# SYNTHESIS AND CYCLOADDITION CHEMISTRY OF 1,3-BIS(PHENYLSULFONYL)PROPADIENE

by

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To Matthew, Neill, Andrea and Irene

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## SUMMARY

An efficient synthesis of the highly activated 1,3-bis(phenylsulfonyl)propadiene is described. Starting from benzenesulfonyl chloride and propargyl bromide the key step of the synthesis is the addition of benzenesulfonyl iodide to phenylsulfonylpropyne. This is demonstrated to occur under thermal conditions in the presence of a radical initiator to obtain (*E*)-2-iodo-1,3-bis(phenylsulfonyl)prop-1-ene. Triethylamine induced dehydroiodination of the above addition product afforded high quality 1,3-bis(phenylsulfonyl)propadiene after an aqueous reverse quench procedure without further purification.

1,3-Bis(phenylsulfonyl)propadiene was shown to be stable under refluxing conditions towards diethyl ether, chloroform, ethyl acetate and benzene. Reaction with methanol occurred to yield (*E*)-2-methoxy-1,3-bis(phenylsulfonyl)prop-1-ene and with tetrahydrofuran to yield 2-(2-tetrahydrofuranyl)-(*E*)-1,3-bis(phenylsulfonyl)propene, in a novel insertion reaction. The homocyclisation of 1,3-bis(phenylsulfonyl)propadiene under thermal conditions was demonstrated to yield the highly substituted 2,7-bis(phenylsulfonylmethylene)-3,4,5,6-tetraphenylsulfonyl-spiro[3.3.0]heptane.

Reaction with cyclopentadiene, furan, butadiene and Danishefsky's diene has been conducted in a regio- and peri-selectivity study to yield the [4+2] cycloadducts. Treatment of the furan cycloadducts with potassium t-butoxide opened up the oxygen bridge of three of the furan cycloadducts and resulted in aromatisation to the 3-phenylsulfonyl-2-phenylsulfonylmethylphenol. The remaining cycloadduct was converted to the phenol derivative by treatment with sodium hydride. Potassium methoxide treatment of the furan cycloadducts resulted in the isolation of a methoxide addition product together with the aromatised adduct.

Procedures for the synthesis of phenylsulfinylpropadiene and phenylsulfonylpropadiene are described.

Throughout the study the high reactivity of 1,3-bis(phenylsulfonyl)propadiene in different reactions is apparent. This, together with the ease of preparation and the demonstrated stability of the compound places it as a powerful tool in organic synthesis.

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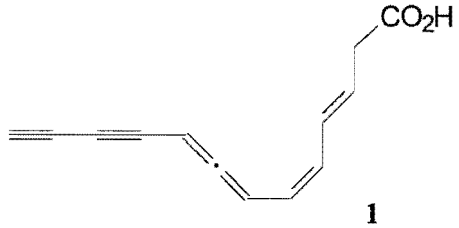
# INTRODUCTION

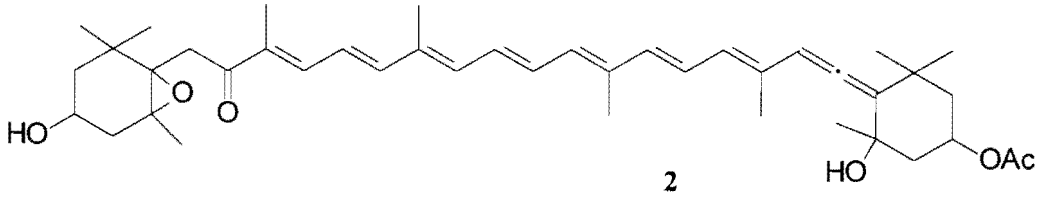
The properties and widespread use of the two contiguous π-bond systems of the propadienyl (allene) motif places it as a very powerful tool in contemporary organic synthesis. Central to its power is the opportunity to differentiate the two orthogonal double bonds by activating groups, resulting in highly regioselective reactions. The activating groups can also play a role in the face selection of a particular π-bond system, resulting in highly stereoselective reactions. In chiral form, the terminally 1,3-substituted allenes can be utilised in diastereoselective reactions. Arguably, the most important aspect of utilising the allenyl motif is the double bond functionality imparted to the reaction product resulting from reaction of only one of the allene double bonds.

In nature, the allene motif has been found in the antibiotic mycomycin (**1**), the fungal metabolite produced by the actinomycete, *Nocardia* acidophilis.[1] The widespread occurrence of the diyne-allene grouping in fungal allenes has helped in the detection and characterisation of many such compounds. Fucoxanthin (**2**), is a carotenoid pigment of brown algae[2] also shown to contain the allenyl motif (Scheme 1).

**Scheme 1**




**1**

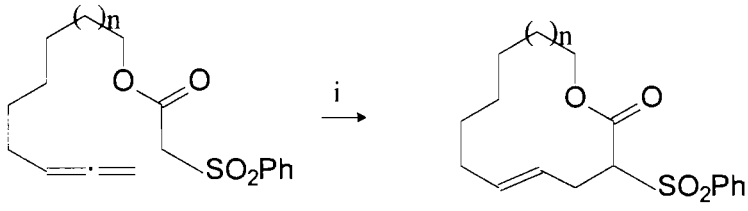



**2**

Some of the widespread uses of selected allenes in organic chemistry are illustrated below.

An interesting macrocyclisation has recently been reported by Trost and others[3] in which macrocycles and macrolactones are synthesised. Macrocycles are useful medicinally because they can adopt a favourable conformation to fit a particular shaped receptor protein, and so enhance biological activity associated with the receptor. The precursors to the cyclisation step (**3**) are easily arrived at and undergo a catalytic palladium-assisted coupling to give the macrocycles (**4**) in good yields, without having to resort to the high dilution methods often associated with these macrocyclisations (Scheme 2).

**Scheme 2**




**3** **4**

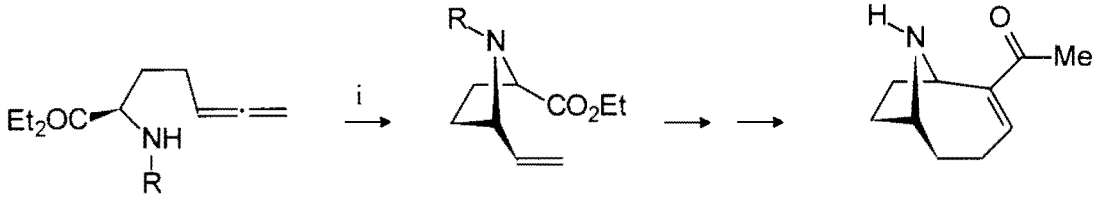
i: 5 % $[\{Pd(C_3H_5)Cl\}_2]$, $Ph_2P(CH_2)_3PPh_2$, AcOH, DMAP

Yield for **4**: n = 6 67%, n=5 57%, n=1 62%

The potent nicotinic agonist (+)-anatoxin-a (**7**) (Scheme 3), found in toxic blooms of *Anabaena flos-aquae* in fresh water supplies, causes extensive loss of wildlife. It is currently the most potent nicotinic agonist known and a ready supply of it and its analogues will allow knowledge of the nicotinic acetylcholine receptor's agonist binding site to be gained. In an approach to obtain the *cis*-2,5-disubstituted pyrrolidines (**6**) as precursors to anatoxin-a and other useful neuroactive cholinergic ligands, Huby and others[4] utilised a functionalised allene (**5**) as a vehicle for a stereoselective silver-mediated cyclisation.

The unreacted double bond is utilised as a handle for manipulating the newly formed heterocycle to obtain the toxin.

**Scheme 3**

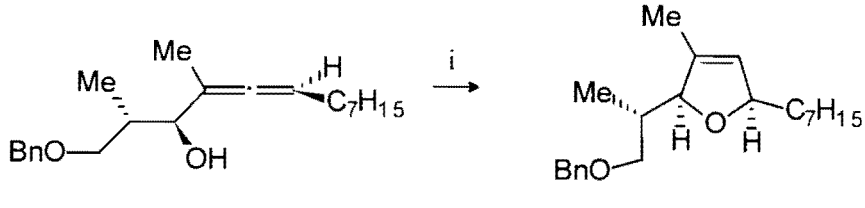



**5** **6** **7**

i: Ag(I), $H_2O$

A similar set of silver-triggered stereoselective cyclisations of allenylcarbinols (**8**) (Scheme 4) has been successfully utilised by the Marshall group[5] to obtain substituted 2,5-dihydrofurans (**9**) which are important subunits of acetogenin and other polyether natural products.

**Scheme 4**

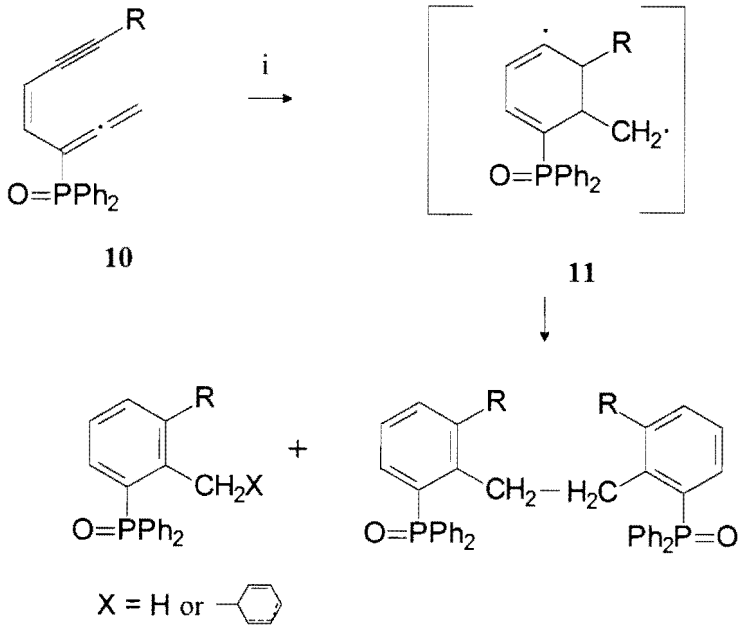



**8** **9**

i: $AgNO_3$, acetone

Apart from these metal induced cyclisations, the allene moiety has been put to good use by Saito and others[6] in attempts to obtain a simplified DNA cleaving molecule which mimics the mechanism of action of natural antitumor antibiotics. The reactive intermediate in these reactions is the benzenoid biradical species (**11**) generated from a Bergman-type cyclisation of an eneyne-allenyl phosphonate (**10**) (Scheme 5). The beauty of using allenylphosphine oxide (**10**) is that the molecule is easily synthesised, stable at room temperature, but at body temperature generates the reactive biradical species at an appreciable rate.

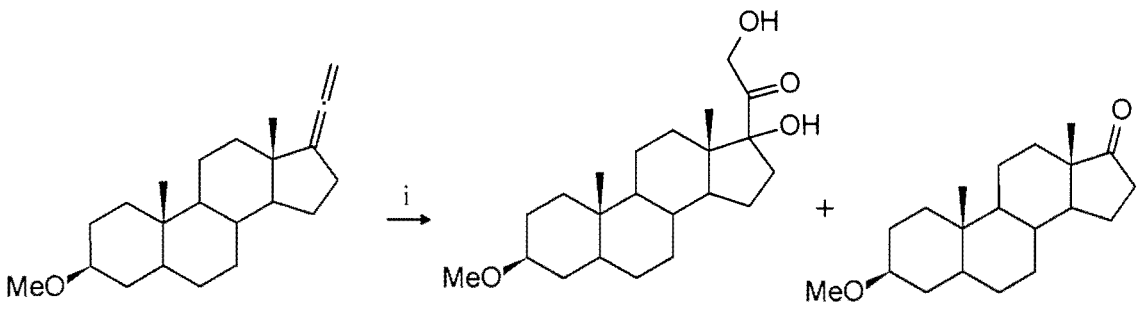
**Scheme 5**




i: Cyclohexadiene, 37 °C, 5 h

Recently, Laux and Krause[7] have used a ruthenium-catalysed flash oxidation of allenes with $NaIO_4$ to give α,α'-dihydroxyketones. A preliminary application of this method was utilised to synthesise a corticosteroid analogue (**13**) from an *epi*-androsterone allene derivative (**12**) (Scheme 6).

**Scheme 6**




**12** **13**

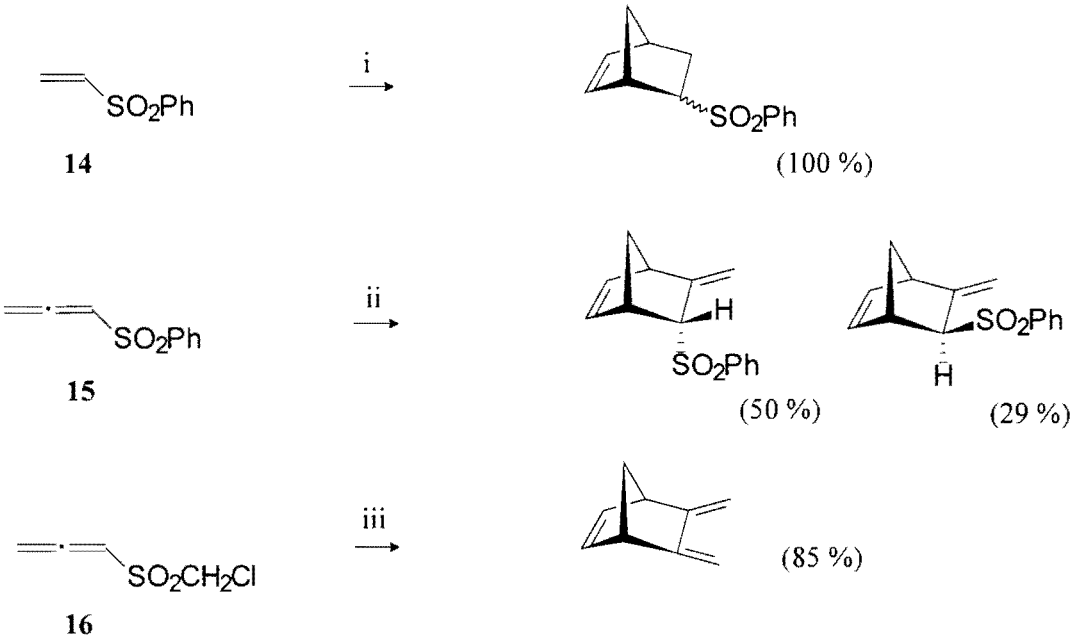
i: $NaIO_4$, $RuCl_3.3H_2O$ (cat)

Allene itself is often thought of as having two separate double bonds independent from one other. In this respect, it is useful to compare its structure to that of ethene. The central sp-hybridised carbon of allene does not have any significant effect on the two π-bond systems, with bond lengths and HOMO and LUMO energies being very similar to that of ethene, as calculated by Pasto.[8] Introduction of a terminal alkyl or a hetero-functional group (*e.g.* $R\text{-}C_1{=}C_2{=}C_3$), causes a change in orbital energy most dramatic for the $C_1{=}C_2$ bond to which the group is attached. The added substituent also affects the energy of the $C_2{=}C_3$ bond by mixing of the in-plane π-type group orbital of $R\text{-}C_1{=}C_2$ with the $C_2{=}C_3$ orbital. Heats of hydrogenation of allene indicate an effective strain of 10 $kcal.mol^{-1}$ associated with the cumulated double bonds when compared to the isolated double bonds. Some of the best known uses of the allenyl moiety are in cycloaddition reactions where the relief of this strain drives the reaction forward.

Houk[9] pointed out that one way of increasing the reactivity of ethylenes in cycloaddition chemistry is to substitute with electron withdrawing groups such as sulfones, as in phenyl vinyl sulfone (**14**) (Scheme 7).[10] Reviews on the use of vinyl sulfones and sulfur functionality's in cycloaddition reactions have been published by Simpkins[11] and De

Lucchi and Pasquato[12] respectively. The reactivity of (**14**) as a dienophile is increased over ethylene because of increased frontier molecular orbital complementarity with dienes.

**Scheme 7**




i: 25 °C, 110 h

ii: 80 °C, 8 h

iii: 25 °C, 25 min, base

By analogy, the electron deficient substituted allenes, *e.g.* phenylsulfonylallene (**15**) (Scheme 7) should be favoured in [4+2] cycloadditions where the dominant interaction is LUMO dienophile, HOMO diene. Calculations of (methylsulfonyl)propadiene by the MNDO method carried out by Padwa and others[13] and by the CNDO/2 method carried out by Kanematsu and others[14] both predict the strong effect of an electron withdrawing group on the allene. There is a lowering of the LUMO energy levels of between 1.3 eV (MNDO method) and 3.07 eV (CNDO/2 method) compared with allene. The largest negative LUMO coefficient resides on the central position, and the next on the position bearing the electron withdrawing group.

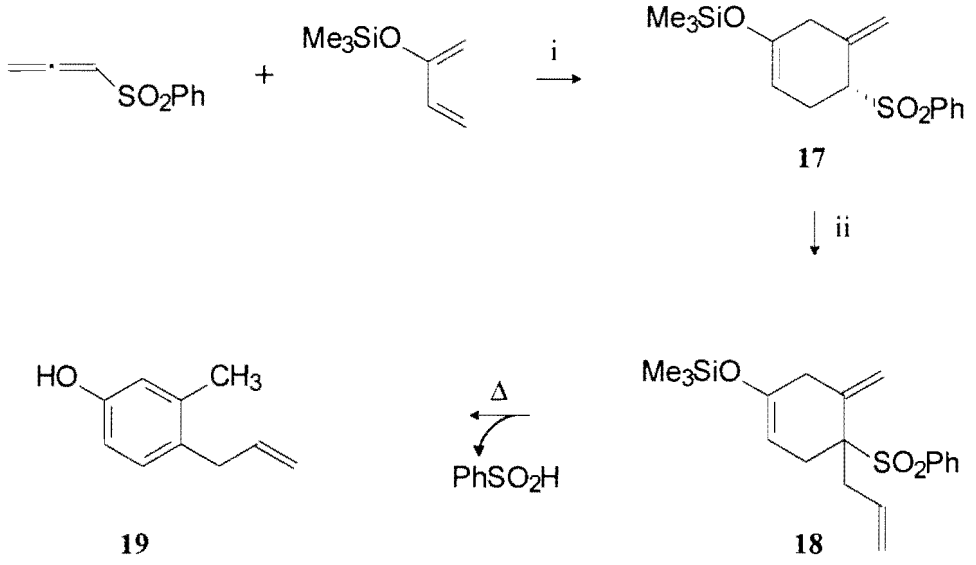
The choice of phenylsulfonyl as activating group lies in the fact that the group is chemically inert, partly because of the "insulating" effect of the sulfonyl moiety and partly because of the unfavourable thermodynamics involved in disrupting the aromaticity of the benzene ring. There are also established methods for removing the phenylsulfonyl activating group. Fabre and Julia[15] used alkyl Grignard reagents with nickel or palladium catalysts for the hydrogenolysis, while Trost and co-workers[16] utilised a treatment of excess 6% Na (Hg) in the presence of phosphate buffer. Little and Myong[17] have oxidatively cleaved the phenylsulfonyl group with a safe molybdenum peroxide reagent.

The increased reactivity and added functionality that phenylsulfonylallene (**15**) has over phenyl vinyl sulfone (**14**) in the Diels-Alder reaction was demonstrated by Kanematsu and others (Scheme 7). [14]

The reaction of phenyl vinyl sulfone with cyclopentadiene, conducted by Carr and Paquette,[10] is slow, and needs extended reaction times, while the increased reactivity of the phenylsulfonylallene, although the reaction is conducted at higher temperature, is evident. An interesting variation is the use of allenylchloromethyl sulfone (**16**) described by Block and Putman[18] which undergoes cycloaddition with greater facility, probably because of the less sterically demanding transition state than with allene (**15**). The product here was obtained by base treatment to effect a Ramberg-Backlund rearrangement of the chloromethyl sulfone.

The use of phenylsulfonylallene in Diels-Alder cycloadditions opens up the possibility of obtaining a variety of methylenecyclohexenes (*e.g.* **17**, Scheme 8) which may be useful building blocks for producing terpenoids, as pointed out by Kanematsu.[14] The known ability of the sulfonyl group to stabilise α-carbanions was used by Kanematsu to effect electrophilic substitution and obtain (**18**), which upon heating eliminated benzenesulfinic acid to give (**19**), a *m*-, *p*-disubstituted phenol.

**Scheme 8**

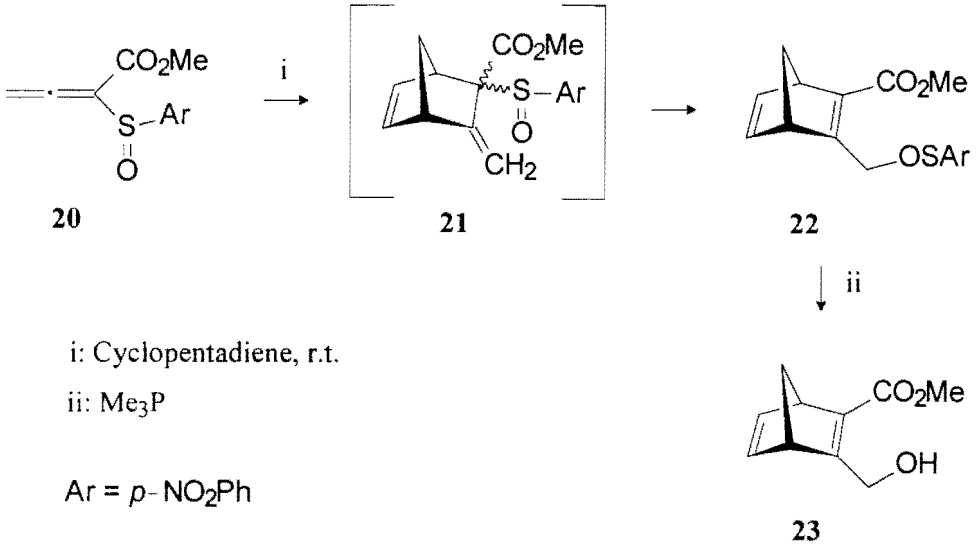



i: 160 °C, 3 h

ii: n-butylithium, -50 °C, allyl bromide, THF

The (nitroaryl)sulfinyl-substituted allene (**20**), Scheme 9, belongs to an important group of activated dienophiles utilised by Padwa[19] as propargyl alcohol synthons.

**Scheme 9**




i: Cyclopentadiene, r.t.

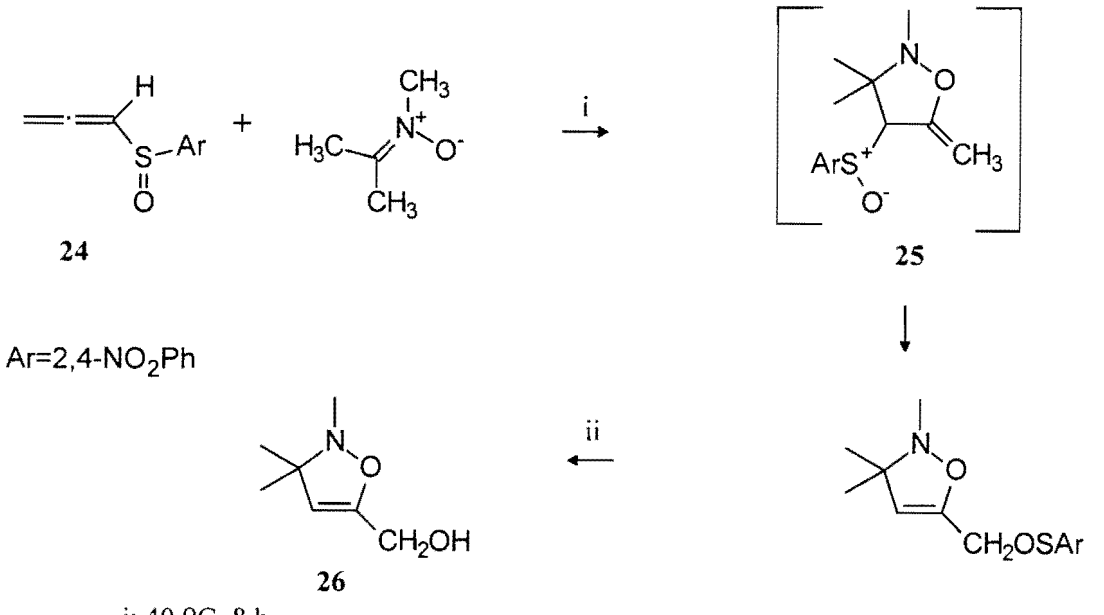
ii: $Me_3P$

Ar = *p*-$NO_2Ph$

The approach here is to enhance the electron withdrawing capacity of the sulfinyl substituent with the nitrophenyl group and to utilise the well studied ability of the allylic sulfoxides (**21**) generated in the cycloaddition products to undergo 2,3-sigmatropic rearrangements to yield the corresponding sulfenates (**22**). The sulfenates were then cleaved with trimethylphosphite to reveal the alcohol (**23**).

In the same study, the related (2,4-dinitroaryl)sulfinyl-substituted allenes (*e.g.* (**24**), Scheme 10) were utilised in 1,3-dipolar cycloaddition reactions with various substituted nitrones, which also rearranged to the corresponding sulfenates **25**. Again, cleavage by treatment with trimethylphosphite or 10 % sodium hydroxide solution yielded the isoxazolidine derivative **26**.

**Scheme 10**

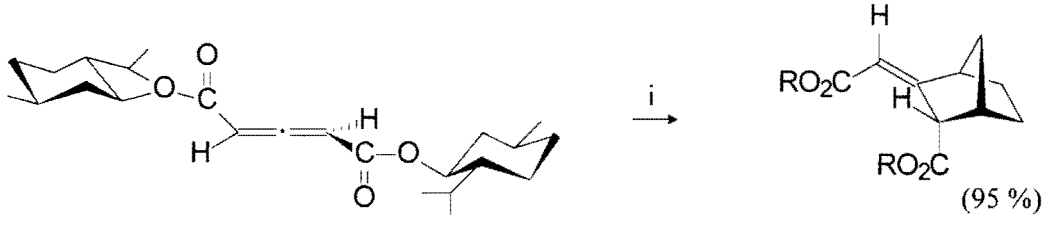



The use of optically active 1,3-disubtituted allenes in cycloaddition reactions opens up the possibility of enantioselective synthesis. Kanematsu and others[20] recently investigated the use of optically active menthol-substituted allene-1,3-dicarboxylates (*e.g.* **27**) in the Lewis acid-catalysed Diels-Alder reaction to obtain an enantiomerically pure norbornene

derivative (**28**) (Scheme 11). In contrast to the sulfonyl-activated ethylene moieties, the use of Lewis acid catalysis of various dienophiles with terminal oxygen functionalities[21] is common. The high *endo*-selectivity obtained with cyclopentadiene in the above reaction was ascribed to the axial asymmetry of the allene, rather than the effect of Lewis acid complexation or the effect of the proximal menthol group over the approach of the diene. In contrast to this, the investigators mention that the distal menthol group enhances the axial dissymetry of the allene function. The π-face selectivities in this reaction are different from that obtained by Yamamoto and others[22] in the reaction of fumarate with menthol as a chiral auxiliary, catalysed by the homogenous diethylaluminium chloride Lewis acid. Here however, the co-ordinated fumarate auxiliaries are thought to co-operatively cover one of the faces of the double bond, resulting in the face selectivity.

In the above-mentioned allene system, the investigators state that the combination of the favoured steric approach of the dienophile with secondary orbital interactions to the carbonyl functions are responsible for the high stereoselectivity. The major expected cycloadducts could be used as chiral synthons for the synthesis of (-)-cyclosarkomycin, a synthetic precursor of the useful antitumor antibiotic, sarkomycin.

**Scheme 11**




**27** **28**

i: Cyclopentadiene, $AlCl_3$, $CH_2Cl_2$, -78 °C, 5 h, R = (-)-menthyl

There are a great many different methods of producing substituted allenes. One of the most obvious methods is a Wittig-type reaction with a ketene equivalent and a terminal olefin. In practice, Fuji and others[23] have used the Horner-Wadsworth-Emmons variation with a binaphthyl chiral auxiliary to enantioselectively produce allenecarboxylates. The dehydrohalogenation of vinyl halides *via* allylic deprotonation is a general method that was used by Kanematsu[21] in the preparation of the previously mentioned allenecarboxylate. In a similar manner Brummond and others[24] eliminated the enol phosphates prepared by enolisation of ketone moieties to obtain allenes. A novel approach developed by Myers and Zheng[25] utilises the addition of a toluenesulfonylhydrazine to a chiral propargylic alcohol under Mitsunobu-type conditions, with the subsequent elimination of toluenesulfinic acid and dinitrogen to give the allenes in a single step and stereospecifically. Yamamoto and others[26] have utilised a palladium-catalysed addition of cyano-based pronucleophiles to conjugated enynes which give the corresponding allenes in good yield. The 2,3-sigmatropic rearrangement of propargyl alcohol sulfenate ethers to the corresponding sulfinylallenes was used by Padwa and others[19] in the reactions described above. A practical procedure for the synthesis of phenylsulfonylallene *via* the propargyl alcohol sulfenate ether is described at the end of the experimental section of this dissertation.

In the Diels-Alder reaction with allenes as dienophiles, additional functionality is carried over to the cycloadducts as the exocyclic double bond. If the allene is substituted at both termini by activating groups, the cycloadducts display one activated ethylene equivalent for further reaction. The use of inert, but easily removable phenylsulfonyl groups as described in the above examples, is desirable. It was for these reasons that an investigation into the use of 1,3-bis(phenylsulfonyl)propadiene was carried out.

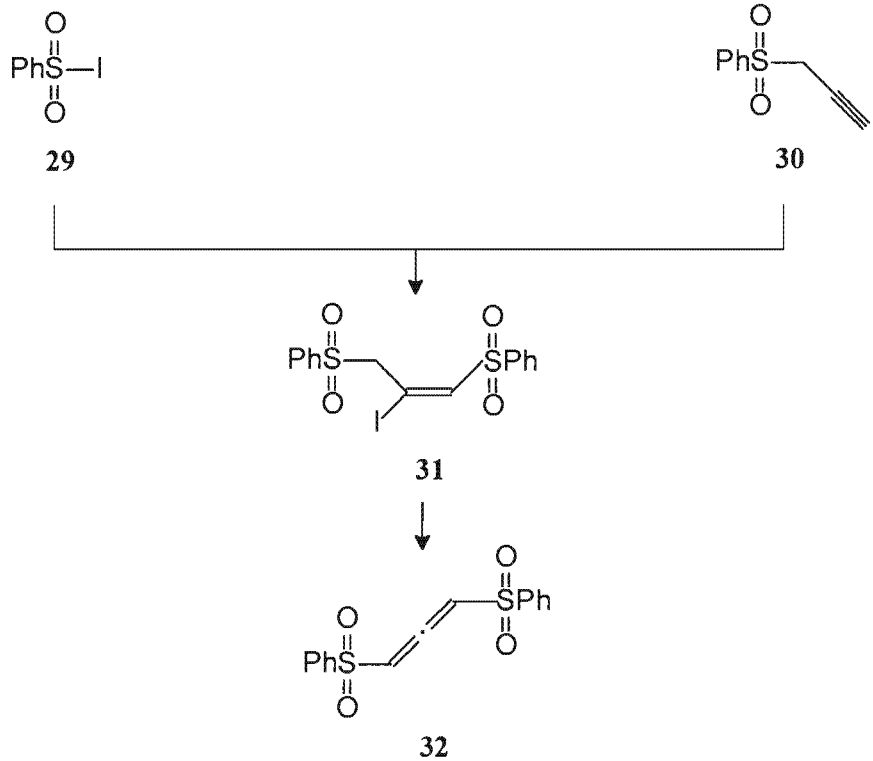
The objectives of this study were to develop an efficient synthesis of 1,3-bis(phenylsulfonyl)propadiene and to determine its handling characteristics and reactivity as a dienophile in the Diels-Alder reaction.

# DISCUSSION

## 1. Synthesis of 1,3-bis(phenylsulfonyl)propadiene

The initial aim of this study was to optimise the conditions for the preparation of 1,3-bis(phenylsulfonyl)propadiene in the synthetic route utilised by Heggie.[27] The route consists of the addition of benzenesulfonyl iodide (**29**) to 3-phenylsulfonylpropyne (**30**), which is easily obtained from propargyl bromide *via* 3-phenylsulfanylpropyne. The resulting addition product 2-iodo-1,3-bis(phenylsulfonyl)prop-1-ene (**31**) is then dehydroiodinated to yield 1,3-bis(phenylsulfonyl)propadiene (**32**) (Scheme 12).

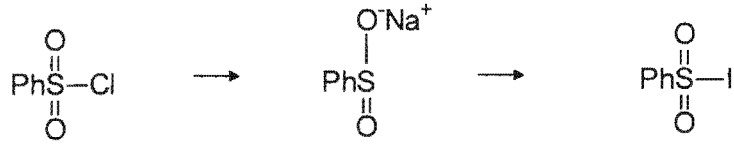
**Scheme 12**




Sulfonyl iodides are highly reactive to homolytic cleavage of the S-I bond. Alkylsulfonyl iodides are used *in situ* without being isolated while the aryl derivatives are more stable and can be isolated. Arylsulfonyl iodides undergo homolysis of the S-I bond with photochemical initiation or in the presence of a radical initiator and are easily prepared

from the arylsulfinate salts which in turn can be obtained from the corresponding sulfonyl chlorides. A reduction - oxidation sequence was used to obtain (**29**) from benzenesulfonyl chloride (**33**) *via* the benzenesulfinate (**34**) (Scheme 13).

**Scheme 13**



**33** **34** **29**

The preparation of (**34**) from (**33**) by reduction with sodium hydrogen carbonate and sodium sulfite in aqueous solution, as described by Truce and others,[28] was investigated, but the yield was low and not reproducible. The well known sodium iodide / acetone method used by Julia and others[29] was investigated and it was found to work well affording (**34**) in good yield and reproducibly.

With access to (**34**) established, the preparation of (**29**) was investigated. The original method of Truce and Wolf [30] required the isolation of benzenesulfonyl iodide precipitate from an aqueous solution of sodium benzenesulfinate when ethanolic iodine was added dropwise. The yields after recrystallisation of (**29**) were unreliable because of variation in the quality of the precipitate. A two-phase extraction method was found to be more reliable and gave higher yields. The aqueous layer containing the benzenesulfinate was repeatedly extracted with portions of iodine dissolved in dichloromethane until a pink colour persisted in the organic layer. The organic layer was then concentrated, a small amount of carbon tetrachloride was immediately added, and the solution rapidly cooled (acetone / dry ice) with scratching. The bright yellow, light sensitive crystals were isolated by filtration and were stable enough to handle for a short time. Surprisingly, it was found that recrystallised (**29**) was stable for extended periods in refluxing benzene.

The original method of Heggie[27] involving photochemically initiated addition of (**29**) to (**30**) (Scheme 12) at room temperature was incomplete after 20 h, complicating the

isolation of product (Table 1). Unsuccessful attempts were made to drive this exothermic reaction to completion by adding up to a 2.5 molar excess of (**29**). The addition of a catalytic amount of AIBN increased the rate of the reaction slightly. However, the discovery of the thermal stability of (**29**) in benzene opened up the possibility of exploring thermal conditions.

**Table 1**. Progress of addition of (**29**) to (**30**) to obtain addition product (**31**) (60 MHz NMR).

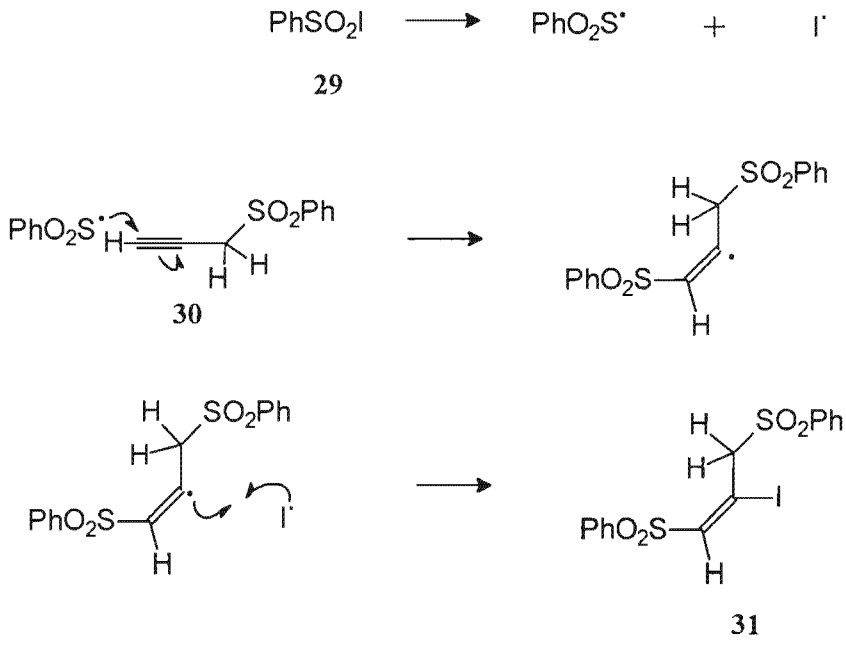
| Reaction conditions[#] | | | Amount of addition product **31** (%) |
|---|---|---|---|
| 100 W white light | | 20 h | 81 |
| 100 W white light | AIBN | 20 h | 87 |
| reflux | AIBN | 1 h | 89 |
| reflux | AIBN | 20 h | 100 |
| reflux | | 35 h | 100 |

[#] All reactions were carried out in benzene.

Thermal conditions were found to be more efficient, with a similar conversion to the photochemical reaction after 20 h obtained within 1 h. By this method, the reaction was shown to be complete after 20 h. Without the presence of AIBN the reaction was markedly slower, reaching completion after 35 h, giving an indication of the stability of (**29**) to homolysis under the thermal reaction conditions. Only one product, the (*E*)-isomer resulting from the *trans*-addition of iodide (**29**), was obtained according to the mechanism shown (Scheme 14).

The phenylsulfonyl radical derived from the homolytic cleavage of iodide (**29**) adds to the terminus of the acetylene unit (**30**), and the resulting vinyl radical develops in an *anti*-orientation to the added phenylsulfonyl group.

**Scheme 14**

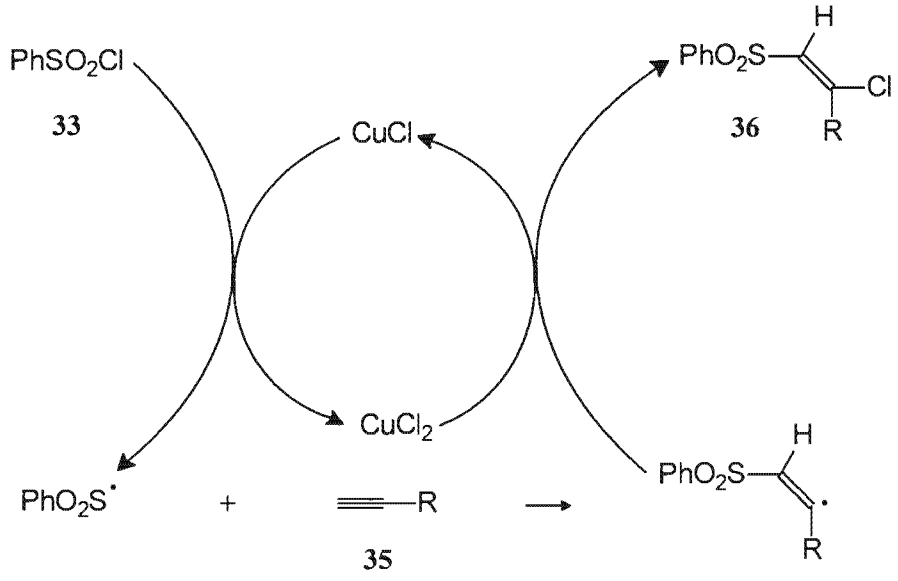



As Padwa and others[31] have noted, if the homolytic cleavage step and the addition to the terminus of the acetylene unit is rapid, then the rate determining step is likely to be the quenching of the vinyl radical by iodide. Under the reaction conditions (refluxing benzene) the developing vinyl radical may encounter a high energy barrier to inversion when associated with the steric bulk of the phenylsulfonyl methylene substituent, and so only the *trans*, thermodynamically more stable addition product is formed. Sterically, capture of the vinylic radical by iodide is also favoured to occur *anti* to the phenylsulfonyl group with iodide approaching along the less hindered trajectory *trans* to the added phenylsulfone. No allylic coupling was obtained between the methylene protons and the vinylic proton of (**31**), probably because of electronic effects due to the iodine atom.

The use of benzenesulfonyl chloride (**33**) acting directly on propyne (**30**) was briefly investigated (Scheme 15). Motivation for this route was based on the reaction of (**33**) with phenylacetylene (**35**) (R=Ph) carried out by Amiel.[32] In this method, copper chloride is used catalytically as a chloride transfer agent in the presence of triethylamine hydrochloride, which solubilizes the catalyst by complexation. The reaction proceeds when

an electrophilic sulfone radical, adds to the terminus of the acetylene unit (**35**). The developing vinyl radical is stabilised by acetonitrile solvent. It is quenched by a chloride radical derived from the catalyst in a stereoselective manner to give the addition product (**36**). The copper chloride catalyst is regenerated by the action of cuprous chloride on (**33**).

**Scheme 15**




Attempts to obtain 2-chloro-1,3-bis(phenylsulfonyl)prop-1-ene (**36**) (R = $CH_2SO_2Ph$), in the same way by the reaction of (**33**) and propyne (**30**) under the set of reaction conditions determined by Amiel,[32] proved unsuccesful, with very low yields (3 %) after extended reaction times (100 °C, sealed tube, 5 d). A possible reason for this poor result lies with the copper chloride, rather than with the lability of the $PhO_2S$-Cl bond. An explanation based on the solvent effect noted by Amiel[33] is that Cu (II) and chloride ions are stabilised by solvation with acetonitrile, retarding chlorine atom transfer to the vinyl radical species.

The dehydroiodination reaction of (**31**) (Scheme 12) occured readily at -78 °C in the presence of triethylamine and a reverse quench in dilute aqueous hydrochloric acid gave a pale ,yellow precipitate that was collected and dried to give 1,3-bis(phenylsulfonyl)propadiene (**32**). Material obtained in this way repeatedly yielded high quality allene (see Figure 1) in yields above 75 % from (**30**). Allene (**32**) is stable on the bench as a solid for 6 months, and to silica gel chromatography with ethyl acetate, hexane eluting mixtures.

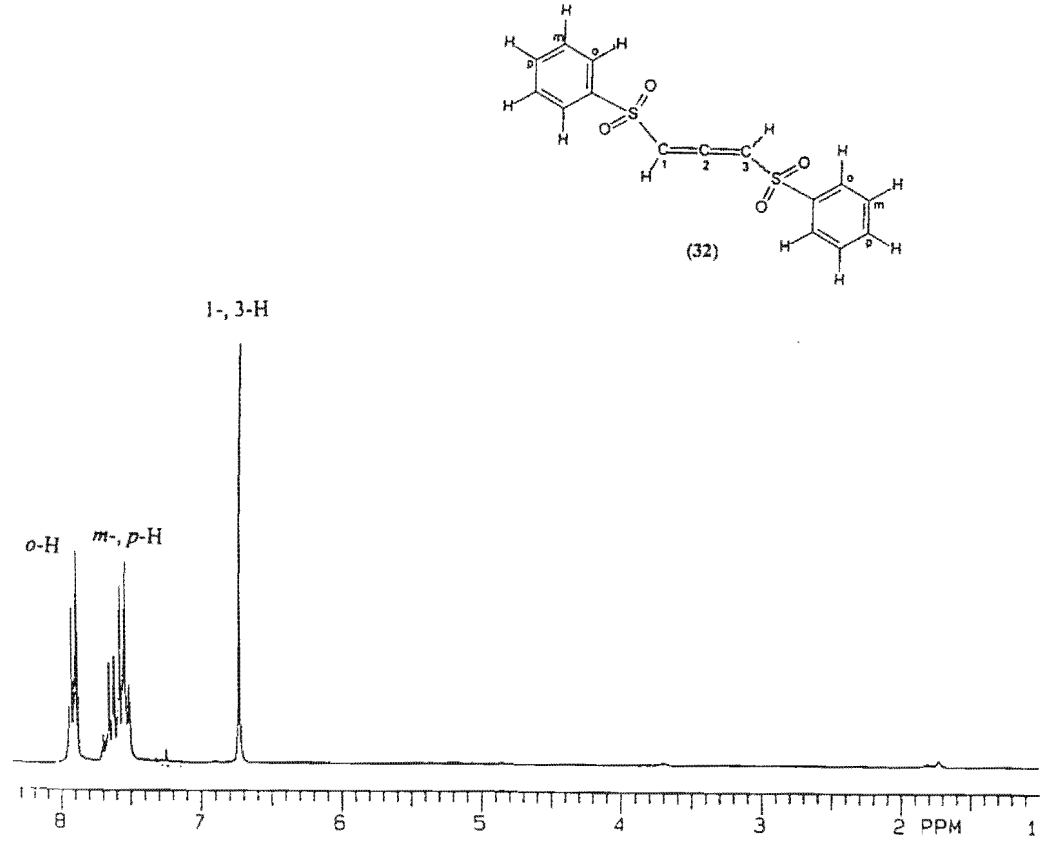
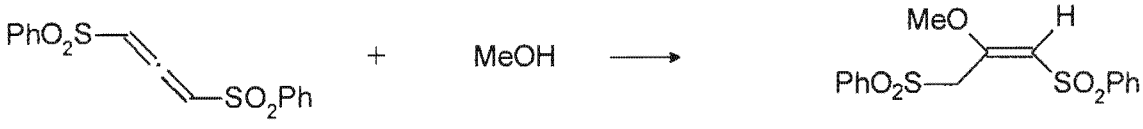



**Figure 1**. 200 MHz Proton NMR spectrum of allene **32** directly after the dehydroiodination step.

## 2. Reactivity of 1,3-bis(phenylsulfonyl)propadiene

It was essential to determine the reactivity of allene (**32**) in a selection of solvents. The allene was shown to be stable (60 MHz NMR) in diethyl ether, acetone, chloroform, ethyl acetate and benzene under reflux conditions for 24 h. When the allene (**32**) was refluxed for 24 h in methanol, it was found to undergo nucleophilic addition to afford the addition product (**37**) in 82 % yield (Scheme 16).

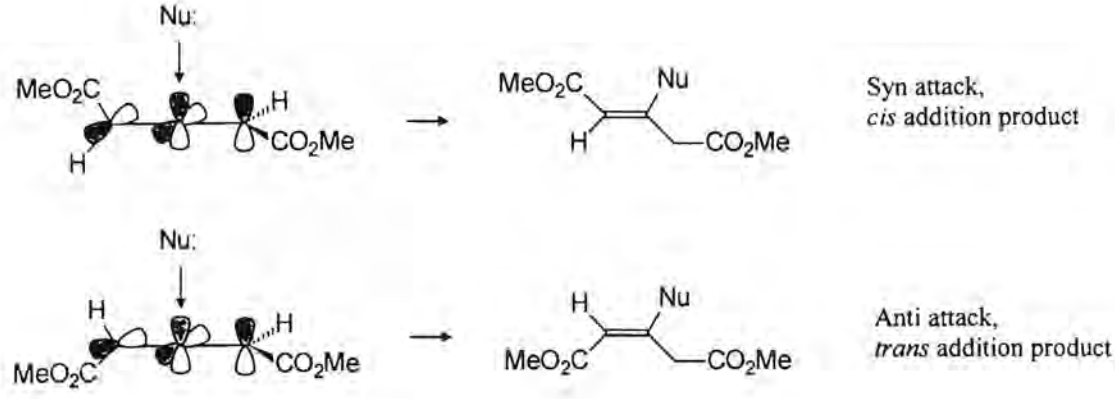
**Scheme 16**




**37**

The addition of nucleophilic reagents to allenes activated by electron withdrawing groups is a well known reaction. With phenylsulfonylpropadiene, the nucleophiles thiolate, methoxide and phenylsulfinate were shown by Stirling[34] to attack the central carbon of the allene. Also, reaction with thebaine, shown by Fujii and others,[35] pyrrolidine, shown by Hayakawa and others[36] and allyl alcohol (with catalytic allyl alkoxide), shown by Denmark and Harmata[37] occurred by attack at the central allenyl carbon, giving the anion α to the sulfonyl functionality which was quenched to give the unconjugated 3-phenylsulfonyl-2-substituted propenes.

Nucleophilic addition to the 1,3-disubstituted allenecarboxylates by diethylamine, lithium phenylsulfanate and lithium aluminium hydride-aluminium chloride reagent was demonstrated by Naruse and others (Figure 2).[38]




| Nu: = | anti : syn |
|---|---|
| $Et_2NH$ | 99 : 1 |
| PhSLi-PhSH | 86 : 14 |
| LAH-$AlCl_3$ | 0 : 100 |

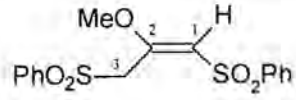
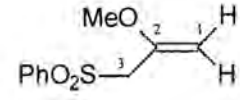
**Figure 2.** Illustration of the two modes of nucleophilic attack at the central carbon of a substituted allene.

The stereoselectivity leading to the predominantly *trans* diethylamine addition product was rationalised in terms of steric effects. In the case of thiolate addition these were somewhat overridden by chelation control leading to a mixture of *cis* and *trans* addition products and completely overridden by chelating factors in the case of hydride addition. The authors conducted *ab initio* calculations of the model addition of ammonia to allene and predicted approach of the ammonia nucleophile along the $C_2$ axis direction with the lone pair of the nucleophile delocalising into the LUMO's of the two equivalent double bonds of the allene in a co-operative manner. The addition of methanol to the electron deficient central carbon atom of allene (**32**) yielded only one geometric isomer, formulated as the *trans* addition product (**37**), and is thought to occur by *anti* approach of methanol along the $C_2$ trajectory yielding only the *trans* addition product.

The proton chemical shifts of the methanol addition product (**37**) and that of the methoxide addition to phenylsulfonylpropadiene,[34] product (**38**), are compared in Table 2. The

chemical shifts of the methoxy and C-1 protons are similar while in (**37**) 1-H is deshielded by the phenylsulfonyl group.

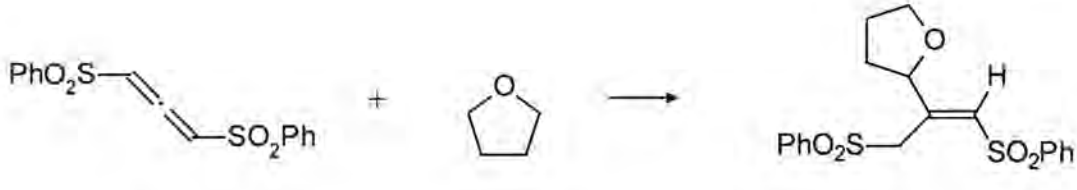
**Table 2.** Comparison of proton chemical shifts of addition products (**37**) and (**38**).

| Chemical shifts of addition products (ppm) | | | |
|---|---|---|---|
|  | |  | |
| **37** | | **38** | |
| MeO | 3.54 | MeO | 3.30 |
| 3-$H_2$ | 4.79 | 3-$H_2$ | 4.10 |
| 1-H | 5.59 | 1-$H_2$ | 3.95 |

The nucleophilic addition of methanol to allene (**32**) can also be viewed as an indication of the Michael-type acceptor reactivity of this highly activated allene system.

The reaction with allene (**32**) and tetrahydrofuran at reflux, initially for 24 h, showed the presence of a new product by 60 MHz NMR. After further reflux for 5 d, all the material was consumed and a single product, formulated as (**39**) (Scheme 17) was obtained.

**Scheme 17**



**32** **39**

Compound (**39**) was isolated in 71 % yield and gave a fragment of mass equivalent to cleavage of a phenylsulfonyl group [M requires 392. Found *m/z* 141 ($M^+$-$PhSO_2$) and *m/z* 251] by mass spectrometry. Initially, it was thought that compound (**39**) may contain the oxepane ring. A seven membered ring system may arrive by attack of the oxygen of tetrahydrofuran at the central allenyl carbon followed by attack with the developing anion α to the sulfonyl group on the 2' position on the tetrahydrofuran ring, quenching the developing oxonium ion. The NMR spectrum of compound (**39**) indicated the presence of an AB system for the two 3-H allylic to the sulfonyl group which was taken as evidence against the formation of an oxepane ring system. A COSY experiment showed cross peaks between the 1-H and 2'-H of the furan ring, further correlations being followed around the ring (Figure 3).

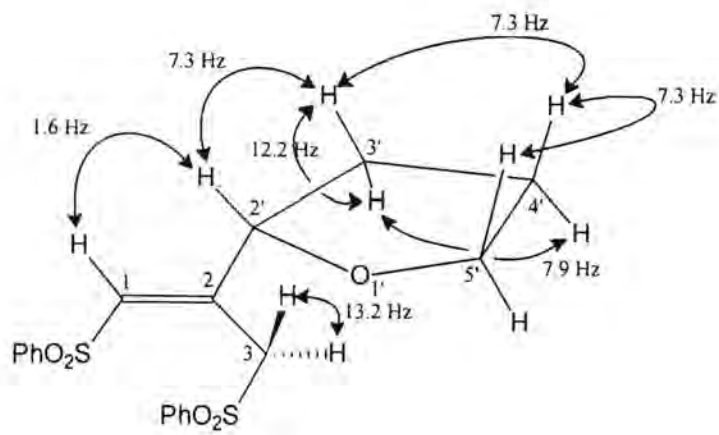
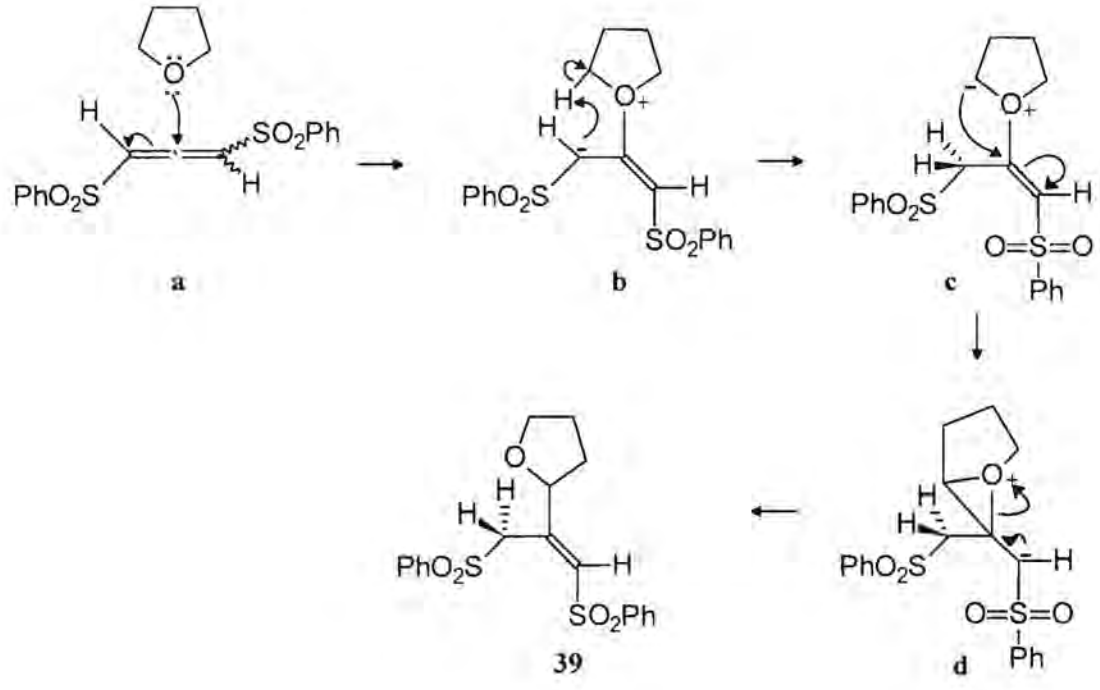



**Figure 3.** Coupling constants for the tetrahydrofuran addition product (**39**).

A plausible mechanism for the formation of (**39**) is presented in Scheme 18. It is proposed that the highly electrophilic central carbon of the allene (**32**), as shown in **a**, is attacked by tetrahydrofuran, leading to the ionic intermediate, **b**. The anion α to sulfonyl group abstracts a proton from tetrahydrofuran, forming the transient oxonium-ion ylide **c** that adds in a Michael sense to the vinyl sulfonyl group to form (**39**) via the epoxide-like intermediate, **d**.

**Scheme 18**




Although tetrahydrofuran is more basic than diethyl ether with which allene (**32**) did not show reactivity, the result presented here is a remarkable testament to the reactivity of this highly activated molecule. This result opens up new methodological possibilities for the synthesis of substituted tetrahydrofuran rings commonly found in many biologically active natural products.

In an attempt to recrystallise allene (**32**) from boiling carbon tetrachloride by heating over a steam bath, a dark insoluble residue remained after the removal of the boiling solvent. No precautions against moisture and oxygen were taken in this procedure. An attempt was made to recover allene (**32**) from this material by chromatography.

The allene (**32**) was recovered in 4 % from this residue and a new compound, obtained in 34 % yield, was isolated. Accurate FAB mass spectroscopy of the latter compound gave M+1=961. This analysis led to the formulation of the latter compound as a trimer, derived from 3 molecules of the allene (**32**). A high field NMR spectrum of this compound is shown below (Figure 4).

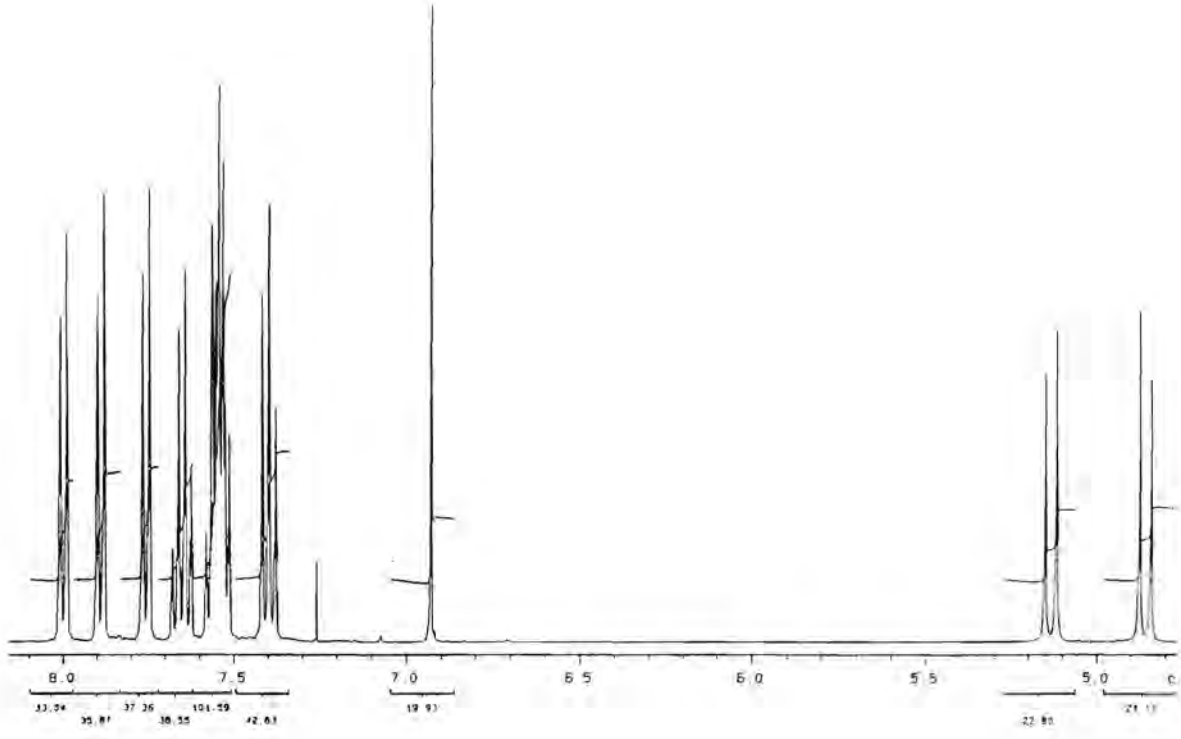



**Figure 4**. 400 MHz Proton NMR spectrum of the trimer.

The downfield region between 7.7 and 8.1 ppm reveal three triplets of doublets, each with couplings of 2.1 Hz and 7.4 Hz. This region is commonly associated with the *o*-protons of the phenylsulfonyl group and it is postulated that the different chemical shifts of the signals represent three different sets of phenylsulfonyl rings in the structure. The singlet at 6.92 ppm occurs at a similar field strength to the allene (**32**) protons and is associated with protons that are both vinylic and α to the phenylsulfonyl group. The two upfield doublets at 4.86 ppm and 5.13 ppm may arise from the presence of two sets of deshielded protons that

show very strong couplings, 2 x 13.4 Hz, to each other. This information is taken as evidence in support of structure (**40**), shown in Figure 5. It is postulated that the downfield doublet (5.13 ppm) arises from the two protons at either diametrically opposed terminus of structure (**40**) and that the upfield doublet (4.86 ppm) arises from the two protons diametrically opposed to each exocyclic double bond. In the carbon-13 spectrum, a signal occurs at 123.3 ppm and is assigned to the quaternary carbon of the spiro junction. Normally quaternary carbons occupy positions in the upfield aliphatic region around 40 - 50 ppm but in this case a large amount of deshielding occurs because of substitution by the electron withdrawing phenylsulfonyl groups.

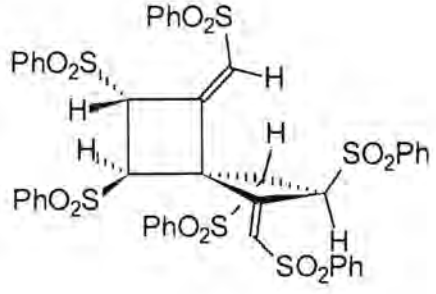
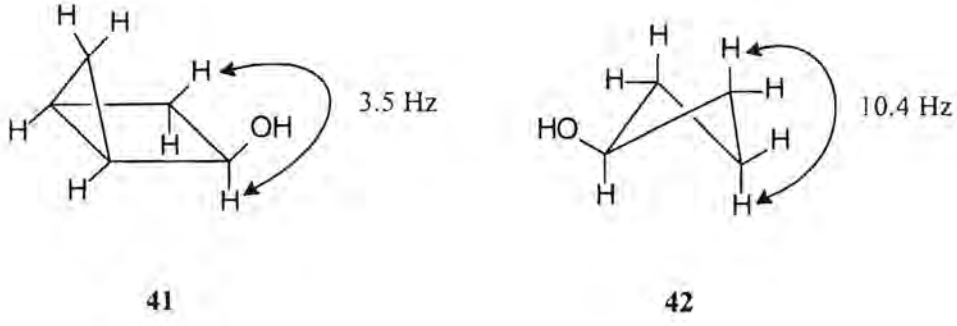



**Figure 5**. Structure of trimer (**40**).

The two very large couplings were assigned by analogy with the study by Wiberg and Barth[39] in which a comparison of proton NMR spectra between a planar and a puckered cyclobutane was conducted. The planar cyclobutane ring was exemplified by bicyclo[2.1.0]pentan-2-ol (**41**) in which the cyclobutane is fused to a cyclopropane ring forcing it into planarity while the puckered system was modelled by cyclobutanol (**42**) (Figure 6).



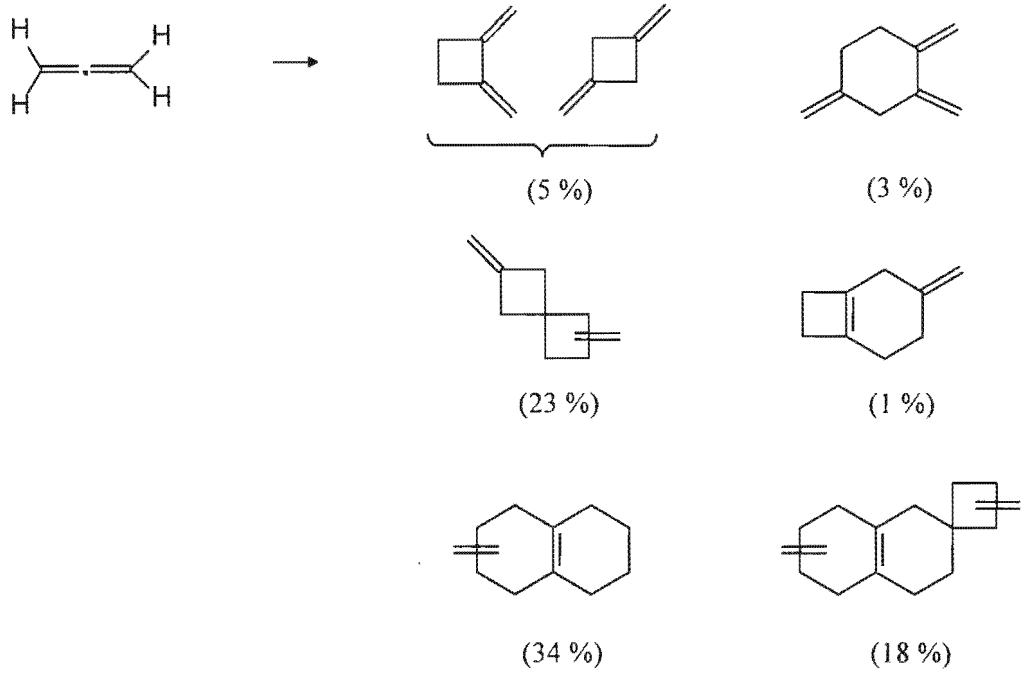

**41** **42**

**Figure 6.** *Trans*-diaxial couplings of (**41**) and (**42**).

Results from this study revealed that as the ring puckering got larger, so did the *trans*-diaxial coupling constants (3.5 Hz for the planar ring and 10.4 Hz for the puckered ring). It is envisioned that the trimer experiences puckering of the cyclobutane rings because of steric crowding of the phenylsulfonyl substituents on the carbons diametrically opposite to the exocyclic double bonds. This causes the *trans*-vicinal hydrogens to take up an anti-periplanar orientation and by analogy to cyclobutanol, results in the very large couplings (13.4 Hz).

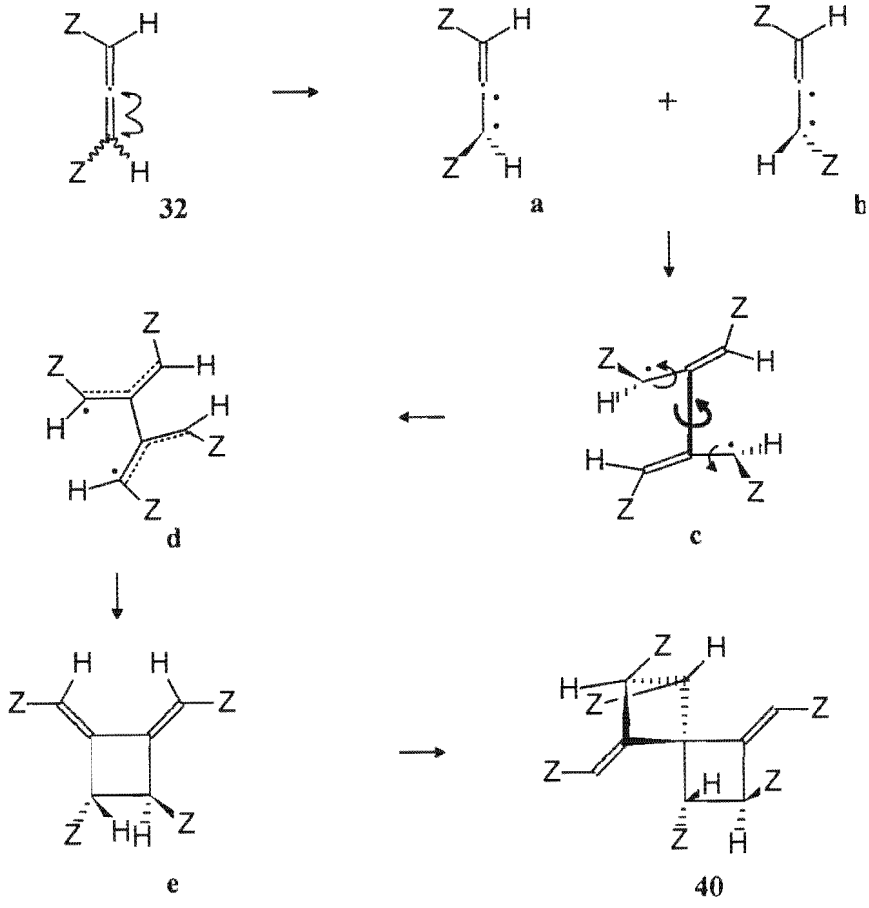
In a review on allenes, Griesbaum[40] cited reports of homocyclisation and oligomerisation of allene under thermal conditions (heating in a sealed tube at 110 °C to 160 °C) (Scheme 19).

**Scheme 19**



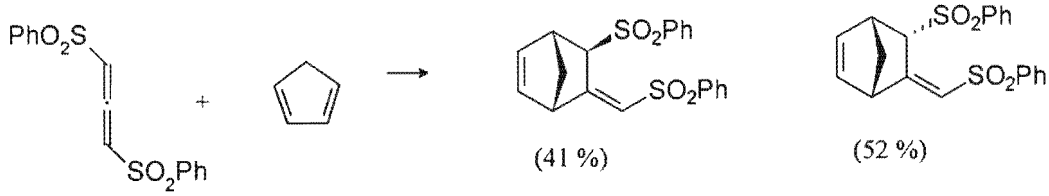

Based on earlier work by Dolbier and Dai[41] on secondary deuterium kinetic isotope effects, and Pasto and Warren's work on the cycloaddition of substituted allenes with 1,1-dichloro-2,2-difluoroethene,[42] much information has been gained on the asynchronous nature of allene [2+2]cycloadditions. These cycloadditions have been shown to proceed *via* a two step process involving an intermediate diradical. It has also been reported by Padwa and others[31] that carbon radicals with sulfonyl substituents are stabilised. It is postulated that the trimer could arise by a pathway shown below in which there is the development of a diradical intermediate under thermal conditions (Scheme 20).

**Scheme 20**



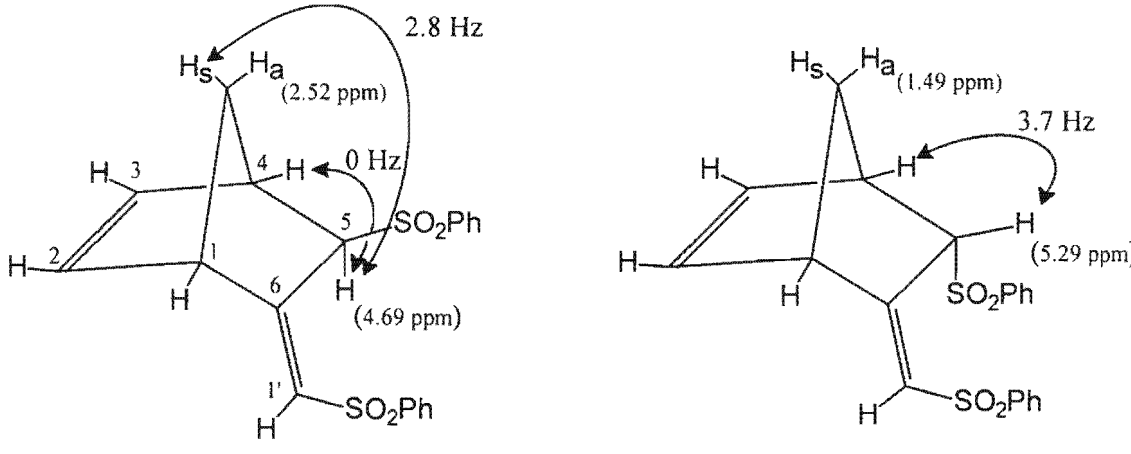

It is postulated that under the thermal conditions, one component of the allenyl π-system cleaves in a homolytic manner (**32**) to form two persistent diradicals represented as **a** and **b** for each component of the racemic mixture. These then combine in the sterically least demanding manner to give intermediate **c.** Because of the orthogonality of the two allenyl π-systems, the radicals present in **c** are not allylically stabilised, and rotation of the phenylsulfonylmethyl groups is required to give stabilised intermediate **d.** Bond formation then occurs to give **e**, with the *trans-* relationship of the two phenylsulfonyl groups established and the phenylsulfonylmethylene groups pointing to the outside of the molecule. Another molecule now adds to the dimeric structure in a way that minimises all

**Scheme 21**




**32** (41 %) **43 a** (52 %) **43 b**

High resolution NMR analyses of these adducts has been carried out by Heggie.[27] The "W coupling" from the bridge proton *syn* to the endocyclic double bond and the *endo* 5-H (**43 a**), as well as the vicinal coupling between the bridgehead proton and the *exo* 5-H (**43 b**) were instrumental in assigning the structures shown (Figure 7). With compound (**43 a**) the bridgehead proton does not show any coupling with the *endo* 5-H because the dihedral angle between these two protons is close to 90 °C.



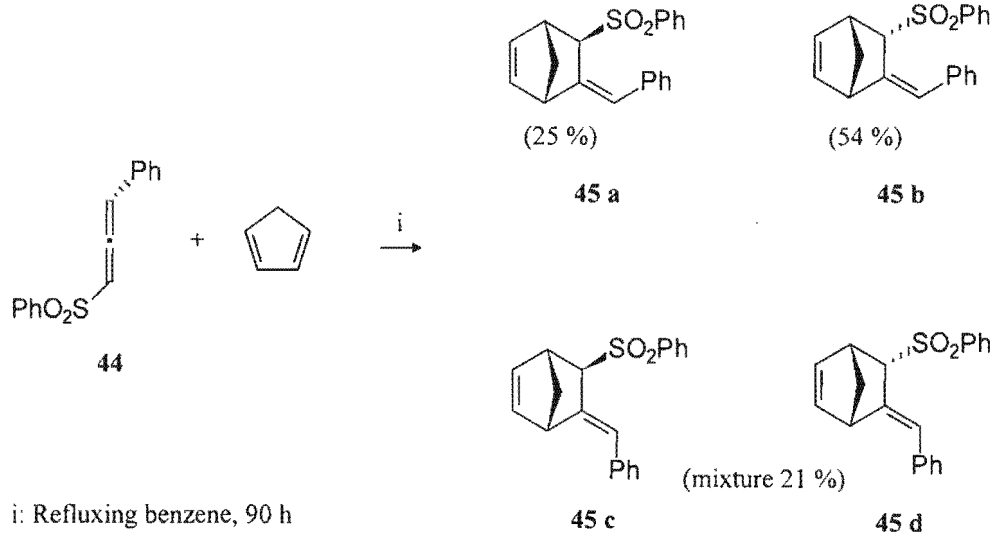

**43 a** **43 b**

**Figure 7.** Defining coupling constants and selected chemical shifts of cycloadducts (**43 a**) and (**43 b**)

The characteristic downfield absorption of the *exo* 5-H (**43 b**) (5.29 ppm) as compared to the *endo* 5-H (**43 a**) (4.69 ppm) is a common feature in norbornene type cycloadducts and occurs because of shielding of the *endo* 5-H (**43 a**) by the endocyclic double bond. Similar examples of this phenomenon have been reported by Maccagnani and others[43] and Barbarella and others.[44] By analogy with the phenylsulfonylpropadiene and cyclopentadiene cycloadducts described by Hayakawa and others[14] the bridge proton *anti*- to the endocyclic double bond in compound (**43 a**) is found at a lower field strength (2.52 ppm) compared to the same proton of (**43 b**) (1.49 ppm). It is speculated that this relative deshielding is due to the anisotropic effect of the phenylsulfonyl group in the *exo*-position.

Barbarella and others[44] conducted a study of the Diels-Alder reaction with a variety of 1,3-disubstituted allenes and cyclopentadiene and found similar preferences for *endo*-selectivity.

**Scheme 22**




i: Refluxing benzene, 90 h

In some examples cycloaddition products were isolated in which the unreacted allenyl double bond was in the (*E*)-configuration. Of particular note was the reaction of chiral

(+)-(*S*)-3-phenyl-1-(phenylsulfonyl)propadiene (**44**) which required 90 h in refluxing benzene to afford the products (**45 a-d**) in 74 % overall yield (Scheme 22).

It is speculated that the trigonal spread of the phenylsulfonyl group prevents the formation of (*E*)-substituted phenylsulfones in the reaction of allene (**32**) with cyclopentadiene (Figure 8). This is in contrast to the (*E*)-substituted phenyl adducts (**45 c**) and (**45 d**) obtained by Barbarella and others[44] in Scheme 22 where this inhibition does not operate because the terminal substituent is planar.

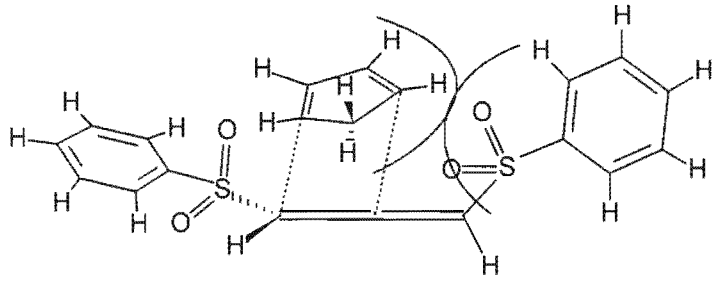


**Figure 8.** Representation of the steric crowding in an unfavourable transition state.

When heated, cycloadduct (**43 b**) exhibited an interesting morphological change between 192 °C and 204 °C, taking up a different crystal packing structure, before melting at 213°C. A differential scanning calorimetric determination (DSC) was conducted to see if this could be measured by an enthalpy difference, and indeed this was found to be the case (Figure 9).

Thermal events in the sample appear as deviations along the DSC base line, as either an endothermic (increase in heat flow) or exothermic (decrease in heat flow) enthalpy change. When (**43 b**) was heated, a small endotherm at 197 °C, followed by a larger exotherm at 198 °C occurred. This was due to the structural rearrangement of the compound prior to melting, which occurred at 213.7 °C. The large endotherm after 255 °C occurred when the sample decomposed.

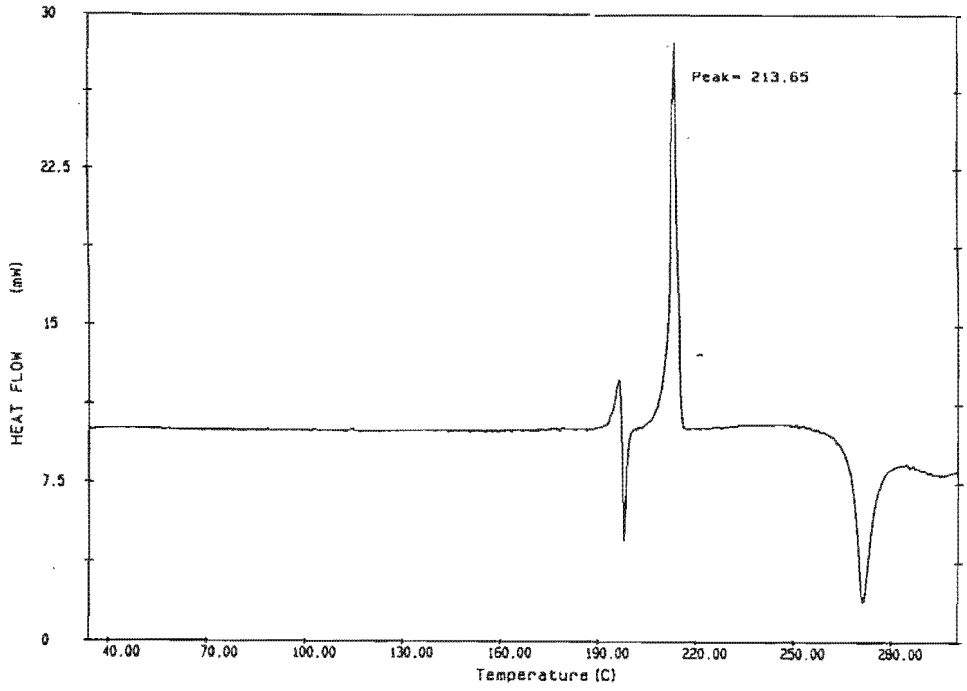
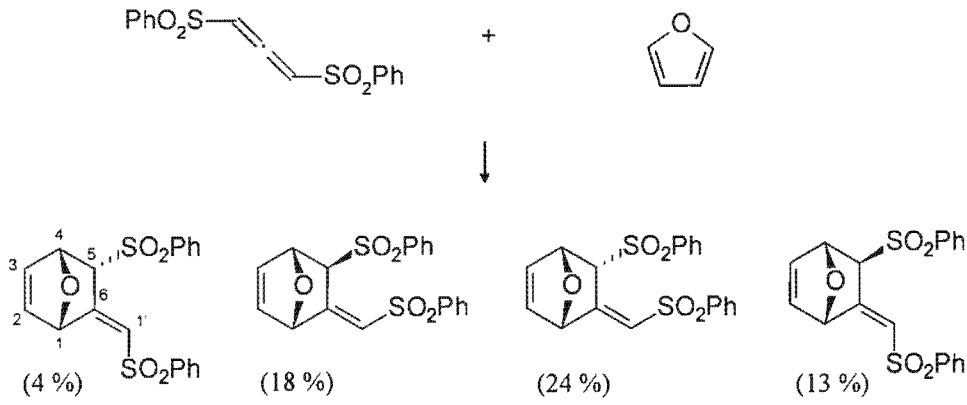



**Figure 9.** Differential scanning calorimetric analysis of (**43 b**).

The cycloaddition of allene (**32**) with furan was undertaken for the purpose of re-examining the reaction first carried out by Heggie.[27] In some of the early work with furan, high pressures, reported by Dauben and Krabbenhoft[45] and Lewis acid catalysis, reported by Fraile and others[46] were used to effect cycloaddition. The reaction with allene (**32**) was relatively rapid, being complete after 2 h at 80 °C to give the 4 possible [4+2] cycloadducts (Scheme 23).

**Scheme 23**




Cycloadduct (**46 a**) was not previously identified in the reaction carried out by Heggie[27] at 100 °C. The experiment at 80 °C was repeatedly conducted and very similar isolated yields were obtained, as presented. In this reaction the activating effect the two phenylsulfonyl functionalities have on the allenyl dienophile is reflected by the short duration of the reaction. The structure of cycloadduct (**46 a**) (Figure 10) was assigned by reference to the detailed high resolution NMR experiments carried out on (**46 b-d**) by Heggie.[27] The 5-H of cycloadduct (**46 a**) occurred as a doublet of doublets and was assigned to the *exo*-orientation with a 3.9 Hz vicinal coupling to 4-H. The *endo*-5-H of cycloadduct (**46 d**), assigned by Heggie,[27] was shown to have a smaller coupling of 0.8 Hz to 4-H, reflecting the larger dihedral angle. The geometry of the (*E*)-phenylsulfonyl group of cycloadduct (**46 a**) was rationalised by the smaller *cis*-allylic coupling (1.9 Hz) obtained than the *trans*-allylic coupling of (**46 c**) (2.1 Hz). The 5-H of (**46 a**) occurs at a higher field (4.31 ppm) than the 5-H of (**46 c**) (5.35 ppm). It is rationalised that the *exo*-5-H of (**46 a**) is not deshielded by the anisotropic effect of the (*Z*)-orientated phenylsulfonyl group as with (**46 c**).

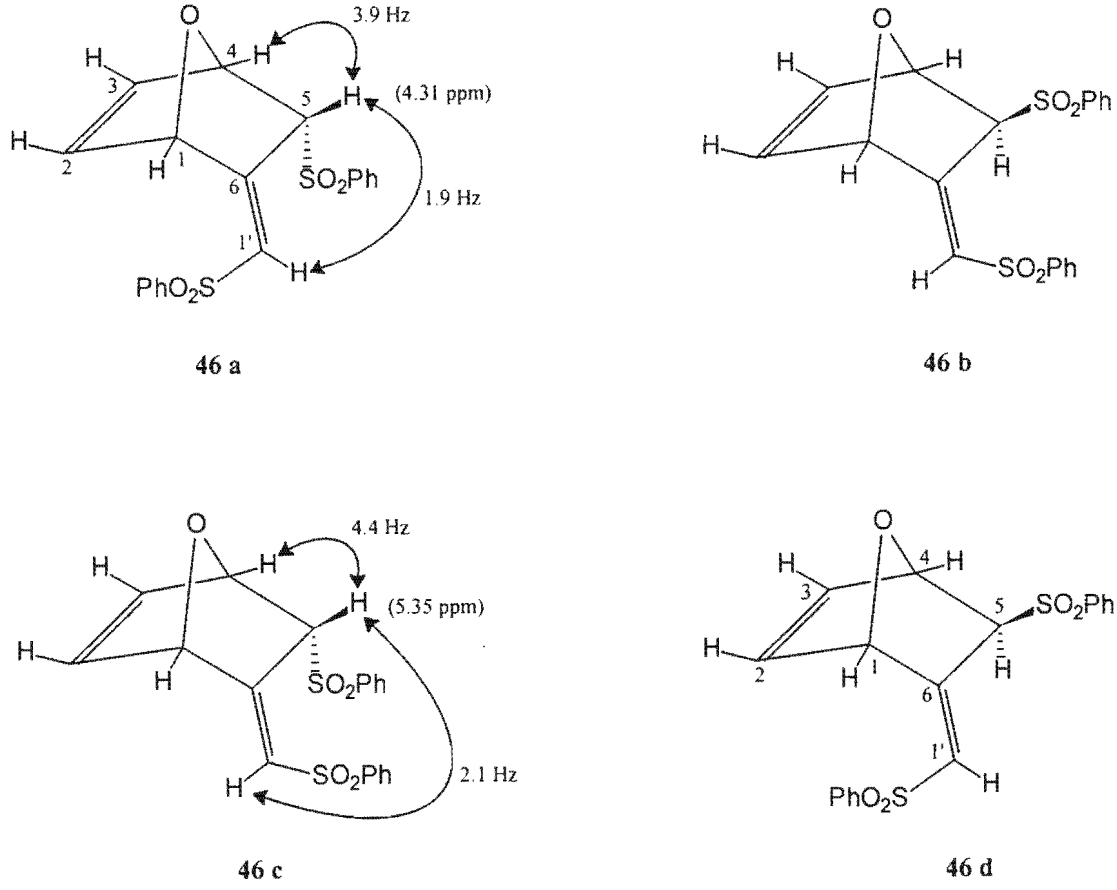



**Figure 10.** Characteristic coupling constants of the furan cycloadducts (**46 a-d**).

Numerous authors, *e.g.* Dauben and Krabbenhoft,[45] Lee and Herndon,[47] Cook and Cracknell[48] and Padwa and others,[49] have commented on the reversible nature of certain furan cycloadditions under thermal conditions, with initially the *endo*-isomers being formed and then the gradual accumulation of the more stable *exo*-isomer *via* a *retro*-Diels-Alder process. HPLC analysis of the cycloaddition reaction mixture of furan and allene (**32**) was conducted at various time intervals during the progress of the reaction and no change in the ratio's of the cycloadducts were found (Figure 11), indicating that no *retro*-Diels-Alder reaction was occurring whereby a thermodynamically more stable product accumulates. Despite the strain of the oxabicyclo[2.2.1]heptane system the cycloadducts are stable to the prolonged thermal treatment and the abundance of each cycloadduct may

be an indication of the activation energy needed to reach a particular transition state under set reaction conditions.

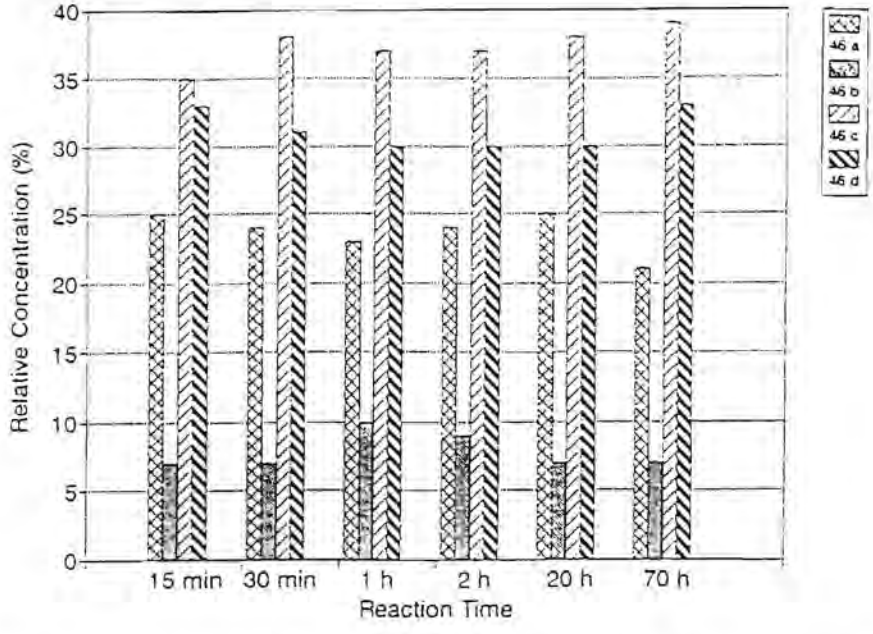
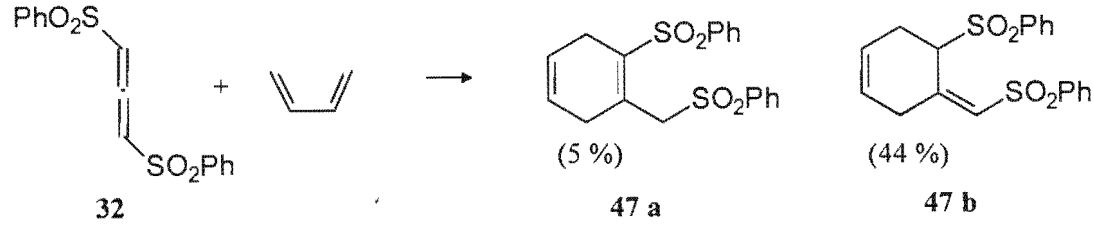



**Figure 11**. HPLC analysis of the reaction of furan and allene (**32**) conducted at various time intervals.

The study of the cycloaddition of isoprene and 2,3-dimethylbutadiene with allene (**32**) was carried out by Heggie.[27] In both cases a separable mixture of [4+2] and [2+2] cycloadducts was obtained. It was of interest to study the cycloaddition of allene (**32**) with butadiene to determine if this pattern would be repeated. Butadiene is a very unreactive diene not electronically activated, resulting in a large energy difference between the HOMO of butadiene and LUMO of allene (**32**). Also, the conformational flexibility of butadiene results in a diminished percentage of butadiene molecules occuring in the planar s-*cis* conformation needed for the reaction to take place. Reaction of allene (**32**) with butadiene required heating for 26 h at 80 °C in a sealed tube to consume all of the dienophile. A considerable amount of polymerised butadiene was noted after the reaction and a poor conversion of 49 % to reaction products was obtained. The minor product (**47 a**) was obtained in 5 % yield while the major product (**47 b**) was obtained in 44 % yield (Scheme 24).

**Scheme 24**



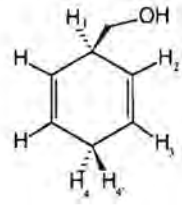
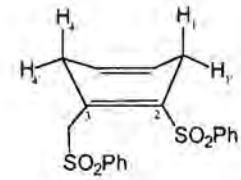

**32** **47 a** **47 b**

The structural assignment of cycloadduct (**47 a**) was derived from an analysis of the proton NMR spectrum. The appearance of a two proton singlet at 4.89 ppm was assigned to the exocyclic methylene protons. The two endocyclic vinyl proton signals were superimposed and seen as a two proton multiplet between 5.58 ppm and 5.67 ppm. Two symmetrical signals at 2.81 ppm and 3.30 ppm were assigned to the 1,4-disposed protons on the cyclohexadiene ring. Separate cross peaks for each of the proton signals were obtained in a HETCOR experiment to carbons with chemical shifts of 27.9 ppm and 34.6 ppm respectively. Strong cross peaks in a COSY experiment of (**47 a**) were obtained for the 1,4-disposed protons, ($J_{1,4}$ *cis*-, 8.3 Hz; $J_{1,4}$ *trans*-, 6.7 Hz, see Table 3) but elements of non-first order interactions were present. Large through-bond couplings of the 1,4-disposed protons on a cyclohexadiene ring have been described in analogous examples in the literature. In particular, studies on the conformational analysis of 1,4-cyclohexadienes carried out by Rabideau[50] and Rabideau and Wetzel[51] have unravelled the relationship between the magnitude of the coupling constant and the conformational state of the ring.

In these studies it was found that the experimentally obtained constants for 3-hydroxymethyl-1,4-cyclohexadiene (**48**) were similar to those calculated for planar 1,4-dihydrobenzene. In the planar geometry, the $J_{1,4}$ / $J_{1,4'}$ (*cis* / *trans*) ratio has been established at about 1.1 (Table 3). It was calculated that as the 1,4-cyclohexadiene begins to pucker, the *cis*-1,4 diaxial homoallylic coupling becomes considerably bigger, (from *ca.* 8 Hz to 12 Hz), the *trans*-axial / equatorial value decreases slightly (from *ca.* 8 Hz to 5 Hz) and the ratio $J_{1,4}$ / $J_{1,4'}$ (*cis* / *trans*) becomes larger (up to about 2.5 for a rigid boat

conformation). Although the two systems in comparison are considerably different in relation to the substitution pattern on the ring, the 1,4-diaxial couplings of (**47 a**) are similar to those of 3-hydroxymethyl-1,4-cyclohexadiene (**48**) showing that the proton assignments are reasonable. Speculation as to the conformational state of compound (**47 a**) would, however, be unreasonable without further studies.

**Table 3.** Comparison of 1,4-homoallylic coupling constants of 3-hydroxymethyl-1,4-cyclohexadiene (**48**) and minor product (**47 a**).

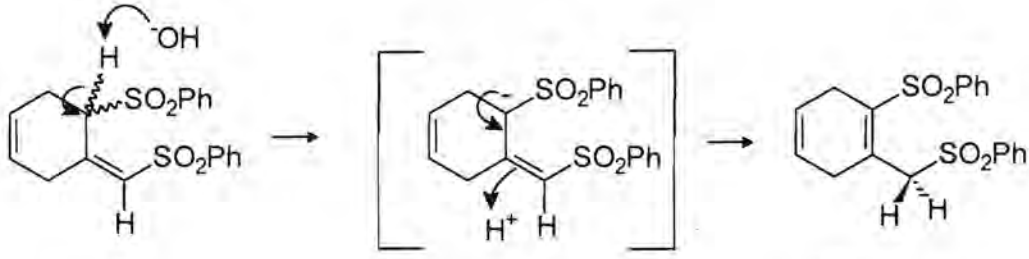
| Coupling constants (Hz). |  3-hydroxymethyl-1,4-cyclohexadiene **48** |  **47 a** |
|---|---|---|
| $J_{1,4}$ (cis) | 8.3 | 8.3 |
| $J_{1,4'}$ (trans) | 7.5 | 6.7 |
| $J_{cis}$ / $J_{trans}$ | 1.11 | 1.24 |

The structure of the major product (**47 b**) (Scheme 24) follows from NMR spectra and was assigned from cross peaks in a COSY experiment between the endocyclic vinyl protons and the two signals for the 1,4-disposed methylene protons on the cyclohexene ring. The downfield doublet (6.36 ppm, 2.3 Hz) was assigned to the deshielded vinyl proton α to the sulfonyl group of product (**47 b**). It is postulated that the occurrence of cycloadduct (**47 a**)

can be rationalised in one of three ways. Firstly, a [1,3]-sigmatropic rearrangement of the proton α- to the sulfonyl group of (**47 b**) to the allylic position would yield compound (**47 a**). By the Woodward and Hoffmann rules[52] for the conservation of orbital symmetry, this thermally allowed process would have to take place by a geometrically unfavourable antarafacial movement of hydrogen and such rearrangements are unknown. Secondly, cycloadduct (**47 a**) may arise from a proton shift whereby the proton α to the sulfonyl group of (**47 b**) undergoes an allylic rearrangement occurs to give the more stable endocyclic double bond of compound (**47 a**) (Scheme 25).

Attempts were carried out to transform (**47 b**) into (**47 a**) by treatment of (**47 b**) on a small scale with oxalic acid, alumina, base (lithium diisopropylamide, -78 °C) and acid (2 M HCl), but none of these treatments met with any success and so this explanation for the formation of (**47 a**) is unlikely.

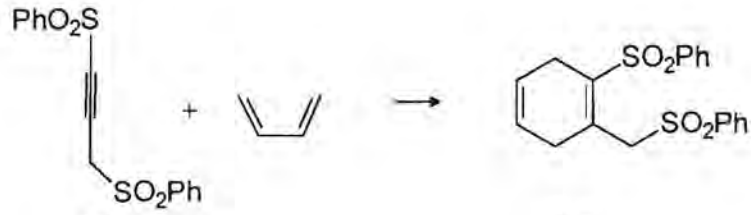
**Scheme 25**




**47 b** **47 a**

Thirdly, the cycloaddition with the alkynyl dienophile (**48**) obtained by isomerisation of the allene (**32**) to butadiene, would yield product (**47 a**) (Scheme 26). However, throughout the course of this investigation no evidence for such an alkynyl species was detected. Further studies on the conditions under which product (**47 a**) may form need to be carried out.

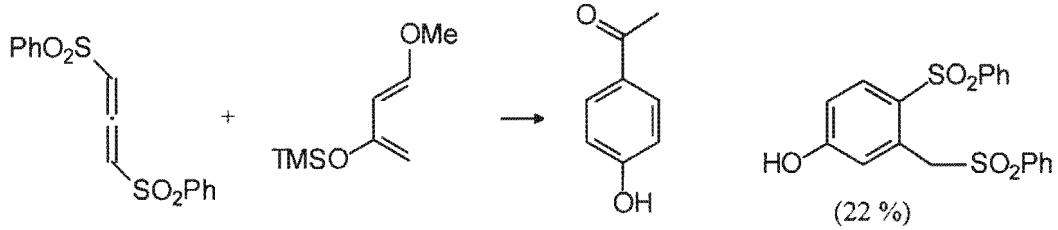
**Scheme 26**




**48** **47 a**

The last diene in the series to be investigated is the disubstituted butadiene, (*E*)-1-methoxy-3-trimethylsilyloxybutadiene (**49**), commonly known as Danishefsky's diene. It was easily prepared by treatment of *trans*-4-methoxybutene-2-one (**51**) with triethylamine and zinc chloride, followed by quenching with chlorotrimethylsilane as described by Danishefsky and Kitahara.[53] Unfortunately, after repeated distillation less than 3 % of starting *trans*-4-methoxybutene-2-one was present and Danishefsky's diene was routinely used containing 13 % of *trans*-4-methoxybutene-2-one. Danishefsky's diene is useful because of the oxygen functionality it adds to the cycloaddition product and because the electron donating substituents activate the diene to undergo highly regioselective reactions due to the complementarity of frontier molecular orbital interactions with electron deficient dienophiles.[54] This is also the first unsymmetrical diene investigated in this study and preference for a certain regiochemical outcome is expected. Unfortunately, the reaction of allene (**32**) with Danishefsky's diene (**49**) proved troublesome. Progress of the reaction was monitored by thin layer chromatography and was shown to require heating at 80 °C for 8 h for the complete conversion of allene (**32**) into product. Also, a very large excess (10 x) of the diene was used and the presence of charred material upon the completion of reaction was noted. Reaction of a mixture of Danishefsky's diene and *trans*-4-methoxybutene-2-one with allene (**32**) afforded compound (**50 a**) quantitatively as a side product and (**50 b**) in 22 % yield (Scheme 27).

**Scheme 27**




**49** **50 a** **50 b**

The structure of product (**50 b**) was rationalised on the basis of microanalytical data and a proton NMR spectrum. The presence of a broad singlet at 7.34 ppm that disappeared after exchange with $D_2O$ was assigned as the phenolic hydroxyl function. A sharp singlet at 4.94 ppm integrating for two protons was assigned to the two 1'-H (Figure 12).

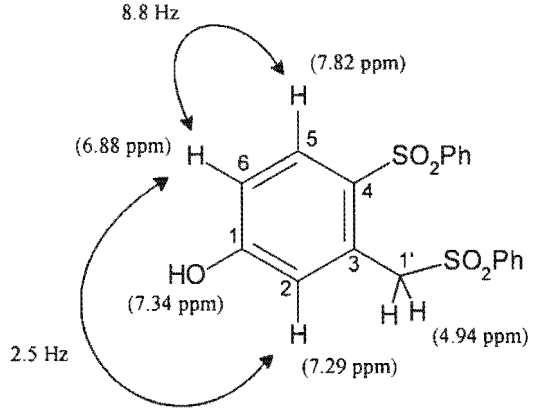
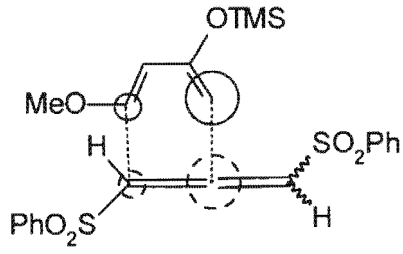



**Figure 12.** Coupling constants of Danishefsky's diene cycloadduct (**50 b**).

The 5-H was deshielded by the phenylsulfonyl group and appeared downfield at 7.82 ppm as a doublet (8.8 Hz). This couples to an upfield signal at 6.88 ppm occurring as a doublet of doublets (8.8 Hz and 2.5 Hz) that was assigned to 6-H with shielding by the hydroxyl group evident. The 2-H was seen as a doublet at 7.29 ppm with a coupling of 2.5 Hz to 6-H. The above analysis was taken as evidence for the regiochemistry

presented in Scheme 28. It is envisioned that the opposite regiochemistry would have resulted in the downfield proton, deshielded by the phenylsulfonyl group, occurring as a doublet with a small coupling to the proton adjacent to phenolic hydroxyl group.

**Scheme 28**

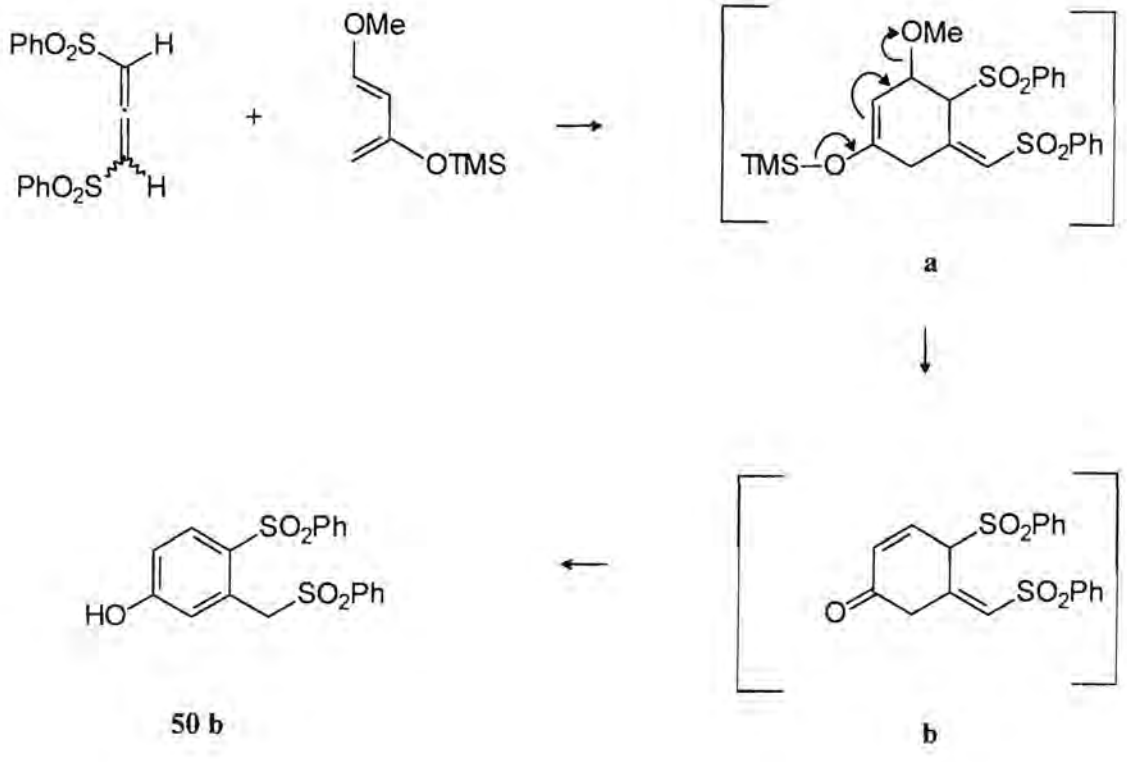



By analogy to Fleming's[54] treatment of the Frontier Orbital theory of Fukui,[55] the favoured regiochemical outcome in a Diels-Alder reaction is determined by the similarity in relative magnitude of a LUMO coefficient on the dienophile with a HOMO coefficient on the diene. Electron donating groups on the diene which increase the energy of the interacting HOMO and electron withdrawing functionality on the dienophile which decrease the energy of the interacting LUMO will have a positive effect on reaction rate. The largest LUMO coefficient for the dienophile resides on the central carbon of the allenyl system, and the largest HOMO coefficient for Danishefsky's diene on the terminal carbon, with the most favourable orbital overlap between the two nuclei bearing the two largest and the two smallest coefficients respectively (Scheme 28). This is reflected in the observed regioselectivity obtained for the reaction of Danishefsky's diene with allene (**32**). The extended reaction times needed for the formation of the Diels-Alder adduct, in spite of the favourable combination of orbital overlaps, may be due to a sterically demanding transition state.

The reaction is proposed to proceed by the intermediate structure **a** formed from an *exo* transition state (Scheme 29). The breakdown of the *endo* principle is well known for substituted acrylic dienophiles, as pointed out by Danishefsky and others.[56] It is

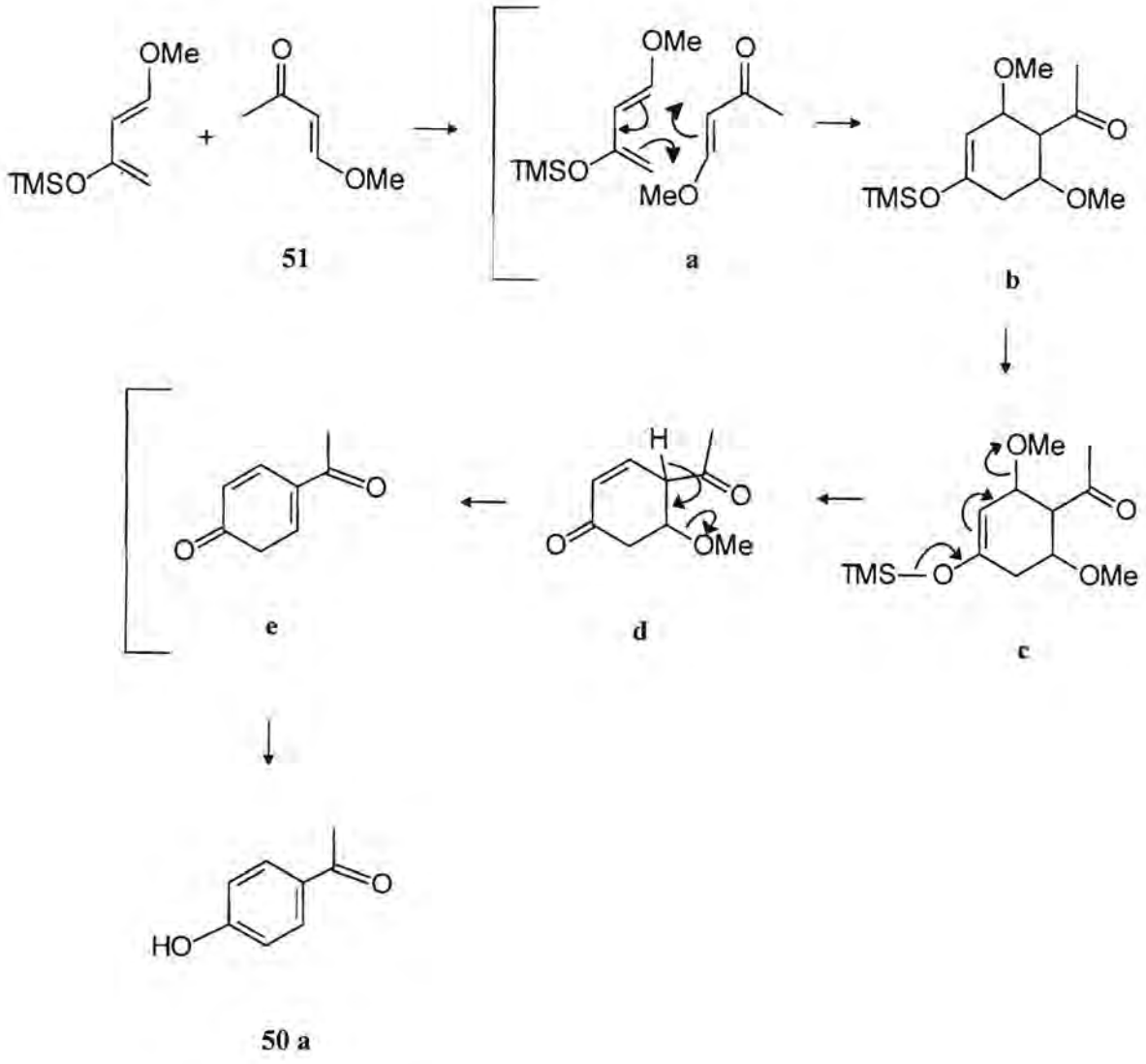
thought that intermediate **a** undergoes hydrolysis of the silyl enol ether during the reaction due to the presence of a contaminant with loss of methanol to arrive at intermediate **b** that undergoes tautomerism to yield (**50 b**). In a similar cycloaddition with [(2-nitrophenyl)sulfinyl]propadiene, carried out by Padwa and others,[19] the aromatised product (3-hydroxyphenyl)methyl 2-nitrobenzenesulfenate was similarly arrived at.

**Scheme 29**



The formation of the less polar 4-hydroxyacetophenone was rationalised to occur by the reaction of Danishefsky's diene with starting *trans*-4-methoxybutene-2-one, (**51**), present in 13 % under the conditions investigated. A plausible sequence of events is shown below (Scheme 30). Under the thermal conditions a [4+2] cycloaddition takes place **a**, to yield **b** which undergoes enol silyl ether hydrolysis with methanol elimination **c**, to yield **d**. Further methanol elimination occurs to give **e**, which tautomerises to give (**50 a**) with the stable aromatic structure.

**Scheme 30**



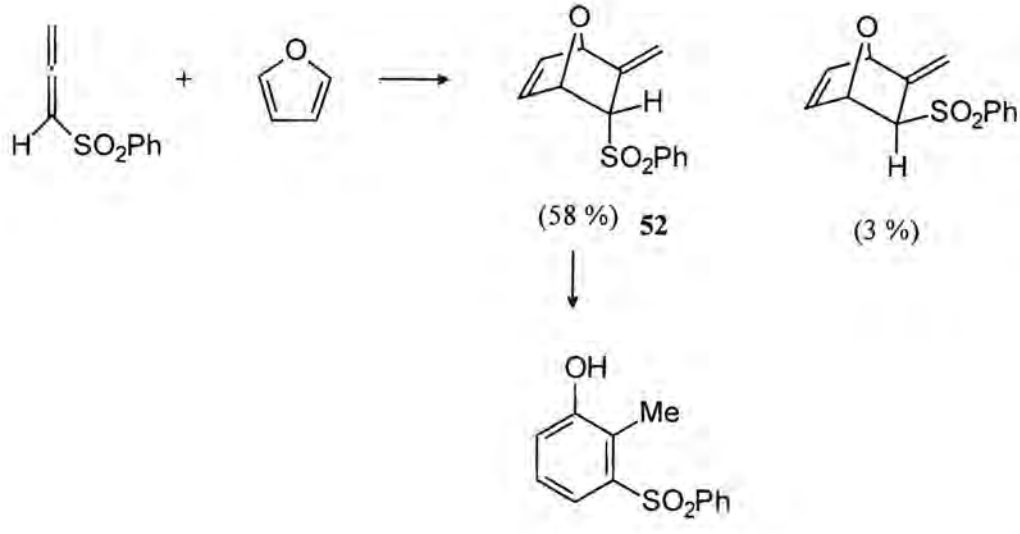
**4. Base treatment of furan cycloadducts**

The four furan cycloadducts obtained by the reaction of furan and allene (**32**), (**46 a-d**) (Scheme 23) were subjected to base treatment in an attempt to open the oxo-bridge and induce aromatisation. If successful, this procedure would lead to a convenient method to obtain *o*- and *m*-disubstituted phenols.

Similar base treatments of furan-derived cycloadducts have been carried out. The zinc iodide catalysed cycloaddition of furan with a number of electron deficient dienophiles (including methacrylate, acrylonitrile and *a*-chloroacrylonitrile), described by Brion[57] yielded the substituted 7-oxabicyclo[2.2.1]heptenes. These were then treated with a base, lithium bis(trimethylsilyl)amide, to yield the substituted cyclohexadienes.

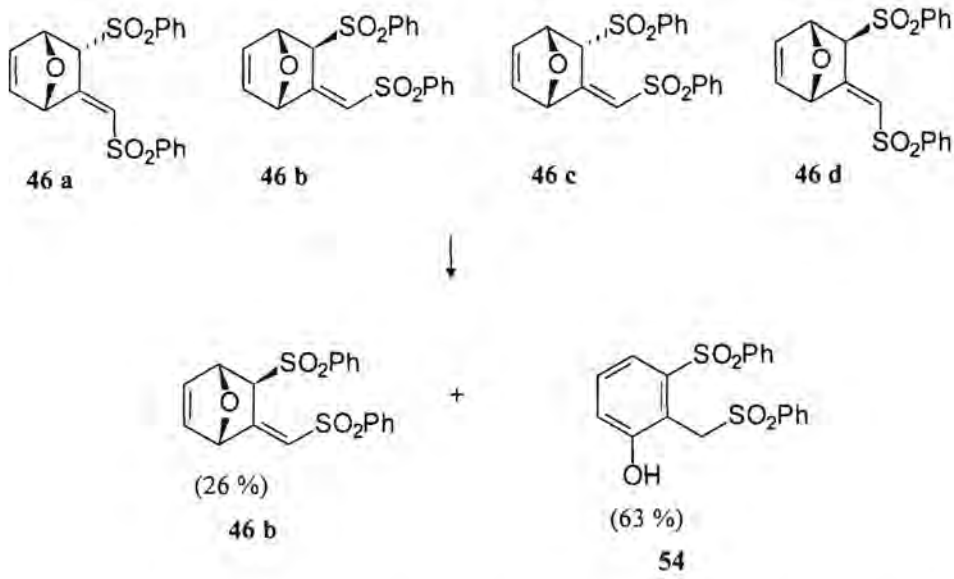
The reaction of furan with phenylsulfonylpropadiene described by Guilford and Turner,[58] yielded predominantly the *endo*-methylene sulfone (**52**) which was subjected to *n*-butyl lithium treatment at low temperature to yield 3-phenylsulfonyl-2-methylphenol (**53**) (Scheme 31).

**Scheme 31**



Treatment of the furan cycloadduct mixture (**46 a-d**), obtained under previously described reaction conditions with 4 molar equivalents of potassium *t*-butoxide gave (**46 b**) and (**54**) in a total yield of 89 % (Scheme 32).

**Scheme 32**




The structure of the surviving cycloadduct was confirmed by a mixed melting point and gave a proton NMR spectrum identical to (**46 b**). The structure of aromatised product (**54**) was assigned by NMR (Figure 13). In the 200 MHz proton spectrum, a broad singlet between 8.05 ppm and 8.65 ppm disappeared by exchange with $D_2O$ and was assigned as the hydroxyl group. The sharp two-proton singlet at 5.19 ppm was assigned as the methylene 1'-H. A single proton signal obscured by the *m*- and *p*-protons of the phenylsulfonyl groups occurred between 7.74 ppm and 7.76 ppm and was assigned as 4-H which experiences deshielding from the phenylsulfonyl group attached to carbon 3. The two proton multiplet between 7.24 ppm and 7.40 ppm was assigned as 5-H and 6-H. In the 50 MHz carbon NMR spectrum, the upfield signal at 115.3 ppm was assigned to carbon 2, which is shielded by the mesomeric release of electron density by the hydroxyl group.

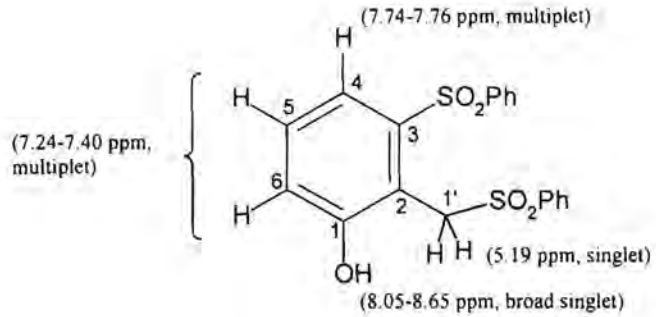
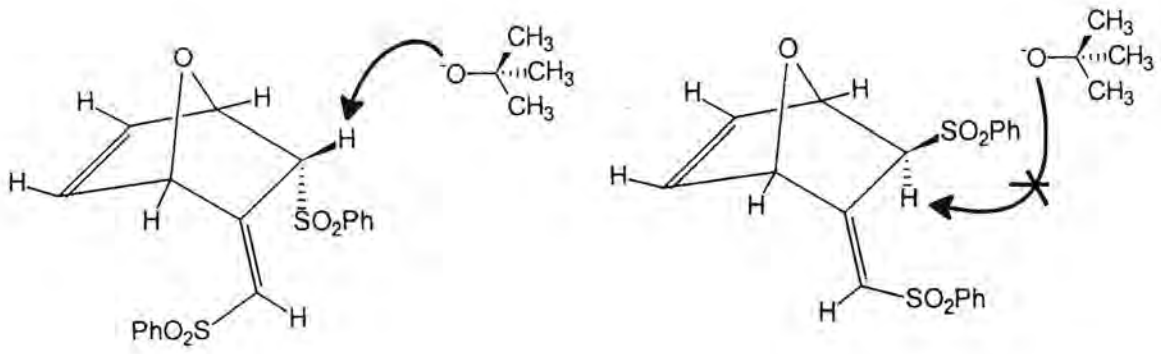



**Figure 13**. Chemical shifts of signals for aromatised product (**54**).

The amount of unreacted compound (**46 b**) after the base treatment was approximately the same as that in the original furan cycloadduct mixture. This indicated that the unreacted material corresponded to (**46 b**) present before the treatment, and did not arise from an indirect route. The question of why only one of the furan cycloadducts did not undergo aromatisation may have something to do with the accessibility of the proton α to the sulfonyl group to the base. From a study of models of the furan cycloadducts (**46 a-d**) it is postulated that the two extremes for the availability of the proton α to the sulfonyl group to *t*-butoxide abstraction are represented by (**46 a**) and (**46 b**) (Figure 14). It is well known that in these bicycloheptenes the *exo*- face is more sterically accessible than the *endo*-face. Also, with (**46 a**) the (*E*)-methylene phenylsulfonyl substituent points away from the proton α to the sulfonyl group. The opposite situation is found with (**46 b**) where the (*Z*)-methylene phenylsulfonyl substituent points towards the proton α to the sulfonyl group. The sum of these two steric effects work together resulting in the inaccessibility of *t*-butoxide to the vicinity of the proton α to the sulfonyl group.

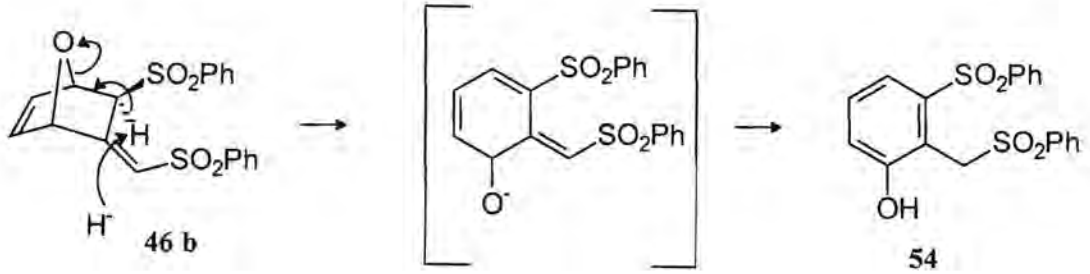



**46 a** **46 b**

**Figure 14.** Diagrammatic representation of the trajectories of *t*-butoxide approach for proton abstraction of (**46 a**) and (**46 b**).

Sodium hydride treatment of (**46 b**) was carried out to test whether the more compact hydride would cause aromatisation, and indeed this was found to be the case (Scheme 33). It is postulated that the reaction proceeds through the intermediate shown below, which rapidly aromatises to (**54**).

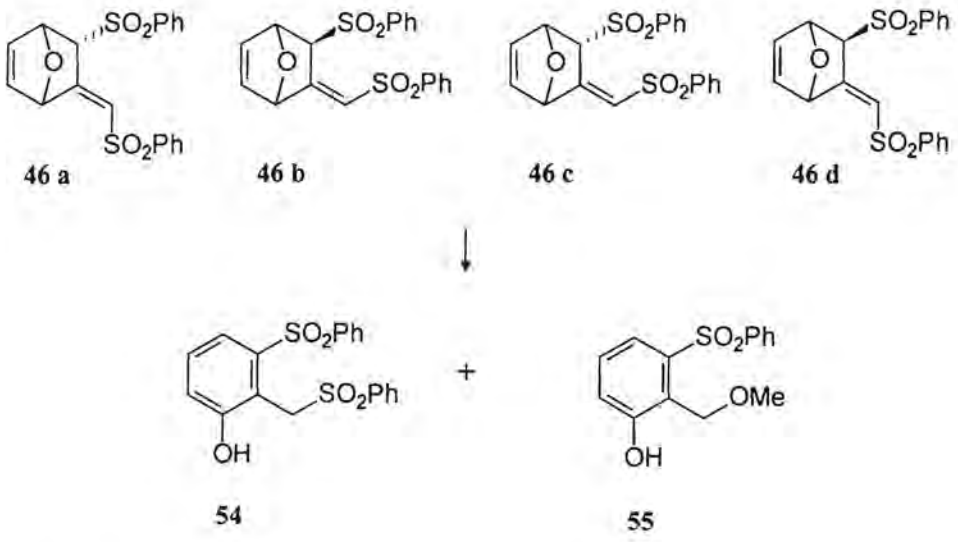
**Scheme 33**




It was also useful to determine the reactivity of the mixture of furan cycloadducts to the readily available base, potassium methoxide. Treatment of the mixture with potassium in methanol at reflux for 24 h yielded the aromatised product (**54**) in 15 % yield and a compound assigned as (**55**) in 14 % yield.

The product (**55**) was obtained as a solid of low melting point (41 - 44 °C) which gave a molecular ion of 278 atomic mass units by mass spectroscopy, which corresponds to the calculated mass of the structure presented. Recrystallisation of the sample from chloroform failed to yield material that presented accurate combustion analysis data.

**Scheme 34**




The proton NMR spectrum revealed the presence of two sharp singlets integrating for 3 protons (3.19 ppm) and 2 protons (4.99 ppm) which were assigned to the the methoxide and 1'-H respectively (Figure 15).

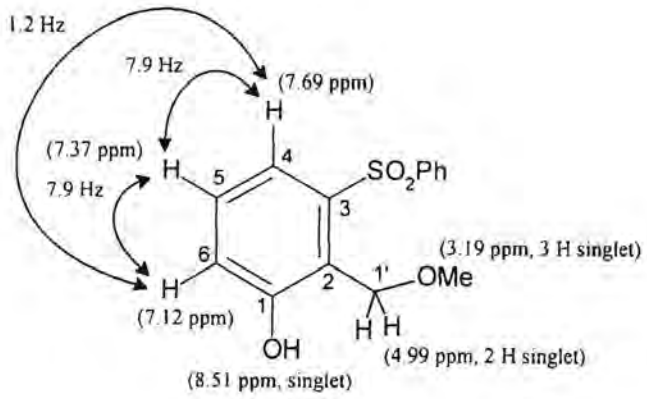



**Figure 15.** Chemical shifts and coupling constants of aromatised product (**55**).

The single proton doublet of doublets at 7.69 ppm was assigned as 4-H and displayed couplings of 1.2 Hz and 7.9 Hz. This proton is deshielded by the phenylsulfonyl group and occurs downfield relative to 5-H and 6-H. The large coupling of 4-H (7.9 Hz) is to a single proton triplet at 7.37 ppm assigned as 5-H (2 x 7.9 Hz). The small coupling of 4-H (1.2 Hz) is to proton 6-H, which also occurs as a doublet of doublets with couplings of 7.9 Hz and 1.2 Hz at 7.12 ppm, shielded by the mesomeric release of electron density from the hydroxyl group. The singlet at 8.51 ppm disappeared with exchange by $D_2O$ and was assigned to the hydroxyl function at C-1. It is postulated that formation of (**55**) occurs by a route described in a reaction performed by Julia[59] whereby methoxide adds to a styrene with a β- substituted sulfonyl group and eliminates benzenesulfinate ion. Unfortunately, no further studies were carried out in this investigation to confirm this.

# CONCLUSION

This study was undertaken to optimise the synthesis of 1,3-bis(phenylsulfonyl)propadiene and to explore its reactivity under various conditions. The improved synthesis of 1,3-bis(phenylsulfonyl)propadiene presented here has made gram quantities of high quality material readily available.

The stability of the above allene to handling in the laboratory and to a selection of commonly used solvents was demonstrated. The addition reaction with methanol and the reaction with tetrahydrofuran indicate the highly reactive nature of this molecule and has opened up new methodological possibilities. The results of a preliminary study of the homocyclisation of the allene leading to a highly substituted spiro-trimer compound are presented.

Reaction with cyclopentadiene, furan, butadiene and Danishefsky's diene has been demonstrated to occur *via* the [4+2] mode of cycloaddition. In the case of cyclopentadiene and furan, no large *endo*- or *exo*-addition bias is evident, pointing towards the lack of secondary orbital interactions during the reaction. With Danishefsky's diene the regiochemistry obtained in the cycloaddition product can be explained by frontier molecular orbital theory in which the electron withdrawing 1,3-bis(phenylsulfonyl)-substituents on the allene result in the central allenyl carbon dominating the reaction outcome.

This study has extended the understanding of the cycloaddition reaction with furan. The relatively rapid reaction yields the full spectrum of possible [4+2] cycloadducts and demonstrates the reactivity of 1,3-bis(phenylsulfonyl)propadiene to furans. Base treatment of the furan cycloaddition mixture led to an *o*-, *m*- disubstituted phenol compound.
The study presented above is ongoing and is opening up many areas that have seemingly unlimited potential. The search for new areas of synthetic application of this methodology is on.

# EXPERIMENTAL

Melting points were measured using a Reichert-Jung Thermovar hot stage microscope and are uncorrected. Microanalyses were determined using a Fisons EA 1108 CHNS-O instrument. Mass spectra were recorded on a VG micromass 16F spectrometer operating at 70 eV with an accelerating voltage of 4 kV and a variable source temperature, depending on the nature of the compound. Accurate masses were determined on a KRATOS Limited MS9/50 spectrometer.

Differential Scanning Calorimetry was conducted on a Perkin-Elmer PC Series DSC7 instrument with a programmed temperature run performed over 30 °C to 300 °C at a heating rate of 10 °C $min^{-1}$ under dry nitrogen purge gas flowing at 30 $cm^3$ $min^{-1}$. The sample was finely ground and 3.287 mg was used.

Infrared spectra were recorded in chloroform solutions using a Perkin-Elmer Paragon 1000 FT-IR spectrometer, over the range 4000-800 $cm^{-1}$. $^1$H-NMR spectra were recorded using $CHCl_3$ as an internal standard on a Varian EM360A (60 MHz), Varian VXR-200 (200 MHz) or a Varian Unity (400 MHz) Spectrometer. $^{13}$C-NMR spectra were recorded on the same instruments at 50 MHz and 100 MHz respectively.

High Performance Liquid Chromatography was carried out using a Waters Model 510 dual pump unit with a Waters U6K injector unit. HPLC grade methanol (Hipersolv by BDH) and analytically pure water (Millipore) were used as a 60 % methanol solution that was degassed for 1 h (sonication) before use. A Phenomenex reverse phase column (250 mm x 4.6 mm, packed with Hypersil 10 $C_{18}$ resin; flow rate: 1.5 ml $min^{-1}$) connected to a Waters Model 440 fixed wavelength detector (254 nm) was used. Thin layer chromatography was performed on aluminium backed silica gel 60 $F_{254}$ plates in a variety of solvent systems using the ascending technique. The plates were visualised by illumination under ultra violet light, or sprayed with anisaldehyde spray reagent (freshly prepared by mixing equal volumes of an ethanolic 5% anisaldehyde solution with an ethanolic 10 % sulfuric acid

solution) and developed in an oven at 200 °C. Column chromatography was conducted with Merck Kieselgel 60, 70-230 mesh for gravity and 230-400 mesh for flash chromatography.

Extractions were carried out three times with the specified solvent. All solvents used in reactions were dried by the appropriate method,[60] and unless otherwise specified, all reactions were carried out under a nitrogen atmosphere with the exclusion of water and oxygen.

Abbreviations:

| | |
|---|---|
| AIBN | α, α'-azobis(isobutyronitrile) |
| COSY | correlation spectroscopy |
| FAB | fast atom bombardment |
| $W_{1/2}$ | width of peak at half height, Hz |
| W coupling | through four bond proton coupling, trace of bonds have shape of letter W. |

Conventions used to identify protons of Diels-Alder cycloaddition products:

| | |
|---|---|
| *Endo* proton | Proton of dienophile on the face of the newly formed bonds where dienophile has bonded to diene in an *exo* manner. |
| $H_n$ and $H_x$ | *Endo* and *exo* protons respectively. |
| *Syn* proton | Proton of a carbon bridge facing the endocyclic double bond of the cyclohexene part of a bicyclic[2.2.1]heptenoid system. |

**Sodium benzenesulfinate (34)**

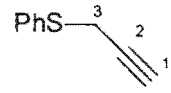
(**a**) A mixture of benzenesulfonyl chloride (**33**) (6.90 g, 39 mmol) and sodium sulfite (6.30 g, 50 mmol) in water (100 $cm^3$) was heated to 75 °C with vigorous stirring. Sodium hydrogen carbonate (3.36 g, 40 mmol) in water (40 $cm^3$) was added slowly (10 min) and the temperature of the mixture was maintained for 20 min. The solution was cooled to 25 °C and concentrated under reduced pressure to a white solid which was washed with hot ethanol (2 x 50 $cm^3$) and dried under reduced pressure to yield sodium benzenesulfinate (**34**)[28] (4.63 g, 72 %) as a white powder which was used directly in the following reaction.

(**b**) A mixture of benzenesulfonyl chloride (**33**) (26.77 g, 152 mmol) and sodium iodide (68.00 g, 454 mmol) in acetone (400 $cm^3$) was stirred for 3 h. The dark precipitate was collected by filtration and washed with acetone and dried under reduced pressure to yield sodium benzenesulfinate (**34**)[29] (23.9 g, 96 %) as a white powder which was used directly in the following reaction.

**Benzenesulfonyl iodide (29)**

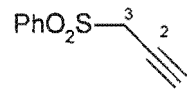
A solution of iodine (8.80 g, 69 mmol) in dichloromethane (80 $cm^3$) was added in portions (10 $cm^3$) to aqueous sodium benzenesulfinate (**34**) (0.04 $mol.dm^{-3}$, 5.72 g, 35 mmol). The two phase mixture was shaken after each addition and the organic layer was dried ($MgSO_4$) and the solvent was removed under reduced pressure to yield a dark residue which was crystallised from carbon tetrachloride at low temperature to yield benzenesulfonyl iodide (**29**) (6.85 g, 73 %) as yellow crystals, m.p. 46 - 47 °C (from carbon tetrachloride) (lit.[29], 45 - 46 °C) (Found: C, 27.2; H, 1.9; S, 12.2 %; $M^+$, 268. $C_6H_5IO_2S$ requires C, 26.9; H, 1.9; S, 12.0 %; *M*, 268).

**3-Phenylsulfanylprop-1-yne**




3-Bromopropyne (80 % solution in toluene, 12.20 $cm^3$, 110 mmol) was added slowly over 2 h to a stirred solution of thiophenol (10.94 g, 100 mmol) in methanolic potassium hydroxide (5.72 g, 102 mmol) at 0 °C. The solution was warmed to 25 °C and stirred for 16 h after which water (300 $cm^3$) was added and the solution was concentrated under reduced pressure and extracted with ethyl acetate. The combined organic phase was washed (saturated $NH_4Cl$, water and brine), dried ($MgSO_4$), and concentrated under reduced pressure to yield a yellow oil which was distilled to yield 3-phenylsulfanylprop-1-yne (13.73 g, 93 %) as a clear oil, (b.p. 114 - 116 °C, 16 mm Hg) (lit.[61], 104 - 110 °C, 10 mm Hg) (Found: C, 68.5; H, 5.4; S, 21.7 %; $M^+$, 148. $C_9H_8S$ requires C, 72.9; H, 5.4; S, 21.6 %; *M*, 148); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 3320 (alkynyl H); $\delta_H$(200 MHz; $CDCl_3$) 2.32 (1 H, t, *J* 2 x 2.7 Hz, 1-H), 3.65 (2 H, d, *J* 2.7 Hz, 3-$H_2$), 7.25 - 7.44 (3 H, m, *m*-, *p*-H, $C_6H_5S$), 7.50 - 7.57 (2 H, m, *o*-H, $C_6H_5S$).

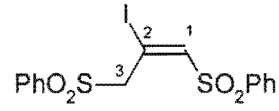
**3-Phenylsulfonylprop-1-yne (30)**




Hydrogen peroxide solution (8 $mol.dm^{-3}$, 220 $cm^3$, 1.76 mol) was added dropwise to a stirred solution of 3-phenylsulfanylprop-1-yne, (13.94 g, 94.0 mmol) in glacial acetic acid (150 $cm^3$) at 16 °C. The solution was left at 25 °C for 36 h after which sodium chloride (5 g) was added to the reaction mixture to assist separation and the mixture was extracted with ethyl acetate. The combined organic phase was washed (saturated $NaHCO_3$, water and

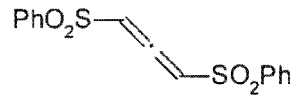
brine), dried ($MgSO_4$), and concentrated under reduced pressure to yield 3-phenylsulfonylprop-1-yne (**30**) (16.48 g, 97 %) as a white crystalline residue, m.p. 89 - 91 °C (from ethyl acetate - hexane) (lit.[34], 93 °C) (Found: C, 60.2; H, 4.6; S, 17.95 %; $M^+$, 180. $C_9H_8O_2S$ requires C, 60.0; H, 4.5; S, 17.8 %; *M*, 180); $\nu_{max}(CHCl_3)/cm^{-1}$ 3306 (alkynyl H); 1326, 1166 ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 2.36 (1 H, t, *J* 2 x 2.7 Hz, 1-H), 3.96 (2 H, d, *J* 2.7 Hz, 3-$H_2$), 7.51 - 7.73 (3 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.92 - 7.99 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 48.2 (C-1), 76.2 (C-3), 71.5 (C-2), 128.7 (*o*-C), 129.0 (*m*-C), 134.2 (*p*-C), 137.5 (*quat*-C, $C_6H_5O_2S$).

**(*E*)-2-Iodo-1,3-bis(phenylsulfonyl)prop-1-ene (31)**




3-Phenylsulfonylprop-1-yne, (**30**), (4.65 g, 25.81 mmol) and AIBN (1 mg) were added to benzene (20 $cm^3$) and heated to 80 °C with stirring. Benzenesulfonyl iodide, (**29**), (6.92 g, 25.81 mmol) in benzene (10 $cm^3$) was added dropwise over 1 h and the mixture was stirred for a further 20 h. The solution was cooled to 0 °C, the crystals were collected by filtration, washed (40 % $Na_2S_2O_5$ solution and cold water), and dried under reduced pressure to yield (*E*)-2-iodo-1,3-bis(phenylsulfonyl)prop-1-ene (**31**) (11.22 g, 97 %) as a brown crystalline product, m.p. 118 - 120 °C (from carbon tetrachloride) (lit.[27], 119 - 121 °C) (Found: C, 40.5; H, 2.9; S, 14.4 %; $M^+$, 448. $C_{15}H_{13}IO_4S_2$ requires C, 40.2; H, 2.9; S, 14.3 %; *M*, 448); $\nu_{max}(CHCl_3)/cm^{-1}$ 1326, 1154 ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 5.21 (2 H, s, 3-$H_2$), 7.20 (1 H, s, 1-H), 7.51 - 7.79 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.91 - 8.08 (4 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 62.9 (C-3), 98.7 (C-1), 128.1 (*o*-C), 128.8 (*o*-C), 129.4 (*m*-C), 129.6 (*m*-C), 134.4 (*p*-C), 138.9 (*quat*-C, $C_6H_5O_2S$), 139.1 (*quat*-C, $C_6H_5O_2S$), 143.8 (C-2).

**1,3-Bis(phenylsulfonyl)propadiene (32)**



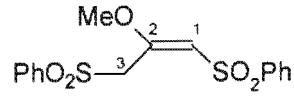

Triethylamine (0.1 mol.dm$^{-3}$, 3.13 mmol) in tetrahydrofuran was added slowly to a stirred solution of 2-iodo-1,3-bis(phenylsulfonyl)prop-1-ene (**31**), (1.34 g, 3.12 mmol) in tetrahydrofuran (4 cm$^3$) at -78 °C. After 30 min the reaction was poured into a cold, aqueous solution of hydrochloric acid (2 mmol.dm$^{-3}$, 200 cm$^3$). The precipitate was isolated and dried under reduced pressure to yield 1,3-bis(phenylsulfonyl)propadiene (**32**) (0.819 g, 82 %) as a pale yellow solid, m.p. 103 - 105 °C (from carbon tetrachloride - hexane) (lit.[27], 105 - 106 °C) (Found: C, 55.9; H, 3.7; S, 19.9 %; $M^+$, 320. $C_{15}H_{12}O_4S_2$ requires C, 56.2; H, 3.8; S, 20.0 %; *M*, 320); $\nu_{max}(CHCl_3)$/cm$^{-1}$ 1965 (C=C=C), 1330, 1158 ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 6.74 (2 H, s, 1- and 3-H), 7.48 - 7.79 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.94 - 8.01 (4 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 107.9 (C-1, C-3), 127.9 (*o*-C), 129.4 (*m*-C), 134.4 (*p*-C), 139.7 (*quat*-C, $C_6H_5O_2S$), 206.3 (C-2).

**Solvent dependent reactivity of 1,3-bis(phenylsulfonyl)propadiene**

**(a) Diethyl ether, acetone, chloroform, ethyl acetate and benzene.**

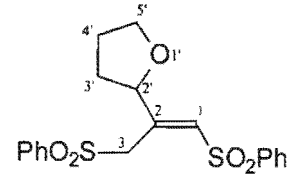
1,3-Bis(phenylsulfonyl)propadiene (**32**), (180 mg, 0.56 mmol) was added to 6 cm$^3$ of each of the above solvents and refluxed for 24 h, after which the solution was concentrated and dried under reduced pressure to yield a residue (180 mg) that was shown by NMR (60 MHz) to be unchanged in each case.

**(b) Methanol**




1,3-Bis(phenylsulfonyl)propadiene (**32**), (180 mg, 0.56 mmol) in methanol (6 $cm^3$) was refluxed for 24 h, after which the solution was concentrated and dried under reduced pressure to yield a residue (219 mg) that was chromatographed on silica gel (20 g) with ethyl acetate - toluene (1:9) as eluent to yield (E)-2-*methoxy*-1,3-*bis(phenylsulfonyl)prop*-1-*ene* (**37**) (163 mg, 82 %), m.p. 148 - 149 °C (from ethyl acetate - toluene) (Found: C, 54.45; H, 4.6; S, 18.2 %; *m/z*, 211 ($M^+$-$C_6H_5O_2S$). $C_{16}H_{16}O_5S_2$ requires C, 54.5; H, 4.6; S, 18.2 %; *M*, 352); $\nu_{max}$($CHCl_3$)/$cm^{-1}$ 1276 (OMe), 1149, 1310 ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 3.54 (3 H, s, 2-OMe), 4.79 (2 H, s, 3-$H_2$), 5.59 (1 H, s, 1-H), 7.44 - 7.71 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.88 - 8.00 (4 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 56.5 (2-OMe), 56.8 (C-3), 107.4 (C-1), 127.1 (*o*-C), 128.2 (*o*-C), 129.1 (*m*-C), 133.2 (*p*-C), 133.9 (*p*-C), 139.5 (*quat*-C, $C_6H_5O_2S$), 142.1 (*quat*-C, $C_6H_5O_2S$), 158.7 (C-2).

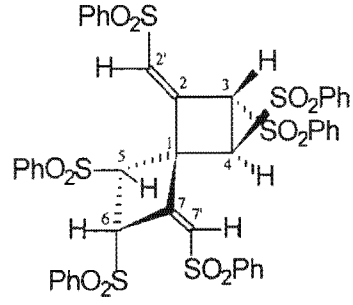
**c) Tetrahydrofuran**




1,3-Bis(phenylsulfonyl)propadiene (**32**), (180 mg, 0.56 mmol) in tetrahydrofuran (6 $cm^3$) was refluxed for 5 d, after which the solution was concentrated and dried under reduced pressure to yield a residue (192 mg) which was chromatographed on silica gel (20 g) with ethyl acetate - toluene (1:9) as eluent to yield (E)-2-*(2-tetrahydrofuranyl)*- 1,3-*bis(phenylsulfonyl)propene* (**39**) (157 mg, 71 %), m.p. 133 - 135 °C (from ethyl acetate - toluene) (Found: C, 58.1; H, 5.3; S, 16.2 %; *m/z* 251, ($M^+$-$C_6H_5O_2S$). $C_{19}H_{20}O_5S_2$ requires

C, 58.1; H, 5.1; S, 16.3 %; *M*, 392); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1149, 1308 ($C_6H_5O_2S$); $\delta_H$(400 MHz; $CDCl_3$) 1.64 (1 H, dq, *J* 12.2, 3 x 7.9 Hz, 3'-H), 1.88 - 1.99 (2 H, m, 4'-$H_2$), 2.39 (1 H, dtd, *J* 12.2, 2 x 7.3, 5.3 Hz, 3'-H), 3.84 - 3.88 (2 H, m, 5-$H_2$) 3.91 (1 H, d, *J* 13.2 Hz, 3-H), 4.92 (1 H, td, *J* 2 x 1.6, 7.3 Hz, 2'-H), 5.65 (1 H, d, *J* 13.2 Hz, 3-H), 6.66 (1 H, d, *J* 1.6 Hz, 1-H), 7.50 - 7.72 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.87 - 7.89 (2 H, m, *o*-H, $C_6H_5O_2S$) 8.01 - 8.04 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(100 MHz) 25.6 (C-4'), 31.5 (C-3'), 54.3 (C-3), 68.8 (C-5'), 79.4 (C-2'), 127.7 (*o*-C), 128.5 (*o*-C), 129.0 (C-1), 129.2 (*m*-C), 129.3 (*m*-C), 133.7 (*p*-C), 134.1 (*p*-C), 139.2 (*quat*-C, $C_6H_5O_2S$), 140.5 (*quat*-C, $C_6H_5O_2S$), 144.3 (C-2).

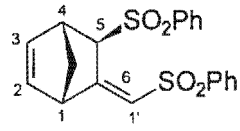
**2,7-Bis(phenylsulfonylmethylene)-3,4,5,6-tetraphenylsulfonyl-spiro[3.3.0]heptane (40)**



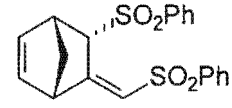

1,3-Bis(phenylsulfonyl)propadiene (**32**) (3.00 g) was taken up in 10 x 10 $cm^3$ portions of boiling carbon tetrachloride over a steam bath. The dark insoluble residue remaining (1.29 g) was dried under vacuum. A portion of this (663 mg) was chromatographed on silica gel (80 g) with ethyl acetate - toluene (1:9) as eluent to yield uncharacterised material (25 mg), followed by 1,3-bis(phenylsulfonyl)propadiene (**32**) (54 mg, 4 %) $\delta_H$(60 MHz; $CDCl_3$) 6.7 (2 H, s, 1- and 3-H), 7.1-7.9 (10 H, m, $C_6H_5O_2S$) followed by uncharacterised material (53 mg), followed by *2,7-bis(phenylsulfonylmethylene)-3,4,5,6-tetraphenylsulfonyl-spiro[3.3.0]heptane* (**40**) (498 mg, 34 %), m.p. 141 - 142 °C (from ethyl acetate - hexane) (Found: C, 56.1; H, 3.8; S, 20.1%; $M^+$, 960. $C_{45}H_{36}O_{12}S_6$ requires C, 56.2; H, 3.8; S, 20.0 %; *M*, 960); $\nu_{max}$($CHCl_3$)$cm^{-1}$ 1318, 1307, 1151 ($C_6H_5O_2S$);

$\delta_H$(400 MHz; $CDCl_3$) 4.86 (2 H, d, *J* 13.4 Hz, 4-, 5-H), 5.13 (2 H, d, *J* 13.4 Hz, 3-, 6-H), 6.92 (2 H, s, 2'-, 7'-H), 7.40 (4 H, t, *m*-H, $C_6H_5O_2S$), 7.50-7.60 (10 H, m, *m*-H (8 H), *p*-H (2 H) $C_6H_5O_2S$), 7.62-7.69 (4 H, m, *p*-H, $C_6H_5O_2S$), 7.76 (4 H, dd, *J* 1.2, 7.4 Hz, *o*-H, $C_6H_5O_2S$), 7.89 (4 H, dd, *J* 2.1, 7.4 Hz, *o*-H, $C_6H_5O_2S$ ), 8.00 (4 H, dd, *J* 1.2, 7.4 Hz, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 54.7 (C-4), 123.3 (C-1), 127.8 (C-2), 128.1 (*o*-C), 128.8 (*o*-C), 129.0 (*o*-C), 129.1 (*m*-C), 129.4 (*m*-C), 129.5 (*m*-C), 134.2 (*p*-C), 135.1 (*p*-C), 136.9 (*quat*-C, $C_6H_5O_2S$), 137.2 (C-2'), 138.5 (*quat*-C, $C_6H_5O_2S$), 139.2 (*quat*-C, $C_6H_5O_2S$), 207.0 (?), followed by a mixed uncharacterised fraction (21 mg).

**Cycloaddition of 1,3-bis(phenylsulfonyl)propadiene and cyclopentadiene**




**43 a**




**43 b**

Cyclopentadiene (0.85 $cm^3$, 10 mmol) was added to 1,3-bis(phenylsulfonyl)propadiene (**32**) (320 mg, 1.00 mmol) in dichloromethane (1.2 $cm^3$) at 0 °C and the reaction mixture was stirred for 3 min. The reaction mixture was chromatographed on silica gel (55 g) with ethyl acetate - toluene (1:40) as eluent under pressure to yield (*exo*)-(1'-Z)-5-*phenylsulfonyl-6-phenylsulfonylmethylene-bicyclo[2.2.1]hept-2-ene* (**43 a**) (160 mg, 41 %), m.p. 146 - 147 °C (from ethyl acetate - hexane) (Found: C, 61.9; H, 4.9; S, 16.5 %. $C_{20}H_{18}O_4S_2$ requires C, 62.2; H, 4.7; S, 16.6 %); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1334, 1313, 1140 ($C_6H_5O_2S$); $\delta_H$(200 MHz, $CDCl_3$)* 1.80 (1 H, br d, *J* 9.8, $W_{1/2}$ 1.2 Hz, 7-$H_s$), 2.52 (1 H, d, *J* 9.8 Hz, 7-$H_a$), 3.43 (2 H, br s, $W_{1/2}$ 8.0 Hz, 1-H and 4-H), 4.69 (1 H, t, *J* 2 x 2.1 Hz, 5-$H_n$), 6.17 - 6.29 (2 H, m, 3-H and 2-H), 6.53 (1 H, d, *J* 1.6 Hz, 1'-H), 7.46 - 7.72 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.98 (2 H, m, *o*-H, $C_6H_5O_2S$), 8.16 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 47.2, 47.2 (C-4 and C-7), 51.0 (C-1), 68.2 (C-5), 126.3 (C-1'), 127.6 (*o*-C), 128.5 (*o*-C),

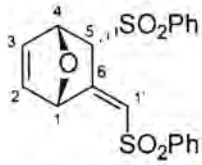
* A detailed NMR study of compounds **43 a** and **43 b** has been performed. See Ref. 27.

128.9 (*m*-C), 129.1 (*m*-C), 133.2 (*p*-C), 133.6 (*p*-C), 137.9 (C-3), 139.9 (C-2), 141.1 (*quat*-C, $C_6H_5O_2S$), 151.0 (C-6), followed by (*endo*)-(1'-Z)-5-*phenylsulfonyl*-6-*phenylsulfonylmethylene-bicyclo*[2.2.1]*hept*-2-*ene* (**43 b**) (202 mg, 52 %), m.p. 212 - 214 °C; phase change at 194 °C (from ethyl acetate - hexane) (Found: C, 62.3; H, 4.8; S, 16.3 %. $C_{20}H_{18}O_4S_2$ requires C, 62.2; H, 4.7; S, 16.6 %; $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1325, 1313, 1140 ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 1.49 (1 H, d, *J* 9.1 Hz, 7-$H_a$), 1.82 (1 H, dt, *J* 9.1, 2 x 1.6 Hz, 7-$H_s$), 3.44 (2 H, br s, $W_{1/2}$ 8.0 Hz, 1-H and 4-H), 5.29 (1 H, m, 5-$H_x$), 6.17 (1 H, dd, *J* 2.9, 5.6 Hz, 2-H), 6.51 (1 H, d, *J* 2.1 Hz, 1'-H), 6.71 (1 H, dd, *J* 2.9, 5.6 Hz, 3-H), 7.46 - 7.67 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 8.23 (4 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 46.4 (C-4), 51.0 (C-7), 55.5 (C-1), 70.9 (C-5), 124.6 (C-1'), 127.6 (*o*-C), 128.0 (*o*-C), 128.7 (*m*-C), 128.9 (*m*-C), 131.1 (C-3), 133.1 (*p*-C), 133.2 (*p*-C), 139.4 (C-2), 141.1 (*quat*-C, $C_6H_5O_2S$), 142.3 (*quat*-C, $C_6H_5O_2S$), 152.1 (C-6).

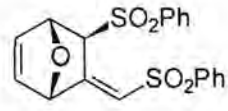
**Estimation of cycloaddition reaction rate of 1,3-bis(phenylsulfonyl)propadiene and cyclopentadiene by 60 MHz NMR**

1,3-Bis(phenylsulfonyl)propadiene (**32**) (96 mg, 0.3 mmol), in $CDCl_3$ (0.4 $cm^3$, 0.075 $mol.dm^{-3}$) was added to a 2.5 $cm^3$ Norell XR-55 NMR tube and cooled to 0 °C. Cyclopentadiene (0.2 $cm^3$, 2.7 mmol, 9 molar equivalents) was added and the spectrum obtained at 30 s intervals on an NMR instrument (60 MHz). The appearance of signals at $\delta_H$ 3.4 - 3.5 (bridgehead protons of cycloadducts) was monitored and complete conversion taken as the time when the ratio of bridgehead to $C_6H_5O_2S$ protons was equal to 0.2. This was determined to be 90 s.

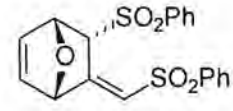
**Cycloaddition of 1,3-bis(phenylsulfonyl)propadiene and furan**



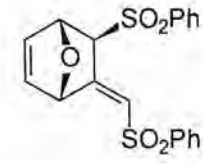

**46 a**




**46 b**




**46 c**




**46 d**

1,3-Bis(phenylsulfonyl)propadiene (320 mg, 1.00 mmol) and furan (10 $cm^3$) were added to a 20 $cm^3$ tube and the sealed tube was heated at 80 °C. After 2 h the reaction was cooled and concentrated under reduced pressure to yield a residue (504 mg) that was chromatographed on silica gel (50 g) with ethyl acetate - toluene (1:39) as eluent under pressure to yield (*endo*)-(1'-E)- 5-*phenylsulfonyl*-6-*phenylsulfonylmethylene*-7-*oxabicyclo*[2.2.1]*hept*-2-*ene* (**46 a**) (14 mg, 4 %), m.p. 141 - 143 °C (from ethyl acetate - toluene) (Found: C, 58.8; H, 4.2; S, 16.4 %; $M^+$, 388. $C_{19}H_{16}O_5S_2$ requires C, 58.8; H, 4.1; S, 16.5 %; *M*, 388); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1152, 1324, ($C_6H_5O_2S$); $\delta_H$(400 MHz; $CDCl_3$) 4.31 (1 H, dd, *J* 1.9, 3.9 Hz, 5-$H_x$), 4.96 (1 H, dt, *J* 2 x 1.3, 3.9 Hz, 4-H), 6.39 (2 H, m, 1-H and 3-H), 6.46 (1 H, dd, *J* 1.9, 5.8 Hz, 2-H), 6.76 (1 H, dd, *J* 1.2, 1.9 Hz, 1'-H), 7.58 (4 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.69 (2 H, m, *m*-H, $C_6H_5O_2S$), 7.79 (2 H, m, *o*-H, $C_6H_5O_2S$) 7.89 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(100 MHz) 67.4 (C-5), 77.9 (C-4), 81.1 (C-1), 125.8 (C-1') 127.4 (*o*-C) 128.6 (*o*-C), 129.5 (*m*-C), 129.6 (*m*-C), 133.7 (*p*-C), 133.9 (*p*-C), 134.7 (C-2), 134.9 (C-3), 137.9 (*quat*-C, $C_6H_5O_2S$), 140.5 (*quat*-C, $C_6H_5O_2S$), 145.9 (C-6), followed by (*exo*)-(1'-Z)- 5-*phenylsulfonyl*-6-*phenylsulfonylmethylene*-7-*oxa*-*bicyclo*[2.2.1]*hept*-2-*ene* (**46 b**)* (71 mg, 18 %), m.p. 185 - 186 °C (from ethyl acetate) (Found: C, 58.7; H, 4.2; S, 16.5 %; $M^+$, 388. $C_{19}H_{16}S_2O_5$ requires C, 58.7; H, 4.2; S, 16.5 %; *M*, 388); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1141, 1309, 1318, ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 3.73 (1 H, br s, 5-$H_n$), 5.42 (1 H, s, 1-H), 5.99 (1 H, m, 4-H), 6.50 (1 H, dd, *J* 1.7, 5.6 Hz, 2-H), 6.61 (1 H, dd, *J* 1.7, 5.6 Hz, 3-H), 6.79 (1 H, m, 1'-H), 7.28 (2 H, m, *m*-H, $C_6H_5O_2S$), 7.47 - 7.64 (6 H, m, *o*-, *m*-, *p*-H, $C_6H_5O_2S$), 7.88 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 69.1 (C-5), 79.2 (C-4), 79.4 (C-1),

* A detailed NMR study of compounds **46 b-d** has been performed. See Ref. 27.

127.2 (C-1'), 127.6 (*o*-C), 128.9 (*o*-C), 129.5 (*m*-C), 129.6 (*m*-C), 133.9 (*p*-C), 134.1 (*p*-C), 136.4 (C-2), 136.6 (*quat*-C, $C_6H_5O_2S$),137.4 (C-3), 140.4 (*quat*-C, $C_6H_5O_2S$), 146.1 (C-6), followed by (*endo*)-(1'-Z)- 5-*phenylsulfonyl*-6-*phenylsulfonylmethylene*-7-*oxa*-*bicyclo*[2.2.1]*hept*-2-*ene* (**46 c**) (93 mg, 24 %), m.p. 158 - 159 °C (from ethyl acetate - toluene) (Found: C, 59.0; H, 4.6; S, 15.5 %; $M^+$, 388. $C_{19}H_{16}O_5S_2$ requires C, 58.7; H, 4.2; S, 16.5 %; *M*, 388)[#] ; $\nu_{max}(CHCl_3)/cm^{-1}$ 1151, 1309, 1318, ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 5.16 (1 H, br s, $W_{1/2}$ 4.0 Hz, 1-H), 5.35 (1 H, dd, *J* 2.1, 4.4 Hz, 5-$H_x$), 5.46 (1 H, m, 4-H), 6.47 (1 H, d, *J* 2.1 Hz, 1'-H), 6.57 (1-H, dd, *J* 1.7, 5.7 Hz, 3-H), 7.06 (1 H, dd, *J* 1.7, 5.7 Hz, 2-H), 7.46 - 7.70 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.90 (2 H, m, *o*-H, $C_6H_5O_2S$), 8.01 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz), 69.2 (C-5), 80.3 (C-4), 85.3 (C-1), 125.8 (C-1'), 127.8 (*o*-C), 128.2 (*o*-C), 128.8 (*m*-C), 129.2 (*m*-C), 132.3 (C-3), 133.5 (*p*-C), 133.7 (*p*-C), 139.5 (C-2), 140.5 (*quat*-C, $C_6H_5O_2S$), 141.9 (*quat*-C, $C_6H_5O_2S$), 144.3 (C-6), followed by (*exo*)-(1'-E)-5-*phenylsulfonyl*-6-*phenylsulfonylmethylene*-7-*oxa*-*bicyclo*[2.2.1]*hept*-2-*ene* (**46 d**) (49 mg, 13 %), m.p. 187 - 188 °C (from ethyl acetate - toluene) (Found: C, 58.8; H, 4.2; S, 16.3 %; $M^+$, 388. $C_{19}H_{16}O_5S_2$ requires C, 58.7; H, 4.2; S, 16.5 %; *M*, 388); $\nu_{max}(CHCl_3)/cm^{-1}$ 1151, 1311, 1325, ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 4.82 (1 H, m, 5-$H_n$), 5.16 (1 H, m, 4-H), 5.48 (1 H, m, 1-H), 6.43 (1 H, dd, *J* 1.8, 5.6 Hz, 3-H), 6.53 (1 H, dd, *J* 1.8, 5.6 Hz, 2-H), 6.57 (1 H, m, 1'-H), 7.49 - 7.69 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 8.05 (4 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(50 MHz) 67.8 (C-5), 81.3 (C-4), 81.9 (C-1), 127.0 (C-1'), 128.1 (*o*-C), 129.0 (*o*-C), 129.1 (*m*-C), 133.7 (*p*-C), 133.8 (*p*-C), 136.0 (C-2), 138.6 (C-3), 139.9 (*quat*-C, $C_6H_5O_2S$), 140.4 (*quat*-C, $C_6H_5O_2S$), 145.4 (C-6).

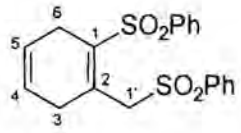
**Estimation of cycloaddition reaction rate of 1,3-bis(phenylsulfonyl)propadiene and furan by 60 MHz NMR.**

1,3-Bis(phenylsulfonyl)propadiene (**32**) (224 mg, 0.7 mmol) in $CDCl_3$ (0.75 $cm^3$, 0.09 $mol.dm^{-3}$) was added to a 2 $cm^3$ cycloaddition tube. Furan (0.25 $cm^3$, 3.5 mmol, 5 molar equivalents) was added, and the sealed tube was heated to 80 °C for 15 min. The

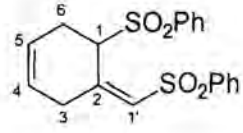
[#] After repeated recrystallisation this microanalysis was not improved upon. Accurate microanalysis has been obtained for this compound. See Ref 27.

tube was removed from the heat, cooled, and a portion removed for NMR analysis. After the measurement the sample was returned to the cycloaddition tube and reheated for 15 min. This cycle was repeated. The disappearance of the allenyl peak at $\delta_H$ 6.7 indicated the complete cycloaddition of the allene. This was determined to be 2 h.

**Cycloaddition of 1,3-bis(phenylsulfonyl)propadiene and butadiene**




**47 a**




**47 b**

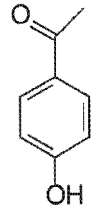
Butadiene (0.85 $cm^3$, 10 mmol) was bubbled through 1,3-bis(phenylsulfonyl)propadiene (**32**) (320 mg, 1.00 mmol) in dichloromethane (1.17 $cm^3$) in a 10 $cm^3$ tube at -78 °C to a total volume of 2.0 $cm^3$. The tube was sealed and heated at 80 °C for 26 h after which the solution was cooled and concentrated under reduced pressure to give a residue (528 mg) that was chromatographed on silica gel (50 g) with ethyl acetate - toluene (1:40) as eluent to yield 1-*phenylsulfonyl*-2-*phenylsulfonylmethylcyclohexa*-1,4-*diene* (**47 a**) (21 mg, 5 %), m.p. 151 - 152 °C (from ethyl acetate - hexane) (Found: C, 61.35; H, 5.4; S, 15.1 %; $M^+$, 374. $C_{19}H_{18}O_4S_2$ requires C, 60.9; H, 4.8; S, 17.1 %; *M*, 374); $\nu_{max}(CHCl_3)/cm^{-1}$ 1325, 1311, 1151, ($C_6H_5O_2S$); $\delta_H$(400 MHz; $CDCl_3$) 2.81 (2 H, m, 3-$H_2$), 3.30 (2 H, m, 6-$H_2$), 4.89 (2 H, s, 1'-H), 5.58 - 5.67 (2 H, m, 4-H, 5-H), 7.52 - 7.72 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.99 (2 H, m, *o*-H, $C_6H_5O_2S$), 8.05 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(100 MHz) 27.9 (C-3), 34.6 (C-6), 58.3 (C-1'), 122.1 (C-4), 122.2 (C-5), 128.2 (*o*-C), 128.4 (*o*-C) 129.1 (*m*-C), 129.3 (*m*-C), 133.7 (*p*-C), 134.0 (*p*-C), 134,1 (C-1), 137.5 (C-2), 139.1 (*quat*-C, $C_6H_5O_2S$), 139.5 (*quat*-C, $C_6H_5O_2S$) followed by (±)-1-*phenylsulfonyl*-2-*phenylsulfonylmethylenecyclohex*-4-*ene* (**47 b**) (165 mg, 44 %), m.p. 129 - 130 °C (from ethyl acetate - hexane) (Found: C, 60.8; H, 5.0; S, 16.8 %; $M^+$, 374. $C_{19}H_{18}O_4S_2$ requires C, 60.9; H, 4.8; S, 17.1 %; *M*, 374); $\nu_{max}(CHCl_3)/cm^{-1}$ 1325, 1311, 1151, ($C_6H_5O_2S$); $\delta_H$(400 MHz; $CDCl_3$) 2.54 (1 H, m, H-6), 2.66 - 2.84 (2 H, m, H-3, H-6), 3.55 (1 H, m, H-3), 5.67 - 5.76 (2 H, m, H-4, H-5), 6.08

(1 H, dt, *J* 2 x 1.6, 7.6 Hz, H-1), 6.36 (1 H, d, *J* 2.3 Hz, H-1'), 7.61 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.91 (2 H, m, *o*-H, $C_6H_5O_2S$), 8.02 (2 H, m, *o*-H, $C_6H_5O_2S$); $\delta_C$(100 MHz) 26.4 (C-6), 33.3 (C-3), 57.8 (C-1), 122.6 (C-5), 124.4 (C-4), 127.6 (*o*-C), 128.9 (*o*-C), 129.3 (*m*-C), 129.8 (C-2), 133.7 (*p*-C), 134.0 (*p*-C), 138.1 (*quat*-C, $C_6H_5O_2S$), 140.6 (*quat*-C, $C_6H_5O_2S$), 144.3 (C-1') followed by two uncharacterised fractions of 29 mg and 30 mg.

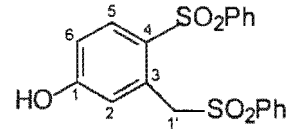
**(*E*)-1-Methoxy-3-trimethylsilyloxy-1,3-butadiene (49)**[56]

Zinc chloride (340 mg, 2.5 mmol), dried by heating in a crucible for 10 min and cooling under nitrogen, was added to triethylamine (20.18 g, 200 mmol) at 0 °C and stirred for 1 h. (*E*)-4-Methoxy-3-buten-2-one (**51**) (9.82 g, 88 mmol) in benzene (25 $cm^3$) was added to the reaction mixture and stirred for 5 min. Chlorotrimethylsilane (19.17 g, 177 mmol) was then added and the reaction mixture was stirred for a further 30 min after which the temperature was raised to 43 °C for 24 h. The reaction mixture was then poured into diethyl ether (400 $cm^3$), filtered through Celite, washed with diethyl ether (3 x 10 $cm^3$) and concentrated under reduced pressure to yield a brown oil (18.1 g) which was distilled to give a clear liquid (*E*)-1-methoxy-3-trimethylsilyloxy-1,3-butadiene (**49**) (11.59 g, 76 %), (b.p. 79 - 82 °C, 2 mm Hg) shown to contain 13 % of the starting (*E*)-4-methoxy-3-buten-2-one (**51**) by NMR (60 MHz).

**Cycloaddition of 1,3-bis(phenylsulfonyl)propadiene with (*E*)-1-methoxy-3-trimethylsilyloxy-1,3-butadiene**




**50 a**

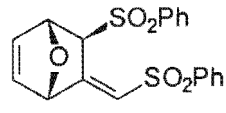



**50 b**

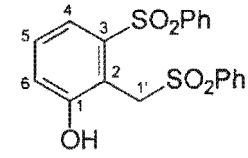
1,3-Bis(phenylsulfonyl)propadiene (**32**) (320 mg, 1 mmol) and a mixture of (*E*)-1-methoxy-3-trimethylsilyloxy-1,3-butadiene (**49**) containing 13 % of (*E*)-4-methoxy-3-buten-2-one (**51**) (1.72 g,), dissolved in dichloromethane (0.3 $cm^3$), was added to a 10 $cm^3$ tube. The sealed tube was heated at 80 °C for 8 h, after which the dark brown solid was removed and ground to a fine powder and extracted with dichloromethane. The soluble material was concentrated under reduced pressure to give a residue (390 mg) that was chromatographed on silica gel (100 g) with ethyl acetate - toluene (1:9) as eluent to yield an uncharacterised fraction (17 mg) followed by 4-hydroxyacetophenone (**50 a**) (166 mg), m.p. 108 - 109 °C (from ethyl acetate - hexane) (lit[62], 109 °C), followed by *4-phenylsulfonyl-3-phenylsulfonylmethylphenol* (**50 b**) (86 mg, 22 %), m.p. 157 - 159 °C (from benzene - hexane) (Found: C, 59.1; H, 4.2; S, 16.4 %; $M^+$, 388. $C_{19}H_{16}O_5S_2$ requires C, 58.8; H, 4.2; S, 16.5 %; *M*, 388); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1150, 1309 ($C_6H_5O_2S$), 3553 (O-H); $\delta_H$(400 MHz; $CDCl_3$) 4.94 (2 H, s, 1'-$H_2$), 6.88 (1 H, dd, *J* 2.5, 8.8 Hz, 6-H), 7.29 (1 H, d, *J* 2.5 Hz, 2-H) 7.34 (1 H, br s, $D_2O$ exch., 1-OH), 7.43 - 7.67 (6 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.77 (4 H, m, *o*-H, $C_6H_5O_2S$), 7.82 (1 H, d, *J* 8.8 Hz, 5-H); $\delta_C$(100 MHz) 57.6 (C-1'), 116.7 (C-6), 120.3 (C-2), 127.0 (*o*-C), 128.2 (C-4), 128.5 (*o*-C), 129.1 (*m*-C), 129.2 (*m*-C), 131.1 (C-3), 133.1 (*p*-C), 133.3 (C-5), 134.2 (*p*-C), 138.3 (*quat*-C, $C_6H_5O_2S$), 142.2 (*quat*-C, $C_6H_5O_2S$), 160.5 (C-1).

**Base treatment of furan cycloadducts.**

**(a) Potassium tert-butoxide**




**46 b**




**54**

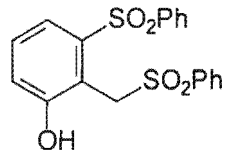
1,3-Bis(phenylsulfonyl)propadiene (**32**) (320 mg, 1.00 mmol) and furan (10 $cm^3$) in a sealed 20 $cm^3$ cycloaddition tube were heated at 80 °C for 2 h after which the reaction was cooled and concentrated under reduced pressure to yield a yellow residue (511 mg). A portion (164 mg) of this residue was added to tetrahydrofuran (10 $cm^3$) and cooled to -78 °C with stirring. A preformed solution containing potassium (66 mg, 1.68 mmol) in butyl alcohol (5 $cm^3$) was added dropwise to the reaction and after 10 min the dark brown solution was warmed to 25 °C and stirred for a further 2 min. The reaction was concentrated under reduced pressure and poured into an excess of aqueous hydrochloric acid (1 %) at 0 °C. The aqueous layer was extracted (ethyl acetate) and the combined organic phase was washed (saturated $Na_2CO_3$, water and brine), dried ($MgSO_4$), and concentrated under reduced pressure to yield a residue (202 mg) that was added to silica gel (20 g) with ethyl acetate, toluene as eluent to yield a compound which displayed an NMR spectrum identical to (**46 b**) (43 mg, 26 %), m.p. and mixed m.p. 186 - 187 °C (from ethyl acetate - hexane) followed by 3-*phenylsulfonyl*-2-*phenylsulfonylmethylphenol* (**54**) (102 mg, 63%), m.p. 165 - 167 °C (from ethyl acetate - hexane) (Found: C, 58.6; H, 4.05; S, 16.4 %, $M^+$, 388. $C_{19}H_{16}O_5S_2$ requires C, 58.7; H, 4.2; S, 16.5 %; *M*, 388); $\nu_{max}(CHCl_3)/cm^{-1}$ 1151, 1311, 1325 ($C_6H_5O_2S$); $\delta_H$(200 MHz; $CDCl_3$) 5.19 (2 H, s, 1'-$H_2$), 7.24 - 7.40 (2 H, m, 6-H, 5-H), 7.40 - 7.76 (7 H, m, 4-H, *m*-, *p*-H, $C_6H_5O_2S$), 7.79 - 7.94 (4 H, m, *o*-H, $C_6H_5O_2S$), 8.05 - 8.65 (1 H, br s, exch. by $D_2O$, O-H); $\delta_C$(50 MHz; $CDCl_3$) 54.3 (C-1'), 115.3 (C-2), 124.2 (C-6), 124.9 (C-5), 127.5 (*o*-C), 128.7 (*o*-C), 129.3 (*m*-C),

130.7 (C-4), 133.5 (*p*-C), 134.6 (*p*-C), 137.4 (*quat*-C, $C_6H_5O_2S$), 141.3 (C-3), 141.6 (*quat*-C, $C_6H_5O_2S$), 157.8 (C-1).

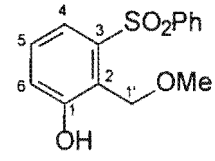
**(b) Sodium hydride**

(**46 b**) (80 mg, 0.206 mmol) was dissolved in tetrahydrofuran (10 $cm^3$) and cooled to -78 °C with stirring. Sodium hydride was washed with hexane and dried under reduced pressure to yield a fine grey powder, of which 20 mg, (0.82 mmol), was added to the solution. The reaction was warmed slowly to 25 °C for 16 h, after which the solution was concentrated under reduced pressure. Ethyl acetate (5 $cm^3$) and brine (2 $cm^3$) were added to assist separation of the two phases, and hydrochloric acid solution (1 %, 3 $cm^3$) was added and the solution was extracted. The aqueous layer was extracted (ethyl acetate) and the combined organic phase was washed (brine), dried ($MgSO_4$), and concentrated under reduced pressure to yield a yellow crystalline residue (76 mg) that was chromatographed on silica gel (13 g) with ethyl acetate - toluene (1:9) as eluent to yield 3-*phenylsulfonyl*-2-*phenylsulfonylmethylphenol* (**54**) (51 mg, 64 %), m.p. 165 - 167 °C (from ethyl acetate - hexane).

**(c) Sodium methoxide**




**54**




**55**

1,3-Bis(phenylsulfonyl)propadiene (**32**) (206 mg, 0.60 mmol) and furan (0.44 $cm^3$) were added to a 5 $cm^3$ tube and the sealed tube was heated at 80 °C for 2 h after which the cooled reaction was concentrated under reduced pressure to yield a yellow foam. A methanolic potassium hydroxide solution (0.04 $mol.dm^{-3}$, 8 $cm^3$) was added and the reaction was heated to reflux for 24 h, cooled and acidified with hydrochloric acid solution

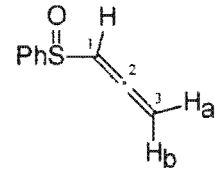
(2 %, 10 $cm^3$) and extracted (ethyl acetate). The combined organic phase was washed (brine), dried ($MgSO_4$), and concentrated under reduced pressure to yield a residue (216 mg) that was chromatographed on silica gel (5 g) with ethyl acetate - toluene (1:9) as eluent to yield an uncharacterised fraction (6 mg), followed by the phenol (**54**) (33 mg, 15 %) m.p. 165 - 167 °C (from ethyl acetate - toluene) ($M^+$, 388. $C_{19}H_{16}O_5S_2$ requires *M* 388) followed by 2-*methoxymethyl*-3-*phenylsulfonylphenol* (**55**) (23 mg, 14 %) m.p. 41 - 44 °C (from chloroform) ($M^+$, 278. $C_{14}H_{14}O_4S$ requires *M*, 278); $\nu_{max}(CHCl_3)/cm^{-1}$ 1155, 1307 ($C_6H_5O_2S$), 1262 (OMe), 3297 (O-H); $\delta_H$(400 MHz; $CDCl_3$) 3.19 (3 H, s, OMe), 4.99 (2 H, s, 1'-$H_2$), 7.12 (1 H, dd, *J* 1.2, 7.9 Hz, 6-H), 7.37 (1 H, t, *J* 2 x 7.9 Hz, 5-H), 7.49 - 7.60 (3 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.69 (1 H, dd, *J* 1.2, 7.9 Hz, 4-H), 7.84 (2 H, m, *o*-H, $C_6H_5O_2S$), 8.51 (1 H, s, exch. with $D_2O$, O-H); $\delta_C$(100 MHz; $CDCl_3$), 58.1 (OMe), 69.5 (C-1'), 120.3 (C-2), 121.1 (C-5), 122.9 (C-6), 127.3 (*o*-C), 129.1 (*m*-C), 129.2 (*m*-C), 133.3 (C-4), 133.7 (*p*-C) 139.0 (*quat*-C, $C_6H_5O_2S$), 141.5 (C-3), 158.6 (C-1).

**Phenylsulfenyl chloride**

**(a)** Sulfuryl chloride (16.20 g, 120 mmol) was added dropwise over 1.5 h to a stirred solution of thiophenol (11.02 g, 100 mmol) in pentane at 0 °C. The solution was warmed to 20 °C (colour change to red) and stirred overnight, after which the reaction mixture was concentrated under reduced pressure and the resulting oil was distilled to yield phenylsulfenyl chloride, (0.844 g, 6 %) as an orange oil, (b.p. 64 - 65 °C, 3 mm Hg) (lit.[63], 66 °C, 4 mm Hg).

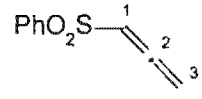
**(b)** Thiophenol (11.02 g, 100 mmol) in benzene (20 $cm^3$) was added over 0.5 h to a stirred solution of *N*-chlorosuccinimide (14.68 g, 110 mmol) in benzene (100 $cm^3$) at 0 °C. The temperature of the resulting yellow-orange solution was maintained at 20 °C overnight after which carbon tetrachloride (10 $cm^3$) was added and the solution was filtered and concentrated under reduced pressure to a red oil which was distilled to yield phenylsulfenyl chloride (8.80 g, 60.8 %) as an orange oil, (b.p. 62 - 63 °C, 2 mm Hg) (lit.[64], 58 °C, 0.8 mm Hg).

**Phenylsulfinylpropadiene**[65]




Phenylsulfenyl chloride (4.30 g, 30.00 mmol) in dichloromethane (30 $cm^3$) was added dropwise over 0.5 h to a stirred solution of triethylamine (3.54 g, 35.0 mmol) and propargyl alcohol (1.96 g, 35.0 mmol) in dichloromethane (140 $cm^3$) at -84 °C. After 0.5 h the temperature was raised to -10 °C and the reaction was quenched by adding aqueous hydrochloric acid (0.01 $dm^{-3}$, 100 $cm^3$) and then extracted (dichloromethane). The combined organic phase was washed (brine), dried ($MgSO_4$), and concentrated under reduced pressure to a straw coloured oil (4.51 g) that was distilled to yield phenylsulfinylpropadiene (3.63 g, 63 %) as a clear oil, (b.p. 115 - 120 °C, 0.2 mm Hg) (Found: C, 64.7; H, 5.1; S, 19.5 %; $M^+$, 164. $C_9H_8OS$ requires C, 65.8; H, 4.9; S, 19.5 %; *M*, 164]; $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1941 (C=C=C), 1030 ($C_6H_5OS$). $\delta_H$(200 MHz; $CDCl_3$) 5.18 (1 H, m, H-$3_b$), 5.22 (1 H, m, 3-$H_a$), 5.87 (1 H, t, *J* 6.3 Hz, 1-H), 7.34 - 7.48 (3 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.50 - 7.61 (2 H, m, *o*-H, $C_6H_5O_2S$), $\delta_C$(50 MHz) 82.1 (C-3), 101.8 (C-1), 123.9 (*o*-C), 129.0 (*m*-C), 130.9 (*p*-C), 144.3 (*quat*-C, $C_6H_5O_2S$), 207.3 (C-2).

**Phenylsulfonylpropadiene**




Glacial acetic acid (20 $cm^3$) was added to a stirred solution of phenylsulfinylpropadiene (2.00 g, 12.18 mmol) and $H_2O_2$ (1 mol.$dm^{-3}$, 11.8 $cm^3$, 0.12 mol) at 25 °C. After 4 d, water (50 $cm^3$) was added and the solution was cooled to 4 °C. The crystals were collected by

filtration and dried under reduced pressure to yield phenylsulfonylpropadiene (1.58 g, 72 %) as transparent needles, m.p. 43 - 44 °C (from hexane) (lit.[34], 40 - 41 °C) (Found: C, 60.0; H, 4.5; S, 17.85 %; $M^+$, 180. $C_9H_8O_2S$ requires C, 60.0; H, 4.5; S, 17.8 %; *M*, 180); $\nu_{max}$ ($CHCl_3$)/$cm^{-1}$ 1968 (C=C=C); 1324, 1150 ($C_6H_5O_2S$). $\delta_H$(200 MHz; $CDCl_3$) 5.44 (2 H, d, *J* 6.4 Hz, 3-H), 6.24 (1 H, t, *J* 6.4 Hz, 1-H), 7.48 - 7.68 (3 H, m, *m*-, *p*-H, $C_6H_5O_2S$), 7.91 (2 H, m, *o*-H, $C_6H_5O_2S$), $\delta_C$(50 MHz) 83.9 (C-3), 100.6 (C-1), 127.2 (*o*-C), 129.0 (*m*-C), 133.4 (*p*-C), 140.9 (*quat*-C, $C_6H_5O_2S$), 209.1 (C-2).

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