NOVEL ROUTES TO 2-SUBSTITUTED-1,3-BUTADIENES

BY CHELOTROPIC EXTRUSION REACTIONS

by

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Thesis presented for the degree of

Doctor of Philosophy

To my parents and family

for their continuous support

In this round world of many circles within circles, do we make a weary journey from the high grade to the low, to find at last that they lie close together, that the two extremes touch, and that our journey's end is but our starting-place?

Dombey and Son - Charles Dickens

DECLARATION

I declare that this thesis is my own composition, that it is a record of the work which has been carried out by myself, and that it has not been submitted in any previous application for a higher degree.

The thesis describes the results of research carried out in the Department of Chemistry, University of Edinburgh, under the supervision of Dr. I. Gosney since 1st October 1989, the date of my admission as a research student.

POST-GRADUATE LECTURE COURSES

The following is a statement of the courses attended during the period of research:

- Organic research seminars (3 years attendance).
- Current Topics in Organic Chemistry, various lectures (14 lectures).
- Synthesis and Activity of Agrochemicals - Schering Agrochemicals (6 lectures).
- Aspects and Applications of NMR Spectroscopy, Dr. I. Sadler and Dr. J. Parkinson (5 lectures).
- Discovery of zoladex for treatment of prostrate cancer - ICI Pharmaceuticals (6 lectures).
- Topics in Organic Chemistry, various speakers (5 lectures).
- Royal Society of Chemistry, Perkin Division meetings (3 years attendance).
- Synthesis of New Herbicides - ICI Agrochemicals (2 lectures).
- Postgraduate computer lectures, Dr. K. Lawley (3 lectures).

Attended and passed the Scientific German Course 1990.

ACKNOWLEDGEMENTS

ABSTRACT

2-Substituted-1,3-butadienes are simple dienes generally prepared by elimination rearrangement reactions under pyrolytic conditions, and are of interest as monomers for polymer synthesis.

The most important of these dienes is 2-vinyl-1,3-butadiene ([3]dendralene), the simplest member of a group of acyclic and cyclic cross-conjugated polyolefins known as the dendralenes, which are suitable polyenes for multiple additions of the Diels-Alder type, used to produce large complex polycycles.

The work in this thesis concentrates on the novel synthesis of four 2-substituted-1,3-butadienes by chelotropic extrusion reactions via SO_2 extrusion from sulfolenes (3-substituted tetrahydrothiophene-1,1-dioxides) and ethene extrusion from 1-substituted cyclohexenes. Such chelotropic extrusion reactions were performed using an efficient and selective technique known as Flash Vacuum Pyrolysis (FVP), which was used to prepare 2-cyanobutadiene via SO_2 extrusion and via ethene extrusion from the respective cyano-substituted sulfolene and cyclohexene derivatives, and 2-vinyl-1,3-butadiene and 2-ethynyl-1,3-butadiene by ethene extrusion.

Additionally, a novel compound, 2-phenylethynyl-1,3-butadiene, was prepared using both SO_2 extrusion from the respective sulfolene derivative and ethene extrusion form the respective cyclohexene derivative.

The diene-transmissive nature of this novel compound together with the diene-transmissive nature of 2-cyano-1,3-butadiene was investigated by performing a number of Diels-Alder reactions with cyclic and acyclic dienophiles.

Characterisation of all compounds by various analytical techniques including melting point analysis, mass spectroscopy, nuclear magnetic resonance and infrared spectroscopy is also discussed.

CONTENTS

INTRODUCTION

INTRODUCTION

The following work concentrates on the dendralene group of cross-conjugated molecules and in particular [3]dendralene, the smallest representative of the dendralene group and its analogues. An introduction to this type of polyene is given in Section A, together with a summary of the various preparations of the dendralenes in their framework as cross-conjugated molecules.

The dendralenes possess the ability to undergo diene-transmissive cycloaddition reactions, thereby making them useful tandem annulating reagents hence the widespread interest in these compounds (Section C).

The synthetic routes chosen for the preparation of [3]dendralene and its analogues, incorporate thermal extrusion of SO_2 or retro-diene splitting. The preparation of 1,3-butadienes is well-documented and Section D provides the basis for this topic.

INTRODUCTION

CONTENTS

A. DENDRALENES

1. Introduction

The dendralenes are acyclic and cyclic cross-conjugated polyolefins formally derived from the C=C building block by 1,1-coupling (the name "dendralene" is derived from the Greek "Dendros", meaning tree[1]). The simplest dendralene is 3-methylene-1,4-pentadiene and is known as [3]dendralene **1**. The next member of the series is 3,4-bismethylene-4,5-hexadiene ([4]dendralene) **2** and the third member is 3,4,5-trimethylene-1,6-heptadiene ([5]dendralene) **3**, which to date has not been prepared, but has been the subject of quantum mechanical calculations[2].

Dendralenes may be formed by the rupture of the specific C-C bonds of cross-conjugated cyclopolyolefins, e.g. [4]dendralene is obtained from [4]radialene **4** (a polyolefin with its double bond arrangement occupying exocyclic positions) by cleavage (and saturation) of one cyclobutane bond, and [3]dendralene is derived from fulvene **5**, by removal of the C_3-C_4 bond (Figure 1).

[3]dendralene	[4]dendralene	[5]dendralene
1	**2**	**3**

[4]radialene	fulvene
4	**5**
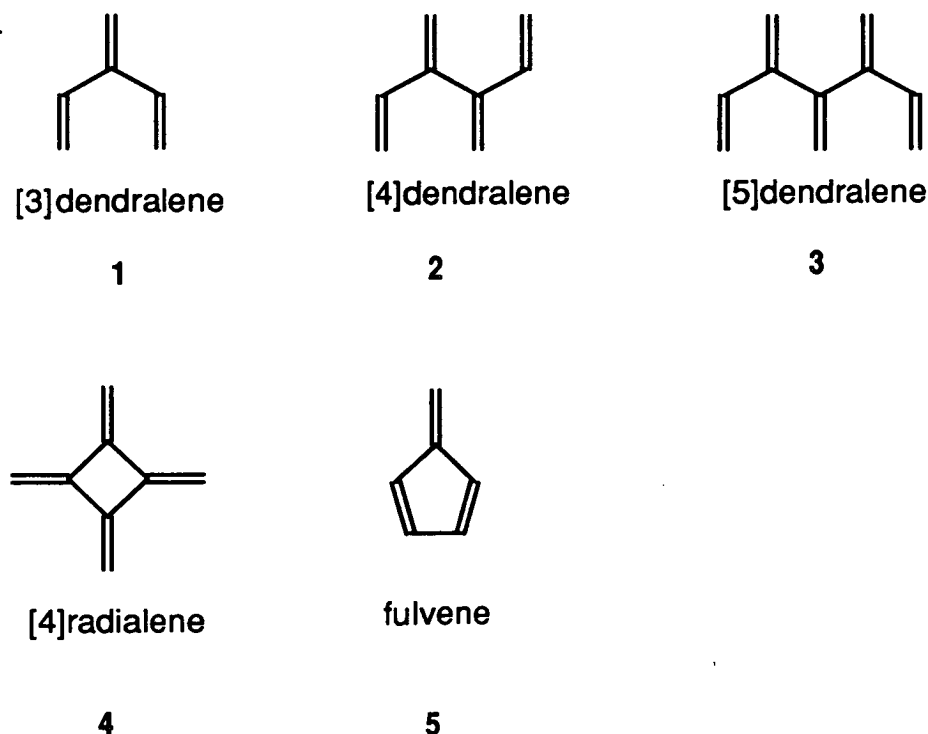
Figure 1

The dendralenes are suitable educts for multiple additions of the Diels-Alder type since each addition of a dienophile generates a new diene system which can undergo further cycloadditions. Therefore large complex polycycles may be built with the aid of the dendralenes.

Dendralenes may also undergo thermal and photochemical rearrangements since they behave in a similar manner to the other polyolefins such as radialenes, fulvenes, cumulenes and annulenes.

The dendralenes are of interest from a structural perspective since they are assumed to occupy a non-planar structure similar to 1,3-butadienes. Since dendralenes contain cross-conjugation they are also of interest in natural product and dyestuff chemistry.
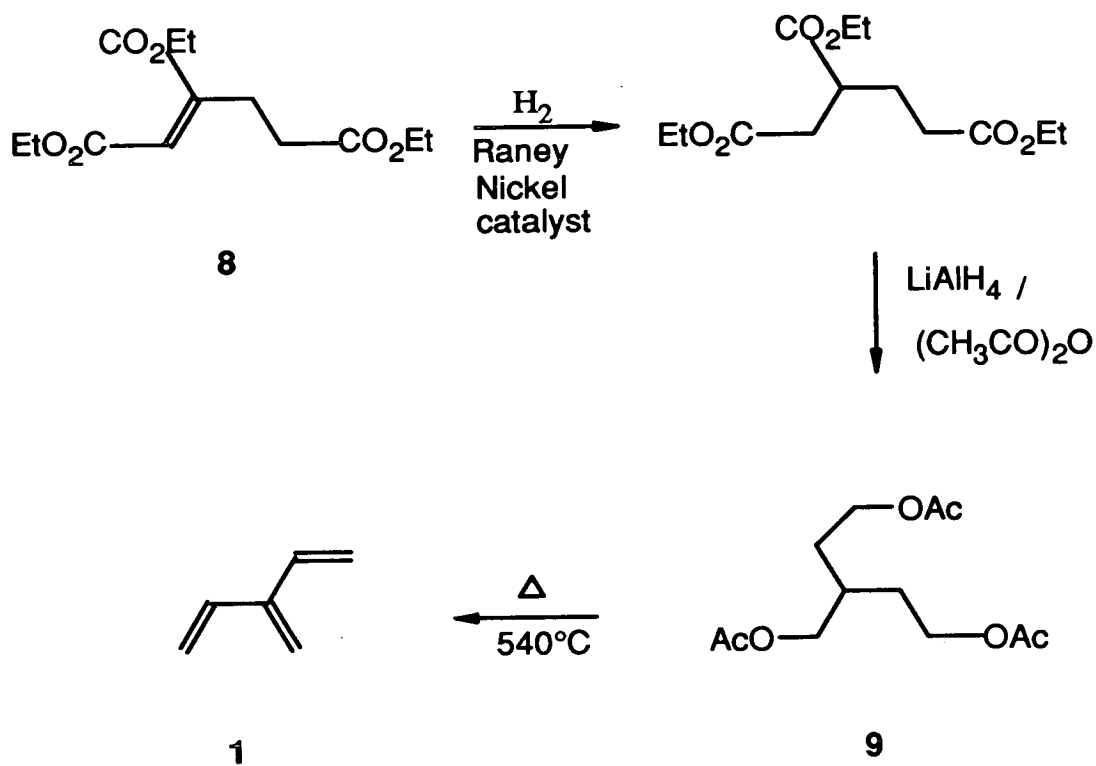
B.   [3]DENDRALENE

1.   Synthesis

In general the dendralenes are synthesised by elimination or rearrangement reactions under pyrolytic conditions. [3]Dendralene (2-vinyl-1,3-butadiene) **1** was first prepared by Blomquist and Verdol[3] by pyrolysis of 3-methylene-1,5-pentadiacetate **6** (which is a product of the thermal condensation of isobutylene with formaldehyde). By varying the flow rate through a Pyrex column either [3]dendralene **1** or 2-(β-acetoxyethyl)-1,3-butadiene **7** can be predominantly produced. Pyrolysis at 485°C over nitrogen and carborundum gives the optimum yield of [3]dendralene (26% after redistillation) (Scheme 1).


| 6 | 7 | 1 |
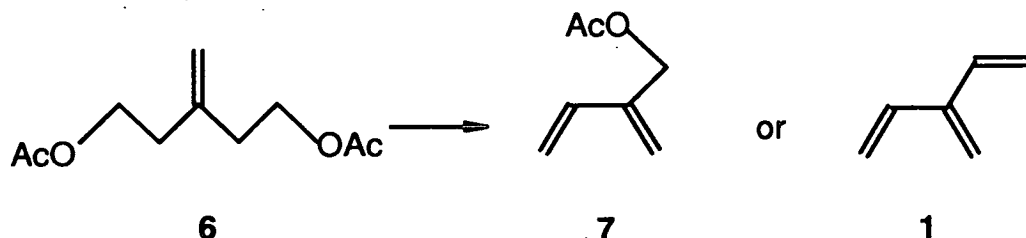
Scheme 1

In the same year as Blomquist and Verdol, a second preparation of [3]dendralene **1** was reported by Bailey and Economy[4] which again employed pyrolysis to produce the diene from aconitric ester **8** in a three step synthesis which includes hydrogenation, reductive acetylation with lithium aluminium hydride and acetic anhydride, and finally the pyrolysis of the triacetate **9** to produce [3]dendralene **1** in a 43% yield (Scheme 2).
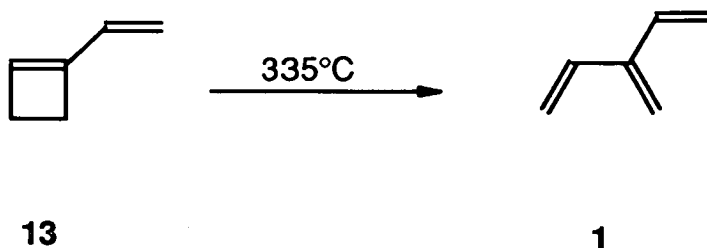

Scheme 2

Priebe and Hopf[5] also prepared [3]dendralene using thermolysis. The synthesis started with the dimerisation of propargyl bromide **10** in the presence of magnesium metal and copper (I) chloride to give the 1,2-hexadiene-5-yne compound **11**. This compound is then isomerised at 500°C to give its acetylenic derivative **12**. Lindlar-catalysed hydrogenation of the acetylene functionality produces the [3]dendralene **1** in moderate yield (Scheme 3).
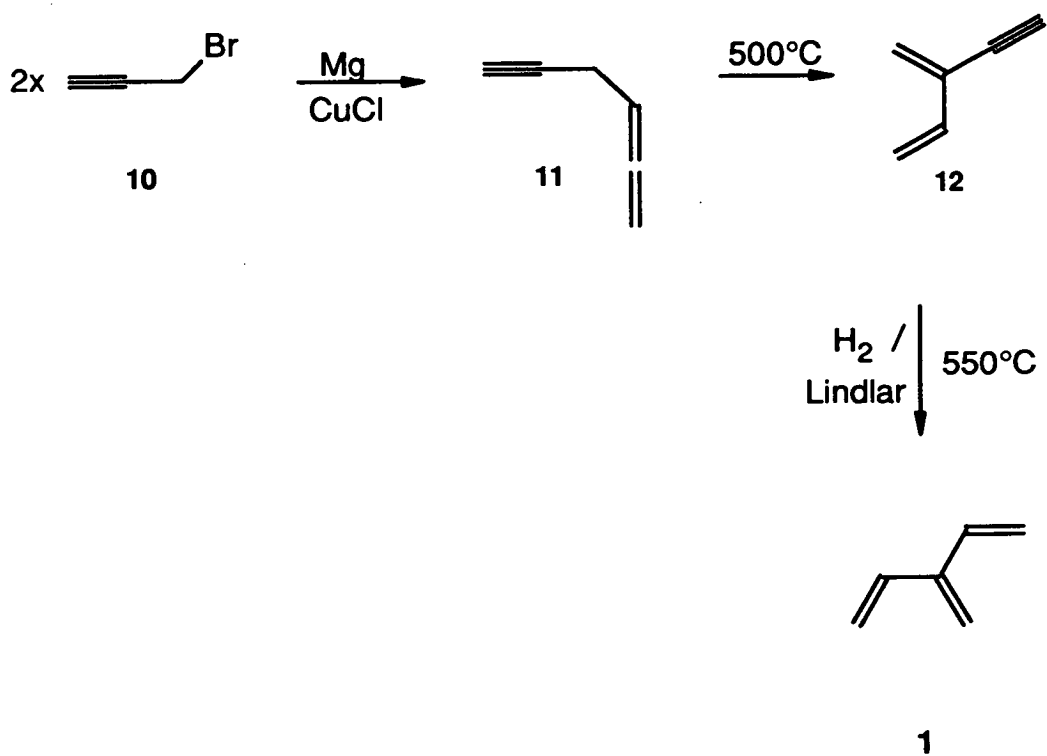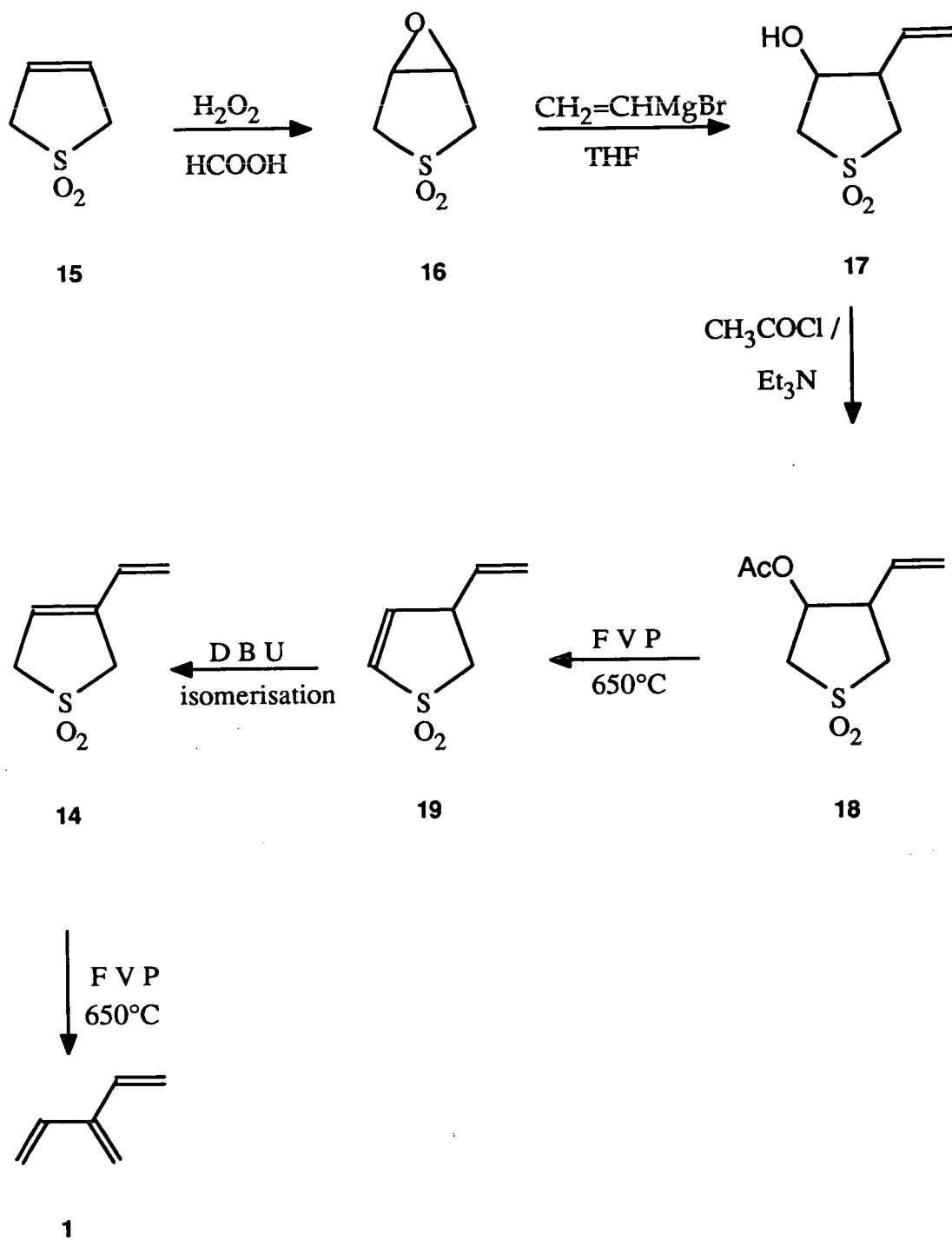

Scheme 3

A later synthesis by Vdovin *et al.*[6] involved the thermal ring opening of 1-vinylcyclobutene **13**, with 100% conversion (Scheme 4).

Scheme 4

The most recent synthesis of [3]dendralene was performed at the University of Edinburgh by Gillam *et al.*[7], who used 3-vinyl-2,5-dihydrothiophene-1,1-dioxide **14** as an easily accessible precursor. Initially, butadiene sulfone (2,5-dihydrothiophene-1,1-dioxide) **15** was epoxidised with formic acid and hydrogen peroxide to form a sulfone epoxide **16**. Nucleophilic ring-opening of this epoxide with vinylmagnesiumbromide affords the 3-vinyl, 4-hydroxide of the sulfone **17**. This compound was then acetylated with acetyl chloride in triethylamine to produce the acetate **18**, then pyrolysed using the flash vacuum pyrolysis (FVP) technique at 650°C. Isomerisation of the resultant product **19** with 1,8-diazabicyclo[5.4.0]undecene-7 (DBU) produced the 3-vinyl-2,5-dihydrothiophene-1,1-dioxide **14**. FVP of this precursor afforded the [3]dendralene **1** in an overall 20% yield (Scheme 5).

Scheme 5

Removal of sulfur dioxide from the precursor **14** occurs cleanly and smoothly at 550°C to produce [3]dendralene **1** as a colourless mobile oil, along with a small amount of a polymeric material. A subsequent flash distillation of the mixture gave pure [3]dendralene **1** as determined by high resolution proton nuclear magnetic resonance (^{1}H NMR) in 87% yield.

2. Physical and structural properties of [3]dendralene

[3]Dendralene **1** is a colourless mobile oil (boiling point 48-50°C). U.V. spectroscopy shows that it possesses a broad absorption (ε_{max} of 205,000 at 231 mμ) indicating a conjugated double bond system and a n^{20} density of 1.4559. ^{13}C NMR shows peaks at δ115.38, 115.35 and 135.62 ppm. IR and Raman spectroscopy allow us to draw some conclusions as to its structure. The Raman effect[7] suggests a structure with some symmetry. In particular the region associated with C=C stretches contains a depolarised band at high frequency, then a polarised band and finally a weak band (probably polarised) which coincides with a strong IR band. These three bands were assigned to the three C=C stretching modes expected, suggesting that the highest and lowest frequency bands are respectively out of phase and in phase combinations of two symmetry related bond stretches, while the band at intermediate frequency is due to the unique double substituted bond.

These observations are consistent with a structure with a two-fold axis or mirror plane of symmetry. The two-fold axis is more likely as it allows the two equivalent CH_2 groups to be nearly co-planar with the unique CH_2 group, as well as with each other. Such a structure is opposed to the structure proposed by Norinder[9] (Figure 2) on the basis of the similarity of the uv spectrum (λ_{max} = 224 nm, log ε = 4.4), to that of butadiene (217 nm, 4.32) and also theoretical calculations. In the case of Figure 2(a) simple calculations show that to bring the two conflicting hydrogens 2.0 Å apart (the sum of the

Van der Waals radii) requires a twist of approx. 25° around each single bond. This reduces the conjugation in each *trans*-butadiene unit by a factor of 0.90, which is greatly preferable to the structure Figure 2(b) with only one conjugated unit, where the corresponding factor is 0.5.


(a)   (b)
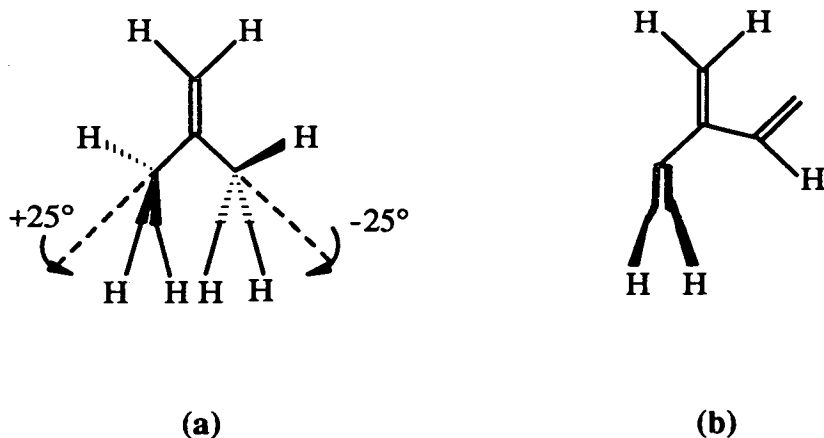
Figure 2

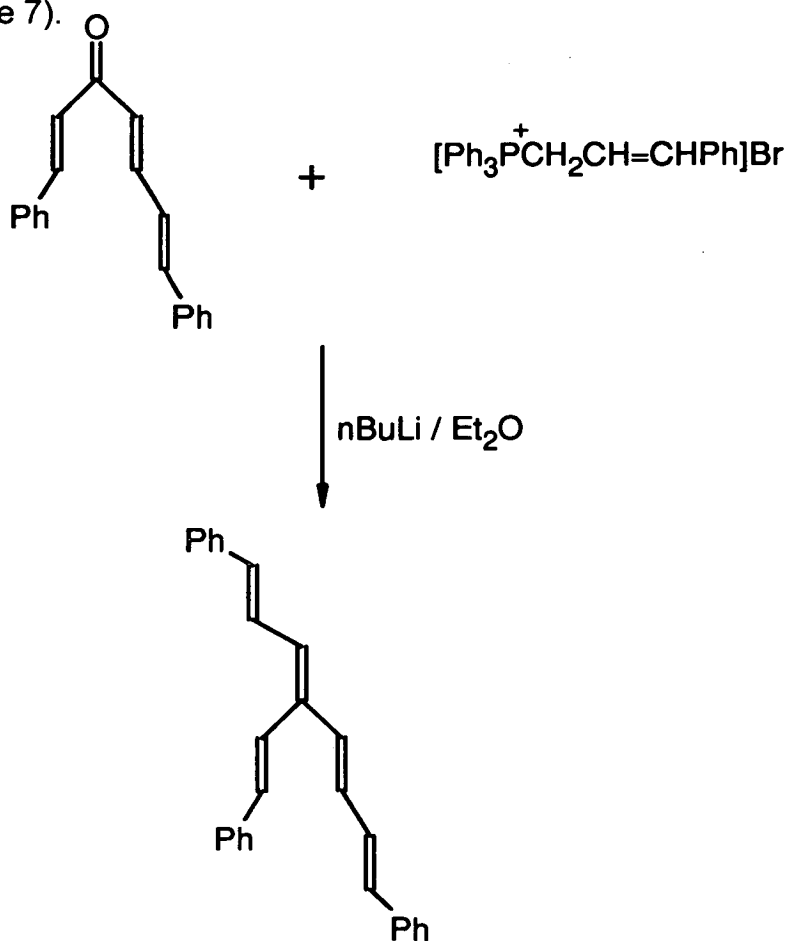## 3.   Derivatives of [3]dendralene

Although the study and synthesis of [3]dendralene is relatively limited, preparations of its derivatives are numerous. Many of these derivatives are produced by thermal rearrangements of substituted cyclobutanes[10] involving 1,5-hydrogen shifts and electrocyclic ring-opening.

Kiefer *et al.*[11] prepared a derivative **21** of [3]dendralene from 1,2-diisopropylidenecyclobutane **20** by thermolysis at 260°C (Scheme 6).

20   **21**
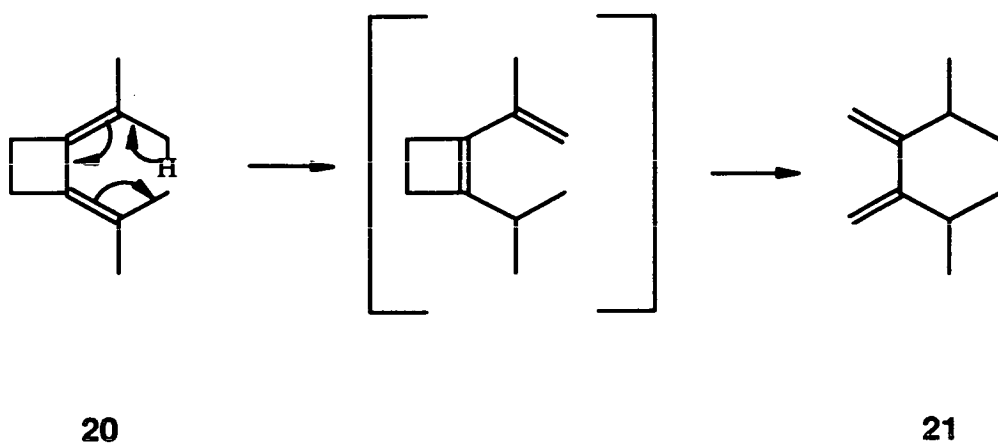
Scheme 6

Wittig reactions on ketone derivatives have also been employed. In one such example Bohlmann[12] synthesised some highly conjugated dendralenes (Scheme 7).

$[Ph_3\overset{+}{P}CH_2CH=CHPh]Br$

nBuLi / Et$_2$O

Scheme 7

Halogenated derivatives of dendralenes have also been prepared[13], as have synthetic equivalents of [3]dendralene, which may undergo Diels-Alder cycloadditions, e.g. 3-methylene-5-phenylsulfinyl-1-pentene[14] **22** undergoes Diels-Alder cycloadditions, which corresponds to diene-transmissive Diels-Alder cycloaddition of the parent [3]dendralene **1** (Figure 3).


Synthetic equivalent

22   **1**
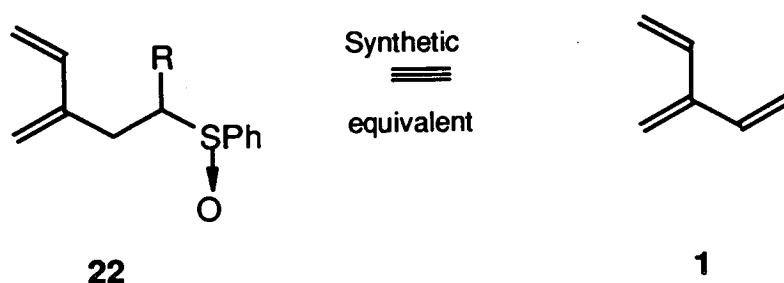
Figure 3

C.   DIENE-TRANSMISSIVE PROPERTIES OF [3]DENDRALENE

Previous reports[15] have identified the dendralenes' ability to undergo Diels-Alder reactions and their subsequent diene-transmissive properties.

In the Diels-Alder reaction a double bond adds in a 1,4-fashion to a conjugated diene (i.e. 4+2 cycloaddition) so that the product is a six-membered ring. The double bond compounds (dienophiles) of various types may cycloadd to the diene ([3]dendralene). The Diels-Alder reaction becomes diene-transmissive when the reaction shifts the diene moiety to a second part of the molecule. The Diels-Alder adduct thus formed may undergo a second cycloaddition to form a larger adduct if a second

dienophile cycloadds to the molecule containing the diene moiety. The diene-transmissive nature of [3]dendralene stems from its ability to undergo numerous annulations (ring-forming) as shown in Scheme 8.
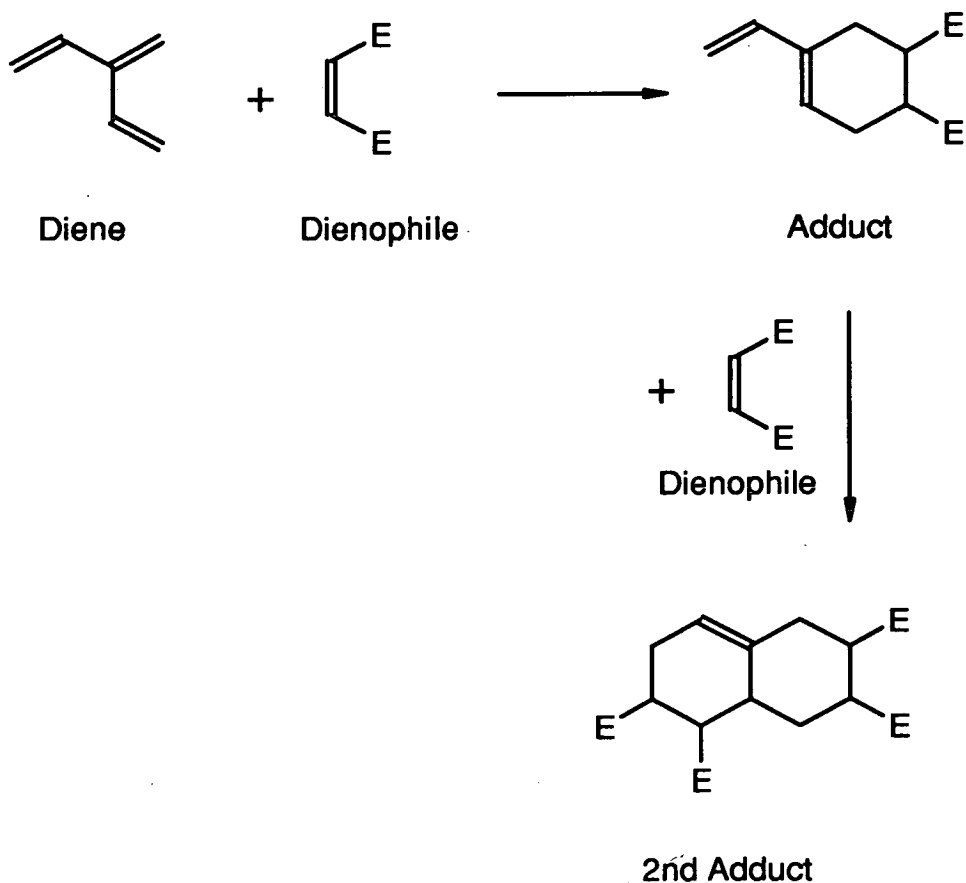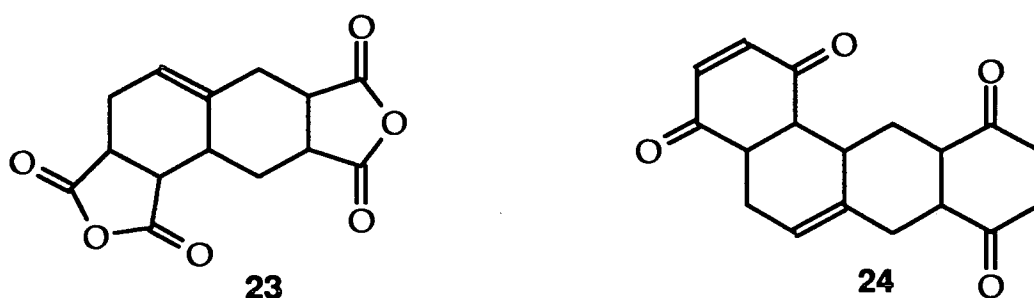

Scheme 8

Due to its simplicity [3]dendralene undergoes many cycloaddition reactions producing products that are either mono- or bis-adducts, unlike higher polyolefins such as [4]dendralene, which lack regioselectivity and therefore can produce a variety of products. This simplicity of structure

allows [3]dendralene to utilise its ability as a suitable tandem annulating reagent, although there are only a few reports of its use in such cycloadditions.

It has been reported[7] that [3]dendralene reacts with maleic anhydride and also with quinone to produce the bis adducts **23** and **24** in Diels-Alder type reactions (Figure 4).

Figure 4

When naphthoquinone **25** and decahydroanthracene-1,4-dione **26** were reacted with [3]dendralene **1**, the hexaphene **27** and octaphene **28** derivatives are isolated[4] (Scheme 9).

25   **1**   **27**

**26**   **1**   **28**
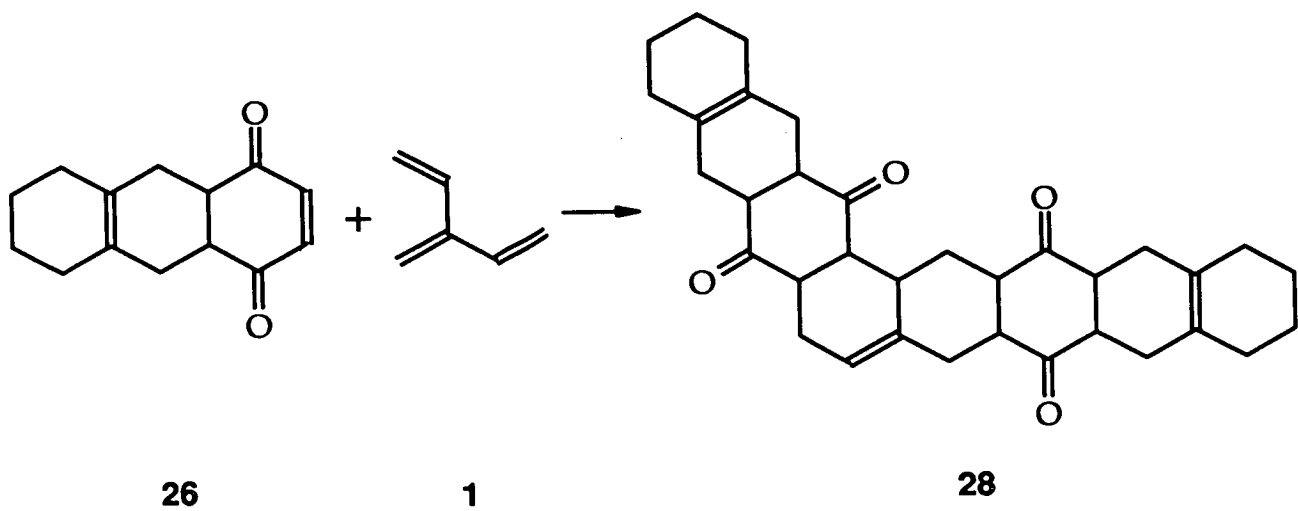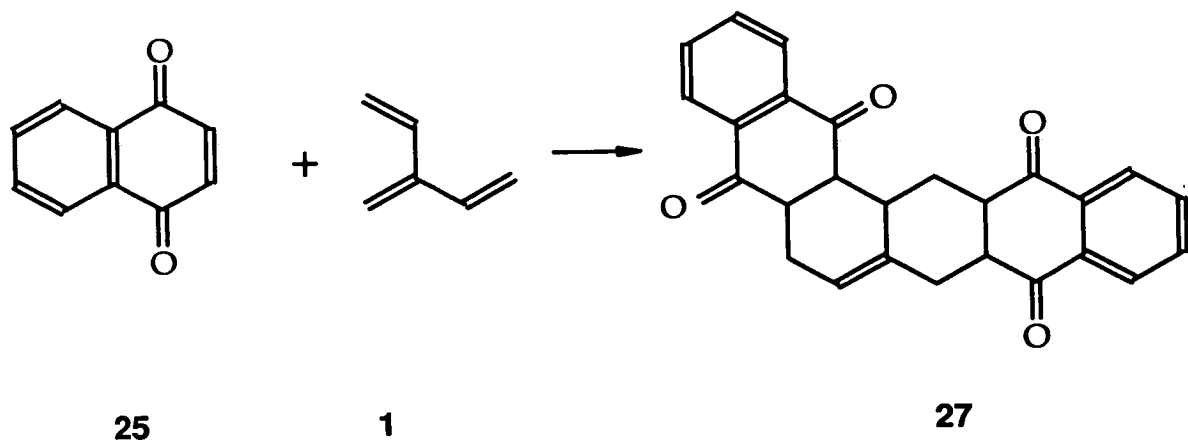
Scheme 9

Recently Gillam[7,8] extensively studied tandem annulations of **1** with a variety of dienophiles by careful regulation of reaction conditions. Some selectivity towards mono- and bis-annulations was subsequently achieved. Initially **1** was reacted with five different dienophiles. These included *p*-benzoquinone, 4-phenyl-1,2,4-triazoline-3,5-dione, tetracyanoethylene (TCNE), maleimide and dimethylacetylenedicarboxylate (DMAD). A number of second cycloadditions were then carried out with the newly formed cycloadducts, *e.g.* the reaction of [3]dendralene **1** with an equimolar quantity of *p*-benzoquinone afforded the monoadduct **29**, which in turn underwent a second Diels-Alder cycloaddition with 4-phenyl-1,2,4-triazoline-3,5-dione to form the mixed adduct **30**. Alternatively when **29** was treated with a second equivalent of *p*-benzoquinone, the bis adduct **31** is formed.

Other bis-adducts were obtained from the reaction of **1** with excess dienophile including **32** from maleimide and compound **33** which was formed by tandem annulation with 4-phenyl-1,2,4-triazoline-3,5-dione. In sharp contrast TCNE reacted with **1** to form only the monoadduct **34**, even in the presence of excess reagent. However **34** did react with the more reactive 4-phenyl-1,2,4-triazoline-3,5-dione to yield the mixed adduct **35**. DMAD added selectivity to **1** to produce the mono-adduct **36**, which then underwent a second cycloaddition to give the bis-adduct **37** (Scheme 10).
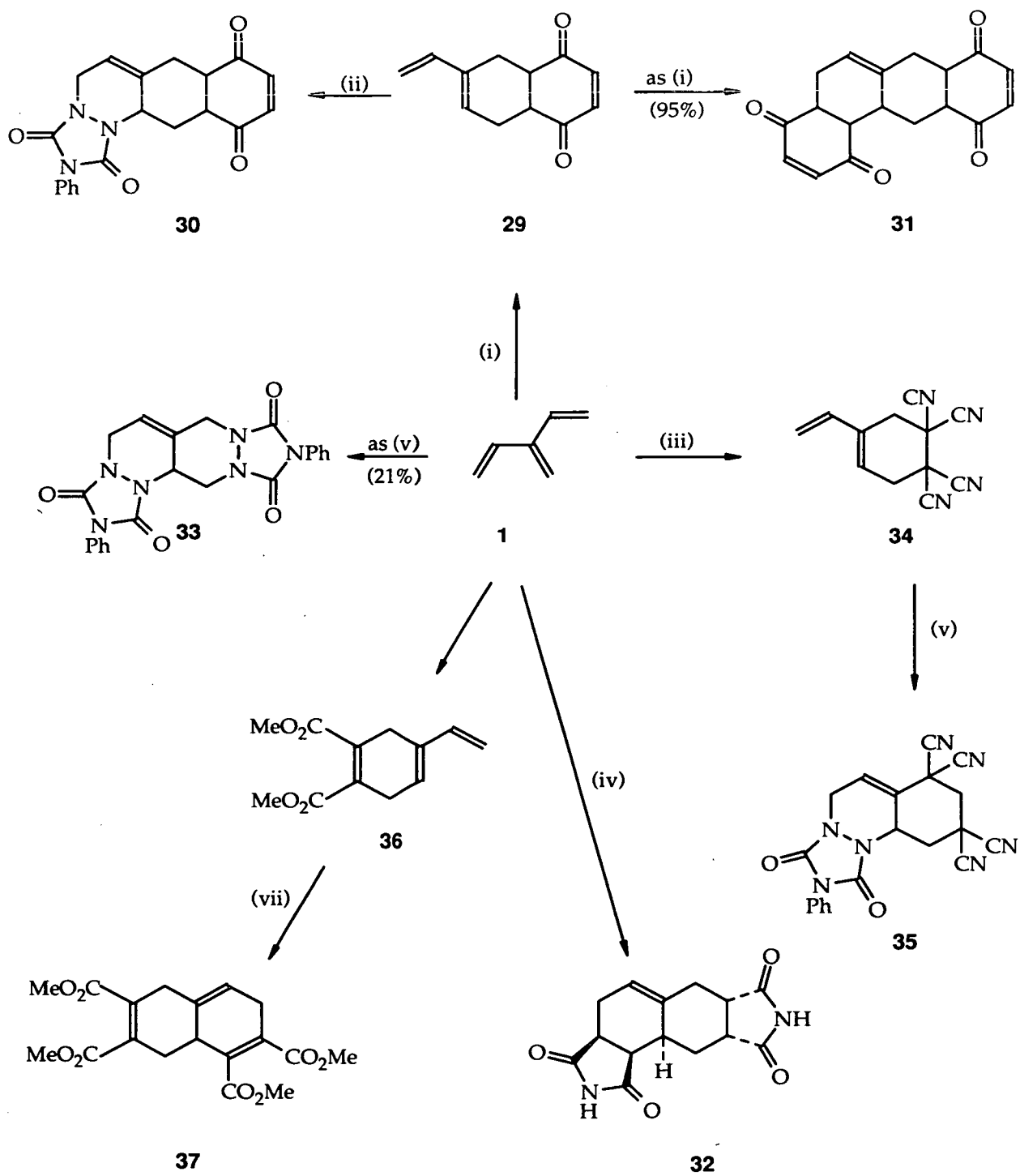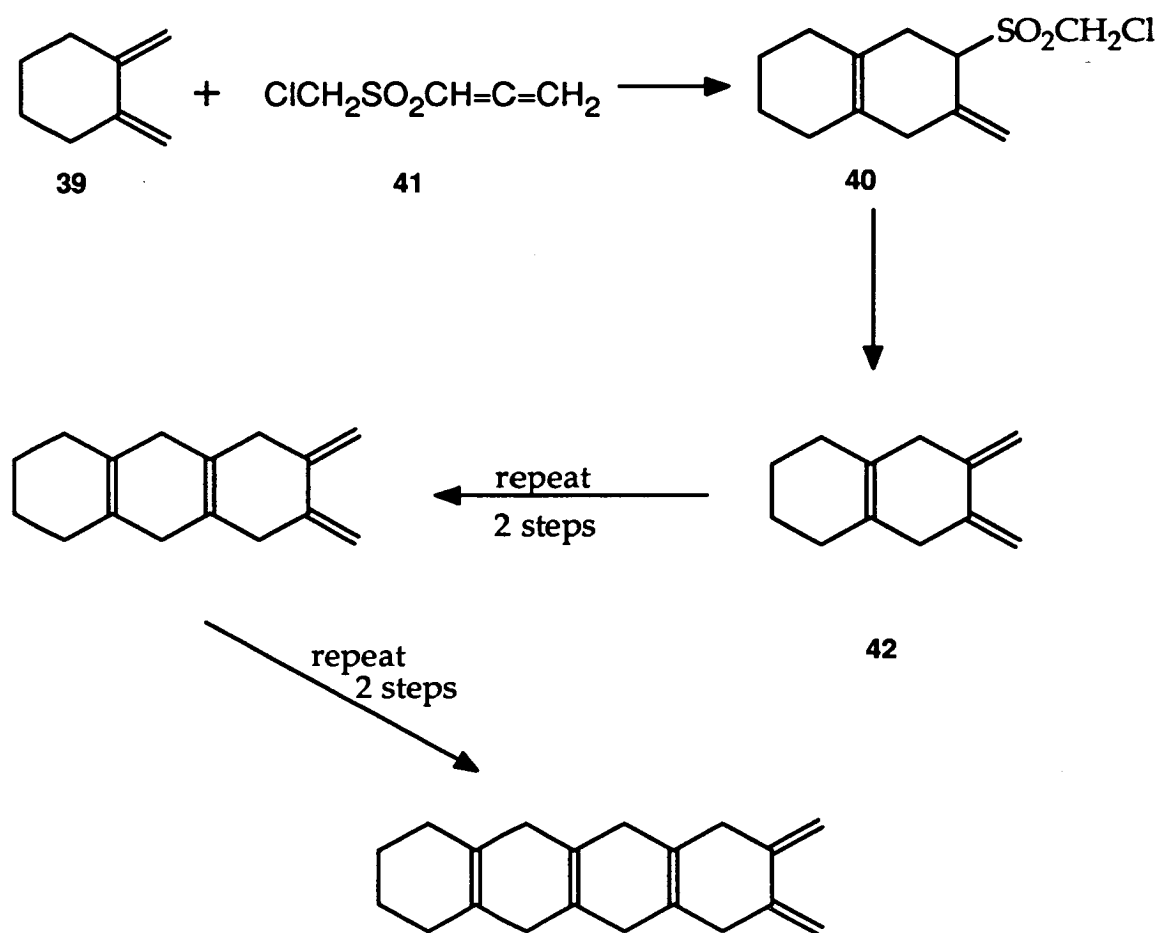
Scheme 10

As previously mentioned (Page 13) derivatives of [3]dendralene **1** have been widely studied for their tandem annulations. Tsuge *et al.*[15,16] prepared the triene **38** and studied its cycloaddition reactions with several acetylenic and cyclic dienophiles (Scheme 11).


E=CO$_2$Me
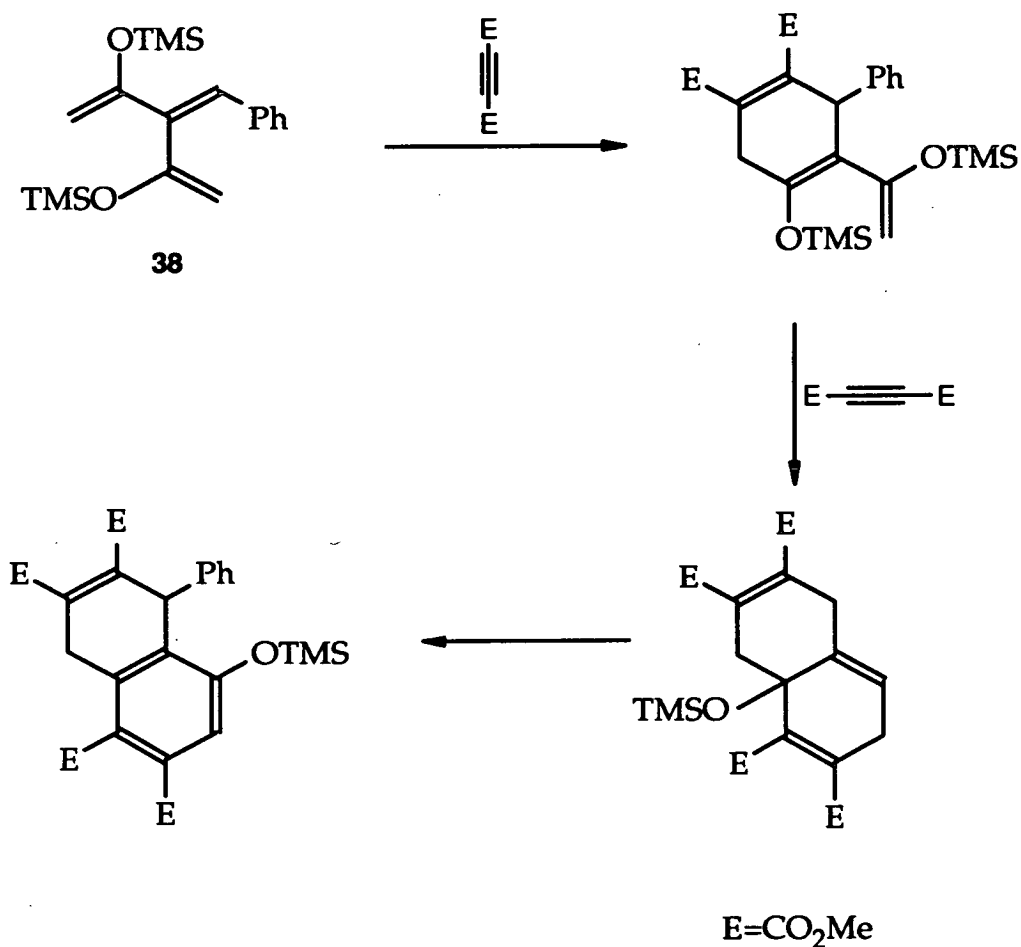
Scheme 11

Dendralene derivatives have also been used for the preparation of large polycyclic compounds through multiple annulations. One example was

that performed by Block *et al.*[17], which used the Ramberg-Backlund reaction to prepare linear-fused carbocycles and polyarene precursors. Specifically 1,2-dimethylcyclohexane **39** was converted into the naphthalene derivative **40** by treatment with chloromethyl-1,2-propadienyl sulfone **41**, whilst sulfonyl chloride elimination gave the exocyclic butadiene derivative **42**. These two steps were repeated until the desired number of annulations were achieved (Scheme 12).


$$ClCH_2SO_2CH=C=CH_2$$

Scheme 12

Cross-conjugation is often found in pigment and dye chemistry. In one such example Reichardt and Mormann[18] used a [3]dendralene type centre in a trinuclear guanidinium cation dye **43** (Figure 5).

43

$$2 \ BF_4^-$$

Figure 5

$$Z=C(CH_3)_2,O,Se,S,(CH=CH)$$
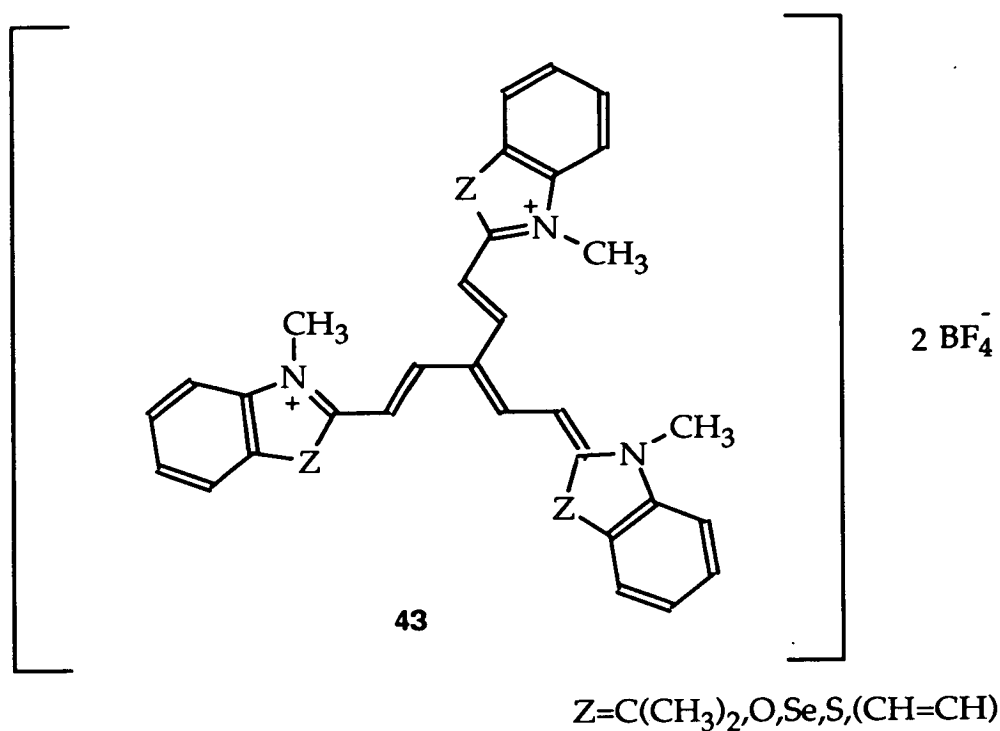
Dendralenes have also been incorporated into polymer chemistry by utilising their cross-conjugation properties. They enable cross-linking and also provide a pendant diene for cycloaddition reactions. In 1954 Bailey and Economy[19] prepared the ladder polymer **44** using benzoquinone as a cycloaddend (Scheme 13).

1

44
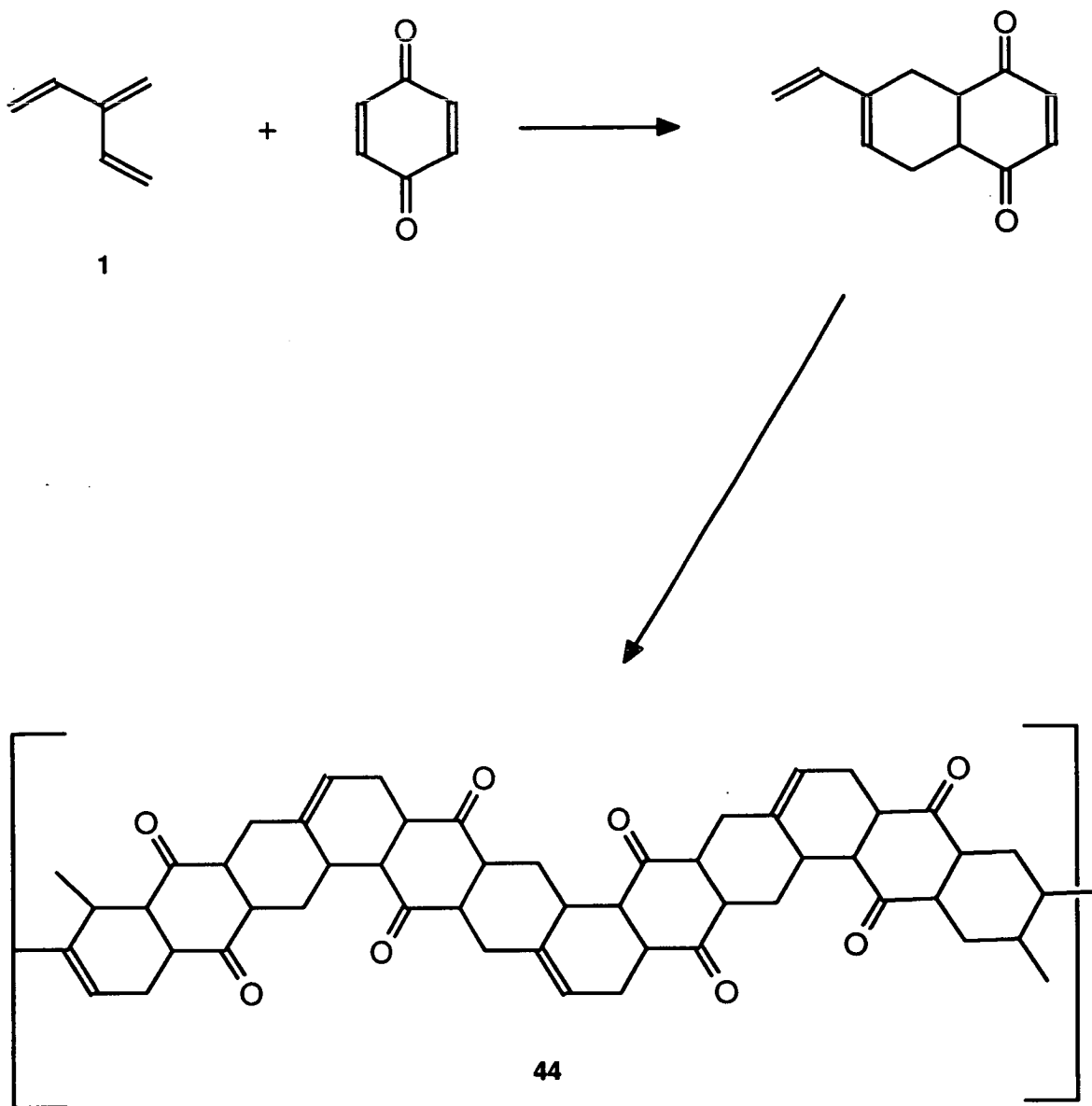
Scheme 13

This procedure was later used by Bailey and Feinberg[20] to prepare **45** amongst a number of other ladder polymers (Scheme 14).

45
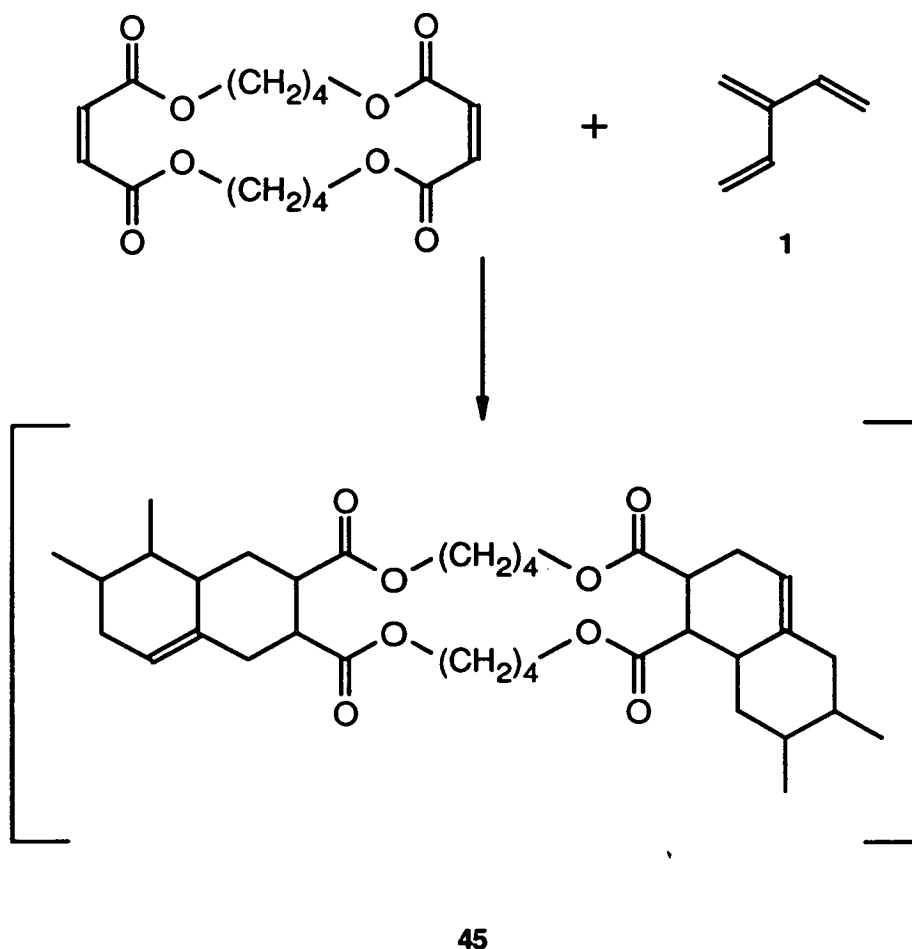
Scheme 14

D. SULFOLENES: MASKED FORMS OF 1,3-BUTADIENES

The sulfolenes (2,5-dihydrothiophene-1,1-dioxide) may be considered as chelotropic adducts of sulfur dioxide and a (poly)alkene *e.g.* butadiene, hexatriene etc. Sulfur dioxide loss from sulfolenes has been analysed from a theoretical viewpoint[21-23] using a number of different approaches. According

to frontier orbital theory[22], the main factor in determining selection rules is the symmetry of the HOMO and LUMO (highest occupied and lowest unoccupied molecular orbitals) of the reactants, which are in turn related to the number of electrons involved in each reactant. Any component (other than a neutral polyene) which can supply the same number of electrons in an orbital of the same symmetry is consequently able to participate in a cycloaddition in place of a polyene. One such component that is of great importance to us and is in fact the topic of this thesis is sulfur dioxide.

Sulfur dioxide has a lone pair of electrons (Figure 6) in the plane of the molecule and a vacant *p*-orbital orthogonal to it. Subsequently, in the extrusion reactions of sulfolenes, the interaction of the HOMO (i.e. lone pair orbital) of sulfur dioxide with the LUMO (i.e. vacant *p*-orbital) of the alkene, as well as the LUMO of the sulfur dioxide with the HOMO of the alkene, must be considered.
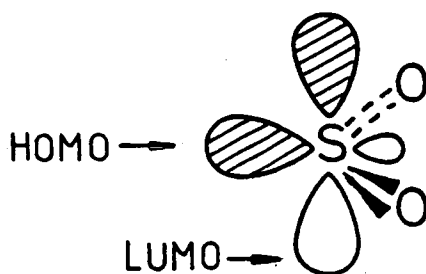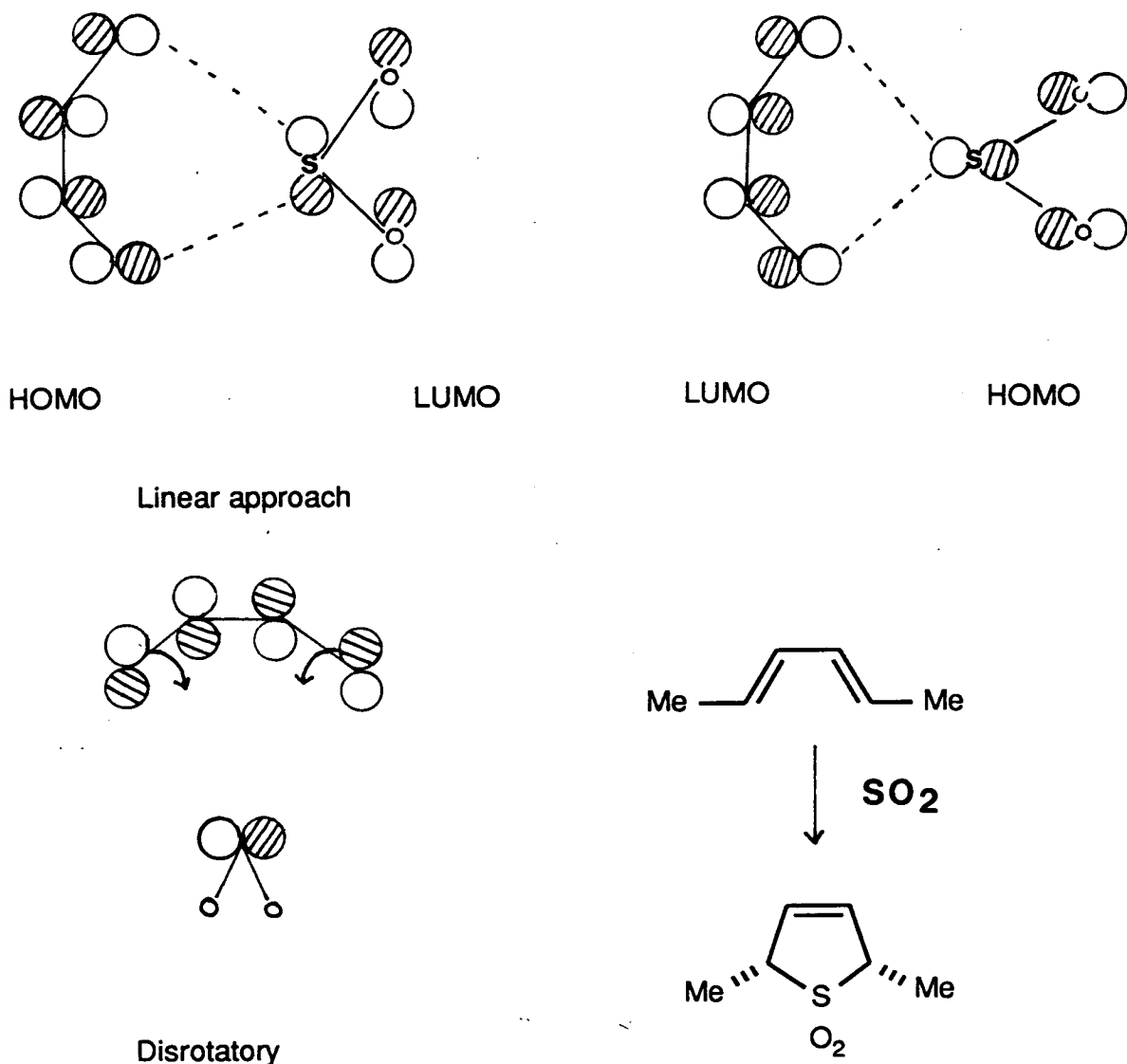

Figure 6

Mock[24] investigated chelotropic reactions, in particular the linear approach of sulfur dioxide to butadiene. The reaction of SO_2 with 1,3-dienes, the so called "sulfolene reaction", has subsequently been extensively studied,

particularly from the stereochemical viewpoint. Both this and the reverse reaction, SO_2 extrusion from 3-sulfolenes, have been shown to be specifically suprafacial (disrotatory) processes[24-26], i.e. the sulfolene forms both the new σ-bonds from the same face of the π-system. It can also be shown that the stereochemistry of the reacting butadiene is inherent in the cyclic product and the reaction is described as a $\pi_{4s} + \omega_{2s}$ process (Figure 7).

HOMO LUMO LUMO HOMO

Linear approach

Disrotatory

Figure 7

Mock suggested that the reverse sulfolene reaction proceeds via the transition state **46**, a linear concerted process described as a retro[$\pi_{4s} + \omega_{2s}$] process in keeping with the orbital symmetry predictions previously described (Scheme 15).

46
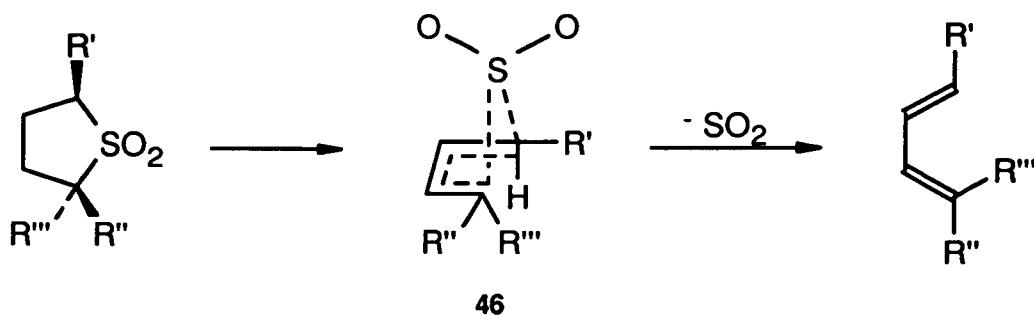
(a) R',R" = CH$_3$, R''' =H
(b) R',R''' = CH$_3$, R" =H

Scheme 15

From kinetic studies[27-30] it has been shown that substituents in the parent sulfone do not affect the rate as much as might be expected for ionic or radical mechanisms.

The first reported sulfolene reaction was published by de Bruin[31], in which he reacted isoprene **47** with liquid SO$_2$ at room temperature and obtained a pure crystalline mono-adduct **48** (Scheme 16).

47

+ SO$_2$ $\xrightarrow{\text{R.T}}$

48
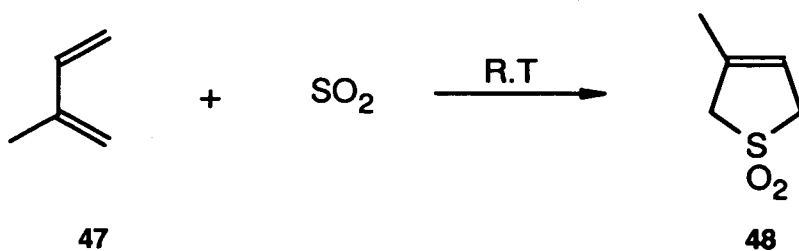
Scheme 16

Since the results of de Bruin, a wide variety of synthetic processes have employed the sulfolene reaction and its reverse mode. The reaction's stereochemistry was demonstrated by Mock[24] when he showed that *cis*-2,5-dimethylsulfolene **49** gave only the E,E-hexa-2,4-diene, on thermolysis at 100°C, while the *trans*-dimethyl compound **50** gave exclusively the E,Z-hexa-2,4-diene at 150°C (Scheme 17).

Scheme 17

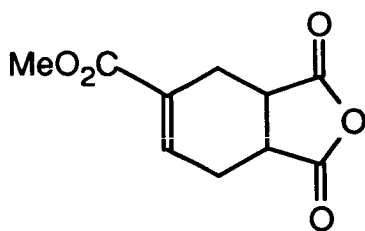Extrusion of SO_2 from 3-sulfolenes to give 1,3-dienes is possibly the most widely used single class of SO_2 extrusion reaction and the generation of dienes in this way followed by either intra or intermolecular Diels-Alder reaction has been applied in many syntheses.

Preparation of sulfolenes **51** functionalised in the 3-position followed by SO_2 extrusion has been widely used to prepare 2-substituted-1-3-dienes **52** which are frequently unstable or difficult to prepare by other routes. In this way 2-bromomethyl-[32], 2-alkylthio-[33], 2-methoxycarbonyl-[34], 2-arenesulfonyl-[35], 2-sulfinyl-[36], 2-phenylthio- and 2-phenylseleno-[37], 2-acyl-[38], 2-acylamino-[39], 1- or 2-trimethylsilyl-[40], and 2-nitro-1,3-dienes[41] have been prepared and their Diels-Alder reactions studied (Scheme 18).

$X=CH_2Br, RS, ArS, ArSO, ArSO_2,$
$ArSe, MeO_2C, RCO, AcNH,$
Me_3Si, NO_2

Scheme 18

For example, 2-methoxycarbonyl-1,3-butadiene **52** (X = CO_2Me) is unstable in the free state but by thermolysing the sulfolene **51** (X = CO_2Me) with maleic anhydride the Diels-Alder adduct **53** was obtained in 73% yield[34] (Figure 8).

53

Figure 8

The alkylation of sulfolene in its acidic α-positions, followed by extrusion of SO$_2$, represents a versatile synthetic method for substituted 1,3-dienes. While exchange with catalytic amounts of K$_2$CO$_3$ in D$_2$O, followed by thermolysis, gave 1,1,4,4-d$_4$-butadiene[42], all attempts at alkylation with other electrophiles were until recently unsuccessful due to the rapid ring opening of the α-anion to butadienyl sulfinate. This problem was overcome in two different ways. First of all Bloch[43] made use of **54**, formally the Diels-Alder adduct of sulfolene with cyclopentadiene (although it cannot be made directly by this route), as a masked form of sulfolene. This can be alkylated in the α-position with butyllithium and alkyl halides to give, after pyrolysis, 1-alkylated 1,3-butadienes. A second alkylation took place on the other α-carbon to give **55** leading to disubstituted dienes (Scheme 19). A particular advantage of using **54** is that a single pyrolysis step, usually under flash vacuum conditions, serves to remove both the cyclopentadiene and the SO$_2$ to give the pure diene in high yield. The method has been extended: by alkylation of **54** with carbonyl compounds leading to α-hydroxy-dienes[44]; by alkylation with chlorotrimethylsilane followed by aldehydes, resulting in Peterson olefination of **54** in the α-position and leading ultimately to α,β-unsaturated allenes; and by reaction with other electrophiles[45]. Attempts to

prepare trienes by direct pyrolysis of **55** (R = alkenyl, R' = H) resulted in double bond migration in the products but this problem could be overcome by pyrolysis of the sulfide corresponding to **55** to remove the cyclopentadiene, followed by oxidation to the alkenylsulfolene which could then be thermolysed under milder conditions to afford the 1,3,5-trienes in good yield[46].


54   **55**
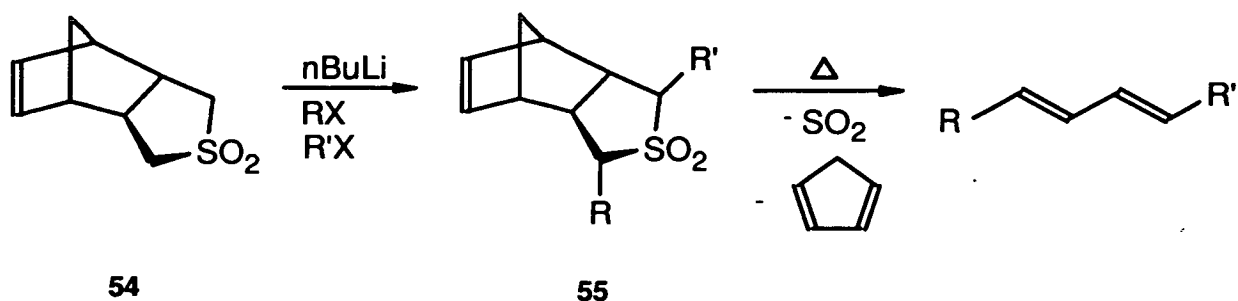
Scheme 19

The other method of sulfolene alkylation is the use of hindered and non-nucleophilic bases which are compatible with alkyl iodides, so that the sulfolene anion can be generated in the presence of the electrophile. Successful diene syntheses have been reported based on alkylation of sulfolenes using sodium hydride/DMF, lithium bis(trimethylsilyl)amide, and lithium tetramethylpiperidide[47]. Subsequent extrusion of SO_2 led to good

yields of 1,3-diene-containing pheromones, terpenes and Vitamin D derivatives.

Alkylation of sulfolenes with ω-iodoalkenes followed by SO_2 extrusion results in an intramolecular Diels-Alder reaction to produce hydroindanes and hydronaphthalenes[48]. A further route for alkylation of sulfolenes used 2-trimethylsilylsulfolene to achieve α,α-dialkylation, thus giving access to 1,1-disubstituted butadienes after SO_2 extrusion[49]. A variety of 2,3-disubstituted butadienes have also been generated for use in cycloaddition reactions, typically by thermolysis of the 3,4-disubstituted sulfolenes at 130°C in a sealed tube[50], and examples with a donor and an acceptor group have been of particular recent interest[51]. Alkylation of 4-methylene-2-sulfolene at the 5-position followed by conjugate addition to the exocyclic methylene group provides convenient access to 2,3-disubstituted 3-sulfolenes and thus to the 1,2-disubstituted dienes after extrusion[52].

Manipulation of 1,3-dienes using their reaction with SO_2 has proved useful in many syntheses. The difficulty in trapping benzyne with butadiene was overcome[53] by the decomposition of benzenediazonium-2-carboxylate 56 and 3-sulfolene 57 to give benzyne 58 and butadiene 59, which combine to form 1,4-dihydronapththalene 60 (Scheme 20). The addition of benzyne to butadiene formed *in situ* is believed to be of a sufficient rate for the butadiene to retain its *cis*-conformation.
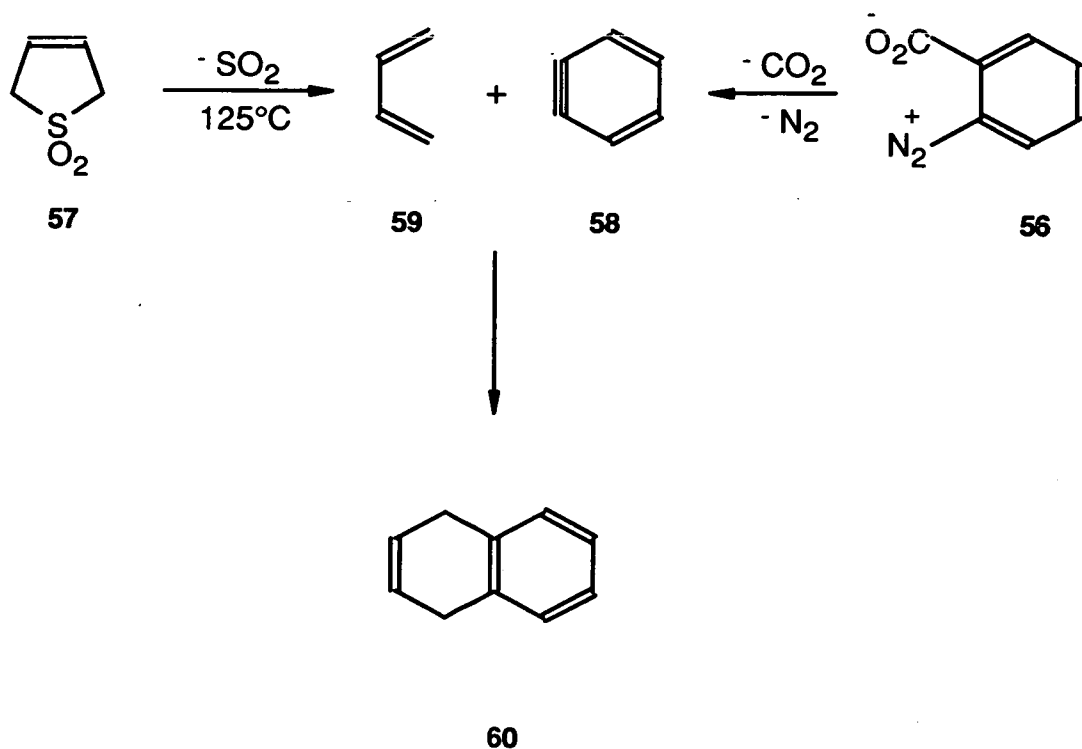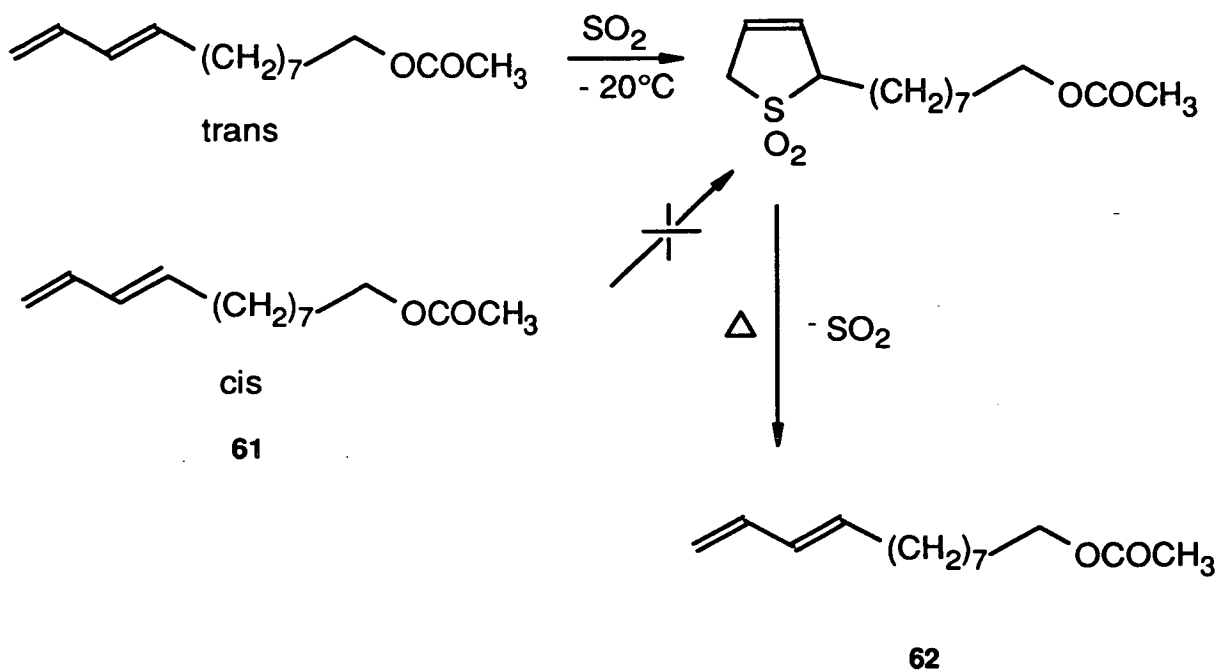
Scheme 20

Since the sulfolene reaction is almost always reversible, sulfolenes are useful intermediates for the modification, purification and storage of 1,3-dienes. In general the addition of SO_2 to 1,3-dienes which are substituted in the 1-position is inhibited; conversely addition to 1,3-dienes substituted in the 2-position is enhanced.

This difference in reactivity has been exploited to separate diene mixtures. In one example Nesbitt et al.[54] separated cis- and trans-isomers of red bollworm moth sex pheromone by selective reaction with SO_2 at 0°C. Since the trans-isomer of 9,11-dodecadiene-1-yl-acetate **61** reacted with SO_2

but the *cis*-isomer did not, the adduct of the sulfolene reaction could be readily separated from the *cis*-isomer. Subsequent thermolysis of the adduct gave pure *trans*-diene **62** (Scheme 21).
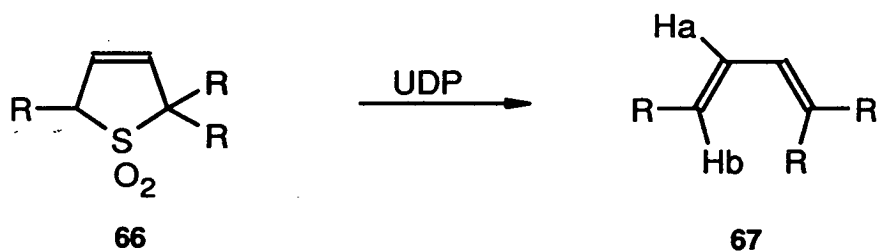

Scheme 21

Chou and You[55] used ultrasonically dispersed potassium (UDP) to promote the extrusion of SO_2 from di- and tri-substituted 3-sulfolenes to give the corresponding dienes stereoselectively. For example 2,6-dialkyl-3-sulfolene **63** was treated with UDP to produce the corresponding dienes **64** and **65** in high yield (Scheme 22).
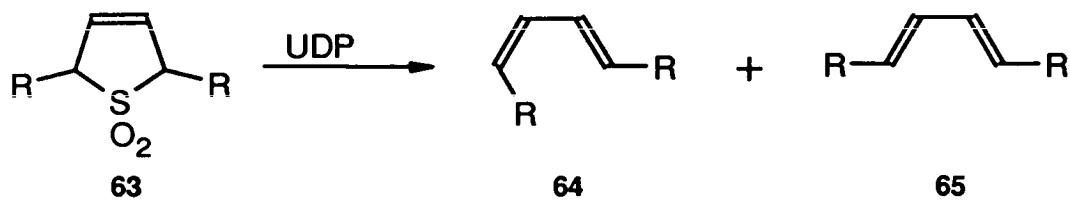
|	64	65
(a) R= n-pentyl (trans)	84%	10%
(b) R= n-hexyl (trans)	86%	11%
(c) R= n-heptyl (trans)	86%	11%
(d) R= n-heptyl (cis)	0%	92%

Scheme 22

Tri-substituted sulfolenes **66** reacted similarly with UDP to give only (> 98% pure) *trans*-tri-substituted dienes **67** in high yield (Scheme 23).

|	67
(a) R=Et	90%
(b) R=Pr	91%

Scheme 23

Recently Chou *et al.*[56] have been able to react tetra-substituted sulfolenes with UDP to produce the corresponding 1,3-dienes in the presence of a proton source (Scheme 24).
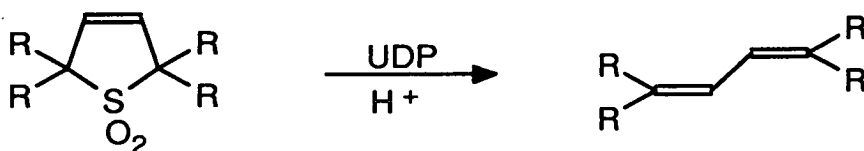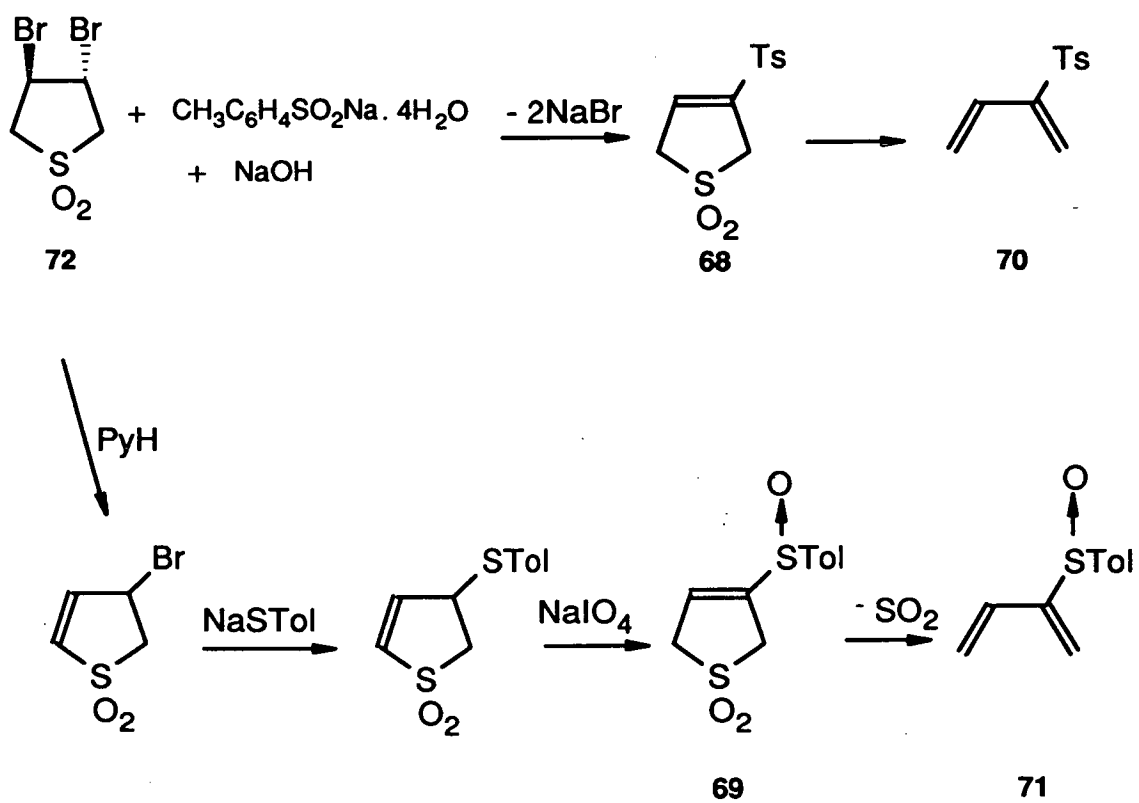

Scheme 24

Gaoni[57] reported that sulfones also undergo elimination of SO_2 when treated with $LiAlH_4$ in ether, as well as by thermolytic methods to give the respective dienes in good yields.

As reported in the earlier section on dendralenes, Gillam *et al.*[7] prepared [3]dendralene **1** using FVP of the precursor 3-vinyl-2,5-dihydrothiophene-1,1-dioxide **14** as a method of SO_2 extrusion (Scheme 25).
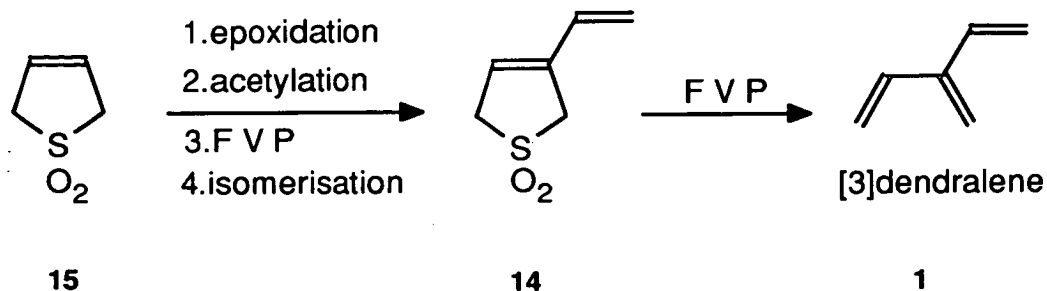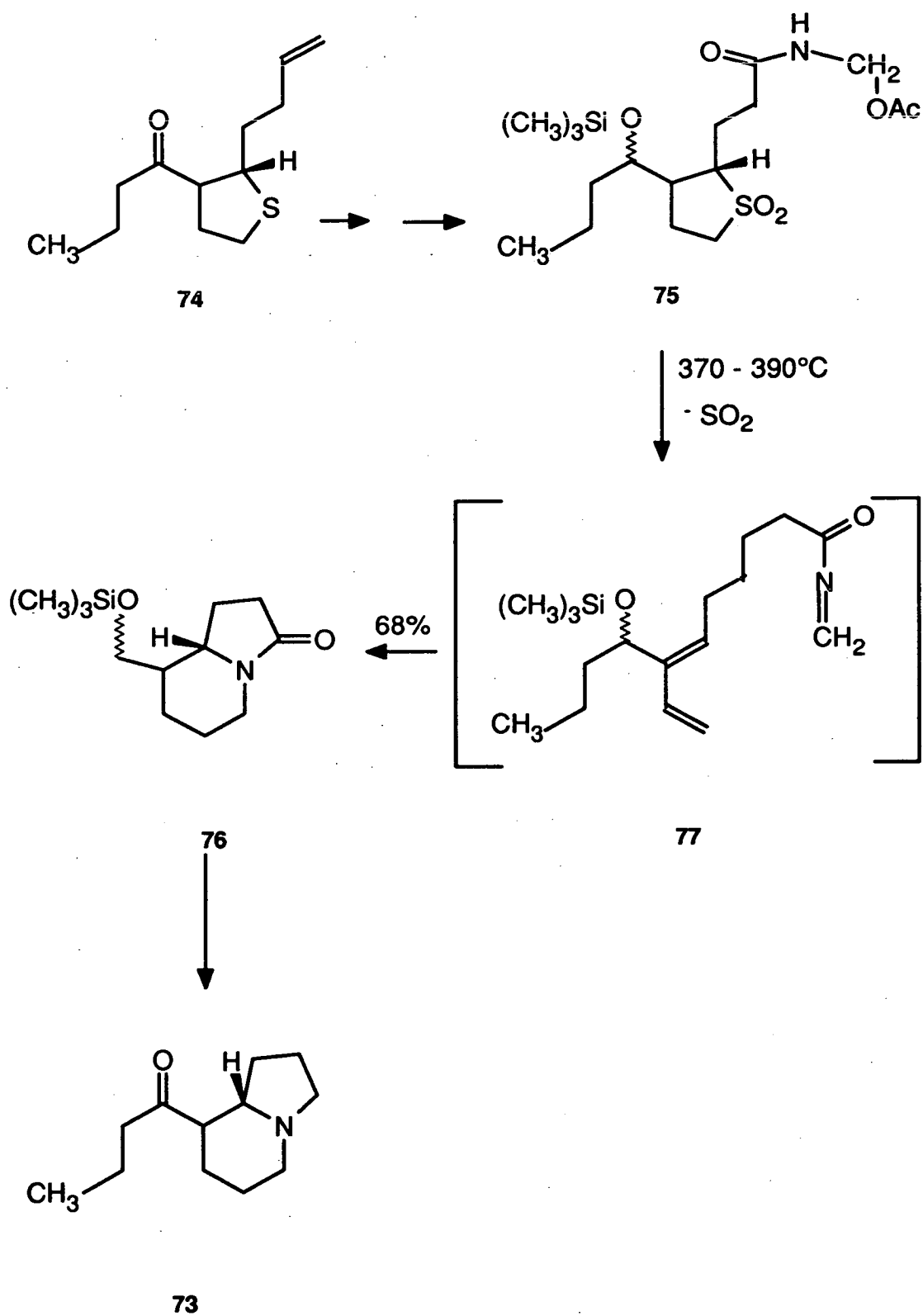
Scheme 25

Numerous other 3-sulfolenes have been used for 1,3-diene preparation by employing the relative ease of "unmasking" sulfolenes. Inomata et al.[35] used 3-(p-tolylsulfonyl)-3-sulfolene **68** and 3-(p-tolylsulfinyl)-3-sulfolene **69** for the preparation of the respective electron-deficient dienes, 2-(p-tolylsulfonyl)-1,3-butadiene **70** and 2-(p-tolylsulfinyl)-1,3-butadiene **71** (Scheme 26). Both sulfolenes **68** and **69** were easily prepared from trans-3,4-dibromosulfolane **72**.
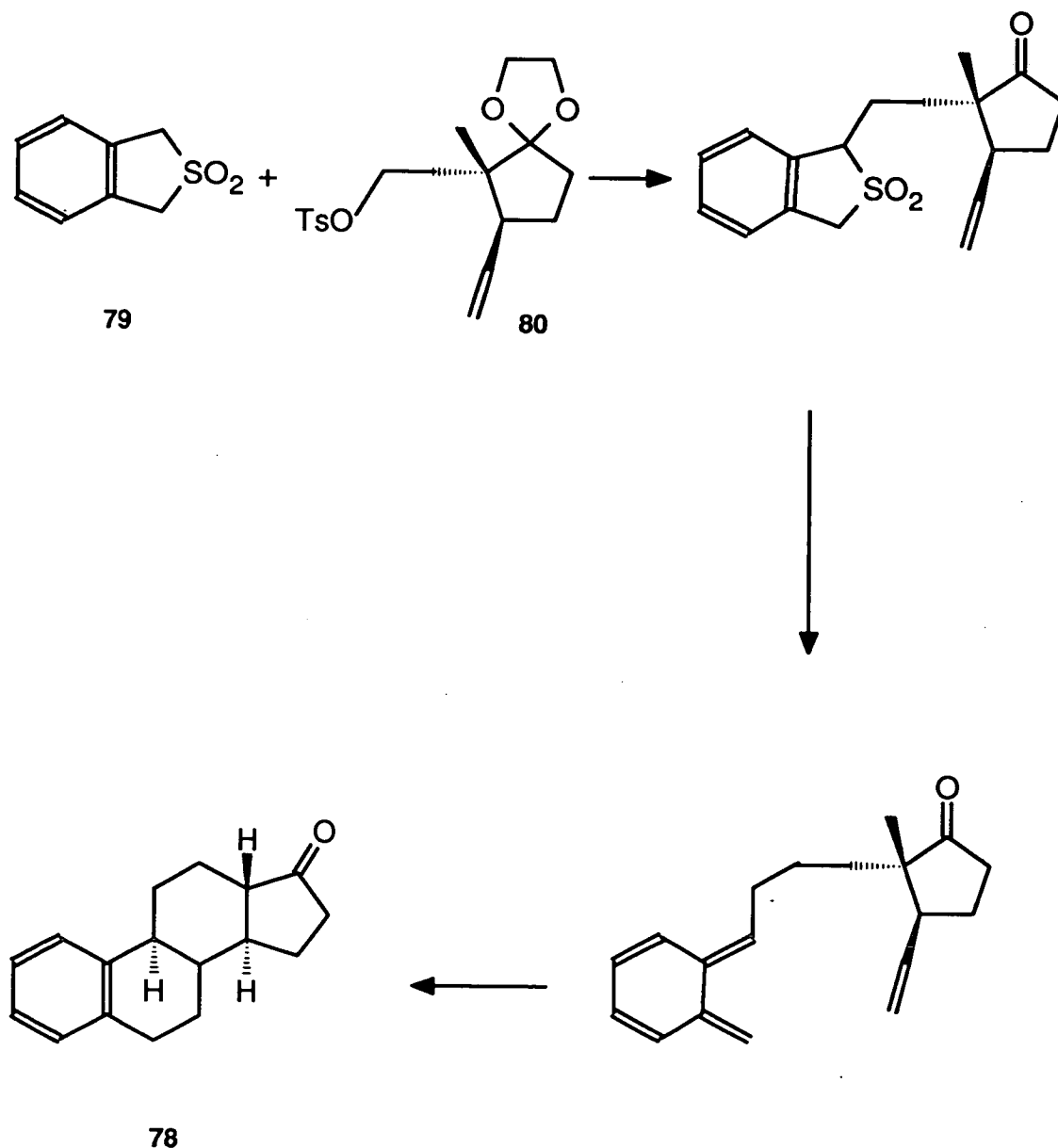
Scheme 26

Manipulation of the sulfolene reaction and its reverse has proved useful in natural product chemistry. Pheromones, terpenes, steroids and alkaloids have been synthesised using sulfolene chemistry. One obstacle that must be overcome is the fact that thermolysis of 2-substituted-2,5-dihydrothiophene-1,1-dioxide leads to E-conjugated dienes, but direct substitution of the parent 2,5-dihydrothiophene-1,1-dioxide is often limited by the opening of the five-membered ring in basic media. An example of how this obstacle has been overcome is the total synthesis of a typical Elaeocarpus alkaloid, Elaeokanine A[58] **73**. Elaeokanine A is one of the compounds isolated from the leaves of a few species of trees of the Elaeocarpacae family, and its synthesis has been completed by using sulfolene and SO_2 extrusion chemistry. Thus, the dihydrothiophene compound **74** is converted into the amide derivative **75**. The retro-Diels-Alder reaction was achieved by passing **75** through a column of glass helices at 370-390°C and produces a bicyclic lactam **76** as a mixture of diastereoismers *via* the diene-acylimine **77**. By a combination of hydrolysis, reduction and oxidation the diene **76** is converted into Elaeokanine A **73** (Scheme 27).

Scheme 27

In a further example the total synthesis of dl-estra-1,3,5(10)-triene-17-one **78** was completed by Nicolauo *et al.*[59], who based their synthesis on the capture of *o*-quinodimethanes generated by chelotropic extrusion of SO_2. Initially the sulfone **79** was alkylated by the tosylate **80** prior to SO_2 extrusion (Scheme 28).
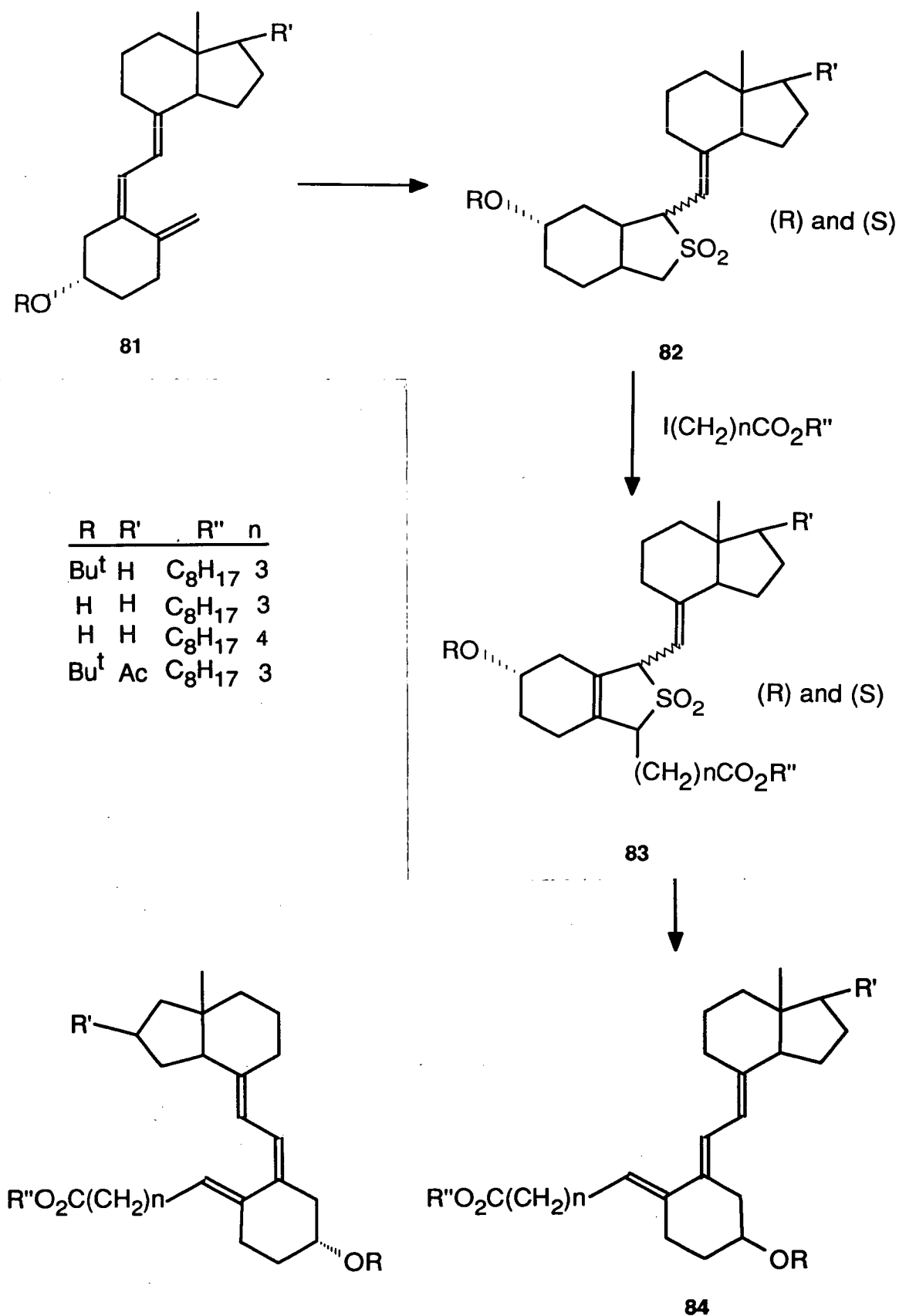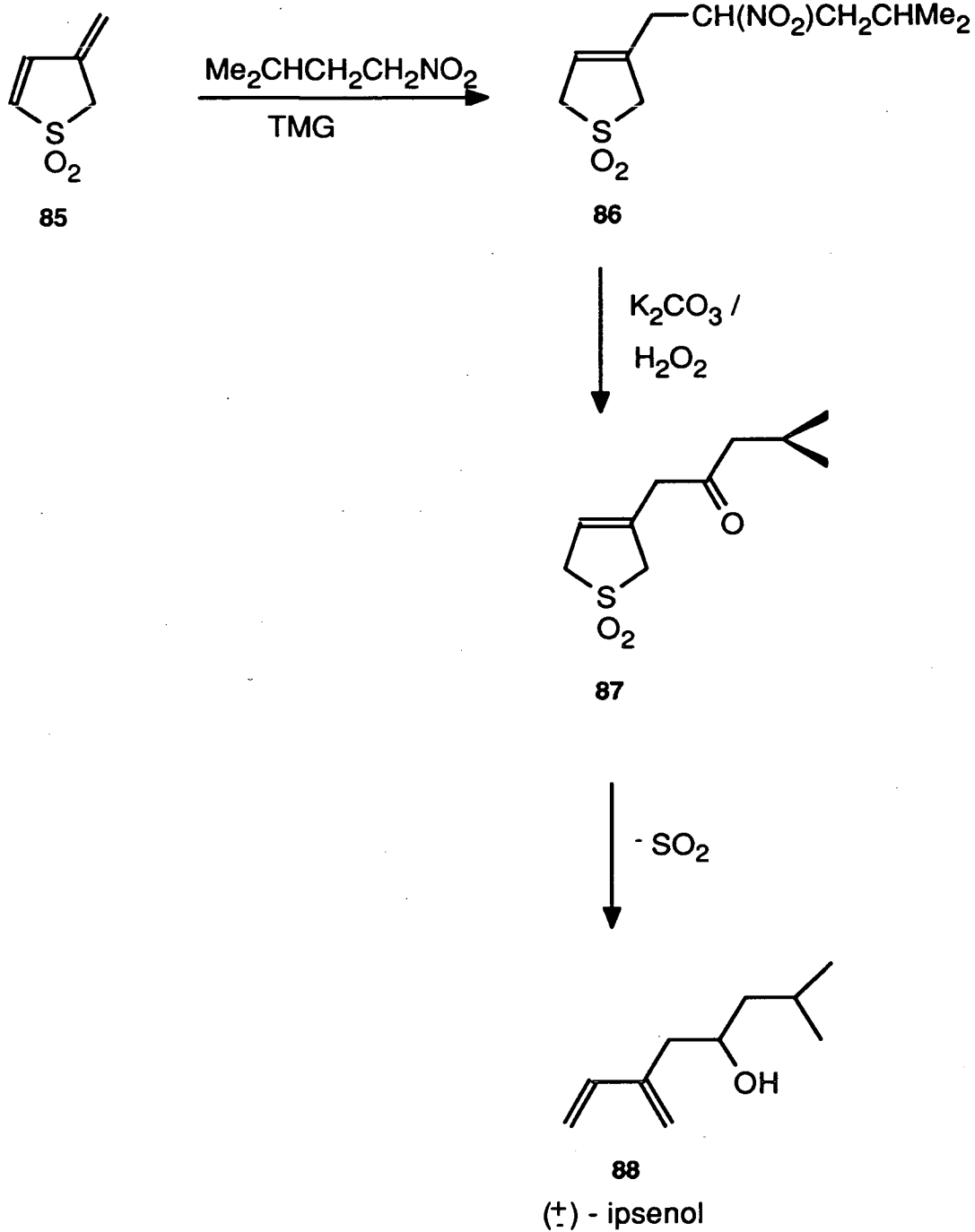

Scheme 28

Yamada *et al.*[60] utilised SO_2 extrusion to prepare (5E)- and (5Z)-vitamin D_3 19-alkanoic acids (Scheme 29). Vitamin D_3 **81**, when treated with SO_2 gave both the S and R isomers of the sulfolane adducts **82**. The epimeric mixture **82** then underwent a highly regioselective and stereospecific alkylation which resulted in two isomer products of **83**, each having *trans*-sulfolane substituents. Desulforylation of the two isomers of **83** occurred in an intrafacial manner to give **84** as the major products. This reaction anomaly was suggested to be due to the fact that the steric bulk of the sulfolane ring substituents causes extrusion to take place in a fashion contrary to the selection rules, to give the most thermodynamically favoured product **84**.

More recently Nomoto and Takayama[61] used SO_2/diene reactions to prepare (±)-ipsenol, the principal components of the aggregation pheromone of bark beetles. The reaction of the sulfone **85** with $Me_2CHCH_2CH_2NO_2$ and 1,1,3,3-tetramethylguanidine (TMG) produced the nitro compound **86**, which was converted into the carbonyl compound **87** by the reaction of hydrogen peroxide/potassium carbonate with **86**. The reduction of **87** by $NaBH_4$ in methanol, followed by SO_2 extrusion gave (±)-ipsenol **88** (Scheme 30).

| R	R'	R"	n
Bu^t	H	C$_8$H$_{17}$	3
H	H	C$_8$H$_{17}$	3
H	H	C$_8$H$_{17}$	4
Bu^t	Ac	C$_8$H$_{17}$	3

Scheme 29

Scheme 30

E.   BENZO FUSED 3-SULFOLENES

Staudinger and Pfenninger[61] observed that the triphenyl benzo sulfolene **89**, formed by base-catalysed rearrangement of tetraphenylthiirane dioxide, lost SO_2 on heating to give a mixture of two hydrocarbons. These were later identified by Backer[62] as 9,10-diphenylanthracene **90** and 9,9-diphenyl-9,10-dihydranthracene **91** formed *via* a diradical mechanism (Scheme 31).
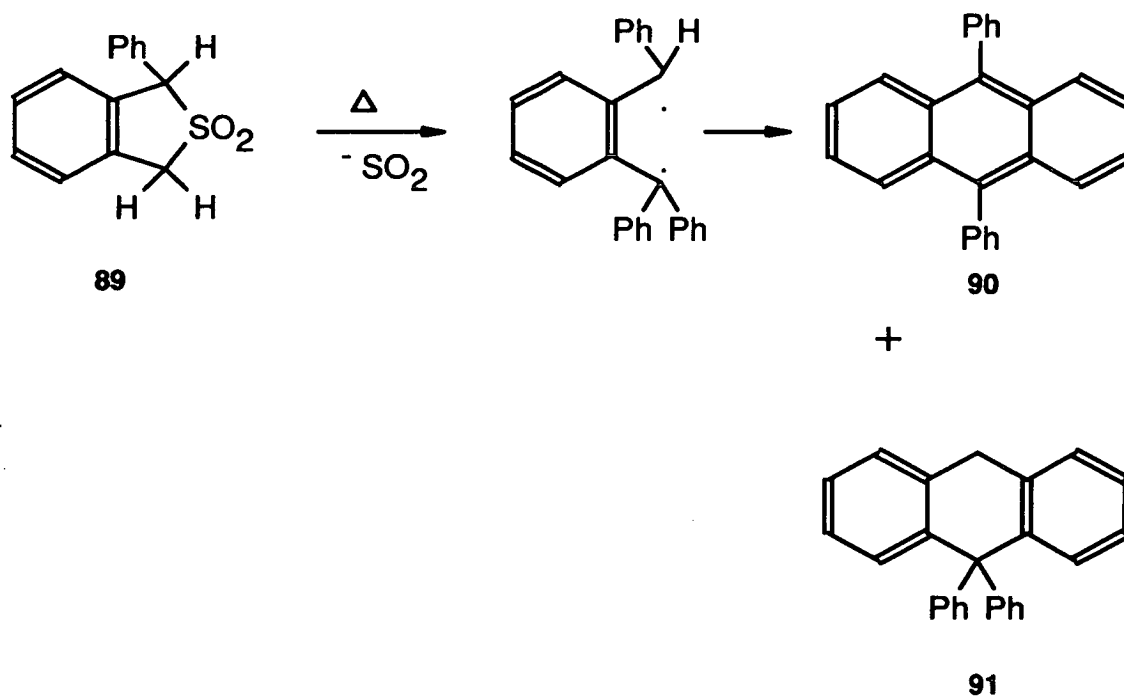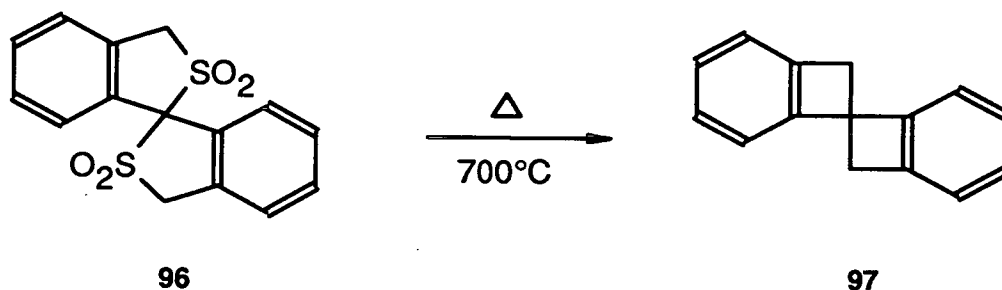

Scheme 31

The parent system 1,3-dihydrobenzo[c]thiophene dioxide **92** was first investigated by Cava and Deana[63] in 1959. The compound extruded SO_2 on heating but the products were dependent on the conditions used. Thus thermolysis of the neat sulfone at 280°C gave benzocyclobutene **93** in 13% yield together with 3% of o-xylene and 4% of dibenzocyclooctadiene **94**. Solution thermolysis in boiling diethyl phthalate, on the other hand, gave the coupling product **94** in 48% yield, while FVP at 500°C gave 60% of **93** (Scheme 32). King[64] showed that the extrusion proceeds in accordance with the Woodward-Hoffmann rules by disrotatory loss of SO_2 followed by conrotatory ring closure of the o-xylylene intermediate **95**.
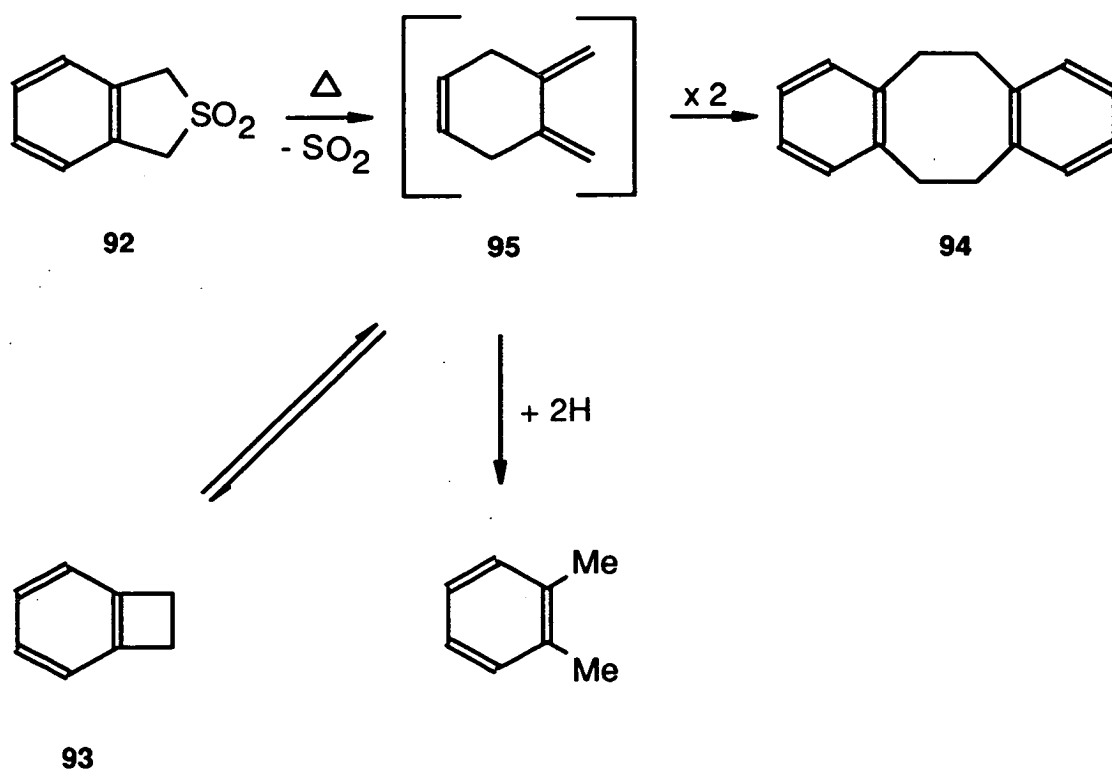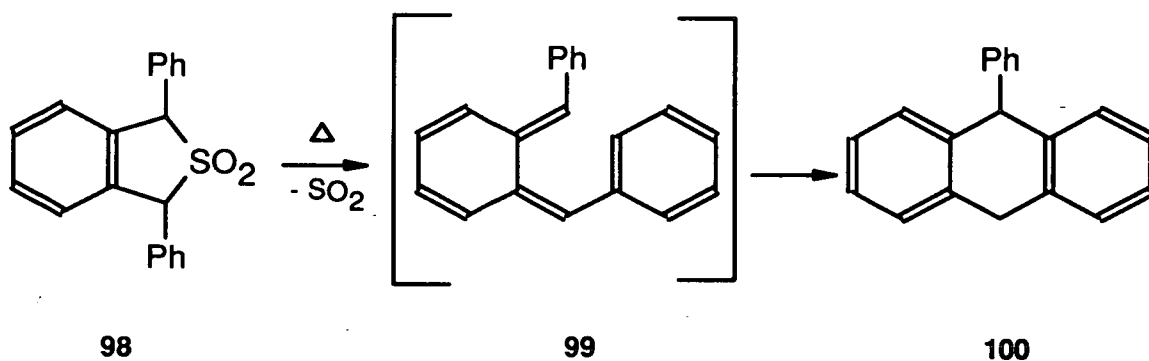

Scheme 32

The decomposition of aromatic fused sulfolenes to the corresponding cyclobutenes is quite general and this method has been used to prepare naphtho[a]cyclobutene[65], naphtho[b]cyclobutene[66], benzo[1.2:4.5]dicyclobutene[67] and benzo[1.2:3.4]dicyclobutene[68]. A particularly elegant example of this reaction is Cava's synthesis[69] of the spiro compound **97** by pyrolysis of the disulfone **96** at 700°C (Scheme 33).

96   **97**

Scheme 33

It should be noted, however, that thermolysis of benzosulfolenes does not always produce the cyclobutene. The intermediates o-quinodimethane or o-xylylene exist in equilibrium with the Diels-Alder reaction. This occurs in

the case of the diphenyl compound **98** which gave 9-phenyl-9,10-dihydroanthracene **100** *via* **99** in 94% yield[70] when thermolysed in solution at 250°C (Scheme 34).

|		
98	**99**	**100**

Scheme 34

F.   [4]DENDRALENE

The principle of extrusion of SO_2 from 3-sulfolenes to give 1,3-dienes can be extended to the synthesis of the second member of the dendralene series, namely [4]dendralene (3,4-bismethylene-1,5-hexadiene).

Work carried out by Buchan[71] at the University of Edinburgh has shown that [4]dendralene **102** can be prepared in almost quantitative yield by SO_2 extrusion from 6,7-dimethylene-3-thiabicyclo[3.2.0]heptane-3,3-dioxide **101**, a masked form of [4]dendralene **102** (Scheme 35). This pyrolytic step was achieved using FVP at 550°C. This preparative route to [4]dendralene was found to give a higher purity and product yield than previously reported preparations, which also rely on elimination and rearrangement reactions under pyrolytic conditions. None include the use of SO_2 extrusion to unmask the sulfones. The earliest example of the preparation of [4]dendralene was reported by Skattebøl and Soloman[72], who prepared **102** by thermolysis of the tetracetate **103** (Scheme 35).
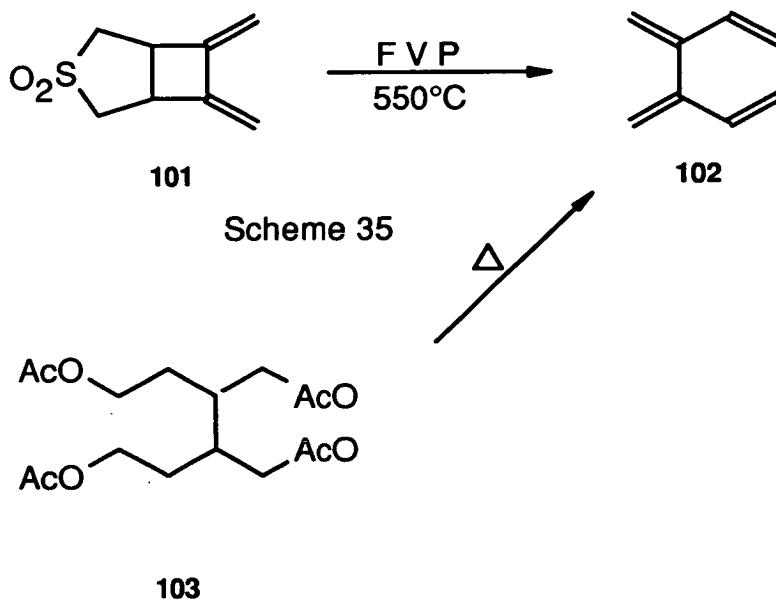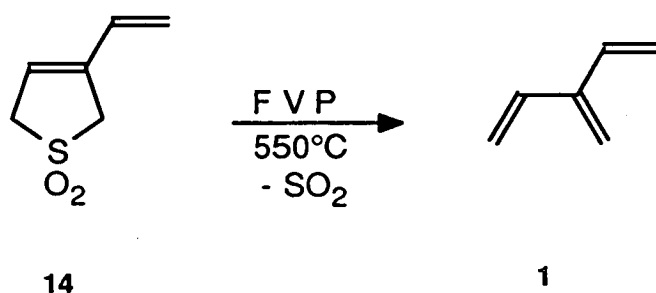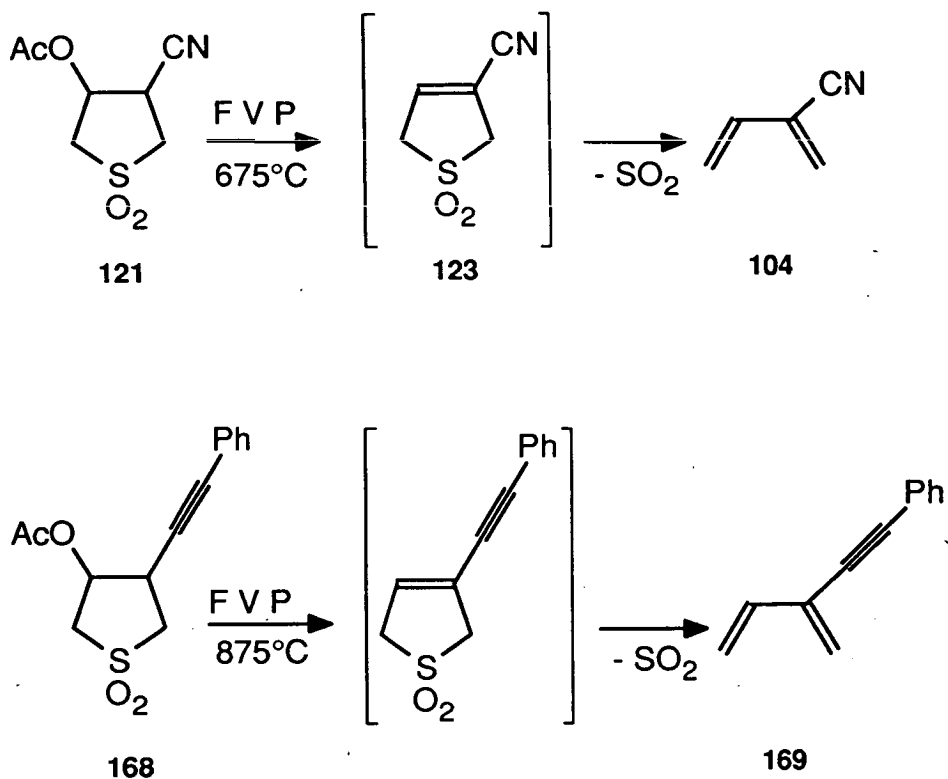

Scheme 35

Scheme 35

RESULTS AND DISCUSSION

The use of sulfolene derivatives as precursors to 2-substituted-1,3-butadienes is a subject which has been covered in Section C of the Introduction. One interesting example of their usefulness, of particular relevance to this work, is found in the simple preparation of [3]dendralene[7] **1**, which requires the thermal extrusion of SO_2 from 3-vinyl-2,5-dihydrothiophene-1,1-dioxide **14** at 550°C to give the vinyl butadiene derivative in almost quantitative yield (Scheme 36).

**14**   **1**

Scheme 36

The success of this pyrolytic step in the synthesis of [3]dendralene **1** provided the basis for new routes to 2-cyano- and 2-phenylethynyl-1,3-butadiene incorporating the chelotropic extrusion of SO_2 from the respective sulfolene derivatives **121** and **168** (Scheme 37).

Scheme 37

In order to achieve these new routes to 2-cyano- and 2-phenylethynylbutadiene, synthesis of the precursors **121** and **168** was required. This was achieved starting from the readily available 2,5-dihydrothiophene-1,1-dioxide (butadiene sulfone) and using the Schemes detailed in Sections A and F.

Additionally the novel preparations of [3]dendralene and 2-ethynyl-1,3-butadiene were performed incorporating the chelotropic extrusion of ethene from the respective cyclohexene derivatives **148** and **163** (Scheme 38).

148 $\xrightarrow[-C_2H_4]{FVP}$ **1**

163 $\xrightarrow[-C_2H_4]{FVP}$ **149**
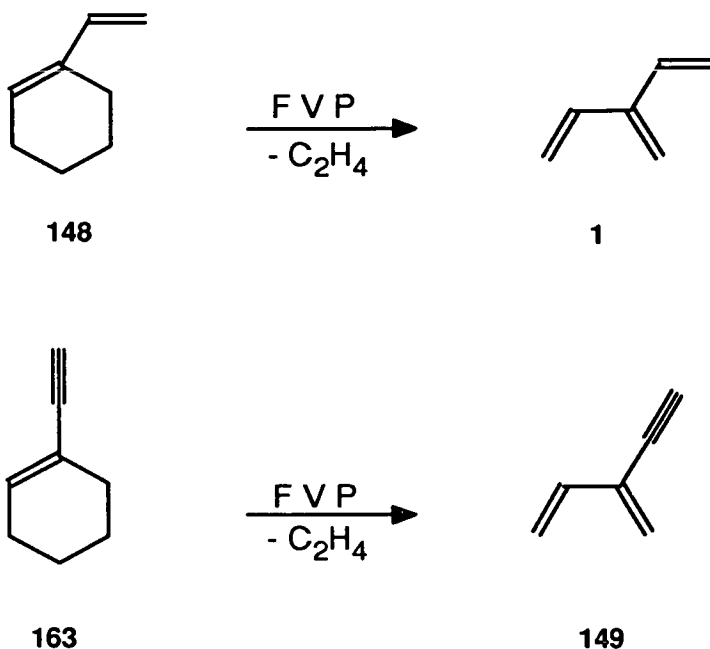
Scheme 38

In order to achieve these new routes to [3]dendralene and 2-ethynyl-1,3-butadiene, the synthesis of their precursors was required. This was accomplished starting from the readily available cyclohexanone and using the Schemes detailed in Sections C and E.

Extending this procedure of chelotropic extrusion of ethene from cyclohexene derivatives, 2-cyano- and 2-phenylethynyl-1,3-butadiene were prepared from their precursors **109** and **172** (Scheme 39).
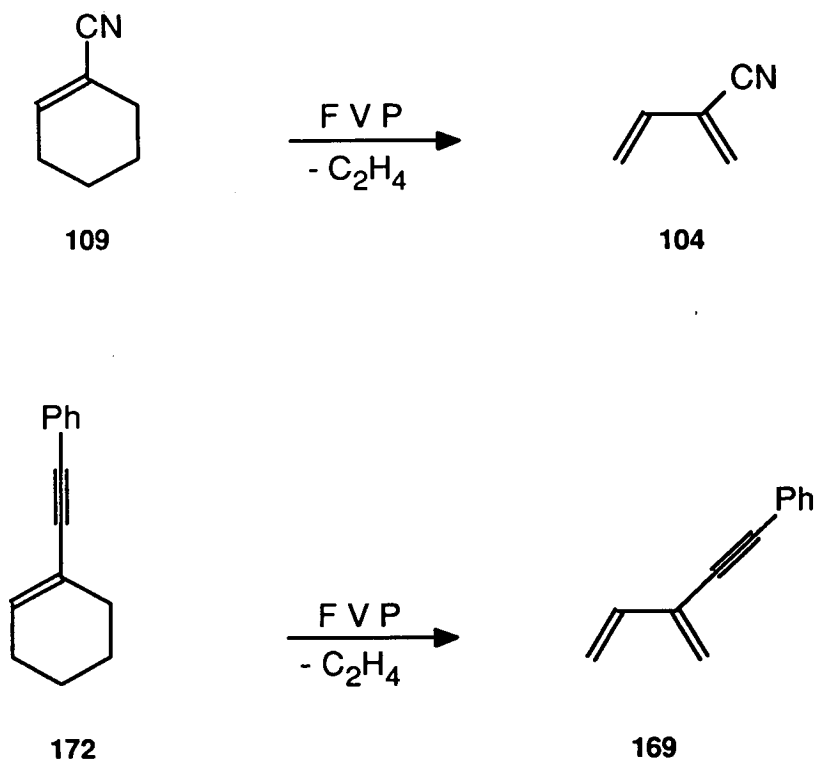
Scheme 39

The preparation of the precursors **109** and **172** of 2-cyano- and 2-phenylethynyl-1,3-butadiene starting from cyclohexanone is detailed in Sections A and G.

Once new routes to 2-cyanobutadiene had been developed, an attempt was made to try to demonstrate the cross-conjugation abilities of the diene in Diels-Alder reactions. A general study of the reactivity of 2-cyanobutadiene with two dienophiles is discussed in Section B.
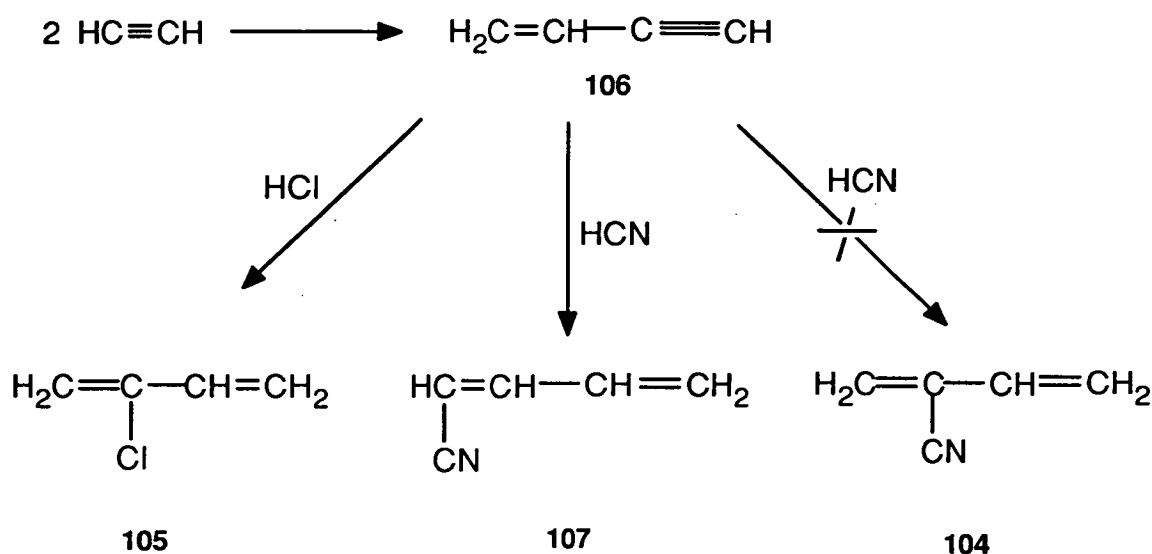
Finally preparation of 2-ethynylbutadiene using chelotropic SO_2 extrusion chemistry was attempted and is detailed in Section D.
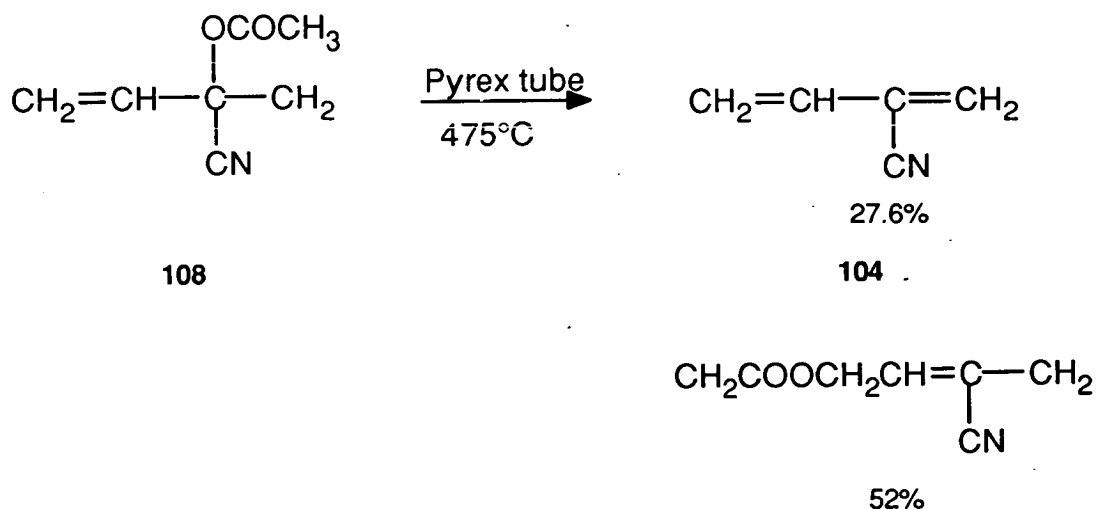
RESULTS AND DISCUSSION

CONTENTS

A. PREPARATION OF 2-CYANO-1,3-BUTADIENE

(i) From Butadiene Sulfone

2-Cyano-1,3-butadiene may be considered to belong to a group of analogous derivatives of the dendralene class of cross-conjugated molecules, as it possesses the ability to undergo diene-transmissive cycloaddition reactions in an analogous fashion to the previously detailed [3]dendralene **1**. 2-Cyanobutadiene **104** (also known as cyanoprene) is not accessible along the lines of chloroprene (2-chlorobutadiene) **105** synthesis by adding hydrocyanic acid (HCN) to vinyl acetylene **106**. Instead HCN addition results in 1-cyano-1,3-butadiene production **107** (Scheme 40).

$$2\ HC\equiv CH \longrightarrow H_2C=CH-C\equiv CH$$

106

HCl

HCN

HCN

$$H_2C=\underset{\underset{\textstyle Cl}{|}}{C}-CH=CH_2$$

105

$$HC=\underset{\underset{\textstyle CN}{|}}{CH}-CH=CH_2$$

107

$$H_2C=\underset{\underset{\textstyle CN}{|}}{C}-CH=CH_2$$

104

Scheme 40

However, in excess of ten references using various conditions exist for the successful preparation of 2-cyanobutadiene. As early as 1935, 2-cyanobutadiene appears in a German Patent[73]. One of earliest cited preparations was performed by Marvel and Brace[74], who synthesised 2-

cyanobutadiene **104** from 3-acetoxy-3-cyano-1-butene **108** in low yield (Scheme 41).

$$CH_2{=}CH{-}\underset{\underset{CN}{|}}{\overset{\overset{OCOCH_3}{|}}{C}}{-}CH_2 \xrightarrow[475°C]{Pyrex\ tube} CH_2{=}CH{-}\underset{\underset{CN}{|}}{C}{=}CH_2$$

108

27.6%

104

$$CH_2COOCH_2CH{=}\underset{\underset{CN}{|}}{C}{-}CH_2$$

52%

Scheme 41

Müller et al.[75] also synthesised 2-cyanobutadiene **104** in good yields by the pyrolysis of 1-cyano-1-cyclohexene **109**. Müller's synthesis is based on the general route for the preparation of 1,3-dienes by retro-diene splitting of cyclohexene derivatives. Thus, starting from cyclohexanone **110**, treatment with HCN yielded the cyanohydrin **111**, which was converted into the 1-cyano-1-cyclohexene **109**. Subsequent pyrolysis yielded 2-cyanobutadiene **104** (Scheme 42) in moderate yield.

110   **111**   **109**   **104**
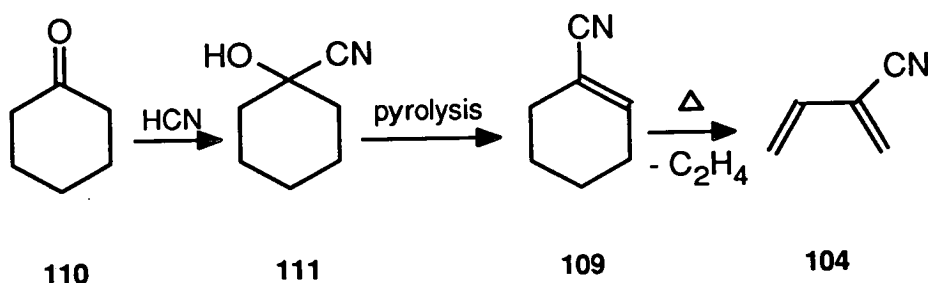
Scheme 42

Prior to Müller's work, three other processes had been described in literature for the preparation of 2-cyanobutadiene. The first process[76] involves the reaction of vinyl methyl ketone **112**, with HCN to form the cyanohydrin **113**, which is acetylated with acetic anhydride to form the acetate **114** and then pyrolysed at 400-500°C to produce 2-cyanobutadiene **104** in 74% yield (Scheme 43).

112   **113**   **114**   **104**
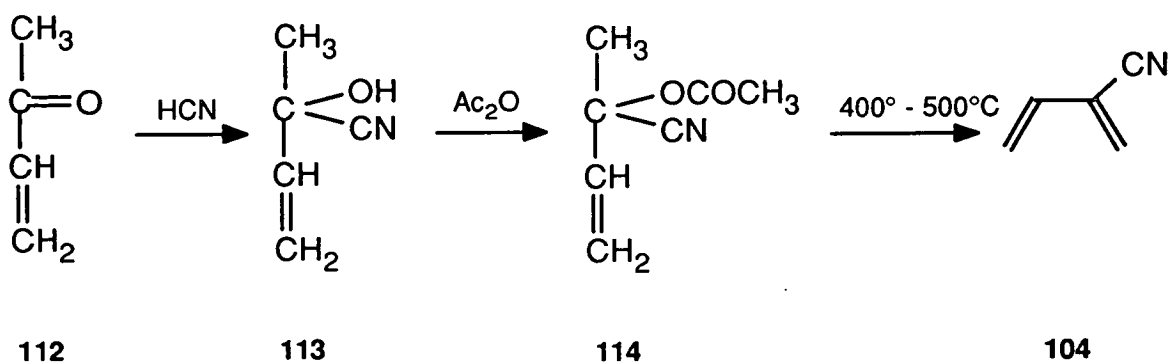
Scheme 43

In the second process[77], ultraviolet irradiation of acrylonitrile **115** was used to form 1,2-dicyanocyclobutane **116**, followed by catalytic splitting at 455°C to give 2-cyanobutadiene **104** in an overall yield of 20% (Scheme 44).

115   **116**   **104**
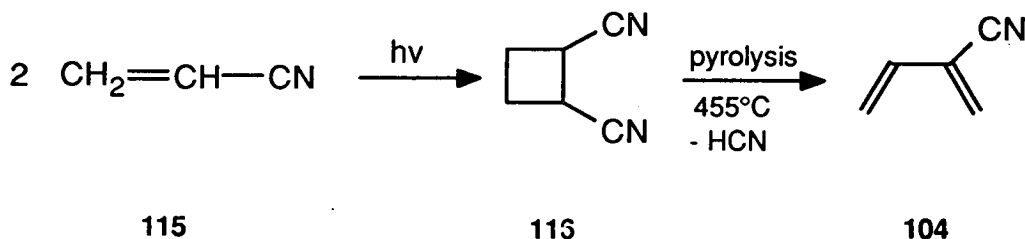
Scheme 44

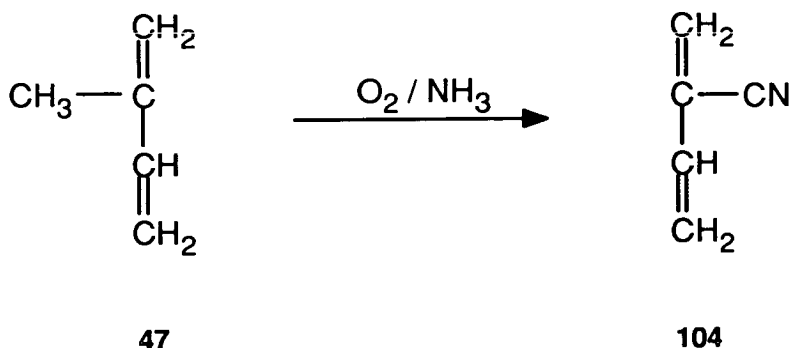Process 3[75] involves ammonoxidation of isoprene **47**, whereby 2-cyanobutadiene **104** is formed by the reduction of ammonia, steam and air at 425°C over a zeolite catalyst containing copper (Scheme 45).

47   104

Scheme 45

Following Müller's work Segawa *et al.*[78] prepared 2-cyanobutadiene **104** by a Diels-Alder reaction between 1,3-butadiene **117** and acrylonitrile **115** to form firstly 4-cyanocyclohexene **118**, which was isomerised by base treatment and then heated in steam and nitrogen to form 2-cyanobutadiene **104** by extrusion of ethene (Scheme 46).

117   115   118
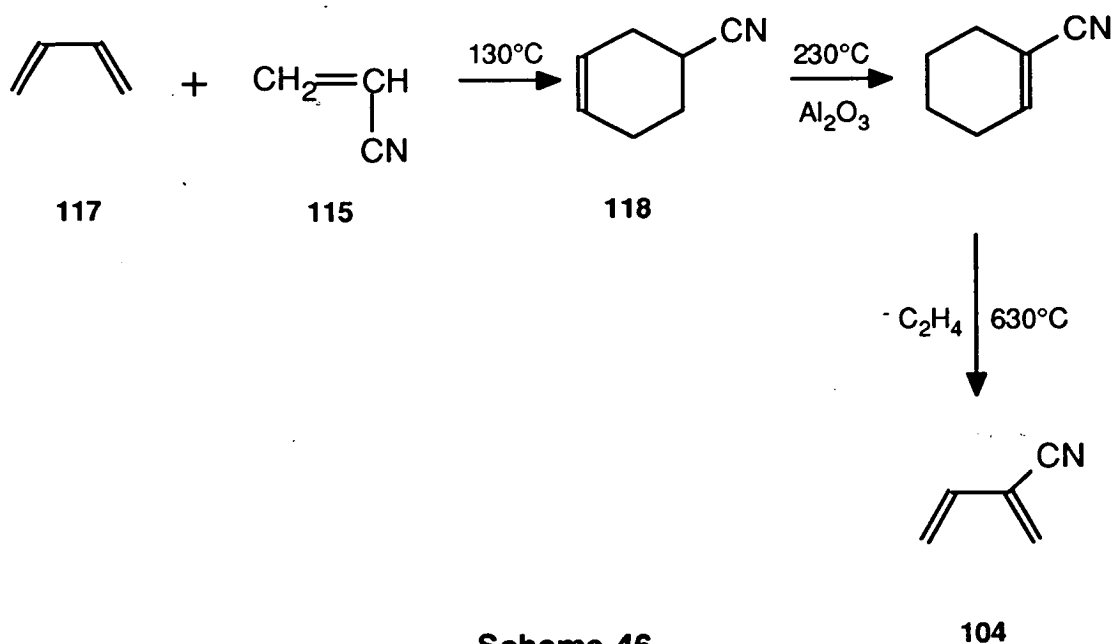
Scheme 46   **104**

In a different approach Nakajima *et al.*[79] produced 2-cyanobutadiene **104** (albeit in low yield) by heating butadiene **117** and hydrocyanic acid together in the presence of oxygen at 100-600°C over a palladium catalyst (Scheme 47).
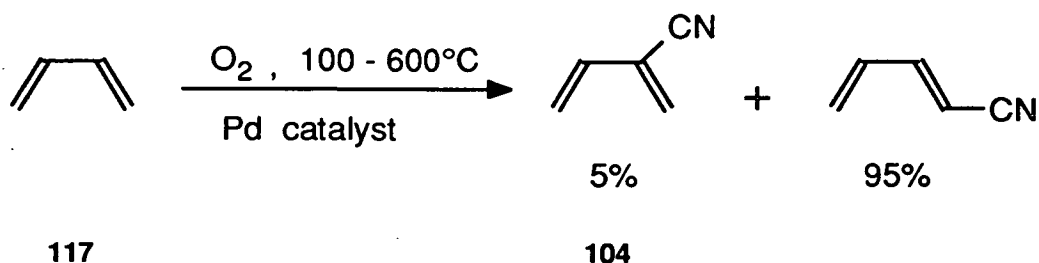
Scheme 47

Finally Nonaka *et al.*[80] prepared 2-cyanobutadiene **104** by dehydration of 2-cyano-3-hydroxy-but-1-ene **119** using three dehydrating reagents (Scheme 48).
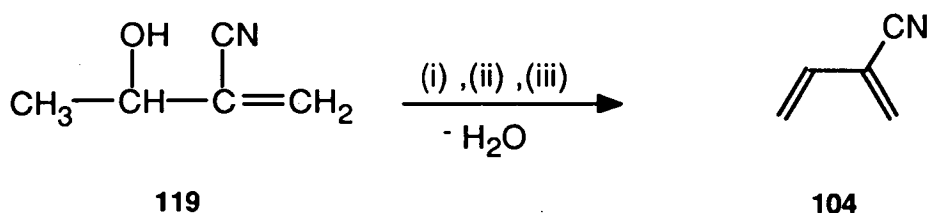
Reagent (i) aqNaOH, KOH or Ba(OH)$_2$ at 80°C

  (ii) K$_2$CO$_3$ on α-alumina at 80-120°C

  (iii) aqK$_2$CO$_3$ at 105°C

Scheme 48

The first of our novel syntheses of 2-cyanobutadiene utilised the formation of the butadiene sulfone epoxide, followed by nucleophilic ring opening, acetylation and finally pyrolysis using FVP. The initial step involves the reaction of the readily available butadiene sulfone (3-sulfolene) **14**, with hydrogen peroxide and formic acid. The epoxide yielding reaction occurs in 60% yield, an improvement on the yield achieved by Gillam[7,8]. This preparation of the epoxide is based on Sorenson's[81] preparation which occurs in 30% yield. Gillam[7,8] believed that a more efficient preparation of the epoxide was required, but all attempted syntheses of the epoxide with *m*-CPBA or peracetic acid failed and the reverse of what might be expected occurred, i.e. performic acid was successfully used to prepare the epoxide from butadiene sulfone. This finding is unexpected because formic acid is considered to be much more destructive of the epoxide ring system, to form α-glycol derivatives, than acetic acid. Therefore the preferred reagents of hydrogen peroxide and formic acid were continued to be used for the preparation of butadiene sulfone epoxide (3,4-epoxytetrahydrothiophene-1,1-dioxide) **16**.

The next stage of the synthesis requires the opening of the epoxide ring of the sulfone and the subsequent incorporation of the cyanide group. The nucleophilic ring opening of the epoxide **16** and the incorporation of the cyano group was achieved in 60% yield by the addition of potassium cyanide in dichloromethane. The additional need for a phase-transfer catalyst was necessary due to the failure to ring-open the epoxide when potassium cyanide in dimethyl sulfoxide (DMSO) was reacted with the epoxide. The phase-transfer catalyst, *t*-butylammonium bromide, was used for this reaction, to produce the β-hydroxynitrile (3-cyano-4-hydroxytetrahydrothiophene-1,1-dioxide) **120** in 60% yield. The catalyst is used to carry the nucleophilic cyanide group from the aqueous into the organic (dichloromethane) phase.

The catalyst, *t*-butylammonium bromide was used because it was known that successful addition of potassium cyanide to 1-chlorooctane to give 1-cyanooctane[82] occurs when a small amount of an appropriate quaternary ammonium salt is added, but fails to proceed if no catalyst is added even upon heating and stirring for several days. This reaction occurs in the above manner because the phase-transfer catalyst enables the anion to pass into the organic phase and allows it to be relatively free to react with the substrate (in this novel synthesis, the butadiene sulfone epoxide).

The cyanohydrin **120** formed, is then acetylated, to convert the hydroxyl functionality into the acetate moiety. This was performed using acetyl chloride in pyridine to produce the acetate compound **121** in approximately 80% yield. A second reagent system was also used for this acetylation. This involved the addition of acetic anhydride and a small amount of a catalyst, 4-dimethylaminopyridine (DMAP), to the cyanohydrin **120** to produce **121** (Scheme 49). This catalyst is known to act very efficiently in acyl-transfer reactions, and is superior to pyridine and other tertiary amines and is particularly useful for the acylation of sterically hindered alcohols[83]. It is believed that DMAP combines with the acid anhydride to form a complex, which takes the acetate functionality to the alcohol site and catalyses the subsequent addition, thereby accelerating the rate of reaction more than pyridine.

On examination of the synthesis of [3]dendralene by Gillam[7,8] it was shown that the analogous acetate underwent elimination of the acetic acid under FVP conditions at 650°C to produce 3-vinyl-2,3-dihydrothiophene-1,1-dioxide **19** (Scheme 5). Therefore it was assumed that the corresponding acetate of the cyano-sulfolene would eliminate acetic acid to produce 3-cyano-2,3-dihydrothiophene-1,1-dioxide **122** under FVP conditions. However when compound **121** was subjected to FVP at 675°C 2-cyano-1,3-butadiene

**104** was formed directly. This dual elimination of both acetic acid and sulfur dioxide from 3-cyano-4-acetoxytetrahydrothiophene-1,1-dioxide **121** to form 2-cyanobutadiene **104**, alleviates the need to firstly, remove acetic acid, isomerise the subsequent compound **122**, and finally pyrolyse the sulfone **123** to remove SO_2 and produce 2-cyanobutadiene **104** (Scheme 49).
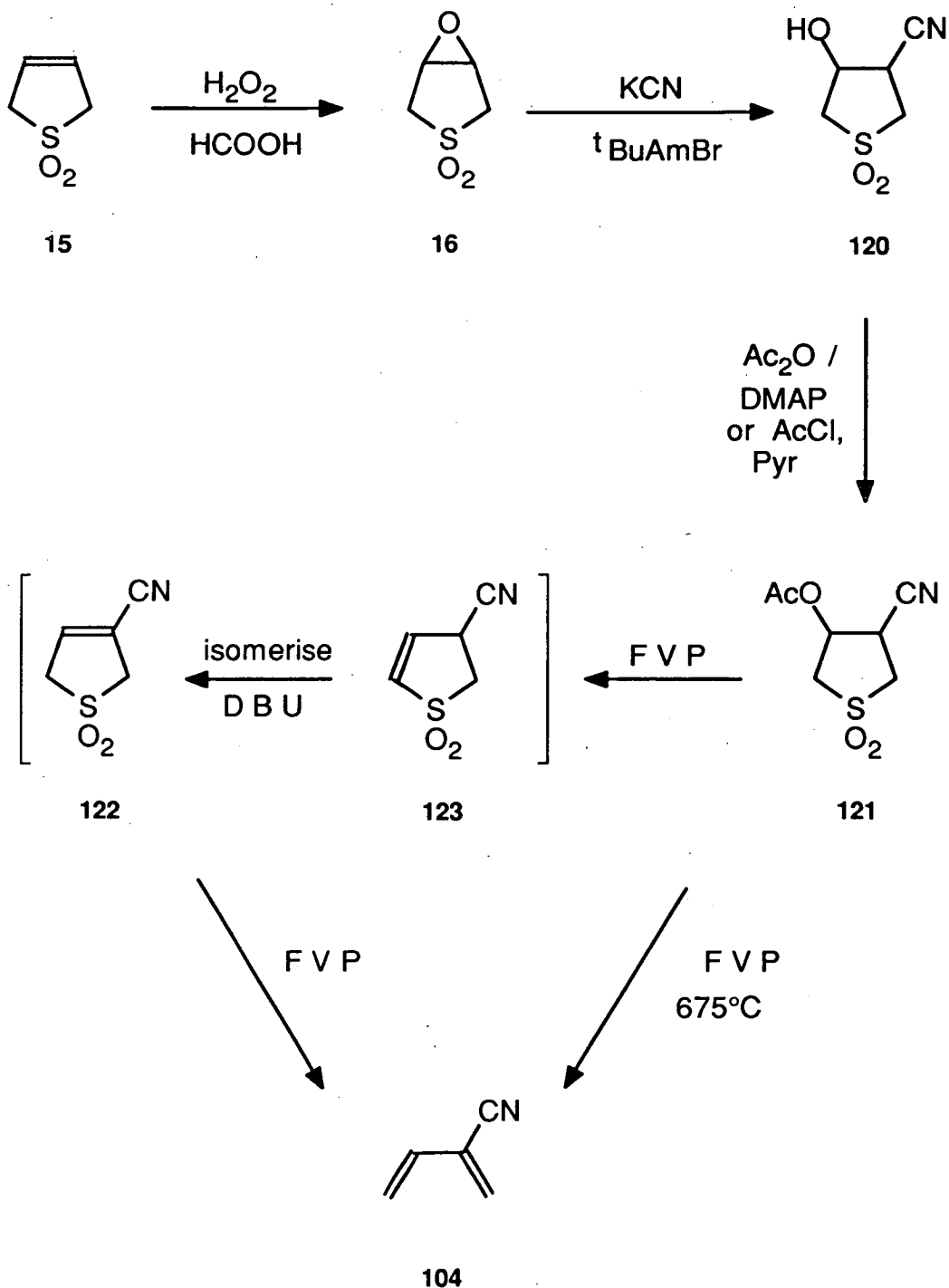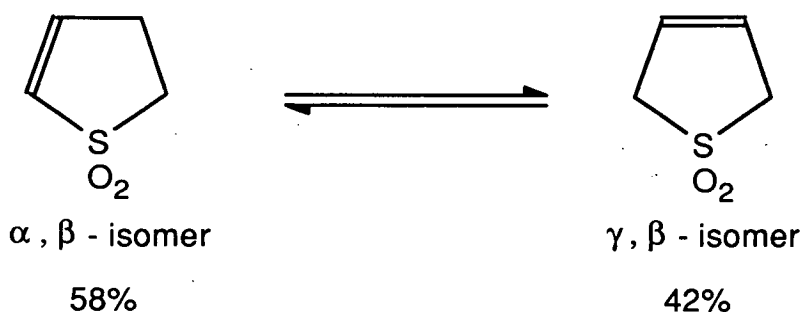

Scheme 49

The present synthesis for 2-cyanobutadiene is in sharp contrast to Gillam's findings for the preparation of [3]dendralene in that elimination of HOAc and SO_2 occurs in a single step. It is not fully understood why direct elimination of acetic acid and SO_2 should occur simultaneously but it must be assumed that the 3-cyano-2,3-dihydrothiophene-1,1-dioxide if formed is not kinetically favoured to the 2,5-dihydro analogue.

The 2,5-dihydro analogue would appear to be unstable at 675°C under FVP conditions and therefore readily undergoes elimination of SO_2 to form 2-cyanobutadiene. This leads to the theory that the conversion of the acetate **121** to 2-cyanobutadiene **104** has proceeded via the β,γ-unsaturated isomer **123** directly, rather than via the α,β-isomer **122**. The elimination of acetic acid from the β,γ-positions presumably enables the nitrite group and the double bond to conjugate with each other. The large electron-withdrawing effect of the nitrile group must favour the formation of the β,γ-isomer, the thermodynamically most stable isomer. Loss of acetic acid and formation of **123** then facilitates the chelotropic extrusion of SO_2, which would normally occur at lower temperatures (Scheme 50).
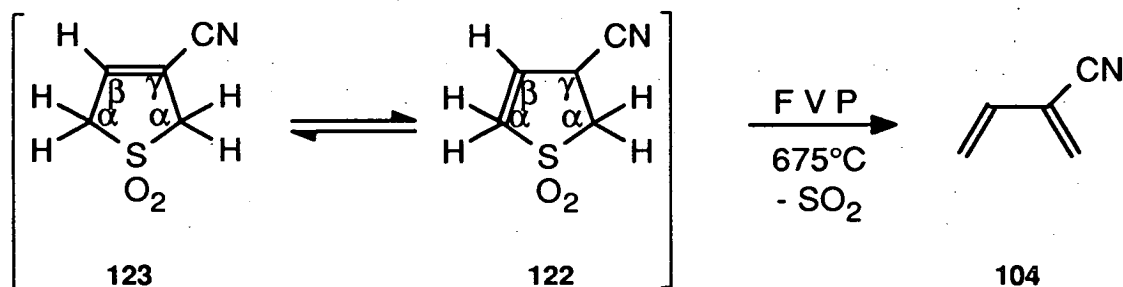
Scheme 50

The predominant formation of α,β-unsaturated sulfolenes is not uncommon. The general preference for α,β-elimination in acyclic derivatives is caused by the enhanced acidity of the α-hydrogens on the carbons adjacent to the SO_2 functional group. This enhanced acidity of the α-hydrogens is believed to arise from a kinetic rather than a thermodynamic influence. This theory is exemplified by base-catalysed isomerisation which proceeds readily to give the thermodynamically favoured β,γ-product when the α,β-product is subjected to the isomerising agent 1,8-diazabicyclo[5.4.0]undecene-7 (DBU). Butadiene sulfone itself exists in an equilibrium of 58% α,β-isomer to 42% β,γ-isomer (Scheme 51).

α , β - isomer   γ , β - isomer

58%   42%

15

Scheme 51

Such 5-membered ring sulfolenes do however exhibit marked substituent effects. For example the presence of a methyl group (weakly electron-donating) favours the α,β-sulfolene over the β,γ-isomer. However with a hydroxyl group (which is strongly electron-donating in the form O⁻) attached to the sulfolene, the β,γ-isomer is virtually absent. Since the nitrile group is relatively strongly electron-withdrawing this may help explain the

favoured, single pyrolysis-step synthesis of 2-cyanobutadiene, presumably through the formation of the thermodynamically favoured β,γ-isomer **123**.

Another point to be studied is π-electron delocalisation and whether the sulfone exhibits a greater stabilising effect (since it is available for π-electron delocalisation), or whether the acidity of the α-hydrogen promoted the elimination *via* the β,γ-unsaturated isomer. Literature[84,85] reports although sparse show isomeric distribution to be favoured by the products thermodynamic stability and this is exhibited through conjugation with the activating group. These findings support the predominant formation of the α,β-sulfolene as being the kinetically-controlled isomer when the following properties of FVP are taken into account.

Flash vacuum pyrolysis (FVP) promotes unimolecular reactions which occur in very short contact times in the furnace, thereby virtually eliminating the possibility of bimolecular reactions and surface catalysis. In the preparation of [3]dendralene the α,β-isomer is completely converted (100% conversion) into the β,γ-sulfolene in the presence of DBU. This implies that α,β-isomer conversion into β,γ-isomer produces the most thermodynamically stable isomer. However, as outlined above for the nitrile analogue, the pyrolysis must proceed *via* the β,γ-isomer, which suggests that the α,β-isomer is the thermodynamically most stable isomer. Additionally Gillam[8] found that if the elimination of the functional group in the 4-position was undertaken, with a tosyl group rather than an acetate group attached to the vinyl sulfolene (formed by the reaction of 3-vinyl-4-hydroxytetrahydrothiophene-1-1-dioxide **14** with p-toluenesulfonyl chloride) the β,γ-isomer was formed in the absence of the α,β-unsaturated sulfolene. In this connection it was not clearly understood whether elimination had taken place to give the α,β-isomer which then underwent isomerisation to the β,γ-isomer, or if the β,γ-product was formed directly.

However, with the cyano analogue, it seems unlikely that under the pyrolytic conditions of FVP, with its unimolecular reactions and short contact times, that the α,β-isomer is isomerised to the β,γ-isomer during thermal elimination. Consequently it can be argued that the reaction proceeds *via* the initial formation of the β,γ-isomer followed by SO_2 extrusion.

It has previously been assumed[8] that the *trans*-antiperiplanar conformation is formed for these sulfolene derivatives. With a *trans*-conformer, eliminations would signify a *cis-syn* conformation elimination, which is the kinetically least favoured conformer.
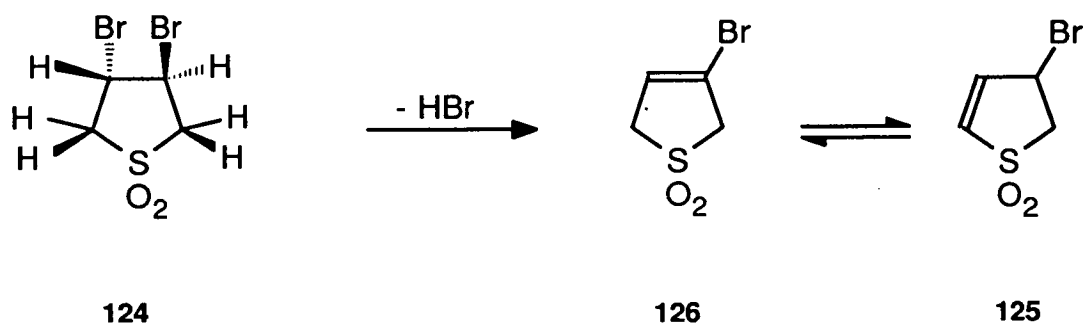

Scheme 52

Indeed, 3,4-dibromotetrahydrothiophene-1,1-dioxide **124** was assumed to attain a *trans*-isomer configuration **125**, since electrophilic addition of bromine to alkenes generally proceeds through a bromonium ion intermediate, therefore nucleophilic addition reactions must favour β,γ- or α,β-conformers (Scheme 52). X-ray crystallographic and electron diffraction data of **124** show that the C2, C5 and bromine atoms occupy the same plane and therefore supports the expected *trans* structure of **124** (see Appendix 1).

Returning to the novel synthesis of 2-cyanobutadiene, it was found that the brown oily product resulting from FVP (675°C) of 3-cyano-4-

acetoxytetrahydrothiophene-1,1-dioxide **121** could be subjected to flash distillation to remove polymeric material that was contaminating the required product 2-cyano-1,3-butadiene **104**. [1]H n.m.r. analysis of the distilled product showed the characteristic 1,3-butadiene peaks (5.4-6.4 ppm). More specifically peaks at 5.45 ppm (d, Hb), 5.71(d, Ha), 5.88(d, He), 5.89(d, Hd) and 6.37(dd, Hc) ppm and a peak at 2.1(s, CH_3) signified the formation of a 1,3-butadiene. The presence of a cyanide peak 115.77 ppm ([13]C n.m.r.) together with mass spectroscopic data (molecular ion M[•+] at 79) show that cyanobutadiene was formed (Figure 9).

Gillam[8] had found that [3]dendralene was far more stable than the literature had previously indicated[14], to the extent that it could be stored at -30°C for several months provided it was admitted with a free-radical inhibitor such as galvinoxyl, even so at room temperature the diene gradually homo-polymerised. This was also found to be the case for 2-cyanobutadiene, in that polymerisation seemed to occur at room temperature (a thick insoluble material resulted) as verified by the lack of characteristic [1]H n.m.r. peaks of the butadiene moiety at 5.4-6.4 ppm. The 2-cyanobutadiene so formed was stored for long periods with the free-radical inhibitor galvinoxyl at -25° to -30°C, although it was found that 2-cyanobutadiene was stable for several weeks when left in deuterated chloroform at room temperature, as determined by repeated [1]H n.m.r. analysis over a set period of time.
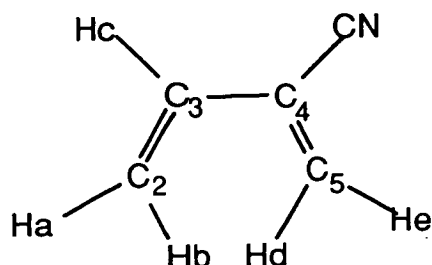

**Figure 9**

(ii)   From Methyl Thioglycolate

The second approach to the preparation of 2-cyano-1,3-butadiene involved the use of the same key intermediate, but started by the initial synthesis of **131** followed by oxidation of the sulfur atom to form 3-cyano-4-acetoxytetrahydrothiophene-1,1-dioxide **121** (see Scheme 56).

The synthesis began by a Dieckmann cyclisation of the Michael adduct between methyl thioglycolate **127** and acrylonitrile **115** in the presence of sodium methoxide in boiling toluene (or methanol). This preparation is based on the synthesis performed by Baraldi et al.[87], whose work on α-substituted acrylonitriles (which are important intermediates in synthetic organic chemistry, including Michael and Diels-Alder reactions) is based on work previously described in a Dutch Patent[88]. These compounds are not directly accessible by reaction of the anion ($H_2C=\bar{C}-C\equiv N$) with electrophiles; in consequence several roundabout routes have been proposed for their preparation, including dehydration of cyanohydrins of methyl ketones, being one example. Baraldi used the heterocyclic anion **128** as a new synthetic equivalent of the $H_2C=\bar{C}-C\equiv N$ anion (Scheme 53).
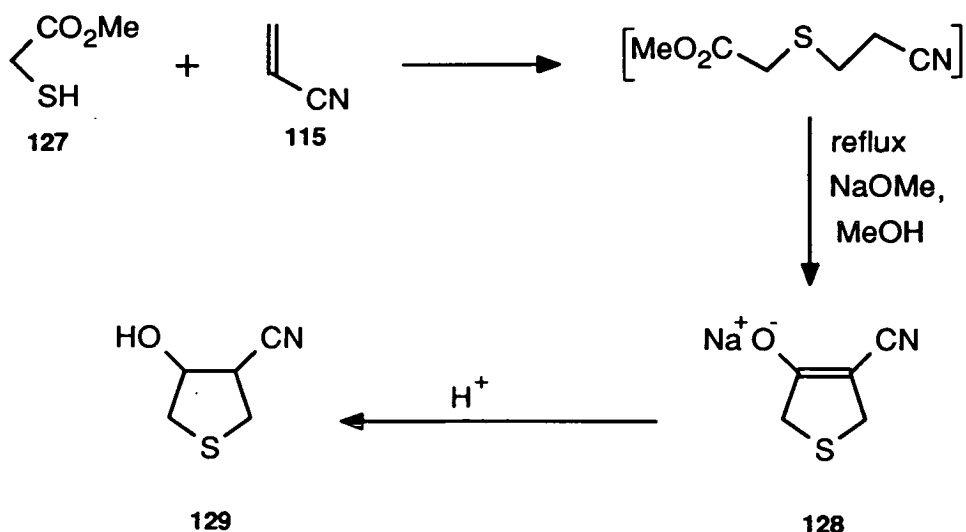
Scheme 53

Sodium borohydride reduction of this Michael adduct **129** produced **130** as an orange oil followed by treatment of the crude reaction mixture with methanesulfonyl chloride to yield 3-cyano-2,5-dihydrothiophene **131** in 72% overall yield. This was then oxidised to a crystalline sulfone **132** using *meta*-chloroperoxybenzoic acid[89] (*m*-CPBA) (Scheme 54).
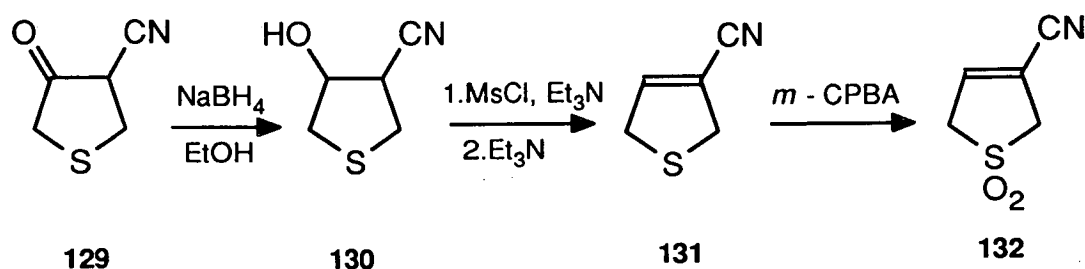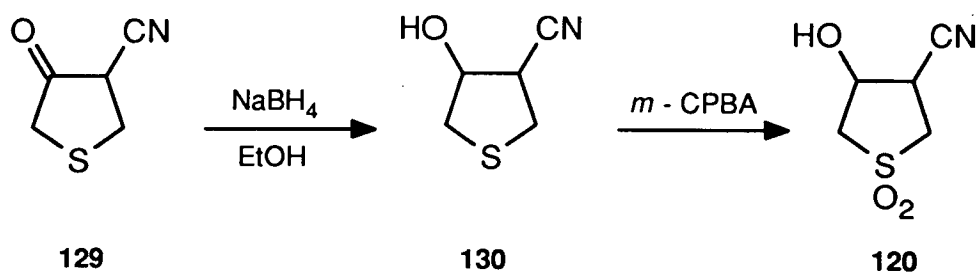

Scheme 54

The mild conditions involved and good overall yields make this sequence of Baraldi's, a novel and convenient route to α-substituted acrylonitrites.

In the second novel route for the preparation of 2-cyanobutadiene, 3-cyano-4-oxotetrahydrothiophene **129**, (*vide supra*) was reduced with sodium borohydride. This involved cooling **129** in ethanol and then adding sodium borohydride in ethanol in equimolar quantities. The resulting suspension was stirred and glacial acetic acid added until effervescence ceased. The crude reaction product was distilled *in vacuo* to produce a clear orange oil of 3-cyano-4-hydroxytetrahydrothiophene **130**. The next step was the oxidation of the sulfur component of this thiophene. The oxidising agent *m*-CPBA which is supplied by Aldrich as a colourless crystalline solid of 80-85% purity (15-20% is *m*-chloroperbenzoic acid), comes in hydrated form, and must be dehydrated by washing with phosphate buffer pH 7.5 solution, filtered and

then dried on a sintered funnel. In excess of two equivalents of *m*-CPBA were required to achieve acceptable conversion of **130** into its dioxide **120**. Two products were formed at the end of the reaction, after removal of solvent, a pale yellow liquid containing some polymeric material. The mixture was filtered under vacuum and the coloured solution concentrated and then purified by consecutive flash- and column-chromatography, using silica gel 60 and solvents, hexane and ethyl acetate to elute the product, a colourless crystalline solid produced in 53% yield. Infrared spectroscopy of the product showed the characteristic peaks for the SO_2 grouping at 1300 and 1150 cm^{-1}, together with absorptions due to hydroxyl group (3600 cm^{-1}) and the nitrile functionality (2200 cm^{-1}). Another distinguishing feature which belies the fact that the sulfur component of **130** is oxidised to the sulfur dioxide is the lack of the pungent sulfur aroma of the thiophene (Scheme 55).

Scheme 55

The acetylation of **130** was performed as in the earlier preparation of 2-cyanobutadiene (Scheme 49) by using acetyl chloride in pyridine or acetic anhydride and DMAP. A variation on this preparation of **121** involved

acetylation of the thiophene **130** with acetic anhydride/DMAP to produce 3-cyano-4-acetoxytetrahydrothiophene **131** in 97% yield, followed by oxidation of sulfur using *m*-CPBA to produce a pale yellow odour-free solid **121** (Scheme 56) in 70% yield.
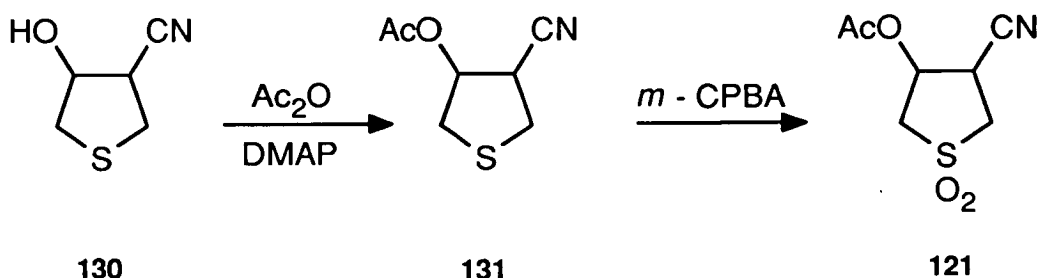
Scheme 56

The former synthetic route for the preparation of **121** *via* oxidation, then acetylation was favoured to the latter route principally because it converts the thiophene into the corresponding thiophene-1,1-dioxide, and subsequently to a solid, at any earlier stage in the synthesis, thereby shortening the time spent manipulating a noxious smelling liquid.

To complete the synthesis, compound **121** was then pyrolysed as detailed in the previous preparation of 2-cyanobutadiene. The preparation of 2-cyanobutadiene from methyl thioglycolate occurs in overall 22-25% yield, which is approximately the same yield as the method starting from butadiene sulfone, although the former route uses a greater number of synthetic steps.

**(iii)   From Cyclohexanone**

The third novel preparation of 2-cyanobutadiene utilises the ability of cyclohexenes to undergo retro-Diels-Alder type reactions to form 1,3-dienes.

The retro-Diels-Alder reaction is a $_\pi 2s$ + $_\sigma 2s$ + $_\sigma 2s$ electrocyclic process that as the name implies is a reverse of the extremely familiar Diels-Alder cycloaddition reaction. The most common of these diene forming reactions is the conversion of cyclohexene into 1,3-butadiene and ethene which has been studied[90] over the temperature range 540-629°C. Some early observations of retro-Diels-Alder reactions were made by Kloetzel[91] who reported that the Diels-Alder adduct of cyclopentadiene with benzoquinone dissociates at its melting point. Diels and Alder themselves reported on the dissociation of a furan-maleic anhydride adduct at its melting point[92]. These phenomena were used to differentiate between the ester adducts of cyclopentadiene and cyclohexadiene.

It has been shown that both diene and dienophile substituents may affect the rate of the retro-Diels-Alder reaction. If both cycloaddition and cycloreversion processes are fast on the time-scale of a given experiment then reversibility in the Diels-Alder reaction is observed. Many retro-Diels-Alder reactions are carried out at temperatures of 150°C or more in solution phase or at temperatures over 400°C using FVP, which is the technique chosen for the third novel synthesis of 2-cyanobutadiene reported in this thesis.

Previous to the work reported, various substituted butadienes had been prepared via the thermal retro-Diels-Alder reaction of substituted cyclohexene derivatives. One example is the preparation of derivatives of 1,3-butadiene-2,3-dicarboxylic acid, which are otherwise difficult to prepare, but are easily synthesised by vapour-phase pyrolysis of cyclohexene-1,2-dicarboxylic acid derivatives. Thus heating of cyclohexene-1,2-dicarboxylate **132** at 700°C yields dimethyl-1,3-butadiene-2,3-dicarboxylate **133**, and under similar conditions cyclohexene-1,2-dicarbonitrile **134** produces 1,3-butadiene-2,3-dicarbonitrile **135** (Scheme 57).
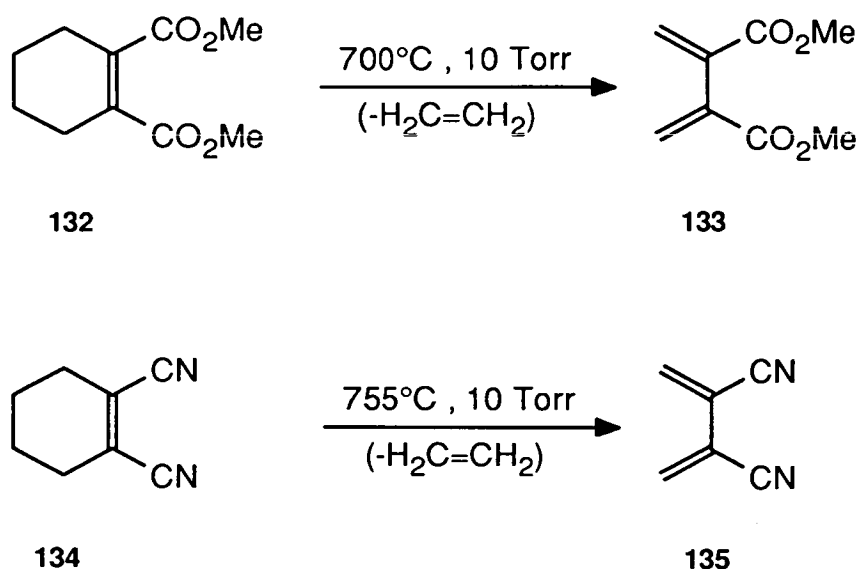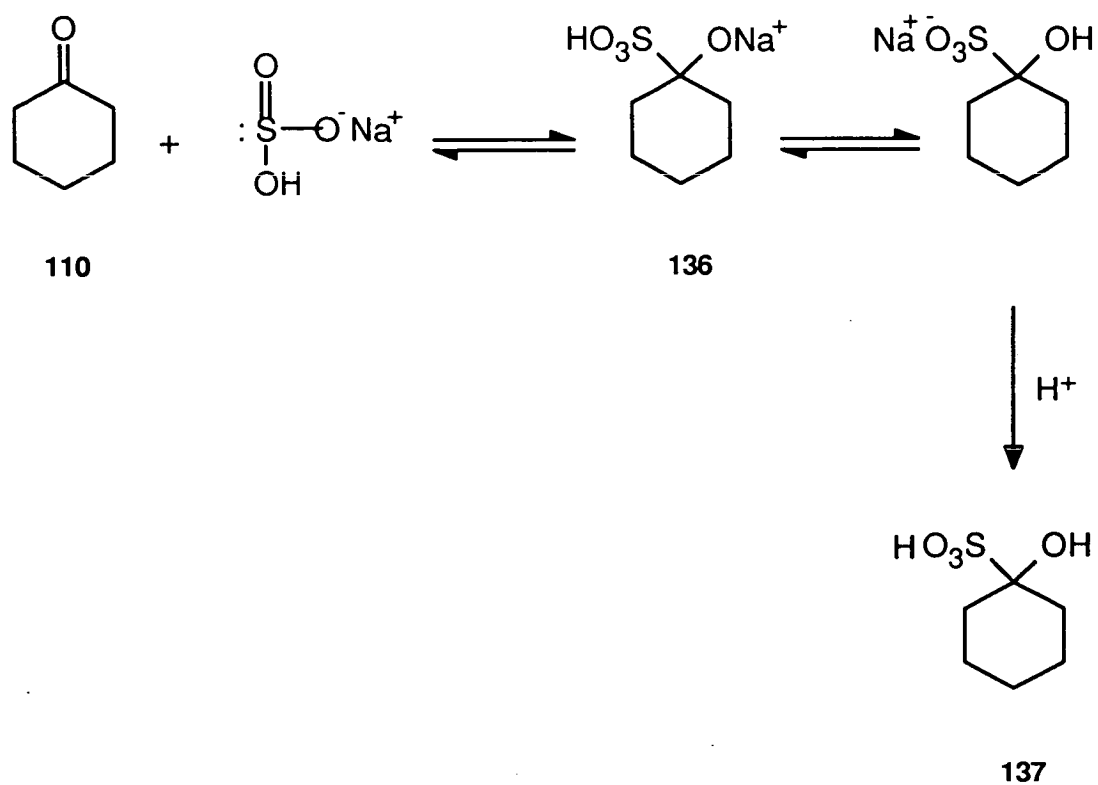
Scheme 57

This basis for the formation of 1,3-butadiene from cyclohexene seemed to suggest a convenient and versatile method for the preparation of the required 2-cyanobutadiene *via* chelotropic extrusion of ethene, *via* FVP of 1-cyanocyclohexene.

Cyclohexanone **110** was chosen as a suitable starting point for the synthesis of 1-cyanocyclohexene, since it is susceptible to nucleophilic addition to produce the corresponding hydrin incorporating the nucleophile. The first step was to convert cyclohexanone **110** into the cyanohydrin **111** (1-cyanocyclohexanol) but unfortunately reaction of potassium cyanide (KCN) with cyclohexanone only produced the desired compound in low yield. Consequently an alternative approach was undertaken, whereby cyclohexanone was reacted with sodium bisulfite to form the bisulfite hydrin **137** (Scheme 58) (after addition of conc. sulfuric acid) as a colourless viscous
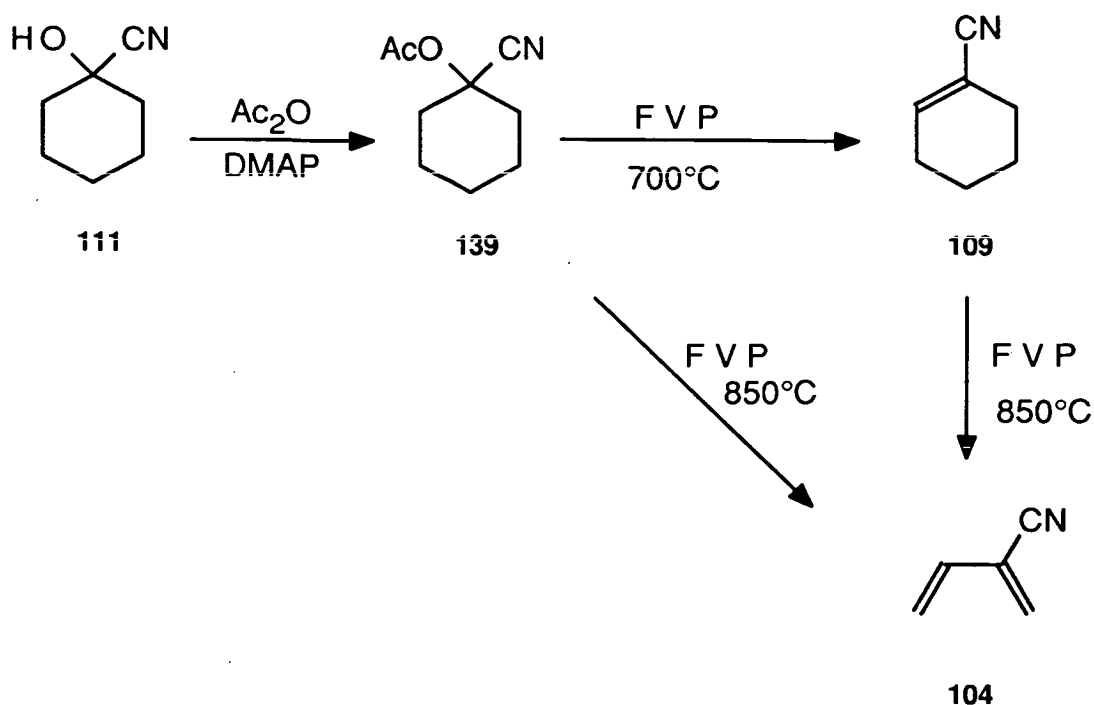
Scheme 58

oil. To this bisulfite **137** was added potassium cyanide to produce a colourless oil of 1-cyanocyclohexanol **111** in 55% overall yield, which was purified by filtration, followed by vacuum distillation. However, when **111** was subjected to FVP at 600°C, the only isolated product was benzene **138** as shown by [1]H n.m.r., and not 1-cyanocyclohexene **104** (Scheme 59).

Scheme 59
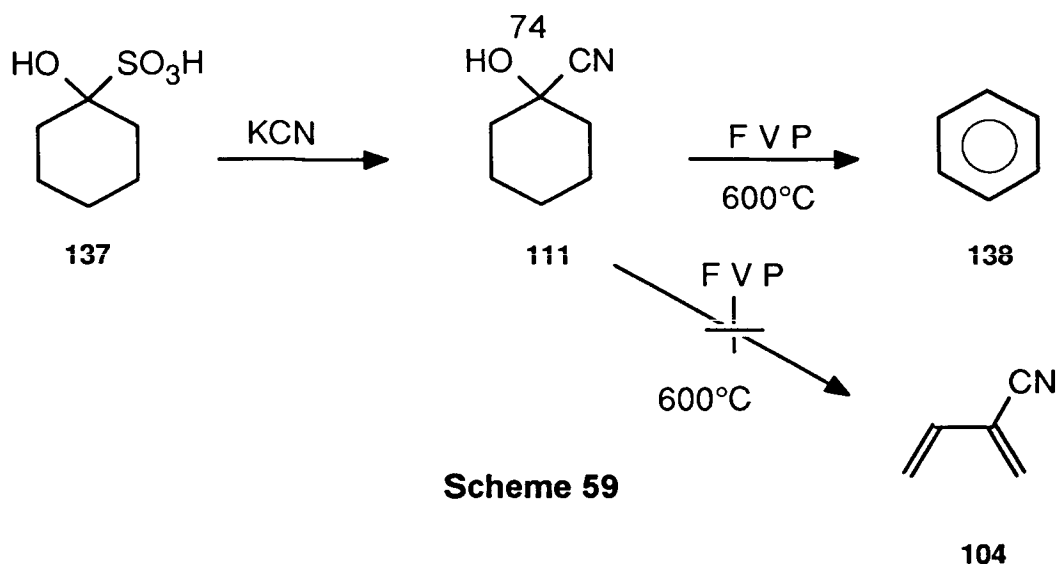
In order to circumvent this problem the next stage in the synthesis required the acetylation of the cyanohydrin **111**. This was undertaken using acetic anhydride and DMAP in triethylamine. The alkaline product that was produced was washed with dilute hydrochloric acid and then vacuum distilled to produce pure 1-cyano-1-acetoxycyclohexene **139**. FVP of the acetate **139** at 700°C, resulted in the elimination of acetic acid and the production of 1-cyanocyclohexene **109** as a yellow viscous oil, which in the ^{1}H n.m.r. showed the absence of the acetate peaks characteristic of compound **138**. Moreover, the spectra showed none of the characteristic butadiene peaks, which further indicated that retro-Diels-Alder splitting of the cyclohexene ring had not occurred but that acetic acid had been eliminated from the ring, infrared spectroscopy shows lack of carbonyl stretching. At higher temperatures i.e. 850°C retro-diene splitting of the acetate **139** did occur and a light brown oil, identified as 2-cyano-1,3-butadiene, **104** was produced, which was then vacuum distilled to produce pure **104** in 81% yield.

2-Cyanobutadiene **104** was also prepared by pyrolysis of **109** at 850°C to produce **104** in 92% yield (Scheme 60). ^{1}H n.m.r. data showed peaks at 5.45(d, Hd) and 6.37(dd, Hc) ppm and a peak at 2.1(s, CH_3), which compares favourably with data for **104** via the butadiene sulfone route (Section A (ii)).

Scheme 60

The reactions in the above sequence illustrate the selectivity of the flash vacuum pyrolysis (FVP) technique. Variation of the furnace temperature may alter the reaction products in significant ways[93]. In the example at hand, a lower temperature (700°C) facilitates the elimination of the acetate functionality of the cyclohexane ring of **139** without splitting the ring itself, whereas a higher temperature (850°C) facilitates both elimination of acetic acid (which occurs at 700°C) and advantageously the splitting of the cyclohexene ring thus formed in the familiar retro-Diels-Alder type reaction. Pyrolysis of 1-cyanocyclohexene **109** at 850°C shows that this temperature is required to split the cyclohexene ring to form the 1,3-butadiene **104**.

B. CYCLOADDITION REACTIONS OF 2-CYANO-1,3-BUTADIENE

It has been shown by numerous previous citations that butadiene is probably the most common diene that can undergo reactions with a suitable dienophile in the familiar Diels-Alder reaction to form the respective six-membered cycloadduct by a $[4\pi+2\pi]$ cycloaddition.

On this basis it was assumed that the diene formed in the previous section, *viz* 2-cyanobutadiene, would undergo similar Diels-Alder type cycloadditions.

In general Diels-Alder cycloadditions are often facile and very broad in scope. Dienophiles that are suitable for such cycloadditions vary widely, but usually appear in the form: -C=C-Z or Z-C=C-Z' where Z and Z' are CHO, COR, COOH, COOR, COCl, CN, NO_2, halogens, C=C etc. The stereochemistry of the Diels-Alder reaction can be considered from several aspects[94]:

(i) With respect to the dienophile, the addition is stereospecifically syn. This means that groups that are *cis* in the alkene will be *cis* in the cyclohexene ring.

(ii) The diene must be in the *cisoid* conformation. If it is frozen into the *transoid* conformation, the reaction does not take place. If the diene does not exist in the *cisoid* conformation, it must be able to achieve this conformation during the reaction for it to occur.

(iii) Electron-donating substituents, i.e. O^-, OCOR, NH_2, CH_3, NR_2, in the diene accelerate the rate of reaction, whereas electron-withdrawing groups, i.e. NH_3^+, NO_2, CN, COOH, CHO, COR, $C \equiv CR$, decreases the rate of reaction. For dienophiles it is just the reverse.

It was Woodward and Hoffmann[95] who published the rules for Diels-Alder reactions, and their frontier orbital theory may be used to explain many of the properties of these [4+2] cycloadditions. The theory concentrates on

the interaction of the reacting orbitals of the diene and the dienophile. The interaction between the highest occupied molecular orbital (HOMO) of the diene, e.g. butadiene or 2-cyanobutadiene, and the lowest unoccupied molecular orbital (LUMO) of the dienophile e.g. ethene, etc., and vice-versa, are simple examples sharing the concept of frontier orbital theory (Figure 10).
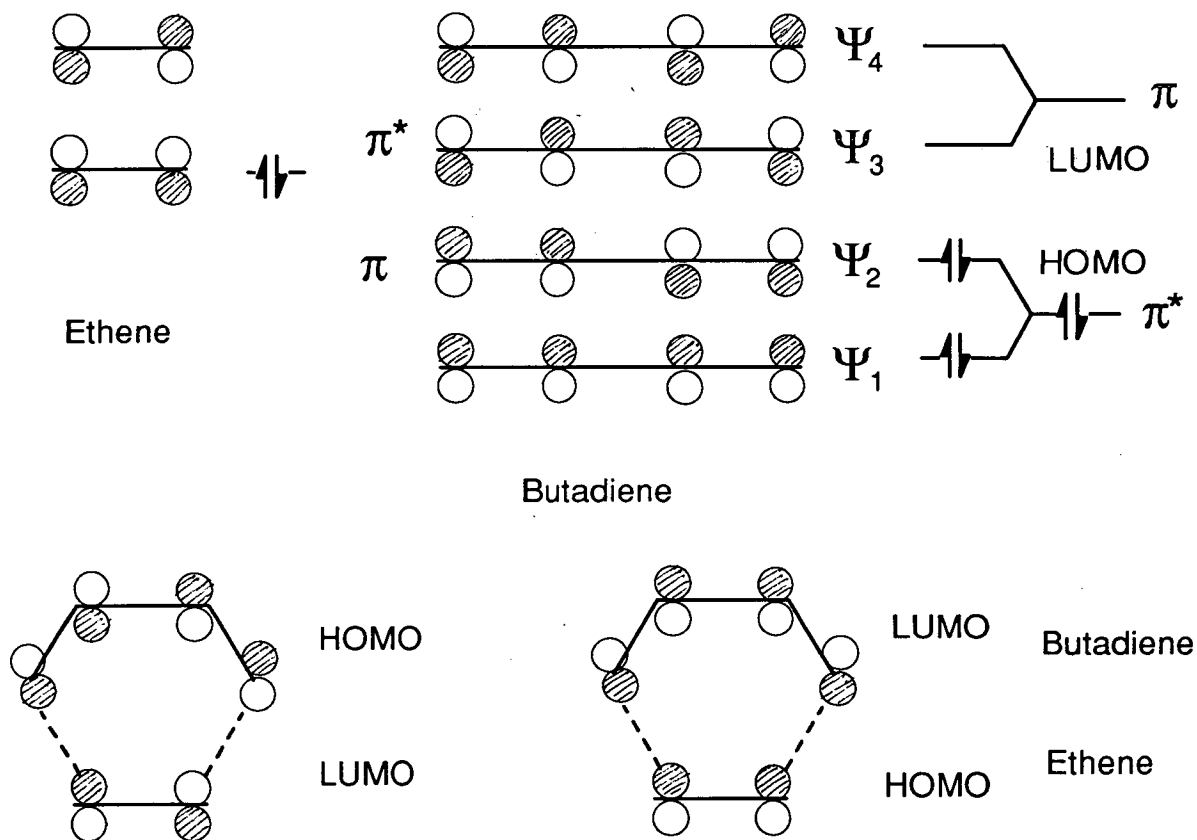
Figure 10

It can be seen that in this Diels-Alder reaction, symmetry is allowed because the combination involves orbitals of the same sign. The influence of activating substituents on both diene and dienophiles, which has been briefly mentioned earlier in this section, can be shown by using frontier orbital theory to affect the relative energies of both HOMO and LUMO. The effect of an

electron-withdrawing substituent is to lower the relative energies of both HOMO and LUMO. An electron-donating substituent raises both HOMO and LUMO energies, whereas conjugated substituents raise the HOMO and lower the LUMO energies. The rate of reaction is increased when E_{LUMO}-E_{HOMO} is smallest. In the example of butadiene and substituted alkenes it was shown that electron-withdrawing groups on the dienophile bring the LUMO closer to the diene HOMO, but the effect is more pronounced when electron-donating groups are present on the diene. Both, however, increase the rate of reaction by lowering the energy gap between the HOMO and LUMO. Similarly, electron-donating substituents on the alkene (dienophile) and electron-withdrawing groups on the diene also affect a reduced energy difference (Figure 11).
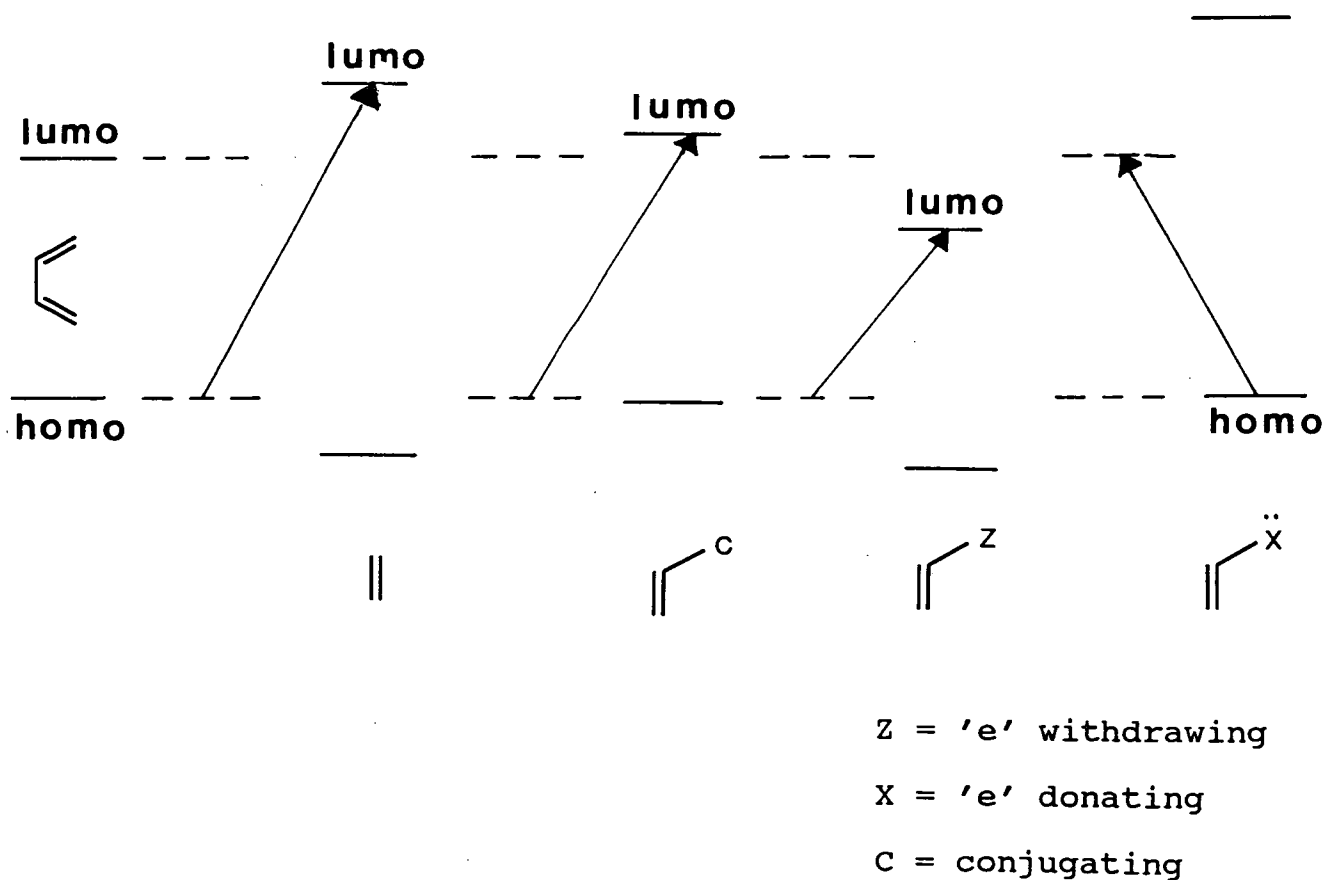

Z = 'e' withdrawing

X = 'e' donating

C = conjugating

Figure 11

With these theories in mind, it was decided to undertake two Diels-Alder cycloaddition reactions with 2-cyanobutadiene by using methyl vinyl ketone and 4-phenyl-1,2,4-triazoline-3,5-dione as the dienophilic component. Both reactions were carried in sealed Carius[96] tubes.

In the first example, 2-cyanobutadiene was reacted with methyl vinyl ketone **140** in chloroform. The reaction was carried out at 50°C in the sealed tube and stirred overnight at this temperature. After evaporation of the solvent and excess reagent, a colourless liquid was formed (Scheme 61), ^{13}C n.m.r. seems to suggest that a mixture of 1,3 and 1,4 cycloadducts **141** were formed i.e. signals: δ 143.25, 130.00, 128.41, 127.51, 126.86, 65.17, 27.94, 26.76, 25.93 and 0.11. The use of lewis acid catalysts may possibly improve the regioselectivity of this reaction.
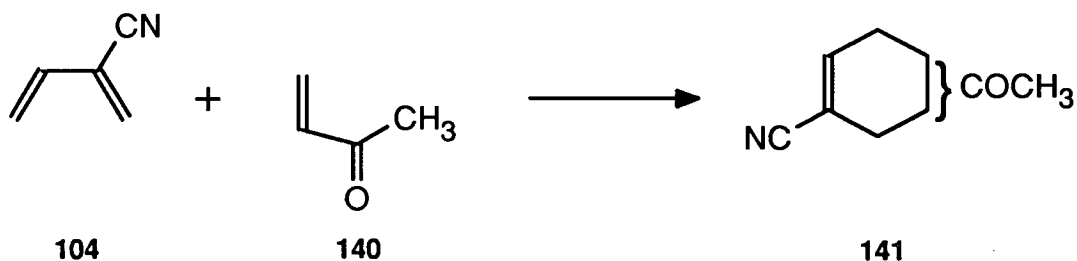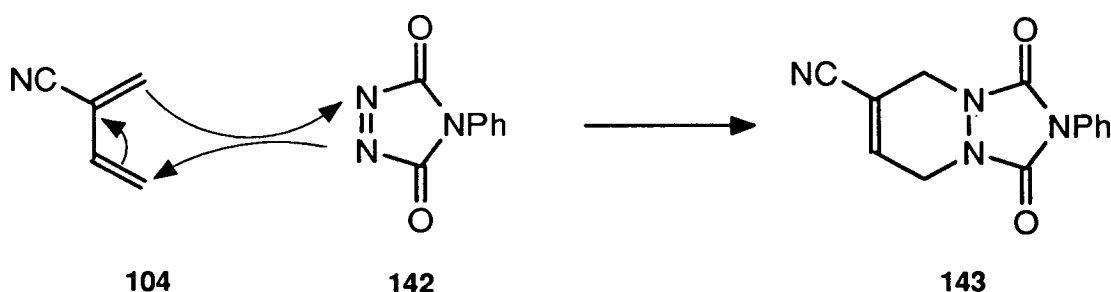

Scheme 61

A second cycloaddition with 4-phenyl-1,2,4-triazoline-3,5-dione **142** in acetone produced a colourless crystalline product **143**, believed to be an adduct of the two reagents. ^{1}H n.m.r. analysis although not totally conclusive did, however, show peaks at δ 7.45 ppm, which are consistent with the five phenyl protons and the spectrum also showed peaks at δ 2.36 ppm and

δ 3.30 ppm corresponding to two methylene hydrogens and a single methane proton. Further support for the structure came from its infrared spectrum which showed the presence of two C=O absorbances (Scheme 62).
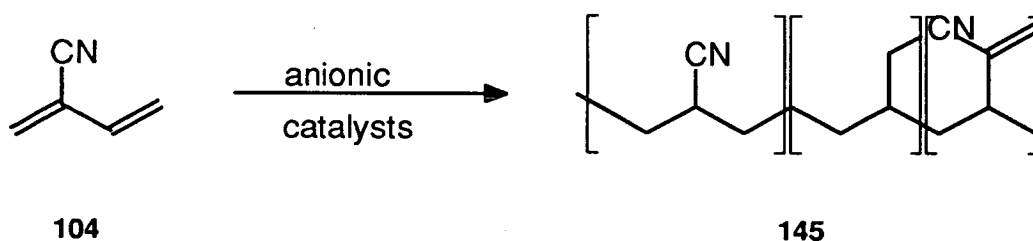

Scheme 62

It was discovered by Wei[97] that 2-cyanobutadiene is susceptible to homo-polymerisation in the presence of butyllithium and organoaluminium compounds. Wei obtained amorphous and partly crystalline products with thermoplastic properties. Infrared spectroscopy showed that these products attained a 1,4-*trans* structure. In other work Müller *et al.*[75] discovered with radical-initiated homo-polymerisation using benzoyl peroxides as initiators that highly cross-linked polymers were formed. These polymers were insoluble in organic solvents such as toluene, benzene or chloroform. However, when polar solvents such as ethers are used, soluble polymers were obtained, which had thermoplastic properties and consisted mainly of 1,4- and 3,4-adducts **144** in a 3:1 ratio, as well as cyclic structures (Scheme 63).
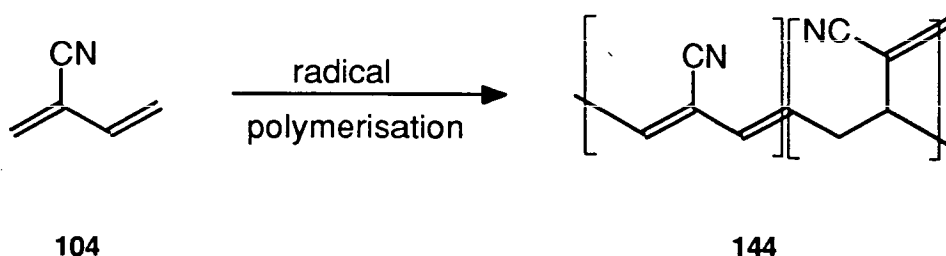
Scheme 63

The disadvantages of soluble polycyanoprenes (polymers of 2-cyanobutadiene) thus obtained by radical polymerisation are that molecular weights below 5000 are produced and moreover, the yields are poor. With the use of anionic initiators, e.g. lithium alkyls, insoluble thermoplastic products can be obtained which possess molecular weights of approximately 10,000. The polycyanoprenes anionically polymerised usually contain 50-70% of 1,2-linkages **145** (Scheme 64).

Scheme 64

When Ziegler-Natta catalysts of the type $TiCl_4$/alkyl aluminium compounds are used, no polymerisation is observed due to the fact that 2-cyanobutadiene preferentially reacts with the catalyst and destroys it.

Co-polymerisation of 2-cyanobutadiene with butadiene has been studied[98] and leads to polymers with poor tensile strength values and elongations, strong odours and polymers which discolour when exposed to light.

## C.   PREPARATION OF [3]DENDRALENE FROM CYCLOHEXANONE

Following on from the synthesis of 2-cyanobutadiene starting from the readily available cyclohexanone, it was decided to attempt to prepare the compound which forms the basis of this work on 2-substituted-1,3-butadienes, namely [3]dendralene (2-vinyl-1,3-butadiene) 1.

Originally based on an idea by Dr. Ian Dawson at the University of Edinburgh, this synthetic route follows analogous pathways to the preparation of 2-cyanobutadiene from cyclohexanone.   The key step again being the retro-Diels-Alder reaction of a 1,1-disubstituted cyclohexane 148 to form [3]dendralene 1 in almost quantitative yield.

The initial synthetic step involved the addition of a vinylic group to the starting material, namely cyclohexanone, and the most convenient source is the Grignard analogue.   In this way vinyl bromide was reacted with magnesium turnings to form vinylmagnesium bromide, which was then reacted with the cyclohexanone in a one-pot reaction to form 1-vinylcyclohexanol 146 as a pale yellow coloured oil in 38% yield after vacuum distillation (at 90°C).   Characterisation by infrared spectroscopy before vacuum distillation indicated peaks at 3400 (O-H), 2930 and 2850 cm^{-1} (CH) and 1700 cm^{-1} signifying the presence of a carbonyl group corresponding to the starting material.   This peak is removed by distillation, but its presence signifies that complete conversion of the cyclohexanone to 1-vinylcyclohexanol 146 had not occurred, which accounts for the relatively poor yield of the reaction.

The second step in the synthesis required the acetylation of the hydroxyl functionality to produce 1-vinyl-1-acetoxycyclohexane 147. Acetyl chloride/pyridine and acetic anhydride/DMAP are both suitable acetylation reagents as previously mentioned in Section A, although the latter reagent was deemed to be higher yielding and therefore was chosen for the

acetylation in hand. The reaction produced **147** in 81% yield after distillation *in vacuo* (at 110°C) as a colourless oil. The final step of the synthetic pathway to [3]dendralene **1** incorporated the chelotropic extrusion of ethene and acetic acid in a single step using FVP at 800°C to produce a colourless oil of [3]dendralene in 92% yield (Scheme 65). ^{1}H n.m.r. showed the characteristic 1,3-butadiene peaks (5.4-6.4 ppm). Alternatively the acetate **147** can be pyrolysed at a lower temperature to produce 1-vinylcyclohexene in 94% yield. A second pyrolysis step at 700°C produced [3]dendralene in 98% yield.
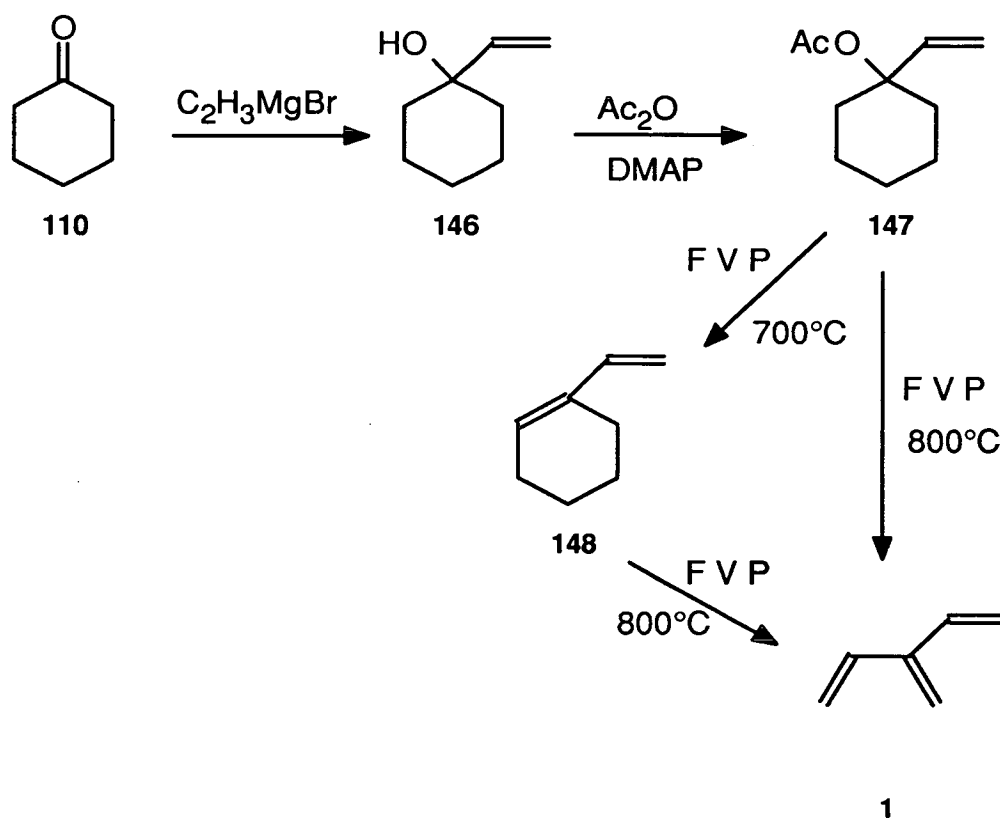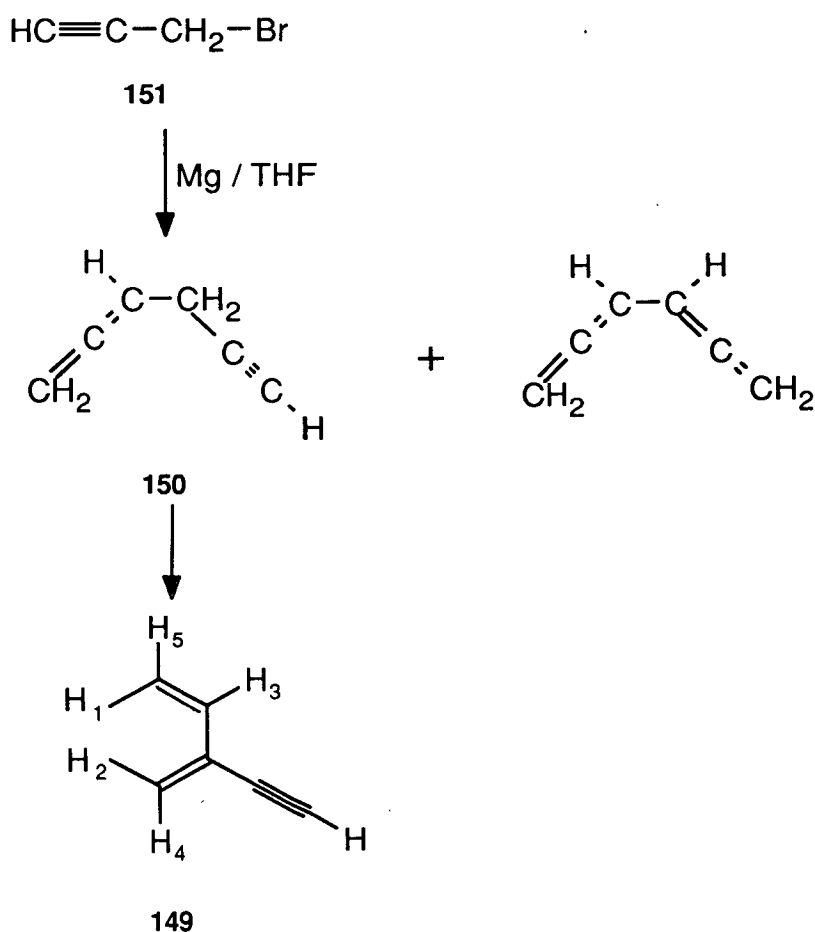
Scheme 65

D. ATTEMPTED PREPARATION OF 2-ETHYNYL-1,3-BUTADIENE

Due to the success of chelotropic extrusion of SO_2 from 3-cyano-4-acetoxytetrahydrothiophene-1,1-dioxide **121** to form 2-cyanobutadiene **104**, it was decided that other butadiene derivatives may be produced by a similar sequence of reactions.

2-Ethynyl-1,3-butadiene **149** although not a novel compound has received little attention apart from recent studies by Hopf and co-workers[99-101]. One of the more intriguing aspects of **149** is that it is a valence isomer of benzene (C_6H_6) of which over 216 other isomers are known (Figure 12).

Hopf[99] prepared **149** by the isomerisation of a propargyl allene **150** at 400-500°C, which in turn was prepared from propargyl bromide **151** (Scheme 66).

$$HC\equiv C-CH_2-Br$$

151

Mg / THF

150

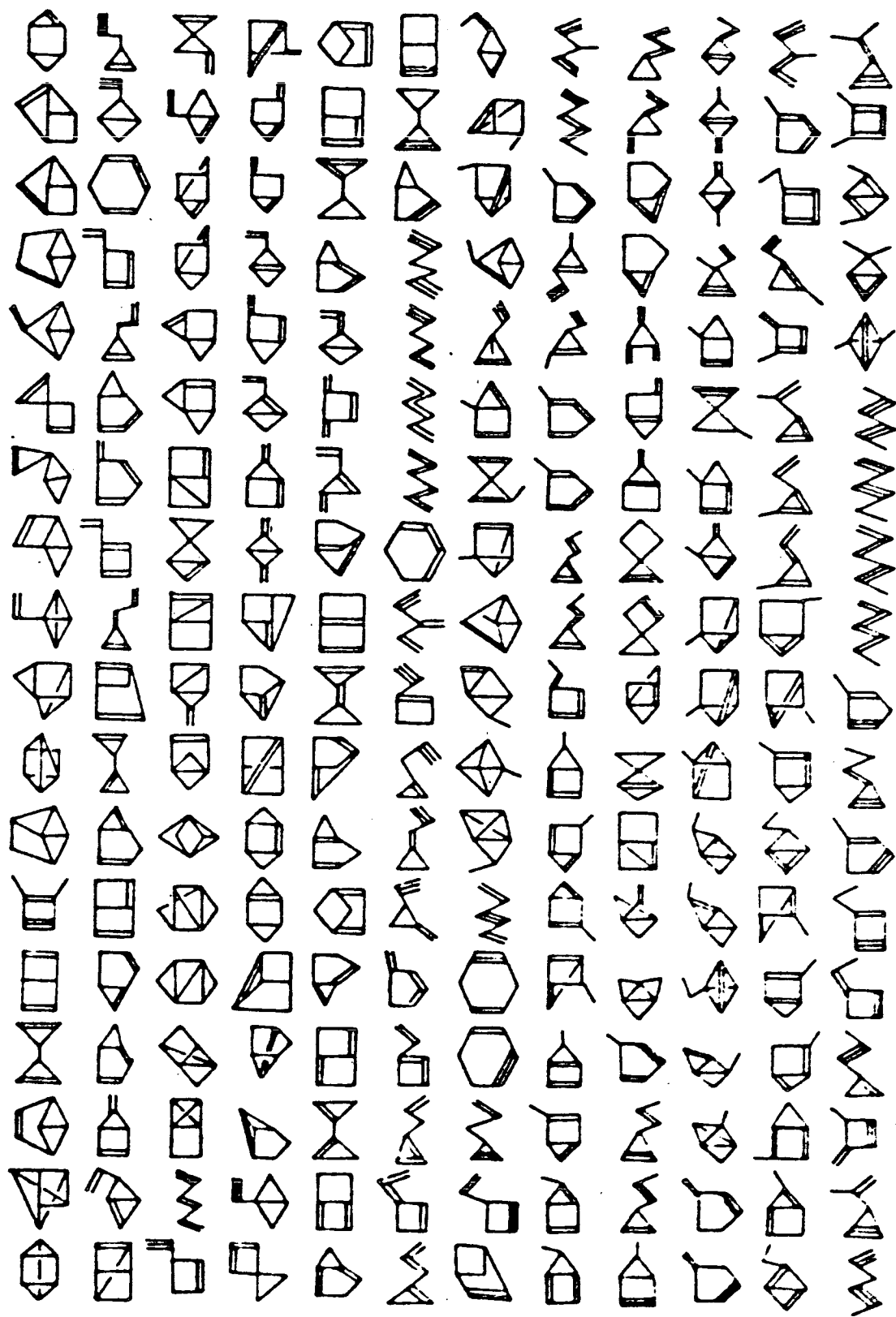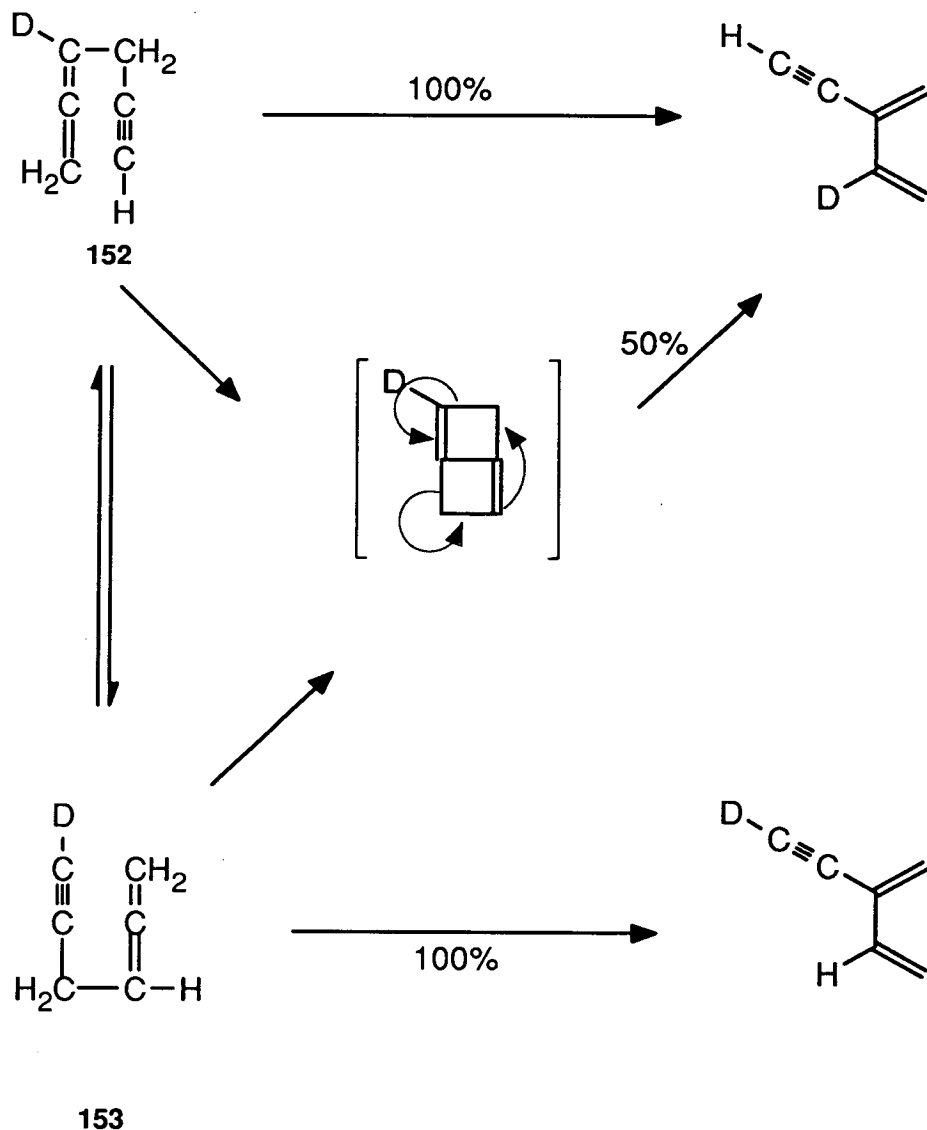**149**

Scheme 66

Valence Isomers of Benzene (C$_6$H$_6$)

Figure 12

This novel C_6H_6 isomerisation of **150** to **151** is accomplished (as shown using the deuterated compounds **152** and **153**) by a degenerate valence isomerisation process (**152** $\rightleftharpoons$ **153**) which impedes the elucidation of the (**150** → **149**) rearrangement mechanism (Scheme 67).
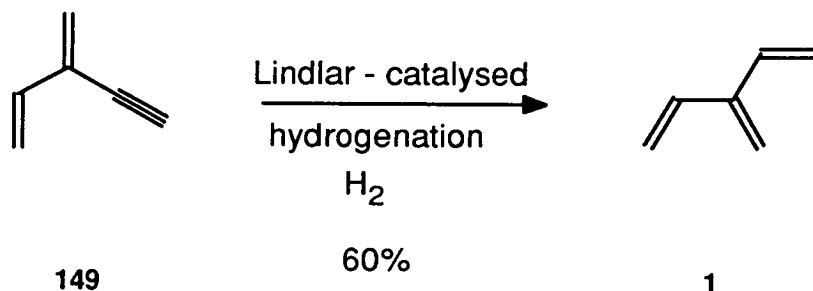

Scheme 67

Hopf[99] showed that the ^1H n.m.r spectrum of 2-ethynyl-1,3-butadiene contained a quartet for one proton between δ 6.66 ppm and δ 6.14 ppm (H_3) and a multiplet for four protons at δ 5.87 and 5.13 ppm (H_1, H_2, H_4, H_5) and a

singlet at δ 3.07 ppm for the -C≡C-H proton (H$_6$). In another paper, Hopf and Priebe[100] used 2-ethynyl-1,3-butadiene **149** for the preparation of [3]dendralene **1** by Lindlar-catalysed hydrogenation (Scheme 68) in an 18% overall yield, lower than that reported by Gillam *et al.*[7] using chelotropic SO$_2$ extrusion (See Scheme 5).
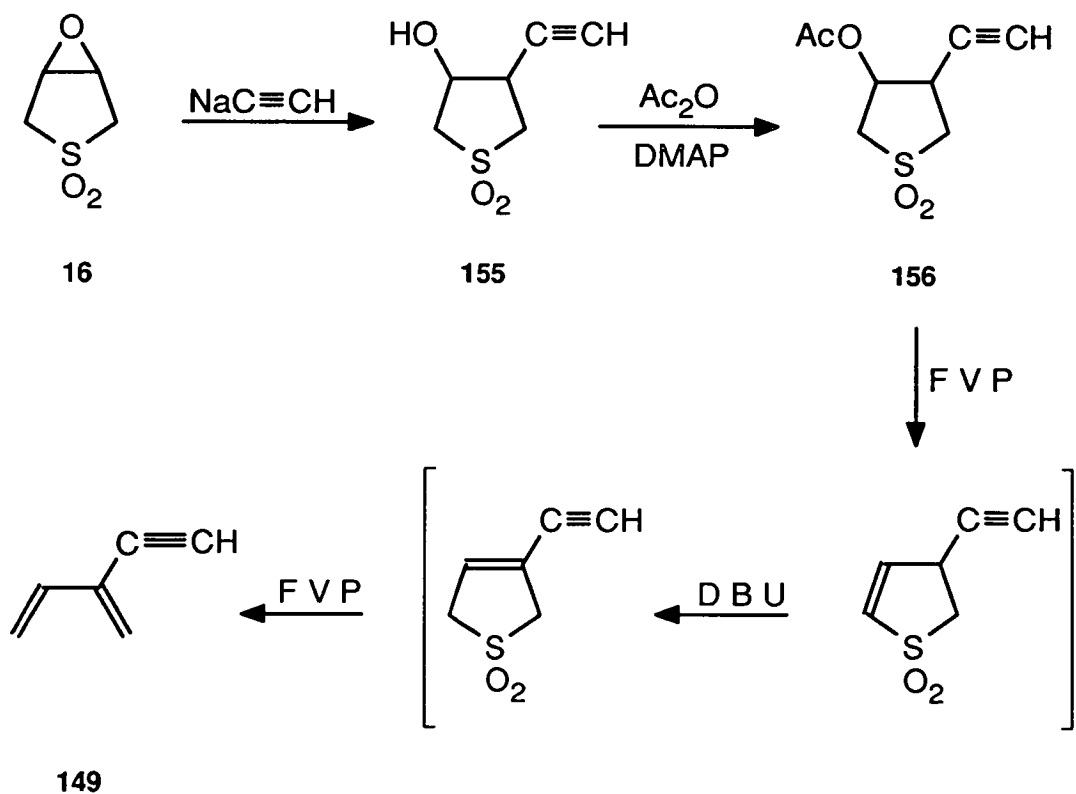

Scheme 68

More recently Hopf, *et al.*[101] quoted several methods for the preparation of **149**, although the only preparative route (63% isolated yield) consisted of the gas-phase dehydration of 3-methyl-1-penten-4-yn-3-ol **154** over molecular sieves (5 Å) at 300°C (Scheme 69).
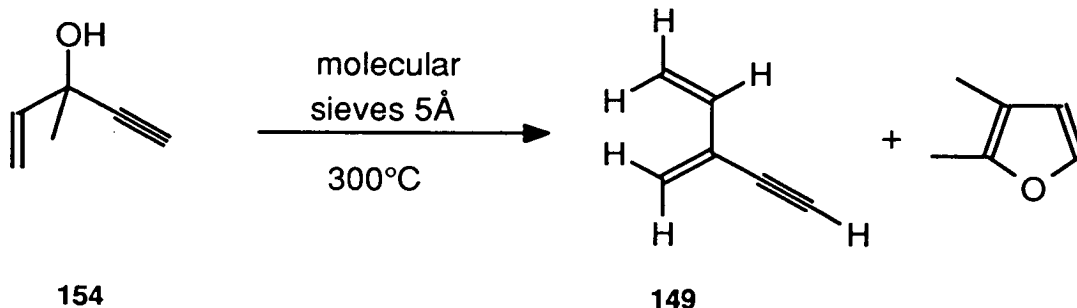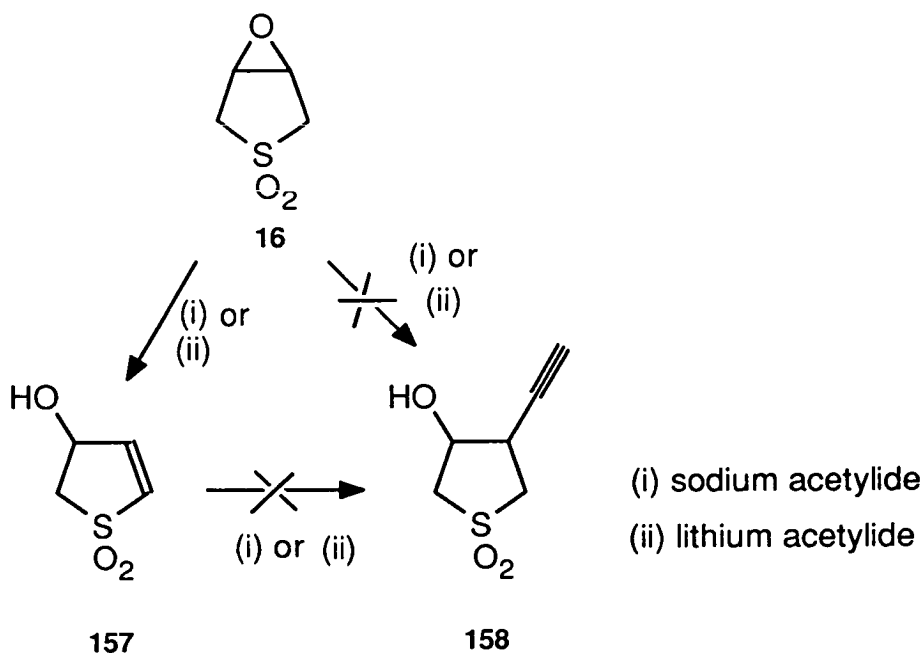

Scheme 69

With these preparations of **149** in mind, together with our knowledge of chelotropic extrusion of SO_2 from sulfones, it was decided to attempt to prepare 2-ethynyl-1,3-butadiene **149** using SO_2 elimination from the appropriately functionalised butadiene sulfone.

The first stages in the synthesis involved ring-opening of the butadiene sulfone epoxide **16** to form 3-ethynyl-4-hydroxysulfolene **155**, followed by acetylation to form **156** (using DMAP/acetic anhydride) and finally pyrolysis with loss of SO_2 (Scheme 70).
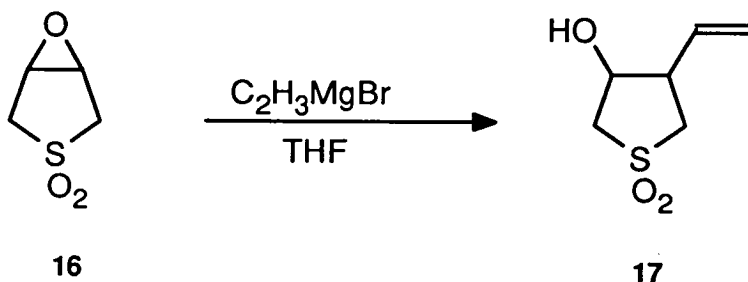

Scheme 70

The initial step in this route required the use of an acetylene-containing compound to ring-open the epoxide **16**. Since acetylene itself was considered to be too hazardous for laboratory scale preparation of **155**, a less hazardous alternative, sodium acetylide slurry was used (available from Aldrich as an 18% slurry in mineral oils). However ring-opening of the epoxide failed to occur in the required way upon addition of sodium acetylide, even under various reaction conditions, including varying the temperature of reaction and mode of addition, reagent quantities and solvent system, as well as attempts to remove the mineral oil from the sodium acetylide, once the slurry was added to the solvent. It was believed that reaction had failed to occur due to the acidity of the protons on C-2 and C-5 of the sulfone **16**, sodium acetylide slurry itself being acidic in nature. A more basic reagent was therefore needed, but one which still contained an acetylene functionality. One such reagent considered was lithium acetylide, which is more basic than sodium acetylide. Lithium acetylide was available as an ethylene diamine complex in powder form. Reaction of this reagent with the epoxide **16** again failed to produce **149**. ^{13}C n.m.r. analysis of the reaction mixture showed that both lithium and sodium acetylide had ring-opened the epoxide, but had failed to produce the required product. Further analysis discovered that ring-opening of the epoxide **16** had failed to facilitate the addition of the nucleophile -C $\equiv$ C-H, but had induced a double bond into the sulfone to form 4-hydroxy-2,5-dihydrothiophene-1,1-dioxide **157** (Scheme 71), as proven by ^{13}C n.m.r. analysis which showed peaks at 56.83 (C2), 67.49 (C3), 132.80 (C4), 143.14 (C5), infrared spectroscopy shows an O-H peak at 3400 cm^{-1}.

Scheme 71

Further addition of sodium or lithium acetylide to **157** failed to produce **158**, and work-up only succeeded in the recovery of the starting material **157**.

In the preparation of [3]dendralene Gillam[7,8] used a Grignard reagent to ring-open the butadiene sulfone epoxide **16** to produce 3-vinyl-4-hydroxysulfolene **17** in good yield (Scheme 72).
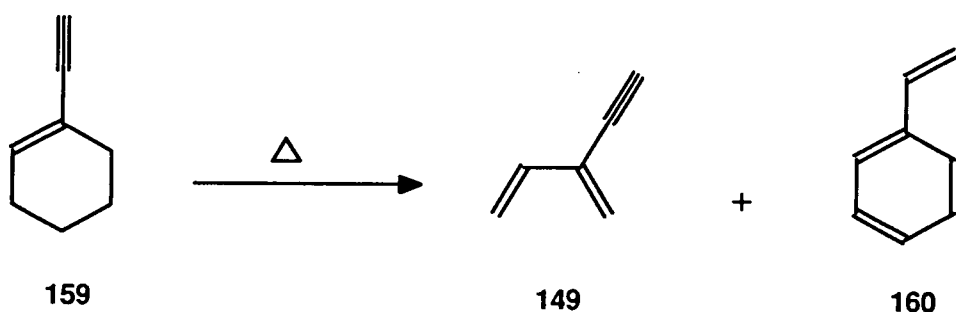

Scheme 72

On this basis, it was considered that ring-opening of **16** might be achieved if the sodium or lithium acetylide could be reacted with a suitable Grignard reagent prior to addition. Ethylmagnesium bromide was chosen, but reaction failed to occur between either acetylide and the Grignard reagent. This failure to ring-open the epoxide in the required way, effectively stopped the synthesis at the first step and prevented the synthesis of 2-ethynylbutadiene *via* SO_2 extrusion of a sulfone. If the preparation of **158** had been possible, there seems little doubt that acetylation followed by pyrolysis of **158** may have been feasible following the same procedure as for 2-cyanobutadiene from the butadiene sulfone epoxide **16**.

E. PREPARATION OF 2-ETHYNYL-1,3-BUTADIENE

Due to the failure of SO_2/sulfone chemistry to produce 2-ethynyl-1,3-butadiene **149**, it was decided to look at an alternative route to the synthesis of **149**. Literature[101] shows that 2-ethynyl-1,3-butadiene **149** can be synthesised by employing retro-Diels-Alder reaction of 1-ethynyl-1-cyclohexene **159**. However styrene **160** was co-produced in significant amounts (11-14%), besides the required product **149** due to hydrogen shift (Scheme 73).


159   **149**   **160**

Scheme 73

With this reaction in mind, it was decided to attempt the preparation of the precursor **159** and by applying FVP conditions, synthesise **149** free from impurities and side-products.

Cyclohexanone **110** was again employed as a suitable starting material for preparation of the cyclohexene **159**, which would ultimately undergo the retro-Diels-Alder reaction necessary to produce **149**. Initially cyclohexanone **110** was reacted with sodium acetylide slurry, in anhydrous diethyl ether. Simple nucleophilic addition of the acetylide sodium salt resulted in the formation of 1-ethynylcyclohexanol **161** after neutralisation by addition of dilute sulfuric acid. As in the preparation of 2-cyanobutadiene, the

hydroxyl moiety of the cyclohexane molecule was acetylated using DMAP/acetic anhydride to form 1-ethynyl-1-acetoxycyclohexane **162** in 90% overall yield (Scheme 74).
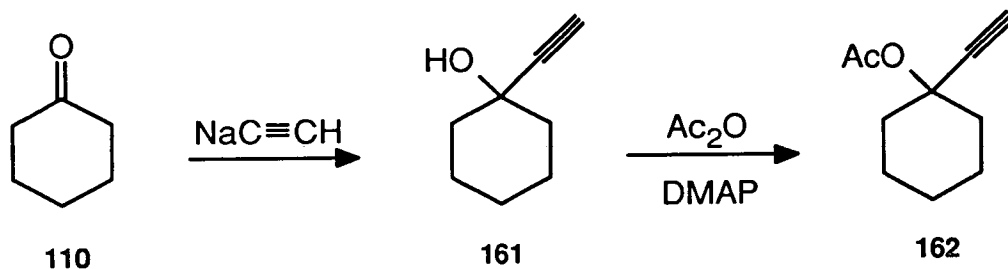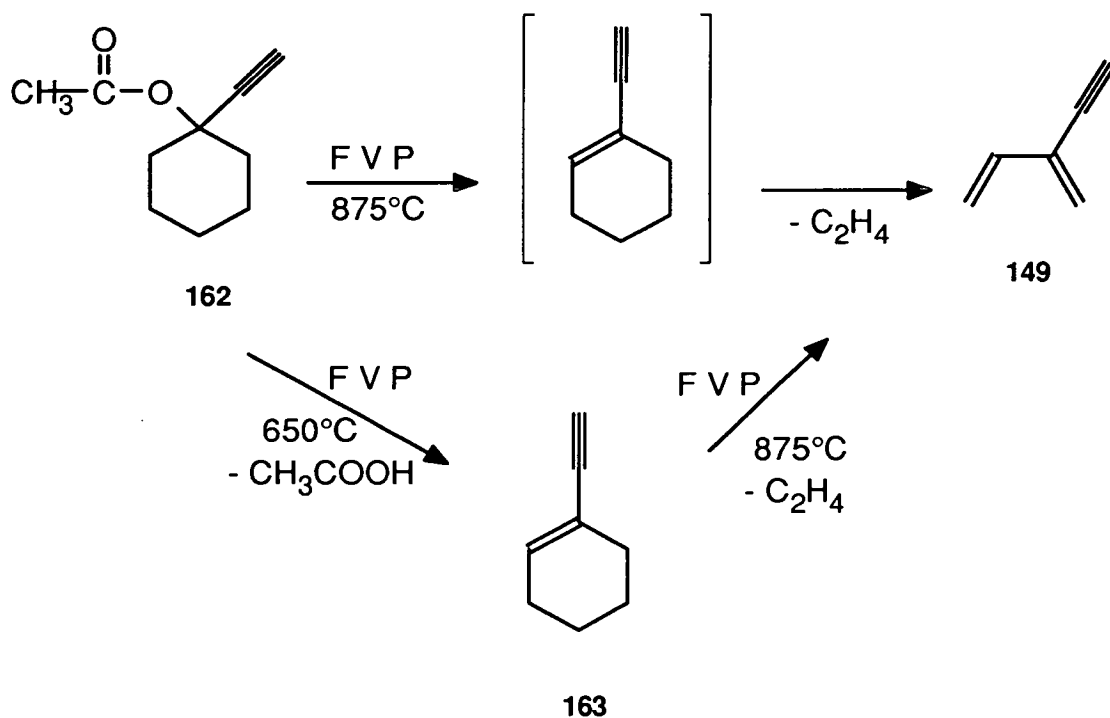

Scheme 74

The next stage in the synthesis was to pyrolyse **162** using FVP at various temperatures to determine whether **162** would eliminate acetic acid only or would split the cyclohexene and together with acetic acid elimination, to form 2-ethynylbutadiene **149** in a single step.

It was found that at a furnace temperature of 650°C, acetic acid was eliminated from **162** to produce 1-ethynylcyclohexene **163** in greater than 90% yield. At higher temperatures (i.e. 875°C), acetic acid was found to be eliminated from **162** and at this temperature the cyclohexene ring thus formed was split in retro-Diels-Alder fashion with loss of ethene, to produce 2-ethynyl-1,3-butadiene **149** in 89% yield. Clearly the elimination of acetic acid facilitates the cleavage of the cyclohexene ring, once the temperature is raised to the required level. Indeed the cyclohexene intermediate **163** formed could not be isolated during the FVP process once the furnace temperature was raised above 800°C. The 2-ethynyl-1,3-butadiene **149** obtained in this way could be produced in pure form by allowing the first trap in the FVP apparatus to warm up to room temperature, whilst maintaining the second

trap at liquid nitrogen temperatures. The final product **149** (Scheme 75) was isolated as a light brown oil and showed the characteristic butadiene peaks in the ^1H n.m.r. spectrum (δ 4.4-5.4 ppm) which also showed the absence of any peaks due to acetic acid or cyclohexene ring protons. Infrared spectroscopy of the oil showed absorbances at 3315 and 2100 cm^{-1} signifying the presence of an acetylene moiety (-C$\equiv$C-H) together with conjugated C=C absorbances at 1572 and 1565 cm^{-1}, which corresponded to the data reported by Hopf *et al.*[100]. However, unlike Hopf's preparation no styrene appears to have been produced during the pyrolysis stage of this synthesis (^1H n.m.r. shows no peaks corresponding to styrene), and in this respect the synthesis appears to be superior.
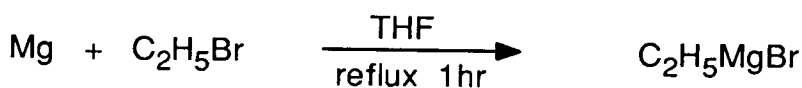

Scheme 75

Mass spectroscopy analysis of **149** produced from **162** gave a molecular ion (M$^{\bullet+}$) value at 78, which correponds with the molecular weight of **149** (C_6H_6).

F.   PREPARATION OF 2-PHENYLETHYNYL-1,3-BUTADIENE FROM BUTADIENE SULFONE

In Gillam's[7] preparation of [3]dendralene from butadiene sulfone, the key step involved reaction of a Grignard reagent (vinylmagnesium bromide) with butadiene sulfone epoxide **16** (see Scheme 5). Following this strategy it was decided to further extend the range of 2-substituted 1,3-butadienes by using alternative Grignard reagents, which are easily prepared by the addition of magnesium turnings to a suitable bromide. The readily available ethyl bromide was used. In this way ethylmagnesium bromide **164** was prepared[106] (Scheme 76).

$$ Mg \ + \ C_2H_5Br \quad \xrightarrow[\text{reflux 1hr}]{\text{THF}} \quad C_2H_5MgBr $$
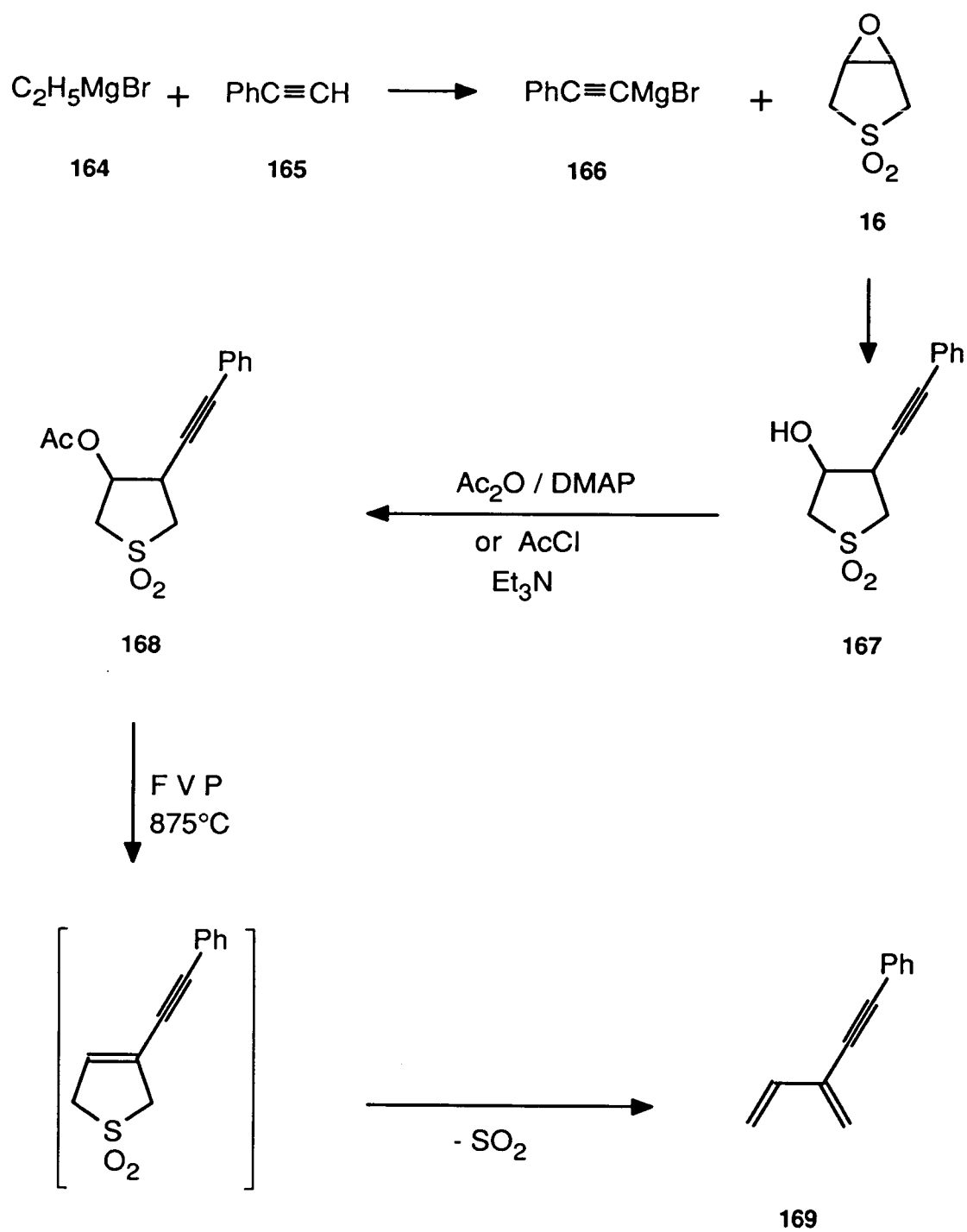
164

Scheme 76

The next stage involved the addition of the Grignard reagent **164** to a suitable precursor, in this case phenylacetylene **165** to form **166**, followed by addition of butadiene sulfone epoxide **16** to produce 3-phenylethynyl-4-hydroxytetrahydrothiophene-1,1-dioxide **167** in 52% overall yield. Infrared spectroscopy showed peaks at 3350 (OH), 2100 (C≡C), 1300 and 1150 (SO_2) and 700 cm^{-1} (Ph) which in addition to mass spectroscopic data (M$^{\bullet+}$ at 236) established the formation of the desired **167**. Acetylation of **167** was performed using acetic anhydride/DMAP as well as with acetyl chloride/triethylamine. Both reagents reacted successfully and produced 3-

phenylethynyl-4-acetoxytetrahydrothiophene1,1-dioxide **168** in 84 and 71% yields, respectively as a colourless solid. Infrared spectroscopy on **168** showed peaks at 2110 (C$\equiv$C), 1750 (CO), 1300 and 1150 (SO$_2$) and < 800 cm^{-1} (Ph) and mass spectroscopy showed a molecular ion at 278 together with the ^{13}C n.m.r. spectrum which showed peaks at δ 20.64 (CH$_3$), 33.02 C3, 53.48 C2, 56.87 C5, 69.06 C4, establishing the formation of the desired product **168**.

The final step in the synthesis required the concomitant elimination of acetic acid from **168**, followed by extrusion of SO$_2$. Indeed when subjected to FVP at 875°C **168** produced 2--phenylethynyl-1,3-butadiene **169** in a single step, albeit in low yield (32%) as a light brown oil.

The apparent reason for the low yield in this case was probably due to the fact that **168** exists as relatively high melting solid (145.3-148.1°C) which upon heating in the inlet oven during pyrolysis, began to polymerise and consequently failed to volatilise and pass through the furnace (Scheme 77). In order to overcome this problem, a different approach was adopted and is detailed in the next section.

C_2H_5MgBr + $PhC{\equiv}CH$ $\longrightarrow$ $PhC{\equiv}CMgBr$ + [epoxide sulfone structure]

164   **165**   **166**   **16**

AcO— [thiolane dioxide with phenyl alkyne] **Ph**

$\xleftarrow{\text{Ac}_2\text{O / DMAP}}$
or AcCl
Et_3N

HO— [thiolane dioxide with phenyl alkyne] **Ph**

168   **167**

F V P
875°C

[bracketed dihydrothiophene dioxide with phenyl alkyne intermediate]

$\xrightarrow{-\ SO_2}$

[diene with phenyl alkyne] **Ph**

169

Scheme 77

G.   PREPARATION OF 2-PHENYLETHYNYL-1,3-BUTADIENE FROM CYCLOHEXANONE

Due to the success of the preparation of 2-ethynyl-1,3-butadiene starting from cyclohexanone, it was decided to attempt to prepare 2-phenylethynyl-1,3-butadiene **169** using a similar route.

The initial step in the synthesis involved the addition of cyclohexanone **110** to the aforementioned Grignard reagent, phenylacetylenemagnesium bromide **166**, to form 1-phenylethynylcyclohexanol **170** in 65% yield (Scheme 78).

$$C_2H_5MgBr \quad + \quad Ph-C\equiv C-H \quad \longrightarrow \quad Ph-C\equiv C-MgBr$$

| 164 | 165 | 166 |

110

170
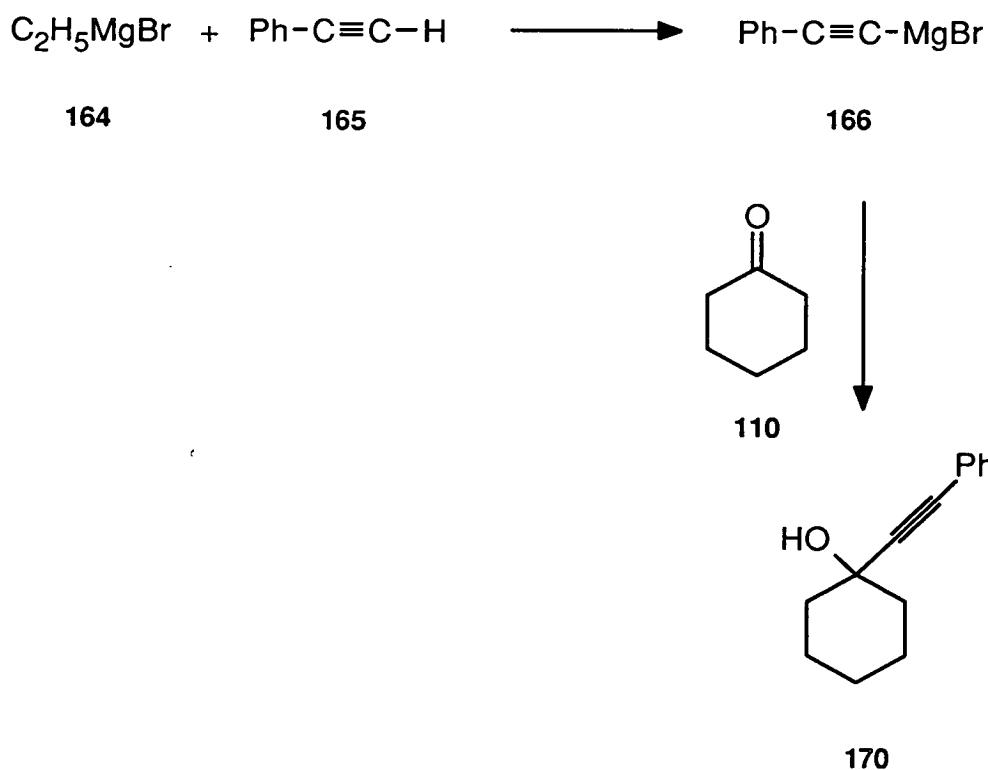
Scheme 78

The next stage in the synthesis required the acetylation of **170**. Acetic anhydride/DMAP was again used and a yellow oil was produced from this reaction. ^1H nmr spectroscopy revealed the existence of five phenyl protons thereby establishing the formation of 1-phenylethynyl-1-acetoxycyclohexane

171. FVP of **171** was performed at a variety of temperatures, and it was found that at a furnace temperature of 550°C, only starting material was recovered. However, when the temperature was raised to 875°C, extrusion of ethene occurred, together with elimination of acetic acid to produce an orange oil (94% yield after vacuum distillation at 100°C) which was shown by ^{13}C n.m.r. to contain peaks at $\delta 20.56$ (CH), 22.15 (CH_2). 29.04 (qC), 41.72 (CH_2), 77.54 ($C \equiv C$), 128.02-131.23 (phenyl CH). Mass spectroscopy analysis showed a molecular ion ($M^{\bullet+}$) peak at 154, together with peaks at 77($M-C_6H_5^+$) and 43($C_3H_7^+$), whilst ^1H n.m.r. analysis revealed the presence of characteristic 1,3-butadiene peaks at δ 5.12-5.17 (1.H, d, F_5, H_6, J_{cis} 11 Hz, J_{gem} 2Hz), 5.15(2H, s, f_5, H_1 and H_1'), 5.41(1.H, dd, H_5, J_{trans} 18 Hz, J_{gem} 2Hz) 6.46(1.H, s, f_5, H_4, J_{trans} 18Hzs, J_{cis} 11 Hz) ppm, together with five phenyl proton resonances observed at δ 7.5-7.1 ppm (Figure 13). This spectroscopic data establishes that 2-phenylethynyl-1,3-butadiene **169** is formed (Scheme 79).
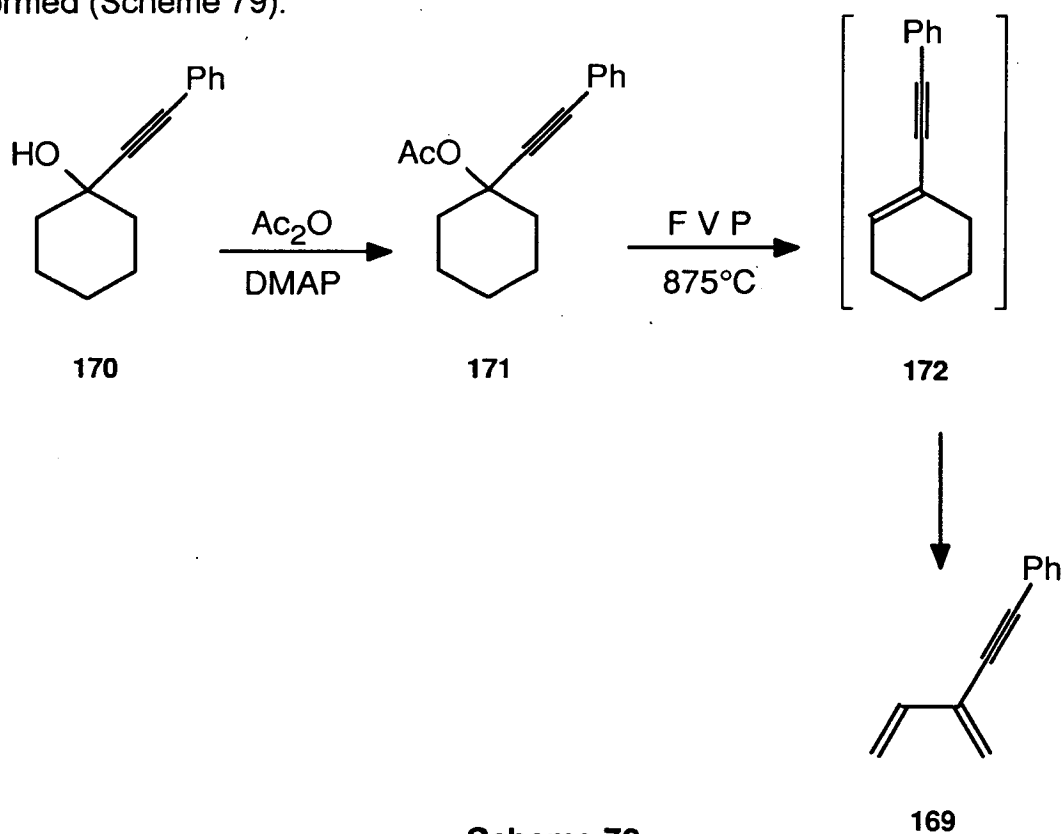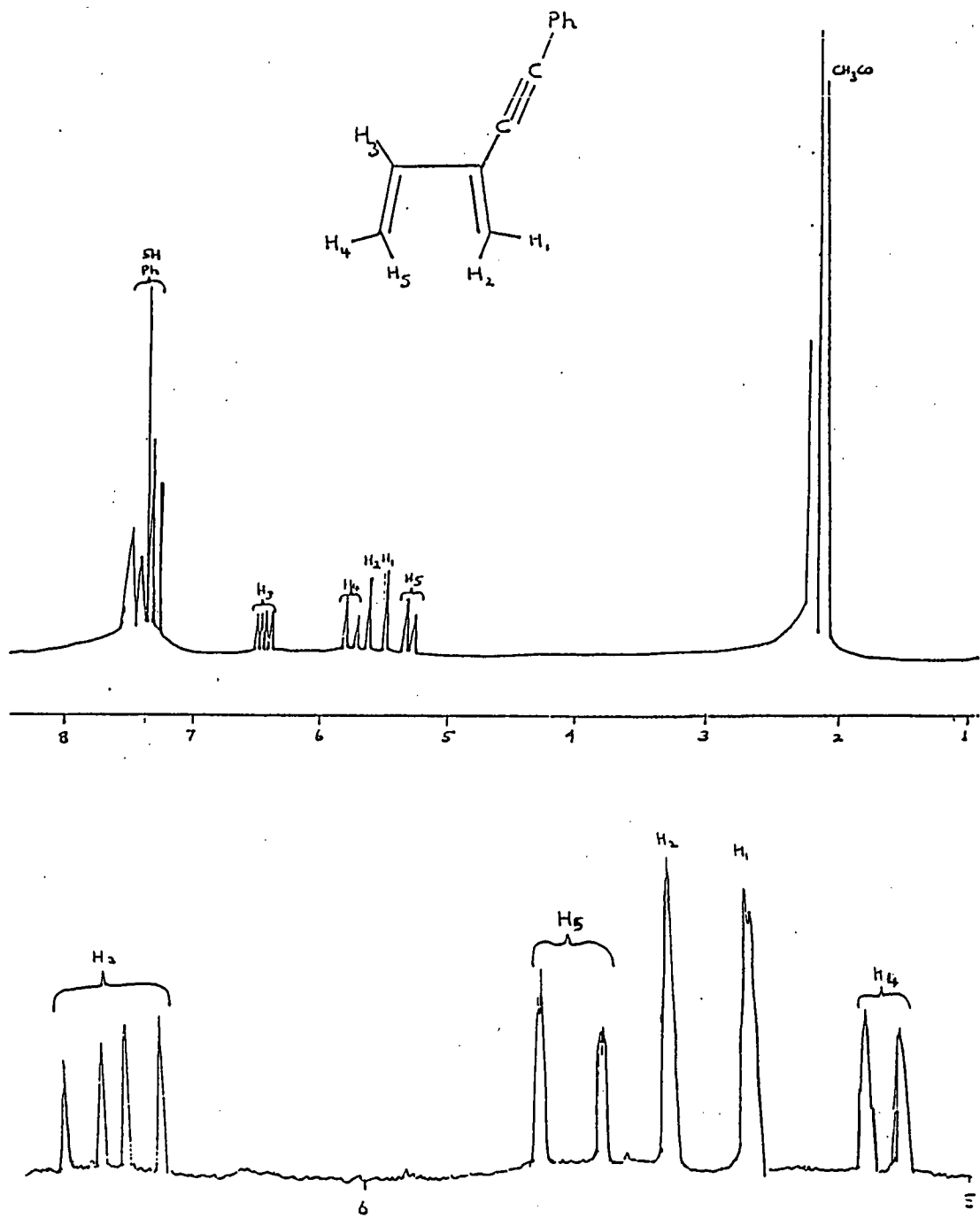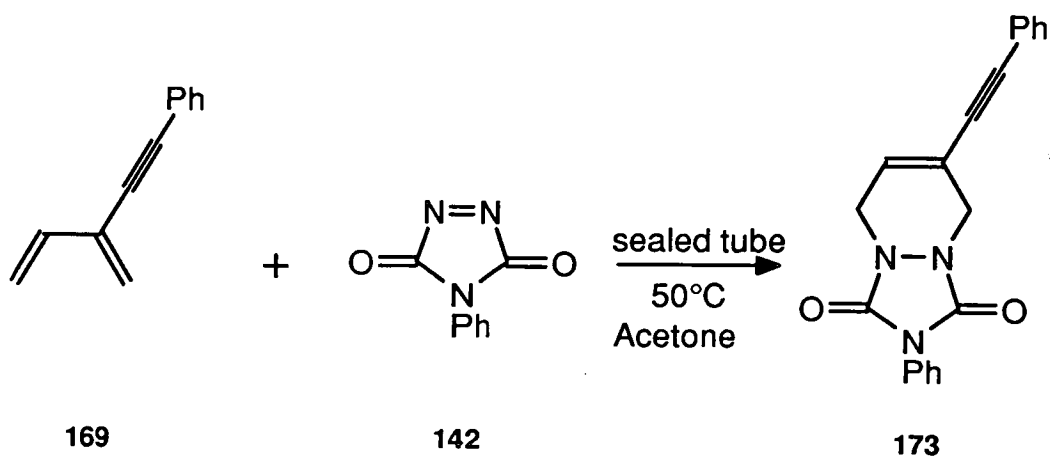

Scheme 79

Figure 13

A thorough literature search has failed to locate any reference to 2-phenylethynyl-1,3-butadiene **169** and it seems likely that this compound is a novel derivative of 1,3-butadiene and is a diphenyl analogue. It would be worthwhile studying the diene-transmissive properties of this diene, in order to determine whether **169** performs in a similar fashion to other 2-substituted 1,3-butadienes described in this thesis. A variety of dienophiles are known which could be expected to react with **169** in Diels-Alder type cycloadditions. Some such dienophiles are detailed in the Introduction (Section A) and include maleimide, 4-phenyl-1,2,4-triazoline-3,5-dione and DMAD to name a few. To date, there has only been time for one such cycloaddition, that with 4-phenyl-1,2,4-triazoline-3,5-dione, but spectroscopic analysis failed to give conclusive evidence that the expected adduct **173** of diene and dienophile had been formed (Scheme 90), although ^{1}H n.m.r. analysis did show peaks at δ 7.6-7.1 ppm for the phenyl protons and infrared spectroscopy showed absorbances (1780 cm^{-1}) corresponding to C=O absorbances.

Further to this, polymerisation of **169** must be carried out in order to determine whether the diene would act as a suitable monomer for polymer synthesis.
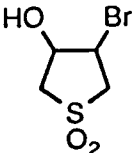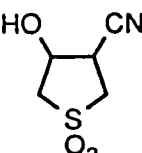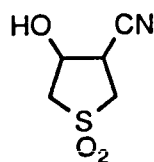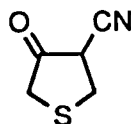

Scheme 80

EXPERIMENTAL

CONTENTS

B.   CYCLOADDITION REACTIONS OF 2-CYANO-
     1,3-BUTADIENE

3. FVP of

SYMBOLS AND ABBREVIATIONS

mol; mmol	moles; millimoles
ml; l	millilitres; litres
g; mg	gram; milligram
M	mol dm^{-3}
m.pt.; b.pt.	melting point; boiling point
Sublm.	sublimation
decomp.	decomposition
hr; min; s	hours; minutes; seconds
Lit.	literature
conc.	concentrated
Vol.	volume
Temp.	temperature
R.Temp.	room temperature
t.l.c.	thin layer chromatography
FAB	fast atom bombardment
CI	chemical ionization
EI	electron impact
f v p.	flash vacuum pyrolysis
m/z	mass to charge ratio
M^{+}	molecular ion mass
Calc	calculated molecular ion mass
n.m.r.	nuclear magnetic resonance
DEPT	distortionless enhancement by polarisation transfer
Q	quaternary carbon atom
δ	chemical shift

ppm	parts per million
J	spin-spin coupling constant
s; d; t; q; m	singlet; doublet; triplet; quartet; multiplet
irrad.	irradiation
O; Mp P	ortho; meta; para
I.R.	infrared
ν_{max}	maximum wave number
liq. cap. film	liquid capillary film
liq. film	liquid film
v/v	volume to volume

NOMENCLATURE

New compounds have been named in accordance with the IUPAC rules of nomenclature (1957) where possible.

PURIFICATION AND TECHNIQUES

1.   General Purification

(i)   Purification and Drying of Solvents and Gases

Commercially available AR solvents were used when high purity was required and these were normally dried over 4A molecular sieves.   Pyridine was dried over potassium hydroxide pellets as was triethylamine. 'Super dry' methanol and ethanol were obtained using the procedure outlined in vogel and stored over 4 Å molecular sieves. Toluene and diethyl ether were dried over sodium wire.   Tetrahydrofuran (THF) was purified by distillation from sodium under an argon atmosphere using a benzophenone indicator. Heptane and hexane were purified by distillation from calcium hydride under an argon atmosphere.

Organic extracts were dried using anhydrous magnesium sulfate by allowing the extract and drying agent to stand for ½ hr. The drying agent was filtered off and the solvent evaporated *in vacuo*.

Products that were not isolated from organic extracts were placed on a high vacuum oil pump for several hours to remove any traces of solvent and water.

Argon and nitrogen gases were dried through a series of dreschel vessels in the gas line containing sulfuric acid, calcium chloride granules and self-indicating silica.

(ii)   Chromatographic Techniques

(a)   Thin layer chromatography

Analytical t.l.c. was performed on aluminium backed Kieselgel 60 GF 254 silica plates with U.V. indicator. When the material was not sensitive to

U.V. light, plates were dipped in a sulfuric acid/dichloromethane (1:10) mix, allowed to dry in air and then charred using a microbunsen burner.

(b)   Dry flash chromatography

Kieselgel 60 (230-400 mesh) silica was used with water pump vacuums of 20-30 mm Hg.

(c)   Flash chromatography

Mixtures were separated on Kieselgel 60 silica. Air pressures of 10-15 psi were employed for flash column grades of silica. The solvent system was a mixture of petroleum ether and ethyl acetate or for more polar compounds petroleum ether (or hexane)/acetone or dichloromethane/acetone. The sample was applied to a column as a fairly concentrated solution (ca. 25% w/v) in the eluting solvent. In cases where the sample was not soluble enough in the eluent then the sample was pre-absorbed on to the adsorbent (silica 60). For air sensitive materials, nitrogen gas was used and the solvents were transferred with the aid of a double ended needle.

(d)   Soxhlet extraction

Some solids were found to be fairly insoluble in common solvents and were purified by soxhlet extraction. This involved placing the material to be purified in a soxhlet thimble where it could be continuously dissolved into the refluxing solvent. When most of the material had been removed from the thimble, the solution was cooled and the purified material precipitated out.

2.   General Techniques

(i)   Cycloaddition Reactions

Diels-Alder reactions were generally carried out in a sealed carius tube[96] that had been pre-rinsed with a galvinoxyl solution, ca. 5 mg of acetone and dried in a stream of warm air.

(ii)   Flash Vacuum Pyrolysis

A diagram detailing a standard flash vacuum pyrolysis apparatus is given in Figure 14 and the pyrolysis procedure is as follows: The liquid or solid sample is placed in the inlet tube and the apparatus is evacuated using an Eduardo high capacity rotary oil pump to pressures of 1×10^{-3} to 3×10^{-2} mol. The inlet tube is heated by means of a Kugelrohr oven to allow volatilisation of the sample to occur. The gaseous sample then passes through a preheated Stanton-Redcroft LM8100 tube furnace, which utilises a Pt/Pt 13% Rh thermocouple located in the centre of the furnace. The pyrolysate is finally condensed onto a liquid nitrogen cooled trap. When flash distillation of the pyrolysate is required a second trap is placed in the sequence and the first trap is allowed to warm to room temperature, while the more volatile components condense into the second trap which is cooled by liquid nitrogen. On completion of the pyrolysis, the apparatus is flooded with nitrogen gas and the traps allowed to reach room temperature before they are exposed to the air. The pyrolysate is then removed by dissolving it into a suitable solvent. FVP although initially appearing to be an undiscriminatingly brutal technique is however a delicate and selective process for bond cleavage.

Figure 14
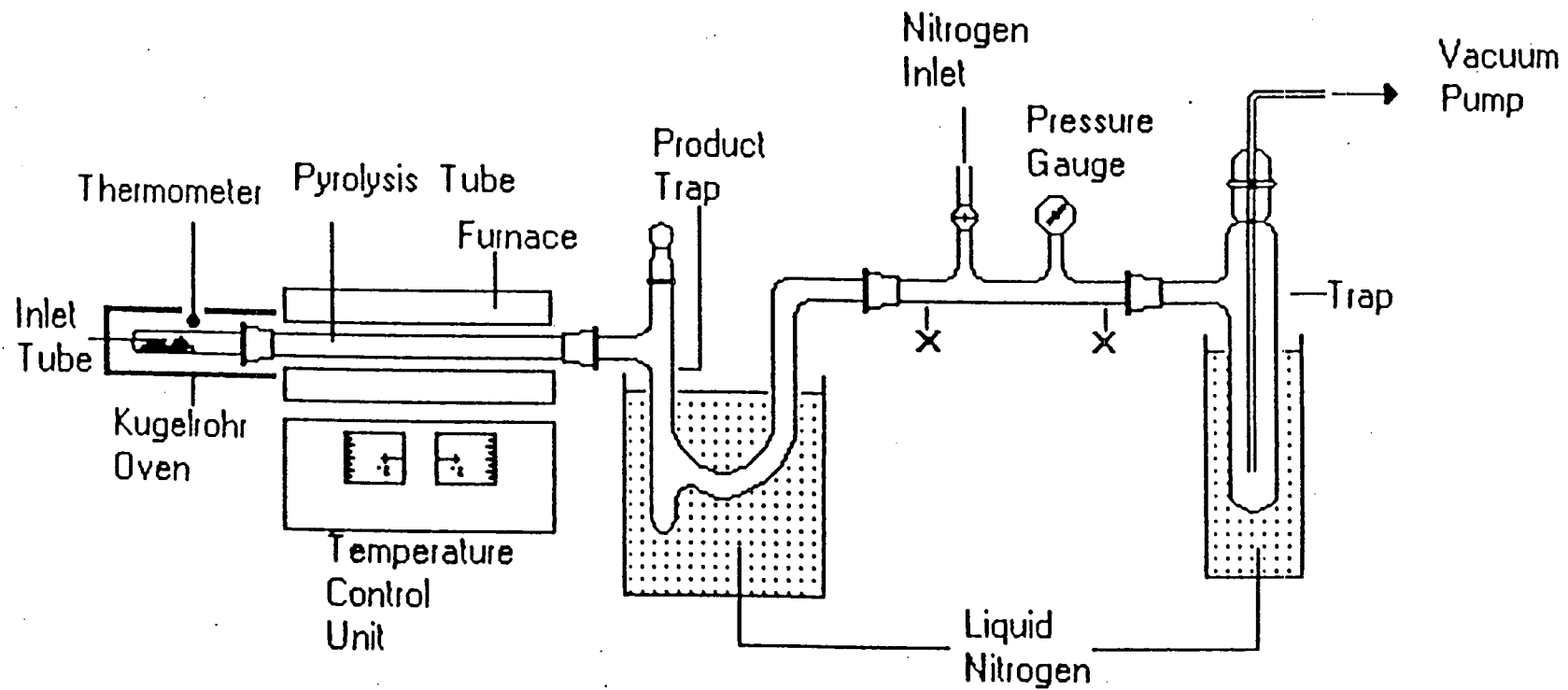
3. Analytical Techniques

(i) Melting Point Determination

Routine melting points were determined using a Gallenkamp melting point apparatus. For new compounds a Reichart hot stage microscope was employed.

(ii) Infrared Spectrometry

Infrared spectra were recorded on a Perkin Elmer 781 instrument. Samples were run neat as thin films or as a nujol mull on sodium chloride plates. All infrared spectra were references to polystyrene 1603 cm^{-1}, and their wavenumbers have been corrected accordingly.

(iii) Nuclear Magnetic Resonance (n.m.r.)

^{1}H and ^{13}C n.m.r. spectra that were recorded on the 80 MHz Bruker WP 80 and the 200 MHz Bruker 200 instruments were operated by Ms. H. Grant and Mr. J. Miller. Chemical shifts are reported in parts per million and are referenced to the deuterated solvent used ($CDCl_3$ or CD_3SOCD_3). All ^{13}C n.m.r. are broad band decoupled unless otherwise stated and DEPT coupled.

(iv) Mass Spectrometry

Low resolution EI mass spectra were recorded by Ms. E. Stevenson on an AEI MS-902 instrument, whereas high resolution EI and FAB mass spectra were obtained on a Kratos MS-50 spectrometer operated by Mr. A. Taylor.

A. PREPARATION OF 2-CYANO-1,3-BUTADIENE

1. Preparation of 3,4-Epoxytetrahydrothiophene-1,1-dioxide

A method similar to Gillam's[8] was used. To butadiene sulfone (28 g, 0.24 mol) was added 98% formic acid (140 ml) and hydrogen peroxide (33 ml) dropwise at 5-10°C. The mixture was stirred continuously for 216 hr at room temperature to produce colourless crystals of 3,4-epoxytetrahydrothiophene-1,1-dioxide (19 g, 69.8%) m.pt. 160-161°C from acetone (lit.[81] 159.5-160°C); ^{13}C n.m.r. $(CD_3SOCD_3$, 200 MHz, DEPT) δ[ppm]: 51.93(CH), 53.30(CH_2).

2. Preparation of 3-Bromo-4-hydroxytetrahydrothiophene-1,1-dioxide

The method of Cameron[102] was used.

To a stirred solution of 3,4-epoxytetrahydrothiophene-1,1-dioxide (5 g, 37.3 mmol) in glacial acetic acid (30 ml) was added hydrogen bromide in glacial acetic acid (3.25 g, 45% solution). The mixture was stirred at 0-5°C for ½ hr and then a further 4 hr at room temperature. After which time the mixture was filtered and the solvent removed *in vacuo* to produce colourless crystals of 3-bromo-4-hydroxytetrahydrothiophene-1,1-dioxide (3.6 g, 45%) m.pt. 188-190°C (lit.[103] 189-190°C); ^{13}C n.m.r. $(CD_3SOCD_3$, 200 MHz, DEPT) δ[ppm] 47.60 C3, 56.76 C2, 67.72 C5, 73.43 C4.

3. Attempted Preparation of 3-Cyano-4-hydroxytetrahydrothiophene-1,1-dioxide with DMSO

The method of Buchan[71] was employed. To 3-bromo-4-hydroxytetrahydrothiophene-1,1-dioxide (3.6 g, 16.8 mmol) was added dimethylsulfoxide (20 ml) and sodium cyanide (1 g, 20.4 mmol). The reaction mixture was heated to 70°C and stirred for 2 hr at this temperature. The

mixture was then diluted with water (50 ml) and extracted into diethyl ether (5 x 40 ml). The extracts were combined, washed with water (10 ml), dried over anhydrous magnesium cream coloured product (3.4 g) shown by m.pt. to be the starting material 3-bromo-4-hydroxytetrahydrothiophene-1,1-dioxide, m.pt. 186-188°C (lit.[103] 189-190°C).

4. Preparation of 3-Cyano-4-hydroxytetrahydrothiophene-1,1-dioxide from 3,4-Epoxytetrahydrothiophene-1,1-dioxide

To a stirred solution of 3,4-epoxytetrahydrothiophene-1,1-dioxide (1 g, 7.5 mmol) in dichloromethane (25 ml) was added potassium cyanide (0.5 g, 7.7 mmol) and tetrabutylammonium bromide (100 mg) in water (20 ml). The mixture was stirred vigorously for 20 hr. After which time the mixture was extracted into dichloromethane (4 x 30 ml), acidified with 2M hydrochloric acid (10 ml) and re-extracted into dichloromethane. The solvent was removed *in vacuo*. Recrystallisation from ethanol produced a light brown solid of 3-cyano-4-hydroxytetrahydrothiophene-1,1-dioxide (0.05 g, 60%), ν_{max} 3350(O-H), 3020(C-H), 2250(C$\equiv$N), 1300 and 1150(SO$_2$), ^{1}H n.m.r. (CD$_3$SOCD$_3$, 200 MHz) δ[ppm]: 2.99-3.57(6H, cm, H2, H5, H4, OH), 4.62-4.73(1H, m, H3); ^{13}C n.m.r. (CD$_3$SOCD$_3$, 80 MHz, DEPT) δ[ppm]: 33.65 C3, 59.92 C2, 58.81 C5, 67.56 C4, 117.84 CN; m.pt. 165-175°C.

5. Preparation of 3-Cyano-4-oxotetrathiophene

To dry toluene (150 ml) was added sodium methoxide (17.3 g, 0.32 mol), followed by methyl thioglycolate (35.7 g, 0.32 mol). Acrylonitrile (16.95 g, 0.32 mol) was added dropwise over 30 min to the stirred reaction mixture. The mixture was heated under reflux for 1 hr, after which time the heat source was removed and the mixture cooled in ice. Diethyl ether (100 ml) was added portionwise to remove the solid from the flask. The solid

was then dried over a sintered filter. This sodium salt of the product thus formed was added portionwise to a two-phase mixture of 2M sulfuric acid (50 ml) and dichloromethane (450 ml) and allowed to stir for ½ hr. The organic layer formed was extracted into dichloromethane (5 x 40 ml), the extracts combined, dried over anhydrous magnesium sulfate and decolourised with charcoal (2 g). The solvent was removed *in vacuo* to produce 3-cyano-4-oxotetrahydrothiophene (35.13 g, 88%) as an orange oil which solidified on standing. ν_{max} 3500(O-H), 3000, 2900(C-H), 2200(C$\equiv$N), 1750(C=O), m.pt. 70-72°C (lit.[87] 72°C). [1]H n.m.r. (CDCl$_3$, 60 MHz) δ[ppm]: 3.25-3.96(4H, cm, H2, H5), 4.75-5.01(1H, m, H3).

6. Preparation of 3-Cyano-4-hydroxytetrahydrothiophene

To a stirred solution of 3-cyano-4-oxotetrahydrothiophene (33.5 g, 0.265 mol) and ethanol (330 ml) was added sodium borohydride (10.0 g, 0.265 mol) in ethanol (10 ml) over 15 min. The mixture was stirred for 1 hr at room temperature and then treated with glacial acetic acid until effervescence ceased. Removal of the solvents *in vacuo* produced a brown semi-solid which was extracted into dichloromethane. The mixture was sinter filtered and the solvent evaporated *in vacuo* to produce a brown oil. This crude product was vacuum distilled (150°C, 0.4 mm Hg) to produce a clear orange oil of 3-cyano-4-hydroxytetrahydrothiophene (22.05 g, 65%), ν_{max} 3480(O-H), 3000(C-H), 2200(C$\equiv$N); [1]H n.m.r. (CDCl$_3$, 60 MHz) δ[ppm]: 3.01-3.52(6H, cm, H2, H5, H4, OH), 4.75-5.01(1H, m, H3).

7. Preparation of 3-Cyano-4-acetoxytetrahydrothiophene

(a) With acetyl chloride

To 3-cyano-4-hydroxytetrahydrothiophene (1 g, 7.8 mmol) in a test tube at 0°C was added pyridine (6.5 ml) and acetyl chloride (1.2 g,

15.3 mmol). The mixture was allowed to stir at 0°C for 15 min and then heated to 50°C for 15 min. After which time 2M hydrochloric acid (10 ml) was added until the mixture just became acidic. The mixture was then extracted into dichloromethane, dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a brown viscous oil, which was recrystallised from ethyl acetate and cleaned up using column chromatography to produce a colourless solid (1.29 g, 97%) of 3-cyano-4-acetoxytetrahydrothiophene; ν_{max} 3480(OH), 3000(C-H), 2200(C≡N), 1750(C=O), 1230(C-CO-O), 1000(CH_2); ^{1}H n.m.r. ($CDCl_3$, 60 MHz) δ[ppm]: 2.02(3H, s, CH_3), 2.96-3.80(5H, m, H2, H5, H4), 5.33-5.66(1H, m, H3).

(b)   With Acetic Anhydride

To 3-cyano-4-hydroxytetrahydrothiophene (1 g, 7.8 mmol) was added anhydrous sodium acetate (0.7 g, 8.5 mmol) and acetic anhydride (10 ml). The mixture was heated under reflux for 3 hr. The hot liquid was carefully poured into water (30 ml) with stirring and a saturated solution of sodium hydrogen carbonate (10 ml) was added until effervescence ceased. The mixture was then extracted into dichloromethane, washed with water, dried over anhydrous magnesium sulfate, decolourised by added charcoal (1 g) and filtering. Finally the solvent was removed *in vacuo* to produce 3-cyano-4-acetoxytetrahydrothiophene as a cream coloured solid (1.30 g, 98%). ν_{max} 3470(OH), 3000(C-H), 2200(C≡N), 1750(C=O), 1240(C-CO-O), 1000(CH_2).

8.   Preparation of 3-Cyano-4-hydroxytetrahydrothiophene-1,1-dioxide

(a)   With m-CPBA

To 3-cyano-4-hydroxytetrahydrothiophene (5 g, 38.8 mmol) was added m-chloroperoxybenzoic acid (16.7 g, 38.8 mmol) in dichloromethane (50 ml)

at 0°C. The mixture was stirred at 0-5°C for 3 hr and then overnight at room temperature. The mixture was then filtered through celite and extracted into dichloromethane (3 x 50 ml), the extracts were combined, dried over anhydrous magnesium sulfate, and the solvent removed *in vacuo* to produce a yellow solid of 3-cyano-4-hydroxtetrahydrothiophene-1,1-dioxide (3.33 g, 53%). ν_{max} 3350(O-H), 3020(C-H), 2250(C$\equiv$N), 1300 and 1150(SO$_2$); ^{1}H n.m.r. (CD$_3$SOCD$_3$, 200 MHz) δ[ppm]: 2.99-3.58(6H, cm, H2, H5, H4, OH), 4.63-4.74(1H, m, H3).

(b)   With MMPP[104]

To 3-cyano-4-hydroxytetrahydrothiophene (1.37 g, 10.6 mmol) was added ethanol (25 ml) and a solution of magnesium monoperoxyphthalic acid (MMPP) (5.1 g, 11.0 mmol) in ethanol (10 ml) and water (20 ml). The mixture was stirred vigorously for 4 hr at 50°C. The mixture was extracted into dichloromethane, dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce 3-cyano-4-hydroxytetrahydrothiophene-1,1-dioxide (1.40 g, 81.9%) as a colourless solid. ν_{max} 3340(O-H), 3020(C-H), 2230(C$\equiv$N), 1300 and 1150(SO$_2$). ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 2.98-3.60(6H, cm,H2, H5, H4, OH), 4.64-4.75(1H, m, H3).

9.   **Preparation of 3-Cyano-4-acetoxytetrahydrothiophene-1,1-dioxide**

From its Thiophene Derivative

To 3-cyano-4-acetoxytetrahydrothiophene (1 g, 5.9 mmol) was added m-chloroperoxybenzoic acid (2.1 g, 4.9 mmol) in dichloromethane (50 ml) at 0°C. The mixture was stirred at 0°C for 3 hr, then a further 3 hr at room temperature. The solvent was then removed *in vacuo* and the product washed with a saturated sodium bicarbonate solution and then extracted into

ethyl acetate, dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce colourless crystals of 3-cyano-4-acetoxytetrahydrothiophene-1,1-dioxide (0.84 g, 70%), m.pt. 100-102°C, ν_{max} 3020(C-H), 2250(C≡N), 1745(C=O), 1310 and 1150(SO$_2$, 1220(C-O): ^{1}H n.m.r. (CD$_3$SOCD$_3$, 200 MHz) δ[ppm]: 2.09(3H, s, CH$_3$), 3.31-3.80(5H, m, H2, H5, H4), 5.53-5.61(1H, m, H3); ^{13}C n.m.r. (CD$_3$SOCD$_3$, 80 MHz) δ[ppm]: 20.53(CH$_3$), 31.10 C3, 50.76 C2, 55.47 C5, 68.47 C4, 116.43(CN), 169.47(CO).

10. Flash Vacuum Pyrolysis of 3-Cyano-4-acetoxytetrahydro-thiophene-1,1-dioxide

All pyrolysis glassware was rinsed with a solution of galvinoxyl (ca. 5 mg) in acetone (25 ml) and then dried in a stream of hot air.

FVP [120°C, 675°C, 1 x 10^{-2} mm Hg] of 3-cyano-4-acetoxytetrahydrothiophene-1,1-dioxide (0.1 g, 0.5 mmol), followed by flash distillation of the pyrolysate into a second liquid nitrogen cooled trap resulting in the isolation of 2-cyano-1,3-butadiene as a light brown coloured oil (0.03 g, 79%) b.pt. 25°C (lit.[75] 24-31°C, 30 mm Hg), m/z 79(M$^{•+}$), 52(M-C$_2$H$_3^+$), 39(C$_2$HN$^+$), ν_{max} 3095(C-H str), 2240(C≡N), 1650(C=C), 995(C-H); ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 5.45-5.71(2H, s, fs, H$_a$ and H$_b$), 5.8(1H, d, H$_e$ J$_{trans}$ 17.37 Hz), 6.37(1H, dd, H$_c$ J$_{trans}$ 17.16 Hz); ^{13}C n.m.r. (CDCl$_3$, 200 MHz), 115.77(CN), 120.71 C2, 122.36 C3, 130.21 C5, 131.93 C4.

11. Preparation of 1-Hydroxycyclohexane Bisulfite

To cyclohexanone (10 g, 0.1 mol) was added dropwise a 40% solution of sodium hydrogen sulfite (10.4 g in 16 ml water). The mixture was warmed to 30°C and stirred for 1 hr. A colourless precipitate resulted, which was dried under suction to produce 1-hydroxycyclohexane bisulfite (20.2 g, 98%),

m.pt. >210°C; ν_{max} 3500(O-H), 2950 and 2860(C-H), 1405(-SO$_2$-O-), 950-650(C-H aromatic).

12. Preparation of 1-Hydroxy-1-cyanocyclohexane

To 1-hydroxycyclohexane bisulfite (20.2 g, 0.1 mol) was added an aqueous solution of potassium cyanide (6.6 g, 0.10 mol) in water (20 ml). The mixture was stirred for 1 hr. The product was extracted into diethyl ether (3 x 40 ml), washed with sodium hydrogen carbonate solution and dried over anhydrous magnesium sulfate. The solvent was removed *in vacuo* and the product vacuum distilled (60°C, 0.3 mm Hg) to produce 1-hydroxy-1-cyanocyclohexane as a colourless oil (6.9 g, 55.2%); ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 1.52-1.78(10H, m, H$_{1-5}$), 2.22(1H, s, OH); m.pt. 32-36°C (lit.[106] 32-35°C).

13. Flash Vacuum Pyrolysis of 1-HYDROXY-1-cyanocyclohexane

All pyrolysis glassware was rinsed with a galvinoxyl solution and dried in air.

FVP [80°C, 600°C, 2 x 10^{-2} mm Hg] of 1-hydroxy-1-cyanocyclohexane (70 mg, 0.56 mmol) with the furnace tube packed with zeolite[105] (0.9 mm pellets) produced a brown oil, which was shown by ^{1}H n.m.r. to be benzene; ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 7.4 ppm(C-H).

14. Preparation of 1-Acetoxy-1-cyanocyclohexane

(a) With Acetyl Chloride

To 1-hydroxy-1-cyanocyclohexane (1.04 g, 8.3 mmol) was added dry pyridine (1 ml) and acetyl chloride (2 ml) at 0°C. The mixture was stirred for 15 min and then heated for 15 min at 50°C. 2M hydrochloric acid (5 ml) was

added and the product extracted into diethyl ether, washed with a saturated solution of sodium hydrogen carbonate (5 ml) and dried over anhydrous magnesium sulfate. The solvent was removed *in vacuo* and the product vacuum distilled (50°C, 0.3 mm Hg) to produce a pale yellow solid of 1-acetoxy-1-cyanocyclohexane (0.84 g, 60.5%), m.pt. 44.5°C (lit.[106] 43-44°C), ν_{max} 2940 and 2860(C-H), 2250(C≡N), 1750(CO), 1450 and 1370(C-H), 1225(C-O), 1150(C-O), 1050(C-H), <800 (aromatic C-H); [1]H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 2.08(3H, s, CH$_3$), 1.55-1.80(10H, m, H1-5).

(b)   **With DMAP**

To 1-hydroxy-1-cyanocyclohexane (1.5 g, 12 mmol) was added acetic anhydride (1.53 g, 15 mmol), triethylamine (1.82 g, 18 mmol) and dimethylaminopyridine (0.5 g, 4.1 mmol). The mixture was stirred for 1 hr at room temperature. Diethyl ether (30 ml) and 2 M hydrochloric acid (10 ml) were then added to the mixture. The product was extracted into diethyl ether (4 x 50 ml), dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a yellow oil which was vacuum distilled (70°C, 0.3 mm Hg) to produce a pale yellow solid of 1-acetoxy-1-cyanocyclohexane (1.09 g, 55%).   m.pt. 45°C (lit.[106] 43-44°C), ν_{max} 2940 and 2860(C-H), 2240(C≡N), 1750(CO), 1370(C-H), 1200(CO) <800 (aromatic C-H).

15.   Preparation of 1-Cyanocyclohexene

All pyrolysis glassware was rinsed with a galvinoxyl solution and dried in a stream of air.

FVP [90°C, 700°C, 2 x 10^{-2} mm Hg] of 1-acetoxy-1-cyanocyclohexane resulted in the isolation of 1-cyanocyclohexene (41 mg, 11.4%) as a yellow oil, ν_{max} 2950 and 2860(C-H), 2250(C≡N), 1640(C=C), 1430(C=C),

<800(aromatic C-H); ^{1}H n.m.r. (CDCl$_3$, 60 MHz) δ[ppm]: 1.41-1.85(4H, m, H1, H2), 2.10-2.51(4H, m, H3, H4), 6.60-6.82(1H, m, H5).

16.   Flash Vacuum Pyrolysis of 1-Cyanocyclohexene

All pyrolysis glassware was rinsed with a galvinoxyl solution and dried in a stream of air.

FVP [40°C, 850°C, 6 x 10^{-2} mm Hg] of 1-cyanocyclohexene (0.85 g, 7.9 mmol) produced a yellow oil of 2-cyano-1,3-butadiene (0.5 g, 91.8%), ν_{max} 2950 and 2860(C-H), 2250(C≡N), 1630(C=C), 1410(C=C), 1280 and 920(C=CH$_2$); ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 5.45-5.71(2H, s, fs, H$_a$, H$_b$), 5.8(1H, d, H$_e$ J$_{trans}$ 17.40 Hz), 6.37(1H, dd, H$_c$, J$_{trans}$ 17.21 Hz); ^{13}C n.m.r. (CDCl$_3$, 200 MHz), 115.77(CN), 120.71 C2, 122.36 C3, 130.24 C5, 132.00 C4.

17.   FVP of 1-Acetoxy-1-cyanocyclohexene

FVP [100°C, 850°C, 3 x 10^{-2} mm Hg] of 1-acetoxy-1-cyanocyclohexane (0.47 g, 2.8 mmol) produced a yellow oil of 2-cyano-1,3-butadiene (0.18 g, 81%),
ν_{max} 2950 and 2870(C-H), 2240(C≡N), 1630(C=C), 1410(C=C), 1280 and 920(C=CH$_2$); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 115.77(CN), 120.72 C2, 127.38 C3, 130.21 C5, 131.93 C4.

B.   CYCLOADDITION REACTIONS OF 2-CYANO-1,3-BUTADIENE

1.   Preparation of
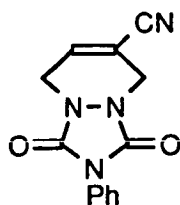
To 2-cyano-1,3-butadiene (0.3 g, 3.8 mmol) was added 4-phenyl-1,2,4-triazoline-3,5-dione (0.75 g, 4.3 mmol) in acetone (12 ml). The mixture was stirred in a carius sealed tube[96] and heated at 40°C for 38 hr. After which time the acetone was removed *in vacuo*, dichloromethane added and the mixture placed in a freezer at -20°C overnight. A colourless solid   (0.6 g, 55%) was produced, m.pt. >180°C (decomposition occurs at 180°C), ν_{max} 3450(O-H), 3150(C-H), 2220(C≡N), 1800(C=O), 1700(C=C), <800(aromatic C-H); m/z 254($M^{\bullet+}$), 177($M-C_5H_3N$), 119($M-C_6H_5N_3O^+$), 77(N-Ph); ^1H n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 2.36-2.40(4H, m (CH_2)), 3.30-3.24(1H, t, CH), 7.41-7.52(5H, m, Ph); ^{13}C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 120.01(CH), 125.1(CH_2), 126.4(CH_2), 137.00(CN), 153.46(C=O).

2.   Preparation of 1-Cyano-4-methylketocyclohex-1-ene

To 2-cyano-1,3-butadiene (0.11 g, 1.3 mmol) was added dry toluene (20 ml) and methylvinyl ketone (0.71 g, 10 mmol) in a carius sealed tube. The mixture was heated at 60°C for 12 hr and then allowed to cool. The solvent was removed *in vacuo* to produce a yellow solid which was cleaned up using column chromatography to produce a colourless solid of 1-cyano-4-methylketocyclohexene (0.18 g, 86.8%); ν_{max} 2970(C-H), 2230(C≡N), 1800 and 1720(CO), 1450(C=C), 1240(C-H), <800(aromatic C-H); ^1H n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 1.61-2.80(7H, m, CH_2, H1), 2.24(1H, s, H5), 6.71(3H, s, (CH_3)).

C.   PREPARATION OF [3]DENDRALENE

1.   Preparation of 1-Vinyl-1-hydroxycyclohexane

Vinylmagnesium bromide[106] 1.0 M solution (24 ml) was placed in a flame-dried three-necked flask under an argon atmosphere. To this solution was added dropwise cyclohexanone (2.12 g, 21.6 mmol) in dry tetrahydrofuran (20 ml). The mixture was heated to reflux for 1 hr. After cooling to room temperature 10% sulfuric acid (10 ml) was added together with water (50 ml). The mixture was then extracted into diethyl ether (5 x 50 ml), dried over anhydrous magnesium sulfate and finally the solvent removed *in vacuo*. The product was vacuum distilled (55°C, 0.2 mm Hg) resulting in a clear oil (1.1 g) of 1-vinyl-1-hydroxycyclohexane, ν_{max} 3375(O-H), 2930 and 2850(C-H), 1490(C=C), 1410(C=C), 1250, 1170(C-H), 980, 960, 850(C-H aromatic); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 21.74(CH$_2$), 25.32(CH$_2$), 37.25(CH$_2$), 71.41(C-OH), 111.15(vinyl CH$_2$), 145.88(vinyl CH).

2.   Preparation of 1-Vinyl-1-acetoxycyclohexane

To 1-vinyl-1-hydroxycyclohexane (1.04 g, 8.2 mmol) was added acetic anhydride (1.05 g, 10.3 mmol), triethylamine (1.25 g, 12.4 mmol) and dimethylaminopyridine (0.2 g, 1.6 mmol). The mixture was stirred at room temperature for 17 hr. Diethyl ether (50 ml) was added, the mixture was filtered under suction and then washed with ice-cold 2 M hydrochloric acid (10 ml), followed by a saturated solution of sodium hydrogen carbonate (10 ml). The mixture was then re-extracted into diethyl ether (4 x 40 ml), dried over anhydrous magnesium sulfate and the solvent removed *in vacuo*. The product was vacuum distilled (60°C, 30 mm Hg) to produce a clear oil of 1-vinyl-1-acetoxycyclohexane (1.06 g, 76%), ν_{max} 2950 and 2850(C-H), 1740(C=O), 1460(C=C); ^{1}H n.m.r. (CDCl$_3$, 60 MHz) δ[ppm]: 1.32-1.74(10H, m,

(CH_2)), 2.05(3H, s, (CH_3)), 5.06-5.42(2H, m, vinyl (CH_2)), 5.98-6.45(1H, m, vinyl (CH)).

3.   Preparation of 1-Vinylcyclohexene

FVP [85°C, 700°C, 3 x 10^{-3} mm Hg) of 1-vinyl-1-acetoxycyclohexane (0.46 g, 2.74 mmol), followed by flash distillation into a 2nd pyrolysis trap at liquid nitrogen temperatures afforded a colourless oil of 1-vinylcyclohexene in 91% yield (0.27 g); [13]C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 24.35(CH_2), 27.87(CH_2), 30.48(CH_2), 37.09(CH), 111.79(vinyl CH_2), 126.33(vinyl CH).

4.   Flash Vacuum Pyrolysis of 1-Vinylcyclohexene

FVP [80°C, 800°C, 3 x 10^{-3} mm Hg] of 1-vinylcyclohexene (0.34 g, 3.15 mmol), followed by flash distillation into a second pyrolysis trap afforded a colourless oil of [3]dendralene[8] (0.23 g, 91.3%); [1]H n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 5.13-5.17(2H, d, H6, J_{cis} 11 Hz, J_{gem} 2Hz), 5.15(2H, s, H1), 5.40(2H, dd, H5, J_{trans} 18 Hz, J_{gem} 2 Hz), 6.46(2H, dd, H4, J_{trans} 18 Hz, J_{cis} 11 Hz); [13]C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 115.39(CH_2, 115.33(CH_3), 135.62(vinyl CH_2).

5.   Flash Vacuum Pyrolysis of 1-Vinyl-1-acetoxycyclohexane

FVP [80°C, 700°C, 3 x 10^{-2} mm Hg] of 1-vinyl-1-acetoxycyclohexane (0.57 g, 4.5 mmol), followed by extraction into deuterated chloroform. Solvent removed *in vacuo* to produce a light brown oil of [3]dendralene[8] (0.28 g, 77.4%); [1]H n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 5.13-5.18(2H, d, H6, J_{cis} 11 Hz, J_{gem} 2 Hz), 5.15(2H, s, H1), 5.42(2H, dd, H5, J_{trans} 18 Hz, J_{gem} 2 Hz), 6.45(2H, dd, H4, J_{trans} 18 Hz, J_{cis} 11 Hz).

D.   ATTEMPTED PREPARATION OF 2-ETHYNYL-1,3-BUTADIENE FROM BUTADIENE SULFONE

1.   Attempted Preparation of 3-Ethynyl-4-hydroxytetrahydro-thiophene-1,1-dioxide

(a)   With Sodium Acetylide Slurry

To 3,4-epoxytetrahydrothiophene-1,1-dioxide (3 g, 22.4 mmol) was added dry tetrahydrofuran (30 ml) and sodium acetylide 18% slurry in mineral oil (6 ml, 22.5 mol) at 0°C. The mixture was stirred for 1 hr at 0°C and then 18 hr at room temperature. After which time the mixture was added to an ice/water mixture (100 ml) and concentrated sulfuric acid (10 ml) was added. The solvent was removed *in vacuo* and the products were extracted into dichloromethane (100 ml). The mixture was then dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a brown oil (1.72 g, 58%) shown by n.m.r. to be 4-hydroxy-2,5-dihydrothiophene-1,1-dioxide; ^{13}C n.m.r. (CD$_3$SOCD$_3$, 200 MHz) δ[ppm]: 56.83 C2, 67.49 C3, 132.80 C5, 143.15 C4.

(b)   From 3-Bromo-4-hydroxytetrahydrothiophene-1,1-dioxide

To 3-bromo-4-hydroxytetrahydrothiophene-1,1-dioxide (5 g, 23.0 mmol) was added tetrahydrofuran (30 ml) and sodium acetylide slurry (6.2 ml, 24 mmol) at 0°C. The mixture was stirred at room temperature for 14 hr. Water (100 ml) and concentrated sulfuric acid (10 ml) were added and the mixture extracted into diethyl ether. This mixture was then dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a cream coloured semi-solid of 4-hydroxy-2,5-dihydrothiophene-1,1-dioxide (3.46 g, 69%); ^{13}C n.m.r. (CD$_3$SOCD$_3$, 200 MHz) δ[ppm] 56.83 C2, 67.49 C3, 132.80 C5, 143.15 C4.

(c)   With Lithium Acetylide Complex

To a solution of lithium acetylide ethylene diamine complex (0.96 g, 10 mmol) in dry tetrahydrofuran (50 ml) was added 3,4-epoxytetrahydrothiophene-1,1-dioxide (1.4 g, 10 mmol) in dry tetrahydrofuran (20 ml). The mixture was warmed to 50°C and stirred for 1 hr, after which time the mixture was cooled to room temperature and stirred for a further 4 hr. Water (20 ml) was added and the mixture refluxed for 1 hr. The solvent was removed *in vacuo* and the mixture extracted into dichloromethane (5 x 50 ml), dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce an orange viscous oil (1.2 g, 85%) of 4-hydroxy-2,5-dihydrothiophene-1,1-dioxide; ^{13}C n.m.r. (CD_3COCD_3, 200 MHz) δ[ppm]: 56.83 C2, 67.49 C3, 132.80 C5, 143.15 C4.

(d)   With 4-Hydroxy-2,5-dihydrothiophene-1,1-dioxide

To 4-hydroxy-2,5-dihydrothiophene-1,1-dioxide (3.5 g, 0.026 mmol) was added to dry tetrahydrofuran (30 ml) and sodium acetylide 18% slurry in mineral oil (7 ml, 26.25 mmol) at 0°C. The mixture was stirred for ½ hr at 0°C then 20 hr at room temperature. After which time the mixture was added to an ice/water mixture (100 ml) and conc. sulfuric acid (10 ml) was added. The solvent was removed *in vacuo* and the products were extracted into dichloromethane (5 x 50 ml). The mixture was then dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a brown oil (2.98 g, 85%), shown by n.m.r. to be the starting material; ^{13}C n.m.r. (CD_3SOCD_3, 200 MHz) δ[ppm]: 56.89 C2, 67.50 C3, 132.81 C5, 143.42 C4.

2.   **Preparation of 4-Hydroxy-2,5-dihydrothiophene-1,1-dioxide**

To 3,4-epoxytetrahydrothiophene-1,1-dioxide (2.1 g, 20 mmol) was added an aqueous suspension of barium carbonate (1.9 g, 9.6 mmol) in water

(30 ml). The mixture was heated to 100°C and stirred for 1 hr at this temperature. After which time the mixture was hot filtered to remove any excess barium carbonate and then the water removed *in vacuo* to produce a clear viscous oil, which solidified on standing and was shown by I.R. to be 4-hydroxy-2,5-dihydrothiophene-1,1-dioxide[107] (2.5 g, 93%), ν_{max} 3350(O-H), 2960 and 2870(C-H), 1460(C=C), 1300 and 1150(SO_2), m.pt. 40-42.5°C; [13]C n.m.r. (CD_3SOCD_3, 200 MHz) δ[ppm]: 56.83 C2 (CH_2, 67.49 C3, 132.80 C5, 143.14 C4.

3.   Attempted Bromination of 3-Vinyl-4-acetoxytetrahydrothiophene-1,1-dioxide

Using a method detailed in Vogel[108], to a stirred solution of 3-vinyl-4-acetoxytetrahydrothiophene-1,1-dioxide[8] (0.91 g, 4.4 mmol) in chloroform (30 ml) was added bromine (1.2 g, 7.7 mmol) in chloroform (30 ml). The mixture was heated to 60°C and stirred for 1 hr at this temperature and then overnight at room temperature. The solvent was removed *in vacuo* to produce a brown solid (0.85 g, 94%) of the starting material. 3-Vinyl-4-acetoxytetrahydrothiophene-1,1-dioxide, m.pt. 110-112°C (lit.[7] 110°C); [13]C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 20.25(CH_3), 43.75 C4, 52.75 C5, 58.41 C2, 71.66 C3, 118.80 vinyl (CH_2), 131.75 vinyl (CH), 169.36(CO).

E. PREPARATION OF 2-ETHYNYL-1,3-BUTADIENE

1. Preparation of 1-Ethynyl-1-hydroxycyclohexane

To cyclohexanone (2 g, 20.4 mmol) was added dry diethyl ether (30 ml) and sodium acetylide slurry (5.45 ml of an 18% slurry, 20.4 mmol) dropwise over 15 min. The mixture was stirred for 14 hr at room temperature. Water (30 ml) and concentrated sulfuric acid (5 ml) were added and the products extracted into diethyl ether (5 x 40 ml), dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a yellow oil, which was placed on a high vacuum rotary evaporator to remove the mineral oil from the slurry. A clear/yellow oil of 1-ethynyl-1-hydroxycyclohexane (1.76 g, 70%) was produced, ν_{max} 3300(OH), 2960 and 2870(C-H), 3310(C≡CH), 1460 (CH$_2$), <800(aromatic C-H); m.pt. 32-33°C (lit.[106] 31-33°C); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 23.36(CH), 39.78(CH$_2$), 68.53(C≡C), 77.53(CH); ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 1.45-1.89(5H, m, CH), 2.51(1H, s, C≡CH), 2.8(1H, s, b, OH).

2. Preparation of 1-Ethynyl-1-acetoxyhexane

To 1-ethynyl-1-acetoxycyclohexane (10 g, 81 mmol) was added anhydride (10.8 g, 0.1 mol) triethylamine (12.5 g, 0.12 mol) and dimethylaminopyridine (0.5 g, 4.1 mmol). The mixture was stirred in an ice/water bath for ½ hr, then overnight at room temperature. The mixture was then extracted into diethyl ether, dried over magnesium sulfate and the solvent removed *in vacuo*. The product was then vacuum distilled (100°C, 0.5 mm Hg) to produce a clear oil (11.0 g, 82%) of 1-ethynyl-1-acetoxycyclohexane, ν_{max} 3340(O-H), 3300(C≡CH), 2960 and 2870(C-H), 1750 and 1700(CO), 1450(CH$_2$) <800(aromatic C-H), ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 22.10(CH$_3$), 36.56(CH$_2$), 73.98(C≡C), 76.90(CH), 168.84(C=O).

3. **Flash Vacuum Pyrolysis of 1-Ethynylcyclohexene**

FVP [100°C, 800°C, 3 x 10^{-2} mm Hg] of 1-ethynylcyclohexene (0.5 g, 4.7 mmol) through a furnace tube two-thirds full of quartz glass wool produced a light brown oil, shown by n.m.r. to be 2-ethynyl-1,3-butadiene (0.31 g, 84.3%); ν_{max} 3315 and 2100(-C≡C-H), 3102, 3019, 1297, 979 and 918(C=CH$_2$), 15.72(C=C conjugated); m/z 78(M$^{\bullet+}$), 63(M-CH$_3^+$), 50(M-C$_2$H$_4^+$), 39(C$_3$H$_3^+$); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 28.92 C2, 79.45(C≡C), 117.95 C3, 128.25 C4; ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 3.04(1H, s, C≡CH), 5.14-5.25(2H, d, H5), 5.51(1H, s, H1), 5.54-5.85(1H, d, H4), 6.12-6.60(1H, dd, H3).

4. **Flash Vacuum Pyrolysis of 1-Ethynyl-1-acetoxycyclohexane**

(a) **At 650°C**

All pyrolysis glassware was rinsed with a galvinoxyl solution and then air dried.

FVP [70°C, 650°C, 2 x 10^{-2} mm Hg] of 1-ethynyl-1-acetoxycyclohexane (0.1 g, 4.2 mmol), followed by extraction into diethyl ether (50 ml), washing with a saturated solution of sodium hydrogen carbonate (10 ml) and drying over anhydrous magnesium sulfate, followed by removal of the solvent *in vacuo* produced a clear oil of 1-ethynylcyclohexene (0.40 g, 89%), ν_{max} 3300(C≡CH), 2960 and 2880(C-H), 1460(C=C).

(b) **At 875°C**

FVP [70°C, 875°C, 4 x 10^{-2} mm Hg] of 1-ethynyl-1-acetoxycyclohexane (0.5 g, 3 mmol), followed by extraction into diethyl ether (50 ml), washing with a saturated solution of sodium hydrogen carbonate, drying over anhydrous magnesium sulfate and removal of the solvent *in vacuo* produced a light brown oil of 2-ethynyl-1,3-butadiene (0.21 g, 89.4%), ν_{max} 3315 and 2100

(-C≡C-H), 3102 and 3019(C-H), 1572(C=C conjugated), 1297, 979 and 918(C=CH$_2$); ^{13}C n.m.r. (CDCl$_3$, 200 MHz), δ[ppm]: 28.93 C2, 79.45(C≡C), 117.94 C3, 128.30 C4, 130.01 C5; ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 3.04(1H, s, H(C≡CH)), 5.14-5.25(2H, d, H5), 5.51(1H, s, H1), 5.54-5.85(1H, d, H4), 6.12-.6.60(1H, dd, H3).

(c) With Quartz Glass Wool in Furnace Tube

FVP [70°C, 875°C, 3 x 10^{-2} mm Hg] of 1-ethynyl-1-acetoxycyclohexane (0.5 g, 3 mmol), through a furnace tube, packed two-thirds full with quartz glass wool produced a brown oil, shown by ^{1}H n.m.r. to be a mixture of benzene and 2-ethynyl-1,3-butadiene (1:3, 0.4 g), ν_{max} 3315(C≡CH), 2960 and 2870(C-H), 1570(C=C conj.), 1290 and 920(C=CH$_2$); ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 3.05(1H, s, H(C≡CH)), 5.14-5.25(2H, d, H5), 5.51(H1, s, H1), 5.54-5.85(1H, d, H4), 6.12-6.60(1H, dd, H3), 7.4(C-H benzene); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 28.93 C2, 79.45(C≡C), 117.94 C3, 128.30 C4, 130.04 C5.

F. PREPARATION OF 2-PHENYLETHYNYL-1,3-BUTADIENE

1. Preparation of 3-Phenylethynyl-4-hydroxytetrahydrothiophene-1,1-dioxide

A three-necked flask was set up with reflux condenser, stirrer bar and pressure-equalised dropping funnel. Magnesium turnings (1.2 g, 50 mmol) were placed in the flask with a few crystals of resublimed iodine. Ethyl bromide (5.46 g, 50 mmol) in dry diethyl ether (50 ml) was added dropwise to the magnesium turnings. Approximately 20 ml of ethyl bromide solution (in ether) was added to initiate the reaction. Initiation of the reaction was shown by gentle refluxing. Once reflux had begun the remaining ethyl bromide solution was added at such a rate that steady refluxing of the mixture was maintained without an external heat source. The mixture was refluxed for a further 2 hr to ensure that all of the magnesium turnings had reacted, then cooled and to it was added dropwise a solution of phenylacetylene (5.6 g, 50 mmol) in dry diethyl ether (30 ml). The mixture was refluxed gently for 2 hr and then cooled to room temperature. To this cooled mixture was then added a suspension of 3,4-epoxytetrahydrothiophene-1,1-dioxide (6.7 g, 50 mmol) in dry diethyl ether (40 ml), stirred at 5°C for 1 hr then a further 1 hr at room temperature. Finally the mixture was refluxed for 1 hr, allowed to cool, washed with a saturated ammonium chloride solution and extracted into diethyl ether (5 x 40 ml). The solvent was dried over anhydrous magnesium sulfate and removed *in vacuo* to produce a yellow oil, which was vacuum distilled (100°C, 30 mm) to produce a clear oil (6.07 g, 51.5%) of 3-phenylethynyl-4-hydroxytetrahydrothiophene-1,1-dioxide; m/z 236($M^{\bullet+}$), 128($C_{10}H_8^+$), 43($C_3H_7^+$), ν_{max} 3350(O-H), 2960 and 2870(C-H), 2100($C \equiv C$ str), 1300 and 1150(SO_2), 1060(C-H), <800(Ph); ^{13}C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 53.48 C2, 69.46 C3, 86.65($C \equiv C$), 131.65 C4, 132.74 C5.

2.   Preparation of 3-Phenylethynyl-4-acetoxytetrahydrothiophene-1,1-dioxide

(a)   With DMAP

To a solution of 3-phenylethynyl-4-hydroxytetrahydrothiophene-1,1-dioxide (3.44 g, 14.6 mmol) in dry tetrahydrofuran (30 ml) at 0°C was added acetic anhydride (2 ml, 28 mmol) dropwise, triethylamine (3 ml, 22 mmol) dropwise and DMAP (0.1 g, 0.82 mmol). The mixture was stirred at 0-5°C for ½ hr then 16 hr at room temperature, after which time citric acid (2 g) in water (20 ml) was added. The solvent was removed *in vacuo* and the mixture extracted into dichloromethane, dried over anhydrous magnesium sulfate and finally the solvent removed *in vacuo* to produce a colourless solid of 3-phenylethynyl-4-acetoxytetrahydrothiophene-1,1-dioxide (3.4 g, 83.5%); m/z 278($M^{•+}$), 128($M-C_3H_5O_4S^+$), 43($C_3H_7^+$), 30($C_2H_6^+$), ν_{max} 2960 and 2880(C-H), 2110(C≡C), 1750(CO), 1300 and 1150(SO_2), <800(Ph), m.pt. 143.3-148.1°C; ^{13}C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 20.64(CH_3), 33.02 C3, 53.48 C2, 56.87 C5, 59.06 C4, 84.68(C≡C), 137.35-128.83(Ph-CH).

(b)   With Acetyl Chloride

To a stirred solution of 3-phenylethynyl-4-hydroxytetrahydrothiophene-1,1-dioxide (5.72 g, 24 mmol) in dry tetrahydrofuran (40 ml) was added triethylamine (16 ml, 0.12 mmol) and acetyl chloride (5 g, 64 mmol) in dry tetrahydrofuran (10 ml). The mixture was stirred at 0°C for ½ hr then at room temperature for 25 hr. The mixture was then extracted into diethyl ether, dried over anhydrous magnesium sulfate and the solvent removed *in vacuo* to produce a cream coloured solid, cleaned up using column chromatography to produce a colourless solid (4.8 g, 71%) of 3-phenylethynyl-4-acetoxytetrahydrothiophene-1,1-dioxide, ν_{max} 2970 and 2870(C-H), 2100(C≡C), 1750(CO), 1300 and 1150(SO_2), <800 (Ph).

3. **Flash Vacuum Pyrolysis of 3-Phenylethynyl-4-acetoxytetra-hydrothiophene-1,1-dioxide**

FVP [200°C, 875°C, 2 x 10^{-2} mm Hg] of 3-phenylethynyl-4-acetoxytetrahydrothiophene-1,1-dioxide (0.51 g, 1.83 mmol) resulted in the isolation of 2-phenylethynyl-1,3-butadiene (0.091 g, 32.2%) as an orange oil; m/z 154($M^{\bullet+}$), 115($M-C_3H_3^+$), 77($M-C_6H_5^+$), 43($C_3H_7^+$), ν_{max} 2960 and 2815(C-H), 1580(C=C conj), 2100(C≡C), 1290 and 920($C=CH_2$), <800(Ph); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 20.56(CH), 22.15(CH_2), 41.72(CH_2), 77.54(C≡C), 131.43-129.42(Ph).

G. PREPARATION OF 2-PHENYLETHYNYL-1,3-BUTADIENE FROM CYCLOHEXANONE

1. Preparation of 1-Phenylethynyl-1-hydroxycyclohexane

Magnesium turnings (1.2 g, 50 mmol) were placed in a three-necked flask, fitted with reflux condenser and equalising dropping funnel. A few crystals of resublimed iodine were added, followed by a solution of ethyl bromide (3.8 ml, 50 mmol) in dry tetrahydrofuran (50 ml), at a sufficient rate to attain gentle reflux without an external heat source. The mixture was refluxed for a further 2 hr, cooled to room temperature and to it was added phenyl acetylene (5.2 ml, 50 mmol). A further 2 hr reflux were needed followed by cooling to room temperature, addition of cyclohexanone (5.2 ml, 50 mmol) in dry tetrahydrofuran (30 ml), 2 hr reflux and finally the mixture was stirred for 14 hr at room temperature. A saturated ammonium chloride (2 g in 10 ml water) solution was added followed by extraction into diethyl ether, drying over anhydrous magnesium sulfate and removal of the solvent *in vacuo* to produce a brown oil, which was vacuum distilled (100°C, 30 mm Hg) to produce a light brown oil (5.5 g, 65%) of 1-phenylethynyl-1-hydroxycyclohexane; m/z 200($M^{•+}$), 185($M-OH^+$), 157($M-C_2H_2OH^+$), 102(Ph-$C \equiv CH$), ν_{max} 3350(O-H), 2970 and 2880(C-H), 2110($C \equiv C$), <800(Ph); ^{13}C n.m.r. ($CDCl_3$, 200 MHz) δ[ppm]: 65.52(CH_2, 84.03($C \equiv C$), 122.86(q, CH), 131.45-127.92(Ph).

2. Preparation of 1-Phenylethynyl-1-acetoxycyclohexane

To 1-phenylethynyl-1-hydroxycyclohexane (5.5 g, 27.5 mmol) was added triethylamine (17 ml), dry tetrahydrofuran (30 ml), and acetyl chloride (6 g, 77 mmol). The mixture was stirred at 0-5°C for ½ hr, then overnight at room temperature. The solvent was removed *in vacuo* and the products extracted in diethyl ether (50 ml), dried over anhydrous magnesium sulfate

and the solvent removed *in vacuo* to produce a yellow oil of 1-phenylethynyl-1-acetoxycyclohexane (5.62 g, 84%), ν_{max} 2970 and 2880(C-H), 2100(C≡C), 1750(C-O), <800(Ph); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 13.70(CH$_3$), 24.75(CH$_2$), 36.65(CH$_2$), 77.54(C≡C), 122.34(qc), 131.96-131.28(Ph-CH), 170.56(C=O).

3.   Flash Vacuum Pyrolysis of 1-Phenylethynyl-1-acetoxycyclohexane

(a)   At 550°C

FVP [120°C, 550°C, 2 x 10^{-2} mm Hg] of 1-phenylethynyl-1-acetoxycyclohexane (0.31 g, 1.3 mmol) resulted in the isolation of a brown oil, shown by n.m.r. to be the starting material (0.25 g, 81%), 1-phenylethynyl-1-acetoxycyclohexane; ν_{max} 2960 and 2870(C-H), 2100(C≡C), 1750(C=O), <500(Ph); ^{13}C n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]: 13.70(CH$_3$), 24.75(CH$_2$), 36.65(CH$_2$) 77.54(C≡C), 122.34(q, CH), 131.96-130.28(Ph), 170.50(C=O).

(b)   At 875°C

FVP [120°C, 875°C, 3 x 10^{-2} mm Hg] of 1-phenylethynyl-1-acetoxycyclohexane (0.32 g, 1.34 mmol) resulted in the isolation of 2-phenylethynyl-1,3-butadiene (0.18 g, 94.3%) as an orange oil; m/z 154(M$^{•+}$), 115(M-C$_3$H$_3$$^+$), 77(M-C$_6H_5$$^+$), 43(C$_3$3H$_7$$^+$), ν_{max} 2960 and 2810(C-H), 1580(C=C conj), 2100(C≡C), 1290 and 920(C=CH$_2$), <800(Ph); ^{13}C n.m.r. (CDCl$_3$, MHz) δ[ppm]: 20.56(CH), 22.45(CH$_2$), 77.54(C≡C), 131.23-129.02(Ph); ^{1}H n.m.r. (CDCl$_3$, 200 MHz) δ[ppm]:   5.30-5.41(1H, m, H5), 5.62-5.69(1H, m, H1), 5.75-5.92(1H, m, H4), 6.35-6.52(1H, dd, H3).

REFERENCES

1. S.F. Mason and W. Foerst, *Optische Arregund Organischen Systeme, Verlag Chemie*, Wienheim 1966, 88.

2. N. Ohkaniand and H. Hosoya, *BullChem.Soc.Jpn.* 1979, 52, 1624.

3. A.T. Blomquist and J.A. Verdol, *J.Am.Chem.Soc.*, 1955, 77, 1806.

4. W.J. Bailey and J. Economy, *J.Am.Chem.Soc.*, 1955, 77, 1133.

5. H. Priebe and H. Hopf, *Angew.Chem.Int.Ed.Engl.*, 1982, 21, 286.

6. V.M. Vdorin, E. Sh. Finkel'shtein, A.V. Shelkov and M.S. Yatsenko, Izveshya Akademii Nauk SSSR, Seriyakhimickeskaya, 1986, 11, 2578.

7. J.I.G. Cadogan, S. Cradock, S. Gillam and I. Gosney, *J.Chem.Soc., Chem.Commun.*, 1991, 114.

8. S.M. Gillam, Ph.D. Thesis, University of Edinburgh, 1990.

9. U. Norinder, *J.Mol.Struct.*, 1987, 150, 85.

10.(a) J.J. Gafewski and C.N. Smith, *J.Org.Chem.*, 1972, 33, 64.

   (b) H. Hopf, W. Lenk and D. Grottschild, *Isr.J.Chem.*, 1985, 26, 79.

11. E.F. Kiefer and C.H. Tanna, *J.Am.Chem.Soc.*, 1969, 91, 4478.

12. F. Bohlmann, *Chem.Ber.*, 1956, 89, 2191.

13. P. Weyerstahl, D. Klamann, C. Finger, M. Fligge, F. Nerdeland and J. Buddruse, *Chem.Ber.*, 1968, 101, 1303.

14. E. Wada, N. Nagasaki, S. Kanemasa and O. Tsuge, *Chem.Lett.*, 1986, 1491.

15. O. Tsuge, E. Wada and S. Kanemasa, *Chem.Lett.*, 1983, 239.

16. O. Tsuge, E. Wada and S. Kanemasa, *Chem.Lett.*, 1983, 1525.

17. E. Block and D. Putnam - International Conference on Heteroatom Chemistry 2 - Albany, N.Y., 1989.

18. C. Reichardt and W. Mormann, *Chem.Ber.*, 1972, 105, 1815.

19. W.J. Bailey, J. Economy and M.E. Hermes, *J.Org.Chem.*, 1962, 27, 3295.

20. W.J. Bailey, B.D. Feinberg, Preprints, Div. Polymerchem., *J.Am.Chem.Soc.*, 1987, 8, 165.

21. R.B. Woodward and R. Hoffman, Angew. Chem. Int. Ed. Engl., 1984,23,948.

22. T.L. Gilchrist and R.C. Storr, Organic Reactions and Orbital Symmetry, 2nd ed., 1979.

23. K. Shen, *J.Chem.Educ.*, 1973, 50, 238.

24. W.L. Mock, *J.Am.Chem.Soc.*, 1975, 97, 3666.

25. W.L. Mock, *J.Am.Chem.Soc.*, 1966, 88, 2857.

26. S.D. McGregor and D.M. Lemal, *J.Am.Chem.Soc.*, 1966, 86, 2858.

27. W.L. Mock, *J.Am.Chem.Soc.*, 1975, 97, 3673.

28. S. Asperger and D. Hegedic, *J.Org.Chem.*, 1972, 37, 1745.

29. O. Grummitt and A.E. Ardis, *J.Am.Chem.Soc.*, 1950, 72, 5167.

30. N.S. Isaacs and A.A.R. Laita, *Tetrahedron Lett.*, 1976, 715.

31.(a) G. de Bruin, *J.Chem.Soc.Abs.*, 1914, 106, 1197.

   (b) G. de Bruin, *Chem.Abs.*, 1915, 9, 623.

32. R.C. Krug and T.F. Yen, *J.Org.Chem.*, 1956, 21, 1082.

33. K.D. Gundermann and P. Holtmann, *Angew.Chem.Int.Ed.Engl.*, 1966, 5, 668.

34. J.M. McIntosh and R.A. Sieler, *J.Org.Chem.*, 1978, 43, 4431.

35. K. Inomoto, H. Kinoshita, H. Takemoto, Y. Murata and H. Kotake, *Bull.Chem.Soc.Jpn.*, 1978, 51, 3341.

36. S.-S.P. Chou and S.-J. Wey, *J.Org.Chem.*, 1990, 55, 1270.

37. C.L. Liotta and J.W. Verbicky, *Tetrahedron Lett.*, 1985, 26, 1395.

38. H.-H. Tso, T.-S. Chou and S.C. Huang, *J.Chem.Soc., Chem.Commun.*, 1987, 1552.

39. J.M. McIntosh and L.Z. Pillon, *Can.J.Chem.*, 1984, 62, 2089.

40. T.-S. Chou, H.T.-S. Chou, H.T.-H. Tso, Y.T. Tao, L.C.-T. Lin, J. Org. Chem., 1987,52,224.

41. V.M. Berestovikskaya, E.M. Speranskii and V.V. Perekalin, *Zh.Org.Khim.*, 1979, 15, 185.

42. A.C. Cope, G.A. Berchbold and D.L. Ross, *J.Am.Chem.Soc.*, 1961, 83, 3859.

43.(a) R. Bloch and J. Abecassis, *Tetrahedron Lett.*, 1983, 24, 1247.

   (b) R. Bloch and J. Abecassis, *Tetrahedron Lett.*, 1982, 23, 3277.

44. R. Bloch, D. Hassan and X. Mandard, *Tetrahedron Lett.*, 1983, 24, 4691.

45. R. Bloch, J. Abecassis and D. Hassan, *Can.J.Chem.*, 1984, 62, 2019.

46. R. Bloch, C. Benecou and E. Guibé-Jampel, *Tetrahedron Lett.*, 1985, 26, 1301.

47.(a) T.-S. Chou, H.H. Tso and L.J. Chang, *J.Chem.Soc., Chem.Commun.*, 1984, 1323.

   (b) T.-S. Chou, H.H. Tso and L.J. Chang, *J.Chem.Soc., Perkin Trans.I*, 1985, 515.

   (c) T.-S. Chou, L.J. Chang and H.H. Tso, *J.Chem.Soc., Perkin Trans.I*, 1986, 1039.

   (d) S. Yamada, T. Suzuki and H. Takayama, *Tetrahedron Lett.*, 1981, 22, 3085.

   (e) S. Yamada, H. Ohsawa, T. Suzuki and H. Takayama, *Chem.Lett.*, 1983, 1003.

48. T.-S. Chou, H.H. Tso and L.J. Chang, *J.Chem.Soc., Chem.Commun.*, 1985, 236.

49. H.H. Tso, T.-S. Chou and W.C. Lee, *J.Chem.Soc., Chem.Commun.*, 1987, 934.

50.(a) T.-S. Chou, S.-J. Lee, M.-L. Peng, D.-J. Sun and S.-S.P. Chou, *J.Org.Chem.*, 1988, 53, 3027.

   (b) S.-S.P. Chou and C.-Y. Tsai, *J.Org.Chem.*, 1988, 53, 5305.

51. T.-S. Chou, C.-Y. Chang, M.-C. Wu, S.-H. Hung, H.-M. Liu and W.-Y. Yeh, *J.Chem.Soc., Chem.Commun.*, 1992, 1643.

52. T. Nomoto and H. Takayama, *J.Chem.Soc., Chem.Commun.*, 1989, 295.

53. L.H. Hatch and D. Peter, *J.Chem.Soc., Chem.Commun.*, 1968, 1499.

54. B.F. Nesbitt, P.S. Beevan, R.A. Cole, R. Lester and P.G. Poppi, *Tetrahedron Lett.*, 1973, 47, 4669.

55. T. Chou and M. You, *J.Org.Chem.*, 1987, 52, 2224.

56. T. Chou and S. Chang, *J.Chem.Soc., Perkin Trans.I*, 1992, 1459.

57.(a) Y. Gaoni, *Tetrahedron Lett.*, 1976, 2167.

  (b) Y. Gaoni, Tetrahedron Lett., 1977, 947.

58. A. Ichihara, *Synthesis*, 1987, 207.

59. K.C. Nicolaou, W.E. Barnette and P. Ma, *J.Org.Chem.*, 1980, 45, 1463.

60. S. Yamada, T. Suzuki and H. Takayama, *J.Org.Chem.*, 1983, 48, 3483.

61. H. Staudinger and F. Pfenninger, *Ber.Dtsch.Chem.Ges.*, 1913, 49, 1491.

62. H. Kloosterziel and H.J. Baker, *Recl.Trav.Chim.Pays-Bas.*, 1953, 584, 199.

63. M.P. Cava and A.A. Deana, *J.Am.Chem.Soc.*, 1959, 81, 4266.

64. J.R. Du Manoir, J.F. King and R.R. Fraser, *J.Chem.Soc., Chem.Commun.*, 1972, 541.

65. M.P. Cava, R.L. Shirley and B.W. Erickson, *J.Org.Chem.*, 1962, 27, 755.

66. M.P. Cava and R.L. Shirley, *J.Am.Chem.Soc.*, 1960, 82, 654.

67. M.P. Cava, A.A. Deana and K. Muth, *J.Am.Chem.Soc.*, 1960, 82, 2524.

68. E. Giovannini and H. Vuilleumier, *Helv.Chim.Acta*, 1977, 60, 1452.

69. M.P. Cava and J.A. Kuczkowski, *J.Am.Chem.Soc.*, 1970, 92, 5800.

70. M.P. Cava, M.J. Mitchell and A.A. Deana, *J.Org.Chem.*, 1960, 25, 1481.

71. C.M. Buchan, Ph.D. Thesis, University of Edinburgh, 1983.

72. L. Skattebøl and S. Solomon, *J.Am.Chem.Soc.*, 1965, 87, 4506.

73. German Patent No. 622,800; 6/12/1935.

74. C.S. Marvel and N.O. Brace, *J.Am.Chem.Soc.*, 1949, 71, 37.

75. E. Müller, R. Mayer-Mader and K. Dinges, *Am.Chem.Soc.*, Advances in Chemistry Series, 1973, 129, 1.

76. S. Carter and F.W. Johnson, U.S. Patent, 2, 205, 239.

77. British Patent, 482,300.

78. Segawa, Hirozo, Yasui, Akin, Kumano and Shigetaka, Japanese Patent, 49028490.

79. Nakajama, Hitoshi, Nisimarii and Hirotsugu, Japanese Patent, 49028495.

80. Nomaka, Yuji, Khara, Keiichi, Hironaka, Toshio, Oda and Yasuhiro, Japanese Patent, 51029443.

81. W.R. Sorenson, *J.Org.Chem.*, 1959, 24, 1796.

82. Dehmlow and Dehmlow, "Phase-Transfer Catalysts", 2nd ed., Verlag Chemie, 1983.

83. G. Höfle and W. Steglich, *Synthesis*, 1972, 619.

84. A. Mccoll, *Theot.Org.Chem.*, papers kekule symposium, London, 1958, 230.

85. R. Taylor, *J.Chem.Soc., Perkin Trans.2*, 1979, 1730.

86. Y. Gaoni and S. Sadeh, *J.Org.Chem.*, 1980, 45, 870.

87. P.G. Baraldi, G.P. Pollini and V. Zanirato, *Synthesis,* 1985, 969.

88.　A.H. Georg, M. Willi, R. Heinrich, Dutch Patent Appl. 6 60474 (1966); C.A. 1967, 67, 21811; P.G. Baraldi, G.P. Pollini, V. Zanirato, A. Barco, S. Benetti, *Synthesis*, 19985, 969.

89.　J.M. McIntosh and G.M. Masse, *J.Org.Chem.*, 1975, 40, 1294.

90.　M. Uchiyama, T. Tomioka and A. Amano, *J.Phys.Chem.*, 1964, 68, 1878.

91.　M.C. Kloetzel, *Org.React.*, 1948, 4, 1.

92.(a) Diels and K. Alder, *Ber.Dtsch.Chem.Ges.*, 1929, 62, 2337.

　(b) Fieser and Fieser, Book 1, p.552.

93.　R.F.C. Brown, Pyrolytic Methods in Organic Chemistry - Academic Press, New York, 1980.

94.　Martin and Hall, *Chem.Rev.*, 1961, 61, 537.

95.　R.B. Woodward and R. Hoffmann "The Conservation of Orbital Symmetry", Verlag Chemie Weinheim, (1970).

96.　A.R. Forrester and G. Soutar, *Chem. and Industry*, 1984, 772.

97.　P.E. Wei, *J.Polym.Sci.*, P.A-1., 1969, 7, 2305.

98.　H.W. Starkweather, *Ind.Eng.Chem.*, 1947, 39, 210.

99.　H. Hopf, Chem. Ber., 1971, 104, 1499.

100.　H. Hopf and H. Priebe, *Angew.Chem.Int.Ed.Engl.*, 1982, 21, 286.

101.　H. Bader, H. Hopf and H. Jäger, *Chem.Ber.*, 1989, 122, 1193; M. Remmier, G. Zimmermann, B. Ondruschka, H. Bader and H. Hopf, *Chem.Ber.*, 1990, 123, 1375.

102.　D.K. Cameron, Ph.D. Thesis, University of Edinburgh, 1987.

103.　F. Ellis and P.G. Sammes, *J.Chem.Soc., Perkin Trans.I*, 1972, 2867.

104.　P. Brougham, M.S. Cooper, D.A. Cummerson, H. Heaney and N. Thompson, *Synthesis*, 1987, 1015.

105.　I. Hodgetts, S.J. Noyce and R.C. Storr, *Tetrahedron Lett.*, 1984, 25, 5435.

106. Aldrich Chemical Company, catalogue, 1992-93.

107. M. Horák and J. Fajkos, *Coll.Czech.Chem.Commun.*, 1959, 24, 151.

108. A.J. Vogel, 'Textbook of Practical Organic Chemistry', 4th edn., Longman, London, 1979.