}
"	6390	9.90	.996	From Slope
"	8360	22.4	1.350	
206	2085	2.62	.418	
"	3650	6.00	.778	
"	5000	10.6	1.025	4.68×10^{-4}
"	6000	16.8	1.225	From Slope
"	7350	30.0	1.477	
210	1030	1.85	.267	
"	2020	3.25	.512	5.80×10^{-4}
"	3010	5.15	.712	From Slope
"	4030	11.3	1.053	
"	5020	17.5	1.243	

Kinetic Data for Cleavage of 5—Hexyn—3—ol

T °C	t sec	C_o/C	log C_o/C	k sec^{-1}
228.5	30,000	1.45	.160	
"	50,000	1.93	.286	
"	86,000	3.08	.486	1.19×10^{-5}
"	64,500	2.12	.326	
"	157,000	6.20	.792	
234	10,000	1.14	.057	
"	18,000	1.34	.128	
"	68,500	4.00	.600	1.99×10^{-5}
"	86,500	5.72	.758	
"	100,000	7.34	.865	
241	10,000	1.30	.115	
"	22,000	1.78	.250	
"	32,750	2.38	.377	2.88×10^{-5}
"	57,600	5.64	.750	
"	82,900	10.0	1.00	
247	10,000	1.43	.154	
"	17,000	1.94	.288	
"	24,000	3.00	.477	4.40×10^{-5}
"	31,000	3.74	.573	
"	48,700	9.14	.960	
252.5	20,000	3.24	.510	
"	25,000	4.40	.644	
"	30,000	5.90	.770	5.90×10^{-5}
"	8,000	1.52	.182	
"	15,300	2.48	.394	
259.0	5,000	1.52	.182	
"	10,000	2.36	.372	
"	15,000	3.69	.567	8.66×10^{-5}
"	19,000	5.50	.740	
"	23,600	7.23	.858	

Kinetic Data for Cleavage of 2-Methyl-4-pentyn-2-ol.

T °C	t sec	C_o/C	log C_o/C	k sec^{-1}
235	25,900	1.19	.073	
"	50,500	1.59	.202	
"	75,500	2.06	.314	$.92 \times 10^{-5}$
"	100,000	2.52	.400	
"	229,000	11.66	1.07	
241	10,000	1.14	.058	
"	20,000	1.37	.134	
"	38,000	1.83	.262	1.50×10^{-5}
"	66,500	2.72	.434	
"	83,000	3.38	.530	
247	10,000	1.17	.070	
"	20,000	1.48	.170	
"	30,000	1.80	.256	2.25×10^{-5}
"	40,000	2.58	.410	
"	52,000	3.45	.528	
"	67,000	4.53	.656	
252	10,700	1.32	.120	
"	20,000	1.75	.244	
"	31,000	2.56	.408	3.01×10^{-5}
"	39,000	3.12	.494	
"	63,300	6.95	.842	
257	10,000	1.42	.152	
"	20,000	2.22	.348	
"	30,000	3.80	.580	4.57×10^{-5}
"	39,000	5.34	.730	
"	50,000	11.40	1.056	

Addition of allylmagnesium chloride to 5-hexen-1-yn-3-ol (63)

The compound 97 obtained as a high boiling byproduct in the synthesis of 5-hexen-1-yn-3-ol was purified by preparative v.p.c. (yield of about 10%), b.p. 188-9°(1 atm), n_D^{27} 1.4675.

Anal. Calcd. for $C_9H_{14}O$: C, 78.22 ; H, 10.21.

Found: C, 77.93 ; H, 10.25.

The infrared spectrum showed bands at 3400(m), 3050(m),2960(m), 2900(m),1830(w,overtone),1650(m),1440(m),1415(m),1310(w),1210(w), 1120(w),1055(m),1030(m),995(s),905(s),and 875(w) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 2.05 (1H, hydroxyl, collapses upon addition of D_2O), a triplet at 2.35 (2H, allylic), a doublet at 2.8 (2H,allylic), a triplet at 4.10 (1H, methine), a complex centered at 5.1 (6H, terminal vinyl), and a complex centered at 5.78 (2H, internal vinyl).

The ultraviolet spectrum showed only end absorption above 220mμ.

Hydrogenation of 5-methylene-1,7-octadiene-4-ol.(97)

A 0.741 g (5.38 mmols) sample of the alcohol in pentane, over Pd/C, was found to absorb 360 ml of hydrogen at 298°K, which was 92% of the 394 ml theoretically required to saturate three double bonds. After filtration to remove the catalyst, the pentane was evaporated, to yield a colorless liquid. V.p.c. analysis indicated the liquid to contain three components which were separated by preparative v.p.c. The lowest boiling product (12% of the mixture)

was shown to be a saturated hydrocarbon by its infrared spectrum. This component, believed to be 4-methyl-octane, was isolated in only trace quantity and was not further identified. The major component (71% of the mixture) was shown to be a saturated ketone by its infrared spectrum. Its physical constants were b.p.179-81°, n_D^{25} 1.4145. The highest boiling component (17% of mixture) was shown by infrared to be a saturated alcohol. The latter two components were identified by comparison to synthetic samples, as described below, as 5-methyl-4-octanone and 5-methyl-4-octanol respectively.

Authentic 5-methyl-4-octanol was synthesized by the reaction of the Grignard reagent prepared from 2-bromopentane with butanal, followed by workup and purification by standard procedures.

The infrared spectrum and v.p.c. retention time of the synthetic material were found to be identical to those of the alcohol obtained from the hydrogenation of 5-methylene-1,7-octadien--4-ol.

Authentic 5-methyl-4-octanone was synthesized by oxidation of 5-methyl-4-octanol with potassium dichromate/sulfuric acid according to standard procedures.

The boiling point, index of refraction, infrared and n.m.r. spectra of the synthetic 5-methyl-4-octanone were identical to those of the ketone obtained from the hydrogenation of 5-methylene--1,7-octadien-4-ol.

Addition of allylmagnesium chloride to propargyl alcohol.

In a 5 liter three neck flask, equipped with mechanical stirrer, dropping funnel, and condenser were placed 72 g (3 mols) of magnesium turnings, 500 ml of dry ether and several crystals of iodine. Then 50 ml of a solution of 115 g (1.5 mols) redistilled allyl chloride in 500 ml of dry ether was added in one portion and the mixture stirred vigorously. After five minutes, the reaction commenced as evidenced by formation of a white solution and vigorous ether reflux. The remainder of the solution was then added dropwise over six hours. Midway through the addition 50 ml of dry tetrahydrofuran was added to redissolve precipitated Grignard complex. After completion of the chloride addition, the solution was stirred for one hour. Then a solution of 28 g (0.5 mol) redistilled propargyl alcohol in 200 ml ether was added, dropwise, over a period of three hours. A vigorous reaction occurred resulting in considerable ether evaporation. At the end of the addition, 300 ml additional ether was added and the solution was then stirred for fifteen hours. The mixture was decomposed with ice/ammonium chloride and the two layers were separated. The aqueous layer was extracted with two 200 ml ether portions. The combined ether layers were washed twice with 100 ml portions of water and dried with magnesium sulfate. The ether was removed, on a steambath, to yield a light yellow oil. Careful fractionation of the oil, under aspirator pressure, with the Tantalum wire column, yielded 22 g of crude material b.p. 75-90° (30 mm).

2-Methylene-4-penten-1-ol (98)

Preparative v.p.c. of the crude distillation mixture described above afforded 17 g (35% yield) of a pure compound, subsequently identified as 2-methylene-4-penten-1-ol, b.p.158-9°, n_D^{27} 1.4535, d_4^{29} 0.860. The compound had not previously been reported. A higher boiling product also was obtained. See page 175.

Anal. Calcd. for $C_6H_{10}O$: C, 73.43 ; H, 10.27.

Found: C, 73.32 ; H, 10.32.

The infrared spectrum showed bands at 3400(s),3050(m),2970(w), 2900(m),1830(w,overtone),1650(m),1440(m),1420(m),1230(m),1100(w), 1060(m),1030(m),1000(m),920(s), and 905(m) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a singlet at 1.92 (1H, hydroxyl, collapses on addition of D_2O), a singlet at 4.10 (2H,aliphatics), a doublet at 2.82 (2H,allylic), a multiplet centered at 5.1 (4H, terminal vinyl), and a multiplet centered at 5.8 (1H, internal olefinic).

The ultraviolet spectrum showed only end absorption above 210 mμ.

Hydrogenation of 2-methylene-4-penten-1-ol

A 0.567 g (5.8 mmols) sample of the alcohol was dissolved in pentane, over 10% Pd/C and hydrogenated until gas absorption ceased. The sample absorbed 295 ml at 298°K, which was 104% of the 284 ml theoretically required to saturate two double bonds. After filtering off the catalyst and evaporation of the pentane, the residue was analyzed by v.p.c. Three hydrogenation products were detected. The

first product, 20% of the mixture, had a v.p.c. retention time in line with that expected for 2-methyl-pentane and was not characterized further. The remaining two products were purified by preparative v.p.c. The major product (70% of the mixture) had a v.p.c. retention time and infrared spectrum identical to those of authentic 2-methylpentanal. The 2,4-dinitrophenylhydrazone was prepared by the method of Shriner and Fuson[60] and recrystallized from ethanol/water, m.p. 101-102° (lit.[62]: m.p. 103°). The compound showed no melting point depression on admixture with an authentic sample. The remaining hydrogenation product, 10% of the mixture, had a v.p.c. retention time and infrared spectrum identical to those of authentic 2-methylpentanol.

The high boiling product (3.14 g) from the reaction of allylmagnesium chloride with propargyl alcohol, was isolated by preparative v.p.c. A Rast determination gave a molecular weight of 180±10. The physical constants were consistent for a twelve carbon alcohol. B.p. 188-9°, n_D^{27} 1.4767.

Anal.	Calcd. for $C_{12}H_{20}O_2$:	C, 73.43 ;	H, 10.27.
	Found:	C, 73.29 ;	H, 10.40.

The infrared spectrum showed bands at 3400(s),3030(w),2900(s), 2850(m),1650(w),1440(w),1360(w),1320(w),1300(w),1265(w),1220(w), 1150(w),1045(s),1015(m),985(m),950(w),935(w),905(w),and 825(w)cm^{-1}.

The n.m.r. spectrum (δ scale) showed a multiplet centered at 2.2 (12H,aliphatics), a broad singlet at 3.95 (2H,hydroxyl,collapses

with D_2O), a multiplet at 4.15 (2H, deshielded aliphatics), and a multiplet at 5.6 (2H, olefinics). No further structure determination was undertaken.

Addition of methallylmagnesium chloride to propargyl alcohol.

A 2-liter three neck flask was fitted with mechanical stirrer, dropping funnel and condenser. Then 54 g (2.25 mols) magnesium, several crystals of iodine, 500 ml dry ether and 20 ml of a solution containing 109 g (1.2 mols) redistilled methallyl chloride in 150 ml ether were added to the flask. After five minutes vigorous bubbling occurred and stirring was commenced. The remaining chloride solution was added dropwise over a period of six hours. A 10 ml portion of anhydrous THF was added during the addition to dissolve precipitated complex. A solution of 20 g (0.35 mol) redistilled propargyl alcohol in 75 ml of dry ether was then added dropwise over a period of two hours so as to maintain a moderate ether reflux. After complete addition, 400 ml additional ether was added and the mixture stirred for 18 hours. After decomposition and extraction in the usual manner, the ether layer was dried with magnesium sulfate and the ether was removed to yield a yellow oil. Fractionation under aspirator pressure gave pure 2-methylene-4-methyl-4-penten-2-ol (99), 11.08 g (28% yield). B.p. 60-61° (10 mm), n_D^{22} 1.4600, d_4^{25} 0.863.

Anal.			
	Calcd. for $C_7H_{12}O$:	C, 74.95 ;	H, 10.78.
	Found:	C, 74.76 ;	H, 11.00.

The infrared spectrum showed bands at 3350(s),3050(w),2950(m), 2900(m),1800(overtone),1650(m),1450(s),1380(m),1230 (m),1065(s), 1025(s),990(m),955(w),895(v.s.), and 825(w)cm^{-1}.

The n.m.r. spectrum (δ scale) showed a broad singlet at 3.4 (1H,hydroxyl), a singlet at 4.0 (2H,aliphatics), a singlet at 2.8 (2H,aliphatics), a triplet (J< 1 cps) at 1.7 (3H,methyl), multiplets at 4.9 and 5.1 (total 2H,methylene) and a multiplet at 4.75 (2H, terminal vinyl).

The following Grignard additions were successfully accomplished using ether volumes and reaction times proportional to those described for the addition of methallylmagnesium chloride to propargyl alcohol.

Addition of n-propylmagnesium chloride to propargyl alcohol.

79 g (1 mol) n-propyl chloride, 18.5 g (0.33 mol) propargyl alcohol and 60 g (2.5 mol) Mg were reacted by the previously described procedure. Preparative v.p.c. yielded 1.57 g of material, 102, (5% yield), b.p. 165-6°, n_D^{27} 1.4355.

Anal. Calcd. for $C_6H_{12}O$: C, 71.95 ; H, 12.08.
Found: C, 72.03 ; H, 12.01.

The infrared spectrum showed bands at 3400(s),3050(m),2930(s), 2860(s),1650(m),1460(m),1380(m),1220(w),1050(s),1030(s),995(m), 980(w),900(s),880(w), and 745(w) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a distorted triplet at 0.90

(3H,methyl), a multiplet at 1.5 (2H,aliphatics), a distorted triplet at 2.0 (2H,aliphatics), a doublet with fine splitting into triplets at 4.95 (2H,methylene), a singlet at 4.05 (2H,aliphatics),and a broad singlet at 3.35 (1H,hydroxyl, collapses on addition of D_2O).

Hydrogenation of 2-methylene-1-pentanol (102)

A 0.535 g (5.35 mmols) sample of the alcohol in pentane, over Pd/C, was found to absorb 140 ml of hydrogen at 298°K which corresponded to 107% of the 131 ml theoretically required to saturate one double bond. The catalyst was removed by filtration and the pentane evaporated yielding a colorless liquid. Extensive hydrogenolysis evidently occured since less than half of the hydrogenated alcohol was recovered. V.p.c.analysis showed the material to consist of three products. The lowest boiling constituent, 13% of the product, had a v.p.c. retention time in line with that expected for 2-methylpentane and was not further characterized. The highest boiling product, 8% of the mixture, had a retention time identical to that of authentic 2-methylpentanol. The major component, 79%, had a v.p.c. retention time and infrared spectrum identical to those of authentic 2-methylpentanal. The 2,4-dinitrophenylhydrazone was prepared by the Shriner and Fuson[60] procedure. Recrystallization from ethanol yielded yellow crystals, m.p. 100-102° (lit.[62] m.p. 103°) which showed no melting point depression on admixture with an authentic sample. A 50/50 mixture with hexanal DNPH, m.p. 103°, was depressed and melted at 85 -90°.

Addition of propargylmagnesium bromide to propargyl alcohol.

48 g (2 mols) magnesium, 0.1 g $HgCl_2$, 400 ml dry ether and a solution of 99 g propargyl bromide (0.84 mol) + 300 ml ether were reacted at -25° by the procedure given in the syntheses of 1-phenyl -3-butyn-1-ol (see page 152). A solution of 15 g (0.27 mol) of propargyl alcohol in 100 ml dry ether was added to the cold Grignard prepared above, over a period of two hours, while allowin the flask to warm from the heat of the reaction. After stirring for fifteen hours the mixture was worked up in the usual manner. Preparative v.p.c. gave 6.80 g (26.4%) of product, b.p. 89-90° (30 mm), n_D^{28} 1.4705. 100 gave the following analysis and spectra.

Anal. Calcd. for C_6H_8O : C, 74.97 ; H, 8.39.

Found: C, 74.53 ; H, 8.62.

The infrared spectrum showed bands at 3400(s),3300(spike), 3080(w),2870(m),2120(w),1650(m),1420(m),1200(w),1290(w),1280(w), 1060(s),1020(s),990(s),905(s), and 620(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a triplet at 2.2 (1H, acetylenic), a multiplet centered at 3.0 (2H,aliphatics), a broad singlet at 4.30 (1H,hydroxyl,collapses on addition of D_2O), a singlet at 4.1 (2H,aliphatics), and a multiplet centered at 5.2 (2H,methylene).

Hydrogenation of 2-methylene-4-pentyn-1-ol (100).

A 0.410 g (4.28 mmols) sample of the alcohol, in pentane, over Pd/C, was found to absorb 450 ml of hydrogen at 293° K which corres-

ponded to 145% of the 310 ml theoretically required to saturate three double bonds. The catalyst was filtered off and the pentane evaporated. Extensive hydrogenolysis appeared to have occurred as less than 25% of the initial alcohol volume was recovered. V.p.c. analysis showed the material to contain four products. Two low boiling constituents (17% of the mixture) were probably residual pentane and 2-methylpentane. The major product (62%) had a v.p.c. retention time equal to that of authentic 2-methylpentanal. The longest eluting product (21%) gave a v.p.c. retention time equal to that of authentic 2-methylpentanol. The hydrogenated product was dissolved in ethanol and was then treated with 2,4-dinitrophenylhydrazine reagent. The resulting precipitate was recrystallized twice from ethanol to yield yellow crystals, m.p. 98-100° (lit.[62] m.p. 103°). The crystals showed no melting point depression on admixture with an authentic sample of 2-methylpentanal-2,4-dinitrophenylhydrazone.

Addition of allylmagnesium chloride to allyl alcohol.

The Grignard reagent prepared from 60 g (2.5 mols) magnesium and 77 g (1 mol) allyl chloride was treated with 19 g (0.33 mol) of allyl alcohol. The yield was 4.10 g (13%), b.p. 56° (12 mm), n_D^{21} 1.4347.

Anal.			
	Calcd. for $C_6H_{12}O$:	C, 71.95 ;	H, 12.08.
	Found:	C, 71.81 ;	H, 11.80.

Compound 106 had the following spectral properties.

The infrared spectrum showed bands at 3400(s),3080(m),2960 (s), 2900(s),2870(s),1640(m),1450(m),1430(m),1410(m),1380(m),1210(w), 1090(w),1040(s),990(s),950(w),910(s), and 870(w) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a distorted doublet at 0.95 (3H,methyl), a multiplet at 1.90 (3H,allylic + methine), a singlet overlapping a doublet centered at 3.4 (3H,hydroxyl + aliphatics), which collapsed to a clean doublet (2H) at 3.4 on addition of D_2O, a multiplet at 5.0 (2H,terminal vinyl) and a multiplet centered at 5.8 (1H,internal vinyl).

Hydrogenation of 2-methyl-4-penten-1-ol (106)

A 0.879 g (8.79 mmols) sample of the alcohol in pentane over 10% Pd/C was found to absorb 235 ml of hydrogen at 295°K which corresponds to 109% of the 215 ml theoretically required to saturate one double bond. The catalyst was removed by filtration and the pentane evaporated yielding a colorless liquid. V.p.c. of the hydrogenated product showed a low boiling constituent (10% of the mixture), believed to be residual pentane. A higher boiling product (10%) had a v.p.c. retention time identical to that of authentic 2-methylpentanal. The major hydrogenation product, isolated by preparative v.p.c., had v.p.c. retention time and infrared spectrum identical to those of authentic 2-methylpentanol but different from those of authentic 1-hexanol.

The aldehydic component was isolated as its 2,4-dinitrophenylhydrazone. Recrystallization from ethanol/water gave yellow crys-

tals, m.p. 104-105.5°(lit.[62] m.p. 103°) which showed no melting point depression on admixture with the authentic derivative of 2-methylpentanal.

Addition of benzylmagnesium chloride to propargyl alcohol.

The Grignard reagent prepared from 60 g (2.5 mols) Mg and 154 g (1.25 mols) benzyl chloride was treated with 19.5 g propargyl alcohol (0.35 mol). The yield was 5.70 g (12%) b.p. 96-97° (2 mm), n_D^{25} 1.5427. Compound 101 gave the following spectra.

The infrared spectrum showed bands at 3400(s),3050(m),3040(m), 3010(m),2920(m),2870(m),1640(m),1600(m),1490(s),1450(s),1435(m), 1400(m),1075(m),1055(s),1030(s),990(m),900(s),840(w),825(w),740(s) and 700(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a broad singlet at 3.0 (1H,hydroxyl), a singlet at 3.20 (2H,methylene), a singlet at 3.90 (2H,benzylic), broad singlets with fine splitting at 4.85 and 5.10 (2H,olefinics) and a singlet at 7.20 (5H,phenyl).

Hydrogenation of 3-phenyl-2-methylene-1-propanol (101)

A 1.90 g (1.28 mmols) sample of the alcohol, in pentane, over 10% Pd/C, absorbed 225 ml of hydrogen at 300°K which corresponded to 72% of the 316 ml theoretically required to saturate one double bond. Analysis by v.p.c. showed three products. The low boiling constituent (29%) had a retention time in line with isobutyltoluene. The major product (62%) had a v.p.c. retention time in line with

that expected for 2-methyl-3-phenylpropanal. The remaining high boiling product had a v.p.c. retention time in line with that expected for 2-methyl-3-phenyl-1-propanol. Two derivatives of the major hydrogenation product were prepared. Recrystallization of the 2,4-dinitrophenylhydrazone from 1:1 ethanol/ethyl acetate yielded yellow crystals m.p. 120-122° (lit.[62]: m.p. 119° for DNPH derivative of 2-methyl-3-phenylpropanal). The semicarbazone, after recrystallization from ethanol/water, gave m.p. 118-121° (lit.[62]: m.p. 123-4°).

Addition of allylmagnesium chloride to 3-butyn-2-ol.

The Grignard reagent prepared from 30 g (1.25 mols) Mg, 250 ml ether and 54 g (0.7 mol) allyl chloride was treated with 13 g (0.185 mol) 3-butyn-2-ol in 50 ml ether. After stirring for 18 hours, the solution was decomposed and worked up in the usual manner. Preparative v.p.c. gave 4.63 g (22% yield) of pure compound. B.p. 64-5° (22 mm).

The infrared spectrum showed bands at 3400(s), 3030(m), 2960(s), 2900(m), 1640(m), 1425(m), 1410(m), 1370(m), 1280(m), 1100(m), 1070(m), 995(m), 960(m), and 905(s) cm^{-1}.

The n.m.r. spectrum (δ scale) showed a doublet at 1.25 (3H, methyl), a doublet at 2.75 (2H, aliphatic methylenes), a broad singlet at 3.0 (1H, hydroxyl, collapses with D_2O addition), a quartet at 4.1 (1H, methine), a multiplet at 4.8 (4H, terminal olefinic), and a multiplet at 5.6 (1H, internal olefinic). The 3-methylene-5-penten-2-ol (104) structure assignment is based solely on the above data.

The following attempted reactions did not afford Grignard addition products under the same conditions as those previously described and only afforded recovered starting materials.

With allylmagnesium chloride

a) 1-hexyne (109)

b) 2-methyl-3-butyn-2-ol (107)

c) 3-butyn-1-ol (92)

With n-propylmagnesium chloride

a) 1-hexyne

b) 2-methyl-3-butyn-2-ol

c) 3-butyn-1-ol

d) allyl alcohol (105)

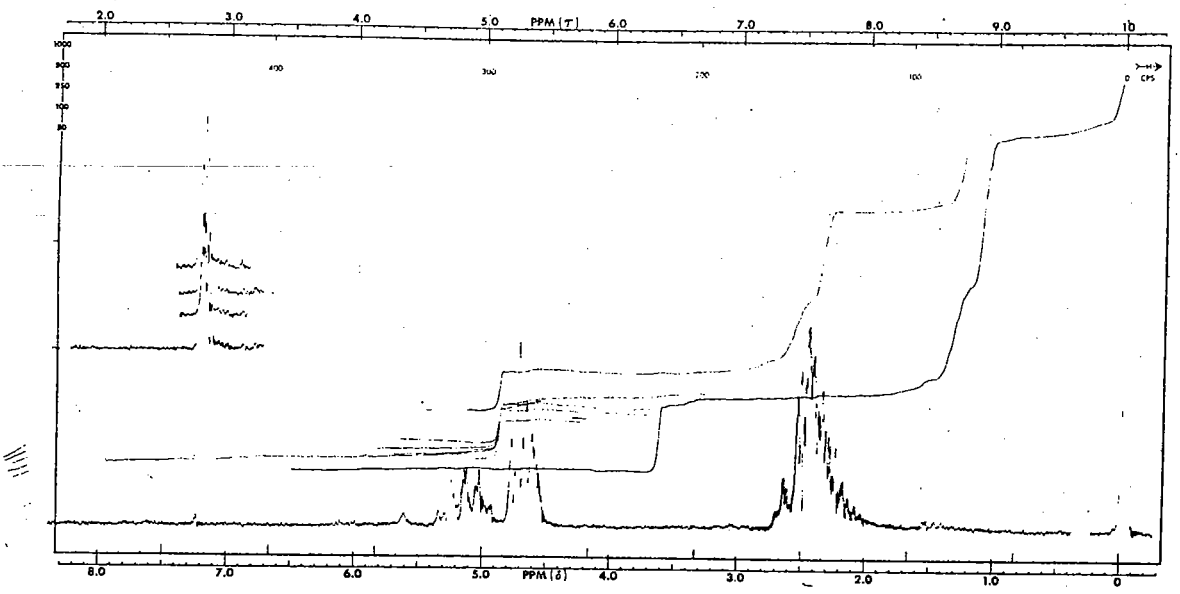

Figure IX: N.M.R. Spectrum of 4,5-hexadienal
Sweep offset = 150 cps.

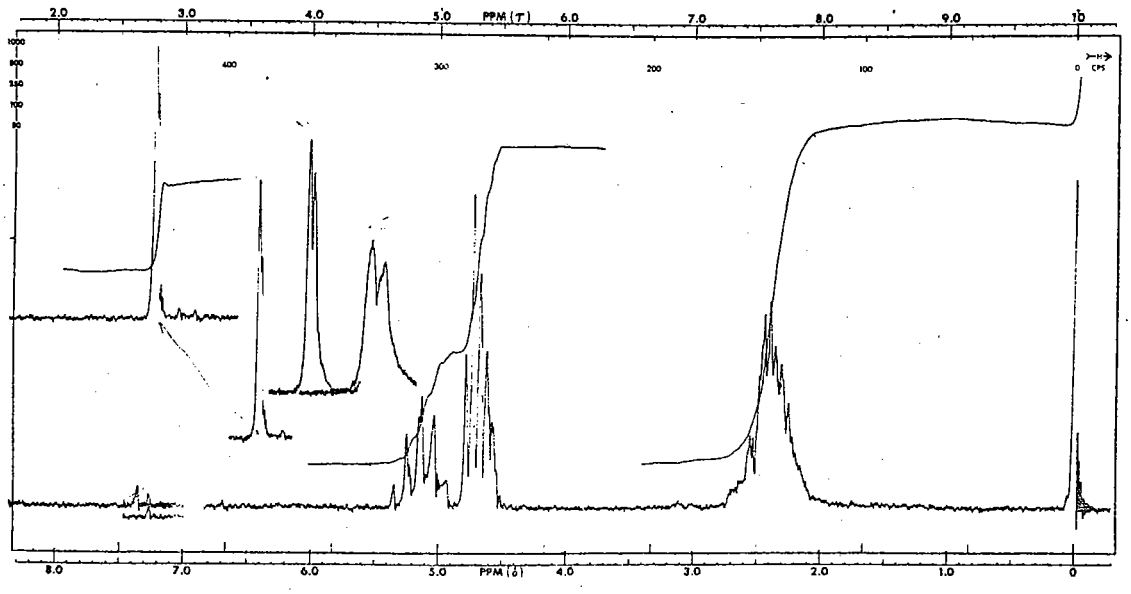

Figure X: N.M.R. Spectrum of 4,5-hexadienal-2-d
Sweep offset = 150 cps.

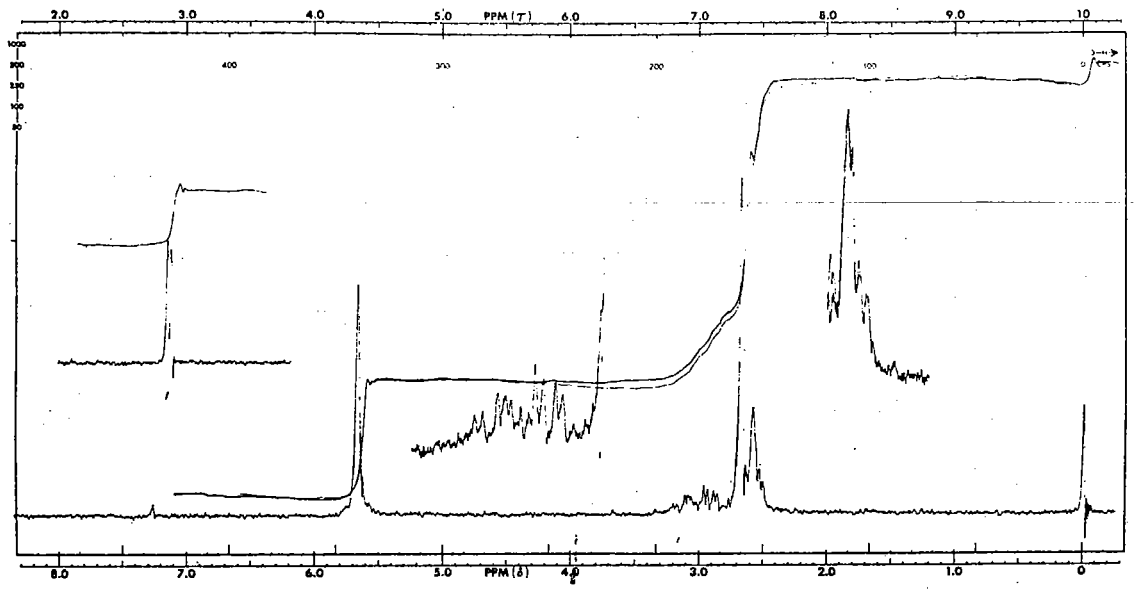

Figure XI: N.M.R. Spectrum of Δ^3-cyclopentenecarboxaldehyde Sweep offset = 150 cps.

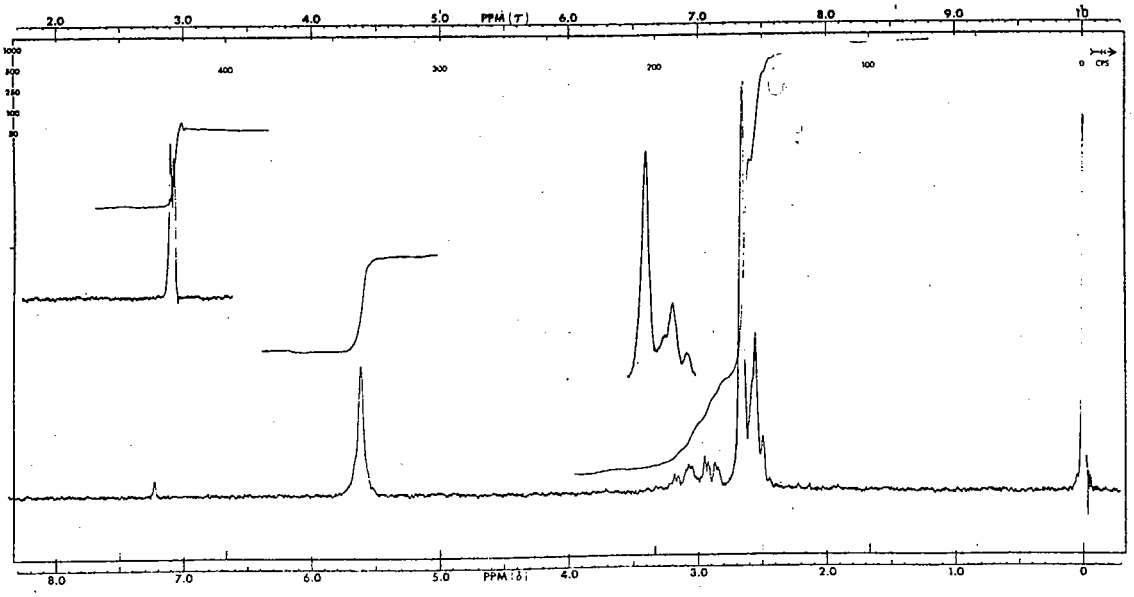

Figure XII: N.M.R. Spectrum of Δ^3-cyclopentenecarboxaldehyde-3-d. Sweep offset = 150 cps.

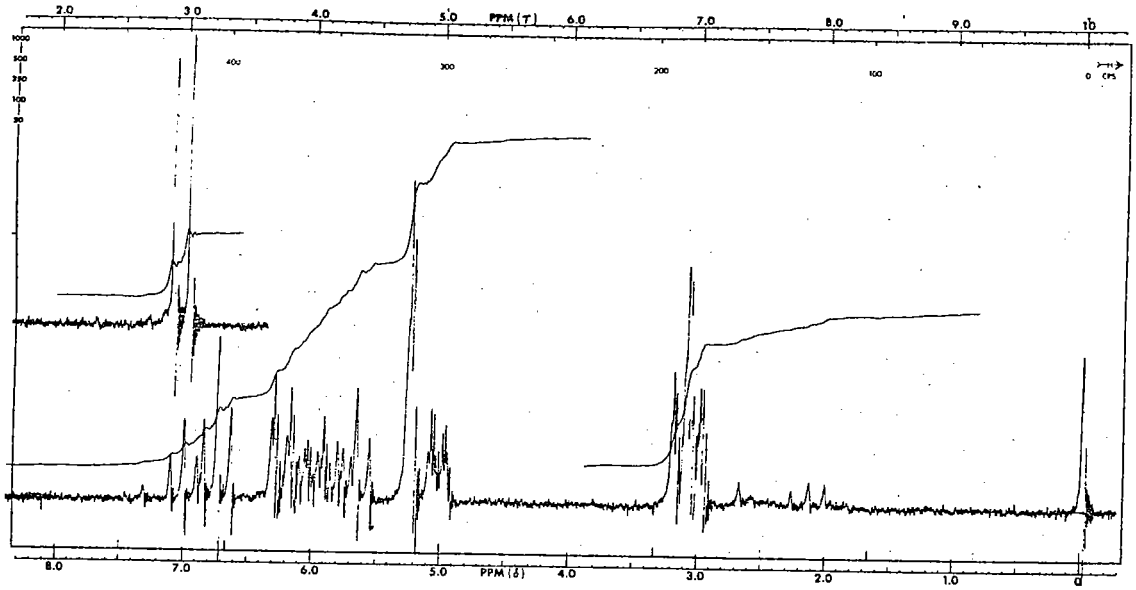

Figure XIII: N.M.R. Spectrum of trans-2,5-hexadienal
Sweep offset = 150 cps.

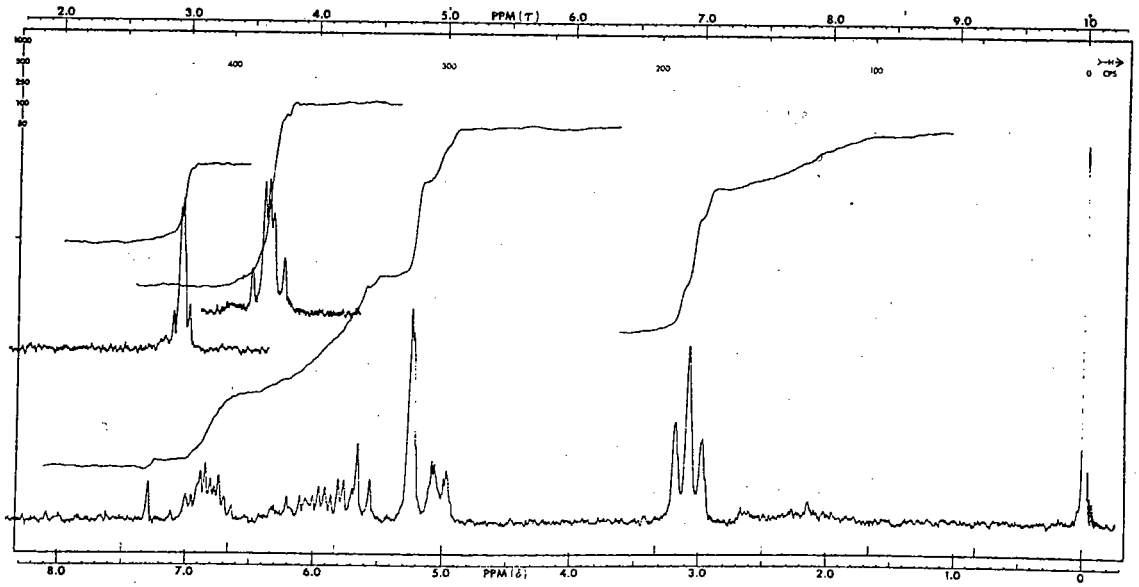

Figure XIV: N.M.R. Spectrum of trans-2,5-hexadienal-2-d
Sweep offset = 150 cps.

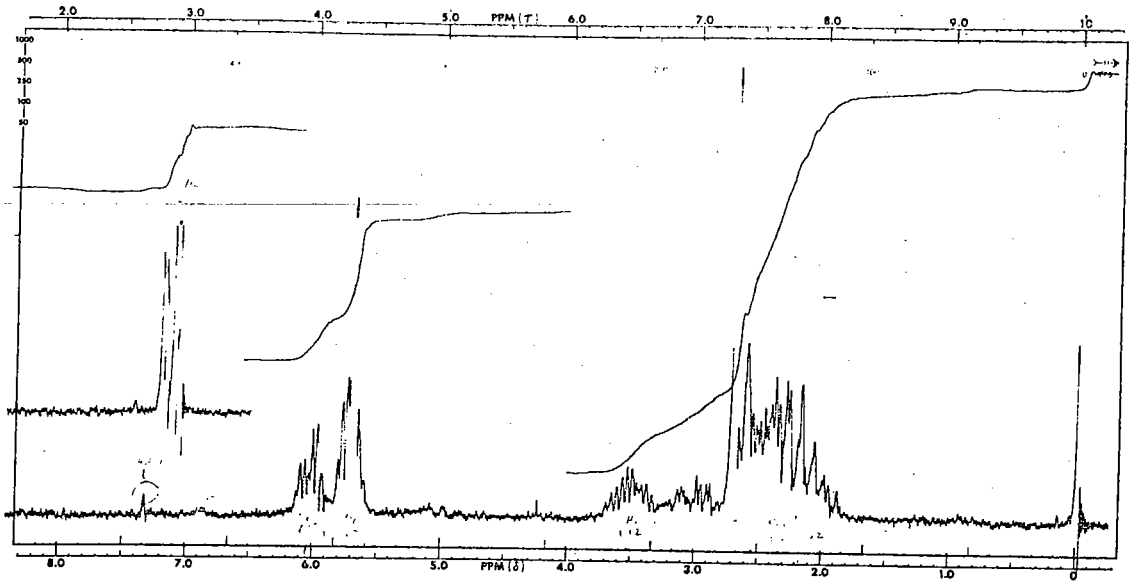

Figure XV: N.M.R. Spectrum of mixture of Δ^2- and Δ^3-cyclopentenecarboxaldehydes.
Sweep offset = 150 cps.

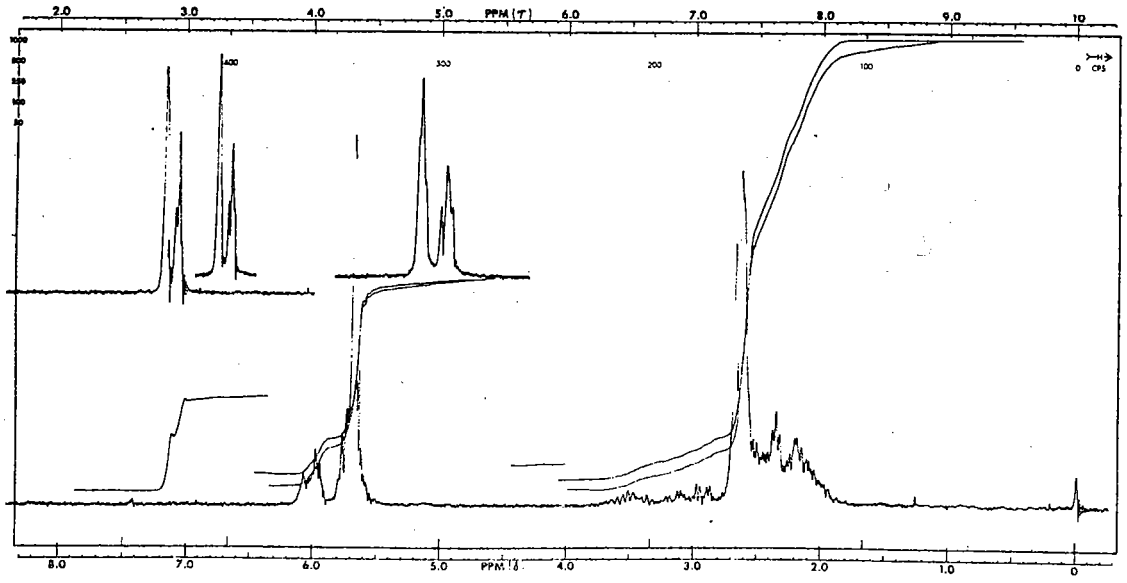

Figure XVI: N.M.R. Spectrum of deuterated mixture of Δ^2- and Δ^3-cyclopentenecarboxaldehydes.
Sweep offset = 150 cps.

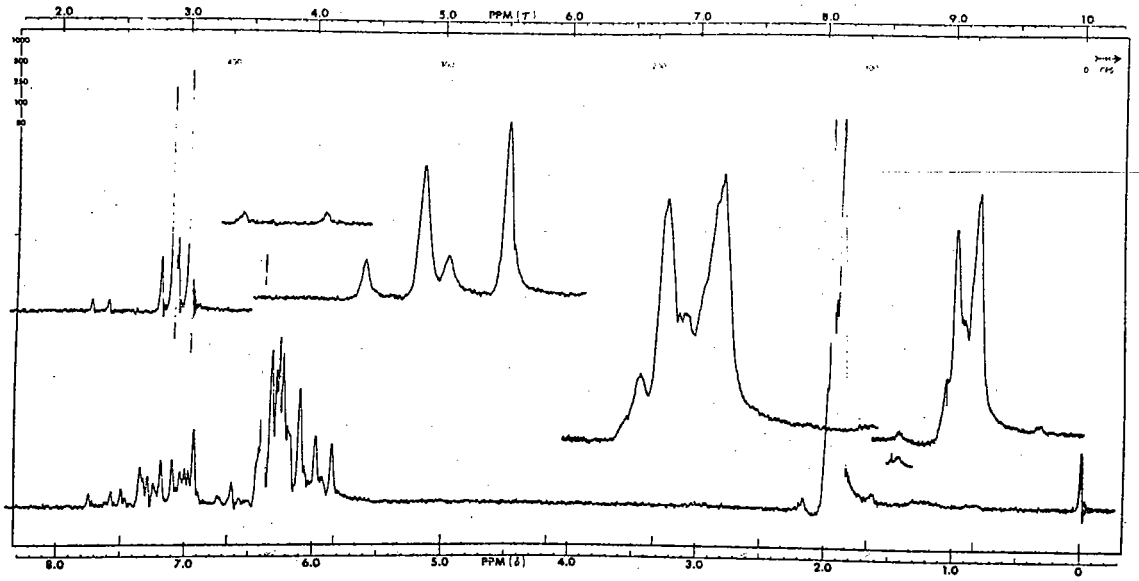

Figure XVII: N.M.R. Spectrum of sorbaldehyde
Sweep offset = 150 cps.

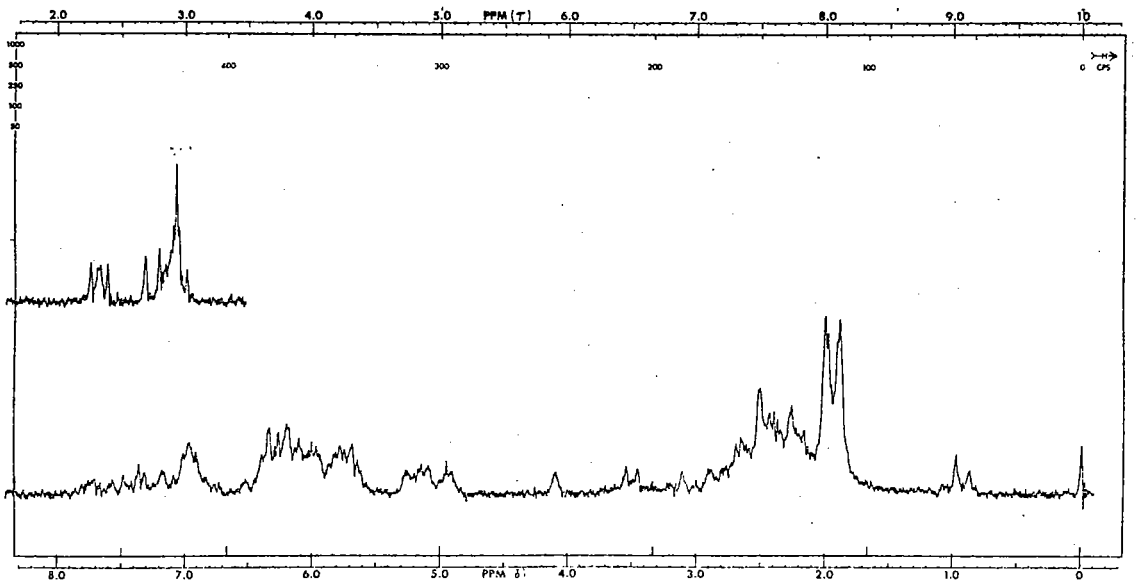

Figure XVIII: N.M.R. Spectrum of deuterated sorbaldehyde
Sweep offset = 150 cps.

Comparisons of N.M.R. bands with literature values for model compounds

100 MHz N.M.R. spectrum of trans-2-vinyl-cyclopropanecarboxaldehyde[a]

The spectrum (δ scale) showed multiplets centered at 1.1 and 1.5 (2H, ring methine) 1.93 and 2.13 (2H, ring methylene).

100 MHz N.M.R. spectrum of 1-acetyl-2-vinylcyclopropane (44)

The spectrum (δ scale) showed multiplets centered at .95 and 1.35 (2H, ring methine), and a multiplet centered at 2.0 (2H, ring methylene).

3,4-Diisopropylidenecyclobutene[18]

The n.m.r. spectrum (δ scale) showed a singlet at 6.69 (2H, ring olefinic), a singlet at 1.87 (6H, methyl) and a singlet at 1.73 (6H, methyl).

4-Isopropylidene-Δ^2-cyclobutenecarboxaldehyde (85)

The spectrum (δscale) showed a singlet at 1.60 (3H, methyl), a singlet at 1.80 (3H, methyl), and doublets at 6.40 and 6.83 (2H, ring olefinics).

1,2,3-Trimethyl-3-acetyl-4-methylenecyclobutene[69]

The spectrum (δscale) showed a singlet at 2.0 (3H,acetyl methyl) and doublets at 3.53 and 3.85 (2H, terminal methylene).[b]

3-Acetyl-4-methylenecyclobutene (83)

The spectrum (δscale) showed a singlet at 2.15 (3H,methyl) and multiplets at 4.65 and 4.85 (2H, terminal methylene).

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a) We wish to thank Prof. S. J. Rhoads, U. of Wyoming, for furnishing us with n.m.r. spectra of cis and trans-2-vinylcyclopropanecarboxaldehydes.
b) Prof. Story has privately informed us that the literature values for the terminal methylene protons should read 4.53 and 4.85δ.

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