SOME ASPECTS OF THE CHEMISTRY OF CHLOROSULPHONYL ISOCYANATE

A thesis presented for the degree of Doctor of Philosophy in the Faculty of Science of the University of Leicester

by

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STATEMENT

The experimental work in this thesis has been carried out by the author in the Department of Chemistry of the University of Leicester, between October 1971 and August 1974. This work has not been presented, and is not currently being presented, for any other degree.

N. Weddle

University of Leicester
February 1975
TO HEATHER
I would like to thank my Supervisor, Dr. J.R. Malpass, for his continual aid and encouragement throughout this work. My thanks also go to Mrs. Barbara Hamner who typed this thesis, and to my fellow research students, the staff and the technicians in the Organic Chemistry Department for all their assistance. Finally, I would like to thank the Science Research Council for a maintenance grant.
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Chlorosulphonyl isocyanate (CSI) (1) was first prepared by R. Graf\textsuperscript{1,2} by the reaction of equimolar proportions of cyanogen chloride and sulphur trioxide.

CSI acts as a very powerful uniparticulate electrophile and in this respect is the most reactive isocyanate known. This may be attributed to the high electronegativity of the chlorosulphonyl group which, by a combination of inductive and resonance effects, increases the electron deficiency and thus the electrophilicity of the carbon atom of the isocyanate group and stabilizes the ambident anion produced by nucleophilic attack at this centre.

\[
\begin{align*}
\text{O=CSO}_2\text{Cl} & \quad \text{NUC} \\
\text{(1)} & \quad \text{C} \quad \text{NUC}^+ \\
\text{N-SO}_2\text{Cl} & 
\end{align*}
\]

In general the reactions of CSI are those of the isocyanate group rather than the chlorosulphonyl group. Where a reagent could react with either centre, the isocyanate group reacts preferentially and the chlorosulphonyl group only reacts when a second equivalent of the reagent is present.

Since the isocyanate group is a hard acid\textsuperscript{3} it would be expected that the products formed in the reactions of CSI with hard bases (e.g. alcohols, amines) would be more stable than the corresponding products derived from

* An alternative name for this compound, which is encountered in German chemical literature, is N-carbonylsulphamoyl chloride (NCSA)
soft bases (e.g. thiols, phosphines).

The reactions of CSI may be conveniently divided into two main categories; reaction with active hydrogen compounds and reaction with multiple bonds.

1.1. Reaction with active hydrogen compounds.

This topic has been extensively reviewed by Graf and, in view of the limited relevance of these reactions to the material in this thesis, only a brief summary of this type of reaction will be given.

These reactions proceed via nucleophilic attack, of the atom bearing the active hydrogen, at the carbon atom of the isocyanate group yielding a dipolar intermediate (2). This is followed by proton transfer to the nitrogen atom of the ambident anion to yield the product (3). Other sulphonyl isocyanates also behave in this manner but are less reactive than CSI.

\[
\begin{align*}
O=C=NSO_2Cl + R\cdot X\cdot H & \rightarrow O=C\cdot NSO_2Cl \rightarrow RX\cdot C\cdot NH\cdot SO_2Cl \\
(2) & \\
(3)
\end{align*}
\]

If a second equivalent of an active hydrogen compound is added, further reaction may occur at the chlorosulphonyl group of (3) with elimination of hydrogen chloride; in some cases a hydrogen chloride acceptor is needed to enable this second reaction to occur.

\[
RX\cdot C\cdot NH\cdot SO_2Cl + HCl \rightarrow RX\cdot C\cdot NH\cdot SO_2\cdot YR'
\]
Water

Under controlled conditions CSI reacts with one mole of water forming N-chlorosulphonyl carbamic acid (4), which readily loses carbon dioxide yielding sulphanoyl chloride (5).

\[
\begin{align*}
\text{O}=\text{C}=&\text{N}\text{SO}_2\text{Cl} \\
+ & \rightarrow \ HO\text{CNHSO}_2\text{Cl} \xrightarrow{-\text{CO}_2} \ NH_2\text{SO}_2\text{Cl} \\
(4) & (5)
\end{align*}
\]

Sulphanoyl chloride (5) readily reacts with a second mole of water forming sulphamic acid (6), which is also the product of the explosive reaction of CSI with an excess of water².

\[
\begin{align*}
\text{NH}_2\text{SO}_2\text{Cl} + \text{H}_2\text{O} \xrightarrow{\text{HCl}} \ NH_2\text{SO}_3\text{H} \\
(5) & (6)
\end{align*}
\]

Other hydroxylic compounds

Alcohols⁴,⁷,⁸, phenols⁴,⁷,⁸,⁹, and hydroxylamines¹¹ react readily with CSI yielding the corresponding esters of N-chlorosulphonyl carbamic acid. e.g.

\[
\begin{align*}
\text{OH} + \text{O}=\text{C}=&\text{NSO}_2\text{Cl} \rightarrow \text{OCNHSO}_2\text{Cl} \\
(7)
\end{align*}
\]

The reaction of CSI with carboxylic acids yields N-chlorosulphonyl amides (8) with elimination of carbon dioxide⁴,¹⁰,¹²,¹³.

\[
\begin{align*}
\text{O}=\text{C}=&\text{NSO}_2\text{Cl} \\
+ & \left[ \text{RCO}\text{CNHSO}_2\text{Cl} \right] \rightarrow \text{RCNHSO}_2\text{Cl} + \text{CO}_2 \\
(7) & (8)
\end{align*}
\]

Although these reactions presumably occur via initial formation of the
expected 1:1 adduct (7), only in the case of malonic acid (9) was the mixed anhydride (10) isolated\textsuperscript{10}, supporting the supposition that such compounds as (7) are intermediates in the reaction of CSI with other carboxylic acids.

\[\begin{align*}
\text{H}_2\text{C}\text{-}\text{C-}\text{OH} + 2\text{O=C=NSO}_2\text{Cl} & \rightarrow \text{H}_2\text{C}\text{-}\text{C-}\text{OH} \\
\text{C-}\text{-}\text{OH} & \text{C-}\text{-}\text{OH} \\
\text{(9)} & \text{(10)}
\end{align*}\]

**Sulphydryl compounds.**

Compounds containing the sulphydryl group react readily with CSI\textsuperscript{4,7,14} yielding thioesters of N-chlorosulphonyl carbamic acid (11), analogous to the esters obtained by the reaction of CSI with hydroxylic compounds.

\[\begin{align*}
\text{R-SH} + \text{O=C=NSO}_2\text{Cl} & \rightarrow \text{RSCNHSO}_2\text{Cl} \\
\text{(11)}
\end{align*}\]

As would be expected in view of the greater "hardness" of oxygen nucleophiles compared to the corresponding sulphur nucleophiles, the thioesters (11) are less stable than the corresponding esters.

**Amines, amides and related compounds.**

In general the reaction of CSI with compounds containing a nitrogen-hydrogen bond\textsuperscript{4,9,15,16} (imides, lactams, amines, amides, sulphonamides) yields the corresponding N-chlorosulphonyl urea.

\[\begin{align*}
\text{H}_2\text{C}\text{-}\text{C-}\text{NH} - \text{O=C=NSO}_2\text{Cl} & \rightarrow \text{H}_2\text{C}\text{-}\text{C-}\text{NH} - \text{NCNHSO}_2\text{Cl} \\
\text{H}_2\text{C}\text{-}\text{C-} & \text{O}
\end{align*}\]
In many of these reactions it is necessary to add the substrate to a solution of CSI in order to minimise further reaction of the substrate at the chlorosulphonyl group of the initial product. Hydrolysis of the adducts (13) formed between CSI and β-lactams (12) yields highly crystalline, sparingly soluble dihydouracils (14) which may be used for the characterization of liquid or low melting β-lactams.

\[
\begin{align*}
\text{CSI} & \quad + \quad \text{CSI} \\
\text{(12)} & \quad \rightarrow \quad \text{(13)} & \quad \text{Hyd.} & \quad \text{H}^+ \\
& & \quad \text{(14)}
\end{align*}
\]

**Aromatic systems.**

CSI reacts readily with carbocyclic and heterocyclic aromatic systems yielding N-chlorosulphonyl amides\(^{12,17,18,19}\). The reactions normally proceed readily at ambient temperature and catalysts are not normally used although for benzene and toluene a catalyst, e.g. aluminium trichloride is required\(^{6,20}\).

\[
\text{C}_6\text{H}_6 + \text{C} = \text{N} = \text{SO}_2\text{Cl} \quad \xrightarrow{\text{AlCl}_3} \quad \text{C}_6\text{H}_5\text{C} = \text{N} = \text{SO}_2\text{Cl}
\]

**Phosphonates.**

CSI reacts readily at ambient temperature with dialkyl and diaryl phosphonates (15) yielding the corresponding N-chlorosulphonyl carbamoyl phosphonates (16)\(^{21}\).
Ortho-esters and acetals.

Although these are not active hydrogen compounds their reactions with CSI are formally similar to those of hydroxylic compounds. Bismethoxymethane (methylal) (17) reacts exothermically with CSI, the $\text{CH}_2\text{OCH}_3$ group taking the part of an active hydrogen atom.\(^4\)

\[
\begin{align*}
0 = C = \text{NSO}_2\text{Cl} \\
+ & \text{CH}_3\text{O-CH}_2\text{OCH}_3 \\
\rightarrow & \text{CH}_3\text{O-CNSO}_2\text{Cl} \\
\text{CH}_2\text{OCH}_3
\end{align*}
\]  
(17)

The reaction of CSI with orthoesters\(^{22}\), e.g. trimethyl orthoformate (18), yields esters of $N$-alkyl-$N$-chlorosulphonyl carbamic acid e.g. (20) with elimination of a formate. Although these reactions presumably occur via formation of a 1:1 adduct, e.g. (19), such compounds have not yet been isolated.

\[
\begin{align*}
0 = C = \text{NSO}_2\text{Cl} \\
+ & \text{CH(OCH}_3\text{)}_3 \\
\rightarrow & \left[\begin{array}{c}
\text{CH}_3\text{O-CNSO}_2\text{Cl} \\
\text{CH(OCH}_3\text{)}_2
\end{array}\right] \\
\text{CH}_3\text{O-CNSO}_2\text{Cl} \ + \ \text{HCOCH}_3
\end{align*}
\]  
(19)
1.2. Reaction with multiple bonds.

Although the reactions of CSI with active hydrogen compounds are of great synthetic value, they are of limited mechanistic interest. The most interesting reactions of CSI, from a mechanistic point of view, are the reactions with multiple bond systems, which in many cases lead to novel cycloaddition products.

**Olefins.**

In general, CSI reacts readily under mild conditions with isolated double bonds, yielding N-chlorosulphonyl β-lactams (21) as the major primary products (50-100%)\(^{17,23,24}\).

\[
\begin{align*}
\text{C=C} & \quad \text{Hyd. or} \quad \text{Reduction} \\
\text{O=C=NSO}_2\text{Cl} & \quad \text{C—C—} \\
& \quad \text{C—C—N} \\
& \quad \text{SO}_2\text{Cl} \\
& \quad \text{C—C—H} \\
(21) & \quad (22)
\end{align*}
\]

Such compounds as (21) are easily recognized by the presence of an intense carbonyl band in the i.r. spectrum in the region 1790-1820 cm\(^{-1}\). Although N-chlorosulphonyl β-lactams are often rather unstable, in many cases they can be isolated as crystalline solids\(^{17}\). Reduction of the N-chlorosulphonyl β-lactam to the corresponding stable NH β-lactam (22) may be effected by a variety of techniques\(^{17}\), e.g. reduction with benzenethiol/pyridine, aqueous sodium sulphite\(^{25}\), zinc dust or iron powder in aqueous ethanol, or hydrolysis under neutral or slightly acidic conditions with or without the presence of a small quantity of an iodide, which catalyses the hydrolysis by a redox reaction. For any given N-chlorosulphonyl β-lactam, all the above procedures will not usually be equally efficient but by a judicious choice of work up procedure, high yields of NH β-lactams can usually be obtained.
In addition to the cyclo-adduct (21), many olefins, e.g. 1-heptene (23), also yield small amounts (0-30%) of unsaturated N-chlorosulphonyl amides which are formed in a parallel reaction.

This behaviour has been observed with a large range of olefins, one notable exception being the parent, ethylene, which does not react with CSI under conditions so far obtainable.

Other reactive isocyanates also undergo similar reactions with olefins although, as would be expected, these reactions are slower or require more vigorous conditions.

Mechanism.

Two extreme views may be taken of the mechanism of formation of the N-chlorosulphonyl β-lactams (22). Graf has envisaged a stepwise dipolar addition proceeding via rate determining electrophilic attack of the CSI at the double bond yielding a free 1,4-dipole (24) containing a resonance stabilized anion which then rapidly cyclizes via the nitrogen atom yielding the N-chlorosulphonyl β-lactam without loss of stereochemistry.
Moriconi, on the other hand, has suggested that the reaction may be concerted. By the symmetry rules for thermal processes the concerted pathway would be a π2s+π2a process involving the olefinic bond and the carbon-nitrogen double bond of the CSI. Since the cycloadditions have been shown to proceed in a stereospecific cis manner, the olefin must act as the suprafacial component.

The possibility of a secondary interaction between the π-bonding orbital of the olefin and the π* orbital of the CSI carbonyl group has been suggested as a factor favouring the highly strained transition state for this cycloaddition.

An intermediate mechanism which combines many of the aspects of these two extreme possibilities and which allows for a gradation of mechanism may be envisioned as proceeding via rate determining formation of an associated 1,4 dipolar species aligned for bonding (25) which would give rise to the observed cis stereospecificity of N-chlorosulphonyl β-lactam formation while retaining many of the characteristics of a dipolar mechanism.

The parallel formation of amides could then be explained either in terms of opening of (25) to a free 1,4 dipole (26) followed by proton abstraction by the nitrogen of the ambident anion, or by a proton transfer within the associated 1,4 dipole (25). A considerable degree of charge separation would be expected in the transition state and the reaction would be expected to show the same characteristics as Graf's dipolar
mechanism together with the high sterospecificity expected for a concerted reaction.

\[ \text{CSI} + \rightarrow \text{N Chlorosulphonyl amides} \]

Reversibility of N-chlorosulphonyl \( \beta \)-lactam formation.

The only published observation of reversible formation of an N-chlorosulphonyl \( \beta \)-lactam is that due to Friedrich\(^\text{30}\) whose studies of the reaction between CSI and trans-stilbene (27) revealed a temperature dependent equilibrium between the reactants and the corresponding trans \( \beta \)-lactam (28).

\[ \text{Ph} \quad + \quad \text{CSI} \quad \xleftrightarrow{\text{PROTON TRANSFER}} \quad \text{Ph} \quad \xrightarrow{\text{N Chlorosulphonyl amides}} \]

* For simplicity, reaction schemes in the introduction will not normally specify the nature of any intermediate species in the initial addition, although this should not be taken to imply that a concerted process is suggested.
Orientation of addition.

Without exception the orientation of the addition of CSI to olefins is in accordance with Markovnikov's rule, i.e. attack occurs at the olefin in the manner which would yield the most stable carbonium ion, thus the N-chlorosulphonyl β-lactams are formed with the nitrogen atom bonded to the carbon atom of the olefinic bond which would yield the most stable carbonium ion and in the amides the N-chlorosulphonyl carbamoyl group is attached to the carbon atom which would yield the least stable carbonium ion. For example, with isobutene (29) which yields both a β-lactam (30) and a βγ-unsaturated amide (31).  

\[
\text{CH}_3\text{CH} = \text{CH}_2 + \text{CSI} \rightarrow \text{CH}_3\text{CH} = \text{CH} - \text{N} - \text{ClO}_2\text{S}^+ \text{O} + \text{CH}_3\text{CH} = \text{CH} - \text{CONHSO}_2\text{Cl}
\]

(29) (30) (31)

Steric effects on the orientation of addition are small and only when the difference between the ends of the olefin in terms of carbonium ion stability is very small is any degree of steric control of orientation observed, e.g. with cis 2-hexene (32) both orientations of addition are found.

\[
\text{n-C}_3\text{H}_7\text{CH} = \text{CH}_2 + \text{CSI} \rightarrow \text{CH}_3\text{CH} = \text{CH} - \text{N} - \text{ClO}_2\text{S}^+ \text{O}_2\text{Cl} + \text{CH}_3\text{CH} = \text{CH} - \text{N} - \text{ClO}_2\text{S}^+ \text{O}_2\text{Cl}
\]

(32) 75% 25%

In contrast to this, the direction of attack at the olefinic bond with respect to the skeletal plane is strongly influenced by steric factors,
and occurs preferentially from the least hindered side\textsuperscript{28}. For example, the bicyclic olefin norbornene (33) yields exclusively the exo adduct (34) via attack at the less hindered exo face of the olefin\textsuperscript{28}.

\begin{center}
\begin{align*}
\text{(33)} & \quad + \quad \text{CSI} & \quad \rightarrow & \quad \text{(34)}
\end{align*}
\end{center}

**Stereospecificity.**

In all the cases investigated a high degree of cis stereospecificity has been observed in the formation of N-chlorosulphonyl \(\beta\)-lactams. Even with olefins for which the rate of addition has been shown to increase markedly with solvent polarity, indicating a dipolar mechanism, and which would be expected to yield relatively stable free 1,4 dipoles, which from steric considerations would be expected to lead to a large degree of non-stereospecificity, e.g. cis stilbene (35)\textsuperscript{30}, a very high degree of cis stereospecificity is still observed, suggesting the formation of an associated dipolar intermediate.

\begin{center}
\begin{align*}
\text{Ph} & \quad \text{Ph} & \quad + & \quad \text{CSI} & \quad \rightarrow & \quad \text{Ph} & \quad \text{Ph} & \quad \text{O} & \quad \text{N} & \quad \text{SO}_2\text{Cl}
\end{align*}
\end{center}

\begin{center}
\begin{align*}
\text{Ph} & \quad \text{Ph} & \quad + & \quad \text{CSI} & \quad \rightarrow & \quad \text{Ph} & \quad \text{Ph} & \quad \text{O} & \quad \text{N} & \quad \text{SO}_2\text{Cl}
\end{align*}
\end{center}
Similar results have been obtained with trans stilbene $^{(36)}$, cis 1,2-dicyclopropylhexene $^{(32)}$, and with cis and trans hex-2-ene $^{(31)}$, $\beta$-methyl styrene $^{(31)}$, and but-2-ene $^{(23)}$.

**Concurrent formation of amides.**

In many cases, e.g. with isobutene $^{(17)}$, small amounts of $\beta\gamma$-unsaturated N-chlorosulphonyl amides are formed concurrently with the N-chlorosulphonyl $\beta$-lactam $^{(17)}$. It has been shown that under conditions where the N-chlorosulphonyl $\beta$-lactam is stable, and its formation irreversible, the parallel formation of amides still occurs $^{(24,26)}$. The product ratio remains constant throughout the course of the reaction and is unaffected by solvent polarity or temperature $^{(24,26)}$.

![Chemical structure](image)

This indicates that the formation of the N-chlorosulphonyl $\beta$-lactam and the parallel formation of amides both occur via the same rate determining step and suggests that the proton transfer leading to the amides may occur within the configurationally restricted associated 1,4-dipole although the possibility that these products may arise via proton transfer in a free 1,4-dipole produced from the associated 1,4-dipole cannot be excluded. The extent of amide formation depends strongly on the nature of the olefin and for simple aliphatic olefins increases with increasing unsymmetric substitution.

Olefin

- $\text{CH}_3-\text{CH}=$CH-CH$_2$
- $\text{CH}_3-\text{CH}=\text{CH}_2$
- $\text{CH}_3-\text{CH}=\text{CH}_2$
- $\text{CH}_3-\text{CH}=\text{CH}_2$

% amide 5 10 30
The increase in amide formation from propene to isobutene may be explained in terms of the increased stability of the double bond formed by proton transfer and the increased steric hindrance to ring closure of the dipolar intermediate.

**Reaction rate and order.**

The reaction rates and orders for many olefin/isocyanate reaction partners have been determined by Clauss using i.r. spectroscopy, and in all cases the reactions were found to be second order. From his results the extraordinarily high reactivity of CSI (and to a lesser extent fluorosulphonyl isocyanate (FSI)) compared to other sulphonyl isocyanates may readily be seen (Table 1).

**TABLE 1.** Second order rate constants for the reaction of X-SO₂-NCO with 2-ethyl-hex-1-ene at 25°C in dichloromethane.

<table>
<thead>
<tr>
<th>X</th>
<th>$k_2(1.\text{mol.}^{-1}\text{s}^{-1})$</th>
<th>$k_2\text{rel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>$6-7.5 \times 10^{-2}$</td>
<td>270,000</td>
</tr>
<tr>
<td>F</td>
<td>$2-2.5 \times 10^{-2}$</td>
<td>100,000</td>
</tr>
<tr>
<td>O=C=N-</td>
<td>$6-7.5 \times 10^{-3}$</td>
<td>27,000</td>
</tr>
<tr>
<td>Cl-O=O-Cl</td>
<td>$2.5-3 \times 10^{-4}$</td>
<td>110</td>
</tr>
<tr>
<td>p-tosyl-</td>
<td>$1.2-1.5 \times 10^{-5}$</td>
<td>50</td>
</tr>
<tr>
<td>Cl₂CH-CH₂-</td>
<td>$1-1.2 \times 10^{-5}$</td>
<td>44</td>
</tr>
<tr>
<td>ClCH=CH-</td>
<td>$6.5-8 \times 10^{-6}$</td>
<td>29</td>
</tr>
<tr>
<td>CH₃O-</td>
<td>$1.2-1.5 \times 10^{-6}$</td>
<td>5.4</td>
</tr>
<tr>
<td>CH₂=CH-</td>
<td>$5-8 \times 10^{-7}$</td>
<td>2.6</td>
</tr>
<tr>
<td>ClCH₂-CH₂-</td>
<td>$5-8 \times 10^{-7}$</td>
<td>2.6</td>
</tr>
<tr>
<td>p-tolyl-</td>
<td>$2-3 \times 10^{-7}$</td>
<td>1</td>
</tr>
</tbody>
</table>

$k_2$, $k_2\text{rel}$ – absolute and relative second order rate constants

The variation in reactivity of the isocyanates suggests a considerable build up of negative charge on the isocyanate moiety during the rate determining step in the reactions.

The corresponding development of positive charge on the olefin is indicated by the marked dependence of the reaction rate on the substitution of the double bond, as the substitution increases from 1-alkyl to 1,1-dialkyl.
the reaction rate increases by a factor of $3 \times 10^4$.

**TABLE 2.** Relative second order rate constants for the reaction of CSI with olefins at 25° in dichloromethane.<sup>26</sup>

<table>
<thead>
<tr>
<th>OLEFIN (R=alkyl)</th>
<th>$k_{2\text{rel}}$</th>
<th>OLEFIN</th>
<th>$k_{2\text{rel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-CH=CH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1*</td>
<td>styrene</td>
<td>700</td>
</tr>
<tr>
<td>R-CH=CH-R</td>
<td>0.4</td>
<td>cis</td>
<td>trans</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td></td>
<td>O-methylstyrene</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td></td>
<td>O,p-dimethylstyrene</td>
</tr>
<tr>
<td></td>
<td>15,000</td>
<td></td>
<td>stilbene cis</td>
</tr>
<tr>
<td></td>
<td>15,000</td>
<td></td>
<td>trans 0.1</td>
</tr>
</tbody>
</table>

* absolute value $1.2-1.5 \times 10^{-6}$ (1 mol<sup>-1</sup>sec<sup>-1</sup>)

In the aliphatic series the slight decrease in rate as the substitution is increased from 1,1-dialkyl to 1,1,2,2-tetra-alkyl may be due to increased steric hindrance in the transition state, but the effect is small. The styrenes follow a similar pattern but the rate increase caused by O-alkyl substituents is smaller and the rate decrease caused by O-alkyl substituents is greater than that found in the aliphatic series, presumably due to the greater steric crowding in the transition state caused by the presence of the phenyl group. Britt<sup>33</sup> has shown that for the reaction of CSI with para-substituted styrenes a linear relationship between log $k_2$ and the substituent constants ($\sigma^+$). The magnitude of the reaction constant ($\rho = -5.27$) is amongst the largest known and indicates the presence of a considerable positive charge on the O-carbon of the styrene system.
Further evidence for the dipolar nature of the transition state in the reaction between CSI and olefins has been obtained from studies of solvent effects which show that the reaction rate increases markedly with solvent polarity (Table 3).

**TABLE 3.** Relative second order rate constants \((k_{2rel})\) for the reaction of CSI with 2-ethyl-hex-1-ene at 25° in various solvents.

<table>
<thead>
<tr>
<th>SOLVENT</th>
<th>n-C6H14</th>
<th>CCl4</th>
<th>Et2O</th>
<th>CHCl3</th>
<th>CH2Cl2</th>
<th>CH3NO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Et*</td>
<td>30.9</td>
<td>32.5</td>
<td>34.6</td>
<td>39.1</td>
<td>41.1</td>
<td>46.3</td>
</tr>
<tr>
<td>k2rel</td>
<td>1</td>
<td>3</td>
<td>30</td>
<td>250</td>
<td>1700</td>
<td>20,000</td>
</tr>
</tbody>
</table>

* Dimroth's solvent polarity parameter

**Rearrangement of N-chlorosulphonyl β-lactams.**

It has gradually been realized that N-chlorosulphonyl β-lactams are, in many cases, unstable and may undergo thermal rearrangements to unsaturated open chain amides or to skeletally rearranged products.

These rearrangements may, in principle, occur via ring opening of the β-lactam ring to either a free (37b) or associated (37a) 1,4-dipole. Proton transfer to the nitrogen atom of the ambident anion yielding amides, or rearrangement of the carbonium ion centre followed by cyclization, via the oxygen or nitrogen atom of the anion, yielding rearranged cyclic products may then occur.

[Diagram of rearrangements]
Stereoisomerization of N-chlorosulphonyl β-lactams.

The racemization of the S(+)-enantiomer of the N-chlorosulphonyl β-lactam (38) of α-methyl styrene has been studied, and at the temperature at which rearrangement of (38) to the βγ-unsaturated amide (40) starts to occur the slow racemization of (38) was also observed. The most plausible mechanism for this racemization is ring opening to a free 1,4-dipole (39) followed by rotation of the carbonium ion and re-cyclization. The occurrence of the rearrangement to (40) at the same temperature as racemization, suggests that this also proceeds via (39).

\[
\begin{align*}
&\text{CH}_3 \text{Ph} \quad \text{N} \quad \text{SO}_2 \text{Cl} \\
\text{(38)} &\quad \Leftrightarrow \quad \text{CH}_3 \text{Ph} \quad \text{N} \quad \text{SO}_2 \text{Cl} \\
&\text{O} \quad \text{Ph} \\
\text{(39)} &\quad \leftarrow \quad \text{ClO}_2 \text{SNH} \quad \text{CO} \quad \text{Ph} \\
&\text{(40)}
\end{align*}
\]

Formation of N-chlorosulphonyl amides.

In many of the cases where small amounts of βγ-unsaturated amides are produced in a parallel reaction to the cycloaddition, the same amide is also produced by thermal rearrangement of the N-chlorosulphonyl β-lactam. For example, α-methyl styrene (41) gives an 11:1 mixture of N-chlorosulphonyl β-lactam (42) and N-chlorosulphonyl amide (43) at temperatures below -30° when (42) is formed irreversibly and is stable. The β-lactam (42) may be isolated at low temperature, but above -30° rearrangement to (43) occurs and if the reaction is carried out above -30° the amide (43) is the sole final product.

\[
\begin{align*}
&\text{CH}_3 \quad \text{Ph} \quad + \quad \text{CSI} \quad \rightarrow \quad \text{CH}_3 \quad \text{Ph} \\
&\quad \text{N} \quad \text{SO}_2 \text{Cl} \\
&\quad \text{O} \quad \text{NHSO}_2 \text{Cl} \\
&\text{(41)} \quad \rightarrow \quad \text{(42)} \quad + \quad \text{(43)}
\end{align*}
\]
Formation of the thermodynamically more stable $\alpha\beta$-unsaturated amides in a parallel reaction to cycloaddition or via subsequent rearrangement of the N-chlorosulphonyl $\beta$-lactam only occurs when no $\gamma$-protons are present. This preference for formation of $\beta\gamma$-unsaturated amides suggests that the rearrangement occurs via a free 1,4 dipole which undergoes a kinetically favoured $\gamma$-proton transfer to the nitrogen of the ambident anion via a six-membered cyclic transition state.

\[
\begin{align*}
\text{CH}_2\text{N} & \quad \text{S} & \quad \text{O}_2\text{Cl} \\
\to & \quad \text{CH} & \quad \text{N} & \quad \text{O}_2\text{Cl} \\
\text{S} & \quad \text{O}_2\text{Cl} & \quad \text{S} & \quad \text{O}_2\text{Cl} \\
\end{align*}
\]

In styrene, where no $\gamma$-protons are present, parallel formation of the $\alpha\beta$-unsaturated amide (45) occurs at ambient temperature. At higher temperatures the N-chlorosulphonyl $\beta$-lactam (44) rearranges to (45).

\[
\begin{align*}
\text{Ph} + \text{CSI} & \to \quad \text{N} & \quad \text{O}_2\text{Cl} \\
(44) & \quad \text{Ph} & \quad \text{O}\text{C} & \quad \text{NHSO}_2\text{Cl} \\
(45) & \quad \text{Ph} & \quad \text{NHSO}_2\text{Cl} \\
\end{align*}
\]

Although the great preference for the formation of $\beta\gamma$-unsaturated amides can best be reconciled with the steric requirements of the transition state for an intramolecular proton transfer, the mechanism of formation of $\alpha\beta$-unsaturated amides is uncertain and could conceivably be an intra- or intermolecular process.

An extraordinary example of long range proton transfer is found in the case of $\beta$-pinene (46). Preferential attack of the CSI from the least hindered side of the molecule yields the $\beta$-lactam (47) which then rearranges to the amide (49) by $\varepsilon$-proton transfer.
In this case the rearrangement must occur via a free 1,4 dipole (48) since orbital overlap between the nitrogen atom and the bridge methyl hydrogen atom would be impossible in an associated dipole.

**Skeletal rearrangement.**

In many cases the cationic centre of the 1,4-dipole produced by the ring opening of the N-chlorosulphonyl β-lactam can undergo one or more Wagner-Meerwein type rearrangements. One of the remarkable features of these rearrangements is the ability of the ambident anion to act as an internal nucleophile thus trapping the intermediate carbonium ions at various points on the reaction profile. Cyclization may occur either via the nitrogen or oxygen atoms of the ambident anion, which may also assist the rearrangements by neighbouring group participation.

The first reported example of rearrangement of an N-chlorosulphonyl β-lactam to an imino-lactone was in the reaction of 2,2-tetramethylene-1-methylene-1,2,3,4-tetrahydronaphthalene (50) with CSI.

The N-chlorosulphonyl β-lactam (51) was observed as an unstable intermediate at -60°, which rearranged rapidly to the imino-lactone (52) below 0°.
Many interesting examples of skeletal rearrangements of N-chlorosulphonyl \(\beta\)-lactams are found in the reactions of CSI with bicyclic monoterpenes\(^{37,39}\) e.g. camphene (53)\(^{39}\).

At low temperature (\(-60^\circ\)) the reaction yields the \(\beta\)-lactam (54), by attack of the CSI from the least hindered side of (53); at \(0^\circ\) (54) rearranges
to the lactam (56) and imino-lactone (57) via the non-classical intermediate (55).

Although the formation of rearranged products usually occurs via rearrangement of an initially formed N-chlorosulphonyl β-lactam, in some cases, e.g. α-fenchene\(^{39}\), hexamethyl Dewar benzene\(^{40}\), and cyclopropenes\(^{41}\), β-lactams have neither been detected nor intercepted and it is possible that these reactions proceed without the intermediate formation of a β-lactam, e.g. 1-methyl-cyclopropene (58)\(^{41}\).

Ring closure of the initial 1,4 dipolar intermediate to the strained bicyclo[2,1,0]system is presumably non-competitive with rearrangement to the highly delocalized intermediate (59), which reacts with a second molecule of CSI yielding the hydantoin derivative (60) in preference to ring closure to a 5-ring lactam or imino-lactone. The formation of the 2:1 adduct is very good evidence for the formation of a dipolar intermediate.

Hexamethyl Dewar benzene (61) reacts readily with CSI yielding the tricyclic lactam (64)\(^{40}\), again it appears that cyclization to a highly strained β-lactam (62) is non-competitive with rearrangement of the carbonium ion centre to the allyl carbonium ion (63).
The intermediacy of \( \beta \)-lactams in the reactions of many heterosubstituted olefins is also doubtful\(^{24,42,43,44}\), although \( \beta \)-lactams have been detected or isolated in a few cases, e.g. methyl vinyl ester \((65)\)^{24}, in others, e.g. N-methyl-N-vinyl acetamide \((66)\)^{24} their presence has not been detected and \(\alpha\beta\)-unsaturated amides appear to be formed directly.

![Reaction Diagram 1](image1)

\[
\text{CH}_3\text{C}={\text{O}} + \text{CSI} \rightarrow \text{CH}_3\text{C}({\text{ClO}}_2\text{S})=\text{N}
\]

Allyl iron complexes \((67)\) also fail to give \(\beta\)-lactams, but instead yield \(\gamma\)-lactams or \(\beta\gamma\)-unsaturated amides depending on the substitution, the reactions presumably proceed via formation of a dipolar \(\pi\)-complex which then undergoes cyclization or internal displacement of the olefin\(^{45,46}\).

![Reaction Diagram 2](image2)

\[
\text{Fe} = \text{R}_1 \equiv \text{H} = \text{R}_2 \equiv \text{CH}_3 \quad \text{R}_1 = \text{H}, \text{R}_2 = \text{R}_3 = \text{CH}_3
\]
Other unsaturated systems.

Cyclopropanes.

The reaction of CSI with substituted cyclopropanes yielding \( \beta \)-lactams and unsaturated amides has been interpreted by Moriconi in terms of slow CSI catalysed isomerization of the cyclopropane to an olefin which then reacts rapidly with the CSI. The formation from 1,1,2,2-tetramethyl cyclopropane-3,3-\(d_2\) (68) of a \( \beta \)-lactam (69) and amide (70) containing deuterium almost exclusively in the \( t \)-butyl group supports this mechanism rather than electrophilic attack at the cyclopropane to give the dipolar intermediate (71)\(^{47}\).

A similar process appears to occur in the reaction of bicyclo[2,1,0]
Pentane (72) with CSI, since the initially assigned structure (73) for the lactam\(^{48}\) has recently been disproved by Jagt and van Leusen\(^{49}\). The lactam is actually the same as the \( \beta \)-lactam obtained from cyclopentene, indicating initial isomerization of the bicyclo alkane to cyclopentene.
Paquette and co-workers have studied the reactions of CSI with various substituted bicyclo[1,1,0] butanes and their results indicate initial $S_{E2}$ attack at the strained central bond yielding a cyclobutonium ion. The course of the reaction from this point is determined by the structure of the carbonium ion:

a) for 1,3-dimethyl bicyclo[1,1,0]butane (74) inversion of the four membered ring followed by cyclization to the lactam (75) occurs

\[
\text{CSI} + \text{CH}_3\text{CH}_3 \rightarrow \text{CH}_3\text{CH}_3 \rightarrow \text{CH}_3\text{CH}_3
\]

(74)

b) with 1,2,2-trimethyl bicyclo[1,1,0]butane (76), inversion of the ring is non-competitive with rearrangement to the more stable cyclopropyl carbinyl cation (77) which then cyclizes to the lactam (78).

\[
\text{CSI} + \text{CH}_3\text{CH}_3 \rightarrow \text{CH}_3\text{CH}_3 \rightarrow \text{CH}_3\text{CH}_3
\]

(76)

Acyclic 1,3-dienes.

The reactions of CSI with acyclic 1,3-dienes have been extensively investigated by Goebel and Clauss and Moriconi and Meyer. In all the cases studied the reactions were found to proceed via the formation of N-chlorosulphonyl $\beta$-lactams as the major primary products. The orientation of addition was found to be in accord with a dipolar addition mechanism and attack occurred preferentially at terminal rather than internal double bonds. Goebel and Clauss observed the parallel formation of small amounts of amides and six-membered cyclic imino-lactones, e.g. with
1,3-butadiene (79), although this was not reported by Moriconi and Meyer.

With the exception of the N-chlorosulphonyl β-lactam (80) derived from butadiene, the N-chlorosulphonyl β-lactams were found to be unstable and readily rearranged to amides and six-membered cyclic imino-lactones and lactams. The results obtained by Moriconi and Meyer in their investigations of the rearrangement of the N-chlorosulphonyl β-lactam (81) derived from isoprene indicated that the lactam (82) and imino-lactone (83) were the major products and that only small amounts of the amide (84) were produced.

The investigations of Goebel and Clauss, on the other hand, indicated the formation of only the imino-lactone (83) and amide (84) during the rearrangement of the β-lactam (81). These and other discrepancies between the results obtained by the two groups are probably due to the different experimental conditions employed in their investigations. Moriconi and Meyer observed that the non-conjugated imino-lactone (83) rearranged to
the conjugated imino-lactone (85) by double bond migration.

\[
\begin{align*}
\text{CH}_3 & \\
\text{O} & \\
\text{N} & \\
\text{SO}_2\text{Cl} & \to \\
\text{CH}_3 & \\
\text{O} & \\
\text{N} & \\
\text{SO}_2\text{Cl} & (83) \quad (85)
\end{align*}
\]

In each case it appeared that the products were formed by opening of the \(\beta\)-lactam to a free dipolar intermediate which then underwent competitive, irreversible proton transfer to nitrogen, and/or cyclization via nitrogen and/or cyclization via oxygen. No interconversions of the primary rearrangement products were observed by either group. The failure to observe the rearrangement of the imino-lactone to the corresponding lactam, which occurs in some cyclic 1,3-dienes (see Section Two, p. 34) may be attributed to the ability of the non-conjugated imino-lactone to rearrange to the corresponding conjugated imino-lactone, a reaction pathway which is not available to the bicyclic imino-lactones derived from cyclic 1,3-dienes.

The formation of small amounts of amide and 1,4-addition products during the addition of CSI to the acyclic 1,3-dienes, under conditions where the N-chlorosulphonyl \(\beta\)-lactams are stable (cf parallel formation of amides in the reactions of olefins) suggests the intermediacy of some dipolar species rather than the concerted mechanism proposed by Moriconi.

**Vinyl cyclopropanes.**

Many examples of the reactions of CSI with substrates containing the vinyl cyclopropane system have been investigated, although many of these substrates were not chosen primarily because of the presence of this grouping and the emphasis was placed on other properties, e.g. the bicyclo[6,1,0]nona-2,4,6-trienes studied by Paquette and co-workers\(^54\) were regarded
as potential bishomotropylium cation precursors.

In some cases no rearrangement of the cyclopropyl group was observed, e.g. bicyclo[3,1,0]hex-1-ene reacted as a simple olefin and gave only a \( \beta \)-lactam\(^{55} \), while \( \alpha \)-cyclopropyl styrene apparently gave an \( \alpha \beta \)-unsaturated amide directly\(^{56} \), although more detailed studies, presented in Section Four (p. 73) showed that this reaction proceeded via a \( \beta \)-lactam which could, under certain conditions, undergo a rearrangement involving the cyclopropyl group.

Bullvalene appeared to react via initial formation of the fluxional \( \beta \)-lactam (86) which then rearranged to the lactam (87) and imino-lactone (88) which may be regarded as formal 1,6-addition products\(^{57} \).

Further examples of the reaction of CSI with vinyl cyclopropane systems are given in Section Four (p. 73).

Potential homotropylium cation precursors.

The reactions of many systems which in principle could yield dipolar intermediates containing an "aromatic" cationic moiety have been investigated, mainly by Paquette and his co-workers\(^{54,58,60,61} \). For example, cyclo-octatetraene (89) yields the 1,4 cycloaddition product (91)\(^{58,59} \).
Paquette\textsuperscript{58} has interpreted this reaction in terms of the formation of the dipolar homotropylium ion containing species (90) which cyclizes via a six-membered transition state to the lactam (91). However, the initial formation of a $\beta$-lactam, followed by ring opening to (90) cannot be excluded since although no $\beta$-lactam was detected during the reaction, the conditions (50$^\circ$) may be too vigorous to allow the formation of a detectable standing concentration of the $\beta$-lactam.

The intermediacy of the bis-homotropylium cation (93) in the reaction of CSI with bicyclo[6,1,0]nona-2,4,6-triene (92) has been questioned by Baldwin\textsuperscript{62} whose kinetic investigations of this reaction suggest that reaction occurs via the valence bond isomer (94) which reacts with CSI to give the observed trans fused $\beta$-lactam (95).
Allenes.

The reactions of substituted allenic with CSI have been extensively studied by Moriconi and Kelly\textsuperscript{63} and found to yield \(\beta\)-lactams and/or amides. The course of the reactions may be rationalized in terms of electrophilic attack at the central carbon atom of the allene system to yield the most stable dipolar intermediate followed by ring closure to the \(\beta\)-lactam or proton abstraction yielding an amide, e.g. with 2-methyl-2,3-pentadiene (96).

\[
\begin{align*}
\text{CH}_3\text{CH=CH}_2 + \text{CSI} & \rightarrow \text{CH}_3\text{CH}=-\text{CH}_2 \rightarrow \text{CH}_3\text{CH}=-\text{C}!=\text{CH}_2 \\
(96)
\end{align*}
\]

No subsequent rearrangements of the \(\beta\)-lactams were reported.

Heterocumulenes.

CSI reacts readily with ketene at low temperatures (-50\textdegree) yielding N-chlorosulphonyl maleimide (98), which may be isolated at low temperature but decomposes at ambient temperature\textsuperscript{24,64}.

\[
\begin{align*}
\text{H}==\text{C}!=\text{O} + \text{CSI} & \rightarrow \text{H}==\text{C}!=\text{C}=\text{O} \rightarrow \text{H}==\text{C}!=\text{C}=\text{O} \\
(97) & \rightarrow (98)
\end{align*}
\]

The reaction may be rationalized in terms of attack of CSI at the terminal carbon yielding the acylium ion intermediate (97) followed by ring closure to (98). The ketenimine (99) reacts with CSI yielding an unstable product which can be converted to the diazinone (100) by reduction with benzenethiol/pyridine\textsuperscript{65}. The formation and orientation of
the 2:1 adduct strongly suggests an initial attack, similar to that
postulated for ketene, yielding a free dipolar intermediate which then
reacts with a second molecule of the ketenimine.

\[
\begin{align*}
\text{Ph} & \quad \text{Ph} \\
\text{2} & \quad \text{CSI} / 0^\circ \\
\text{1} & \quad \text{PhSH/Py} \\
\text{N} & \quad \text{p-Tol} \\
(99) & \\
\end{align*}
\]

(100)

**Acetylenes.**

The reactions of CSI with substituted acetylenes have been investigated
by several workers\(^{66-69}\) and in general have been found to yield \(N\)-chloro-
sulphonyl-1,2,3-oxathiazine-2,2-dioxides (104). The reaction may be
envisaged as proceeding via an unstable \(\beta\)-lactam (101) which undergoes
sequential electrocyclic ring opening (102), 1,5-sigmatropic chlorine shift
(103) and cyclization to the observed product (104).

\[
\begin{align*}
R & \quad + \text{CSI} \\
R_1 & \quad \text{R} \\
R_1 & \quad \text{Cl} \\
(101) & \quad (102) \quad (103) \quad (104)
\end{align*}
\]

The stereochemistry of the product is determined by electronic and
steric factors in the initial step in the reaction sequence, and follows
a similar pattern to that found for olefins.
Imines.

The position of the initial attack of CSI depends upon the substituents on the imine bond. For the N-aza-imino compound (105) attack occurs at the carbon atom yielding the amide (106), while the imines (107) yield the triazinediones (109), whose formation may be rationalized in terms of attack at the nitrogen followed by reaction of the dipolar intermediate (108) with a second molecule of CSI.

\[
\text{O}_2\text{N}-\begin{array}{c}
\text{CH}=\text{N} \\
\text{N} \\
\end{array} + \text{CSI} \rightarrow \text{O}_2\text{N}-\begin{array}{c}
\text{C} \\
\text{N} \\
\end{array} \\
\text{N}=\text{N} \text{NSO}_2\text{Cl}
\]

(105) \rightarrow (106)

Carbonyl and related compounds.

Ketones with highly dipolar character\textsuperscript{72}, e.g. tropone (110),\textsuperscript{73} and aldehydes\textsuperscript{17,74}, react readily with CSI yielding N-chlorosulphonyl-imines as the final products.
Although it was originally thought that these reactions occurred via initial 2+2 cycloaddition followed by loss of carbon dioxide from the unstable 1,3-oxazetidin-2-one\(^1\), the recent work by Clauss et al.\(^2\) has shown that the unstable crystalline adducts obtained from aldehydes at low temperature are 2:1 adducts, which readily decompose yielding N-chlorosulphonyl imine, aldehyde and carbon dioxide, e.g.

The formation of imines from carboxylate anions\(^3\), phosphine oxides\(^4\), e.g. (111), sulphoxides\(^4\) and N,N-dialkylamides\(^4\) has also been reported.
The substitution of an α-proton, yielding N-chlorosulphonyl amides, which is found with ketones, β-diketones and β-ketoesters may be explained in terms of initial attack of CSI at the carbonyl oxygen followed by abstraction of an α-proton and rearrangement of the intermediate urethane. For acetylacetone (112), the intermediate urethane (113) is stable at low temperatures and rearranges on warming to the amide (114).

\[
\begin{align*}
\text{CSI} & \quad \text{CH}_3\text{C}H\text{C}=\text{C}\text{CH}_3 \quad -60^\circ \\
& \quad \text{CH}_3\text{C}H\text{C}=\text{C}\text{CH}_3 \quad \text{O} \quad \text{O} \quad \text{O} \\
& \quad \text{CH}_3\text{C}H\text{C}=\text{C}\text{CH}_3 \quad \text{O} \\
& \quad \text{CH}_3\text{C}H\text{C}=\text{C}\text{CH}_3
\end{align*}
\]

(112)  (113)  (114)

1,3-Dipoles.

The reaction of CSI with n-butyl azide and diazoacetic esters yields 1,3-cycloaddition products via initial attack of the CSI at the most nucleophilic terminus of the 1,3-dipole system.

\[
\begin{align*}
\text{CH}_3\text{N}_3 + \text{CSI} & \quad \text{C}_6\text{H}_6 \quad 25^\circ \\
& \quad \text{CH}_3\text{N}=\text{N} \quad \text{NSO}_2\text{Cl} \\
& \quad \text{CH}_3\text{C}H\text{C}=\text{C}\text{CH}_3 \quad \text{O} \\
& \quad \text{CH}_3\text{C}H\text{C}=\text{C}\text{CH}_3
\end{align*}
\]

(115)

Summary.

The foregoing examples illustrate the wide range of substrates which undergo reaction with CSI. Many of these reactions are of great synthetic value and the use of CSI as a reagent in routine synthesis will doubtless become common-place in the future. The remarkable reactivity of CSI as a uniparticulate electrophile, generating and subsequently trapping carbonium ions, makes this reagent a very powerful tool in the study of carbonium ions and their rearrangements.
SECTION TWO

THE REACTION OF CHLOROSULPHONYL ISOCYANATE WITH CYCLIC 1,3-DIENES.

The reaction of chlorosulphonyl isocyanate (CSI) with acyclic 1,3-diienes has been shown to proceed via initial stereospecific cis 1,2-cycloaddition to one of the double bonds\textsuperscript{27,51,53} yielding N-chlorosulphonyl \( \beta \)-lactams. The formation of these products may be rationalized in terms of electrophilic attack of the CSI at the terminus of the diene to yield the most stable associated 1,4 dipole, followed by cyclization via nitrogen forming an N-chlorosulphonyl \( \beta \)-lactam with retention of configuration and the expected Markovnikov orientation. In contrast to the detailed studies of the acyclic systems, the only reports of the reactions of CSI with cyclic 1,3-diienes have been of the formation of N-chlorosulphonyl \( \beta \)-lactams (117) and (120) from 1,3-cyclo-octadiene (116)\textsuperscript{25} and 1,3-cyclopentadiene (119)\textsuperscript{24}, and their conversion to the corresponding NH \( \beta \)-lactams (118) and (121); although in the latter case no details have been published.

\[
\begin{align*}
\text{CSI} & \xrightarrow{\text{Na}_2\text{SO}_3\text{aq.}} \text{cis-CSI} \\
(116) & \xrightarrow{\text{Na}_2\text{SO}_3\text{aq.}} (117) \rightarrow (118) \\
(119) & \xrightarrow{\text{Na}_2\text{SO}_3\text{aq.}} (120) \rightarrow (121)
\end{align*}
\]

The reaction of CSI with acyclic 1,3-diienes has been interpreted in terms of two alternative mechanisms:

a) a kinetically controlled 1,2 dipolar addition\textsuperscript{51}.

or

b) a kinetically controlled concerted \( \Pi_2s+\Pi_2a \) cycloaddition\textsuperscript{27}.
Since the double bonds of acyclic 1,3-dienes usually adopt a transoid conformation, 1,4-cycloaddition, which on the basis of the stereochemical requirements of the transition state and the stability of the products formed, must occur via the cisoid conformation, would not be expected to compete with 1,2-cycloaddition under conditions of kinetic control. The formation of the thermodynamically more stable products of 1,4-cycloaddition in the reaction of CSI with acyclic 1,3-dienes has been observed, but appears to occur almost exclusively via rearrangement of the initially formed N-chlorosulphonyl \( \beta \)-lactam\(^{27,51,53} \).

Small ring cyclic 1,3-dienes however, are held in the cisoid configuration required for 1,4-cycloaddition; and it was thought possible that in the reaction of CSI which such systems, concerted or dipolar 1,4-cycloaddition might be competitive with 1,2-cycloaddition. Apart from the mechanistic interest of the reactions of cyclic 1,3-dienes with CSI, the possible formation of 1,4-addition products, either directly or via rearrangement of an initially formed N-chlorosulphonyl \( \beta \)-lactam offers a possible synthetic route to novel hetero bicyclic systems.

2.1. Investigation of the reaction with 1,3-cyclopentadiene (119), 1,3-cyclohexadiene (122), and 1,3-cycloheptadiene (125).

The cyclic dienes (119), (122) and (125) reacted readily with CSI in dichloromethane at ambient temperature and in each case the appearance of a high frequency carbonyl band in the region of 1810 to 1820 cm\(^{-1}\) in the i.r. spectrum of the reaction mixtures indicated the formation of an N-chlorosulphonyl \( \beta \)-lactam as the sole carbonyl containing product. No attempt was made to isolate these compounds and they were converted in situ to the corresponding NH \( \beta \)-lactams. The reactions of (119) and (122) were carried out by adding the diene to a solution of CSI in order to minimise
the possibility of acid catalysed polymerization of the dienes.

1,3-Cyclopentadiene (119) reacted rapidly with CSI in dichloromethane at ambient temperature. The CSI was almost completely consumed within 10 min., and the i.r. spectrum of the reaction mixture showed an intense band at 1818 cm\(^{-1}\) due to the N-chlorosulphonyl \(\beta\)-lactam (120). Immediate reduction of the reaction mixture with aqueous sodium sulphite gave 6-azabicyclo[3,2,0]hept-3-en-7-one (121) in 40\% yield. The n.m.r. spectrum of (120) was obtained by reacting equimolar proportions of CSI and (119) in deuteriochloroform in an n.m.r. tube. The spectrum showed signals at: \(\delta\) 6.4-6.1 (2H, m), 5.3 (1H, m), 4.1 (1H, m) and 3.1-2.4 (2H, m), and was consistent with the structure (120). By using chloroform as a quantitative internal standard, the yield of (120) was calculated to be 60 \(\pm\) 5\%, the balance of the material appeared to be polymeric since apart from signals ascribable to (120), only very broad, low mounds were present in the spectrum.

\[
\begin{align*}
\text{1,3-Cyclopentadiene} & \quad \text{CSI} \quad \text{CH}_2\text{Cl}_2 \rightarrow \\
(119) & \quad (120) \quad \text{Na}_2\text{SO}_3 \text{aq} \rightarrow \\
& \quad (121)
\end{align*}
\]

1,3-Cyclohexadiene also reacted rapidly with CSI in dichloromethane at ambient temperature, the reaction was almost complete within seven minutes and the formation of the N-chlorosulphonyl \(\beta\)-lactam (123) was indicated by an intense carbonyl band at 1810 cm\(^{-1}\). Reduction of the reaction mixture with benzenethiol/pyridine at \(-78^\circ\) gave 7-azabicyclo[4,2,0]oct-4-en-8-one (124) in 67.5\% yield.
In contrast to the reactions of (119) and (122), the reaction of 1,3-cycloheptadiene (125) with CSI in dichloromethane at ambient temperature occurred quite slowly. The appearance of a band at 1820 cm$^{-1}$ showed the formation of the N-chlorosulphonyl $\beta$-lactam (126), but the reaction was only complete after 1 h, when treatment of the reaction mixture with aqueous sodium sulphite gave 8-azabicyclo[5,2,0]non-5-en-9-one (127) in 38% yield.

The n.m.r. spectrum of (126) was obtained by reacting the diene (125) with CSI in deuteriochloroform at ambient temperature. After 4h the spectrum of the reaction mixture showed signals at $\delta$ 5.73 (2H, m), 4.93 (1H, d, J 7Hz), 3.5 (1H, q, J 7Hz), 2.5-1.2 (6H, m), and was consistent with the structure (126).

The assignment of the structures (121), (124) and (127) was based solely on the spectral properties of the compounds. Each showed a single N-H stretching band in the region 3400 to 3410 cm$^{-1}$ and a high frequency carbonyl band in the region 1750 to 1760 cm$^{-1}$, which is characteristic of $\beta$-lactams. The orientation of the $\beta$-lactam ring with respect to the
remaining double bond was indicated by the n.m.r. spectra (Table 4).

Each of the β-lactams showed a single proton resonance (Ha), in the region expected for a methine proton adjacent to a lactam carbonyl group and two carbons removed from a double bond (3.0-3.5), and a single proton resonance (Hb) in the region expected for a methine proton which is both allylic and adjacent to the nitrogen atom of a lactam function (4.0-4.5).

TABLE 4. Selected n.m.r. data for the bridgehead protons of the β-lactams.

<table>
<thead>
<tr>
<th>n</th>
<th>Ha (S)</th>
<th>Sa (S)</th>
<th>Hb (S)</th>
<th>Sb (S)</th>
<th>Jab (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.37</td>
<td>9.7</td>
<td>4.46</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>3.46</td>
<td>9.0</td>
<td>3.99</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>3.20</td>
<td>9.3</td>
<td>4.40</td>
<td>4.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>

* europium induced shift parameter (± 0.5S), obtained from measurements over a range of molar ratios of Eu(dpm)₃ to substrate from 0 to 0.5 in deuteriochloroform.

The assignment of Ha as the proton adjacent to the carbonyl group was verified by the relative magnitudes of the lanthanide induced shifts of Ha and Hb, produced by the addition of Eu (dpm)₃. The induced
shifts of both Ha and Hb were proportional to the molar ratio of Eu (dpm)\textsuperscript{3} to substrate, and the proportionality constants (Sa and Sb), the so called europium shift parameters\textsuperscript{78}, are shown in Table 4. To a first approximation the magnitude of S increases with decreasing separation of the proton from the europium\textsuperscript{78}. For lactams the shift reagent complexes at the carbonyl oxygen atom\textsuperscript{78} and thus the shift parameters for Ha and Hb show that Ha is closer to the carbonyl group than Hb, confirming the assigned positions of these protons.

Comparison of the coupling between Ha and Hb (Jab) with the values obtained by Moriconi and Meyer\textsuperscript{27,53} for the corresponding vicinal cis (5.0-5.1 Hz) and trans (2.0-2.8 Hz) couplings in \(\beta\)-lactams derived from acyclic 1,3-dienes confirms the cis fusion of the \(\beta\)-lactam ring in (121), (124) and (127).

By a combination of europium induced shift studies and homonuclear spin decoupling, a more detailed assignment of the n.m.r. spectrum of (121) was possible (Table 5). The relative magnitudes of the induced shift parameters for the protons of the ring methylene group showed that He was closer to the carbonyl group than was Hf, confirming the assignment of He as the proton cis to the carbonyl group. The broad singlet due to the olefinic protons (He and Hd) only resolved into two separate resonances at high concentrations of the shift reagent where the signals were too broad to allow the coupling between He and Hd to be observed.

2.2. Rearrangements of the N-chlorosulphonyl \(\beta\)-lactams.

The N-chlorosulphonyl \(\beta\)-lactams (120), (123) and (126) were found to rearrange, with varying degrees of ease, to yield 1,4-cycloaddition products. The rearrangement of the N-chlorosulphonyl \(\beta\)-lactams, produced in situ by the reaction between CSI and the corresponding diene, were followed by monitoring the i.r. spectra of the reaction mixtures, when the gradual decay of the spectra of the initially formed N-chlorosulphonyl \(\beta\)-lactams was observed.
TABLE 5. Coupling and europium induced shift parameters for 6-azabicyclo
[3,2,0]hept-3-en-7-one.

<table>
<thead>
<tr>
<th></th>
<th>Ha</th>
<th>Hb</th>
<th>Hc</th>
<th>Hd</th>
<th>He</th>
<th>Hf</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.37</td>
<td>4.46</td>
<td>5.94</td>
<td>5.94</td>
<td>2.68</td>
<td>2.38</td>
<td>7.42</td>
</tr>
<tr>
<td>s^+</td>
<td>9.7</td>
<td>4.3</td>
<td>(a)</td>
<td>(a)</td>
<td>7.4</td>
<td>4.4</td>
<td>9.0</td>
</tr>
<tr>
<td>Jb</td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jc</td>
<td>(b)</td>
<td>(b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jd</td>
<td>(b)</td>
<td>(b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Je</td>
<td>3.1</td>
<td>2.4</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jf</td>
<td>9.5</td>
<td>1.2</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

+ see Table 4; * Coupling constants ± 0.1 Hz; (a) the induced shift parameters of the olefinic protons (2.6, 2.3) could not be assigned with confidence, due to the similarity of the separations of these protons from the carbonyl group; (b) small couplings (~1Hz) were observed but, due to the accidental equivalence of the olefinic protons, these could not be assigned.

On monitoring the i.r. spectrum of a solution of the N-chlorosulphonyl β-lactam (120), prepared in situ in dichloromethane at ambient temperature, the gradual decay of the carbonyl band at 1818 cm\(^{-1}\) and the appearance of two new bands at 1790 and 1775 cm\(^{-1}\) was observed. A broad band at 1695 cm\(^{-1}\) which also appeared during the rearrangement was ascribed to polymeric material.
CHART 1. Reaction of CSI with 1,3-cyclopentadiene.
After five hours the rearrangement of (120) was almost complete and reduction of the reaction mixture with aqueous sodium sulphite gave 2-azabicyclo[2,2,1]hept-5-en-3-one (130) in 27.5% yield.

The identity of (130) was confirmed by comparison of its spectra properties and melting point with those reported by Van Leusen and Jagt for the lactam (130) prepared independently via hydrolysis of the Diels–Alder adduct of 1,3-cyclopentadiene and tosyl cyanide.  

A detailed analysis of the n.m.r. spectrum of the lactam (130) was obtained by a combination of homonuclear spin decoupling and europium induced shift studies (Table 6). On the basis of the europium shift parameters a complete assignment of the individual resonances was possible, since significant differences of induced shift were observed between the individual members of the proton pairs: Ha and Hb, He and Hd, and He and Hf, due to their differing separations from the carbonyl oxygen atom, which is the co-ordination site of the shift reagent.

The bicyclic lactam (130) offers a ready route to other 2-azabicyclo[2,2,1] systems; for example catalytic hydrogenation of (130) afforded the saturated lactam (131), while treatment of (130) with triethylxonium fluoroborate followed by work up with aqueous potassium carbonate gave the novel 2-azabicyclo[2,2,1] hepta-2,5-diene system (132) (Chart 1).

The i.r. spectrum of (132) showed an intense imine stretching band at 1620 cm⁻¹, and apart from the signals due to the ethyl group, the n.m.r. spectrum of (132) and the coupling pattern derived from spin decoupling were very similar to those found for the lactam (130). Further examples of the use of (130) as a precursor to other 2-azabicyclo[2,2,1] systems are also shown in Section Three.
TABLE 6. Coupling and europium induced shift parameters for 2-azabicyclo(2,2,1)hept-5-en-3-one (130).

\[
\begin{array}{cccccccc}
\text{H}_a & \text{H}_b & \text{H}_c & \text{H}_d & \text{H}_e & \text{H}_f & \text{H}_g \\
\hline
3.21 & 4.34 & 6.65 & 6.81 & 2.38 & 2.20 & 6.7-7.1 \\
13.3 & 3.5 & 5.7 & 3.2 & 6.5 & 4.2 & 13.5 \\
2.05 & & & & & & \\
1.45 & 1.45 & & & & & \\
0.75 & 2.1 & 5.45 & & & & \\
1.6 & 1.9 & & & & & \\
1.35 & 1.65 & & & & & \\
1.8 & 1.35 & & & & & \\
\end{array}
\]

+ See Table 5; * Coupling constants ± 0.05 Hz.

The rearrangement of the N-chlorosulphonyl \( \beta \)-lactam (123) produced in situ from 1,3-cyclohexadiene was also followed in dichloromethane at ambient temperature in the normal way (p.40) and the replacement of the carbonyl band at 1810 cm\(^{-1}\) by an intense imine stretching band at 1588 cm\(^{-1}\) was observed. After 30h, removal of the solvent in vacuo followed by recrystallization of the residue gave the N-chlorosulphonyl-imino-lactone (134) in 69% yield. (Chart 2). The structure of (134) was confirmed by the n.m.r. spectrum which showed single proton resonances at \( \delta \) 5.74 and \( \delta \) 3.90, which are consistent with the positions expected for allylic methine protons adjacent to an oxygen and imino group respectively.
CHART 2. Reaction of CSI with 1,3-cyclohexadiene.

[122] + CSI → [133] → [134] (CHCl₃ reflux) → [135] (NaOH aq.) → [136]
In addition, spin decoupling studies showed that there was no significant coupling between the methine protons or between the olefinic and methylene protons, which is consistent with the assigned bicyclo[2,2,2] structure (134). Although the imino-lactone (134) was isolable and could be fully characterized, further rearrangement to the N-chlorosulphonyl β-lactam (135) was found to occur on carrying out the reaction of CSI with the diene (122) in chloroform and refluxing the reaction mixture. After 17h the imino-lactone (134) had completely disappeared and the i.r. spectrum showed a single carbonyl band at 1753 cm⁻¹ and after removal of a small amount of insoluble polymeric material and evaporation of the solvent, the N-chlorosulphonyl lactam (135) was obtained in 90% yield as a dark red oil. Hydrolysis of the crude (135) with aqueous sodium hydroxide at pH 6-7 afforded the corresponding N-H lactam (136) in 35% yield after purification by chromatography. The i.r. spectrum of (136) showed a single N-H stretching band at 3480 cm⁻¹ and a carbonyl band at 1690 cm⁻¹, consistent with the presence of a 6-membered cyclic lactam moiety, while the n.m.r. spectrum, which showed no significant coupling between the two methine protons and between the olefinic and methylene protons confirmed the assigned bicyclo[2,2,2] structure (136).

The N-chlorosulphonyl β-lactam (126), produced in situ from 1,3-cycloheptadiene, rearranged slowly in dichloromethane at 30° and the gradual decay of the N-chlorosulphonyl β-lactam carbonyl band and the growth of an imine stretching band at 1580 cm⁻¹ were observed. After 25h, removal of the solvent in vacuo gave a quantitative yield of the N-chlorosulphonyl imino-lactone (138), whose spectral properties were consistent with the assigned bicyclo[3,2,2] structure.

Further rearrangement of the N-chlorosulphonyl imino lactone (138) occurred slowly in nitromethane at 80° over 5 days, and the formation of a conjugated nitrile (140) was indicated by the presence of a sharp nitrile
stretching band at 2210 cm$^{-1}$.

**CHART 3. Reaction of CSI with 1,3-cycloheptadiene.**

- Reaction of CSI with 1,3-cycloheptadiene (125) results in a new compound (126).
- Addition of $\text{CH}_2\text{Cl}_2$ at $30^\circ$ leads to compound (127).
- Treatment with $\text{Na}_2\text{SO}_3$ aq results in compound (139).
- Reaction with $\text{CH}_3\text{NO}_2$ at $80^\circ$ leads to compound (141) and (140).
After reduction of the reaction mixture with aqueous sodium sulphite, the nitrile (140) was isolated in 33% yield, together with a small amount (3%) of the corresponding amide (141) (Chart 3). The presence of the \( \alpha \beta, \gamma \delta \) unsaturated nitrile function in (140) was indicated by the sharp, intense nitrile stretching band at 2210 cm\(^{-1}\) and the ultraviolet absorption at 272.5 nm. The n.m.r. spectrum showed three olefinic signals (\( H_a, H_b \) and \( H_c \)) whose appearance as a doublet, doublet of doublets, and doublet of triplets respectively is consistent with the assignments shown below.

\[
\begin{align*}
\text{J}_{ab} &= 7 \text{ Hz.} \\
\text{J}_{bc} &= 12 \text{ Hz.} \\
\text{J}_{cd} &= \text{J}_{ce} = 4 \text{ Hz.}
\end{align*}
\]

The structure of the amide (141) was similarly indicated by the low frequency carbonyl band at 1665 cm\(^{-1}\) and the ultra-violet absorption at 274 nm. Spin decoupling studies showed the same coupling scheme for the olefinic protons as was observed for the nitrile (140), and in addition the central methylene group appeared as a quintet (\( J=5.5\text{Hz} \)) due to coupling to the two flanking allylic methylene groups.

The possibility of obtaining rearranged products in the reaction of CSI with 1,3-cyclo-octadiene was also investigated. In dichloromethane and nitromethane the formation of the N-chlorosulphonyl \( \beta \)-lactam (117) was complete in 24h, and 30 min. respectively, and no further significant changes occurred in the i.r. spectrum of the reaction mixture in dichloromethane after refluxing for 6 weeks. Although gradual decay of the N-chlorosulphonyl \( \beta \)-lactam (117) and the appearance of a broad band at 1720 cm\(^{-1}\) were observed
over 10 days on warming the reaction mixture in nitromethane to 50-60°, only polymeric material was obtained after work up with aqueous sodium sulphite.

2.3. Discussion.

The apparently exclusive initial formation of cis fused N-chlorosulphonyl β-lactams with the Markovnikov orientation expected for a dipolar 1,2-addition is in accord with the general behaviour observed in the reactions of CSI with olefins and acyclic 1,3-dienes. No evidence was obtained for the direct formation of 1,4-cycloaddition products, which appear to arise only via rearrangement of the initially formed N-chlorosulphonyl β-lactams. While the failure to observe direct 1,4-cycloaddition is not conclusive evidence against a concerted mechanism for the addition of CSI to cyclic 1,3-dienes, it is more readily reconciled with a dipolar 1,2-addition occurring via an associated 1,4-dipole (142).

The preferential formation of 1,2-cycloaddition products between CSI...
and acyclic 1,3-dienes may be rationalized, on the basis of a concerted mechanism, in terms of the unfavourable transoid conformation adopted by the dienes. For cyclic 1,3-dienes however, which are held in the cisoid conformation required for 1,4-cycloadditions, there is no obvious reason why the highly strained transition state for $\pi 2s + \pi 2a$ cycloaddition should be preferred to the transition state for a $\pi 2s + \pi 4s$ cycloaddition which, in terms of strain and the stability of the product formed, would be expected to be of lower energy.

The qualitative reactivity order for the dienes: 1,3-cyclopentadiene > 1,3-cyclohexadiene > 1,3-cycloheptadiene > 1,3-cyclo-octadiene, is consistent with the expected decrease in allylic stabilization of the incipient carbonium ion in the transition state for a dipolar addition. As the ring size increases, the conformational requirements of the ring cause the diene system to become progressively more twisted from the preferred coplanar arrangement, thus leading to a decrease in the overlap between the olefinic bonds.

The observed reactivity order is the inverse of that expected in terms of the secondary overlap of the highest occupied orbital of the diene system with the unoccupied antibonding $\pi^*$-orbital of the carbonyl group, which has been proposed as the factor favouring a concerted $\pi 2a + \pi 2s$, mechanism for the addition of CSI to olefinic systems. The expected increase in the energy of the highest occupied olefinic $\pi$ orbitals as the diene system becomes more twisted should lead to a better secondary overlap, due to the decreasing energy gap between the interacting orbitals. Thus the reactivity in a concerted $\pi 2a + \pi 2s$ cycloaddition would be expected to increase with the ring size of the diene.

The rearrangements of the N-chlorosulphonyl $\beta$-lactams (120), (123) and (126) may be rationalized in terms of heterolytic cleavage of the $\beta$-lactam ring to give a free dipolar intermediate (143) which then cyclizes via the oxygen or nitrogen atom of the ambident anion, yielding 1,4-addition products.
The order of the relative rates of rearrangement of the N-chlorosulphonyl β-lactams is similar to that for the reactivity of the corresponding dienes and may also be attributed (see p. 49) to the decreasing allylic stabilization of the incipient carbonium ion in the transition state for the cleavage of the β-lactam ring, due to the decreasing overlap with the double bond as the ring size increases. A similar effect, due to the decrease in overlap between the double bonds as the ring size increases has also been found in the Diels-Alder addition of cyclic 1,3-dienes to maleic anhydride, where the same reactivity order \( 1,3\)-cyclopentadiene > 1,3-cyclohexadiene > 1,3-cycloheptadiene > 1,3-cyclo-octadiene is also observed. For 1,3-cyclo-octadiene this effect is so marked that only polymeric material is formed in the reaction with maleic anhydride, and monomeric adducts are only formed with very reactive dienophiles such as phthalazine 1,4-dione.

The rearrangement of the N-chlorosulphonyl β-lactam (123) derived from 1,3-cyclohexadiene (Chart 2) is a very good example of initial kinetically controlled rearrangement, followed by rearrangement to a thermodynamically more stable product. The sequence of rearrangements may be explained in terms of heterolysis of the N-chlorosulphonyl β-lactam (123)
yielding a free 1,4-dipolar intermediate (133), which undergoes rapid reversible cyclization via the more nucleophilic oxygen atom of the ambident anion yielding the imino lactone (134), which in turn rearranges via irreversible cyclization of the dipolar intermediate through the nitrogen atom of the anionic moiety yielding the thermodynamically more stable N-chlorosulphonyl lactam (135).

The initial kinetically controlled rearrangement of the N-chlorosulphonyl β-lactam (126) derived from 1,3-cycloheptadiene (Chart 3) is followed, not by rearrangement to the corresponding lactam, but apparently by inter-or intra-molecular proton abstraction by the ambident anion of the dipolar intermediate (137) to yield the N-chlorosulphonyl amide (139). This may be due to the N-chlorosulphonyl lactam (144) also being unstable under the vigorous conditions required for the rearrangement of (138), which would then lead directly to the formation of the thermodynamically more stable substitution product.

Whether the proton abstraction step leads directly to the observed conjugated system via α-proton transfer or to a less highly conjugated system (145) via δ-proton transfer is uncertain, since rapid isomerization of (145) to the more stable product (139) would be expected to occur under
the vigorous conditions employed.

\[
\begin{align*}
&\text{NHSO}_2\text{Cl} \\
\Rightarrow &\text{NHSO}_2\text{Cl}
\end{align*}
\]

The conditions required for the rearrangement of (138) also appear to lead to decomposition of the N-chlorosulphonyl amide (139), since the nitrile (140) was detected in the reaction mixture prior to the work up.

The behaviour of the N-chlorosulphonyl \(\beta\)-lactam (120) derived from 1,3-cyclopentadiene is anomalous in that the rearrangement apparently led directly to the N-chlorosulphonyl lactam (129) and the corresponding imino lactone (146) was not detected. This may be due to the imino lactone (146) being so unstable with respect to the lactam (129) that it is present in too small a standing concentration to be detected even by i.r. spectroscopy. Alternatively, the expected smaller energy difference, compared to the 1,3-cyclohexadiene system, between the dipolar intermediate and the 1,4-addition products, due to the more efficient stabilization of the cationic centre and the greater strain in the bicyclo[2,2,1] system, may lead to sufficient "product character" in the transition state to enable the rearrangement to the lactam (129) to be both the kinetically and thermodynamically favoured process.

1,3-Cycloheptadiene appears to mark the limit at which rearrangement products of the N-chlorosulphonyl \(\beta\)-lactams are stable under the conditions
required for the rearrangement to occur, and only polymeric material was produced in the rearrangement of the N-chlorosulphonyl β-lactam derived from 1,3-cyclo-octadiene.

A decreasing tendency to form 1,4-cycloaddition products as the ring size increases has also been observed by Krow in the boron trifluoride catalysed addition of methylene bisurethane to cyclic 1,3-dienes, where the ratio of cyclo-addition (147) to substitution (148) product decreases with increasing ring size of the diene.

\[
\begin{align*}
\text{CH}_2(\text{NHC}_2\text{Et})_2 + \quad \text{BF}_3 & \rightarrow \quad \text{CH}_2\text{NHC}_2\text{Et} \\
\quad \text{(147)} & \quad \text{(148)}
\end{align*}
\]

2.4. Summary.

In general terms the reactions of cyclic 1,3-dienes with CSI are similar to those of acyclic 1,3-dienes, in that initial stereospecific cis Markovnikov addition yielding N-chlorosulphonyl β-lactams is followed by rearrangement to 1,4-addition and/or substitution products. A major difference is found, however, in the course of the rearrangements. With the cyclic 1,3-dienes the rearrangement products are formed in a perfectly delineated stepwise manner. The rearrangements of the N-chlorosulphonyl β-lactams derived from acyclic 1,3-dienes, however, yield mixtures of products, which may be rationalized in terms of irreversible competitive cyclization via oxygen and nitrogen, and proton transfer in the dipolar intermediate produced by heterolysis of the β-lactam.

Although stepwise reaction sequences, similar to those found for the cyclic 1,3-dienes, have been proposed for the reaction of CSI with
1,3,5-cycloheptatriene\textsuperscript{83}, 1,3,5-cyclo-octatriene\textsuperscript{83} and bicyclo[4,2,0]octa-2,4-diene\textsuperscript{84}; the separation of the individual steps was not as clean especially with regard to the initial 1,2-addition and primary rearrangement steps, as that found for the cyclic 1,3-dienes.

The perfectly delineated stepwise reaction sequence shown by 1,3-cyclohexadiene is a unique example of an initial 1,2-cycloaddition followed by successive kinetically and thermodynamically controlled rearrangements to 1,4-cycloaddition products, where, under suitable conditions each of the three isomers may be isolated in high yield.
SECTION THREE

INVERSION AT NITROGEN IN 2-AZABICYCLO[2,2,1]AND[2,2,1] SYSTEMS.

The availability of the azabicyclic systems (149), (152), and (155), via reduction of the carbonyl group of the corresponding lactams (130), (131) and (136), prompted an investigation of inversion at the nitrogen atom, and of the relative populations of the invertomers, in such systems. In most of the reported examples of inversion at a nitrogen atom the populations of the invertomers have been equal or very nearly so. Due to the difference between the environments of the exocyclic substituent on the nitrogen atom in the invertomers of the above bicyclic systems significant difference between the invertomer populations would be expected in these systems.

Previous investigations by other workers have shown that the energy barrier to inversion at a nitrogen atom is raised by inclusion of the nitrogen atom in a cyclic structure and that the energy barrier increases as the ring size decreases, in addition, Lehn and Wagner have noted that the introduction of a second bridge to give a bicyclic structure causes a further increase in the energy barrier. In the present work it was hoped to gain additional information on the effects of the presence of an olefinic bond and variations in ring size on the energy barrier to inversion at nitrogen in azabicyclic systems.

The presence of an electronegative substituent on a nitrogen atom has been shown to increase the energy barrier to inversion and in many cases has showed otherwise rapid inversion to the point where the separate
invertomers could be detected by means of low temperature n.m.r. spectroscopy. In addition, by replacing the hydrogen atom on the nitrogen atom by some other group, the possibility of inversion occurring by an irregular process, such as a protonation/deprotonation equilibrium, may be avoided.

In order to facilitate comparison with the results obtained on inversion at nitrogen atoms in other systems the N-chloro derivatives (151), (154) and (157) of the parent systems were used in this study.
3.1. Results.

Solutions of the chloroamines in Arcton 11 were prepared by a modification of the method of Graefe, by shaking a solution of the corresponding amine hydrochloride (150), (153) or (156) (ca. 100 mg) in water (0.5 ml) with commercial sodium hypochlorite solution (0.5 ml) for 5 min. and extracting the mixture with Arcton 11 (ca. 1 ml). The solutions of the N-chloroamines were washed with water (1 ml), dried and evaporated to a suitable volume for use as an n.m.r. sample.

The n.m.r. spectra of (151), (154) and (157) at or above ambient temperature (Figures 1-3) were consistent with those expected under conditions where inversion was rapid on the n.m.r. time scale and each proton gave only one signal whose position was the population weighted mean of the positions of the signals due to that proton in the separate invertomers.

The signals due to the bridgehead methine protons (H_a and H_d) were assigned on the basis of their chemical shifts. In each case the signals due to the exo (H_b) and endo (H_c) protons of the methylene group adjacent to the nitrogen atom appeared as the two halves of an AB system with a coupling constant typical of those found for geminal protons in such systems (J=10-12 Hz). The assignment of these signals was made on the basis of the fine structure due to vicinal and long range coupling to other protons. In the bicyclo [2,2,1] systems the signal due to H_b showed an additional coupling typical of that found in such systems for coupling between the exo proton and the adjacent bridgehead proton (J=3-4 Hz).
FIGURE 1. N.m.r. spectra of 2-chloro-2-azabicyclo[2,2,1]hept-5-ene (151)
In the bicyclo \([2,2,2]\) system also, \(H_b\) showed an additional coupling \((J=2\ \text{Hz})\) to the bridgehead proton \(H_d\). In addition \(H_c\) showed further coupling and each half of the doublet appeared as a closely spaced triplet \((J=2.5\ \text{Hz})\) due to approximately equal vicinal coupling to \(H_d\) and \(\omega\)-coupling to the anti proton \(H_e\) of the methylene bridge.

As the solutions of the N-chloroamines were cooled, the spectra initially broadened, and then sharpened until further cooling produced no significant changes. The low temperature spectra of each of the N-chloroamines (Figures 1 - 4) indicated the presence of two species, which were assigned as the \textit{exo}-chlorine and \textit{endo}-chlorine invertomers.

In each case the signals due to \(H_b\) (\textit{exo}) and \(H_c\) (\textit{endo}) split out into major and minor signals due to these protons in the two invertomers \((H_b\text{(maj.)}, H_b\text{(min.)})\) and \((H_c\text{(maj.)}, H_c\text{(min.)})\). The assignments of the minor signals were based on their inter-relationships as revealed by INDOR and/or spin decoupling studies.

2-Chloro-2-azabicyclo[2,2,1]hept-5-ene (151)

The minor doublet at \(\delta 1.80\) was found to be coupled to a similar small doublet, half of which was obscured by the signal due to \(H_c\text{(maj.)}\), at \(\delta 2.20\). The coupling between these signals \((J=9\ \text{Hz})\) was significantly smaller than the typical values of \(J_{bc}\) (11-12 Hz) found in this series (Table 7). Neither of these minor doublets showed a line width change consistent with the collapse of a coupling of 3 Hz (expected for coupling between \(H_b\text{(min.)}\) and \(H_d\text{(min.)}\)) on irradiation of the multiplet at \(\delta 3.1\) which was assumed to include \(H_d\text{(min.)}\). On the basis of these results, these minor doublets were assigned to the bridge methylene protons.

The integration of the low temperature spectrum revealed that the multiplet at \(\delta 3.1\) was composed of signals due to one proton \(H_d\text{(maj.)}\) of the major invertomer, and three protons \((H_b\text{(min.)}, H_c\text{(min.)}, H_d\text{(min.)})\) of the minor invertomer.
TABLE 7. Selected n.m.r. data* for the invertomers of the N-chloroamines (151), (154) and (157).

<table>
<thead>
<tr>
<th>INVERTOMER</th>
<th>major</th>
<th>minor</th>
<th>major</th>
<th>minor</th>
<th>major</th>
<th>minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>endo</td>
<td>exo</td>
<td>endo</td>
<td>exo</td>
<td>exo</td>
<td>endo</td>
</tr>
</tbody>
</table>

| H_b(S)     | 3.64  | ca.3.1| 3.49  | 2.76  | 2.98  | 3.41  |
|            | (d^2ll,3) |      | (db 11) | (db 11) | (d^2b 12,4) | (d^2b,10-12,3) |
| H_c(S)     | 2.04  | ca.3.1| 2.50  | 3.22  | 3.20  | 2.37  |
|            | (d,11) |      | (dm 11) | (db 11) | (d,12) | (dm 10-12) |
| H_d(S)     | ca.3.1| ca.3.1|       |       | 2.43  | ca.2.3|
|            | (m)   |      |       |       | (m)   | (m)   |
| H_e(S)     | 1.58  | 1.80  |       |       |       |       |
|            | (db,9) |      |       |       |       |       |
| H_f(S)     | 1.58  | 2.22  |       |       |       |       |
|            | (db,9) |      |       |       |       |       |
| J_{bc}     | **    | 11    | 11    | 11    | 12    | 10-12 |
| J_{bd}     | 3     |       |       |       | 4     | 3     |
| J_{cd}     | 0     |       |       |       |       |       |
| J_{ce}     | 0     |       |       |       |       |       |
| J_{ef}     | 0     |       |       |       | 9     |       |

* - in Arcton 11 (CFCl_3)

** - coupling constants (Hz)
FIGURE 2. N.m.r. spectra of 2-chloro-2-azabicyclo[2,2,2]oct-5-ene (157)
2-Chloro-2-azabicyclo[2,2,2]oct-5-ene (157)

The two minor doublets at \( \delta 2.76 \) and \( \delta 3.22 \) showed the same coupling constant \((J=11 \text{ Hz})\) as was found between \( H_d \) and \( H_c \) and between \( H_d(\text{maj.}) \) and \( H_c(\text{maj.}) \), and on this basis these signals were assigned to the protons of the methylene group adjacent to the nitrogen atom in the minor invertomer. Ideally the position of the signal due to a proton under rapid inversion conditions is the population weighted mean of the positions of the signals due to that proton in the two invertomers, and on this basis only the assignment of the signal at \( \delta 2.76 \) to \( H_d(\text{min.}) \) and that at \( \delta 3.22 \) to \( H_c(\text{min.}) \) would be consistent with the observed magnitudes of these signals. The inverse assignment would lead to an expected invertomer ratio of ca. 1:1 rather than the observed ratio of 12:1.

2-Chloro-2-azabicyclo[2,2,1]heptane (154)

Two minor doublets were also found in the low temperature spectrum of (154) at \( \delta 2.37 \) and \( \delta 3.41 \), and were similarly assigned to \( H_c(\text{min.}) \) and \( H_d(\text{min.}) \) respectively on the basis of the magnitude of their mutual coupling \((J=10-12 \text{ Hz})\) and with due consideration to their relative magnitude and position with respect to the corresponding averaged and major signals. A broad minor signal at \( \delta 2.30 \) was also observed and was assigned to \( H_d(\text{min.}) \) while the two halves of an AB system at \( \delta 2.05 \) and \( \delta 1.37 \) \((J=10 \text{ Hz})\) were assigned to the bridge methylene protons \( H_f(\text{maj.}) \) and \( H_e(\text{maj.}) \) respectively.

For the unsaturated N-chloroamines (151) and (157) the major invertomer would, on the basis of the expected steric interactions experienced by exo and endo substituents in such systems, be expected to have the chlorine atom in the endo position.

Circumstantial evidence for the preference of the endo invertomer in (151) and (157) is found in the change in relative population of the
FIGURE 3. N.m.r. spectra of 2-chloro-2-azabicyclo[2,2,1]heptane (154)
FIGURE 4. Low temperature n.m.r. spectrum of 2-chloro-2-azabicyclo[2,2,1]heptane (154)
invertomers which occurs in going from (151) to the saturated analogue (154). In view of the expected increased steric hindrance in the endo invertomer of (154) due to the replacement of the double bond by methylene groups, the more equal population of the invertomers of (154) can only be explained in terms of the endo invertomer of (151) being the predominant form. A similar argument may be used for (157) whose saturated analogue has equally populated invertomers.

From the differences between the positions of the signals due to $H_b^{maj.}$ and $H_b^{min.}$ and similarly between $H_c^{maj.}$ and $H_c^{min.}$ (Table 7) in (151) and (157) it appears that changing the orientation of the chlorine atom from trans to cis to a proton on the adjacent carbon atom, causes the signal due to that proton to shift to higher field. A similar variation of chemical shift with the orientation of a vicinal chlorine atom is also found in 5,6-dichloro-bicyclo[2,2,1]hept-2-enes, confirming the assignment of the major invertomers of (151) and (157) as having the chlorine atom in the endo position.

On this basis it can be seen that the major invertomer of the saturated [2,2,1] system (154) must have the chlorine atom trans to $H_c^{maj.}$, i.e. in this case the exo invertomer predominates. This is consistent with the similar preference shown for the exo position by substituents in the corresponding carbocyclic system.

The relative populations of the invertomers of (151), (154) and (157) were calculated from integration of the low temperature spectra and, together with the equilibrium constants and free energy differences for the inversions from the endo chlorine to exo chlorine conformations, are shown in Table 8.
TABLE 8. Invertomer populations, equilibrium constants and free energy difference for the N-chloroamines (151), (154) and (157).

<table>
<thead>
<tr>
<th>Exo-Cl(%)</th>
<th>Keq</th>
<th>ΔG° (Kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(151) 54°</td>
<td>12±5</td>
<td>+0.9±0.2</td>
</tr>
<tr>
<td>(154) 84°</td>
<td>9±5</td>
<td>+0.9±0.3</td>
</tr>
<tr>
<td>(157) 87°</td>
<td>75±5</td>
<td>-0.4±0.1</td>
</tr>
</tbody>
</table>

\[ a \] for the equilibrium endo-Cl ⇌ exo-Cl

\[ b \] free energy change from endo-Cl to exo-Cl
Although the coalescence temperatures for the signals due to $H_b$ and $H_c$ could not be obtained directly from the spectra, due to their complexity and the large difference in the size of the signals shown by these protons, in the exo and endo invertomers, crude estimates were obtained from plots of the positions of the major and averaged signals due to the $H_b$ and/or $H_c$ against temperature (e.g. Figure 5). In each case the coalescence temperature was taken as the mean of the temperature range over which the change from rapid to slow inversion occurred and the error as plus or minus half of this range.

By using population weighted values for the lifetimes of the systems (151), (154) and (157) (Equations 1 and 2)\textsuperscript{92} the rate constants for the inversions from endo-chlorine to exo-chlorine at the coalescence temperatures were calculated using the Gutowsky approximation\textsuperscript{93} (Equation 3).
\[ \bar{\tau} = \frac{\tau_{\text{exo}} \cdot \tau_{\text{endo}}}{\tau_{\text{exo}} + \tau_{\text{endo}}} \]  

(1)

\[ \frac{\tau_{\text{exo}}}{\tau_{\text{endo}}} = \text{Keq} \]  

(2)

\[ \bar{\tau} = \frac{\tau_{\text{endo}} \cdot \text{Keq}}{1 + \text{Keq}} = \frac{1}{\pi \cdot \delta v \cdot \sqrt{2}} \]  

(3)

\[ k_{\text{endo}} = \frac{1}{\tau_{\text{endo}}} \]

\( \bar{\tau} \) - population weighted lifetime for the system; \( \tau_{\text{exo}}, \tau_{\text{endo}} \) - lifetimes of \( \text{exo} \) and \( \text{endo} \) invertomers; \( \text{Keq} \) - equilibrium constant for \( \text{endo} \leftrightarrow \text{exo} \); \( \delta v \) - frequency separation between the signals due to the same proton in the two invertomers; \( k_{\text{endo}} \) - rate constant for the inversion \( \text{endo} \to \text{exo} \).

By using the value of \( k_{\text{endo}} \), obtained above, in the Eyring equation (Equation 4) the free energy of activation for the inversion \( \text{endo} \to \text{exo} \) may be calculated.

\[ \Delta G^\pm = 2.303 \ RT_c \ (10.319 + \log_{10} T_c - \log_{10} k_{\text{endo}}) \]  

(4)

\( T_c \) - coalescence temperature for the signals of the proton being studied.

The coalescence temperatures, frequency differences and calculated free energies of activation for the systems studied are presented in Table 9.
TABLE 9. Coalescence temperatures, rate constants and free energies of activation for inversion at nitrogen in the N-chloroamines (151), (154) and (157).

<table>
<thead>
<tr>
<th></th>
<th>(151)</th>
<th>(154)</th>
<th>(157)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta G^{d}$</td>
<td>$14.6^{\pm}1.1$</td>
<td>$11.6^{\pm}0.9$</td>
<td>$11.5^{\pm}0.8$</td>
</tr>
<tr>
<td>$k_{\text{endo}}$</td>
<td>$57^{\pm}26$</td>
<td>$218^{\pm}81$</td>
<td>$29^{\pm}16$</td>
</tr>
<tr>
<td>$T_{c}^{b}$</td>
<td>$15^{\pm}15$</td>
<td>$-30^{\pm}15$</td>
<td>$-50^{\pm}10$</td>
</tr>
<tr>
<td>$\delta\nu^{a}$</td>
<td>$100^{\pm}5$</td>
<td>$44$</td>
<td>$84$</td>
</tr>
</tbody>
</table>

a - frequency separation (Hz) between the signals due to the major and minor invertomers  
b - coalescence temperature ($^\circ$)  
c - rate constants (s. $^{-1}$) for the inversion endo-Cl $\rightarrow$ exo-Cl,  
d - free energy of activation (Kcal.mol.$^{-1}$) for the inversion endo-Cl $\rightarrow$ exo-Cl.

3.2. Discussion.

The exo:endo ratios for the unsaturated N-chloroamines (151) and (157) show a distinct preference for the endo invertomer which is qualitatively consistent with the expected steric interactions in the two invertomers. This behaviour contrasts with the much larger exo:endo ratios found by Ouellette and Booth for the corresponding carbocyclic systems, even with substituents far more bulky than a chlorine atom.$^{94,95}$
An electrostatic repulsion between the olefinic $\pi$-bond and the substituent has been suggested by the above workers to account for the unexpected preference for the exo invertomer in the nitro substituted bicyclo [2,2,1] system. The results obtained in the present studies would suggest that this repulsion is very much smaller in the N-chloroamines and may even be an attractive interaction. This would be consistent with the greater polarizability of the chlorine atom, its expected lower partial negative charge due to the neighbouring nitrogen atom, and the greater bond length of the nitrogen chlorine bond in comparison to the corresponding parameters for the substituents used in the studies of the analogous carbocyclic systems.

The failure of Biehler and Fleury to observe the presence of two invertomers in the low temperature n.m.r. spectra of 2-substituted-3,3-dicyano-2-azabicyclo[2,2,1]hept-5-enes was attributed by these workers to either:

a) the inversion being very rapid even at low temperatures, or

b) an almost 100% population of the exo invertomer.

However, in view of the results obtained in the present study, it appears possible that, due to the large substituents ($\text{OSO}_2\text{C}_6\text{H}_4\text{CH}_3$, $\text{OCOC}_6\text{H}_5$) used by Biehler and Fleury, an almost 100% population of the endo invertomer may be responsible for the failure to observe inversion.

The activation energies for the inversion at nitrogen in the N-chloroamines, while only approximate, agree well with those calculated for other cyclic N-chloroamines (Table 10).
### TABLE 10. Barriers to inversion at nitrogen in N-chloroamines

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>$\Delta G^\ddagger$ (Kcal. mol$^{-1}$)</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-Cl</td>
<td>&gt;23</td>
<td>86</td>
</tr>
<tr>
<td>N-Cl</td>
<td>11.5</td>
<td>86</td>
</tr>
<tr>
<td>N-Cl</td>
<td>10.4</td>
<td>87</td>
</tr>
<tr>
<td>N-Cl</td>
<td>14.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>This work</td>
</tr>
<tr>
<td>N-Cl</td>
<td>11.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>This work</td>
</tr>
<tr>
<td>N-Cl</td>
<td>11.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>This work</td>
</tr>
<tr>
<td>N-Cl</td>
<td>10.5</td>
<td>85</td>
</tr>
<tr>
<td>N-Cl</td>
<td>10.1</td>
<td>85</td>
</tr>
<tr>
<td>N-Cl</td>
<td>8.4</td>
<td>85</td>
</tr>
</tbody>
</table>

<sup>a</sup> - for the inversion endo Cl → exo Cl
From these results the effect of angle strain on the activation energy for the inversion at nitrogen may be seen. If the endocyclic bond angle of the nitrogen atom is decreased, then the angle strain in the transition state for inversion, in which the nitrogen atom is sp$^2$ hybridized with a preferred endocyclic bond angle of 120°, will increase, leading to an increase in the free energy of activation for this process.

The expected increased angle strain in the bicyclo[2,2,1] system (154) compared to the 5-membered monocyclic analogue is reflected in the higher activation energy for inversion found in the bicyclic system, a similar effect has also been noted by Lehn and Wagner in the [3,3,2] system compared to the 7-membered monocyclic analogue.

The increased inversion barrier found for the unsaturated bicyclic systems (151) and (157) compared to those of the corresponding saturated systems (154) and (158) may be explained in terms of the increased angle strain caused by replacing the carbon-carbon single bond with a shorter, and less flexible double bond. By comparison of the bicyclo[2,2,1] systems (151) and (154) with their bicyclo[2,2,2] counterparts the expected additional angular strain engendered by replacing the two carbon atom bridge with a single bridging methylene may be seen.

The cumulative effects of the introduction of a olefinic bond and a two methylene bridge on the energy barrier to inversion may be seen by comparison of the values obtained for N-chloro-pyrolidine and N-chloro-2-azabicyclo[2,2,1]hept-5-ene (151). This latter shows a higher barrier to inversion than is found in any monocyclic chloroamine with the exception of N-chloroaziridines.
SECTION FOUR

REACTION OF CHLOROSULPHONYL ISOCYANATE WITH VINYL CYCLOPROPANES.

Vinyl cyclopropanes show many formal similarities to 1,3-dienes. This may be attributed to the ability of a cyclopropyl group to interact with an adjacent \( \pi \)-system via overlap of the sigma bonds of the cyclopropyl ring with a \( p \)-orbital on an adjacent carbon atom \(^ {97, 98, 99} \) (\( \pi \sigma \pi \) delocalization).

The conjugative ability of the cyclopropyl group may be seen in the spectral properties of systems containing a \( \pi \)-system adjacent to a cyclopropyl ring \(^ {100} \), for example:-

a) cyclopropyl ketones \(^ {101} \), cyclopropyl olefins \(^ {100, 102} \), cyclopropyl benzenes \(^ {103, 104} \) and other cyclopropyl substituted unsaturated systems \(^ {100, 105} \) show u.v. absorption maxima at longer wavelength than those of the corresponding isopropyl-substituted analogues.

b) the carbonyl stretching bands of cyclopropyl ketones are at lower frequency than those of the corresponding alkyl ketones \(^ {106} \).

c) the positions of the signals due to the cyclopropyl carbon atoms and the carbinyl carbon atom in the \(^ {13} \)C n.m.r. spectra of cyclopropyl carbinyl cations, compared to the corresponding signals from alkyl carbonium ions indicates a considerable delocalization of the positive charge into the cyclopropyl ring \(^ {107} \).

d) cyclopropyl carbinyl cations show an intense long wavelength u.v. absorption which is not observed in the corresponding alkyl carbonium ions \(^ {108} \).

Chemical manifestations of the conjugative ability of the cyclopropyl group may be seen in:-

a) the unexpectedly rapid rates of unimolecular solvolysis of cyclopropyl methyl derivatives compared to those of the corresponding alkyl substituted derivatives \(^ {109 - 112} \), which may be attributed to stabilization of the incipient carbonium ion in the transition state.
b) the above reactions lead to rearranged products\textsuperscript{109,113} and can only be explained in terms of delocalization of the charge in the carbonium ion intermediate, allowing nucleophilic attack to occur at the cyclopropyl carbon atoms.

The similarity between 1,3-dienes and vinyl cyclopropanes may be seen in the ability of α-cyclopropylstyrene to undergo conjugate (1,5) electrophilic addition with acetic and trifluoracetic acids\textsuperscript{114}; and to undergo a Diels Alder reaction with maleic anhydride\textsuperscript{115}.

![Reaction diagram](image)

The similarities between 1,3-dienes and vinyl cyclopropanes prompted the investigation of the reactions of chlorosulphonyl isocyanate (CSI) with various substituted vinyl cyclopropanes as a logical extension of the previously described reactions of 1,3-dienes. In view of the ability of vinyl cyclopropanes to undergo conjugate dipolar and concerted additions, and the ready rearrangement of cyclopropyl carbiny! cations observed in the unimolecular solvolysis of cyclopropyl methyl derivatives, it was thought possible that the reaction of CSI with vinyl cyclopropanes might lead to conjugate addition products either directly or via rearrangement of an initially formed N-chlorosulphonyl β-lactam.

The reactions of CSI with various vinylcyclopropane systems have been investigated by other workers. In some cases, e.g. bicyclo[3,1,0]hex-2-ene\textsuperscript{55}, cis-dicyclopentadiene\textsuperscript{32} (159), no rearrangements involving
The object of the work described in this section was to investigate
the possibility of such rearrangement occurring in simple substituted vinyl cyclopropanes. The reactions of 2-cyclopropylpropene and α-cyclopropylstyrene which are presented in this section have recently been the object of less detailed investigations by other workers and preliminary reports of some aspects of the reactions have been published 56, 119.

4.1. Investigation of the reaction of chlorosulphonyl isocyanate with vinyl cyclopropane (162), 2-cyclopropylpropene (165) and α-cyclopropylstyrene (168).

The reactions of CSI with the vinylcyclopropanes (162), (165) and (168) were followed by monitoring the i.r. spectra of the reaction mixtures as in the case of the cyclic 1,3-dienes (Section Two). In each case the formation of a N-chlorosulphonyl β-lactam as the sole carbonyl containing product was indicated by the appearance of a high frequency carbonyl band in the region of 1810 to 1820 cm⁻¹. As in the case of the 1,3-dienes the N-chlorosulphonyl β-lactams were converted to the corresponding NH β-lactams for characterization.

Vinylcyclopropane. (162) reacted smoothly with CSI in deuteriochloroform at ambient temperature over 1h, and the i.r. spectrum of the reaction mixture showed only a single band at 1815 cm⁻¹. Removal of the solvent in vacuo gave a quantitative yield of the N-chlorosulphonyl β-lactam (163), which, after reduction with aqueous sodium sulphite, gave 4-cyclopropyl-2-azetidinone (164) in 90% yield.
On allowing a mixture of CSI and 2-cyclopropylpropene in dichloromethane to warm from -78° to ambient temperature, the CSI was rapidly consumed over 7 min, and the formation of an N-chlorosulphonyl β-lactam was indicated by the presence of an intense carbonyl band at 1815 cm⁻¹. Immediate reduction of the reaction mixture at -78° with benzenethiol/pyridine gave 4-cyclopropyl-4-methyl-2-azetidinone (167) in 86% yield.

\[ \text{CSI} + \text{CH}_2\text{Cl}_2 \xrightarrow{\text{CH}_3} \text{N}^\text{SO}_2\text{ClO} \xrightarrow{\text{PhSH/Py}} \text{CH}_3 \]

The reaction between CSI and (165) was also followed by n.m.r. spectroscopy by slowly warming a reaction mixture in deuteriochloroform from -196° to -50° over 2h in the spectrometer probe. The olefin (165) was completely consumed and the spectrum of the reaction mixture, which showed signals at: δ 2.73 (2H, s), 1.7 (3H, s), 1.8-1.3 (1H, m) and 1.1-0.4 (4H, m), was consistent with the structure (166). No other signals were observed in the spectrum and by using chloroform as a quantitative internal standard the yield of (166) was calculated to be 85%.

The reaction of CSI with α-cyclopropylstyrene (168) in dichloromethane was also very rapid. On allowing the reaction mixture to warm from -78° to -30° for 15 min. the i.r. spectrum of the mixture showed almost complete consumption of the CSI and the formation of an N-chlorosulphonyl β-lactam was indicated by the appearance of an intense band at 1810 cm⁻¹. Reduction of the reaction mixture with benzenethiol/pyridine at -78°
gave a 57% yield of 4-cyclopropyl-4-phenyl-2-azetidinone (170).

\[
\text{Ph} + \text{CSI} \xrightarrow{\text{CH}_2\text{Cl}_2} \text{Ph} \text{N} \text{SO}_2\text{Cl} \text{O} \xrightarrow{\text{PhSH/Py}} \text{Ph} \text{N} \text{O}
\]

The reaction between CSI and (168) in carbon tetrachloride was also followed by n.m.r. spectroscopy in the manner described for the reaction between CSI and (165) (p. 77). On warming the reaction mixture from -30° to -15° over 2h, the olefin was completely consumed. The spectrum of the reaction mixture which showed signals at: \(7.25\) (5H, m), \(2.85\) (2H, s), \(2.4-1.4\) (1H, m) and \(1.4-0.4\) (4H, m) was consistent with the assigned structure (169) of the N-chlorosulphonyl \(\beta\)-lactam.

Each of the NH \(\beta\)-lactams (164), (167) and (170) showed the single NH stretching band and high frequency carbonyl band characteristic of such compounds. The retention of the cyclopropyl ring in the NH and N-chlorosulphonyl \(\beta\)-lactams was confirmed by the presence of a characteristic high field four proton multiplet between \(1.4\) and \(0.4\) due to the methylene groups in the cyclopropyl ring.

The orientation of the N-chlorosulphonyl \(\beta\)-lactam ring in (163), (166) and (169) was confirmed by their n.m.r. spectra, each of which showed signals corresponding to two protons in the region expected for a methylene group adjacent to the carbonyl group of an N-chlorosulphonyl \(\beta\)-lactam. Although the two protons in these methylene groups are adjacent to an assymetric centre and thus non equivalent, only in (163) were the two protons observed as well separated, mutually coupled signals. In (166) and (169) the methylene groups appeared as broad singlets due to the near magnetic equivalence of the individual protons. For the NH
β-lactam (164) the methine and methylene protons on the β-lactam ring formed a complex pattern and no confident assignments of these signals could be made. Although (167) and (170) each showed a two proton signal in the region expected for a methylene adjacent to the carbonyl group of a β-lactam ring, only the very closely spaced inner lines of the expected AB quartet were observed, the outer lines being too weak to be observed due to the near magnetic equivalence of the individual protons.

4.2. Rearrangements of the N-chlorosulphonyl β-lactams.

In general the initially formed N-chlorosulphonyl β-lactams (163), (166) and (169) rearranged with varying degrees of ease to βγ- and/or αβ-unsubstituted N-chlorosulphonyl amides. Retention of the cyclopropyl group in these compounds and their derivatives was indicated by the presence in their n.m.r. spectra, of a four proton multiplet between δ 1.2 and δ 0.4, characteristic of the methylene protons of a cyclopropyl ring. Only with the phenyl substituted olefin (168) was a rearrangement involving the cyclopropyl ring observed and even then this only occurred in preference to rearrangement to an αβ-unsaturated amide when the rearrangement was carried out in ether.

In each case the rearrangement of the N-chlorosulphonyl β-lactam, produced in situ by the reaction of CSI with the corresponding olefin, was followed by monitoring the i.r. spectrum of the reaction mixture, when the decay of the N-chlorosulphonyl β-lactam carbonyl band and the appearance and growth of bands due to the rearrangement products was observed.

The rearrangement of the N-chlorosulphonyl β-lactam (163) occurred slowly in dichloromethane at ambient temperature. After six weeks, the i.r. spectrum showed only a broad band at 1750 cm⁻¹ in the carbonyl region and treatment of the reaction mixture with triethylamine gave the
nitriles (175) and (174) in 14 and 8% yield respectively (Chart 4).

All other attempted work up procedures (aqueous acid hydrolysis, reduction with aqueous sodium sulphite, hydrolysis at pH 6-7 and reduction with benzenethiol/pyridine) failed to yield detectable amounts of amides or other products and only polymeric tars were obtained.

The presence of the $\alpha$-unsaturated nitrile moiety in (175) was indicated by the sharp intense i.r. band (2220 cm$^{-1}$) and the u.v. absorption
at 226.5 nm; and the magnitude of the coupling constant between the olefinic protons (J=16 Hz) confirmed the trans substitution of the olefinic bond. The structure of (174) was confirmed by the weak i.r. band at 2250 cm\(^{-1}\) characteristic of non-conjugated nitriles and the presence of a methylene group coupled (J=6 Hz) only to the single olefinic proton.

After warming a mixture of CSI and a slight excess of 2-cyclopropyl-propene (165) in dichloromethane from -78\(^\circ\) to 0\(^\circ\) for 1h, the i.r. spectrum showed bands at 1750 and 1720 cm\(^{-1}\) in the carbonyl region due to the amides (178) and (179) (Chart 5). Treatment of the reaction mixture with triethylamine afforded a mixture of 3-cyano-2-cyclopropylpropene (180) (46\%) and an E,Z mixture of 1-cyano-2-cyclopropylpropenes (181) (30\%).

The presence of a weak band at 2245 cm\(^{-1}\) in the i.r. spectrum of (180), characteristic of a non conjugated nitrile, and the two broad singlets in the n.m.r. spectrum in the regions expected for an olefinic methylene group and a methylene group which is both allylic and adjacent to a nitrile function were consistent with the assigned structure.

The structure of (181) was indicated by an i.r. band at 2215 cm\(^{-1}\) and a u.v. band at 227 nm, characteristic of an \(\omega\beta\)-unsaturated nitrile, and the absence of major coupling shown by the single olefinic proton. The allylic methyl signals due to the geometric isomers of (181) appeared as doublets at 81.83 (J=1 Hz) and 81.57 (J=1.5 Hz) in the ratio 2:1. The small coupling constant and lower field position of the methyl signal due to the major isomer is consistent with the cis orientation of the nitrile and methyl groups assigned for this isomer (181a).

On carrying out the reaction of equimolar proportions of CSI and the olefin (165) in dichloromethane at ambient temperature the rearrangement of the N-chlorosulphonyl \(\beta\)-lactam (166) to (178) and (179) was followed by rearrangement of the \(\beta\gamma\)-unsaturated N-chlorosulphonyl amide (178) to the \(\omega\beta\)-unsaturated N-chlorosulphonyl amide (179). After
28 h, the i.r. spectrum showed a broad NH band at 3300 cm\(^{-1}\) and carbonyl band at 1720 cm\(^{-1}\) and removal of the solvent gave a quantitative yield of (179) (E,Z mixture). The n.m.r. spectrum of (179) showed only one olefinic proton and the presence of allylic methyl singlets at \(\delta 2.05\) and \(\delta 1.6\) in the ratio 1.8:1.2 was consistent with the assignment of the major isomer as (179a).

Treatment of the N-chlorosulphonyl amide (179) with triethylamine gave the expected nitrile (181) as a mixture of isomers (181a) and (181b) in the ratio 2:1. Hydrolysis of (179) with aqueous hydrochloric acid yielded the expected mixture of geometric isomers of 3-cyclopropyl-2-buteneamide (182) (49\%) together with the open chain non-conjugated amide, 6-chloro-3-methyl-3-hexeneamide (184) (28\%).

The \(\alpha\beta\)-unsaturated amide (182) showed a u.v. absorption at 230.5 nm and, apart from a broad two proton mound due to the NH\(_2\) group, the n.m.r. spectrum of (182) was similar to that of the \(\alpha\beta\)-unsaturated nitrile (181). The signals due to the allylic methyl groups of the geometric isomers appeared as doublets at \(\delta 2.0\) (\(J=1\) Hz) and \(\delta 1.5\) (\(J=1.5\) Hz) in the ratio 2.1:0.9 and were consistent (cf. the \(\alpha\beta\)-unsaturated nitrile (181) with the assignment of the major isomer as that with the amide and methyl groups cis to each other.

The positions of the olefinic bond and the allylic methyl group in the open chain amide (184) were indicated by the n.m.r. spectrum which showed a two proton singlet in the region expected for an allylic methylene group adjacent to an amide function, and a broad quartet (\(J=7\) Hz) due to an allylic methylene group coupled to both an adjacent olefinic proton and a methylene group.

The N-chlorosulphonyl amide (179) reacted readily with hydrogen chloride in chloroform to give the open chain N-chlorosulphonyl amide (183) which, after hydrolysis with aqueous hydrochloric acid, gave a good yield (48\%) of the corresponding amide (184), which was identical with that obtained by the hydrolysis of (179).
CHART 5. Reaction of CSI with 2-cyclopropylpropene.

\[
\begin{align*}
\text{CH}_3\text{C} & + \text{CSI} \rightarrow \text{CH}_3\text{N} & \rightarrow \text{CH}_3\text{N} \\
\text{CH}_3 & \text{SO}_2\text{Cl} & \text{CH}_3 & \text{SO}_2\text{Cl} \\
\end{align*}
\]

- (165) \rightarrow (166) \rightarrow (167)

\[
\begin{align*}
\text{CH}_3\text{NH} & \rightarrow \text{CH}_3\text{CN} \\
\end{align*}
\]

- (180)

- (181a)

- (181b)

- (182a)

- (182b)

- (183)

- (184)

- (179a)

- (179b)

- (176)

- (185)
An attempt to obtain the $\beta\gamma$-unsaturated amide (185) by reduction, with benzenethiol/pyridine, of a mixture of the N-chlorosulphonyl amides (178) and (179) gave the $\alpha\beta$-unsaturated nitrile (181) as the major product (58%) and only a small yield (5.5%) of the desired amide (185) together with small amounts of the $\beta$-lactam (167) (2.5%), $\alpha\beta$-unsaturated amide (182) (1%) and an unknown crystalline material (46 mg). Apart from a broad two proton mound due to the NH$_2$ group, the n.m.r. spectrum of the $\beta\gamma$-unsaturated amide (185) was very similar to that of the corresponding nitrile (180), confirming the assigned structure.

The n.m.r. spectrum of the unknown product was almost identical to that of the $\alpha\beta$-unsaturated amide (182) but the i.r. spectrum showed only an intense band at 1597 cm$^{-1}$ in the carbonyl region. This material appears to be an artifact since no trace of it was detected on repeating the above reaction.

From the preparative studies of the reaction of CSI with 2-cyclopropylpropene (165) it appeared that the N-chlorosulphonyl $\beta$-lactam (166) rearranges to the $\beta\gamma$-unsaturated amide (178) which subsequently undergoes a double bond migration yielding the thermodynamically more stable $\alpha\beta$-unsaturated amide (179). This was confirmed by n.m.r. studies (Figure 6) of a reaction mixture of CSI and a slight excess of the olefin (165) in deuteriochloroform. The rearrangement of the N-chlorosulphonyl $\beta$-lactam (166) gave solely the $\beta\gamma$-unsaturated amide (178) which was stable up to at least 70$^\circ$ in the absence of acidic catalysts such as hydrogen chloride, traces of water or an excess of CSI. On adding a trace of water and saturating the reaction mixture with hydrogen chloride, rearrangement of (178) to the $\alpha\beta$-unsaturated amide (179) followed by the reaction of (179) with the hydrogen chloride, yielding the open chain amide (183) were observed.
85 -

CH₃

(40 mg 0.5 mmol)

+ 15 µl CHCl₃

in CDCl₃ (ca. 0.4 ml)

+ CSI (35 µl, 0.4 mmol)

at 78° + 2 min. in

probe (35°)

heated to 50°

for 15 min

saturated with HCl

+ 0.2 µl H₂O

+ 10 min at 50°

+ 58 h at 35°

FIGURE 6. N.m.r. study of the reaction of CSI with 2-cyclopropylpropene (165)
The rearrangement of the N-chlorosulphonyl β-lactam (169), produced in situ by the reaction of CSI with α-cyclopropylstyrene (168), also occurred readily at ambient temperature in dichloromethane. After 30 min. the i.r. spectrum of the reaction mixture showed a broad NH stretching band at 3300 cm\(^{-1}\) and a single carbonyl band at 1700 cm\(^{-1}\) and removal of the solvent gave a quantitative yield of the αβ-unsaturated N-chlorosulphonyl amide (187).

**CHART 6. Reaction of CSI with α-cyclopropylstyrene.**
Treatment of (187) with triethylamine gave a 78% yield of the expected nitrile (188), while hydrolysis of (187) with hydrochloric acid gave only the amide (189) in 38% yield (Chart 6). In contrast to the methyl analogue (179) (Chart 5) the hydrolysis of (187) gave no ring opened amide (191), although the amide (187) was found to react with hydrogen chloride in chloroform to give the ring opened N-chlorosulphonyl amide (190), which on hydrolysis with hydrochloric acid gave the corresponding NH$_2$ amide (191). The position of the phenyl group and olefinic bond in (191) were indicated by the presence in the n.m.r. spectrum of a broad two proton singlet due to the methylene group adjacent to the amide function. Spin decoupling studies showed that the olefinic proton and the allylic methylene groups each gave rise to only one signal suggesting that only one of the two geometric isomers of (191) was produced although no assignment of the stereochemistry of (191) was possible on the basis of its spectral characteristics.

The course of the rearrangement of the N-chlorosulphonyl $\beta$-lactam (169) in ether was completely different to that observed in dichloromethane. On allowing a mixture of the olefin (168) and CSI in ether to warm from $-78^\circ$ to ambient temperature the N-chlorosulphonyl $\beta$-lactam carbonyl band at 1810 cm$^{-1}$ slowly decayed and was replaced by a band at 1735 cm$^{-1}$. After 6 h, the rearrangement was complete and treatment of the reaction mixture with aqueous sodium sulphite gave only 1,2,5,6-tetrahydro-3-phenyl-7-azepinone (193) in 20% yield. The positions of the phenyl group and the olefinic bond were indicated by the appearance of the methylene group adjacent to the carbonyl group as a singlet in the n.m.r. spectrum, and the presence of the lactam function was confirmed by the single NH stretching band in the i.r. spectrum and the broad one proton mound in the n.m.r. spectrum.

4.3 Reaction of CSI with $\alpha$-cyclopropyl-$\alpha$-substituted-styrenes)

The reactions of the $\alpha$-substituted olefins (194) - (197) were investigated, in less detail than those of the parent system, to
determine whether these reactions also proceeded via initial formation of N-chlorosulphonyl β-lactams. This information was required to ensure the validity of the kinetic studies described in Section Five (p. 96), since meaningful comparisons between the rates of reaction of these olefins could only be made if each reaction followed the same course.

The i.r. spectra of aliquots of reaction mixtures of CSI and the olefins (194) - (196) (p-F, p-Et, p-tBu) at -78°C in dichloromethane showed intense bands at 1810 cm\(^{-1}\) indicating the formation of N-chlorosulphonyl β-lactams (198) - (200) as the sole carbonyl containing products. On allowing the reaction mixtures to warm to ambient temperature the bands at 1810 cm\(^{-1}\) decayed and were replaced by bands at 1700 cm\(^{-1}\). In each case, when the rearrangement of the N-chlorosulphonyl β-lactam was complete, removal of the solvent gave a good yield of the corresponding N-chlorosulphonyl amide (202) - (204) which was readily converted to the expected nitrile (206) - (208) by treatment with triethylamine.
In the case of the p-methoxy olefin (197) the rearrangement of the N-chlorosulphonyl \( \beta \)-lactam (201) appeared to occur rapidly even at low temperatures. The i.r. spectrum of an aliquot of a mixture of CSI and the olefin (197) in dichloromethane at \(-78^\circ\text{C}\) showed an intense band at 1700 cm\(^{-1}\) and only a small band due to the \( \beta \)-lactam (201) at 1810 cm\(^{-1}\), and treatment of the reaction mixture with triethylamine gave the nitrile (209). Although only a small residual concentration of the N-chlorosulphonyl \( \beta \)-lactam (201) was observed it is reasonable to assume that the reaction of the p-methoxy olefin, in common with the other para-substituted olefins, also proceeded via the formation of an N-chlorosulphonyl \( \beta \)-lactam.

4.4. Discussion.

The initial exclusive formation of N-chlorosulphonyl \( \beta \)-lactams with Markovnikov orientation (cf. cyclic 1,3-dienes, Section Two), and the lower reactivity of vinylcyclopropane (162) compared to 2-cyclopropylpropene (165) and \( \alpha \)-cyclopropylstyrene are consistent with a dipolar mechanism proceeding via an associated 1,4-dipole.

The initial formation of an N-chlorosulphonyl \( \beta \)-lactam in the reaction of 2-cyclopropylpropene with CSI has also been reported by Barton and Rogido, but the formation of an N-chlorosulphonyl \( \beta \)-lactam (169) in the reaction of \( \alpha \)-cyclopropylstyrene was not observed by Pasto and Chen who reported that this reaction yielded the \( \alpha \beta \)-unsaturated N-chlorosulphonyl amide (187) directly.
The subsequent rearrangements of the N-chlorosulphonyl β-lactams lead, in general, to N-chlorosulphonyl amides in which the cyclopropyl group remains intact, although rearrangement involving the cyclopropyl ring is observed under certain conditions in the rearrangement of the N-chlorosulphonyl β-lactam derived from α-cyclopropylstyrene. The failure to observe rearrangement of the cyclopropyl ring in the case of vinylcyclopropane and 2-cyclopropylpropene may be attributed to the conformation of the cyclopropyl ring in the dipolar intermediates (171) and (176) produced by ring opening of the corresponding N-chlorosulphonyl β-lactams.

![PROTON TRANSFER](image)

Due to the smaller bulk of a hydrogen atom or methyl group compared to a cyclopropyl group the most stable conformation of the intermediates (171) and (176) will have the cyclopropyl group and CSI moiety transoid to each other. In this conformation, attack of the ambident anion at the cyclopropyl group is impossible, and, since unassisted ring opening to give a primary carbonium ion is energetically unfavourable, the only energetically and sterically possible reaction pathway available is prototropy yielding unsaturated N-chlorosulphonyl amides.

In the case of the dipolar intermediate (186) in the rearrangements of the N-chlorosulphonyl β-lactam derived from α-cyclopropylstyrene, the phenyl group, being larger than the cyclopropyl group, would be expected to adopt a transoid conformation to the CSI moiety.
Furthermore, due to steric interaction with the phenyl group, the cyclopropyl group would be expected to adopt a transoid conformation to this group. In this conformation the intermediate (186) is ideally set up for a nucleophilic attack of the nitrogen atom at the cyclopropyl ring yielding the N-chlorosulphonyl-azepinone (192) via a 6-membered cyclic transition state.

The transoid orientation of the phenyl group and cyclopropyl ring is also suggested by the ability of α-cyclopropylstyrene to undergo a Diels Alder addition with maleic anhydride\textsuperscript{115} and the stereochemistry of the 1,5 addition product (210) containing a cis olefinic bond with acetic acid\textsuperscript{114}. In both these reactions a transoid orientation of the phenyl group and cyclopropyl ring is required.
The remarkable difference in the courses of the rearrangement of N-chlorosulphonyl β-lactam (169) derived from α-cyclopropylstyrene in ether and dichloromethane may be attributed to the differing solvation of the intermediate 1,4-dipole (186) in these two solvents. In ether the charged centres would not be as well stabilized by solvation as in dichloromethane, thus the anionic moiety would be expected to be more nucleophilic. In addition, due to the less efficient solvation of the cation, a larger degree of charge delocalization into the cyclopropyl ring would be expected. The combination of the greater electrophilicity of the cyclopropyl ring and the greater nucleophilicity of the anion may then cause a sufficient lowering of the activation energy for attack at the cyclopropyl ring to allow this process to compete effectively with the prototropic rearrangement.

Although proton abstraction from the cyclopropyl ring would be expected to lead to a relatively stable product containing a 1,3-diene system, this process was not observed in any of the rearrangements of the N-chlorosulphonyl β-lactams.

The reason for this may readily be seen by consideration of the incipient carbanion which would be produced in such a process.
Due to the almost orthogonal orientation of the orbitals of the carbon-hydrogen and carbon-carbon bonds which would produce the terminal olefinic bond, no overlap between these orbitals could occur in the transition state and such a process would have a prohibitively high activation energy. In contrast, in both nucleophilic attack at the cyclopropyl ring and $\alpha$- or $\gamma$-proton abstraction, overlap between the orbitals which will eventually form the olefinic bond in the product is possible very early on the reaction co-ordinate and such overlap will exert a stabilising effect on the transition states for these processes.

From the n.m.r. studies of the rearrangement of the N-chlorosulphonyl $\beta$-lactam (166) derived from 2-cyclopropylpropene the initial exclusive formation of the $\beta\gamma$-unsaturated amide (178) is apparent, although Barton et al.\textsuperscript{119} reported the formation of a mixture of both $\alpha\beta$- and $\beta\gamma$-unsaturated amides during this rearrangement. While $\beta$-proton abstraction from the methyl group in the dipolar intermediate (176) is obviously statistically favoured, this process would also be expected to have a lower energy transition state than the alternative intramolecular proton abstraction processes. Intramolecular $\alpha$-proton abstraction would require a highly strained 4-membered cyclic transition state, while removal of the cyclopropyl methine proton would lead to a highly strained product containing an olefinic bond exocyclic to the cyclopropyl ring. In addition, intermolecular $\alpha$- or $\beta$-proton abstraction, in the absence of catalysts such as water, hydrogen chloride or an excess of CSI, would not be expected to compete with the intramolecular abstraction of a proton from the methyl group. The $\alpha\beta$-unsaturated amide (179) appeared to be formed via an acid catalysed double bond migration in the $\beta\gamma$-unsaturated amide (178). From the n.m.r. studies of this rearrangement it was apparent that the addition of hydrogen chloride to the $\beta\gamma$-unsaturated amide (178) was non-competitive with the rearrangement to the $\alpha\beta$-unsaturated amide. These observations, together with the ability of the N-chlorosulphonyl $\alpha\beta$-unsaturated amide (179) to
undergo a 1,5-addition reaction with hydrogen chloride, and the failure to observe such a reaction on treating the corresponding NH$_2$-amide (182) with aqueous hydrochloric acid under the conditions used for the hydrolysis of the N-chlorosulphonyl amide (179), suggest that the open chain amide (184) could not be formed, as was suggested by Barton and Rogido$^{119}$, via addition of hydrogen chloride to the N-chlorosulphonyl $\beta\gamma$-unsaturated amide (178), but arose via addition to the N-chlorosulphonyl $\alpha\beta$-unsaturated amide (179).

\[
\text{HCl} + \overset{\text{NHSO}_2\text{Cl}}{\text{O}} \xrightarrow{\text{hydrolysis}} \overset{\text{O}}{\text{NHSO}_2\text{Cl}}
\]

In the case of the N-chlorosulphonyl $\beta$-lactam (169) derived from $\alpha$-cyclopropylstyrene, the only product of prototropic rearrangement was the $\alpha\beta$-unsaturated amide (187) which may have arisen via either an inter- or intramolecular process. Although both $\beta\gamma$- and $\alpha\beta$-unsaturated nitriles (174) and (175) were isolated after the rearrangement of the N-chlorosulphonyl $\beta$-lactam (163) derived from vinylcyclopropane, the mode of formation of these compounds is not certain. In addition to the possibilities of initial $\gamma$-proton transfer yielding (172) followed by partial rearrangement to the $\alpha\beta$-unsaturated amide (173), and competitive formation of (172) and (173); the possibility of exclusive formation of the $\beta\gamma$-unsaturated system followed by partial isomerization during the work up procedure cannot be discounted. A precedent for this latter possibility may be seen in the almost exclusive formation of $\alpha\beta$-unsaturated products during the benzenethiol/pyridine reduction of a mixture of the N-chlorosulphonyl $\alpha\beta$- and $\beta\gamma$-
unsaturated amides obtained from 2-cyclopropylpropene (p. 84).

4.5. Summary.

The initial formation of the N-chlorosulphonyl β-lactam was followed, in general, by prototropic rearrangement, via a free 1,4-dipole, yielding unsaturated N-chlorosulphonyl amides in which the cyclopropyl group was retained. A rearrangement involving the cyclopropyl group was only observed with α-cyclopropylstyrene and this reaction provided a remarkable example of the ability of the solvent to determine the course of the rearrangement of the N-chlorosulphonyl β-lactam. The sequence of reactions observed with 2-cyclopropylpropene provided a very good example of an initial kinetically controlled addition yielding an N-chlorosulphonyl β-lactam, followed by a kinetically controlled intramolecular prototropic rearrangement to a β,β'-unsaturated N-chlorosulphonyl amide which subsequently underwent an intermolecular prototropic rearrangement to the thermodynamically stable αβ-unsaturated amide.
SECTION FIVE

KINETIC STUDIES OF THE REACTION OF CHLOROSULPHONYL ISOCYANATE WITH VINYL CYCLOPROPANES.

Vinylcyclopropane (162), 2-cyclopropylpropene (165) and α-cyclopropylstyrene (168) were chosen as suitable substrates for the examination of solvent and substituent effects on the rate of 2+2 cycloaddition of CSI to olefinic systems, since all three olefins had been shown, by n.m.r. studies, to react with CSI to give initially the expected N-chlorosulphonyl- β-lactams (163), (166) and (169) as the sole detectable products.

The concurrent formation of N-chlorosulphonyl-amides which occurs with simple olefins 17, 23 was not observed with (162), (165) and (168) and such products were found to arise only via rearrangement of the N-chlorosulphonyl β-lactams (see Section Four, p. 73).

Furthermore, in view of the ability of a cyclopropyl ring to stabilize a neighbouring carbonium ion by pπ σπ delocalization, 97-99,100 the inclusion of such a substituent would provide an additional probe of the degree of charge separation in the transition state for the formation of the N-chlorosulphonyl β-lactams.

Of the spectroscopic methods normally used for kinetic studies it was decided that i.r. spectroscopy was the most suitable. In view of the lack of suitable chromophores in some of the olefins or their reaction products, ultra-violet spectroscopy could not be used to monitor all of the reactions, and the variation in reactivity between the olefins was so large that, at the high concentrations required for n.m.r. spectroscopy, it would be impossible to obtain adequate kinetic data for all three olefins at the same temperature due to the inherently slow sampling rate of this method.

The use of i.r. spectroscopy as a means of monitoring the reaction of CSI with olefins by following the growth of the N-chlorosulphonyl β-lactam and/or amide, carbonyl bands in the spectrum of the reaction mixture has
been reported by Graf\textsuperscript{17} and Clauss \textsuperscript{26}. This method requires the
determination of the dependence of absorbance on concentration for the
carbonyl bands of the N-chlorosulphonyl $\beta$-lactams and amides, and the
simultaneous determination of the intensities of the carbonyl bands of the
products in the reaction mixture at suitable time intervals. In view of
the instability of the N-chlorosulphonyl $\beta$-lactams derived from (165) and
(168), the calibration of their carbonyl bands would be very difficult;
and in the case of 2-cyclopropylpropene (165) the monitoring of the reaction
at ambient temperature would require the simultaneous determination of the
intensities of carbonyl bands due to the N-chlorosulphonyl $\beta$-lactam (166),
$\beta\gamma$-unsaturated amide (178) and $\alpha\beta$-unsaturated amide (179).

In view of these difficulties, the reactions were followed by monitoring
not the appearance of the products, but the disappearance of the CSI, which
shows an intense, sharp isocyanate stretching band at 2250 cm\textsuperscript{-1}. This method
has several advantages over that used by Clauss:–

a) The band which is monitored is well separated from other major bands
and is in a region of the spectrum which is a window in most i.r.
solvents.

b) Since only one band is monitored, this may be done continuously, by
using the fixed wavelength and time drive modes of the spectrometer,
to produce a continuous transmittance/time curve.

c) The much higher intensity of the isocyanate stretch on CSI compared
to those of the carbonyl bands of the products allows the use of much
more dilute reaction mixtures, thus lessening the risk of precipitation
of the reaction products from nonpolar solvents and allowing more
accurate rate measurements to be made for reactive olefins.

d) Since CSI reacts very rapidly with water and it is impossible to
obtain perfectly dry solvents, then the true concentration of CSI will
always be slightly less than the nominal concentration. In the method
used by Clauss, the concentration of CSI is taken as the difference between the nominal initial concentration and the total concentration of products, which will lead to an increasing inaccuracy in the value used for the concentration of CSI as the reaction proceeds; by monitoring the CSI the concentration of this reagent is determined directly.

5.1. Calibration of the isocyanate stretch band of CSI.

The absorbance at 2250 cm\(^{-1}\) of solutions of CSI of accurately known nominal concentration from ca. 0.006 to 0.03 M in the three reaction solvents (carbon tetrachloride, chloroform and nitromethane) was determined as described in the experimental section (p.168). For each solvent a good linear correlation between absorbance (A) and nominal CSI concentration (\(C_{nom}\)) was obtained (e.g. Fig. 7). The data was processed by a linear least squares regression on an ICL 4130 computer, and the best values of the slope and intercept are given in Table 11.

<table>
<thead>
<tr>
<th>SOLVENT</th>
<th>(m^a)</th>
<th>(C_0^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCl(_4)</td>
<td>27.54</td>
<td>1.6 (\times 10^{-3})</td>
</tr>
<tr>
<td>CHCl(_3)</td>
<td>27.06</td>
<td>3.5 (\times 10^{-3})</td>
</tr>
<tr>
<td>CH(_3)NO(_2)</td>
<td>28.07</td>
<td>3.8 (\times 10^{-3})</td>
</tr>
</tbody>
</table>

\(a\) - slope of calibration line (\(\pm\) 3%)

\(b\) - intercept on concentration axis (\(\pm\) 25%)

The slope (m) is the product of the cell path length (nominally 0.1 mm) and the extinction coefficient of the CSI isocyanate stretch, and the intercept (\(C_0\)) represents the concentration of CSI destroyed by water and/or reactive impurities in the solvent. The excellent linear correlation
FIGURE 7. Plot of absorbance at 2250 cm$^{-1}$ versus nominal CSI concentration in carbon tetrachloride.
between A and $C_{\text{nom}}$ shows that, over the concentration range required for the kinetic studies, the CSI isocyanate stretch obeys Beer's Law; and from the intercepts the maximum limit of residual water in the solvents is calculated to be less than $0.007\%$ (v/v).

5.2. Kinetic Method.

The transmittance of mixtures of equal volumes of solutions of CSI and the olefin was monitored continuously at $2250\ \text{cm}^{-1}$ as described in the experimental section (p.169). The transmittance corresponding to the time of mixing was obtained, for slow reactions, by extrapolation of the transmittance curve, while for fast reactions the initial transmittance was taken to be that of a mixture of equal volumes of solvent and CSI solution.

From the transmittance/time curves, values of the transmittance at suitable time intervals were taken and the data was analysed, using an ICL 4130 computer, in terms of second order kinetics by means of a linear least squares regression of the data to the integrated second order rate expression (Equation 1). This may be expressed in terms of the transmittance data by means of equations 2, 3 and 4 which relate the CSI and the olefin concentrations to the transmittance.

$$k_2t = \frac{1}{[\text{Olefin}]_0 - [\text{CSI}]_0} \cdot \left[ \log_e \left( \frac{[\text{CSI}]_0 \cdot [\text{Olefin}]_t}{[\text{CSI}]_t \cdot [\text{Olefin}]_0} \right) \right]$$

(1)

$$[\text{CSI}]_0 = m \log_{10} \left( \frac{100}{T_0} \right)$$

(2)

$$[\text{CSI}]_t = m \log_{10} \left( \frac{100}{T_t} \right)$$

(3)

$$[\text{Olefin}]_t = [\text{Olefin}]_0 - ([\text{CSI}]_0 - [\text{CSI}]_t)$$

(4)

$t$ - reaction time (sec.)

$[\text{Olefin}]_0, [\text{CSI}]_0$ - initial olefin and CSI concentrations

$[\text{Olefin}]_t, [\text{CSI}]_t$ - olefin and CSI concentrations at time t

$T_0$ - initial transmittance
For all the reactions studied, reasonable correlation with second order kinetics was obtained (deviation ± 20%) and a kinetic plot for a typical run is shown in Fig. 8.

The reported rate constants (Table 12) are the mean rate constants for a minimum of two runs at different initial olefin concentration, each of which included a minimum of six data points covering a minimum of 50% reaction.

**TABLE 12. Second order rate constants* (l.mol.⁻¹s.⁻¹) for the reaction of CSI with vinylcyclopropanes,\( \text{R} = \text{H}, \text{Ph}, \text{Me} \) at 31 ± 1°C.**

<table>
<thead>
<tr>
<th>SOLVENT</th>
<th>CCl₄</th>
<th>CHCl₃</th>
<th>CH₃NO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>R=H</td>
<td>5.5 x 10⁻⁴</td>
<td>1.6 x 10⁻²</td>
<td>0.33</td>
</tr>
<tr>
<td>Ph</td>
<td>1.5 x 10⁻²</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Me</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - ± 20%

5.3. Discussion

From Table 12 the marked increase of the rate constants with increasing polarity of the reaction solvent may be seen, and for vinylcyclopropane a good linear correlation is found between log \((k_2)\) and Dimroth's solvent polarity parameter \((E_p)\) 35, 36 (Figure 9). The large solvent effects together with the exclusively Markovnikov orientation of the addition suggest that these reactions occur via a polar transition state rather than by a concerted mechanism. The magnitude of the solvent effects for these and other reactions of unsymmetric olefins with CSI are comparable to those
FIGURE 8. Second order kinetic plot for the reaction of CSI with vinylcyclopropane in chloroform at 31 ± 1°C.
found in reactions which are considered to proceed via polar transition states, and are much larger than those found for reactions which are considered to be concerted cycloadditions (Table 13).

**FIGURE 9.** Plot of $\log_{10} k_2$ vs $E_t$ for the addition of CSI to vinyl-cyclopropane at 31 ± 1°C.
### TABLE 13. Comparison of solvent effects for various reactions.

<table>
<thead>
<tr>
<th>REACTION</th>
<th>$k_\text{CH}_3\text{NO}_2$&lt;sup&gt;a&lt;/sup&gt;</th>
<th>$k_\text{CCl}_4$</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI + trans - C₆H₅CH=CHCH₃</td>
<td>685</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>CSI + cis - C₆H₅CH=CHCH₃</td>
<td>554</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>CSI + CH₂ = C(C₂H₅)C₆H₆</td>
<td>3,500</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>CSI + [Image]</td>
<td>600</td>
<td></td>
<td>This work</td>
</tr>
<tr>
<td>C₆H₅CH = CH₂ + Cl₆</td>
<td>2</td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>C₆H₅CH = CH₂ + Ph-N=N-Ph</td>
<td>3</td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>Ph₂C-N = N + [Image]</td>
<td>1.2</td>
<td></td>
<td>121</td>
</tr>
<tr>
<td>C₆H₅NH₂ + BrCH₂COC₆H₅</td>
<td>3,500</td>
<td></td>
<td>122</td>
</tr>
<tr>
<td>(C₂H₅)₃N + C₂H₅I</td>
<td>5,000</td>
<td></td>
<td>123</td>
</tr>
<tr>
<td>(NC)₂C = C(CN)₂ + [Image]</td>
<td>4,500</td>
<td></td>
<td>124</td>
</tr>
</tbody>
</table>

*a* - In order to facilitate comparison these values are calculated by extrapolation or interpolation of the data given in the appropriate reference, and represent the expected values if linearity of log $k/E_\text{t}$ is maintained.
The effect of the presence of the cyclopropyl group on the rate of addition of CSI to olefins may be seen in Table 14 where the rate of reaction of CSI with vinylcyclopropane is compared with the rates of reaction of CSI with other mono substituted olefins.

**TABLE 14.** Second order rate constants for the addition of CSI to vinyl-cyclopropane and other mono-substituted olefins.

<table>
<thead>
<tr>
<th>Olefin</th>
<th>$k_2$(1.mol.$^{-1}$s.$^{-1}$)</th>
<th>$k_2$(relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>But-1-ene</td>
<td>$1.2 - 1.5 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Pent-1-ene</td>
<td>$1.2 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Hex-1-ene</td>
<td>$1.2 - 1.5 \times 10^{-6}$</td>
<td>1</td>
</tr>
<tr>
<td>Hept-1-ene</td>
<td>$1.5 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Oct-1-ene</td>
<td>$1.2 - 1.5 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>1,3-Butadiene</td>
<td>$2 - 2.5 \times 10^{-5}$</td>
<td>20</td>
</tr>
<tr>
<td>Styrene</td>
<td>$0.8 - 1.0 \times 10^{-3}$</td>
<td>700</td>
</tr>
<tr>
<td>Vinylcyclopropane</td>
<td>$1.6 \times 10^{-2}$</td>
<td>10,000</td>
</tr>
</tbody>
</table>

**a** - in CHCl$_3$ at 31° ± 1°  
**b** - in CH$_2$Cl$_2$ at 25°

Although the reaction temperatures and solvents differ slightly these effects will tend to cancel each other and the above values may be used as a close approximation to the true relative rates. From the observed increase in rate of approximately four orders of magnitude which occurs on replacing the alkyl substituent by a cyclopropyl group it is obvious that some effect other than purely inductive effects are responsible for the greater reactivity of vinylcyclopropane. Similar effects are observed in the unimolecular solvolysis of cyclopropylmethyl derivatives, for example, the solvolysis rate of cyclopropylmethylchloride in 50% ethanol/water at 50° is forty times greater than that of β-methallyl chloride. This may be explained in terms of delocalization of the positive charge in the transition state by $\pi\pi\sigma\pi$ overlap between the $\sigma$-bonds of the...
cyclopropyl group and the incipient carbonium ion p-orbital.

In the reaction between CSI and olefins, the five hundred fold increase in rate from 1,3-butadiene to vinylcyclopropane indicates that the transition state for the reaction of CSI with vinylcyclopropane must involve considerable carbonium ion character at the carbon atom adjacent to the cyclopropyl ring, supporting the proposed dipolar mechanism.

The order of reactivity of the olefins (162), (165) and (168) (Table 12) at first sight does not correspond to that expected for a reaction which proceeds via a carbonium ion intermediate, in that the methyl substituted olefin (165) reacts more rapidly than the phenyl substituted analogue (168). For reactions which proceed via a carbonium ion-like transition state, phenyl groups are usually more efficient than alkyl groups at stabilizing the transition state and the phenyl substituted compounds are thus more reactive than the corresponding alkyl substituted compounds. The "normal" reactivity order is found for olefins bearing only alkyl and phenyl substituents (Table 15), and it appears that the anomalous order with the cyclopropyl olefins is in some way due to the presence of the cyclopropyl group.

<table>
<thead>
<tr>
<th>TABLE 15. Second order rate constants for the reaction of olefins with CSI in dichloromethane at 25°.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olefin</td>
</tr>
<tr>
<td>R-CH=CH$_2$</td>
</tr>
<tr>
<td>Ph</td>
</tr>
<tr>
<td>R$_1$</td>
</tr>
<tr>
<td>R$_2$</td>
</tr>
<tr>
<td>Ph</td>
</tr>
<tr>
<td>CH$_3$</td>
</tr>
</tbody>
</table>
A possible explanation of this anomalous reactivity order is that steric hindrance between the cyclopropyl and phenyl groups in (168) prevents one or both of these groups from attaining their electronically preferred orientations for the stabilization of a carbonium ion site on the adjacent carbon atom. The orientation for a cyclopropyl ring which allows maximum conjugative interaction with a neighbouring \( \Pi \)-system is that in which the axis of the adjacent \( \pi \)-orbital is parallel to the plane of the cyclopropyl ring, the so called bisected conformation.\(^{97}\). For a phenyl group the preferred orientation is with the ring coplanar with the \( \sigma \)-framework of the adjacent \( \pi \)-orbital.

From studies of molecular models it can be seen that, due to steric interactions between the cyclopropyl and phenyl groups, the best orientation of these groups which still allows maximum conjugative interaction with the adjacent \( \pi \)-orbital is with the cyclopropyl group transoid to the phenyl ring (211)
Even in this conformation steric interaction is found between the methine hydrogen of the cyclopropyl ring (H\textsubscript{A}) and the ortho hydrogen (H\textsubscript{B}) of the phenyl group and from models it appears that a relative twisting of ca. 60° of the cyclopropyl and phenyl groups would be required to relieve this interaction (212). The degree to which each group is twisted with respect to the \( \sigma \)-framework of the adjacent \( \Pi \)-system will depend upon the relative conjugative abilities of the cyclopropyl and phenyl groups. The effect of this twisting of the substituents from their preferred orientations is to decrease their ability to stabilize the transition state thus leading to a lower reaction rate than expected.

A similar steric inhibition of resonance has been invoked to explain the observation that the rate of hydration of isobutene in 29.6% perchloric acid at 25° is ca. 1.6 times that of \( \alpha \)-methylstyrene\textsuperscript{126}.

5.4. Hammett study of the reaction of \( \alpha \)-cyclopropyl(p-substituted styrenes) with chlorosulphonyl isocyanate.

The Hammett reaction constant (\( \rho \)) is a measure of the sensitivity of a reaction to the electronic effect of aryl substituents. For an electrophilic addition to an olefin the rate constant would be expected to increase with increasing electron releasing ability of aryl substituents adjacent to the incipient carbonium ion site of the transition state, and \( \rho \) would have a negative value. The magnitude of the substituent constant will depend, in the main, on the degree of positive charge development on the carbon atom adjacent to the aryl substituents, but will also be influenced by the steric and electronic effects of the other substituents in the olefin:

a) if the aryl group is twisted out of its preferred orientation by steric interactions with other substituents then the overlap between the developing carbonium ion and the aryl ring will decrease and the magnitude of \( \rho \) will decrease\textsuperscript{127}.
b) the presence of other electron releasing substituents will reduce the electron demand of the carbonium ion thus causing a decrease in the magnitude of $\epsilon^{127}$.

The second order rate constants for the reaction of various $\alpha$-cyclopropyl-$\beta$-substituted styrenes with CSI in carbon tetrachloride were determined by the method described previously and the mean rate constants are shown in Table 16.

**TABLE 16.** Second order rate constants for the addition of CSI to $\alpha$-cyclopropyl-$\beta$-substituted styrenes.

<table>
<thead>
<tr>
<th>SUBSTITUENT</th>
<th>F</th>
<th>H</th>
<th>Et</th>
<th>$t$-Bu</th>
<th>MeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2 k_2$</td>
<td>1.1</td>
<td>1.5</td>
<td>6.6</td>
<td>6.6</td>
<td>37</td>
</tr>
</tbody>
</table>

a - mean second order rate constant (1.mol.$^{-1}$s.$^{-1}$)

The significant increase in the rate constant with increasing electron donating ability of the substituent indicates a considerable build up of positive charge in the transition state on the carbon atom adjacent to the aryl substituent. A Hammett plot of $\log_{10} k_2$ against Brown's substituent constants ($\sigma_p^{128}$) shows only a fair linear correlation, with a $\rho$-value of -2.0 (Figure 10).

The value of the reaction constant is intermediate between the ranges expected for a concerted cycloaddition and a stepwise dipolar addition (Table 17) but does indicate a considerable degree of charge separation in the transition state.

From the relative rates of addition of CSI to vinyl cyclopropane and styrene (Table 14), and the greater hydration rate of cyclopropylmethyl chloride compared to that of benzyl chloride$^{129}$, it is reasonable to deduce that the conjugative ability of the cyclopropyl group is greater than that of the phenyl group. On this basis it would be expected that in
### TABLE 17. Comparison of $\rho$ values for various reactions.

<table>
<thead>
<tr>
<th>REACTION</th>
<th>SOLVENT</th>
<th>TEMP.</th>
<th>$\rho$</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI + Ar-CH=CH$_2$</td>
<td>CH$_2$Cl$_2$</td>
<td>25</td>
<td>-5.27</td>
<td>33</td>
</tr>
<tr>
<td>CSI +</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSI +</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl$_6$-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O +</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Br$_2$ + Ar-CH=CH$_2$</td>
<td>CH$_3$OH</td>
<td>25</td>
<td>-4.30</td>
<td>132</td>
</tr>
<tr>
<td>H$_2$O + ArC(CH$_3$)Cl</td>
<td>acetone-H$_2$O</td>
<td>25</td>
<td>-4.62</td>
<td>133</td>
</tr>
<tr>
<td>C$_2$H$_5$OH + ArC(Ph)Cl</td>
<td>C$_2$H$_5$OH</td>
<td>25</td>
<td>-5.09</td>
<td>133</td>
</tr>
</tbody>
</table>
$\alpha$-cyclopropylstyrenes the phenyl group would be twisted further from its preferred conformation than would the cyclopropyl group. In view of this the magnitude of the reaction constant ($\rho$) for the addition of CSI to $\alpha$-cyclopropyl styrenes would appear to be attributable to steric inhibition of resonance rather than being a reflection of the degree of dipolar character in the reaction mechanism. A similar effect may also be seen in the hydration of styrenes in aqueous sulphuric acid$^{134}$ where the $\rho$-value for $p$-substituted $\alpha$-methylstyrenes (-3.3) is considerably smaller than that found for $p$-substituted styrenes (-4.0).

![FIGURE 10. Hammet plot for the addition of CSI to $\alpha$-cyclopropyl-($p$-substituted-styrenes) in carbon tetrachloride at 31 ± 1°](image)

5.5. Summary.

In view of the magnitude of the $\rho$-value for $p$-substituted styrenes and the large solvent effects shown by $\beta$-methylstyrenes in their reaction with CSI, Britt has suggested that these reactions proceed via a dipolar...
intermediate. From the large solvent effects shown by vinylcyclopropane and α-cyclopropylstyrene, the great increase in rate caused by the cyclopropyl group and the large increase in rate from vinylcyclopropane to 2-cyclopropylpropene, it is reasonable to suggest that the cyclopropyl substituted olefins also react via a dipolar mechanism.

The difference between the ρ-values for styrenes and α-cyclopropyl-styrenes may then be largely attributed to a steric inhibition of resonance caused by the cyclopropyl group.
SECTION SIX.

REACTION OF CHLOROSULPHONYL ISOCYANATE WITH EPOXIDES.

Apart from a report of the use of CSI in forming polymeric products with simple epoxides, such as 1,2-epoxypropane\textsuperscript{135} and 1,2-epoxy-3-phenoxyp propane\textsuperscript{135}, no studies of the reactions of CSI with three membered heterocyclic systems have been published.

In contrast, the reactions of other isocyanates with epoxides yielding 2-oxazolidinones have been well documented\textsuperscript{136}. A variety of substances (metal chlorides, amines, amine hydrochlorides and carboxylate anions) may be used to catalyse the reactions of alkyl and aryl isocyanates with epoxides and the 2-oxazolidinones are formed with the nitrogen atom of the oxazolidinone ring bonded to the least hindered carbon atom of the epoxide ring.

A suggested mechanism for these reactions involves nucleophilic opening of the epoxide ring by the catalyst, followed by attack of the oxygen anion in (213) at the isocyanate yielding the ambident anion (214).

\[
\begin{align*}
\text{O} & \quad \text{O}^+ \\
\text{Nuc}^\ominus & \quad \text{Nuc}^+ \\
(213) & \quad \text{RNCO} \\
\end{align*}
\]

Nucleophilic displacement of the catalyst by the nitrogen atom of the ambident anion (214) then yields the 2-oxazolidinone (215).

This mechanism also explains the observed orientation of the addition since the initial attack of the catalyst would be expected to occur at the least hindered carbon atom of the epoxide ring leading to the formation of the 2-oxazolidinone with the nitrogen atom bonded to the least hindered (i.e. least substituted) carbon atom of the epoxide ring. With
highly electrophilic isocyanates, e.g. p-tosyl isocyanate\textsuperscript{137} (216) and acyl isocyanates\textsuperscript{138} both orientations of addition may be observed.

\[
\begin{align*}
\text{Ph} & \\
\text{CH}_3\text{-SO}_2\text{-NCO} & \quad \text{LiBr} \\
\end{align*}
\]

In these cases, uncatalysed electrophilic addition of the isocyanate, via nucleophilic attack of the epoxide oxygen atom at the isocyanate group, appears to be competitive with the catalysed addition.

\[
\begin{align*}
\text{X-NCO} & \quad \rightarrow \\
\text{O} \quad \rightarrow \\
\end{align*}
\]

This uncatalysed addition, proceeding via the most stable dipolar intermediate, leads to the opposite orientation of addition to that found for the catalysed addition.

6.1. General Comments.

The reaction of CSI with epoxides appears to occur via electrophilic attack of the CSI at the epoxide oxygen atom to yield the most stable dipolar intermediate (217) which then cyclizes competitively via the oxygen and nitrogen atoms of the ambident anion yielding an N-chlorosulphonyl-2-imino-1,3-dioxolan (218) and an N-chlorosulphonyl-1,3-oxazolidin-2-one (219) respectively.
In several cases, evidence for the intermediacy of a free 1,5-dipole was obtained by the isolation of carbamates, whose formation could only be explained in terms of the occurrence of proton transfer from the epoxide moiety to the nitrogen atom of the ambident anion.

The possibility that these proton transfer products were produced via dipolar rearrangement of (218) or (219) would appear to be ruled out by the failure to observe any rearrangement of (218) or (219) in the cases where these compounds could be isolated. In addition, in the cases where proton transfer products were isolated, no decay with time of the i.r. absorptions due to (218) or (219) was observed.

The stability of the N-chlorosulphonyl-2-imino-1,3-dioxolans (218) and N-chlorosulphonyl-1,3-oxazolidin-2-ones (219) confirms the assumption that the ratio of these products is determined, not by their relative thermodynamic stabilities, but by the relative rates of cyclization of the dipolar intermediate (217) via the oxygen and nitrogen atoms of the ambident anion.

The majority of the reactions were carried out in dichloromethane at 0° or ambient temperature, and in many cases it was necessary to add the epoxide slowly to a solution of CSI in order to minimize the extent of acid-catalysed polymerization of the epoxide. In each case (except 1,2-epoxy-cyclo-oct-3,5,7-triene) the i.r. spectrum of the reaction mixture showed a carbonyl band in the region of 1800 cm⁻¹ due to the N-chlorosulphonyl-1,3-oxazolidin-2-one and a much more intense imine stretching band in the region of 1600 cm⁻¹ due to the N-chlorosulphonyl-2-imino-
1,3-dioxolan. A broad band of variable intensity in the region of 1750-1770 cm\(^{-1}\) was also observed in the i.r. spectra of many of the reaction mixtures and was attributed to polymeric material.

In a few cases the N-chlorosulphonyl compounds could be separated by chromatography, or the N-chlorosulphonyl-2-imino-1,3-dioxolan (218) could be isolated as a crystalline solid by trituration of the crude reaction product. Treatment of the reaction mixture with aqueous sodium sulphite generally converted the N-chlorosulphonyl-2-imino-1,3-dioxolan (218) and N-chlorosulphonyl-1,3-oxazolidin-2-one (219) to the corresponding dioxolanone (220) and oxazolidinone (221) respectively, which were readily separated by chromatography.

The structures of the compounds described in this section were assigned on the basis of their spectral properties and, where possible, by comparison of their properties with those reported in the literature.

The reaction of CSI with a wide range of epoxides was investigated and a wide spectrum of behaviour was observed. For the sake of clarity the reactions are presented in two major sections:

a) simple epoxides yielding only N-chlorosulphonyl-1,3-oxazolidin-2-ones and N-chlorosulphonyl-2-imino-1,3-dioxolans - the "normal" or "typical" reaction pathway

b) epoxides which yield additional or alternative products to these "typical" products.
6.2. Reaction of chlorosulphonyl isocyanate with simple epoxides.

Further subdivision of this category is used to group together epoxides which illustrate particular aspects of the reaction and, for the sake of brevity, pertinent spectral data for the compounds described in this section are presented in tabular form (Tables 18 and 19).

6.3. Reaction of CSI with 1,2-epoxycyclohexane (222) and 1,2-epoxycyclooctane (226).

On reacting equimolar proportions of CSI and 1,2-epoxycyclohexane the i.r. spectrum of the reaction mixture showed an intense band at 2250 cm\(^{-1}\) due to unreacted CSI, indicating that a considerable amount of the epoxide had polymerized. After removal of the solvent, trituration of the residue with 50% ether/petrol afforded N-chlorosulphonyl-8-imino-7,9-dioxabicyclo[4,3,0]nonane (223) (17.5%).

\[
\text{ Reaction of CSI with a two-fold excess of the epoxide, when complete consumption of the CSI was observed, followed by treatment of the reaction mixture with aqueous sodium sulphite yielded cis-cyclohexane-1,2-diol (224) (11%) and cis-7,9-oxazabicyclo[4,3,0]nonan-8-one (225) (3%). The assignment of the stereochemistry of the diol (224) was based on comparison of the melting point of this material with those reported for the cis and...}
trans cyclohexane-1,2-diols\textsuperscript{139}. The stereochemistry of the oxazolidinone (225) was also assigned by comparison of its melting point and n.m.r. spectrum with those reported for the cis and trans isomers\textsuperscript{140,141}.

Much less polymerization occurred during the reaction of CSI with 1,2-epoxycyclo-octane (226), and only a small band due to residual CSI was observed in the i.r. spectrum of the reaction mixture. The N-chlorosulphonyl-imino-dioxolan (227) was obtained in 35\% yield by trituration of the crude product with ether and was readily converted in high yield (89\%) to the corresponding dioxolanone (229) by hydrolysis with aqueous sodium hydroxide.

\[
\begin{align*}
\text{CH}_2\text{Cl}_2 + \text{CSI} & \rightarrow \\
\text{NaOH aq} & \rightarrow \\
\text{Na}_2\text{SO}_3 \text{ aq} & \rightarrow
\end{align*}
\]

Treatment of the trituration residues with aqueous sodium sulphite afforded the NH-oxazolidinone (230) in 7\% yield. An attempt to isolate the N-chlorosulphonyl-oxazolidinone (228) by chromatographic separation of the trituration residues was unsuccessful and only the NH-oxazolidinone (230), produced by hydrolysis of (228) on the column, was isolated in 8\% yield. The assignment of the cis fused ring junction in the NH-oxazolidinone (230) was based on the comparison of the magnitude of the coupling between the bridgehead protons (9.5Hz) with the typical values found by Herweh and
co-workers for the corresponding vicinal cis (8-10Hz) and trans (5-7.5Hz) couplings in other oxazolidinones.

6.4. Reaction of CSI with 1,2-epoxy-1-phenylcyclohexane (231) and epoxystyrene (236).

The reaction of 1,2-epoxy-1-phenylcyclohexane (231) with CSI was much cleaner than that of the corresponding unsubstituted epoxide and the i.r. spectrum of the reaction mixture indicated the presence of only the N-chlorosulphonyl-oxazolidinone (233) and imino-dioxolan (232). Chromatographic separation of the reaction products yielded mainly mixed fractions of (232) and (233) and only a small amount of the pure N-chlorosulphonyl-imino-dioxolan (232) (12.5%).

\[ \text{Ph} \quad \text{O} + \text{CSI} \xrightarrow{\text{CH}_2\text{Cl}_2} \text{Ph} \quad \text{O} \quad \text{NSO}_2\text{Cl} + \text{Ph} \quad \text{O} \quad \text{N} \quad \text{SO}_2\text{Cl} \]

\[ \text{Ph} \quad \text{O} \quad \text{Ph} \quad \text{N} \quad \text{SO}_2\text{Cl} \]

Hydrolysis of the reaction product with aqueous sodium sulphite gave a good yield of the expected NH-oxazolidinone (235) (19%) and dioxolanone (234) (47%). Although the assumed cis ring fusion of (234) and (235) was not confirmed unequivocally, the gross structure of (235) was indicated by the appearance of the n.m.r. signal due to the bridgehead proton in the region expected for a methine proton adjacent to the oxygen atom of an oxazolidinone ring (δ4.0-4.8)\textsuperscript{141,142}.

Chromatographic separation of the products from the reaction of epoxystyrene (236) with CSI afforded the expected N-chlorosulphonyl-
oxazolidinone (238) (14%) and imino-dioxolan (237) (12%) together with
the NH-oxazolidinone (240) (11%) which was presumably produced by
hydrolysis of the N-chlorosulphonyl-oxazolidinone (238) on the column.
Treatment of the reaction mixture with aqueous sodium sulphite readily
converted the N-chlorosulphonyl compounds (238) and (237) to the
corresponding NH-oxazolidinone (240) and dioxolanone (239) respectively,
each of which was isolated in 44% yield. The structures of (237), (238),
(239) and (240) were consistent with their spectral properties.

\[
\begin{align*}
\text{Ph} & \quad \text{O} \quad + \quad \text{CSI} \quad \text{CH}_2\text{Cl}_2 \quad \rightarrow \\
\text{Ph} & \quad \text{O} \quad \text{NSO}_2\text{Cl} \quad + \\
\text{Ph} & \quad \text{O} \quad \text{NSO}_2\text{Cl} \\
\text{Ph} & \quad \text{O} \quad \text{Na}_2\text{SO}_3 \text{aq,} \quad \downarrow \\
\text{Ph} & \quad \text{O} \quad \text{NH} \\
\text{Ph} & \quad \text{O} \quad \text{Ph}
\end{align*}
\]

In addition the assignment of the structures of (239) and (240) was
confirmed by comparison of their melting points with those reported in
the literature\textsuperscript{143,140}, and in particular the melting point of (240)
identified this compound as having the phenyl group in the 4-position.

6.5. Reaction of CSI with 3,4-epoxycyclo-oct-1-ene (241), 3,4-epoxy-3-
 methyldenet-1-ene (246), and 3,4-epoxy-2,3-dimethylbut-1-ene (252).

The reaction of CSI with 3,4-epoxycyclo-oct-1-ene (241) appeared to
occur without significant polymerization of the epoxide, and removal of
the solvent from the reaction mixture gave a brown crystalline mass, which,
after trituration with ether, afforded the N-chlorosulphonyl-imino-dioxolan
(242) in 54% yield. The N-chlorosulphonyl-imino-dioxolan (242) was readily
converted in 63% yield to the corresponding dioxolanone (244) by treatment
with aqueous sodium hydroxide. Spin decoupling studies showed that
the magnitude of the coupling between the bridgehead protons in (242)
and (244) was 11Hz and 10Hz respectively, which, by comparison with
the corresponding couplings found in oxazolidinones\textsuperscript{141}, was consistent
with the assigned \textit{cis} fusion of the rings.

\begin{center}
\includegraphics[width=\textwidth]{reaction_diagram.png}
\end{center}

While attempts to isolate the N-chlorosulphonyl-oxazolidinone (243)
by fractional crystallization or chromatographic separation of the
trituration residues failed; treatment of the residues with aqueous sodium
sulphite readily afforded the corresponding NH-oxazolidinone (245) in
9.5% yield. The similarity of the position of the n.m.r. signal due to the
non-allylic bridgehead proton in (245) to that of the corresponding proton
in the dioxolanone (244), together with the appearance of the signal due
to the allylic bridgehead proton in (245) at higher field than the
corresponding proton in the dioxolanone (244) confirmed the gross structure
of the oxazolidinone (245). The assignment of the \textit{cis} fusion of the rings
in the oxazolidinone (245) was based on the magnitude (11Hz) of the
coupling between the bridgehead protons.
On carrying out the reaction of CSI with the epoxide (241) in n-pentane, the products precipitated as an oil, which, on trituration with ether, gave the N-chlorosulphonyl-imino-dioxolan (242) in 23% yield, while treatment of the trituration residues with aqueous sodium sulphite gave the NH-oxazolidinone (245) in 8% yield together with a considerable amount of polymeric material.

3,4-Epoxy-3-methylbut-1-ene (246) also reacted readily with CSI. Chromatographic separation of the reaction products afforded the N-chlorosulphonyl-oxazolidinone (248) (6.5%) as a crystalline solid, the N-chlorosulphonyl-imino-dioxolan (247) (53.5%) as a colourless oil, mixed fractions of (247) and (248) and a dark polymeric tar.

\[
\text{CH}_3\text{CO\Clor} + \text{CSI} \xrightarrow{\text{CH}_2\text{Cl}_2 \text{ or n-pentane}} \text{CH}_3\text{NSO}_2\text{Cl} + \text{ClO}_2\text{SN} \text{O} \\
\xrightarrow{\text{NaOH aq or Na}_2\text{SO}_3 \text{ aq}} \text{CH}_3\text{O} \text{O} \xrightarrow{\text{Na}_2\text{SO}_3 \text{ aq}} \text{CH}_3\text{HN} \text{O} \\
\text{(247)} + \text{(248)} \quad \text{(249)} + \text{(250)}
\]

Treatment of the N-chlorosulphonyl-imino-dioxolan (247) with aqueous sodium sulphite gave a good yield (72%) of the corresponding dioxolanone (249), while treatment of a reaction mixture of the epoxide and CSI in dichloromethane with aqueous sodium sulphite afforded the NH-oxazolidinone (250) (12.5%) and the dioxolanone (249) (35%).

Careful chromatographic separation of a mixture of the N-chlorosulphonyl-oxazolidinone (248) and imino-dioxolan (247), obtained by partial separation of several reaction mixtures, gave only (248) (9.5%), (247) (20%), the
NH-oxazolidinone (250) (17%) and the carbamate (251) (15.5%), together with mixed fractions of these compounds (14.5%).

The high overall recovery (76.5%) and absence of polymeric material suggests that the polymers obtained during the separation of the reaction mixture were formed during the reaction rather than via polymerization of (247) or (248) during the separation process. The NH-oxazolidinone (250) was presumably formed via hydrolysis of the N-chlorosulphonyl-oxazolidinone (248) on the column, while the carbamate (251) was probably produced by hydrolysis and addition of hydrogen chloride to the N-chlorosulphonyl-oxazolidinone (248) or imino-dioxolan (247).

On carrying out the reaction of CSI with the epoxide (246) in n-pentane, the products precipitated as an oil. The i.r. spectrum of the supernatant n-pentane layer showed an intense band at 2250 cm⁻¹ due to unreacted CSI and no absorptions in the carbonyl region. From the intensity of the band due to unreacted CSI it was calculated that at least 14% of the epoxide must have polymerized. Treatment of the precipitated oil with aqueous sodium sulphite gave mainly polymeric material and only small yields of the dioxolanone (249) (14.5%) and NH-oxazolidinone (250) (12%).

The reaction of CSI with 3,4-epoxy-2,3-dimethylbut-1-ene (252) also occurred readily, and treatment of the reaction mixture with aqueous
sodium sulphite gave the expected NH-oxazolidinone (254) (12.5%) and
dioxolanone (253) (33%).
TABLE 18. Selected n.m.r. and i.r. data for the N-chlorosulphonyl-imino dioxolans and dioxolanones.

![Diagram of N-chlorosulphonyl-imino dioxolans]

**Z = O (dioxolanones)**

<table>
<thead>
<tr>
<th>CPD</th>
<th>R₂</th>
<th>R₃</th>
<th>R₄</th>
<th>ν_C=O</th>
<th>H₁</th>
<th>H₂</th>
<th>H₄</th>
<th>J₁₄</th>
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<tbody>
<tr>
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<td></td>
<td></td>
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<tr>
<td>(239)</td>
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<td>Ph</td>
<td>H</td>
<td>1815</td>
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<td>5.6</td>
<td>8</td>
</tr>
<tr>
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<tr>
<td>(249)</td>
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<td>CH₂=CH⁻</td>
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<td>1805</td>
<td>4.18</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>CH₂=CMe⁻</td>
<td>Me</td>
<td>1820</td>
<td>4.06</td>
<td>4.27</td>
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</tbody>
</table>

**Z = NSO₂Cl (N-chlorosulphonyl imino dioxolans)**

<table>
<thead>
<tr>
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<th>R₂</th>
<th>R₃</th>
<th>R₄</th>
<th>ν_C=N</th>
<th>H₁</th>
<th>H₂</th>
<th>H₄</th>
<th>J₁₄</th>
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<tr>
<td>(227)</td>
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<td>5.19</td>
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</tr>
<tr>
<td>(223)</td>
<td>-(CH₂)₄⁻</td>
<td>H</td>
<td>1615</td>
<td>5.25</td>
<td>5.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(232)</td>
<td>-(CH₂)₄⁻</td>
<td>Ph</td>
<td>1610</td>
<td>5.2</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(237)</td>
<td>H</td>
<td>Ph</td>
<td>H</td>
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<td>5.25</td>
<td>4.77</td>
<td>6.2</td>
<td>8</td>
</tr>
<tr>
<td>(247)</td>
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<td>H</td>
<td>1615</td>
<td>4.56</td>
<td>5.64</td>
<td>11</td>
<td></td>
<td></td>
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<tr>
<td>(242)</td>
<td>H</td>
<td>CH₂=CH⁻</td>
<td>Me</td>
<td>1615</td>
<td>4.6</td>
<td>4.72</td>
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a - cm⁻¹, b - p.p.m. (δ) from TMS, c - Hz.
**TABLE 19. Selected n.m.r. and i.r. data for the oxazolidinones**

\[
\begin{align*}
\text{X} &= \text{H (NH-oxazolidinones)} \\
\text{X} &= \text{SO}_2\text{Cl (N-chlorosulphonyl-oxazolidinones)}
\end{align*}
\]

### X = H (NH-oxazolidinones)

<table>
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<tr>
<th>CPD</th>
<th>R&lt;sub&gt;2&lt;/sub&gt;</th>
<th>R&lt;sub&gt;3&lt;/sub&gt;</th>
<th>R&lt;sub&gt;4&lt;/sub&gt;</th>
<th>ν&lt;sub&gt;C=O&lt;/sub&gt;</th>
<th>δ&lt;sub&gt;H&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt;</th>
<th>δ&lt;sub&gt;H&lt;sub&gt;2&lt;/sub&gt;&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt;</th>
<th>δ&lt;sub&gt;H&lt;sub&gt;4&lt;/sub&gt;&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt;</th>
<th>J&lt;sub&gt;14&lt;/sub&gt;&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(230)</td>
<td>-(CH&lt;sub&gt;2&lt;/sub&gt;)&lt;sub&gt;6&lt;/sub&gt;-</td>
<td>H</td>
<td></td>
<td>1755</td>
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<td>3.81</td>
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<tr>
<td>(225)</td>
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<td>H</td>
<td></td>
<td>1755</td>
<td>4.57</td>
<td>3.75</td>
<td>6.5</td>
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</tr>
<tr>
<td>(235)</td>
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<td>Ph</td>
<td></td>
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<tr>
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<td>H</td>
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<td>4.13</td>
<td>4.96</td>
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<tr>
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</tr>
<tr>
<td>(250)</td>
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<td>Me</td>
<td>1760</td>
<td>4.1</td>
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<tr>
<td>(254)</td>
<td>H</td>
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<td>1760</td>
<td>3.98</td>
<td>4.15</td>
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</tbody>
</table>

### X = SO<sub>2</sub>Cl (N-chlorosulphonyl-oxazolidinones)

<table>
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<th>R&lt;sub&gt;3&lt;/sub&gt;</th>
<th>R&lt;sub&gt;4&lt;/sub&gt;</th>
<th>ν&lt;sub&gt;C=O&lt;/sub&gt;</th>
<th>δ&lt;sub&gt;H&lt;sub&gt;1&lt;/sub&gt;&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt;</th>
<th>δ&lt;sub&gt;H&lt;sub&gt;2&lt;/sub&gt;&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt;</th>
<th>δ&lt;sub&gt;H&lt;sub&gt;4&lt;/sub&gt;&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt;</th>
<th>J&lt;sub&gt;14&lt;/sub&gt;&lt;sup&gt;c&lt;/sup&gt;</th>
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<tbody>
<tr>
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<tr>
<td>(248)</td>
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<td>1810</td>
<td>4.2</td>
<td>4.34</td>
<td> </td>
<td> </td>
</tr>
</tbody>
</table>

*a* - cm<sup>-1</sup>, *b* - p.p.m. (δ) from TMS, *c* - Hz.
Yields (%) of N-chlorosulphonyl-oxazolidinone and imino-dioxolan, or products derived therefrom, in the reaction of CSI with epoxides.

\[
\begin{align*}
\text{Epoxide} & | \quad \text{R}_2 | \quad \text{R}_3 | \quad \text{R}_4 \quad | \quad \text{N-cyclized}^* | \quad \text{O-cyclized}^{**} | \quad \text{Total} \\
226 & | (\text{CH}_2)_6^- & \text{H} & \text{7}^b & 35^c & 42 \\
222 & | (\text{CH}_2)_4^- & \text{H} & \text{3}^b & 11^d & 14 \\
231 & | (\text{CH}_2)_4^- & \text{Ph} & \text{19}^b & 47^e & 66 \\
236 & | \text{H} & \text{Ph} & \text{H} & \text{44}^b & 44^e & 88 \\
241 & | (\text{CH}_2)_4^-\text{CH=CH-} & \text{H} & \text{9.5}^b & 54^c & 63.5 \\
241 & | (\text{CH}_2)_4^-\text{CH=CH-} & \text{H}^+ & \text{8}^b & 23^c & 31 \\
246 & | \text{H} & \text{CH}_2=\text{CH-} & \text{Me} & \text{12.5}^b & 35^e & 47.5 \\
246 & | \text{H} & \text{CH}_2=\text{CH-} & \text{Me}^+ & \text{12}^b & 14.5^e & 26.5 \\
252 & | \text{H} & \text{CH}_2\text{CMe-} & \text{Me} & \text{12.5}^b & 33^e & 45.5 \\
\end{align*}
\]

*a* - for reaction in dichloromethane unless marked + when the reaction was carried out in n-pentane.

b - NH-oxazolidinone
c - N-chlorosulphonyl-imino-dioxolan
d - cis-1,2-cyclohexanediol
e - dioxolanone
6.6. Discussion.

The foregoing reactions of typical epoxides with CSI serve to illustrate the major features of what may be termed "normal" behaviour in such reactions. The predominant formation of N-chlorosulphonyl-imino-dioxolans and the high stereospecificity observed in the formation of the oxazolidinones strongly suggest that the reaction proceeds via a 1,5-dipolar intermediate which then cyclizes predominantly via the more nucleophilic oxygen atom of the ambident anion.

The variation in overall yield found between 1,2-epoxycyclohexane, (222), 1,2-epoxycyclo-octane (226) and 1,2-epoxy-1-phenylcyclohexane (231) (Table 20) may also be explained in terms of the proposed dipolar mechanism. On the basis of its greater flexibility the cyclo-octane ring would be expected to accommodate fusion to a five membered ring more readily than would the less flexible cyclohexane ring. The activation energy for ring closure of the dipolar intermediate would thus be expected to be higher in the case of 1,2-epoxycyclohexane (222) than in the case of 1,2-epoxycyclo-octane (226). This would allow bimolecular polymerization to compete with the formation of monomeric products in the reaction of 1,2-epoxycyclohexane (222) thus leading to a lower overall yield for the reaction of 1,2-epoxycyclohexane (222) (14%), than for the reaction of 1,2-epoxycyclo-octane (226) (42%). The much higher yield in the reaction of 1,2-epoxy-1-phenylcyclohexane (231) (66%) compared with 1,2-epoxycyclohexane (222) (14%) may be rationalised in terms of the greater stability of the cationic centre of the dipolar intermediate in the former reaction. This would be expected to reduce the reactivity of the cationic centre with respect to cationic polymerization without reducing the charge controlled cyclization of the intermediate to the same extent. Thus a higher yield of monomeric products would be expected for 1,2-epoxy-1-phenylcyclohexane (231) than for 1,2-epoxycyclohexane (222). The marked decrease in yield
in the reaction of CSI with 3,4-epoxy-3-methylbut-1-ene (246) and 3,4-epoxycyclo-oct-1-ene (241) in n-pentane compared with those obtained in dichloromethane may be attributed to the dependence of the stability of the 1,5-dipolar intermediate on the solvent polarity. As the solvent polarity decreases the formation of the dipolar intermediate will become less favourable due to the decreasing solvation of the charged sites. Thus the rate of formation of monomeric products would be expected to decrease relative to the rate of acid catalysed polymerization of the epoxide, causing a decrease in the yield of monomeric products as the solvent polarity decreases.

6.7. Reaction of CSI with other epoxides.

Although N-chlorosulphonyl-oxazolidinones and imino-dioxolans may be regarded as the "normal" products of the reaction of CSI with epoxides, in some cases additional or alternative products are obtained. The formation of these products may also be interpreted in terms of a dipolar stepwise addition, and the partial or complete diversion of the reaction into these atypical products may be rationalized in terms of structural features of the dipolar intermediates.

The reaction of CSI with 1,2-epoxycyclopent-3-ene (255) followed by treatment of the reaction mixture with aqueous sodium sulphite gave small yields of the dioxolanone (256) (4%) and the isomeric oxazolidinones (257) (1.5%) and (258) (2%).

\[
\begin{align*}
1) & \text{CSI} \\
2) & \text{Na}_2\text{SO}_3\text{aq}
\end{align*}
\]

\[
\text{(255)} \quad \text{(256)} \quad \text{(257)} \quad \text{(258)}
\]

The n.m.r. signals due to the bridgehead protons of the dioxolanone (256) appeared at \$5.59\text{ and }\$5.24\text{, and spin decoupling showed that the lower}
field signal was due to the allylic bridgehead proton. The assignment of the structures of the oxazolidinones was based on the positions and coupling of the n.m.r. signals due to the bridgehead protons in these compounds. Spin decoupling showed that in the n.m.r. spectrum of (258) the bridgehead proton signal at $\delta 5.52$ was due to the allylic bridgehead proton which (c.f. the dioxolanone (256)) is consistent with the assignment of this signal to a bridgehead proton which is both allylic and adjacent to the oxygen atom of the oxazolidinone ring. In addition only the signal due to the non-allylic bridgehead proton in (258) sharpened on irradiation of the NH proton. Similarly the isomeric oxazolidinone (257) was shown to have the opposite orientation of the oxazolidinone ring.

Although the anti-Markovnikov oxazolidinone (258) may have been produced via a double bond shift in either the NH- or N-chlorosulphonyl-oxazolidinone ((257) or (259)) it is interesting to speculate that (258) may have arisen via 1,5-addition to the epoxide yielding the bicyclo[3,2,1] structure (260). Ring opening of (260) could then give a dipolar intermediate (261), with an acetate anionic centre, which could then cyclize to give, after hydrolysis, the anti-Markovnikov oxazolidinone (258).
The very low overall yield obtained in this reaction (7.5%) may be attributed to the strain involved in the formation of the bicyclo[3,3,0] structures.

The reaction of CSI with 1,2-epoxycyclo-octa-3,5,7-triene (cyclo-octatetraene epoxide) (262) gave a quantitative yield of N-chlorosulphonylcyclo-octatetraenyl carbamate (264), whose i.r. spectrum showed an intense carbonyl stretching band at 1785 cm\(^{-1}\) and a broad NH stretching band at 3300 cm\(^{-1}\) consistent with the presence of the N-chlorosulphonyl-carbamate grouping.
The n.m.r. spectrum of (264) showed a broad signal at $\delta 8.7$ due to the
NH$_2$ group, a six proton multiplet at $\delta 7.7-6.9$ and a single proton doublet
($J = 7$Hz) at $\delta 5.8$. This latter signal was assigned to the olefinic proton
Ha which was shielded relative to the other olefinic protons by the high
electron density on the carbon atom C$_2$, caused by delocalization of a lone
pair from the oxygen atom.

\[ \text{H}_2^2 \text{C}_2^2 \text{O} \text{NH}_2 \delta 5.8, J_{\text{vic}}=7 \text{ Hz} \]

Treatment of the N-chlorosulphonyl-carbamate (263) with triethylamine
in dichloromethane, followed by treatment with ether saturated with
water, gave a good yield (70%) of the carbamate (265). The i.r. and n.m.r.
spectra of (265) were consistent with the assigned structure, and, apart
from the presence of a broad two proton signal due to the NH$_2$ group rather
than a single NH proton, the n.m.r. spectrum of (265) was very similar to
that of the N-chlorosulphonyl analogue (264). Low temperature n.m.r.
and i.r. studies of the reaction indicated that (264) was formed directly
rather than via rearrangement of an initially formed N-chlorosulphonyl-
oxazolidinone or imino-dioxolan. This behaviour may be attributed to the
conformation of the epoxide (262) and 1,5-dipolar intermediate (263).

Of the two possible conformations of the epoxide the extended form
(262a) would be expected to be more stable than the more crowded folded
conformer (262b).

\[ \text{(262a)} \quad \xrightarrow{\text{extended}} \quad \text{(262b)} \quad \text{folded} \]

This is supported by the observation by Huisgen et al that treatment
of the epoxide (262) with fluorosulphonic acid at -75° yields solely the anti-hydroxy homotropylium ion (266). [Image]

Attack of CSI at the epoxide oxygen atom would thus be expected to yield the anti homotropylium dipolar intermediate (263a), which would also be expected to be more stable than the syn conformer (263b). [Image] From models it may be seen that the dipolar intermediate (263a) is ideally set up to undergo intramolecular proton abstraction of Ha via a five-membered transition state. In contrast to this cyclization at C₁ and C₃ may be seen to involve a considerable degree of strain, especially in the latter case, in the transition states and products.

The contrast between the behaviour of the epoxide (262) and cyclo-octatetraene (89) towards CSI may be attributed to difference in the stereochemistry at C₈ in the dipolar intermediates in these reactions.
Preferential attack of CSI at the electron rich fold of the tub shaped cyclo-octatetraene molecule yields the syn dipolar intermediate\(^{58}\) (90) which cyclizes at C\(_3\) (or C\(_5\)) to yield the bicyclic lactam (91) rather than undergo abstraction of H\(_a\) via a strained 4-membered transition state.

In view of the extensive studies of the reactions of CSI with bicyclic monoterpenes\(^{37, 39, 145}\) it was of interest to investigate the reactions of CSI with the corresponding epoxides.

The reaction of CSI with 2\(\alpha\),3\(\alpha\)-epoxy pinane (267) followed by treatment of the reaction mixture with aqueous sodium sulphite afforded, in addition to the expected oxazolidinone (269) (5.5\%) and dioxolanone (268) (7.5\%), the carbamate (270) (5\%).

The assignment of the structure (268) was confirmed by comparison
of the melting point and n.m.r. spectrum of the dioxolanone with those reported for (268) by Coxon et al.\textsuperscript{146} and on the basis of the great similarity between the n.m.r. spectra of the dioxolanone (268) and oxazolidinone (269) it is reasonable to assign the orientation of the oxazolidinone ring as shown in (269). The i.r. spectrum of (270) showed a carbonyl band at 1725 cm\textsuperscript{-1} and two NH stretching bands at 3530 and 3420 cm\textsuperscript{-1} confirming the presence of the carbamate group. The n.m.r. spectrum of (270) showed two broadened single proton resonances at $\delta 4.83$ and $\delta 4.74$ due to the exocyclic olefinic methylene group, and a six proton singlet at $\delta 1.07$ due to the C\textsubscript{6} methyl groups. The orientation of the carbamate group was tentatively assigned as shown in (270) on the basis of the magnetic equivalence of the C\textsubscript{6} methyl groups and by analogy with the structures assigned for the dioxolanone (268) and the oxazolidinone (269).

The formation of the carbamate (270) may be readily explained in terms of proton abstraction from the C\textsubscript{2} methyl group in the dipolar intermediate (271) yielding the N-chlorosulphonyl-carbamate (272).

![Diagram](image)

CSI was found to react readily with 2\textalpha,10-epoxypinane (273) in dichloromethane and the i.r. spectrum of the reaction mixture showed a broad NH
band at 3300 cm\(^{-1}\) and carbonyl bands at 1810, 1770 and 1605 cm\(^{-1}\).

Treatment of the reaction mixture with aqueous sodium sulphite afforded the dioxolanone (274) (0.7%), perilla alcohol (275) (5.4%) and two oxazolidinones which were tentatively assigned as (276) (4%) and (277) (1%). The spectral properties of the dioxolanone (274) were consistent with the assigned structure and the stereochemistry of (274) was confirmed by comparison of its melting point with that reported by Coxon et al.\(^{146}\).

The similarity of the gross structures of the oxazolidinones (276) and (277) and the dioxolanone (274) was indicated by the similarity of their n.m.r. spectra. The tentative assignment of the stereochemistries of the oxazolidinones (276) and (277) was based on the observation that the n.m.r. signal due to the exocyclic methylene group in both the dioxolanone (274) and the oxazolidinone (276) appeared as a singlet (\(\delta 4.27\) and \(\delta 4.10\) respectively), while the exocyclic methylene group in (277) appeared as an AB system (\(\delta 4.20, J=8\text{Hz}\) and \(\delta 4.06, J=8\text{Hz}\)).

The structure of the alcohol (275) was deduced for its spectral
properties and consideration of the possible modes of opening of the pinane skeleton. The presence of a single allylic methyl triplet 
(J = 1 Hz) and a broadened two proton olefinic singlet in the n.m.r. spectrum of (275) confirmed the presence of the isopropenyl group, while the appearance of the exocyclic methylene group as a broadened two proton singlet in the region expected for an allylic methylene group which is adjacent to a hydroxy group indicated the position of the second olefinic bond.

Additional confirmation of the assignment of the structure of (275) was provided by the similarity of the n.m.r. spectrum of (275) to that of the amide obtained by the rearrangement of the N-chlorosulphonyl-β-lactam derived from β-pinene. (p.19)

\[
\begin{align*}
\text{CH}_2\text{H} & \quad \text{SO}_2\text{Cl} \\
\text{N} & \quad \text{O} \\
\end{align*}
\]

(280)

\[
\begin{align*}
\text{Na}_2\text{SO}_3 \text{aq.} & \quad \text{NO}_3\text{Cl} \\
\text{OH} & \quad \text{ONHSO}_3 \text{Cl} \\
\end{align*}
\]

(279)

(275)

The presence of the broad NH stretching band in the i.r. spectrum of the reaction mixture of CSI and (273) suggests that the alcohol (275) was probably produced by hydrolysis of the N-chlorosulphonyl carbamate (279), which is formed via an intramolecular proton abstraction similar to that found in the rearrangement of the N-chlorosulphonyl-β-lactam derived from β-pinene. This proton transfer, and the formation of the two isomeric oxazolidinones (276) and (277), strongly suggests that the reaction proceeds via a free 1,5-dipole (280) which, in addition to cyclizing to the "normal" products (274) and (276), can also undergo the free rotation necessary for the formation of the oxazolidinone (277) and
the proton transfer to give (275).

CSI also reacted readily with 3α,4α-epoxycarane (281) in dichloromethane at ambient temperature. The i.r. spectrum of the reaction mixture showed a broad NH stretching band at 3310 cm\(^{-1}\), and bands at 1810, 1770 and 1600 cm\(^{-1}\) in the carbonyl region; and treatment of the reaction mixture with aqueous sodium sulphite gave a mixture of at least seven products. Chromatographic separation of this mixture afforded 1-isopropyl-4-methylbenzene (\(\pi\)-cymene) (286) (4.7%), trans-3,6,6-trimethyl-bicyclo[3,1,0]hexane-3-carboxaldehyde (287) (7.7%), the cis-1,2-diol (288) (3%), dioxolanone (289) (18.5%), carbamate (290) (0.5%) and the oxazolidinones (291) (5.5%) and (292) (2.5%).

The identity of (286) as \(\pi\)-cymene was confirmed by comparison of its spectral properties (i.r. and n.m.r.) with those of an authentic sample, while the assignment of the aldehyde (287) was confirmed by comparison of its n.m.r. and i.r. spectra with those reported by Settine and McDaniel\(^{147}\).

Both the oxazolidinone (291) and dioxolanone (289) showed a single proton multiplet in their n.m.r. spectra in the region expected for a methine proton adjacent to the oxygen atom of an oxazolidinone or dioxolanone ring.
CHART 7. Reaction of CSI with 3α,4α-epoxycarane.

CSI + [3α,4α-epoxycarane] → [281] + CSI

CH₂Cl₂ → [282] → [286] + CO₂ + ClSO₂NH₂

Na₂SO₃ aq. → [283] → [284] → [285] → [288]

[285] → [290]

[282] → [287]
The i.r. spectrum of the diol (288) showed an intense broad band at 3400 cm⁻¹ and a weaker, sharp band at 3580 cm⁻¹ due to hydrogen bonded and free hydroxy groups respectively. The structure of (288) was confirmed by spin decoupling and INDOR studies which showed that the methine ring proton, which appeared as a doublet of doublets (J = 10 and 6 Hz), was coupled to an allylic methylene group which in turn appeared as two doublets of doublets at δ2.32 and δ1.84 (J = 16 and 6 Hz and J = 16 and 10 Hz respectively) which showed no significant coupling to the olefinic proton.

The assignment of the orientation of the ring methine proton was based on the magnitudes of the couplings (10 and 6 Hz) between this proton and the adjacent methylene group, which were consistent with those expected for an axial proton (Jₐa = 10-13 Hz, Jₐe = 2-5 Hz, Jₑₑ = 2-5 Hz). Thus, since the ring methyl group would be expected to be in the equatorial position, the hydroxy groups were tentatively assigned the cis orientation shown.

The n.m.r. spectrum of the oxazolidinone (292) was consistent with either of the structures (292a) and (292b) and no definite assignment of the position of the isopropyl substituent on the olefinic bond was possible on the basis of spin decoupling and INDOR studies.
The i.r. spectrum of the carbamate (290) showed NH stretching bands at 3540 and 3430 cm\(^{-1}\) and a carbonyl band at 1720 cm\(^{-1}\) confirming the presence of the carbamate grouping. The position of the carbamate group was indicated by the observation that the broad doublet (J = 15 Hz) at \(\delta 2.76\) due to one of the ring methylene protons showed considerable sharpening on irradiation of the broad signal at \(\delta 4.66\) due to the NH\(_2\) group and the methine proton adjacent to the carbamate group.

The formation of all the products isolated in the reaction of CSI with 3\(\alpha\),4\(\alpha\)-epoxycarane (281) may be rationalized in terms of a common dipolar intermediate (282) as shown in the suggested reaction scheme (Chart 7).

Acid catalysed rearrangement of the epoxide (281) to the aldehyde (287), and dehydration of the epoxide (281) to p-cymene (286) have also been observed by Settine and McDaniel on treating the epoxide (281) with zinc bromide or boron trifluoride etherate in refluxing benzene\(^{147}\).

The diol (288) is probably produced from the N-chlorosulphonyl-dioxolan (283) via acid catalysed rearrangement of the cyclopropyl ring, either by CSI or during the work up, followed by complete hydrolysis of the N-chlorosulphonyl-dioxolan ring; while the oxazolidinone (292) is similarly derived from the N-chlorosulphonyl-oxazolidinone (284).

The carbamate (290) is the only product which cannot be regarded as being derived from cyclization of the dipolar intermediate (282), and must have arisen via a proton transfer followed by rearrangement of the cyclopropyl group.


The foregoing examples of the reactions of CSI with epoxides illustrate the importance of the structure and stereochemistry of the dipolar intermediate in determining the nature of the products. Behaviour ranging from the exclusive irreversible formation of cyclization products
in the case of simple epoxides, to exclusive formation of a proton transfer product in the case of cyclo-octatetraene epoxide (262) is observed.

The formation of carbamates in the reactions of cyclo-octatetraene epoxide (262) and terpene epoxides provides good evidence for the intermediacy of a free 1,5-dipole in the reaction of CSI with epoxides. A point of special interest is that in the reaction of 2α,10-epoxypinane, the product derived from proton transfer (perilla alcohol (275)) is very similar to the amide produced via the rearrangement of the N-chlorosulphonyl-β-lactam derived from β-pinene37.
SECTION SEVEN

EXPERIMENTAL

Instrumentation.

Melting points were determined using a Kofler micro heating stage and are uncorrected.

Infra-red spectra were recorded on a Perkin-Elmer 237 grating spectrometer for solutions in dichloromethane using 0.1 mm sodium chloride cells. Band positions are recorded in wave numbers ($\text{cm}^{-1}$) and the following abbreviations are used to describe the bands:-

(s) - strong, (m) - medium, (w) - weak, (b) - broad.

N.m.r. spectra were recorded on Varian Associates T60, A60 or DA60 spectrometers or on a Jeol JNM - PS100 spectrometer. Spin decoupling and INDO R studies were carried out on the DA60 or PS100 instruments. Peak positions are recorded in p.p.m. ($\delta$) from tetramethylsilane. The following abbreviations are used to describe signals:-

(s) - singlet, (d) - doublet, (t) - triplet, (q) - quartet,

(m) - multiplet, ($d^2$) - doublet of doublets, (dt) - doublet of triplets, etc.

Unless otherwise stated, n.m.r. spectra were recorded for solutions in deuteriochloroform.

Ultra-violet spectra were recorded on a Unicam SP800 spectrometer using 1 cm quartz cells.

Mass spectra were recorded using an AEI MS9 spectrometer, the molecular ion ($M^+$) followed by peaks of structural significance, including the base peak (b) are given.

Gas-liquid chromatography was performed on a Pye 104 instrument; 1.5 m x 6 mm o.d. 10% E 30 and 3% OV 17 glass columns were used for analysis and a 2.1 m x 9 mm o.d. 20% E 30 glass column was used for preparative work. Nitrogen flows of 40 ml/min and 80 ml/min were used for analysis and preparative work respectively.
General.

All reaction solvents were dried prior to use.

Hydrocarbons were dried over sodium wire. Chloroform was freed from ethanol by shaking with aqueous calcium chloride solution, dried over anhydrous calcium chloride and distilled from fresh anhydrous calcium chloride. Dichloromethane was refluxed over and distilled from calcium hydride. Carbon tetrachloride was refluxed over and distilled from anhydrous calcium chloride. Ether was refluxed over and distilled from lithium aluminium hydride. Acetone, acetonitrile and nitromethane were dried over molecular sieves (Type 4A). Pyridine and triethylamine were dried over sodium hydroxide and distilled from fresh sodium hydroxide.

Chlorosulphonyl isocyanate (CSI) was supplied by Ralph N. Emanuel Ltd. and was distilled from anhydrous potassium carbonate prior to use.

Solvents were evaporated from solutions using a rotary evaporator.

Reactions with chlorosulphonyl isocyanate were carried out by adding the substrate dropwise via a syringe to a stirred solution of chlorosulphonyl isocyanate, or vice versa, under dry nitrogen. In many cases the reactions were followed by monitoring the i.r. spectra of aliquots of the reaction mixture, and significant features of the spectrum of the reaction mixture are given in parentheses at the appropriate place in the experimental text.

The n.m.r. studies of reactions, mentioned in the discussion, were carried out by adding CSI (0.3-0.5 mmol), via a microsyringe, to a solution of an equimolar amount of the substrate in deuteriochloroform (ca. 0.5 ml) in an n.m.r. tube and monitoring the spectrum of the mixture. When it was desired to follow a reaction at low temperature, the substrate solution was frozen prior to the addition of the CSI. Traces of CSI on the wall of the n.m.r. tube were washed down with the minimum volume of deuteriochloroform. The tube was then slowly warmed until the contents became "slushy" when they were mixed with a fine glass rod, the tube was then rapidly transferred at low temperature (ca. -80°) to the spectrometer.
probe and warmed until the reaction mixture melted. The spectrum was then monitored as the probe temperature was slowly increased.
Reaction of chlorosulphonyl isocyanate with 1,3-cyclopentadiene (119)

1,3-Cyclopentadiene (119) was prepared by thermolysis of dicyclopentadiene 148, the distilled cyclopentadiene (b.p. 41-42°) was freshly prepared for each reaction and stored at -78°, until required, to prevent dimerization.

Preparation of 6-azabicyclo[3,2.0]hept-3-en-7-one (121)

A solution of 1,3-cyclopentadiene (119) (1.5g; 22.7 mmol) in dichloromethane (3 ml) was added to a solution of CSI (1.75 ml; 20.5 mmol) in dichloromethane (30 ml) at ambient temperature over 10 min. After a further 5 min. the vigorously stirred reaction mixture (ν max. 1818(major) and 2250(minor) cm⁻¹) was treated with a solution of anhydrous sodium sulphite (6g) in water (25 ml), after 30 min. the organic layer was separated and the aqueous layer was extracted with dichloromethane (2 x 15 ml). The combined organic layer and extracts were dried and the solvent was evaporated yielding 6-azabicyclo[3,2.0]hept-3-en-7-one (121) (889 mg; 40%) as a pale yellow oil which on distillation afforded pure (121) as a colourless oil (755 mg; 34%), b.p. 90-95°/0.2 mm.Hg; ν max 3410(m) and 1755(s) cm⁻¹; δ 7.42 (1H,broad), 5.94 (2H, m), 4.46 (1H, m), 3.37 (1H, m), 2.68 (1H, d,m, J 18Hz), 2.38 (1H, d,m, J 18, and 9.5Hz; m/e 109 (M⁺), 80, 78, 66(b), 65, 43. Found: C,64.3; H,6.6; N,12.5. * C₆H₇NO requires: C,66.0; H,6.5; N,12.8%.

Preparation of 2-azabicyclo[2,2.1]hept-5-en-3-one (130)

A solution of 1,3-cyclopentadiene (119) (3.0 g; 45.4 mmol) in dichloromethane (5 ml) was added to a solution of CSI (3.53 ml; 41.3 mmol) in dichloromethane (125 ml) at ambient temperature over 30 min. and the reaction mixture (ν max. 1818 cm⁻¹) was stirred for 5h at ambient temperature. The resulting deep red solution (ν max. 1790 and 1775(major), 1818 and 1695(minor) cm⁻¹) was treated with a solution of anhydrous sodium

* Analysis consistently agreed with theory + ca. 3.5% water
sulphite (12g) in water (50 ml) for 30 min. at ambient temperature and worked up in the normal way (p.146) yielding a yellow oil (2.3g) which was separated by chromatography on alumina (Grade II; 50g). Elution with methanol-ether yielded the \( \beta \)-lactam (121) (258 mg; 5.5%) as a yellow oil, a 1:1 mixture of (121) and (130) (115 mg; 2%) as a yellow oil, and 2-azabicyclo[2,2,1]hept-5-en-3-one (130) (1.281g; 27.5%) as white crystals, m.p. 54-56° (from acetone-ether) (lit. 54-55°); \( \nu \) max. 3430 (m) and 1715 (s) cm\(^{-1}\); \( \delta \) 7.1-6.7 (1H, broad), 6.81 (1H, d\(^3\), \( J \) 5.45, 2.1 and 0.75 Hz), 6.65 (1H, d\(^3\), \( J \) 5.45, 3.2 and 1.45 Hz), 4.34 (1H, m), 3.21 (1H, m), 2.38 (1H, dm, \( J \) 7.7H), 2.20 (1H, dm, \( J \) 7.7H); m/e 109 (M\(^+\)), 78, 66 (b), 65, 43. Found: C, 66.1; H, 6.6; N, 12.8. Calculated for \( \text{C}_6\text{H}_7\text{NO} \): C, 66.0; H, 6.5; N, 12.8%.

Conversion of the lactam (130) to 3-ethoxy-2-azabicyclo[2,2,1]hepta-2,5-diene (132)

A solution of the lactam (130) (100 mg; 0.92 ml) in dichloromethane (1 ml) was added to a stirred solution of triethyloxonium fluoroborate (250 mg; 1.3 mmol) in dichloromethane (5 ml) under dry nitrogen at ambient temperature. After 1h the reaction was stirred with 50% aqueous potassium carbonate (4 ml) for 15 min. After filtration through Celite to break up the emulsion, the organic layer was separated, dried, and the solvent was evaporated yielding 3-ethoxy-2-azabicyclo[2,2,1]hepta-2,5-diene (132) (110 mg; 80%) as a colourless oil which rapidly darkened and resinified at ambient temperature, \( \nu \) max. (CCl\(_4\)) 1620 (s), 1325 (s) and 1263 (s) cm\(^{-1}\); \( \delta \)(CCl\(_4\)) 6.86 (1H, d\(^3\), \( J \) 5.5, 2.7 and 0.7 Hz), 6.64 (1H, d\(^3\), \( J \) 5.5, 1.4 and 3.1 Hz), 4.63 (1H, m), 4.05 (2H, m), 3.32 (1H, m) 2.21 (1H, dt, \( J \) 6.6 and 1.65 Hz), 1.95 (1H, dt, \( J \) 6.6 and 1.0 Hz), 1.27 (3H, t, \( J \) 7.0 Hz); m/e 137 (M\(^+\)), 109, 108, 71, 66 (b), 65.

Reduction of the lactam (130) to 2-azabicyclo[2,2,1]hept-5-ene (149)

A mixture of lithium aluminium hydride (150 mg; 3.95 mmol) and the
lactam (130) (200 mg; 1.83 mmol) in ether (15 ml) was refluxed under
dry nitrogen for 4 h. Ether saturated with water was then added cautiously
to destroy the excess lithium aluminium hydride, the reaction mixture was
filtered and the filtrate was dried and the solvent was evaporated yielding
2-azabicyclo[2,2,1]hept-5-ene (149) (140 mg; 80%) as a colourless oil,
\[ \text{Vmax. (film)} 3380 \text{ (mb)}, 3060 \text{ (m)}, 2990, 2950, 2880 \text{ (s)} \text{ and } 1335 \text{ (s) cm}^{-1}; \]
\[ \delta(\text{CCl}_4) 6.0 \text{ (2H, m)}, 3.77 \text{ (1H, m)}, 3.2-2.8 \text{ (2H, m)}, 2.1 \text{ (1H, s, disappeared on shaking with D}_2\text{O), 1.9} \text{ (1H, d, J 8 Hz), 1.25 (2H, s - fine splitting)}; \]
m/e 95 (M^+), 94, 78, 66(b), 65.

The amine (149) was converted to the hydrochloride salt (150) by
bubbling hydrogen chloride into a solution of the amine (114 mg; 1.2 mmol)
in ether (5 ml) until no more precipitate was produced. The solvent was
then evaporated yielding 2-azabicyclo[2,2,1]hept-5-ene hydrochloride (150)
(110 mg; 70%) as white hygroscopic crystals, m.p. 90-95°C (decomp.) (from
ethanol-ether); \[ \text{Vmax. 3100-2800 (s), 2740, 2680 (s), 2630, 2600, 2480 (m) and} \]
1590 (m) cm\(^{-1}; \delta 9.7 \text{ (1H, broad), 8.7 (1H, broad), 6.5 (1H, m), 6.3 (1H, m),} \]
4.63 (1H, m), 3.23 (2H, m), 2.6 (1H, m), 1.8 (2H, m). Found: C,53.3;
H,7.7; N,10.25; \(^*\) C\(_6\)H\(_{10}\)NCl requires: C,54.75; H,7.7; N,10.6%.

Catalytic hydrogenation of the lactam (130)

A solution of the lactam (130) (500 mg; 4.6 mmol) in ethyl acetate
(15 ml) was hydrogenated at atmospheric pressure for 100h at ambient
temperature using 10% Pd on charcoal (20 mg) as catalyst. The catalyst
was filtered off and the solvent was evaporated yielding 2-azabicyclo[2,2,1]
heptan-3-one (131) (502 mg; 99%) as a pasty white solid which rapidly
deliqüesced on exposure to air, \[ \text{Vmax. 3430 (m) and 1700 (s) cm}^{-1; \delta 7.2 (1H, broad), 3.83 (1H, m), 2.67 (1H, m), 2.1-1.2 (6H, m); m/e 111 (M^+)}, 96, 83,
82, 68, 67(b), 55, 43.

\(^*\) Analysis consistently agreed with theory + ca. 3% water.
Reduction of 2-azabicyclo[2,2,1]heptan-3-one (131)

The lactam (131) (200 mg; 1.8 mmol) was reduced with lithium aluminium hydride (150 mg; 3.95 mmol) in ether (15 ml) as described previously (p.148). The free amine was not isolated but was converted in situ to the hydrochloride salt (153) as described earlier (p.148) yielding 2-azabicyclo[2,2,1]heptane hydrochloride (153) as white deliquescent crystals, m.p. 206-210° (decomp.) (from ethanol-ether); $\nu$ max. 3100-2800 (s), 2750, 2700, 2670 (s), 2550, 2500, 2440 (m) and 1595 (m) cm$^{-1}$; $\delta$ 9.1 (2H, broad), 4.07 (1H, m), 3.07 (2H, m), 2.88 (1H, m), 2.5-1.4 (6H, m). Found: C, 53.1; H, 9.1; N, 10.2. $^* C_6H_{12}NCl$ requires: C, 53.9; H, 9.1; N, 10.5%.

Reaction of chlorosulphonyl isocyanate with 1,3-cyclohexadiene (122)*

Preparation of 7-azabicyclo[4,2,0]oct-4-en-8-one (124)

A solution of 1,3-cyclohexadiene (122) (2.0 g; 23.8 mmol) in dichloromethane (10 ml) was added to a solution of CSI (1.73 ml; 20.0 mmol) in dichloromethane (75 ml) at ambient temperature. After 5 min. the reaction mixture ($\nu$ max. 1810 (major) and 2250 (minor) cm$^{-1}$) was cooled to $-78^\circ$ and acetone (15 ml) followed by benzenethiol (4.5 ml; 43 mmol) were added dropwise; pyridine (3.0 ml; 40 mmol) was then added dropwise and the reaction mixture was allowed to warm to $0^\circ$, when water (10 ml) was added. The mixture was stirred for 30 min. at ambient temperature, the organic layer was separated and the aqueous layer was extracted with dichloromethane (3 x 20 ml). The combined organic layer and extracts were dried and the solvent was evaporated yielding a mixture of the $\beta$-lactam (124) and diphenyl disulphide as a pale yellow solid which was separated by chromatography on alumina (Grade I; 70 g). The diphenyl disulphide was removed by elution with petrol and ether. Elution with methanol-ether afforded 8-azabicyclo[4,2,0]oct-2-en-7-one (124) (1.651 g; 67.5%) as off white crystals, m.p. 70.5-71.5° (from acetone-ether); $\nu$ max. 3410 (m), 1755 (s), and

* Supplied by Ralph N. Emanuel Ltd.  + Analysis consistently agreed with theory + ca 1% water
1590 (m) cm⁻¹; δ 6.92 (1H, broad), 6.16 (1H, d₂, J 10 and 4Hz), 5.90 (1H, d₂, J 10 and 4Hz), 3.99 (1H, t.m., J 5Hz), 3.46 (1H, m), 2.3-1.42 (4H, m); m/e 123 (M⁺), 80(b), 79, 78, 77, 43. Found: C, 68.3; H, 7.35; N, 11.1. 
C₇H₅NO requires: C, 68.3; H, 7.4; N, 11.4%.

Preparation of N-chlorosulphonyl-3-imino-2-oxabicyclo[2,2,2]oct-5-ene (134) 
A solution of 1,3-cyclohexadiene (122) (2.0 g; 23.8 mmol) in dichloromethane (10 ml) was added to a solution of CSI (1.75 ml; 20.5 mmol) in dichloromethane (50 ml) at ambient temperature over 10 min. After 30h at ambient temperature the solvent was evaporated from the reaction mixture (νmax. 1588 cm⁻¹) yielding crude N-chlorosulphonyl-3-imino-2-oxabicyclo[2,2,2]oct-5-ene (134) (4.7 g) as pale yellow crystals containing some residual dichloromethane. Recrystallization from acetone afforded pure (134) (3.12 g; 69%) as white crystals, m.p. 76.5-78°C (from acetone); νmax. 1588 (s) and 1619 (m) cm⁻¹; δ 6.61 (2H, m), 5.74 (1H, m), 3.90 (1H, m), 2.3-1.42 (4H, m); m/e 223, 221 (M⁺), 195, 193, 186, 158, 143, 141, 122, 107, 106, 105, 101, 99, 80(b), 79, 78, 77, 74. Found: C, 38.2; H, 3.5; N, 6.5. C₇H₅NO₃SCl requires: C, 37.9; H, 3.6; N, 6.3%.

Preparation of N-chlorosulphonyl-2-azabicyclo[2,2,2]oct-5-en-3-one (135) 
A solution of 1,3-cyclohexadiene (122) (2.0 g; 23.8 mmol) in dichloromethane (10 ml) was added to a solution of CSI (1.75 ml; 20.5 mmol) in dichloromethane (50 ml) at ambient temperature over 10 min. After 30h at ambient temperature the solvent was evaporated from the reaction mixture (νmax. 1588 cm⁻¹) yielding crude N-chlorosulphonyl-2-azabicyclo[2,2,2]oct-5-en-3-one (134) (4.7 g) as pale yellow crystals containing some residual dichloromethane. Recrystallization from acetone afforded pure (134) (3.12 g; 69%) as white crystals, m.p. 76.5-78°C (from acetone); νmax. 1588 (s) and 1619 (m) cm⁻¹; δ 6.61 (2H, m), 5.74 (1H, m), 3.90 (1H, m), 2.3-1.42 (4H, m); m/e 223, 221 (M⁺), 195, 193, 186, 158, 143, 141, 122, 107, 106, 105, 101, 99, 80(b), 79, 78, 77, 74. Found: C, 38.2; H, 3.5; N, 6.5. C₇H₅NO₃SCl requires: C, 37.9; H, 3.6; N, 6.3%.
Preparation of 2-azabicyclo[2,2,2]oct-5-en-3-one (136)

A solution of crude (135) (1.9 g; 8.6 mmol) in acetone (5 ml), and aqueous (2M) sodium hydroxide were simultaneously added dropwise to a stirred 1:1 mixture of acetone and water (20 ml) saturated with sodium chloride; the rates of addition were controlled so as to maintain the reaction mixture at pH 6-7. The mixture was extracted with dichloromethane (4 x 25 ml), the extract was dried and the solvent was evaporated yielding crude 2-azabicyclo[2,2,2]oct-5-en-3-one (136) (0.87 g; 80%) as yellow oily crystals. Chromatography on alumina (Grade I; 30 g) eluting with ether and ether-methanol afforded pure (136) (381 mg; 35%) as white crystals, m.p. 124.5-125° (after sublimation at 100°/20 mm Hg); V max. 3430(m), 1690(s) and 1613(w) cm⁻¹; δ 7.8 (1H, broad), 6.35 (2H, m), 4.26 (1H, m), 3.33 (1H, m), 2.13-1.2 (4H, m); m/e 123 (M+), 95, 80(b), 79, 67, 43. Found: C,68.3; H,7.3; N,11.2. C₁₂H₁₈NO requires: C,68.3; H,7.4; N,11.4%.

Reduction of the lactam (136) to 2-azabicyclo[2,2,2]oct-5-ene (155)

The lactam (136) (400 mg; 3.25 mmol) was reduced with lithium aluminium hydride (200 mg; 5.25 mmol) in ether (25 ml) as described previously (p.148) yielding crude 2-azabicyclo[2,2,2]oct-5-ene (155) (268 mg; 70%) as a colourless oil, V max.(film) 3270(s.b.), 3040, 2940, 2860(s), 1170 and 1060(m) cm⁻¹; δ (CFCl₃) 6.23 (2H, m), 3.33 (1H, m), 2.87 (1H, d, J 8Hz), 2.63-2.2 (2H, m), 2.0-1.0 (5H, m; which after shaking with D₂O became 4H, m); m/e 109 (M⁺), 95, 94, 80(b), 79, 78, 77, 64, 57.

The amine (155) (170 mg; 1.56 mmol) was converted to the hydrochloride salt as described previously (p.148) yielding 2-azabicyclo[2,2,2]oct-5-ene hydrochloride (156) as white crystals, m.p. 235-236°(decomp.) (from ethanol-ether); V max. 3080-2850(s), 2800, 2750, 2700(s), 2460(m) and 1590(m) cm⁻¹; δ 9.8 (2H, broad), 6.4 (2H, m), 4.23 (1H, m), 3.4-2.2 (4H, m), 2.0-1.2 (3H, m). Found: C,57.3; H,8.3; N,9.6. C₁₂H₂₄NCl requires: C,57.7; H,8.3; N,9.6%.
Reaction of chlorosulphonyl isocyanate with 1,3-cycloheptadiene (125)

Preparation of 8-azabicyclo[5,2,0]non-5-en-9-one (127)

CSI (0.43 ml; 5.0 mmol) was added to a solution of the diene (125) (0.5 g; 5.3 mmol) in dichloromethane (15 ml) at ambient temperature. After 1h the reaction mixture ($\nu_{\text{max}}$ 1820 (major) and 2250 (minor) cm$^{-1}$) was treated with a solution of anhydrous sodium sulphite (2 g) in water (10 ml) for 30 min. and worked up in the usual manner (p.l46) yielding 8-azabicyclo[5,2,0]non-5-en-9-one (127) (260 mg; 38%) as white crystals, m.p. 71-74° (from dichloromethane-ether); $\nu_{\text{max}}$ 3405 (m) and 1753 (s) cm$^{-1}$; $\delta$ 6.8 (1H, broad), 5.53 (2H, s), 4.4 (1H, d, J 5Hz), 3.2 (1H, m), 2.5-1.2 (6H, m); m/e 137 ($M^+$), 122, 94 (b), 93, 91, 80, 79, 78, 77, 67, 66, 65, 43.

Found: C, 69.8; H, 8.1; N, 10.3. C$_8$H$_{11}$NO requires: C, 70.0; H, 8.1; N, 10.2%.

Preparation of N-chlorosulphonyl-7-imino-6-oxabicyclo[3,2,2]non-8-ene (138)

CSI (0.43 ml; 5.0 mmol) was added to a solution of the diene (125) (0.5 g; 5.3 mmol) in dichloromethane (15 ml) at ambient temperature, and the reaction mixture was warmed to 30°. After 25h the solvent was evaporated from the reaction mixture ($\nu_{\text{max}}$ 1580 cm$^{-1}$) yielding crude N-chlorosulphonyl-7-imino-6-oxabicyclo[3,2,2]non-8-ene (138) (1.2 g; 100%) as pink crystals. Recrystallization from dichloromethane-ether afforded pure (138) as white crystals, m.p. 87-89°; $\nu_{\text{max}}$ 1580 (s), 1407 (m), 1365 (m), and 840 (m) cm$^{-1}$; $\delta$ 6.37 (2H, m), 5.43 (1H, m), 3.45 (1H, m), 1.8 (6H, m); m/e 237 and 235 ($M^+$), 200, 136, 119, 94, 93, 91, 81, 79, 78, 77, 64.

Found: C, 40.8; H, 4.2; N, 5.9. C$_8$H$_{10}$NO$_3$SCl requires: C, 40.8; H, 4.3; N, 5.9%.

Rearrangement of N-chlorosulphonyl-7-imino-6-oxabicyclo[3,2,2]non-8-ene (138)

CSI (0.43 ml; 5.0 mmol) was added to a solution of the diene (125)

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(0.5 g; 5.3 mmol) in nitromethane (15 ml) at ambient temperature.

The reaction mixture (νmax. 1820 cm⁻¹) was stirred at ambient temperature for 24 h and the solvent was then evaporated yielding crude (138) (1.2 g; 100%) as pale yellow crystals. The product was dissolved in nitromethane (20 ml) and heated to 80° for 5 days, the resulting dark brown solution (νmax. 2210 (major), 1720 (b) (major) and 1580 (minor) cm⁻¹) was treated with a solution of anhydrous sodium sulphite (2 g) in water (10 ml) for 30 min. and worked up in the usual way (p.146) yielding an orange oil (300 mg) which was separated by chromatography on silica (10 g). Elution with ether yielded 1-cyano-1,3-cycloheptadiene (140) (195 mg; 33%) as a pale yellow oil. Preparative g.l.c. (160°) afforded a pure sample of (140) as a colourless oil, which rapidly turned yellow on exposure to light at ambient temperature, ν max.(film) 3020 (m), 2930 (s), 2210 (s) and 1600 (m) cm⁻¹; δ 6.4 (1H, d, J 7 Hz), 6.1 (1H, d, J 12 and 4 Hz), 5.7 (1H, d, J 7 and 12 Hz), 2.43 (4H, m), 1.9 (2H, m); λ max.(EtOH) 272.5 nm, ε 11,900; m/e 119 (M⁺), 118, 117, 116, 104, 103, 93, 92, 91 (b), 77, 67, 61, 39.

Found: C, 78.0; H, 7.3; N, 11.45. C₉H₇N requires: C, 80.6; H, 7.6; N, 11.75%

Elution with 5% methanol-ether afforded a small fraction (45 mg) which was purified by preparative t.l.c. (alumina/5% methanol-ether) yielding 1,3-cycloheptadieneamide (141) (22 mg; 3%) as oily crystals, m.p. 70-75° (after sublimation at 100°/0.5 mm Hg); ν max. 3505 (m), 3405 (m), 1665 (s), 1630 (m) and 1355 (m) cm⁻¹; δ 6.61 (1H, d, J 7 Hz), 6.5-5.7 (4H, m), 2.5 (4H, m), 1.87 (2H, quintet, J 5.5 Hz); λ max.(EtOH) 274 nm, ε 8,600; m/e 137 (M⁺, b), 136, 135, 122, 121, 119, 109, 93, 92, 91, 79, 78, 77, 74, 59.
Reaction of chlorosulphonyl isocyanate with vinyl cyclopropane (162)

Vinylcyclopropane (162) (b.p. 39-41°, lit. 149 40-40.2°) was prepared from cyclopropyl methyl ketone in 13% yield by the method of Demjanov and Dojarenko 148.

Preparation of 1-chlorosulphonyl-4-cyclopropyl-2-azetidinone (163)

CSI (0.17 ml; 2.05 mmol) was added to a solution of the olefin (162) (140 mg; 2.06 mmol) in deuteriochloroform (5 ml) at ambient temperature. After 30 min. the solvent was evaporated yielding crude 1-chlorosulphonyl-4-cyclopropyl-2-azetidinone (163) (440 mg; 100%) as a pale amber oil, Vmax. (CDCl3) 1815 (s) and 1410 (s) cm^-1; 8 3.9 (1H, d, J 4, 6 and 8 Hz), 3.45 (1H, d, J 6 and 16.5 Hz), 3.0 (1H, d, J 4 and 16.5 Hz), 1.6-1.0 (1H, m), 1.0-0.4 (4H, m). Analysis was not obtained as it was not possible to induce the crude material to crystallize.

Preparation of 4-cyclopropyl-2-azetidinone (164)

A solution of (163) (440 mg; 2.05 mmol) in ether (15 ml) was treated with a solution of anhydrous sodium sulphite (1 g) in water (10 ml) for 30 min. and worked up in the normal way (p.146) yielding 4-cyclopropyl-2-azetidinone (164) (204 mg; 90%) as a pale yellow oil. Distillation (120-125°/15 mm Hg) followed by preparative g.l.c. (150°) afforded pure (164) as a colourless oil, Vmax. 3405 (m) and 1763 (s) cm^-1; 8 7.1 (1H, broad), 3.6-2.4 (3H, m), 1.4-0.8 (1H, m), 0.7-0.2 (4H, m); m/e 111 (M^+), 83, 82, 70, 69, 68(b), 67, 66, 65, 56, 55, 54, 53, 52, 51, 50, 43.

Found: C, 64.6; H, 8.4; N, 12.4. C_6H_7NO requires: C, 64.8; H, 8.2; N, 12.6%.

Rearrangement of the N-chlorosulphonyl-β-lactam (163)

CSI (0.53 ml; 6.4 mmol) was added to a solution of the olefin (162) (434 mg; 6.4 mmol) in dichloromethane (20 ml) at ambient temperature. After 5 weeks the solvent was evaporated from the reaction mixture
(vmax. 1750 (broad) cm\(^{-1}\)) yielding a brown tar (1.24 g). The crude product was dissolved in dichloromethane (10 ml), and triethylamine (1.0 ml; 0.73 mmol) was added dropwise with stirring to the resulting brown solution. After 1 h the mixture was evaporated to ca. 3 ml and extracted with ether (3 x 20 ml). The solvent was evaporated from the reaction mixture yielding a yellow oil which was freed from most of the residual triethylamine hydrochloride by chromatography on a short (2") alumina (1 g) column; elution with ether afforded a yellow oil (200 mg) which was a mixture of 1-cyano-2-cyclopropyldiene-ethane (174), 1-cyano-2-cyclopropyl-ethylene (175) and triethylamine hydrochloride.

From the n.m.r. spectrum of the crude product the yields of the nitriles were calculated to be (174) (8%) and (175) (14%). Preparative g.l.c. (75°) afforded pure 1-cyano-2-cyclopropyldiene-ethane (174) as a pale yellow oil, \(\nu\) max. \((\text{CCl}_4)\) 2250 (w) cm\(^{-1}\); \(\delta\) (\text{CCl}_4) 3.55 (1H, m), 2.95 (2H, d, J 6Hz), 1.0-0.4 (4H, m); m/e 95 (M\(^+\), b), 67, 66, 65, 53, 41. Found: C, 77.2; H, 7.3; N, 15.0. \(\text{C}_6\text{H}_7\text{N}\) requires: C, 77.4; H, 7.6; N, 15.0%.

and pure 1-cyano-2-cyclopropyl-ethylene (175) as a pale yellow oil, \(\nu\) max. \((\text{CCl}_4)\) 2220 (s) and 1660 (m) cm\(^{-1}\); \(\delta\) (\text{CCl}_4) 6.15 (1H, d\(^2\), J 6 and 16Hz), 5.15 (1H, d, J 16Hz), 1.8-1.3 (1H, m), 1.0-0.5 (4H, m); \(\lambda\) max. 226.5 nm \(\varepsilon\) 17,600; m/e 93 (M\(^+\)), 78, 67, 66 (b), 65, 64, 63, 54, 53, 52, 51, 50, 41. Found: C, 77.1; H, 7.2; N, 15.0. \(\text{C}_6\text{H}_7\text{N}\) requires: C, 77.4; H, 7.6; N, 15.0%.

Reaction of chlorosulphonyl isocyanate with 2-cyclopropylpropene (165)

2-cyclopropylpropene (165) (b.p. 66-70°, lit.\(^{150}\) 70.4°) was prepared in 55% yield by the method of Volkenburgh et al.\(^{150}\). Reaction of cyclopropyl-methyl-ketone with methyl-lithium yielding 2-cyclopropyl-2-propan-2-ol was followed by sulphuric acid catalysed dehydration of the alcohol to the required olefin (165).
Preparation of 4-cyclopropyl-4-methyl-2-azetidinone (167)

A solution of the olefin (165) (1.0 g; 12.2 mmol) in dichloromethane (5 ml) was added to a solution of CSI (1.0 ml; 12.0 mmol) in dichloromethane (25 ml) at -78°. After 7 min. the reaction mixture (ν max. 1815 cm⁻¹) was treated with acetone (10 ml), benzenethiol (2.8 ml; 25 mmol) and pyridine (1.9 ml; 24 mmol) and worked up in the normal manner (p.149) yielding a yellow oil which was separated by chromatography on alumina (Grade I; 60 g). After removal of diphenyl disulphide by elution with petrol and ether, elution with 5-10% methanol-ether yielded 4-cyclopropyl-4-methyl-2-azetidinone (167) (1.22 g; 86%) as a viscous pale yellow oil. Rechromatographing to remove residual traces of diphenyl disulphide, and distillation (85-87°/0.2 mm Hg) afforded pure (167) as white crystals, m.p. 37-38° (from ether-petrol) (lit. 39-41°); ν max. 3405(m), and 1760(s) cm⁻¹. 7.08 (IH, broad), 2.69 and 2.65 (2H, central lines of AB system), 1.47 (3H, S), 1.3-0.9 (1H, m), 0.9-0.1 (4H, m); m/e 125 (M⁺), 110, 97, 82, 81, 67, 58, 43, 42. Found: C,67.3; H,8.9; N,11.4. Calculated for C₇H₁₁NO: C,67.2; H,8.9; N,11.2%.

Preparation of N-chlorosulphonyl-3-cyclopropyl-2-buteneamide (179)

CSI (1.5 ml; 18.0 mmol) was added to a solution of the olefin (165) (1.5 g; 18.3 mmol) in dichloromethane (50 ml) at ambient temperature. After 1h the i.r. spectrum of the reaction mixture showed major bands at 1750 and 1720 cm⁻¹ and a minor band at 1815 cm⁻¹. After a further 27h the solvent was evaporated from the reaction mixture (ν max. 1720 cm⁻¹) yielding crude N-chlorosulphonyl-3-cyclopropyl-2-buteneamide (E,Z mixture) (179) (4.1 g) as a pasty yellow solid containing some residual dichloromethane, ν max. 3300(s.b.), 1720(s), and 1605(s) cm⁻¹; δ 9.3 (1H, broad), 5.95 (1H, s), 2.05 and 1.6 (1.8H, s, and 1.2H, s; Me groups of geometric isomers), 1.9-1.5 (1H, m), 1.2-0.7 (4H, m). Analysis could not be obtained as it was not possible to induce crystallization of the crude product.
Acid hydrolysis of N-chlorosulphonyl-3-cyclopropyl-2-buteneamide (182)

Hydrochloric acid (1M) (20 ml) was added to a stirred solution of (179) (2.0 g; 8.6 mmol) in acetone (10 ml) at ambient temperature. After 8 h the mixture was neutralized with aqueous sodium hydroxide (1 M) and extracted with dichloromethane (4 x 25 ml). The extract was dried and the solvent was evaporated yielding a mixture of 3-cyclopropyl-2-buteneamide (E,Z mixture) (182) and 6-chloro-3-methyl-3-hexeneamide (184) as pale yellow crystals (1.11 g). The mixture was separated by chromatography on Kieselgel (GF 254; 80g). Elution with 5% methanol-ethyl acetate afforded mixed fractions of (182) and (184), and pure (184) (161 mg). From the n.m.r. spectra of the mixed fractions the overall yields of (182) (49%), and (184) (28%) were calculated. Recrystallization from ether-acetone and sublimation at 100°/0.5 mm Hg afforded pure 6-chloro-3-methyl-3-hexeneamide (184), m.p. 112-113° (with sublimation), (lit. 119 113-114.5), ν max. 3505(m), 3390(m), 1683(s), and 1580(m) cm⁻¹, δ 6.5-5.2 (2H, broad), 5.5 (1H, tm, J 8Hz), 3.65 (2H, t, J 7Hz), 3.0 (2H, s), 2.6 (2H, qb, J 7Hz), 1.75 (3H, s); m/e 163 and 161 (M⁺), 148, 146, 126, 125(b), 110, 108, 84, 83, 82, 81, 69, 67, 59, 56, 55. Found: C,52.1; H,7.4; N,8.6. Calculated for C₇H₁₂NOCl: C,52.0; H,7.5; N,8.7%. Fractional recrystallization, from ether-acetone, of the mixed fractions most enriched in the amide (182) afforded pure 3-cyclopropyl-2-buteneamide (E,Z mixture) (182), m.p. 135-137° (after sublimation at 90°/0.5 mm Hg); ν max. 3525(m), 3410(m), 1670(s), 1625(m) and 1585(m) cm⁻¹; δ 7.5-5.2 (2H, broad), 5.73 (1H, s), 2.0 and 1.5 (2.1H, d, J 1Hz), and 0.9H, d, J 1.5 Hz; Me groups of geometric isomers, 1.8-1.3 (1H, m), 0.95-0.5 (4H, m); λ max.(EtOH) 230.5 nm, ε 18,500; m/e 125 (M⁺), 124, 110, 97(b), 82, 81, 43. Found: C,67.3; H,8.9; N,11.1. C₇H₁₁NO requires: C,67.2; H,8.9; N,11.2%.

Preparation of 1-cyano-2-cyclopropylpropene (E,Z mixture) (181)

Triethylamine (0.9 ml; 6.3 mmol) was added dropwise to a stirred
solution of the N-chlorosulphonyl amide (179) (1.25 g; 5.6 mmol) in dichloromethane (20 ml). The reaction mixture was evaporated to ca. 3 ml, ether (10 ml) was added and the mixture was filtered to remove the precipitated triethylamine hydrochloride. The filtrate was passed through a short silica column, eluted with 50% petrol-ether to remove residual triethylamine hydrochloride and the solvent was evaporated from the eluant yielding 1-cyano-2-cyclopropyl-propene (E,Z mixture) (181) (431 mg; 71%) as a pale yellow oil. Distillation (118-120°/1 atm) followed by preparative g.l.c. (130°) afforded pure (181) as a colourless oil, ν max. (CCl₄) 2215 (s) and 1615 (m) cm⁻¹; δ (CCl₄) 5.2 (1H, s), 2.4-1.8 (1H, m), 1.83 and 1.57 (1.95H, d, J 1Hz, and 1.05H, d, J 1.5Hz; Me groups of geometric isomers), 1.0-0.8 (4H, m); λ max.(cyclohexane) 227 nm, ε 14,500; m/e 107 (M⁺), 108, 92, 81, 80(b), 79, 66, 65, 41. Found: C, 78.5; H, 8.7; N, 13.0. Calculated for C₇H₉N: C, 78.5; H, 8.5; N, 13.1%.


CSI (0.6 ml; 7.3 mmol) was added to a solution of the olefin (165) (0.67 g; 8.1 mmol) in dichloromethane (15 ml) at -78°. After 5 min. the reaction mixture was allowed to warm to ambient temperature and after 1h the reaction mixture (ν max. 1750 (major) and 1720 (minor) cm⁻¹) was treated with triethylamine (1.1 ml; 8.0 mmol). After 30 min. the mixture was evaporated to ca. 3 ml, ether (30 ml) was added and the mixture was stirred vigorously for 30 min. The precipitated triethylamine hydrochloride was filtered off and the filtrate was evaporated to ca. 1 ml yielding a yellow oil containing the αβ-unsaturated nitrile (E,Z mixture) (181) and 3-cyano-2-cyclopropylpropene (180). From the n.m.r. spectrum of the crude product containing chloroform as a quantitative internal standard the yields of the nitriles (180) (46%) and (181) (30%) were calculated. Pure samples of the nitriles were obtained by preparative g.l.c. (130°).
yielding (181) as a colourless oil with identical spectral properties and retention time to an authentic sample, and 3-cyano-2-cyclopropyl-propene (180) as a colourless oil, \( \nu_{\text{max.}} \) (CCl\(_4\)) 3080(m), 2245(w), and 1648(m) cm\(^{-1}\), \( S \) (CCl\(_4\)) 5.17 (1H, s), 5.0 (1H, s), 3.1 (2H, s), 1.7-1.0 (1H, m), 1.0-0.4 (4H, m), m/e107 (M\(^+\)), 106, 92, 81, 80, 67(b), 41.

Found: C,78.6; H,8.5; N,13.3. Calculated for C\(_7\)H\(_8\)N: C,78.5; H,8.5; N,13.1%.

Reaction of chlorosulphonyl isocyanate with (165). Isolation of 3-cyclopropyl-3-buteneamide (185).

A solution of the olefin (165) (1.0 g; 12.2 mmol) in dichloromethane (5 ml) was added to a solution of CSI (1.0 ml; 12.0 mmol) in dichloromethane (20 ml) at ambient temperature. After 35 min. the reaction mixture (\( \nu_{\text{max.}} \) 1750 and 1720(major), and 1815(minor) cm\(^{-1}\)) was cooled to -78°C, treated with acetone (10 ml), benzenethiol (2.8 ml; 25 mmol) and pyridine (1.9 ml; 24 mmol) and worked up in the normal manner (p.149) yielding a yellow oil which was separated by chromatography on alumina (Grade I; 100 g). Diphenyl disulphide was first eluted with petrol, the solvent polarity was gradually increased by addition of ether, and elution with 50-100% ether yielded the conjugated nitrile (181) (E,Z mixture) (700 mg; 58%) as a pale yellow oil. Elution with 20% methanol-ether yielded a mixture of carbonyl compounds (372 mg) which was separated by chromatography on alumina (Grade I, 30 g). Elution with methanol-ether yielded a yellow oil (96 mg) containing the \( \beta \)-lactam (167); and a mixture of the \( \alpha \beta \)-unsaturated amide (182) and 3-cyclopropyl-3-buteneamide (185) as oily white crystals (95 mg). The yellow oil was separated by preparative t.l.c. on alumina yielding the \( \beta \)-lactam (167) (35 mg; 2.5%) and an unknown pale yellow crystalline material (46 mg) m.p. 109-113°C (from ether), \( \nu_{\text{max.}} \) 3490(m), 3375(m), and 1597(s) cm\(^{-1}\), \( S \) 8.1-6.5 (2H, broad), 6.3 (1H, s), 2.0 and 1.6 (2H, d J1.5 Hz and 1H, d, J 1 Hz), 1.8-1.1 (1H, m), 1.0-0.6 (4H, m). From the n.m.r. spectrum of
the mixture of amides (182) and (185), the yields of (182) (1%) and (185) (5.5%) were calculated. Fractional recrystallization of the mixture from ether-acetone yielded pure 3-cyclopropyl-3-butenamide (185) as white crystals, m.p. 104-108° (after sublimation at 105°/25 mm Hg); ν max. 3495 (m), 3405 (m), 1682 (s) and 1640 (m) cm⁻¹; δ 7.0-5.4 (2H, broad), 4.95 (2H, s), 3.0 (2H, s), 1.7-1.1 (1H, m), 0.8-0.4 (4H, m); m/e 125 (M⁺), 124, 110, 97, 82, 81, 67(b), 59, 41. Found: C, 67.1; H, 8.8; N, 11.5. C₇H₇NO requires: C, 67.2; H, 8.9; N, 11.2%.

Conjugate addition of hydrogen chloride to N-chlorosulphonyl-3-cyclopropyl-2-butenamide (179)

Dry hydrogen chloride was bubbled into a solution of (179) (1.9 g; 8.44 mmol) in chloroform (30 ml) at ambient temperature. After 30 min. the flask was stoppered and the reaction mixture was stirred for 30 min., and the solvent was then evaporated yielding crude N-chlorosulphonyl-6-chloro-3-methyl-3-hexeneamide (183) (2.42 g) as a brown oil containing residual chloroform ν max. (CHCl₃) 3260 (m.b.), 1740 (s), 1440 (s) and 1375 (s) cm⁻¹; δ 5.8 (1H, tb, J 7 Hz), 3.7 (2H, t, J 6.5 Hz), 3.3 (2H, s), 2.65 (2H, qb, J 6.5 Hz), 1.8 (3H, s). Analysis was not obtained as it was not possible to induce crystallization of the crude product.

Preparation of 6-chloro-3-methyl-3-hexeneamide (184)

The crude N-chlorosulphonyl amide (183) (2.42 g) was dissolved in acetone (10 ml) and treated with hydrochloric acid (20 ml; 1M). After 1 h the reaction mixture was neutralized with aqueous sodium hydroxide (1M), and extracted with dichloromethane (3 x 15 ml). The extract was dried and the solvent was evaporated yielding (184) (0.768 g; 48%) as a pale yellow solid. Recrystallization from chloroform-petrol afforded pure (184) as white crystals, m.p. 111.5-113°; mixed m.p. 111-113°; spectral properties (i.r. and n.m.r.) were identical to those of an authentic sample of (184).
Preparation of α-cyclopropylstyrene.

A solution of n-butyl-lithium in hexane (38 ml; 2.0 M) was added slowly to a vigorously stirred suspension of methyl-triphenyl-phosphonium bromide (27 g; 76 mmol) in ether (200 ml) at ambient temperature under dry nitrogen. After 1 h a solution of cyclopropyl-phenyl-ketone (10 g; 69 mmol) in ether (20 ml) was added dropwise to the orange ylid solution and the mixture was refluxed overnight. Water (100 ml) was added, the organic layer was separated, dried and the solvent was evaporated yielding a pasty yellow mass which was extracted with petrol (200 ml). The precipitated triphenylphosphine oxide was filtered off and the solvent was evaporated from the filtrate, yielding a yellow oil which on distillation afforded α-cyclopropylstyrene (168) (7.0 g; 70%) as a colourless oil, b.p. 94-96°/20 mm Hg; (lit. 107°/25 mm Hg).

Preparation of 4-cyclopropyl-4-phenyl-2-azetidinone (170)

CSI (0.65 ml; 7.8 mmol) was added to a solution of the olefin (168) (1.0 g; 6.9 mmol) in dichloromethane (25 ml) at -78°. After warming to -30° for 15 min. the reaction mixture (ν max. 1810 cm⁻¹) was cooled to -78°, treated with acetone (5 ml), benzenethiol (1.8 ml; 16 mmol) and pyridine (1.25 ml; 16 mmol) and worked up in the normal manner (p.149) yielding a pasty yellow solid which was separated by chromatography on Florisil (60 g). Diphenyl disulphide was eluted with petrol and ether, elution with methanol-ether yielded 4-cyclopropyl-4-phenyl-2-azetidinone (170) (729 mg; 57%) as white crystals, m.p. 113.5-114.5° (from acetone-ether and sublimation at 100°/0.2 mm Hg); ν max. 3500(m) and 1763(s) cm⁻¹; δ 7.8-7.2 (1H, broad) 7.35 (5H, s), 3.06 and 3.03 (2H, inner lines of AB system), 1.6-1.2 (1H, m), 0.7-0.2 (4H, m); m/e 187 (M⁺), 186, 159, 158, 144, 129(b), 104, 103, 77, 43. Found: C,77.0; H,7.1; N,7.6.

C₁₂H₁₃NO requires: C,77.0; H,7.0; N,7.5%.
Preparation of N-chlorosulphonyl-3-cyclopropyl-3-phenyl-propeneamide (187)

CSI (0.75 ml; 9.0 mmol) was added to a solution of the olefin (168) (1.1 g; 7.6 mmol) in dichloromethane (30 ml) at ambient temperature. After 30 min. the solvent was evaporated from the reaction mixture yielding N-chlorosulphonyl-3-cyclopropyl-3-phenyl-propeneamide (187) (2.2 g; 100%) as pale yellow crystals. Recrystallization from chloroform afforded pure (187) as white crystals, m.p. 112-114° (decomp.) (lit.56 109-110°); v max. 3300(s.b.), 1700(s), 1615(m) and 1595(m) cm⁻¹; δ 8.6 (1H, broad), 7.8-7.3 (5H, m), 5.93 (1H, s), 2.1-1.4 (1H, m), 1.1-0.5 (4H, m); m/e 287 and 285 (M⁺), 259, 257, 205, 169(b), 168, 159, 154, 143, 142, 141, 130, 129, 128, 78, 77, 64. Found: C,50.2; H,4.2; N,4.6. Calculated for C₁₂H₁₂NO₃SCl: C,50.4; H,4.2; N,4.9%.

Preparation of 3-cyclopropyl-3-phenyl-propeneamide (189)

Hydrochloric acid (1M) (10ml) was added to a solution of (187) (0.5 g; 1.75 mmol) in acetone (10 ml) at ambient temperature. After 8h the mixture was neutralized with aqueous sodium hydroxide (1M) and extracted with dichloromethane (4 x 20 ml). The extract was dried and the solvent was evaporated yielding 3-cyclopropyl-3-phenyl-propeneamide (189) (126 mg; 38%) as white crystals, m.p. 105-106° (from acetone-ether and sublimation at 100°/0.5 mm Hg), (lit.56 100-101°), v max. 3505(m), 3390(m), 1665(s), 1625(m), 1596(m) and 1575(m) cm⁻¹; δ 7.6-7.1 (5H, m), 5.9 (1H, s), 6.0-4.5 (2H, broad), 2.0-1.4 (1H, m), 1.0-0.4 (4H, m); λ max. (EtOH) 217 nm, ε 13,000, shoulder 230 nm; m/e 187 (M⁺), 186, 159(b), 143, 142, 141, 130, 128, 115, 77, 43. Found: C,76.9; H,6.7; N, 7.4. Calculated for C₁₂H₁₁NO: C,77.0; H,7.0; N,7.5%.

Preparation of β-cyano-α-cyclopropylstyrrene (188)

Triethylamine (0.2 g; 2.0 mmol) was added to a stirred solution of (187) (0.5 g; 1.8 mmol) in dichloromethane (20 ml) at ambient temperature. After 3h the solvent was evaporated from the reaction mixture yielding a yellow oil which was extracted with ether (2 x 25 ml). The extract
was filtered and the solvent was evaporated yielding \(\beta\)-cyano-\(\alpha\)-cyclopropylstyrene (188) (240 mg; 78\%) as a pale yellow oil. Preparative g.l.c. (150°) afforded pure (188) as a colourless oil, \(\nu_{\text{max}}\) (CCl\(_4\)) 2220 (s) and 1615 (m) cm\(^{-1}\); \(\delta\) (CCl\(_4\)) 7.43 (5H, s), 5.17 (1H, s), 2.0–1.4 (1H, m), 1.1–0.5 (4H, m); \(\lambda_{\text{max}}\) (cyclohexane) 214 nm \(\varepsilon\) 22,000, 256 nm \(\varepsilon\) 15,000; m/e 169 (M\(^+\)), 168, 154 (b), 143, 142, 141, 129, 128, 127, 115, 77. Found: C, 85.3; H, 6.7; N, 8.3. \(\text{C}_6\text{H}_{11}\text{N}\) requires: C, 85.2; H, 6.55; N, 8.3%.

Addition of hydrogen chloride to (187). Preparation of N-chlorosulphonyl-6-chloro-3-phenyl-3-hexeneamide (190).

Dry hydrogen chloride was passed into a solution of (187) (936 mg; 3.28 mmol) in chloroform (25 ml) at ambient temperature. After 1h the flask was stoppered, the reaction mixture was stirred for 2h and the solvent was evaporated yielding N-chlorosulphonyl-6-chloro-3-phenyl-3-hexeneamide (190) as white crystals (1.004g; 99\%), m.p. 91–94° (from ether-petrol); \(\nu_{\text{max}}\) (CHCl\(_3\)) 3260 (m) and 1745 (s) cm\(^{-1}\); \(\delta\) 8.6 (1H, broad), 7.4 (5H, s), 6.15 (1H, t, \(J\) 7Hz), 3.73 (2H, t, \(J\) 6Hz), 3.70 (2H, s), 2.73 (2H, approx.q, \(J\) 6Hz); m/e (no M\(^+\)), 224, 223, 222, 221, 197, 181, 179, 178, 101, 77. Found: C, 35.0; H, 4.3; N, 5.8. \(\text{C}_{12}\text{H}_{13}\text{NO}_3\text{SCl}_2\) requires: C, 35.1; H, 4.2; N, 5.8%.

Preparation of 6-chloro-3-phenyl-3-hexeneamide (191)

A solution of (190) (750 mg; 2.63 mmol) in acetone (5 ml) was treated with hydrochloric acid (2 M) (10 ml) at ambient temperature for 30 min. and worked up in the normal manner (p.157) yielding 6-chloro-3-phenyl-3-hexeneamide (191) (370 mg; 71\%) as white crystals, m.p. 83.5–85° (from acetone-ether); \(\nu_{\text{max}}\) max. 3510 (m), 3495 (m) and 1680 (s) cm\(^{-1}\); \(\delta\) 3.5 (5H, m), 6.02 (1H, t, \(J\) 7Hz), 6.4 (2H, broad), 3.66 (2H, t, \(J\) 7Hz), 3.44 (2H, s), 2.71 (2H, q, \(J\) 7Hz); m/e 225 and 223 (M\(^+\)), 188, 187, 143, 129 (b), 77. Found: C, 64.3; H, 6.35; N, 6.2. \(\text{C}_{12}\text{H}_{14}\text{NOCl}\) requires: C, 64.4; H, 6.3; N, 6.3%.
Preparation of 1,2,3,6-tetrahydro-5-phenyl-7-azepinone (193)

CSI (0.32 ml; 3.8 mmol) was added to a solution of the olefin (168) (0.5 g; 3.45 mmol) in ether (25 ml) at -78° and the reaction mixture (ν max. 1810 cm⁻¹) was allowed to warm to ambient temperature. After 6 h, the reaction mixture (ν max. 1735 cm⁻¹) was diluted with ether (20 ml), treated with a solution of anhydrous sodium sulphite (2 g) in water (20 ml) for 1 h and worked up in the normal manner (p.146) yielding 1,2,3,6-tetrahydro-5-phenyl-7-azepinone (193) (132 mg; 20%) as white crystals, m.p. 126-128° (from chloroform-petrol); ν max. (CDCl₃) 3410 (m) and 1670 (s); δ 7.28 (5H, s), 7.2 (1H, broad), 5.62 (1H, t, J 4 Hz), 3.64 (2H, s), 3.49 (2H, q, J 6 Hz), 2.48 (2H, m); m/e 187 (M⁺, b), 159, 158, 130, 77.

Found: C, 76.8; H, 7.2; N, 7.5. C₁₂H₁₃NO requires: C, 77.0; H, 7.0; N, 7.5%.

Preparation of α-cyclopropyl-(p-substituted styrenes)

The olefins were prepared by the procedure used for the preparation of α-cyclopropylstyrene (168) (p.161), using n-butyl lithium solution (0.65 M) (55 ml), methyltriphenylphosphonium bromide (12.5 g; 35 mmol) and the appropriate para-substituted cyclopropyl phenyl ketone (28 mmol). The crude olefin was freed from residual triphenylphosphine oxide by chromatography on silica (60 g), eluting with petrol. The product was then distilled yielding:–

α-cyclopropyl-(p-t-butylstyrene) (196), (3.7 g; 67%) as a colourless oil, b.p. 152-156°/30 mm Hg; ν max. (film) 3080 (m), 2960 (s), 1620 (m), 885 (m) and 835 (s) cm⁻¹; δ (CCl₄) 7.5 (2H, d, J 8.5 Hz), 7.3 (2H, d, J 8.5 Hz), 5.23 (1H, s), 4.87 (1H, s), 1.8-1.2 (1H, m), 1.35 (9H, s), 1.0-0.4 (4H m).

Found: C, 89.5; H, 10.4. C₁₅H₂₀ requires: C, 89.95; H, 10.1%.

α-cyclopropyl-(p-ethylstyrene) (195), (3.0 g; 60%) as a colourless oil, b.p. 112-117°/25 mm Hg; ν max. (film) 3080 (m), 2960 (s), 1625 (m), 1510 (m), 880 (m) and 830 (s) cm⁻¹; δ (CCl₄) 7.63 (2H, d, J 9 Hz), 7.27 (2H, d, J 9 Hz), 5.35 (1H, s), 4.97 (1H, s), 2.7 (2H, q, J 8 Hz), 1.9-1.3 (1H, m), 1.23 (3H, t, J 8 Hz), 1.0-0.4 (4H, m). Found: C, 90.9; H, 9.55. C₁₃H₁₆ requires:
C, 90.6; H, 9.4%.

α-cyclopropyl-(p-fluorostyrene) (194), (3.0g; 63%) as a colourless oil, b.p. 101-104°/100 mm Hg (lit. 151 72°/40 mm Hg), \( \nu \max \) (film) 3080 (m), 3000 (m), 1625 (m), 1605 (s), 890 (m), 840 (s) \( \text{cm}^{-1} \). \( \delta (\text{CCl}_4) \) 7.6 (2H, d\(^2\), J 5 and 9Hz), 7.03 (2H, t, J 9Hz), 5.27 (1H, s), 4.95 (1H, s) 2.0-1.2 (1H, m), 1.1-0.5 (4H, m).

α-cyclopropyl-(p-methoxystyrene) (197), (2.8g; 56%) as a colourless oil, b.p. 136-142°/100 mm Hg (lit. 151 116°/50 mm Hg); \( \nu \max \) (film) 3080 (m), 2940 (m), 1610 (m), 1250 (s), 1040 (s), 880 (m) and 830 (s) \( \text{cm}^{-1} \); \( \delta (\text{CCl}_4) \) 7.6 (2H, d, J 8.5Hz), 6.9 (2H, d, J 8.5Hz), 5.23 (1H, s), 4.9 (1H, s), 3.8 (3H, s), 1.9-1.2 (1H, m), 1.1-0.5 (4H, m).

Reaction of chlorosulphonyl isocyanate with the α-cyclopropyl-(p-substituted styrenes) (194), (195) and (196)

CSI (0.11 ml; 1.27 mmol) was added to a solution of the olefin (1.22 mmol) in dichloromethane (5 ml) at -78° and the reaction mixture (\( \nu \max . 1810 \text{ cm}^{-1} \)) was allowed to warm to ambient temperature when the N-chlorosulphonyl β-lactam carbonyl band (\( \nu \max . 1810 \text{ cm}^{-1} \)) was observed to decay and was replaced by a new band (\( \nu \max . 1700 \text{ cm}^{-1} \)). When the N-chlorosulphonyl β-lactam carbonyl band had disappeared the solvent was evaporated from the reaction mixture yielding:

N-chlorosulphonyl-3-cyclopropyl-3-(p-t-butylphenyl)-propeneamide (204), (420 mg; 100%), orange oil; \( \nu \max . 3280 \text{ (m.b.)}, 1700 \text{ (s)} \) and 1600 (m) \( \text{cm}^{-1} \); \( \delta 9.1 \text{ (1H, broad), 7.33 (4H, m), 6.0 (1H, s), 2.0-1.5 (1H, m), 1.33 (9H, s), 1.2-0.5 (4H, m). \)

N-chlorosulphonyl-3-cyclopropyl-3-(p-ethylphenyl)-propeneamide (203), (375 mg; 96%), pasty orange solid, \( \nu \max . 3300 \text{ (m.b.)}, 1700 \text{ (s)} \) and 1600 (m) \( \text{cm}^{-1} \); \( \delta 8.8 \text{ (1H, broad), 7.25 (4H, m), 5.97 (1H, s), 2.7 (2H, q.b. J 8Hz), 2.1-1.5 (1H, m), 1.23 (3H, t, J 8Hz), 1.2-0.5 (4H, m). \)
N-chlorosulphonyl-3-cyclopropyl-3-(p-fluorophenyl)-propeneamide (202), 365 mg; 95%), yellow crystals, \( \nu \) max. 3300 (m.b.), 1700(s) and 1600(m) cm\(^{-1}\); 8.3 (1H, broad), 7.4 (2H, s), 7.3 (2H, s), 6.1 (1H, s), 1.5-1.2 (1H, m), 1.2-0.5 (4H, m).

**Preparation of \( \beta \)-cyano-\( \alpha \)-cyclopropyl-(p-substituted styrenes) (206), (207) and (208).**

The crude product from the above reaction was dissolved in dichloromethane (25 ml) and treated with triethylamine (0.18 g; 1.8 mmol) at ambient temperature. After 30 min. the solvent was evaporated from the reaction mixture, ether (10 ml) was added and the mixture was stirred for 30 min. The precipitated triethylamine hydrochloride was filtered off and the solvent was evaporated from the filtrate. The crude product was freed from residual triethylamine hydrochloride by chromatography on silica (2 g), elution with ether afforded the nitrile. (Analysis samples were obtained by preparative g.l.c. (225°C)):

**\( \beta \)-cyano-\( \alpha \)-cyclopropyl-(p-t-butylstyrene) (208), (185 mg; 68%), yellow oil, \( \nu \) max. (CCl\(_4\)) 2220(s) and 1608(s) cm\(^{-1}\); \( \delta \) (CCl\(_4\)) 7.47 (4H, s), 5.1 (1H, s), 2.0-1.5 (1H, m), 1.33 (9H, s), 1.1-0.5 (4H, m). Found: C, 84.7; H, 8.9; N, 6.0. C\(_{16}\)H\(_{19}\)N requires: C, 85.3; H, 8.5; N, 6.2%.

**\( \beta \)-cyano-\( \alpha \)-cyclopropyl-(p-ethylstyrene) (207), (174 mg; 70%), pale yellow oil, \( \nu \) max. (CCl\(_4\)) 2220(s) and 1605(m) cm\(^{-1}\); \( \delta \) (CCl\(_4\)) 7.5 (2H, d, J 8Hz), 7.25 (2H, d, J 8Hz), 5.17 (1H, s), 2.73 (2H, q, J 8Hz), 2.0-1.5 (1H, m), 1.3 (3H, t, J 8Hz), 1.1-0.6 (4H, m). Found: C, 84.9; H, 7.9; N, 7.0. C\(_{14}\)H\(_{15}\)N requires: C, 85.2; H, 7.7; N, 7.1%.

**\( \beta \)-cyano-\( \alpha \)-cyclopropyl-(p-fluorostyrene) (206), (152 mg; 65%), colourless oil, \( \nu \) max. (CCl\(_4\)) 2220(s) and 1603(s) cm\(^{-1}\); \( \delta \) (CCl\(_4\)) 7.6 (2H, d\(^2\), J 5 and 8.5Hz), 7.17 (2H, t, J 8.5Hz), 5.2 (1H, s), 2.0-1.4 (1H, m), 1.2-0.6
Reaction of chlorosulphonyl isocyanate with \( \alpha \)-cyclopropyl-(\( \beta \)-methoxy-styrene) (197). Preparation of \( \beta \)-cyano-\( \alpha \)-cyclopropyl-(\( \beta \)-methoxystyrene) (209).

The olefin (197) (1.0 g; 5.75 mmol) was added to a solution of CSI (0.5 ml; 6.0 mmol) in dichloromethane (30 ml) at -78°. The reaction mixture (\( \nu \) max. 1700 (major) and 1810 (minor) cm\(^{-1}\)) was treated with triethylamine (0.8 g; 8 mmol) and worked up in the normal manner (p.166) yielding \( \beta \)-cyano-\( \alpha \)-cyclopropyl-(\( \beta \)-methoxystyrene) (209), (500 mg; 43%) as a yellow oil. Preparative g.l.c. (225°) afforded pure (209) as a very pale yellow oil, \( \nu \) max. (CCl\(_4\)) 2220 (s) and 1607 (s) cm\(^{-1}\); \( \delta \) (CCl\(_4\)) 7.6 (2H, d, J 8Hz), 6.95 (2H, d, J 8Hz), 5.07 (1H, s), 3.8 (3H, s), 2.0-1.4 (1H, m), 1.2-0.5 (4H, m). Found: C, 78.3; H, 6.9; N, 6.9. \( \text{C}_{13} \text{H}_{13} \text{NO} \) requires: C, 78.3; H, 6.6; N, 7.0%.
Investigation of the kinetics of the reaction between chlorosulphonyl isocyanate and vinyl cyclopropanes.

Determination of the dependence of absorbance on concentration for the isocyanate stretch of CSI (Vmax 2250 cm⁻¹)

An approximately 0.03M solution of CSI in carbon tetrachloride was accurately prepared; aliquots of this solution were accurately diluted to yield a total of nine solutions of concentrations from 0.006 to 0.03 molar. The absorbance of each solution at 2250 cm⁻¹ in a 0.1 mm sodium chloride cell, using a reference cell containing pure solvent, was determined using a Perkin-Elmer 257 grating spectrometer in fixed wavelength mode. This procedure was repeated using chloroform (9 solutions), and nitromethane (5 solutions) as solvent and the results are shown in Table 21.

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<td>0.6198</td>
<td>0.0241</td>
<td>0.5229</td>
</tr>
<tr>
<td>0.0211</td>
<td>0.5331</td>
<td>0.0206</td>
<td>0.4522</td>
</tr>
<tr>
<td>0.0176</td>
<td>0.4260</td>
<td>0.0172</td>
<td>0.3665</td>
</tr>
<tr>
<td>0.0140</td>
<td>0.3420</td>
<td>0.0138</td>
<td>0.2682</td>
</tr>
<tr>
<td>0.0105</td>
<td>0.2557</td>
<td>0.0103</td>
<td>0.1986</td>
</tr>
<tr>
<td>0.0070</td>
<td>0.1580</td>
<td>0.0069</td>
<td>0.1051</td>
</tr>
</tbody>
</table>

C(nom.) - nominal molar concentration of CSI
A - absorbance at 2250 cm⁻¹
General Kinetic Procedure

5 ml of an approximately 0.2M solution of the olefin was prepared accurately. 1 ml of an approximately 0.06M solution of CSI in the same solvent was rapidly mixed with 1 ml of the olefin solution and a portion of the mixture was rapidly transferred to a 0.1 mm sodium chloride cell. The transmittance of the solution with reference to a cell containing pure solvent was monitored continuously at 2250 cm$^{-1}$ using a Perkin-Elmer 257 grating spectrometer. The procedure was then repeated using an approximately 0.1M olefin solution prepared by accurate dilution of the original solution. The reactions were followed for a minimum of 50% reaction and a minimum of two runs per olefin. The reaction temperature was taken to be the temperature of the cell at thermal equilibrium in the spectrometer cavity (31 ± 1°C) and was measured using an electronic thermometer (Comark type 1625). In order to minimise temperature variations the cells and stock solutions were kept in the spectrometer cavity which was protected from draughts by a plastic cover. The time at which the solutions were mixed was taken as the start of the reaction, and the interval between mixing and placing the cell in the spectrometer (approx. 20-30 sec.) was measured with a stop clock. For rapid reactions the initial CSI absorbance was taken as the mean absorbance of three mixtures of 1 ml of the CSI solution and 1 ml of the solvent, otherwise the initial absorbance was taken as the value obtained by extrapolation of the absorbance-time curve to the time of mixing. The initial concentrations and individual and mean second order rate constants for the various reactions studied are shown in Tables 22 and 23.
Initial conditions and second order rate constants for the addition of CSI to the vinyl cyclopropanes \( \( R \) \) \( \) at 31 ± 1° in various solvents.

<table>
<thead>
<tr>
<th>R</th>
<th>SOLVENT</th>
<th>[OLEFIN] (_0)</th>
<th>[CSI] (_0)</th>
<th>( k_2 )</th>
<th>( \bar{k}_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Me</td>
<td>CCl(_4)</td>
<td>8.60 x 10(^{-2})</td>
<td>2.42 x 10(^{-2})</td>
<td>2.9 x 10(^{-1})</td>
<td>3.2 x 10(^{-1})</td>
</tr>
<tr>
<td>Me</td>
<td>CCl(_4)</td>
<td>4.30 x 10(^{-2})</td>
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<td>3.5 x 10(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Ph</td>
<td>CCl(_4)</td>
<td>4.22 x 10(^{-2})</td>
<td>3.34 x 10(^{-2})</td>
<td>1.4 x 10(^{-2})</td>
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</tr>
<tr>
<td>Ph</td>
<td>CCl(_4)</td>
<td>5.52 x 10(^{-2})</td>
<td>2.94 x 10(^{-2})</td>
<td>1.4 x 10(^{-2})</td>
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</tr>
<tr>
<td>Ph</td>
<td>CCl(_4)</td>
<td>8.44 x 10(^{-2})</td>
<td>3.34 x 10(^{-2})</td>
<td>1.3 x 10(^{-2})</td>
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</tr>
<tr>
<td>Ph</td>
<td>CCl(_4)</td>
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<td>2.94 x 10(^{-2})</td>
<td>1.6 x 10(^{-2})</td>
<td></td>
</tr>
<tr>
<td>Ph</td>
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<td>2.89 x 10(^{-2})</td>
<td>1.6 x 10(^{-2})</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CCl(_4)</td>
<td>1.63 x 10(^{-1})</td>
<td>3.51 x 10(^{-2})</td>
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<tr>
<td>H</td>
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<td>8.13 x 10(^{-2})</td>
<td>3.93 x 10(^{-2})</td>
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</tr>
<tr>
<td>Ph</td>
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<td>4.34 x 10(^{-2})</td>
<td>2.58 x 10(^{-2})</td>
<td>1.2 x 10(^{-1})</td>
<td>1.3 x 10(^{-1})</td>
</tr>
<tr>
<td>Ph</td>
<td>CHCl(_3)</td>
<td>2.89 x 10(^{-2})</td>
<td>1.39 x 10(^{-2})</td>
<td>1.4 x 10(^{-1})</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CHCl(_3)</td>
<td>1.28 x 10(^{-1})</td>
<td>2.75 x 10(^{-2})</td>
<td>1.6 x 10(^{-2})</td>
<td>1.6 x 10(^{-2})</td>
</tr>
<tr>
<td>H</td>
<td>CHCl(_3)</td>
<td>6.41 x 10(^{-2})</td>
<td>2.84 x 10(^{-2})</td>
<td>1.6 x 10(^{-2})</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CH(_3)NO(_2)</td>
<td>1.04 x 10(^{-1})</td>
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<td>3.6 x 10(^{-1})</td>
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</tr>
<tr>
<td>H</td>
<td>CH(_3)NO(_2)</td>
<td>1.04 x 10(^{-1})</td>
<td>2.13 x 10(^{-2})</td>
<td>3.2 x 10(^{-1})</td>
<td>3.3 x 10(^{-1})</td>
</tr>
<tr>
<td>H</td>
<td>CH(_3)NO(_2)</td>
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<td>1.85 x 10(^{-2})</td>
<td>3.1 x 10(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

\([\text{OLEFIN}]_0\), \([\text{CSI}]_0\) - initial molar concentrations of the olefin and CSI respectively

\(k_2\), \(\bar{k}_2\) - individual and mean second order rate constants \((\text{l. mol.}^{-1} \text{s}^{-1})\)
TABLE 23.

Initial conditions and second order rate constants for the addition of CSI to α-cyclopropyl-(p-substituted styrenes) at 31 ± 1° in carbon tetrachloride.

<table>
<thead>
<tr>
<th>SUBSTITUENT</th>
<th>[OLEFIN]₀</th>
<th>[CSI]₀</th>
<th>k₂</th>
<th>k₂̄</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>1.08 x 10⁻¹</td>
<td>2.75 x 10⁻²</td>
<td>1.0 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1.08 x 10⁻¹</td>
<td>2.66 x 10⁻²</td>
<td>1.1 x 10⁻²</td>
<td>1.1 x 10⁻²</td>
</tr>
<tr>
<td>F</td>
<td>5.40 x 10⁻²</td>
<td>2.70 x 10⁻²</td>
<td>1.1 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>9.46 x 10⁻²</td>
<td>2.62 x 10⁻²</td>
<td>1.2 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>9.46 x 10⁻²</td>
<td>2.84 x 10⁻²</td>
<td>1.0 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>4.73 x 10⁻²</td>
<td>2.58 x 10⁻²</td>
<td>1.2 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>Et</td>
<td>1.16 x 10⁻¹</td>
<td>3.22 x 10⁻²</td>
<td>6.7 x 10⁻²</td>
<td>6.6 x 10⁻²</td>
</tr>
<tr>
<td>Et</td>
<td>1.16 x 10⁻¹</td>
<td>2.99 x 10⁻²</td>
<td>6.6 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>Et</td>
<td>5.81 x 10⁻²</td>
<td>3.05 x 10⁻²</td>
<td>6.2 x 10⁻²</td>
<td>6.8 x 10⁻²</td>
</tr>
<tr>
<td>Et</td>
<td>5.81 x 10⁻²</td>
<td>3.05 x 10⁻²</td>
<td>6.8 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>t-Bu</td>
<td>1.13 x 10⁻¹</td>
<td>2.32 x 10⁻²</td>
<td>6.2 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>t-Bu</td>
<td>1.13 x 10⁻¹</td>
<td>2.46 x 10⁻²</td>
<td>7.0 x 10⁻²</td>
<td>6.6 x 10⁻²</td>
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<tr>
<td>t-Bu</td>
<td>5.66 x 10⁻²</td>
<td>2.46 x 10⁻²</td>
<td>6.8 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>t-Bu</td>
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<td>2.39 x 10⁻²</td>
<td>6.6 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>t-Bu</td>
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<td>2.42 x 10⁻²</td>
<td>6.7 x 10⁻²</td>
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<td>t-Bu</td>
<td>5.61 x 10⁻²</td>
<td>2.54 x 10⁻²</td>
<td>6.5 x 10⁻²</td>
<td></td>
</tr>
<tr>
<td>MeO</td>
<td>9.08 x 10⁻²</td>
<td>2.75 x 10⁻²</td>
<td>3.7 x 10⁻¹</td>
<td>3.7 x 10⁻¹</td>
</tr>
<tr>
<td>MeO</td>
<td>9.08 x 10⁻²</td>
<td>2.75 x 10⁻²</td>
<td>3.8 x 10⁻¹</td>
<td></td>
</tr>
<tr>
<td>MeO</td>
<td>4.54 x 10⁻²</td>
<td>2.75 x 10⁻²</td>
<td>3.5 x 10⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

[OLEFIN]₀, [CSI]₀ - initial molar concentrations of the olefin and CSI

k₂, k₂̄ - individual and mean second order rate constants

(1, mol⁻¹ s⁻¹)
Preparation of epoxides.

The following olefins and dienes were converted to their corresponding monoepoxides by reaction with commercial 40% peracetic acid using the procedure of Heap and Whitham¹⁵².

1-Phenylcyclohexene (38 g) gave 1,2-epoxy-1-phenylcyclohexane (231) (31 g; 74%), b.p. 140-145°/25 mm Hg (lit.¹⁵³ 136°/15-16 mm Hg).

1,3-Cyclo-octadiene (45 g) gave 3,4-epoxycyclo-oct-1-ene (241) (33.5 g; 65%), b.p. 88-90°/25 mm Hg (lit.¹⁵⁴ 81-87°/22 mm Hg).

2-Methyl-1,3-butadiene (isoprene) (60 g) gave 3,4-epoxy-3-methylbut-1-ene (246) (37.5 g; 51%), b.p. 78°/760 mm Hg (lit.¹⁵⁵ 78-82°/760 mm Hg).

2,3-Dimethyl-1,3-butadiene (23 g) gave 3,4-epoxy-2,3-dimethylbut-1-ene (252) (17 g; 62%), b.p. 101-104°/760 mm Hg (lit.¹⁵⁶ 45°/100 mm Hg).

α-Pinene (21 g) gave 2α,3α-epoxypinane (267) (15.6 g; 67%), b.p. 82-87°/30 mm Hg (lit.¹⁵⁷ 82°/20 mm Hg).

Δ³-Carene (21 g) gave 3α,4α-epoxycarane (281) (17.3 g; 74%), b.p. 73-76°/20 mm Hg (lit.¹⁵⁸ 77°/12 mm Hg).

1,3-Cyclopentadiene, cyclo-octatetraene and β-pinene were converted to their monoepoxides by reaction with commercial 40% peracetic acid using the procedure of Crandall et al¹⁵⁹.

1,3-Cyclopentadiene (35 g) gave 3,4-epoxycyclopent-1-ene (255) (22.8 g; 52%), b.p. 40-42°/50 mm Hg (lit.¹⁵⁹ 39-41°/46 mm Hg).

Cyclo-octatetraene (45 g) gave 7,8-epoxycyclo-octa-1,3,5-triene (262) (23 g; 44%), b.p. 81-85°/25 mm Hg (lit.¹⁵⁹ 74-75°/12 mm Hg).

β-Pinene (42 g) gave 2α,10-epoxypinane (273) (28 g; 60%), b.p. 78-82°/15 mm Hg (lit.¹⁶⁰ 83°/12 mm Hg).

Reaction of chlorosulphonyl isocyanate with 1,2-epoxycyclo-octane (226)*

CSI (2.0 ml; 23.4 mmol) was added to a solution of the epoxide (226) (2.8 g; 22.1 mmol) in dichloromethane (30 ml) at -20°. After 15 min. the

* Supplied by Aldrich Chemical Company Inc.
reaction mixture (νmax. 2250 and 1605(major), 1800 and 1770(minor) cm⁻¹) was allowed to warm to ambient temperature. After 90 min. the solvent was evaporated from the reaction mixture (νmax. 1605(major), 1800, 1770 and 2250(minor) cm⁻¹) yielding a yellow oil (6.32 g) which, after trituration with ether (20 ml), yielded N-chlorosulphonyl-10-imino-9,11-dioxabicyclo[6,3,0]undecane (227) (2.05 g; 35%) as off white crystals, m.p. 109-110° (from acetone-ether); νmax. 1605(s), 1370(m), 1190(m), 1105(m), 930(m) and 835(m) cm⁻¹; δ 5.19 (2H, m), 2.4-0.9 (12H, m); m/e 269 and 267(M⁺), 232(b), 204, 169, 141, 126, 109, 99, 98, 82, 81, 64. Found: C, 40.3; H, 5.3; N, 5.3. C₉H₁₄NO₄Cl requires: C, 40.4; H, 5.3; N, 5.2%. The trituration liquors were treated with a solution of anhydrous sodium sulphite (3 g) in water (30 ml) for 30 min. and worked up in the normal manner (p.146) yielding a colourless viscous oil which was separated by chromatography on alumina (Grade I; 30 g). Elution with 3% methanol-ether yielded 9,11-oxabicyclo[6,3,0]undecan-10-one(230) (271 mg; 7%) as white crystals, m.p. 106-108° (from acetone-ether and sublimation at 120°/5 mm Hg); νmax. 3440(m), 1755(s) and 1112(m) cm⁻¹; δ 6.65 (1H, broad), 4.59 (1H, m), 3.81 (1H, t, J 9.5 Hz), 2.4-1.0 (12H, m); m/e 169(M⁺), 141, 126, 125, 99, 98, 85, 82, 77, 69, 68, 56, 43. Found: C, 63.9; H, 8.9; N, 8.35. C₉H₁₉NO₂ requires: C, 63.9; H, 8.9; N, 8.3%.

Preparation of 9,11-dioxabicyclo[6,3,0]undecan-10-one (229).

A suspension of the imino compound (227) (1.0 g; 3.6 mmol) in ether (25 ml) was treated with 0.2M aqueous sodium hydroxide (30 ml), the mixture was stirred at ambient temperature for 2h, the ether layer was separated and the aqueous layer was extracted with ether (2 x 20 ml). The combined organic layer and extracts were dried and the solvent was evaporated yielding 9,11-dioxabicyclo[6,3,0]undecan-10-one (229) (540 mg; 89%) as white crystals, m.p. 100-102° (from ether); νmax. 1798(s), 1420(s) and 895(s) cm⁻¹; δ 4.8 (2H, m), 2.5-1.0 (12H, m); m/e 170 (M⁺),
Attempted isolation of N-chlorosulphonyl-9,11-oxazabicyclo[6,3,0]undecan-10-one (228).

CSI (2.0 ml; 23.4 mmol), was added to a solution of the epoxide (226) (3.0 g; 23.8 mmol) in dichloromethane (30 ml) at 0°C. After 10 min. the solvent was evaporated from the reaction mixture (\(\nu_{\text{max.}}\) 1605 (major), 1770, 1800, 2250 (minor) cm\(^{-1}\)), yielding a white pasty mass which after trituration with ether (20 ml) yielded white crystals of (227) (2.42 g; 39%). The trituration liquors were evaporated and the residue was separated by chromatography on Florisil (20 g). Elution with carbon tetrachloride and 50% dichloromethane-carbon tetrachloride yielded mixed fractions (2.43 g) (\(\nu_{\text{max.}}\) 1605 (major) and 1800 (minor) cm\(^{-1}\)) and elution with dichloromethane yielded white crystals of the NH-oxazolidinone (230) (330 mg; 8%).

Reaction of chlorosulphonyl isocyanate with 1,2-epoxycyclohexane (222)*

The epoxide (222) (1.1 g; 11.2 mmol) was added to a solution of CSI (1.0 ml; 11.7 mmol) in dichloromethane at ambient temperature over 2h. The solvent was evaporated from the reaction mixture (\(\nu_{\text{max.}}\) 2250, 1615 (major) and 1760 (minor) cm\(^{-1}\)) yielding a clear oil (3.07 g) which after trituration with 50% ether-petrol (30 ml) yielded white crystals of N-chlorosulphonyl-8-imino-7,9-dioxabicyclo[4,3,0]nonan-8-one (223) (450 mg; 17.5%), m.p. 88-90.5°C (from acetone-ether); \(\nu_{\text{max.}}\) 1615 (s), 1405 (m) and 1370 (m) cm\(^{-1}\); \(\delta\) 5.25 (2H, m), 2.08 (4H, m), 1.65 (4H, m). m/e 241 and 239 (M\(^+\)), 204 (b), 141, 98, 64. Found: C, 35.0; H, 4.3; N, 5.8. \(\text{C}_{7}\text{H}_{10}\text{NO}_{4}\text{SCl}\) requires: C, 35.1; H, 4.2; N, 5.8%. The solvent was evaporated from the trituration liquors and the residue was dissolved in ether (20 ml), treated with a solution of anhydrous sodium sulphite (2 g) in water (20 ml) for 1 h, and

* Supplied by Koch-Light Laboratories Ltd.
worked up in the normal manner (p.146) yielding a brown oil (1.2 g) which gave only polymeric tars after chromatography on silica (30 g).

Reaction of chlorosulphonyl isocyanate with 1,2-epoxycyclohexane (222).

Hydrolysis of the products.

The epoxide (222) (2.4 g; 24.5 mmol) was added to a solution of CSI (1.0 ml; 11.7 mmol) in dichloromethane (30 ml) at ambient temperature, over 1 h. The reaction mixture (\(\nu_{\text{max}}\) 1615 (major), 1760 (minor) and 1803 (v.small) cm\(^{-1}\)) was treated with a solution of anhydrous sodium sulphite (3 g) in water (30 ml) for 1 h, and worked up in the normal manner (p.146) yielding a white foam (1.96 g) which was separated by chromatography on alumina (Grade II; 50 g). Elution with ether/5% methanol-ether yielded only polymeric tar, elution with 10% methanol-ether afforded a fraction (198 mg) which on t.l.c. showed a discrete spot "embedded" in a "streak" of polymeric material. Separation of this fraction by preparative t.l.c. on alumina yielded crude 7,9-oxazabicyclo[4,3,0]nonan-8-one (225) (47 mg; 3%) as brown oily crystals, m.p. 47-50\(^\circ\) (lit.\(^{140}\) cis 55\(^\circ\)), \(\nu_{\text{max}}\) 3430 (m) and 1755 (s) cm\(^{-1}\); \(\delta\) 6.23 (1H, broad), 4.57 (1H, dt, \(J\) 6.5 and 4.5 Hz), 3.75 (1H, q.b., \(J\) 6.5 Hz), 2.5-1.0 (8H, m); m/e 141 (M\(^{+}\), b) 99, 98, 82, 78, 69, 56, 55, 54, 53. Elution with 25% methanol-ether yielded white crystals of cis-1,2-cyclohexanediol (224) (154 mg; 11%), m.p. 95-98.5 (from ether) (lit.\(^{139}\) cis 98\(^\circ\)), \(\nu_{\text{max}}\) 3580 (s), 3400 (s.b.), 1420 (s) and 1060 (s) cm\(^{-1}\); \(\delta\) 3.6 (2H, m), 3.0 (2H, s - disappears on shaking with D\(_2\)O), 2.2-1.0 (8H, m); m/e 116 (M\(^{+}\)), 98(b), 83, 80, 70, 69, 57, 56, 55, 54, 42, 41.

Reaction of chlorosulphonyl isocyanate with 1,2-epoxy-l-phenylcyclohexane (231). Isolation of N-chlorosulphonyl-8-imino-l-phenyl-7,9-dioxabicyclo-[4,3,0]nonane (232).

The epoxide (231) (2.0 g; 11.5 mmol) was added to a solution of CSI (1.0 ml; 11.7 mmol) in dichloromethane (25 ml) at ambient temperature.
The solvent was evaporated from the reaction mixture ($\nu_{\text{max.}}$ 1610 (major) and 1800 (minor) cm$^{-1}$) yielding a clear oil (3.86 g) which was separated by chromatography on Florisil (30 g). Elution with carbon tetrachloride dichloromethane yielded mixed fractions ($\nu_{\text{max.}}$ 1610 and 1800 cm$^{-1}$) (2.76 g), elution with dichloromethane afforded N-chlorosulphonyl-8-imino-1-phenyl-7,9-dioxabicyclo[4,3,0]nonane (232) (400 mg; 12.5%) as a colourless oil, $\nu_{\text{max.}}$ 1610 (s) cm$^{-1}$; $\delta$ 7.33 (5H, s), 5.2 (1H, t, $J$ 4 Hz), 2.4-1.9 (4H, m), 1.9-1.5 (4H, m). Analysis was not obtained as it was not possible to recrystallize the product.

Reaction of chlorosulphonyl isocyanate with (231). Sodium sulphite hydrolysis of the products.

The epoxide (231) (1.7 g; 9.8 mmol) was added to a solution of CSI (0.85 ml; 9.9 mmol) in dichloromethane (20 ml) at -30°. After 5 min. the solvent was evaporated from the reaction mixture ($\nu_{\text{max.}}$ 1610 (major) and 1800 (minor) cm$^{-1}$), yielding a colourless oil (3.3 g) which was dissolved in ether (30 ml), treated with a solution of anhydrous sodium sulphite (3 g) in water (30 ml) for 1h and worked up in the normal manner (p. 146) yielding a colourless oil (2.05 g) which was separated by chromatography on alumina (Grade II; 40 g). Elution with ether afforded 1-phenyl-7,9-dioxabicyclo[4,3,0]nonan-8-one (234) (998 mg; 47%) as a colourless oil, b.p. 133-136°/0.1 mm Hg; $\nu_{\text{max.}}$ (CCl$_4$) 1810 (s), 1595 (w), 1060 (s) and 695 (s) cm$^{-1}$; $\delta$ (CCl$_4$) 7.23 (5H, s), 4.6 (1H, t, $J$ 4 Hz), 2.2-1.8 (4H, m) 1.8-1.4 (4H, m); m/e 218 (M$^+$, b), 174, 173, 145, 133, 130, 128, 127, 120, 118, 115, 106, 105, 104, 103, 78, 77. Found: C, 71.5; H, 6.6.

C$_{13}$H$_{14}$O$_3$ requires: C, 71.5; H, 6.5%. Elution with 5% methanol-ether yielded 1-phenyl-7,9-oxazabicyclo[4,3,0]nonan-8-one (235) (400 mg; 19%) as white crystals, m.p. 120-122° (from dichloromethane-ether); $\nu_{\text{max.}}$ (CCl$_4$) 3220 (m.b.), 1753 (s), 1450 (m) and 695 (m) cm$^{-1}$; $\delta$ (CCl$_4$) 7.87 (1H, s.broad), 7.23 (5H, m), 4.53 (1H, m), 2.3-1.2 (8H, m); m/e 217 (M$^+$), 175, 174 (b),
Reaction of chlorosulphonyl isocyanate with epoxystyrene (236).

CSI (2.0 ml; 23.4 mmol) was added to a solution of the epoxide (236) (2.8 g; 23.3 mmol) in dichloromethane (30 ml) at 0°. After 5 min. the solvent was evaporated from the reaction mixture (νmax. 1615 (major), 1810 and 1770 (minor) cm⁻¹) yielding a pink foam (6.0 g) which was separated by chromatography on Florisil (20 g). Elution with carbon tetrachloride yielded N-chlorosulphonyl-4-phenyl-1,3-oxazolidin-2-one (238) (840 mg; 14%) as white crystals, m.p. 76.5-77° (from acetone-ether); νmax. 1810 (s), 1610 and 1407 (m) cm⁻¹; δ 7.5 (5H, s), 5.5 (1H, d, J 8 and 4.5 Hz), 4.87 (1H, t, J 8 Hz), 4.43 (1H, d, J 8 and 4.5 Hz). m/e 263 and 261 (M⁺), 238, 236, 164, 163, 162, 161, 133, 132, 105, 104 (b), 91, 78, 77, 64. Found: C, 41.4; H, 3.2; N, 5.5. C₁₅H₁₅NO₂SCl requires: C, 41.3; H, 3.1; N, 5.35%. Elution with 25% dichloromethane-carbon tetrachloride yielded an oil (1.0 g) (νmax. 1615, 1760 and 1810 cm⁻¹) which was a mixture of (237), (239) and (240). Elution with 50% dichloromethane-carbon tetrachloride yielded N-chlorosulphonyl-2-imino-4-phenyl-1,3-dioxolan (237) (728 mg; 12%) as a colourless oil, which could not be obtained pure enough for analysis; νmax. 1615 (s) and 1375 (s) cm⁻¹; δ 7.5 (5H, s), 6.2 (1H, t, J 8 Hz), 5.25 (1H, t, J 8 Hz), 4.77 (1H, t, J 8 Hz), m/e 263 and 261 (M⁺), 226, 164, 163, 133 (b), 120, 118, 105, 104, 103, 91, 78, 77, 64. Elution with dichloromethane yielded 4-phenyl-1,3-oxazolidin-2-one (240) (436 mg; 11%) as white crystals, m.p. 135-137° (from chloroform) (lit. 140 136°) νmax. 3440 (m), 1760 (s) and 1405 (m) cm⁻¹; δ 7.35 (5H, s), 4.96 (1H, d, J 8.7 and 6.7 Hz), 4.68 (1H, t, J 8.5 Hz), 4.13 (1H, d, J 8.5 and 6.7 Hz); m/e 163 (M⁺), 133 (b), 119, 104, 103, 91, 78, 77, 43; Found: C, 65.6; H, 5.4; N, 8.7. C₁₅H₁₅NO₂ requires: C, 66.2; H, 5.6; N, 8.6%. Elution with 20% acetone-dichloromethane afforded only a brown polymeric tar (1.4 g).
Reaction of chlorosulphonyl isocyanate with epoxystyrene (236).

Sodium sulphite hydrolysis of product.

The epoxide (236) (1.46 g; 12.2 mmol) was added to a solution of CSI (1.0 ml; 11.7 mmol) in dichloromethane (20 ml) at 0°. The reaction mixture (∊max. 1615 (major), 1810 and 1770 (minor) cm⁻¹) was treated with a solution of anhydrous sodium sulphite (3 g) in water (30 ml) for 1 h and worked up in the usual way (p.146) yielding a white solid which was separated by chromatography on silica (50 g). Elution with ether yielded white crystals of 4-phenyl-1,3-dioxolan-2-one (239) (850 mg; 44%), m.p. 50.5-52° (from ether) (lit. 53-55°); ∊max. 1815 (s), 1163 (s) and 1067 (s) cm⁻¹; δ 7.3 (5H, s), 5.6 (1H, t, J 8 Hz), 4.75 (1H, t, J 8 Hz), 4.23 (1H, t, J 8 Hz); m/e 164 (M⁺, b), 120, 119, 105, 91, 90, 89, 78, 77. Found: C, 65.8; H, 5.0. C₉H₈O₃ requires: C, 65.85; H, 4.9%. Elution with 5% methanol-ether afforded white crystals of the oxazolidinone (240) (830 mg; 44%).

Reaction of chlorosulphonyl isocyanate with 3,4-epoxycyclo-oct-1-ene (241).

The epoxide (241) (4.2 g; 34 mmol) was added to a solution of CSI (3.0 ml; 35 mmol) in dichloromethane (60 ml) at ambient temperature. The i.r. spectrum of the reaction mixture (∊max. 1615 (major), 1810 and 2250 (minor) cm⁻¹) remained unchanged after 66 h at ambient temperature except for the decay of the band due to residual CSI (∊max. 2250 cm⁻¹). The solvent was then evaporated yielding a brown crystalline mass (9.5 g) which was washed with ether (3 x 8 ml) yielding white crystals of N-chlorosulphonyl-10-imino-9,11-dioxabicyclo[6,3,0]undec-2-ene (242) (4.85 g; 54%), m.p. 120-122° (from acetone-ether); ∊max. 1615 (s), 1385 (m), 1370 (m), 1190 (m), 1090 (m) and 840 (m) cm⁻¹; δ 5.88 (2H, m), 5.64 (1H, d, J 3 and 11 Hz), 4.56 (1H, d.t., J 3 and 11 Hz), 2.7-1.0 (8H, m); m/e 267 and 265 (M⁺), 230, 167, 124, 107, 95 (b), 83, 82, 80, 79, 64. Found: C, 40.7; H, 4.5; N, 5.2. C₉H₁₂NO₄SCl requires: C, 40.7; H, 4.55; N, 5.3%. The solvent was evaporated from the ether washings, yielding a brown tar
(4.85 g). Attempts to recrystallize half of the residues (2.43 g) failed to yield any crystalline material; the remaining residues (2.42 g) were dissolved in ether (15 ml), treated with a solution of anhydrous sodium sulphite (6 g) in water (30 ml) for 2h, and worked up in the normal way (p.146) yielding a brown oil (1.6 g) which was separated by chromatography on alumina (Grade I; 40 g). Elution with 5% methanol-ether yielded white crystals of 9,10-oxazabicyclo[6,3,0]undec-2-en-10-one (245) (266 mg; 9.5%) m.p. 113.5-114.5° (from acetone-ether and sublimation at 100°/5 mm Hg); \( \nu \) max. 3430(m) and 1760(s) cm\(^{-1}\); \( \delta \) 6.7 (1H, broad), 5.64 (2H, m), 4.53 (1H, d\(^2\), J 3 and 11 Hz), 3.9 (1H, dt, J 3 and 11 Hz), 2.6-1.0 (8H, m); m/e 167 (M\(^+\)), 139, 138, 124, 96, 95, 94, 82(b). Found: C, 64.7; H, 7.8; N, 8.35. \( \text{C}_{9}\text{H}_{13}\text{NO}_{2} \) requires: C, 64.7; H, 7.8; N, 8.4%.

Preparation of 9,11-dioxabicyclo[6,3,0]undec-2-en-10-one (244).

A stirred suspension of (242) (500 mg; 1.89 mmol) in ether (20 ml) was treated with aqueous sodium hydroxide (20 ml; 0.2M) for 30 min., the ether layer was then separated and dried and the solvent was evaporated yielding white crystals of 9,11-dioxabicyclo[6,3,0]undec-2-en-10-one (244) (200 mg; 63%), m.p. 41-46° (from ether-petrol), \( \nu \) max. 1815(s), 1420(m), 1190(m) and 1150(m) cm\(^{-1}\); \( \delta \) 5.84 (2H, m), 4.91 (1H, d\(^2\), J 4 and 10 Hz), 4.07 (1H, dt, J 3 and 10 Hz), 2.7-0.8 (8H, m); m/e 168 (M\(^+\)), 167, 139, 138, 133, 124, 95, 91, 82, 81, 80, 79, 68(b), 67, 59, 58, 57, 55, 54, 53. Satisfactory analysis could not be obtained for this material.

Attempted isolation of N-chlorosulphonyl-9,11-oxazabicyclo[6,3,0]undec-2-en-10-one (243).

The epoxide (241) (4.2 g; 34 mmol) was added to a solution of CSI (3.0 ml; 35 mmol) in dichloromethane (60 ml) at ambient temperature, after 15 min. the solvent was evaporated from the reaction mixture (\( \nu \) max. 1615 (major), 1810 and 2250(minor) cm\(^{-1}\)) and the residue was washed with ether (3 x 8 ml) yielding pale yellow crystals of (242) (4.76 g; 53%). The
solvent was evaporated from the washings and an attempt was made to separate the resulting brown oil by chromatography on Florisil (30 g). Elution with carbon tetrachloride-dichloromethane yielded only mixed fractions ($\nu$ max. 1615 and 1810 cm$^{-1}$) (3.1 g).

Reaction of chlorosulphonyl isocyanate with (241) in n-pentane.

CSI (2.0 ml; 23.4 mmol) was added to a solution of the epoxide (241) (2.8 g; 22.6 mmol) in n-pentane (30 ml) at 0°. The pentane was decanted from the precipitated oil and the oil was triturated with ether (10 ml) yielding white crystals of (242) (1.35 g; 23%). The trituration liquors ($\nu$ max. 1750 (major), 1615 and 1810 (minor) cm$^{-1}$) were diluted to 30 ml with ether, treated with a solution of anhydrous sodium sulphite (3 g) in water (30 ml) for 1h and worked up in the normal way (p.146) yielding a yellow tar (1.735 g) which, on t.l.c., showed a single spot corresponding to the oxazolidinone (245) "embedded" in a continuous "streak". Separation of the oil by chromatography on alumina (Grade II; 40%) eluting with 5% methanol-ether yielded white crystals of the oxazolidinone (245) (300 mg; 8%) and a dark polymeric tar (930 mg).

Reaction of chlorosulphonyl isocyanate with 3,4-epoxy-3-methylbut-1-ene (246).

CSI (2.0 ml; 23.4 mmol) was added to a solution of the epoxide (246) (2.2 g; 26.2 mmol) in dichloromethane (40 ml) at 0°. After 5 min. the solvent was evaporated from the reaction mixture, ($\nu$ max. 1615 (major), 1810 and 1780 (minor) cm$^{-1}$) yielding a brown oil (6.01g) which was separated by chromatography on Florisil (13 g). Elution with carbon tetrachloride afforded white crystals of N-chlorosulphonyl-4-methyl-4-vinyl-1,3-oxazolidin-2-one (248) (348 mg; 6.5%); m.p. 69.5-70.5°(from acetone-ether); $\nu$ max. 1810(s) and 1410(m) cm$^{-1}$; $\delta$ 6.16 (1H, $d^2$, J 10 and 17 Hz), 5.50 (1H, $d$, J 10 Hz), 5.48 (1H, $d$, J 17 Hz), 4.34 (1H, $d$, J 9 Hz), 4.2 (1H, $d$, J 9 Hz), 1.85 (3H, s); m/e 227 and 225 (M$^+$), 212, 210(b), 200, 198, 190, 168, 166,
156, 154, 126, 112, 102, 100, 99, 96, 83, 69, 68, 67, 64, 55, 54.

Found: C, 31.8; H, 3.7; N, 6.2. C\textsubscript{6}H\textsubscript{8}NO\textsubscript{4}S\textsubscript{2}Cl requires: C, 31.9; H, 3.6; N, 6.2%; and a 55:45 mixture of (248) and N-chlorosulphonyl-2-imino-4-methyl-4-vinyl-1,3-dioxolan (247) (600 mg; 9%) as a yellow oil. Elution with dichloromethane yielded (247) (2.82 g; 53.5%) as a colourless oil, V\textsubscript{max}. 1615(s) and 1370(m) cm\textsuperscript{-1}; \$ 6.04 (1H, d\textsuperscript{2}, J 10 and 16 Hz), 5.56 (1H, d, J 16 Hz), 5.48 (1H, d, J 10 Hz), 4.72 (1H, d, J 9 Hz), 4.6 (1H, d, J 9 Hz), 1.80 (3H, s); m/e 227 and 225 (M\textsuperscript{+}), 212, 210, 190(b), 112, 106, 83, 64. Analysis could not be obtained as the product could not be crystallized. Elution with 20% acetone-dichloromethane afforded a brown polymeric tar (V\textsubscript{max}. 1740(sb) cm\textsuperscript{-1}) (0.96 g).

Preparation of 4-methyl-4-vinyl-1,3-dioxolan-2-one (249).

A stirred solution of the imino compound (247) (1.0 g; 4.4 mmol) in ether (20 ml) was treated with 0.2M aqueous sodium hydroxide (20 ml) for 15 min. The ether layer was then separated, dried and the solvent was evaporated yielding 4-methyl-4-vinyl-1,3-dioxolan-2-one (249) (410 mg; 72%) as a yellow liquid. Preparative g.l.c. (130\textdegree) afforded pure (249) as a colourless oil, V\textsubscript{max}. (CDCl\textsubscript{3}) 1805(s) and 1065(s) cm\textsuperscript{-1}; \$ 5.96 (1H, d\textsuperscript{2}, J 10 and 16 Hz), 5.44 (1H, d, J 16 Hz), 5.32 (1H, d, J 10 Hz), 4.30 (1H, d, J 8 Hz), 4.18 (1H, d, J 8 Hz), 1.60 (3H, s). Found: C, 56.0; H, 6.45. C\textsubscript{6}H\textsubscript{8}O\textsubscript{3} requires: C, 56.2; H, 6.3%.

Reaction of chlorosulphonyl isocyanate with (246). Sodium sulphite hydrolysis of products.

The epoxide (246) (2.0 g; 23.8 mmol) was added to a solution of CSI (1.9 ml; 22.2 mmol) in dichloromethane (25 ml) at 0\textdegree. The reaction mixture was treated with a solution of anhydrous sodium sulphite (5 g) in water (30 ml) for 1h and worked up in the normal manner (p.146) yielding a colourless oil (2.1 g) which was separated by chromatography on silica
(50 g). Elution with ether afforded the dioxolanone (249) (992 mg; 35%) as a colourless oil, elution with 2% methanol-ether yielded 4-methyl-4-vinyl-1,3-oxazolidin-2-one (250) (355 mg; 12.5%) as a very pale yellow oil, b.p. 125-130°/0.2 mm Hg; ν max. 3435 (m), 1760 (s), and 1045 (m) cm⁻¹; δ 6.76 (1H, broad), 5.92 (1H, d^2, J 10 and 17 Hz), 5.30 (1H, d, J 17 Hz), 5.20 (1H, d, J 10 Hz), 4.20 (1H, d, J 8 Hz), 4.10 (1H, d, J 8 Hz), 1.45 (3H, s); m/e 127 (M⁺), 112(b), 100, 84, 78, 68, 67, 56, 55, 54, 53, 43.

Found: C, 56.0; H, 7.2; N, 10.6. C₆H₅NO₂ requires: C, 56.7; H, 7.1; N, 11.0%

Reaction of chlorosulphonyl isocyanate with (246) in n-pentane.

The epoxide (246) (2.2 g; 26.2 mmol) was added to a solution of CSI (2.0 ml; 23.4 mmol) in n-pentane (27.5 ml) at 0° and a yellow brown oil was precipitated. A sample (1 ml) of the n-pentane layer (ν max. 2250 cm⁻¹) was diluted with n-pentane (4 ml) and the transmittance at 2250 cm⁻¹ was determined to be 33% (equivalent to 0.9 mmol of unreacted CSI). The n-pentane was decanted from the brown oil which was dissolved in ether (30 ml) and treated with a solution of anhydrous sodium sulphite (4 g) in water (30 ml) for 1 h. The ether layer was separated, dried and evaporated yielding a brown oil (1.65 g) which on distillation yielded the dioxolanone (249) (410 mg; 14.5%)*, b.p. 120-130°/20 mm Hg. The residue was separated by chromatography on alumina (Grade II; 5 g). Elution with ether yielded the oxazolidinone (250) (350 mg; 12%)* as a yellow oil.

Separation of a mixture of the N-chlorosulphonyl-imino-dioxolan (247) and N-chlorosulphonyl-oxazolidinone (248).

A 1:2 mixture** of (248) and (247) (2.8 g), obtained from partial chromatographic separation of the product from several reactions of the epoxide (246) with CSI, was separated by chromatography on Florisil (20 g). Elution with carbon tetrachloride yielded the N-chlorosulphonyl oxazolidinone (248) (267 mg; 9.5%) as white crystals, elution with 25% carbon tetrachloride-chloroform yielded the N-chlorosulphonyl imino-dioxolan (247) (195 mg; 7.2%) as a yellow oil.

* Based on CSI consumed. ** Ratios were obtained from the n.m.r. spectrum.
dichloromethane-carbon tetrachloride afforded a 1:1 mixture of (248) and the N-chlorosulphonyl-imino-dioxolan (247) (226 mg; 8%) as a yellow oil, elution with 50% dichloromethane-carbon tetrachloride yielded (247) (570 mg; 20%) as a colourless oil. Elution with dichloromethane yielded a 5:1 mixture (170 mg) of (247) (5.5%) and the oxazolidinone (250) (1%), and a pure fraction of (250) (280 mg; 17%); finally, elution with 20% acetone-dichloromethane yielded white crystals of 5-chloro-2-methyl-pent-2-enyl carbamate (251) (310 mg; 15.5%), m.p. 75.79° (from ether), \( \nu \) max. 3520 (m), 3410 (m), 1735 (s) and 1585 (m) cm\(^{-1}\); \( \delta \) 5.8 (1H, tm, J 7.5 Hz), 4.96 (2H, broad), 4.55 (2H, s), 4.13 (2H, d J 7.5 Hz), 1.77 (3H, s); m/e (no M\(^+\)), 128, 127(b), 85, 84, 67, 62, 55, 53, 43; Found: C, 44.25; H, 6.3; N, 8.5. \( \text{C}_{6} \text{H}_{10} \text{NO}_{2} \text{Cl} \) requires: C, 44.0; H, 6.2; N, 8.6%.

Reaction of chlorosulphonyl isocyanate with 3,4-epoxy-2,3-dimethylbut-1-ene (252).

A solution of the epoxide (252) (2.2 g; 22.5 mmol) in dichloromethane (3 ml) was added to a solution of CSI (1.9 ml; 22.2 mmol) in dichloromethane (25 ml) at 0°. The reaction mixture (\( \nu \) max. 1610 (major) and 1805 (minor) cm\(^{-1}\)) was treated with a solution of anhydrous sodium sulphite (6 g) in water (30 ml) for 1h. and worked up in the normal way (p.146) yielding a colourless oil (1.9 g) which was separated by chromatography on silica (50 g). Elution with ether afforded 4-isopropenyl-4-methyl-1,3-dioxolan-2-one (253) (1.04 g; 33%) as a colourless oil, b.p. 120-125°/20 mm Hg; \( \nu \) max. (CCl\(_4\)) 1820 (s), 1630 (m) and 1070 (m) cm\(^{-1}\); \( \delta \) (CCl\(_4\)) 5.07 (1H, m), 4.96 (1H, m), 4.27 (1H, d, J 8 Hz), 4.06 (1H, d, J 8 Hz), 1.8 (3H, \( \mathrm{d}^2 \), J 0.6 and 1.4 Hz), 1.57 (3H, s); m/e 142 (M\(^+\)), 127, 126, 100, 83, 82, 70, 69, 68, 67, 56, 55(b), 41. Found: C, 59.6; H, 7.2. \( \text{C}_{7} \text{H}_{10} \text{O}_{3} \) requires: C, 59.15; H, 7.1%. Elution with 3% methanol-ether yielded 4-isopropenyl-4-methyl-1,3-oxazolidin-2-one (254) (396 mg; 12.5%) as a colourless oil, b.p. 120-125°/0.2 mm Hg; \( \nu \) max. 3435 (m), 1760 (s) and 1045 (m) cm\(^{-1}\).

* Ratios were obtained from the n.m.r. spectra.
Reaction of chlorosulphonyl isocyanate with 3,4-epoxycyclopent-l-ene (255).

A solution of the epoxide (255) (10 g; 122 mmol) in dichloromethane (20 ml) was added over 90 min. to a solution of CSI (10.3 ml; 119 mmol) in dichloromethane (80 ml) at ambient temperature. The reaction mixture (V max. 1750(b) and 1603(major), 1800 and 2250(minor) cm⁻¹) was treated with a solution of anhydrous sodium sulphite (20 g) in water (100 ml) and worked up in the normal manner (p.146) yielding a yellow oil (2.4 g) which was separated by chromatography on alumina (Grade II; 60 g). Elution with ether yielded 2,4-dioxabicyclo[3,3,0]oct-5-en-3-one (256) (554 mg; 4%) as a colourless oil, b.p. 110-115°/0.5 mm Hg; V max. 1800(s), 1370(m), 1355(m), 1065(s) and 1045(cm⁻¹); δ 6.15 (1H, m), 5.87 (1H, m), 5.59 (1H, dm, J 7Hz), 5.24 (1H, m), 2.79 (2H, m); m/e 126 (M⁺), 83, 82, 81, 80, 66(b), 55, 54. Found: C,56.8; H,4.8. C₆H₆O₃ requires: C,57.1; H,4.8%. Elution with 5% methanol-ether afforded 2,4-oxazabicyclo[3,3,0]oct-6-en-3-one (257) (226 mg; 1.5%) as white crystals, m.p. 64-66° (from dichloromethane-ether); V max. 3460(m) and 1760(s) cm⁻¹; δ 7.09 (1H, broad), 5.91 (1H, m), 5.73 (1H, dt, J 6 and 2 Hz), 5.20 (1H, dm, J 7 Hz), 2.74 (2H, m); m/e 125 (M⁺), 97, 96, 82, 81(b), 80, 69, 68, 66, 54, 53, 43. Found: C,57.4; H,5.6; N,11.15. C₆H₆NO₂ requires: C,57.6; H,5.6; N,11.2%. Elution with 5% methanol-ether also yielded 2,4-oxazabicyclo[3,3,0]oct-7-en-3-one (258) (270 mg; 2%) as white crystals, m.p. 117-119° (from dichloromethane-ether); V max. 3460(m) and 1755(s) cm⁻¹; δ 7.09 (1H, broad); 6.06 (1H, m), 5.82 (1H, dt, J 6 and 2 Hz), 5.52 (1H, dm, J 8 Hz), 4.42 (1H, tm, J 7 Hz), 2.9-2.3 (2H, m); m/e
125 (M⁺), 82, 81, 80(b), 66, 43. Found: C, 57.2; H, 5.6; N, 11.2.

C₆H₈NO₂ requires: C, 57.6; H, 5.6; N, 11.2%.

Reaction of chlorosulphonyl isocyanate with 7,8-epoxycyclo-octa-1,3,5-triene (262).

The epoxide (262) (1.5 g; 12.5 mmol) was added to a solution of CSI (1.0 ml; 11.7 mmol) in dichloromethane (30 ml) at ambient temperature. The solvent was evaporated from the reaction mixture yielding crude N-chlorosulphonyl cyclo-octatetraenyl carbamate (264) (3.1 g; 100%) as a pale green solid. Recrystallization from dichloromethane-ether afforded pure (264) (1.58 g; 52%) as white crystals, m.p. 113-116° (decomp.); ν max. 3300(m), 1785(s) and 1660(m) cm⁻¹; δ 8.7 (1H, broad), 7.7-6.9 (6H, m), 5.8 (1H, d, J 7 Hz). Found: C, 40.7; H, 3.0; N, 5.1.

CgH₈NO₄S Cl requires: C, 41.3; H, 3.1; N, 5.35%.

Preparation of cyclo-octatetraenyl carbamate (265).

Triethylamine (0.27 ml; 1.9 mmol) was added to a solution of the N-chlorosulphonyl carbamate (264) (450 mg; 1.7 mmol) in dichloromethane (2 ml) at ambient temperature. The mixture was then shaken vigorously with water saturated ether (10 ml) for 5 min., washed with water (1 ml) and dried. The solvent was then evaporated yielding a yellow solid which was freed from residual triethylamine hydrochloride by chromatography on Florisil (5 g). Elution with ether afforded cyclo-octatetraenyl carbamate (265) (198 mg; 70%) as white crystals, m.p. 125-127° (from dichloromethane-ether); ν max. 3540(m), 3420(m), 1755(s), 1662(m), 1585(m), 1330(s) and 1070(s) cm⁻¹; δ 7.6-6.9 (6H, m), 5.57 (1H, d, J 7 Hz), 5.1 (2H, broad); m/e 163 (M⁺), 121, 120(b), 92, 91, 90, 89, 78, 77, 65, 63, 58, 43. Found: C, 66.1; H, 5.5; N, 8.5.

C₉H₈NO₂ requires: C, 66.2; H, 5.6; N, 8.6%.
Reaction of chlorosulphonyl isocyanate with 2α,3α-epoxypinane (267).

A solution of the epoxide (267) (3.0 g; 19.7 mmol) in dichloromethane (3 ml) was added over 20 min. to a solution of CSI (1.7 ml; 19.9 mmol) in dichloromethane (40 ml) at ambient temperature. The solvent was evaporated from the reaction mixture (νmax. 3310(b), 1810, 1760(b) and 1600 cm⁻¹) and the residue (7.6 g) was dissolved in ether (40 ml), treated with a solution of anhydrous sodium sulphite (3 g) in water (20 ml) for 30 min. and worked up in the normal manner (p.146) yielding a yellow oil which was separated by chromatography on silica (40 g). Elution with ether afforded white crystals of (1α,2β,6β,8α)-2,9,9-trimethyl-3,5-dioxabicyclo[6,1,1,0²,6]decan-4-one (268) (295 mg; 7.5%), m.p. 72-77° (from ether-petrol) (lit.¹⁴₆ 80-82°); νmax. 1800(s), 1220(m), 1060(m) and 1050(s) cm⁻¹; δ 4.5 (1H, d, J 7 and 2.5 Hz) 2.7-1.8 (6H, m), 1.5 (3H, s), 1.3 (3H, s), 0.85 (3H, s); m/e 196 (M⁺), 181, 152, 141, 137, 134, 128, 119, 104, 102, 99, 83, 82(b), 79, 69, 67. Found: C,67.5; H,8.3. C₁₁H₁₆O₃ requires: C,67.3; H,8.2%. Elution with 2% methanol-ether afforded white crystals of (1α,3β,5α)-2-methylene-6,6-dimethylbicyclo[3,1,1]hept-3-yl carbamate (270) (202 mg; 5%), m.p. 119-121° (from acetone-ether and sublimation at 110°/5 mm Hg); νmax. 3530(m), 3420(m), 1725(s), 1585(m), 1380(m), 1330(m), 1125(m) and 1060(m) cm⁻¹; δ 4.83 (1H, s); 4.74 (1H, s), 5.2-4.1 (2H, mound), 3.02 (1H, db, J 4 Hz), 1.95-1.2 (6H, m), 1.07 (6H, s); m/e 195 (M⁺), 180, 144, 121, 119, 109, 108(b), 107, 93, 91, 79, 78, 77, 67, 43. Found: C,68.0; H,8.8; N,6.9. C₁₁H₁₇NO₂ requires: C,67.7; H,8.8; N,7.2%. Elution with 2% methanol-ether also yielded white crystals of (1α,3β,7β,8α)-7,9,9-trimethyl-4,6-oxazatricyclo[6,1,1,0³,7]decan-5-one (269) (215 mg; 5.5%), m.p. 139-140.5° (from ether-petrol); νmax. 3450(m) and 1755(s) cm⁻¹; δ 6.3 (1H, mound), 4.45 (1H, d, J 7.5 and 2.5 Hz), 2.7-1.7 (6H, m), 1.37 (3H, s), 1.26 (3H, s), 0.83 (3H, s); m/e 195 (M⁺), 180 152, 137, 136, 134, 119, 114, 99, 83, 82, 78, 70, 43(b). Found: C,67.75;
H,8.8; N,7.2%.

Reaction of chlorosulphonyl isocyanate with 2α,10-epoxypinane (273)

A solution of the epoxide (273) (13 g; 85.5 mmol) in dichloromethane (20 ml) was added over 3 h to a solution of CSI (8.0 ml; 93 mmol) in dichloromethane at ambient temperature. The reaction mixture (νmax.3330(b), 1810, 1770 and 1605 cm⁻¹) was treated with a solution of anhydrous sodium sulphite (20 g) in water (100 ml) for 1 h and worked up in the normal way (p.146) yielding a yellow oil (5.05 g) which was separated by chromatography on alumina (Grade II; 100 g). Elution with 50% ether-petrol afforded a clear oil, which was rechromatographed on silica to yield (1α,2β,5α)-6,6-dimethylbicyclo[3,1,1]heptane-2-spiro-4'-1',3'-dioxolan-2'-one (274) (110 mg; 0.7%) as white crystals, m.p. 140-145° (from ether-petrol) (lit.⁴⁶ 141-142°); νmax. 1796(s), 1060(m), and 1050(m) cm⁻¹; δ 4.27 (2H, s), 2.5-1.1 (8H, m), 1.05 (3H, s), 0.97 (3H, s); m/e 196 (M⁺), 181, 152, 138, 135, 134(b), 128, 126, 121, 119, 113, 109, 83, 81, 69, 67, 58, 55. Elution with ether afforded 1-hydroxy-methyl-4-isopropenylcyclohex-1-ene (perilla, alcohol) (275) (700 mg; 5.4%) as a colourless oil, b.p. 105-111⁰/15 mm Hg (lit.⁴⁶ 107-110°/ 12.5 mm Hg); νmax. 3590(m), 3430(m.b.), 1640(m), 1450(m), 1435(m) and 885 (m) cm⁻¹; δ 5.6 (IH, m), 4.65 (2H, s), 3.9 (2H, s), 2.4-1.9 (8H, m; becomes 7H, m after shaking with D₂O), 1.7 (3H, t, J 1 Hz); m/e 152 (M⁺), 135, 134, 121, 119, 109, 108, 107, 106, 105, 93, 91, 79, 69, 68(b), 67, 55. Elution with 2% methanol-ether afforded a viscous yellow oil which was rechromatographed on alumina to yield (1α,2β,5α)-6,6-dimethylbicyclo[3,1,1]heptane-2-spiro-4'-1',3'-oxazolidin-2'-one (277) (155 mg; 1%) m.p. 110-112° (from dichloromethane-ether and sublimation at 100°/ 2 mm Hg); νmax. 3460(m), 1755(s), 1380(m) and 1060(m) cm⁻¹; δ 6.5 (1H, broad), 4.20(1H, d, J 8 Hz), 4.06 (1H, d, J 8 Hz), 2.4-1.4 (8H, m), 1.21 (3H, s), 1.02 (3H, s); m/e
Elution with 5% methanol-ether afforded (1α,2β,5α)-6,6-
dimethylbicyclo[3,1,1]heptane-2-spiro-4'-1',3'-oxazolidin-2'-one
(276) (650 mg; 4%) as a pale yellow oil which slowly solidified to a white
crystalline mass, m.p. 162.5-165.5° (from dichloromethane-ether); ν max.
3440 (m), 1755 (s), 1385 (m), 1045 (m); δ 7.3 (1H, mound), 4.1 (2H, s),
2.4-1.6 (8H, m), 1.2 (3H, s), 0.83 (3H, s); m/e 195 (M+), 180, 167, 152,
140, 134, 125, 119, 112 (b), 96, 81, 55, 43, 41. Found: C, 67.6; H, 8.7;
N, 7.1. C11H17NO2 requires: C, 67.7; H, 8.8; N, 7.2%.

Reaction of chlorosulphonyl isocyanate with 3α,4α-epoxycarane (281)

A solution of the epoxide (281) (10 g; 66 mmol) in
dichloromethane (20 ml) was added over 90 min. to a solution of CSI
(6.5 ml; 76 mmol). The solvent was then evaporated from the reaction
mixture (ν max. 3310 (b), 1810, 1770 and 1600 cm⁻¹), the residue was
dissolved in ether (100 ml), treated with a solution of anhydrous
sodium sulphite (20 g) in water (100 ml) and worked up in the normal
manner (p. 146) yielding a yellow oil (6.15 g) which was separated by
chromatography on alumina (Grade II; 250 g). Elution with petrol (b.p.<
40°) yielded a mixture of l-isopropyl-4-methylbenzene (p-cymene) (286)
(4.7%) and trans-3,6,6-trimethylbicyclo[3,1,0]hexane-3-carboxaldehyde
(287) (7.7%) as a colourless liquid (1.19 g). Preparative g.l.c. (80°)
afforded a pure sample of p-cymene (286) as a colourless liquid; ν max.
(CC14) 3020 (m), 2960 (s), 2920 (m), 2870 (m), 1515 (m), 1460 (m) and 860 (m)
cm⁻¹; δ (CC14) 6.87 (4H, s), 2.80 (1H, septet, J 7 Hz), 2.23 (3H, s)
1.20 (6H, d, J 7 Hz); m/e 134 (M+), 119 (b), 104, 91, 79, 78, 77; and
a pure sample of the aldehyde (287) as a colourless liquid, ν max. (CC14)
3020 (m), 2960 (s), 2870 (m), 2800 (m), 2700 (m), 1720 (s), 1450 (m), 1375 (m),

* Yields were calculated from the n.m.r. spectrum of the mixture.
1250(s) and 860(s) cm\(^{-1}\); \(\delta\)(CCl\(_4\)) 9.1 (1H, s), 2.53-1.9 (2H, m),
1.4-1.07 (2H, m), 0.97 (11H, s-broadened); m/e 152 (M\(^+\)), 137, 134, 123,
119(b), 109, 95, 93, 91, 81, 79, 77, 69, 67, 55, 53, 51. Elution with
ether afforded (1α,3β,5β,7α)-1,4,4-trimethyl-8,10-dioxatricyclo[5,3,0,0\(^3\),5]
decan-9-one (289) (2.38 g; 18.5%) as a white crystalline solid, m.p.
95-97\(^{\circ}\) (from ether and sublimation at 100\(^{\circ}\)/0.1 mm Hg), \(\nu\) max. 1790(s),
1367(m), 1202(m) and 1065(s) cm\(^{-1}\); \(\delta\) 4.33 (1H, m), 2.6-1.8 (4H, m),
1.4 (3H, s), 1.03 (3H, s), 0.95 (3H, s), 0.9-0.7 (2H, m); m/e 196 (M\(^+\)),
181, 152, 140, 137, 134, 125, 123, 121, 119, 112, 99, 96, 81(b), 78, 77,
69, 67, 57, 56. Found: C,67.3; H,8.2. \(\text{C}_{11}\text{H}_{16}\text{O}_{3}\) requires: C,67.3;
H,8.2%. Elution with 2% methanol-ether yielded 5-isopropylidene-2-
methylcyclohex-3-en-1-yl carbamate (290) (56 mg; 0.5%) as a white
crystalline solid, m.p. 150-155\(^{\circ}\) (from ether and sublimation at 80-90\(^{\circ}\)/
2 mm Hg); \(\nu\) max. 3540(m), 3430(m), 1720(s) and 1580(m) cm\(^{-1}\); \(\delta\) 6.40
(1H, \(d^2\)-broadened, J 10 and 2 Hz), 5.41 (1H, \(d^2\)-broadened, J 10 and 3 Hz),
5.0-4.4 (3H, m-broad), 2.76 (1H, d-broad, J 14 Hz), 2.4-1.85 (2H, m),
1.76 (3H, s), 1.71 (3H, s), 1.06 (3H, d, J 7 Hz); m/e 195 (M\(^+\)), 152, 135,
134, 120, 119(b), 109, 107, 105, 93, 91, 81, 79, 77, 67, 65, 55, 53, 51.
Elution with 2% methanol-ether also afforded 3 (or 4)-isopropyl-1-methyl-
7,9-oxazabicyclo[4,3,0]non-3-en-8-one (292) (350 mg; 2.5%) as a colourless
oil which slowly solidified to a white crystalline solid, m.p. 75-82\(^{\circ}\)
(after sublimation at 100\(^{\circ}\)/ 2 mm Hg), \(\nu\) max. 3420(m), 1760(s), 1585(m),
and 940(m) cm\(^{-1}\); \(\delta\) 6.54 (1H, sb), 5.36 (1H, m), 4.12 (1H, \(d^2\), J 11 and 6
Hz), 2.7-2.0 (5H, m), 1.08 (3H, s), 0.98 (6H, d, J 7 Hz); m/e 195.127 (M\(^+\))
(Calculated for \(\text{C}_{11}\text{H}_{17}\text{NO}_{2}\) 195.126), 190(b), 152, 136, 119, 109, 81, 79,
78, 77, 43. Elution with 5% methanol-ether yielded (1α,3β,5β,7α)-1,4,4-
trimethyl-8,10-oxazatricyclo[5,3,0,0\(^3\),5]decan-9-one (291) (698 mg; 5.5%)
as a very pale yellow oil which slowly solidified to a white crystalline
solid, m.p. 105-110\(^{\circ}\) (after distillation, b.p. 145-150\(^{\circ}\)/0.1 mm Hg);
$\nu$ max. 3450 (m) and 1755 (s) cm$^{-1}$; $\delta$ 6.5 (1H, mound), 4.3 (1H, m),
2.4-1.6 (4H, m), 1.27 (3H, s), 1.0 (3H, s), 0.93 (3H, s), 0.87-0.63
(2H, m); m/e 195 ($M^+$), 180, 152, 136, 134, 119, 113, 112 (b), 109, 100,
99, 96, 82, 81, 66, 77, 43. Found: C, 67.7; H, 8.8; N, 7.1. C$_{11}$H$_{17}$NO$_2$
requires: C, 67.7; H, 8.8; N, 7.2%. Elution with 10-20% methanol-ether
afforded three mixed fractions which, after chromatography on alumina,
yielded 4-isopropyl-1-methylcyclohex-3-ene-cis-1,2-diol (288) (339 mg;
2.5%) as a colourless oil, $\nu$ max. (CDCl$_3$) 3580 (m), 3400 (s, b), 2960 (s)
and 2920 (s) cm$^{-1}$; $\delta$ 5.16 (1H, m), 3.69 (1H, d$^2$, J 10 and 6 Hz), 3.52
(variable) (2H, s, b), 2.5-1.64 (5H, m), 1.12 (3H, s), 0.96 (6H, d, J
7 Hz); m/e 170 ($M^+$), 153, 152, 143, 141, 139, 137, 125, 123, 109,
98, 97, 95, 74 (b), 71, 69, 67.
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ABSTRACT

The reactions of chlorosulphonyl isocyanate with cyclic 1,3-dienes gave thermally unstable N-chlorosulphonyl β-lactams which were intercepted by reduction to the corresponding stable NH-β-lactams. The exclusively Markovnikov orientation of the addition suggests a considerable degree of dipolar character in the transition state.

Stepwise rearrangement of the initial 1,2-addition products to thermodynamically more stable 1,4-addition or substitution products was observed and the assignment of these products is discussed.

The invertomer ratios and activation energies for inversion at nitrogen in several 2-chloro-2-azabicyclo[2,2,1] and [2,2,2] systems, derived from rearrangement products obtained in the reactions of chlorosulphonyl isocyanate with 1,3-cyclopentadiene and 1,3-cyclohexadiene, were determined using variable temperature n.m.r. spectroscopy. The assignment of the invertomers, and factors influencing the invertomer ratio and activation energy for inversion at nitrogen in bicyclic systems are discussed.

The reactions of chlorosulphonyl isocyanate with vinylcyclopropanes also gave unstable Markovnikov orientated N-chlorosulphonyl β-lactams which were readily reduced to the corresponding stable NH-β-lactams. Rearrangement of the initial 1,2-addition products occurred, in general, via proton transfer to yield N-chlorosulphonyl amides with retention of the cyclopropyl ring. A rearrangement involving the cyclopropyl ring, to give an N-chlorosulphonyl azepinone, was only observed under certain conditions in the case of α-cyclopropylstyrene.

The kinetics of the reactions of chlorosulphonyl isocyanate with vinylcyclopropanes were investigated using i.r. spectroscopy; the effects of solvent polarity and substituents on the reaction rate were
consistent with an initial dipolar addition. The unexpectedly low reactivity and magnitude of the Hammett reaction constant found for α-cyclopropylstyrenes was explained in terms of steric inhibition of resonance in the dipolar intermediate.

The reactions of chlorosulphonyl isocyanate with epoxides, yielding, in general, N-chlorosulphonyl-1,3-oxazolidin-2-ones and N-chlorosulphonyl-2-imino-1,3-dioxolans, were investigated. The assignment of the products is discussed and a dipolar addition mechanism is proposed. This mechanism is supported by the isolation of proton transfer products in the reactions of cyclo-octatetraene epoxide and terpene oxides, and the influence of the structure of the dipolar intermediate on the course of the reaction is discussed.