AN ABSTRACT OF THE THESIS OF

ALICE-WAI LEE CHIN for the M.S.
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Title: Oxy-Cope, and Siloxy-Cope Rearrangement of cis-1-vinyl-
cyclooct-3-en-1-ol.

Abstract approved: Redacted for Privacy

Dr. Richard W. Thies

Both oxy-Cope and siloxy-Cope rearrangements involve
(1, 3) and (3, 3) sigmatropic shifts. Both the concerted mechanism,
and the stepwise mechanism via a diradical intermediate are possible.
In a cyclic system such as cis-1-vinylcyclooct-3-en-1-ol, the thermal
rearrangement takes place preferably through a diradical intermediate.
At high temperature, the reaction also prefers the diradical mechan-
ism.

There are two pathways for the formation of the compounds,
cis- and trans-bicyclo(5, 3, 0)decan-2-one in the oxy-Cope thermal
rearrangement. One is directly from the starting compound, cis-
1-vinylcyclooct-3-en-1-ol, and the other is the result of the inter-
conversion from cis- and trans-5-cyclodecenone. This bicyclic com-
pound is not observed in the siloxy-Cope thermal rearrangement.
The siloxy-Cope thermal rearrangement gives a sizable amount of cis- and trans-1-siloxy-1,2-divinylcyclohexane by (1, 3) shift, and then they rearrange to form the ring expanded products. This trend is not observed in the oxy-Cope rearrangement of cis-1-vinylcyclooct-3-en-1-ol.

The oxy-Cope, and siloxy-Cope rearrangement can be used for synthesis of cyclic, unsaturated ketones, and carbonyl compounds.
Oxy-Cope, and Siloxy-Cope Rearrangement of
 cis-1-Vinylcyclooct-3-en-1-ol

by

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Professor of Chemistry Department in charge of major

Redacted for Privacy

Head of Chemistry Department

Redacted for Privacy

Dean of Graduate School

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OXY-COPE, AND SILOXY-COPE REARRANGEMENT
OF cis-1-VINYL-CYCLOOCT-3-EN-1-OL

INTRODUCTION

When 1, 5-hexadiene systems are heated, they undergo an intramolecular thermal rearrangement. This is called the Cope rearrangement. The following is an example:

\[ \text{X = H, OH, OSi(CH}_3\text{)}_3, \text{C}_6\text{H}_5, \text{CN, or COOC}_2\text{H}_5 \]

In the above generalized reaction, the rearrangement takes place faster if the group \( X \) is more electronegative. The electron attracting group at \( X \) increases the rate by attraction for the electron pair between carbon atom 1 and 6, then it lowers the dissociation energy at this bond (1). The rate of rearrangement increases as the \( \text{COOC}_2\text{H}_5 \) group is replaced by a CN group (2).

The Cope rearrangement is similar to the Claisen rearrangement. Both are cyclic, and intramolecular reactions of purely thermally induced type. The Claisen reaction involves the allyl ethers of an enol, or phenol (see Eq. 2, and Eq. 3).
Both the Claisen reaction and Cope rearrangement are well known examples of sigmatropic change of order (3,3), in a symmetry allowed process of \( (\pi^2 s + \sigma^2 s + \pi^2 s) \). The sigmatropic change of order \((i, j)\) is defined as the migration of a \( \sigma \) bond in a system like 1,5-hexadiene, "to a new position whose termini are \( i - 1 \), and \( j - 1 \) atoms removed from original bonded loci." The sigmatropic change \((i, j)\) can be a concerted intramolecular process (3). The selection rule is the following: "A ground state pericyclic change is symmetry allowed when the total number of \((4q+2)s\) and \((4r)a\) components is odd. If the designated total is even, the reaction is symmetry forbidden", (where \( q \) represents the total number of electrons in a single orbital, and this single orbital will participate in a suprafacial or antrafacial manner) (4). All concerted pericyclic changes should agree to the principle of orbital symmetry conservation.

The Cope rearrangement has two types of geometry at the transition state. One is a four centered chair-like transition state,
and the other is a six centered boat-like transition state. An example of the first type is the rearrangement of meso-3,4-dimethylhexa-1,5-diene to give cis- and trans-octa-2,6-diene. The same compound would give trans-trans and cis-cis isomer if it passed through a six centered boat-like transition state. The d,1-2,4-dimethylhexa-1,5-diene gives trans-trans and /or cis-cis isomer by a four centered chair-like transition state. It would give only cis-trans product if it went by a six centered transition state (5).

A. Four center chair-like transition state for the meso isomer

![Diagram of a four center chair-like transition state]

B. Six center boat-like transition state for the meso isomer

![Diagram of a six center boat-like transition state]

Non-bonded interactions, steric hinderance, and electronic factors affect the stability of transition state. Usually the four centered equitorial-equitorial chair-like transition state of two parallel allyl groups is kinetically favored over the six centered boat-like forms by a difference in free energy of activation at least 5.7 Kcal/mole (6,7). If the transition state or the product is sterically
strained, rearrangement will take place by six centered transition state. The cis-1,2-divinylcyclobutane gives cis, cis-cycloocta-1,5-diene. The dl-3,4-diphenylhexa-1,5-diene gives 90 percent of trans, trans-octa-2,6-diene, because the phenyl group is coplanar with the allylic unit at four centered transition state. The meso-3,4-diphenylhexa-1,5-diene gives 63 percent cis, trans-1,6-diphenyl-1,5-diene by same route. In the four centered transition state, the phenyl group is not coplanar with the allylic group, so that it is less energetically favored than unsubstituted compound. Therefore, 37 percent of trans, trans-1,6-diphenylhexa-1,5-diene is produced by a six centered boat-like transition state (8).

The Diels-Alder reaction has similar mechanisms to the Cope rearrangement. Here the bonds between the diene and the dienophile are formed more or less simultaneously by a concerted pathway. This reaction is a \( \text{(} \Pi^4 s + \Pi^2 s \text{)} \), or \( \text{(} \Pi^2 s + \Pi^2 s + \Pi^2 s \text{)} \) symmetry allowed cycloaddition process (4).

\[
\text{\includegraphics[width=0.5\textwidth]{diagram.png}}
\]

In this concerted mechanism, three bonds are being formed at the transition state, while three other bonds are suffering cleavage simultaneously (9).

In the Cope rearrangement, the 1,5-diene can be part of a
ring, or it can be part of an allenic system. The reaction does not take place when the diene bond is a part of the aromatic system such as 4-phenyl-1-buten.

If the substituent in equation (1) is hydroxyl, the thermal rearrangement is called the oxy-Cope rearrangement. It forms an enolic intermediate (see Eq. 1), and then converts to keto form by tautomerization (10).

By a concerted pathway, it could thermally rearrange to an enol form by a (1, 3) and (3,3) shift and to a non-enol form by a (1, 3) sigmatropic shift (see Eq. 6, 7, and 8). The superafacial (1, 3) shift is a symmetry allowed process with inversion at the substituted migrating center, and it is a $\left( \Pi^2_s + \sigma^2_a \right)$ process.
Experimentally during the pyrolysis, there always appears a minor product with lower boiling point, such as the formation of acrolein, \( \text{CH}_2 = \text{CHCHO} \), which is \( \beta \)-hydroxyolefin cleavage product \(^{11}\). This is another alternative of oxy-Cope rearrangement. When the temperature increases, this fraction increases.

The formation of a radical pair is an alternative mechanism for oxy-Cope thermal rearrangement. The same products are formed by double inversion (C-1-C-6 bond formation), and single inversion (C-1-C-4 bond formation). Single inversion (C-3-C-6 bond formation) gives back the starting material again \( ^{12, 13} \). Hydrogen abstraction can also take place through this intermediate (see example in Scheme I, and Scheme III for cyclic system), which leads to the \( \beta \)-hydroxyolefin cleavage product.
This process is favored by the formation of allyl radical by cleavage of the bond between C-3 and C-4, because the energy barrier is lowered by resonance energy of 14 Kcal/allyl group (10). One major effect of the hydroxyl group in the oxy-Cope rearrangement is to weaken the central bond of the biallyl system, and to lower the energy of activation for both the concerted, and diradical mechanism (14). The substitution of an α-hydroxy group lowers the bond dissociation energy by 2.4 Kcal/mole.

Another alternative of the Diels-Alder reaction is also to form a diradical intermediate by a stepwise mechanism. The ring reclosure by formation of the second bond must be faster than the rotation about the C-C bond to the radical center.

\[
\begin{align*}
\text{In the case of the thermal rearrangement of endo or exo-2-vinylbicyclo(2.2.2)oct-5-en-2-ol, the concerted Cope process must be sterically impossible, because the rate of rearrangement of A, and B are the same. The alternative is a stepwise rearrangement passing through a common diradical intermediate (15). The slow equilibration of two diradical intermediate accounts for its high product specificity.}
\end{align*}
\]
The compound octalone is formed by double inversion, (3, 3) sigma-tropic shift Cope rearrangement. The monocyclic ketone is formed by \( \alpha \)-hydrogen shift (16). This stepwise mechanism is due to the perturbation of the hydroxyl group, which weakens the central bond of the hexadiene system.

When the trimethylsiloxy group is the substituent in Eq. 1, the reaction has been called the siloxy-Cope rearrangement. The purpose of the siloxy group is to block the \( \beta \)-hydroxyolefin cleavage, and to improve the yield of \( \delta,\epsilon \)-unsaturated ketones by two carbon ring expansion. Its mechanism is similar to the oxy-Cope rearrangement.
In the nine membered cyclic compound, \textit{cis}-1-siloxy-1-vinylcyclonan-3-ene, part of the products formed involved a diradical intermediate. The diradical intermediate has short half life time, so that the stereochemistry is not completely lost (17).
EXPERIMENTAL

Method of Synthesis

The starting compound, cis-1-vinylcycloct-3-en-1-ol is prepared by the following Scheme (18, 19):

The ketone is produced by oxidation of this alcohol, then the cis-cyclooct-3-en-1-one is reacted with Grignard reagent CH$_2$=CHMgBr to obtain the tertiary alcohol, cis-1-vinylcycloct-3-en-1-ol (20).

The cis-1-siloxy-1-vinylcycloct-3-en-1-ol is prepared from its corresponding alcohol by reacting one part of alcohol, two parts of Tri-Sil (Pierce Chemical Co.) and four parts of dimethylsulfoxide (17, 21). The crude mixture is analyzed by Carbowax capillary column.

Pyrolysis Procedure

Each ampoule was made of pyrex glass tubing, and washed with acid, base (dil. NH$_4$OH), water, and acetone. Then it was dried
in the oven overnight. A 10 μl sample was put in the ampoule, which was evacuated for an half hour, and then sealed under vacuum. The sealed ampoule was then heated in an aluminum block oven with thermoregulator at various lengths of time at 340° C (the thermometer was calibrated by National Bureau of Standards thermometer). At the end of each pyrolysis, the mixture of products was analyzed by gas-liquid chromatography.

**Hydrolysis Procedure**

The pyrolysis mixture of trimethylsilyl ethers was hydrolyzed in one ml of pyridene-HCl-H₂O (the stock solution was made of ten ml of pyridine in one ml of H₂O plus two drops of concentrated HCl) by refluxing for two hours in an oil bath at 120° C. The reaction mixture was extracted with the absolute ether, and washed with dilute H₂SO₄, and H₂O. Then they were dried over anhydrous MgSO₄, and analyzed by gas-liquid chromatography on Carbowax 1000 capillary column (22).

The reaction mixture of trimethylsilyl ethers were identified by hydrolyzing to their corresponding ketones, or alcohols. Their retention times were compared with those from oxy-Cope rearrangement products on the same capillary column.
Gas-liquid Chromatographic Procedure

Several runs were conducted in an effort to establish the optimum operating parameters. The isothermal conditions were used during the analysis.

(a) Analysis of pyrolysis products at 310°C for two hours, and at 340°C for three hours on a 0.1 percent Carbowax 1000 on GLC 110 column (1/8" x 7') was conducted to establish the temperature and length of time required for 90 percent conversion by pyrolysis.

(b) A 75' x 0.01" UCON capillary column was tried to improve the separation of each component in the pyrolysis mixture.

(c) A 100' x 0.01" of 0.1% Carbowax 1000 capillary column gave best resolution and separation of all components, and it did not bleed much. Thus it was the column of choice.

(d) A 7' x 1/8" KOH-2.5 percent Carbowax 4000 on CH W was tried to establish the optimum condition for analysis of siloxy-Cope rearrangement products.

(e) A 7' x 1/8", 10 percent DEGS on 60/80 CH W column was also tried for better resolution of siloxy-Cope rearrangement products and to identify the peaks from the Carbowax capillary column.
**Gas-liquid Chromatographic Analysis**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Varian Aerograph HY-FI III Model 1200 with linear program module and hydrogen flame ionization detector, and with all solid state electrometer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column</td>
<td>Stainless steel 100' Carbowax 1000 capillary column (one g of C. W. in eight g of CHCl₂ pushed through the column at five pounds pressure. Then it was baked about 22 hours at 110°C overnight).</td>
</tr>
<tr>
<td>Injection method</td>
<td>Flash vaporization.</td>
</tr>
<tr>
<td>Injector temperature</td>
<td>130°C</td>
</tr>
<tr>
<td>Detector temperature</td>
<td>195°C</td>
</tr>
<tr>
<td>Oven temperature</td>
<td>Isothermal at 105°C for oxy-Cope rearrangement; isothermal at 100°C for siloxy-Cope rearrangement (stability is ± 0.5).</td>
</tr>
<tr>
<td>Carrier gas</td>
<td>He</td>
</tr>
<tr>
<td>Flow rate</td>
<td>1-2 ml/min</td>
</tr>
<tr>
<td>Effluent spilliter</td>
<td>3.0 to 1.0 atmosphere per detector</td>
</tr>
</tbody>
</table>
| Recorder                    | Honeywell single pen six inch chart electronic 193}
Range $10^{-11}$ amp/mv

Sample Usually three $\mu l$ for each injection by using Hamiltonian syringe (the pyrolysis product is dissolved in 0.5 ml of absolute ether).

For each sample, at least two runs were carried out.
DATA AND RESULTS

For Table I and Table III see pages 25 and 35 in Discussion Section.
**TABLE II.** Oxy-Cope thermal rearrangement products of cis-1-vinylcyclooct-3-en-1-ol\(^{(a, b)}\)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Name</th>
<th>% yield, heating time (hour)(^{(c, d)})</th>
<th>(t_r) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>trans-5-cyclodenone</td>
<td>11.8</td>
<td>17.0</td>
</tr>
<tr>
<td>2</td>
<td>cis-5-cyclodecenone</td>
<td>16.8</td>
<td>34.0</td>
</tr>
<tr>
<td>3</td>
<td>cis-bicyclo(5.3.0)-decan-2-one</td>
<td>7.0</td>
<td>26.7</td>
</tr>
<tr>
<td>4</td>
<td>4-vinylcyclooctanone</td>
<td>1.6</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>trans-bicyclo(5.3.0)-decan-2-one</td>
<td>1.1</td>
<td>8.05</td>
</tr>
<tr>
<td>6</td>
<td>cis-1-vinylcyclooct-3-en-1-ol</td>
<td>66.3</td>
<td>11.2</td>
</tr>
</tbody>
</table>

\(^{a}\) The pyrolysis and the chromatographic analysis procedure are described in Experimental section.

\(^{b}\) The oven temperature is corrected to N. B. S. at the end of the oven \(t=339^\circ C\), at the middle \(t=340^\circ C\), and at the front \(t=337.5^\circ C\).

\(^{c}\) The yield of \(\beta\)-hydroxyolefin cleavage products, and the other olefins are not listed here, and will be discussed later.

\(^{d}\) The data here are the average values of two to four determinations.

\(^{e}\) The third peak contains another compound which is probably cis-bicyclo(4.4.0)decan-2-one, and it has similar retention time as cis-5-cyclodecenone.
TABLE IV. Siloxy-Cope thermal rearrangement products of cis-1-vinylcyclooct-3-en-1-ol. (a, b, c)

<table>
<thead>
<tr>
<th>Compound (c)</th>
<th>% yield at each time (d)</th>
<th>t_r (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 min</td>
<td>20 min</td>
</tr>
<tr>
<td>8a</td>
<td>4.46</td>
<td>13.5</td>
</tr>
<tr>
<td>8b</td>
<td>4.07</td>
<td>5.94</td>
</tr>
<tr>
<td>6</td>
<td>88.6</td>
<td>78.0</td>
</tr>
<tr>
<td>4</td>
<td>1.43</td>
<td>6.85</td>
</tr>
<tr>
<td>1</td>
<td>1.78</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>1.05</td>
<td>2.16</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) The pyrolysis and chromatographic analysis procedures are described in Experimental section. Experimental conditions are the same as Oxy-Cope rearrangement (see Table I).
(b) During chromatographic analysis, only slight hydropysis of the trimethylsilyl ethers took place.
(c) The data here are the average values of 2-4 determinations.
## TABLE V. Hydrolysis of siloxy-Cope rearrangement products. (a, b)

<table>
<thead>
<tr>
<th>Compound</th>
<th>% yield, heating time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>8a trans-1,2-divinylcyclohexane</td>
<td>2.25</td>
</tr>
<tr>
<td>8b cis-1,2-divinylcyclohexane</td>
<td>2.25</td>
</tr>
<tr>
<td>1 trans-5-cyclodecenone</td>
<td>1.20</td>
</tr>
<tr>
<td>2 cis-5-cyclodecenone (c)</td>
<td>3.75</td>
</tr>
<tr>
<td>3 cis-bicyclo-(5.3.0)-decan-2-one</td>
<td>0.75</td>
</tr>
<tr>
<td>4 4-vinyl-cyclooctanone</td>
<td>1.35</td>
</tr>
<tr>
<td>5 trans-bicyclo(5.3.0)-decan-2-one</td>
<td>--</td>
</tr>
<tr>
<td>6 cis-1-vinylicyclooct-3-en-1-ol</td>
<td>89.0</td>
</tr>
</tbody>
</table>

\(a\) The hydrolysis procedure is described in Experimental section. The chromatographic analysis is carried out on Carbowax Capillary Column at the conditions as that of oxy-Cope rearrangement. (see Table II).

\(b\) The data here is the average values of two to four runs.

\(c\) A small amount of a ketone, is present at the tail of this peak. It has a similar retention time and mass spectra to cis-bicyclo(4.4.0)decan-2-one.
Figure 1a. Oxy-Cope rearrangement of products of cis-1-vinylcyclooct-3-en-1-ol.
Figure 1b. Oxy-Cope rearrangement of products of cis-1-vinylcyclooct-3-en-1-ol.
Figure 2a. Siloxy-Cope rearrangement products of \textit{cis}-1-vinylcyclooct-3-\textit{eh}-1-\textit{ol}. 
Figure 2b. Siloxy-Cope rearrangement products of cis-1-vinylcyclooct-3-en-1-ol.
Figure 3.
DISCUSSION

Oxy-Cope Rearrangement of cis-1-Vinylcyclooct-3-en-1-ol

The oxy-Cope thermal rearrangement produces four isomeric products when the starting compound, cis-1-vinylcyclooct-3-en-1-ol, is heated at 310°C for two hours. Under these conditions there was only 10 percent conversion, and the peaks were partially resolved on a 0.1 percent Carbowax Column.

\[
\begin{align*}
\text{cis-1-vinylcyclooct-3-en-1-ol} & \rightarrow \quad \text{trans-5-cyclodecenone} & + \quad \text{cis-5-cyclodecenone} \\
6 & & 1 & & 2 \\
\text{4-vinylcyclooctanone} & + \quad \text{1,9-decadien-3-one} \\
4 & & 7
\end{align*}
\]

Theoretically there should be more products obtained from the reaction mixture. In order to increase the conversion rate, a pyrolysis temperature of 340°C was used for the study. The conversions of cis-1-vinylcyclooct-3-en-1-ol, measured with the same column, are listed in Table I.
TABLE I. Conversion rate of oxy-Cope thermal rearrangement of cis-1-vinylcyclooct-3-en-1-ol at 340° C. a

<table>
<thead>
<tr>
<th>Time</th>
<th>%Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 Hr</td>
<td>25.0</td>
</tr>
<tr>
<td>1 Hr</td>
<td>55.0</td>
</tr>
<tr>
<td>2 Hr</td>
<td>94.0</td>
</tr>
<tr>
<td>3 Hr</td>
<td>97.0</td>
</tr>
</tbody>
</table>

aHere 0.1% Carbowax Column was used in this Chromatographic analysis.

In addition to the above four isomers (1, 2, 4, and 7), another compound was observed, which was identified as bicyclo(5.3.0)-decan-2-one. On the 0.1 percent Carbowax column, the peaks were not well resolved, because the retention time of various ketones such as the bicyclo(5.3.0)-decan-2-one, and cis-5-cyclodecenone are very similar.

In order to improve the separation, and identification of each isomer, a 75' UCON capillary column was tried. Six peaks corresponding to six isomers appeared at retention times of about ten minutes, but the resolution still needed to be improved. The gas chromatographic analysis of the pyrolysis derivatives on 100' Carbowax 1000 capillary column gave excellent resolution of seven major peaks which allowed us to calculate the relative amounts of each isomer in the pyrolysis mixture (see Fig. 4 and 5).

Various methods were used to assign the structure of the
pyrolysis products. The simplest method was to utilize a g.l.c.-mass spectrometer instrument and to compare the fragmentation pattern of the mass spectra of different peaks corresponding to the different isomeric components with those of authentic samples. A better alternative was to compare the spectral, and physical properties with those of authentic samples. The cis-5-cyclodecenone gave a derivative of 2,4-dinitrophenylhydrazone, whose m.p. is 175°-177° C (23). Its spectra agreed with those for an authentic sample of cis-5-cyclodecenone. The structure of trans-5-cyclodecenone was assigned by mass spectra and also by analogy with the nine membered ring.

The structures of cis- and trans-divinylcyclohexanol, and the structure of the two isomers of bicyclo (5.3.0) decan-2-one were assigned by comparison to nmr, infrared, and mass spectra with authentic samples. The isomer 1,9-decadien-3-one, and cis-4-vinylcyclooctanone were also assigned from the characteristic infrared and nmr spectra for the terminal groups (28).

The oxy-Cope thermal rearrangement of cis-1-vinylcyclooct-3-en-1-ol by pyrolysis at 340°C produced seven major isomeric compounds: cis- and trans-5-cyclodecenone, cis- and trans-bicyclo (5.3.0)decan-2-one, cis-4-vinylcyclooctanone, 1,9-decadien-3-one, and unreacted starting material. The relative amounts are listed in Table II.
The plot of relative percentage versus time (Fig. 1a, and Fig. 1b) indicates an approximate first order conversion rate from the starting compound to products (24). At early reaction time, the rate of formation of trans- and cis-5-cyclodecenone (compounds 1 and 2) is much faster than the formation of cis- and trans-bicyclo (5.3.0) decan-2-one which shows an induction period. At the end of one hour pyrolysis, the amount of trans- and cis-5-cyclodecenone reaches a maximum. Then the trans isomer decreases much faster, while cis isomer remains essentially constant with pyrolysis time. After two hours the relative amount of cis- and trans-bicyclo(5.3.0) decan-2-one is greater than that of trans- and cis-5-cyclodecenone. This indicates that trans- and cis-5-cyclodecenone convert to cis- and trans-bicyclo(5.3.0)-decan-2-one. The product distribution at 20 hours of pyrolysis also confirms this interconversion step. Both isomers of 5-cyclodecenone are formed by a (1, 3) shift, and the isomers of bicyclo(5.3.0)-decan-2-one are formed by a (3, 3) shift.

The cis-4-vinylcyclooctanone remains essentially constant after two hours and the yield is about six percent. A minor product bicyclo-(4,4.0)-decan-2-one is also formed during interconversion. It has a similar retention time to cis-5-cyclodecenone (see Scheme II and Fig. 4). Its structure was confirmed by fragmentation pattern
Both a concerted and a stepwise mechanism passing through a diradical intermediate are possible for this oxy-Cope rearrangement. For the subsequent formation of trans-bicyclo(5.3.0)-decan-2-one both concerted and diradical mechanism are equally possible (13, 15). From the nine membered analog, it is indicated that at least part of the products are formed by a diradical intermediate. In these systems the geometry of the transition state for a concerted (3, 3) sigmatropic shift must be a six centered boat form. This arrangement avoids the steric hinderance with the cyclic ring system (25), but the model suggests that it is still unfavorable. The double inversion (C-1-C-6 bond formation) gives cis-4-vinylcyclooctanone (26). The single inversion (C-3-C-6 bond formation) would give trans- and cis-1,2-divinylcyclohexan-1-ol, which were not detected (15, 26). Another single inversion (C-1-C-4 bond formation) gives cis- and trans-5-cyclodecenone by a (1, 3) shift pathway (14, 10). The cleavage product, 1,9-decadien-3-one is formed from scission of C-3-C-4 bond followed by a hydrogen shift through a diradical intermediate, or it is formed by a concerted \( \beta \)-hydroxyolefin cleavage if the diradical mechanism is not operative (see Scheme I)(13).

It has been shown that the oxy-Cope rearrangement gives unsaturated ketones as final products by passing through enolic
Scheme I

10 + other Olefin

dehydration

β-hydroxyolefin cleavage

polymer
SCHEME II

(a)

1 + 2

OTMS

3 or 5

1

2

3

4

8a

8b
Scheme IIb.

(b) In this Scheme, the H on OH group can be substituted by

\[
\begin{align*}
\text{Scheme IIb.} & \\
\text{(b) In this Scheme, the H on OH group can be substituted by} & \\
\end{align*}
\]
intermediate (17). The tautomerization between enol and keto forms of the oxy-Cope rearrangement products can take place, and it is overwhelmingly favors the more stable keto forms. After the formation of either \textit{trans} or \textit{cis} isomer of 1,5-cyclodecadien-1-ol, it transforms to \textit{trans} or \textit{cis}-5-cyclodecenone, which is of lower energy. This prevents part of the conversion of 1,5-cyclodecadien-1-ol to bicyclo(5.3.0)-decan-2-one, because the equalibration occurs at the same time as its conversion to bicyclic products. Some enols form compound 1 and 2 while others form compounds 3 and 5 simultaneously even at a very short reaction period although the rate of their formation is different (10). After the formation of \textit{trans}- and \textit{cis}-5-cyclodecenone they will convert to \textit{cis}- and \textit{trans}-bicyclo(5.3.0)-decan-2-one through the enol form (see Scheme II). At 20 hours of pyrolysis, there is 78 percent of \textit{cis}- and \textit{trans}-bicyclo(5.3.0)-decan-2-one (see Table II, or Fig. 5).

At longer reaction time, the thermodynamic factor is much more important to the equilibration of the products. The two isomers of bicyclo(5.3.0)-decan-2-one are more stable than the \textit{cis}- and \textit{trans}-5-cyclodecenone, because the ring strain effects favor the formation of the smaller ring (3, 27). Besides these two factors, the rate of rearrangement increases as the anti-bonding interaction decreases (7).

Theoretically the pyrolysis of \textit{cis}-1-vinylcyclooct-3-en-1-ol
will produce cis- and trans-1,2-divinylcyclohexane. In the reaction mixture, neither was detected, most likely because they interconvert to cis- and trans-5-cyclodecenone rapidly by (3,3) sigmatropic shift, which involves a chair like transition state followed by rapid ketonization (see Scheme IIb) (26).

The slow formation of (3,3) shift product, cis-4-vinylcyclooctanone is probably due to the steric interactions at the transition state. The geometry for a concerted process requires the vinyl group to lie over the crowded ring at the transition state, and this is sterically unfavorable.

The alkene products such as 1-vinyl-1,3-cyclooctadiene, and other short chain olefins are also produced in the reaction mixture even at shorter pyrolysis periods (29). The amount increased as time or temperature were increased. Those olefins appeared at early retention times on Carbowax capillary column. Their exact yield was difficult to determine, because the non-reproducible surface catalyzed reaction depended on the experimental conditions. If the ampoules washed by acid, based (dil. \( \text{NH}_4 \text{OH} \)), were not thoroughly dried or sealed without vacuum, the pyrolysis would give a yellowish brown coating inside the wall of the ampoule. This indicates that more products from surface catalyzed reactions were formed, and then polymerization took place. According to this study, ten \( \mu l \) sample per ten ml ampoule will give enough pyrolysis derivative for gas
chromatographic analysis, and it is the best size. Either the larger sample size, or the larger ampoule (which increases the surface area) will give more polymer during pyrolysis. The chromatographic analysis of the pyrolysis of cis-1-vinyl-cyclooct-3-en-1-ol shows some \( \beta \)-hydroxyolefin cleavage product, 1,9-decadien-3-one, and this product increases as temperature increases, and then more polymer is formed (28).

**Siloxy-Cope Rearrangement of cis-1-vinylcyclooct-3-en-1-ol**

In general trimethylsilyl ethers have higher boiling points than their corresponding alcohols (about \( 10^\circ -15^\circ \) C higher), and they have high density, low viscosity, good heat stability, and high resistance to oxidation (30). It is easy to recover the parent compound by hydrolysis (see experimental section), and the retention time of the hydrolysis product is compared with that from oxy-Cope rearrangement. The retention time of the alcohol, cis-1-vinylcyclooct-3-en-1-ol is 24.8 minutes on the Carbowax capillary column at a temperature of \( 105^\circ \) C. The retention time of compound cis-1-vinyl-1-siloxy-3-cyclooctene is 5.8 minutes on the same column at temperature equals to \( 100^\circ \) C. In the crude trimethylsilyl ethers prepared by the method described in the experimental section, some olefins were present as secondary substances, which also appeared as impurities on the

\[ \text{The abbreviation 'siloxy' stands for a hydroxyl group, in which the hydrogen has been substituted by trimethylsilyl group.} \]
chromatogram (see Fig. 6).

The pyrolysis of trimethylsilyl ether was carried out in the same method as that of cis-1-vinylcyclooct-3-en-1-ol at 340°C (see Experimental section). Theoretically there are eight possible isomers from this siloxy-Cope thermal rearrangement (four isomers of 1-siloxyl-1,5-cyclocadadiene, two isomers of 1-siloxyl-1,2-divinyl-cyclohexane, and another two isomers of 1-siloxyl-4-vinylcyclooct-1-ene. On the C. W. capillary column there were usually six peaks for the corresponding isomers at low temperature, or at shorter pyrolysis periods. Either increasing the temperature, or the time of pyrolysis would increase the conversion, and also two more peaks appeared on the chromatogram for two additional isomers. They are cis-1-siloxyl-4-vinylcyclooct-1-ene, and one isomer of 1-siloxyl-1,5-cyclocadadiene (see Table III). They were identified

TABLE III. Products ratio from pyrolysis of cis-1-siloxyl-1-vinylcyclooct-3-ene for three and one-half hours.

<table>
<thead>
<tr>
<th>Compound ratio</th>
<th>KOH-C.W. after hydrolysis</th>
<th>C.W. Capillary after hydrolysis</th>
<th>C.W. Capillary before hydrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>(8a)+(8b)</td>
<td>1/4</td>
<td>1/4</td>
<td>1/3</td>
</tr>
<tr>
<td>(1)+(2)+(4)+(6)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a The pyrolysis and chromatographic analysis procedures are described in Experimental section. The temperature of pyrolysis was at 345°C which was corrected to N.B.S.

b Both products ratio before hydrolysis, and after hydrolysis were measured.

c Both 2.5 percent KOH - 2.5 percent Carbowax 4000 on Ch W column and Carbowax 1000 capillary column were used.
by comparing the retention times of their corresponding ketones from hydrolysis with that from oxy-Cope rearrangement products.

The starting compound was pyrolyzed at 345°C for three and a half hours, and analyzed on a 2.5 percent KOH-2.5 percent C. W. 4000 on CH W. Column, and also on Carbowax capillary column. Then the pyrolysis products were hydrolyzed to the corresponding ketones, and analyzed in the same manner on both columns. From the peak area, the ratio of the isomers is shown in Table III. The same ratio was obtained from both columns which indicates that there is no loss of compound due to acid dehydration during operation of gas chromatographic analysis on C. W. capillary column. The latter column gives better resolution (see Fig. 6, and Fig. 7). The product ratio is slightly different before hydrolysis, and after hydrolysis. This is due to incomplete hydrolysis of the trimethylsilyl ether, and the presence of the dehydration products in the reaction mixture.

At the end of one hour, the hydrolysis products of siloxy-Cope rearrangement products were analyzed on a 10 percent DEGS on CHW 60-80 capillary column. The chromatogram showed two peaks for isomer, 1-siloxy-1,2-divinylcyclohexane, and one peak for the unreacted starting material. Besides these there were two symmetrical peaks corresponding to four isomers of 1-siloxy-1,5-cyclodecadiene, but the resolution needed to be improved.
The siloxy-Cope thermal rearrangement occurred at 340°C. For each determination, the products were chromatographed on Carbowax capillary column, and the percent yield was calculated from the areas under the peaks (see Table IV). The product distribution indicates that seven major isomers were separated on this column. They are trans- and cis-1-siloxy-1,2-divinylcyclohexane, unreacted cis-4-siloxy-4-vinylcyclooctene, cis-1-siloxy-4-vinylcyclooctene, and three isomers of 1-siloxy-1,5-cyclooctadiene (the double bonds can be trans-trans, trans-cis, cis-cis, and cis-trans). From a plot of log of concentration of starting compound 6 versus time, a linear plot was obtained, and the rate is \( k = -2.303 \times 3.24 \times 10^{-4} \text{ sec}^{-1} \) in this siloxy-Cope rearrangement. This indicates that the reaction obeys first order kinetics up to two hours of pyrolysis (see Fig. 3) (2). This rate suggests a high energy of activation (for \( k = s e^{-E/RT} \), and s is the frequency factor), and the diradical mechanism which is the main pathway for the siloxy-Cope rearrangement (see Scheme III). At early reaction time, four isomers are formed by single inversion (C-1-C-4 bond formation, and C-3-C-6 bond formation) through a common diradical intermediate. They are cis- and trans-1-siloxy-1,2-divinylcyclohexane, and cis- and trans-1-siloxy-1,5-cyclooctadiene. The compound cis-1-siloxy-4-vinylcyclooctene is formed by double inversion (C-1-C-6 bond formation).

Up to one hour of pyrolysis, trans- and cis-1-siloxy-1,
Scheme III

$8a + 8b \rightarrow \text{Clip hydrolysis}$
Scheme IV

\[ \text{desiloxylation} \rightarrow \] 

\[ 10 \]

\[ + \text{Si(CH}_3\text{)}_3\text{OH} \]
2-divinylcyclohexane predominate. At 30 minutes, the relative amount of these two compounds \( 8a \) and \( 8b \) is twice that of two isomers of the 1-siloxy-1,5-cyclooctadiene. The ratio of relative amount of trans- to cis-1-siloxy-1,2-divinylcyclohexane is three to one. This is because the OTMS group at equitorial position of the chair conformation has lower energy than the OTMS at axial position (31), and the chair form has lower energy than the boat form (32). Besides these two factors, the transition states leading to the products are energetically different. At the end of two hours of pyrolysis, the cis- and trans-1-siloxy-1,2-divinylcyclohexane are at equilibrium with each other, and there are 19 percent of each in the total reaction mixture (33).

As the pyrolysis time increases, the conversion rate from starting compound to (1, 3), and (3, 3) shift products decreases. The ratio of trans- to cis-1-siloxy-1,2-divinylcyclohexane decreases gradually, while the yield of three isomers of 1-siloxy-1,5-cyclooctadiene increases very rapidly, especially for the compound (2) (see Fig. 2b, and Table IV). The rate of formation of 1-siloxy-1,2-divinylcyclohexane is faster than the rate of its conversion to 1-siloxy-1,5-cyclooctadiene before two hours, and after two hours the order is reversed. This interconversion could also involve a diradical intermediate, although the concerted (3, 3) shift could be operative (see Scheme IIb, and IV).
Analysis of the rate of formation of 1-siloxy-1,5-cyclodecadiene at various times indicates that there are two different pathways for its formation (see Scheme IIb and III). One is directly from the starting compound, cis-l-siloxy-1-vinylcyclooct-3-ene, and the other is from conversion of cis-and trans-1-siloxy-1,2-divinylcyclohexane. After four hours all the products appear to be in equilibrium (see Fig. 2a and 2b). At this moment, there is 60 percent of 1-siloxy-1,5-cyclooctadiene, which reaches its maximum yield (see Table IV).

The temperature required for this reaction, and the formation of cis- and trans-isomers suggests a diradical intermediate present in the transition state. This intermediate is a resonance stabilized diallyl radical, and the closure of the ring can take place in four different ways. This results in the formation of different products of thermal rearrangement by (1, 3) and (3, 3) sigmatropic shift, and it is also true for oxy-Cope rearrangement (see Scheme I, and III).

**Hydrolysis of Siloxy-Cope Rearrangement Products**

In order to prove the various isomers obtained from siloxy-Cope rearrangement, the pyrolysis reaction mixture was hydrolyzed to its corresponding ketones in a solution of pyridine-HCl-H₂O (for procedure, see Experimental section). The yield of each ketone is listed in Table V. The various cyclic ketones obtained by hydrolysis confirm the seven major trimethylsilyl products from siloxy-Cope
rearrangement. The cis- and trans-bicyclo(5.3.0)decan-2-one are present in a small quantity, which is not observed before hydrolysis (see Table IV). This is due to the conversion of trans- and cis-5-cyclodecenol to cis- and trans-bicyclo(5.3.0)decan-2-one during hydrolysis. This interconversion involves an enolic intermediate (see Fig. 7)(17).

The amount of 1,2-divinyl-cyclohexan-1-ol increases as pyrolysis time increases, and it is at maximum at the end of two hours (about 27 percent of the hydrolysis mixture). After two hours the amount decreases because of interconversion to 5-cyclodecenone during pyrolysis. Therefore, trans- and cis-5-cyclodecenone were obtained in larger amounts at later time, and they had a maximum yield at the end of three hours (about 55 percent of the total yield). The conversion rate of the starting compound is 90 percent at that time.

Both cis- and trans-1,2-divinylcyclohexan-1-ol are in the chair conformation, which has lower energy than the boat form, and the trans isomer has lower energy than the cis isomer (33). The trans-1,2-divinylcyclohexan-1-ol converts to trans-1-hydroxy-1,5-cyclodecadiene, and the cis isomer converts to both trans- and cis-1-hydroxy-1,5-cyclodecadiene. This provides the explanation for the rapid increase of the compound 2, although the isomer 1 increases, but in a slower rate. The rearrangement involves stereospecific
chair like transition state (see Scheme IIb) (26)

The compound cis-4-vinylcyclooctanone was hydrolyzed from its corresponding trimethylsilyl ether, compound (4). Theoretically compound 4 exists in two isomers, trans and cis. But the product distribution indicates that only one isomer was present in a measurable amount during chromatographic analysis. This compound probably is the cis isomer, which is more stable, because the trans isomer is energetically unfavorable in its molecular geometry (34). The observation from the hydrolysis mixture also indicates the presence of cis isomer, which has the same retention time as cis-4-vinylcyclooctanone (see Table II, and Table V).

The total trend in the hydrolysis products distribution agrees well with the trend of the products distribution before hydrolysis. It confirms that the stepwise diradiacal mechanism is the main pathway for the siloxy-Cope rearrangement, although the concerted mechanism could still be operative (see Scheme III and IV).
CONCLUSION

For both the oxy- and siloxy-Cope thermal rearrangements, the yield of ring expanded product reaches a maximum after about three hours, and the cis isomer from the siloxy-Cope rearrangement is greater than that from oxy-Cope rearrangement, and it is observed even at very short reaction period. In the siloxy-Cope rearrangement the rate of formation of compound cis-1-siloxy-1,5-cyclodecadiene is faster than the formation of compound cis-1-hydroxy-1,5-cyclodecadiene in oxy-Cope rearrangement. No tautomerization can take place in the siloxy-Cope rearrangement. In oxy-Cope rearrangement, the trans- and cis-5-cyclodecenone undergo further transformation to form cis- and trans-bicyclo(5,3,0)decan-2-one. This is not observed in the siloxy-Cope rearrangement.

The $\beta$-hydroxyolefin cleavage product is not observed in the pyrolysis reaction mixture of 4-siloxy-4-vinylcyclooctene, because the hydrogen shift cannot take place. There is less 'desiloxylation' product formed from this starting compound, but slight elimination does occur on the Carbowax capillary column during chromatographic analysis of the crude sample. In the oxy-Cope thermal rearrangement, both the $\beta$-hydroxyolefin cleavage product, and the dehydration product of the starting compound are present in the reaction mixture. Both oxy-Cope, and siloxy-Cope thermal rearrangement,
give small amounts of (3,3) shift product 4, and 4. This compound is probably in the cis configuration, which has lower energy than the trans isomer (21).

From the products distribution, more of the trans isomer of the (1,3) shift products is formed from oxy-Cope rearrangement than from siloxy-Cope rearrangement, so that the reaction is stereochemically less selective. This trend is also observed in siloxy-Cope rearrangement of 1-vinyl-cyclonon-3-en-1-ol (17).

Both oxy-Cope, and siloxy-Cope rearrangement probably involves the common diallyl radical intermediate. The energy barrier between the starting compound and the transition state is lowered by the resonance energy of 14 Kcal/allyl group (10). Substitution of an \(\alpha\)-hydroxy group lowers the bond dissociation energy by 2.4 Kcal/mole, and the substitution of trimethylsiloxy group even lowers the bond dissociation energy more.

The inductive, and resonance stabilizing effect at the transition state, the enolization which is the driving force of the rearrangement, and the change of strain energy resulting from angle strain, and non-bonded interaction are the three main factors for the (1,3), and (3,3) sigmatropic shift both in oxy-Cope, and siloxy-Cope
rearrangement. Either the concerted mechanism, or the diradical mechanism is operative, but the high temperature required for reaction suggests the diradical mechanism.

The (1, 3) and (3, 3) sigmatropic shift of oxy-Cope, and siloxy-Cope rearrangement represents a new method of synthesizing the unsaturated cyclic ketones, and for synthesis of unsaturated carbonyl compounds on a preparative scale. The substitution of trimethylsilyl group at hydrogen on hydroxyl group of the cyclic alcohol can improve the yield.
BIBLIOGRAPHY


20. This compound was furnished by Larry Schick.


Figure 4.
Figure 5.
(before hydrolysis)
Figure 7.

OTMS

340°C

2 Hr. (after hydrolysis)